DIVERSITY OF ANGIOSPERMS ALONG ALTITUDINAL GRADIENTS AND MOLECULAR PHYLOGENY OF LAURACEAE OF PHAWNGPUI NATIONAL PARK MIZORAM

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Submitted

In partial fulfillment of the requirement of the Degree of Doctor of Philosophy in Botany of Mizoram university, Aizawl

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CERTIFICATE

This is to certify that this study **"Diversity of Angiosperms along altitudinal gradient and molecular phylogeny of Lauraceae of Phawngpui National Park Mizoram"** submitted by Lalrinmuana (MZU/Ph.D/1116 of 03.05.2018) in partial fulfillment of the requirement for the degree of Doctor of Philosophy in Botany is a record of bonafide work carried out by him under my guidance.

Supervisor

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DECLARATION

MIZORAM UNIVERSITY

MAY, 2025

I **LALRINMUANA**, hereby declare that the subject matter of this thesis is the record of work done by me, that the contents of this thesis did not form basis of the award of any previous degree to me or to do the best of my knowledge to anybody else, and thatthe thesis has not been submitted by me for any research degree in any other University/Institute.

This is being submitted to the Mizoram University for the **Degree of Doctor of Philosophy in Botany.**

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Date: **(LALRINMUANA)**

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LISTS OF ABBREVIATIONS AND SYMBOLS

AGB	**Aboveground Biomass**
DNA	**Deoxyribonucleic Acid**
PD	**Phylogenetic Diversity**
ITS2	**Internal Transcribed Spacer 2 (DNA marker)**
matK	**Maturase K gene (chloroplast DNA marker)**
DBH	**Diameter at Breast Height**
IVI	**Importance Value Index**
LAI	**Leaf Area Index**
LAF	**Low Altitude Forest (273–900 m)**
MAF	**Mid Altitude Forest (900–1500 m)**
HAF	**High Altitude Forest (1500–2157 m)**
RH	**Relative Humidity**
SOC	**Soil Organic Carbon**
N	**Nitrogen**
P	**Phosphorus**
K	**Potassium**
NMDS	**Non-Metric Multidimensional Scaling**
ANOSIM	**Analysis of Similarities**
CCA	**Canonical Correspondence Analysis**
PCA	**Principal Component Analysis**
IndVal	**Indicator Value**

SD	**Standard Deviation**
CS	**Carbon Stock**
ISA	**Indicator Species Analysis**
FIVI	**Family Importance Value Index**
SAC	**Species Accumulation Curve**
BIV	**Biomass Importance Value**
MAFFT	**Multiple Alignment using Fast Fourier Transform**
ML	**Maximum Likelihood (phylogenetic inference method)**
MEGA	**Molecular Evolutionary Genetics Analysis (software)**
WFO	**World Flora Online**
POWO	**Plants of the World Online**
WSG	**Wood Specific Gravity**
°C	**Degree Celsius**
mm	**Millimeter (unit of rainfall)**
cm	**Centimeter (used in DBH and sapling classification)**
m	**Meter (used for elevation, height, plot size)**
km²	**Square kilometer (used for area)**
R	**R Programming Language**
RStudio	**Integrated Development Environment (IDE) for R program**
v.	**Version**
H′	**Shannon Diversity Index**
D	**Simpson Diversity Index**
J′	**Pielou's Evenness Index**

β	**Beta Diversity**
Faith's PD	**Faith's Phylogenetic Diversity**
PDw	**Abundance-weighted Phylogenetic Diversity**
MPD	**Mean Pairwise Distance**
MNTD	**Mean Nearest Taxon Distance**
rbcL	**Ribulose-1,5-bisphosphate carboxylase/oxygenase large subunit**
GenBank	**Genetic Sequence Database**
CTAB	**Cetyltrimethylammonium Bromide**
PCR	**Polymerase Chain Reaction**
BLAST	**Basic Local Alignment Search Tool**
BIC	**Bayesian Information Criterion**
AIC	**Akaike Information Criterion**
MUSCLE	**Multiple Sequence Comparison by Log-Expectation**
picante	**R package for phylogenetic diversity analysis**
ape	**R package for analysis of phylogenetics and evolution**
ggtree	**R package for visualization of phylogenetic trees**
Newick	**Format for representing phylogenetic trees**
L	**Branch length in Faith's PD**
Ai	**Abundance of species i**
dij	**Phylogenetic distance between species i and j**
S	**Species richness**
%	**Percentage**
Mg ha^{-1}	**Megagrams per hectare**

Mg C ha^{-1}	**Megagrams of Carbon per hectare**
<	**Less than**
>	**Greater than**
±	**Plus or minus**

CHAPTER I

1. Introduction

Covering 24% of the Earth's land surface, mountain ecosystems host 50% of the planet's total biological diversity (Körner, 2004). In mountain ecosystems, the diversity of habitats and vegetation types within short altitudinal ranges contributes to the region's rich biodiversity (Boscutti et al., 2018; Sinha et al., 2018). The endeavour to understand vegetation composition, its diversity, patterns of change, and the driving forces behind its variation along altitude and across different zones has consistently driven intensive field research worldwide. Along an altitudinal gradient, climatic and ecological factors impact species composition, growth trends, and ecosystem processes, driving shifts in vegetation composition over time (Guo et al., 2013; Krömer et al., 2013; Malizia et al., 2020). Various factors, including climatic variables such as temperature, precipitation, and humidity (Bhattarai & Vetaas, 2003; Tito et al., 2020),as well as topography (Martínez-Camilo et al., 2018) and soil properties (Tomar et al., 2024a), have been shown to influence altitudinal patterns of species diversity.

Phawngpui National Park, located in Mizoram, Northeast India, served as a pivotal study site for investigating the ecological and evolutionary dynamics of angiosperms along altitudinal gradients. Nestled within the Indo-Burma biodiversity hotspot, the park spanned elevations from 273 to 2157 m, encompassing a spectrum of forest types, from lowland tropical to high-altitude montane. This altitudinal range provided a natural laboratory to explore how environmental gradients, including temperature, precipitation, soil nutrients, and light availability, shaped plant diversity, forest structure, and ecosystem functions (Körner, 2007). The park’s unique biogeographic position, at the confluence of Sino-Himalayan and Indo-Burman floristic elements, amplified its ecological significance, making it an ideal setting for studying angiosperm responses to environmental heterogeneity (Myers et al., 2000).

Angiosperms, comprising trees, shrubs, and herbs, formed the cornerstone of terrestrial ecosystems, contributing significantly to biodiversity, forest dynamics, and carbon sequestration (Brodribb et al., 2010). In montane ecosystems, altitudinal

gradients drove shifts in species diversity, community composition, and forest structure, often resulting in distinct ecological zones (Rahbek, 2005). Trees provided structural integrity, defining forest architecture, while shrubs enhanced understory diversity, and herbs reflected microhabitat variability (Gilliam, 2007). These plant groups responded differentially to altitudinal changes, with mid-elevations frequently supporting peak diversity due to optimal climatic conditions (Sharma et al., 2017). Such patterns were particularly pronounced in biodiversity hotspots like Northeast India, where high species richness and endemism underscored the need for comprehensive ecological studies (Myers et al., 2000).

Forest regeneration and canopy structure played critical roles in maintaining ecosystem stability. Regeneration dynamics, including seedling establishment and survival, varied with altitude, influenced by environmental constraints such as temperature, soil fertility, and light availability (Bharali et al., 2012). Canopy characteristics, such as openness and density, affected light penetration, shaping understory communities and regeneration processes (Ashton, 2014). Understanding these dynamics was essential for assessing forest resilience, particularly in montane ecosystems facing climate change and anthropogenic pressures (Malhi et al., 2009).

Aboveground biomass (AGB) and carbon stocks represented key ecosystem services, reflecting the capacity of forests to sequester carbon and mitigate climate change (Spracklen & Righelato, 2014). In tropical and subtropical montane forests, AGB varied with altitude, driven by changes in species composition, tree density, and growth conditions (Singh et al., 2018). These variations highlighted the importance of quantifying biomass and carbon storage across altitudinal zones, contributing to global carbon accounting and conservation strategies (Pan et al., 2011). In Northeast India, where forests served as significant carbon sinks, such studies were critical for informing sustainable management practices (Thong et al., 2020).

The Lauraceae family, a dominant component of Phawngpui's subtropical and montane forests, exhibited high species diversity and ecological importance, contributing to forest structure, biomass, and ecosystem stability (Chanderbali et al., 2001). Molecular phylogenetic studies offered insights into evolutionary

relationships, revealing diversification patterns and community assembly processes across environmental gradients (Tan et al., 2023). The integration of ecological and molecular approaches enabled a holistic understanding of how evolutionary history interacted with ecological processes to shape forest communities in montane ecosystems (Pennington et al., 2009).

Past studies in the Eastern Himalayan and Indo-Burman biodiversity hotspot region have examined vegetation attributes along the altitudinal gradient. However, similar studies are lacking in the state of Mizoram. This study provides a critical assessment of angiosperm's diversity, composition, structure, regeneration dynamics, and phylogenetic diversity along a steep elevational gradient in the Phawngpui mountain, a globally significant yet understudied region. By systematically sampling 120 plots across an altitudinal range of nearly 2000 m of elevation, it has been captured key ecological transitions and forest zonation patterns, offering a rare dataset for comparative studies. By integrating field-based ecological assessments with molecular phylogeny, this research aimed to provide a comprehensive framework for understanding biodiversity patterns and ecosystem functions in a montane ecosystem. Conducted in the intersect of Eastern Himalayas and Indo-Burma biodiversity hotspot, the study sought to contribute to conservation strategies, emphasizing the protection of altitudinal gradients to preserve taxonomic, functional, and evolutionary diversity in one of the world's most biodiverse regions (Mittermeier et al., 2011). While this research findings aligned with global elevational diversity trends, unexpected patterns in species distribution and structural attributes challenged conventional assumptions, highlighting the need for further exploration of underlying ecological drivers. To address these knowledge gaps, this thesis investigated four objectives to elucidate the interplay of altitude and angiosperm dynamics in Phawngpui National Park:

1. The influence of altitude on the diversity, structure, and composition of angiosperms.
2. Regeneration dynamics and canopy structure along altitudinal gradients.
3. Estimation of aboveground biomass and carbon stocks across altitudinal zones.
4. Assessing the phylogenetic diversity of Lauraceae through molecular insights.

CHAPTER II

2. Review of literature

Altitudinal gradients served as a robust framework for examining ecological and evolutionary processes in montane ecosystems, influencing plant diversity, forest structure, regeneration dynamics, biomass accumulation, and phylogenetic patterns (Körner, 2007). This review synthesized literature pertinent to the four objectives of this study in Phawngpui National Park, Mizoram: (1) angiosperm diversity, structure, and composition; (2) regeneration dynamics and canopy structure; (3) aboveground biomass (AGB) and carbon stocks; and (4) phylogenetic diversity of Lauraceae. The scope encompassed Northeast India, Eastern Himalayas, and global montane ecosystems, providing a comprehensive foundation for understanding biodiversity and ecosystem functions in the Indo-Burma biodiversity hotspot.

2.1. Angiosperm Diversity, Structure, and Composition

Angiosperm diversity exhibited significant variation along altitudinal gradients, driven by environmental factors including temperature, precipitation, soil nutrients, and light availability (Rahbek, 2005). In India, peak species richness at mid-elevations (800–1500 m) was reported in Garhwal Himalaya, employing Shannon, Simpson, and Pielou indices to quantify diversity (Sharma et al., 2017). Whittaker's beta diversity revealed high species turnover, reflecting habitat heterogeneity across altitudinal zones. In Arunachal Pradesh, tree, shrub, and herb diversity was investigated using non-metric multidimensional scaling (NMDS) and Indicator Species Analysis to identify dominant species such as *Castanopsis indica* in lowland forests, *Melastoma malabathricum* among shrubs at mid-elevations, and *Ageratina adenophora* among herbs (Saikia et al., 2017). In Mizoram, Importance Value Index (IVI) and Family Importance Value Index (FIVI) was employed to assess community composition, linking species distributions to environmental variables like soil pH, moisture, and nitrogen through canonical correspondence analysis (CCA) (Singh et al., 2018). Diversity along altitudinal gradient was analysed in Sikkim's mid-altitude forests, attributing it to optimal temperature and precipitation regimes (Acharya et

al., 2011). Similarly, high species richness was found in subtropical forests of Meghalaya, driven by favourable climatic conditions and soil fertility (Tripathi et al., 2010).

Globally, peak diversity was observed in Ecuadorian montane forests at 1000–1500 m, linked to reduced environmental stress and higher resource availability (Homeier et al., 2010). Several studies in the Eastern Himalaya have reported a hump-shaped pattern in species richness and diversity, peaking at mid-altitude and declining at both lower and higher elevations (Behera & Kushwaha, 2007; Manish et al., 2016; Sharma et al., 2019; Sun et al., 2020). In the Andes, it was noted an increase beta diversity with altitude, reflecting species turnover due to environmental gradients (Myers et al., 2013). Previous studies have highlighted that Eastern Himalayan forests transitioned from tropical to temperate assemblages, influenced by altitude and soil properties (Maren et al., 2014).

Forest structure, encompassing stem density, basal area, and diameter at breast height (DBH), reflected altitudinal influences on tree architecture and community dynamics. Past study recorded peak stem density and basal area at mid-elevations in Sikkim Himalaya, using boxplot analyses to visualize structural shifts (Bhutia et al., 2019). In Northeast India, basal area peaked at 900–1200 m in subtropical forests, driven by dominant species like *Schima wallichii* and *Engelhardia spicata* (Pandey et al., 2018). Globally, a reduced basal area was documented at higher elevations in Indonesian montane forests, attributed to lower temperatures and nutrient limitations (Culmsee et al., 2010). The forest structural complexity enhanced biodiversity, underscoring the need for integrated diversity and structural analyses in montane ecosystems like Phawngpui mountain (McElhinny et al., 2005).

2.2. Regeneration Dynamics and Canopy Structure

Regeneration dynamics were pivotal for forest succession and long-term stability, influenced by altitudinal variations in temperature, soil fertility, moisture, and light availability (Grubb, 1977). Among various ecological processes, regeneration of tree species is a crucial process for their existence in a community under varied environmental conditions (Negi, Giri, et al., 2018). The regeneration pattern depicts

the current status of forest health and indicates the future composition of a particular community (Gairola et al., 2011; Joshi, et al., 2018; Tesfaye et al., 2002). In the Eastern Himalayas, an increasing trend of seedling and sapling density was observed at higher elevations (Negi et al., 2024). Previous studies in Northeast India using regression analyses demonstrated that seedling survival decreased with increasing altitude, a pattern correlated with soil moisture and organic carbon as revealed by principal component analysis (PCA) (Tripathi et al., 2010). Seedling emergence and survival of *Cinnamomum* species studied under varied microhabitat conditions in a subtropical moist forest revealed the influence of canopy cover and disturbance (Sharma et al., 2009).

Canopy structure, including canopy openness and Leaf Area Index (LAI), played a critical role in regeneration by regulating light penetration and understory conditions (Ashton, 2014). Higher LAI in lowland forests, facilitating seedling growth, while montane forests exhibited greater canopy openness, limiting understory development (Moser et al., 2007; Zhou et al., 2023). Recent studies showed that canopy gaps promoted regeneration by creating favourable light conditions for shade-intolerant species (Tafesse et al., 2025; Xie et al., 2024). Canopy structure varied along the altitudinal gradient, influencing both species composition and regeneration dynamics (Bharali et al., 2012; Muñoz Mazón et al., 2022). In the Andes, an increased canopy openness at higher elevations was found affecting seedling survival (Myers et al., 2013). Past studies highlighted that canopy gaps enhanced species diversity by allowing pioneer species to establish (Denslow, 1987), a pattern relevant to Phawngpui's forests. Importantly, canopy structure mediated microclimatic conditions, thereby shaping regeneration patterns across the altitudinal zones (Jia et al., 2024; Jucker et al., 2018). These studies underscored the interconnectedness of canopy structure and regeneration, critical for assessing forest resilience in montane ecosystems.

2.3. Aboveground Biomass and Carbon Stocks

AGB and carbon stocks represented essential ecosystem services, varying along altitudinal gradients due to differences in species composition, tree density, and growth conditions (Pan et al., 2011). In Mizoram, carbon stocks ranging from 71.20 to 158.91 Mg C ha^{-1} were estimated in subtropical forests using non-destructive allometric equations (Singh et al., 2018). Aboveground biomass (AGB) ranging from 46.5 to 144.2 Mg ha^{-1} was reported in Manipur, with the Biomass Importance Value highlighting significant contributions from species such as *Castanopsis hystrix* and *Engelhardia spicata* (Sharma et al., 2017). In Assam's tropical forests, aboveground biomass (AGB) ranging from 71.20 to 77.47 Mg ha^{-1} was recorded, with tree density identified as a key contributing factor (Nath et al., 2022). A similar range of aboveground biomass (AGB) values has been reported from forests across Northeast India (Chaudhury et al., 2022; Das et al., 2024; Hauchhum, 2017; Monsang et al., 2023).

Globally, aboveground biomass (AGB) in tropical montane forests has been reported to range from 100 to 300 Mg ha^{-1}, with peaks at mid-elevations attributed to favourable growth conditions (Spracklen & Righelato, 2014). Several studies conducted along altitudinal gradients in subtropical montane ecosystems have reported findings consistent with this result (Gonmadje et al., 2017; Maza et al., 2022; Thakur et al., 2024). Allometric models developed by Chave et al. have significantly improved the accuracy of biomass estimation in tropical forests (Chave et al., 2005). Subtropical forests have a significant capacity to store above-ground biomass and carbon (Chan et al., 2021; Pandit et al., 2018), and the biomass storage is primarily driven by the presence of large-sized trees and the annual temperature range (Chan et al., 2021). Standardized allometric equations are critical for consistent and accurate carbon accounting, particularly in biodiversity hotspots where ecological variability is high (Gibbs et al., 2007). Therefore, region-specific allometric equation is essential for accurately estimating AGB and carbon stock (Nath et al., 2019).

2.4. Phylogenetic Diversity of Lauraceae

Lauraceae, a plant family with a global distribution, comprises an estimated 2,500–3,500 species across approximately 50 genera, with peak species richness occurring in the tropical forests of Southeast Asia and the Americas (Rohwer, 1993; Rohwer et al., 2014; Yahara et al., 2016). In Southeast Asia, Lauraceae trees are widespread from lowland areas to high elevations (van der Werff, 2001; Wuu-Kuang, 2011; Yahara et al., 2016), and frequently rank among the most dominant canopy components in montane forests (Ohsawa, 1991; Tagawa, 1995). The Lauraceae family exhibited high phylogenetic diversity, shaped by evolutionary and ecological processes in subtropical and montane forests (Chanderbali et al., 2001). Molecular phylogenetic studies resolved major clades, including *Cinnamomum, Litsea,* and *Persea*, using chloroplast markers like matK and nuclear markers like ITS (Trofimov et al., 2022).

Phylogenetic diversity metrics, such as Mean Pairwise Distance (MPD) and Mean Nearest Taxon Distance (MNTD), provide valuable insights into community assembly processes (Luo et al., 2023). Pennington et al. (2009) argued that phylogenetic approaches were essential for understanding evolutionary history in tropical forests. Webb et al. (2008) developed tools for phylogenetic community analysis, applied to families like Lauraceae. Phylogenetic diversity (PD) was found to decrease with altitude, reflecting environmental filtering due to low temperatures and nutrient limitations (Manish & Pandit, 2018). Phylogeographic studies, particularly from East Asia, suggest in situ survival and demographic stability or expansion of Lauraceae during the Quaternary, although many systematic relationships remain unresolved, highlighting the need for further research into the family's complex biogeographic history and ecological roles (Li et al., 2025). These studies highlighted the importance of molecular phylogenetic analyses to elucidate Lauraceae diversification and community structure in montane ecosystems like Phawngpui, where species like *Cinnamomum verum* played significant ecological roles.

The reviewed literature provided a comprehensive foundation for studying angiosperm diversity, regeneration, biomass, and Lauraceae phylogeny along altitudinal gradients in Phawngpui National Park. Previous studies in the Himalayan region have demonstrated consistent patterns, including mid-altitude peaks in tree species diversity, upward shifts in regeneration towards higher elevations, and the significant influence of altitude and environmental factors on species diversity and structure (Bhutia et al., 2019; Negi et al., 2024; Shrestha et al., 2012; Sinha et al., 2018; Tomar et al., 2024; Wani et al., 2022). Global research (Chave et al., 2005; Homeier et al., 2010; Körner, 2007; Spracklen & Righelato, 2014) reinforced these findings, emphasizing the universal influence of altitudinal gradients on forest ecosystems. However, gaps persisted in integrating ecological and molecular approaches, particularly for Lauraceae phylogeny in Mizoram, where molecular data were scarce. This study aimed to address these gaps by combining field-based ecological assessments with molecular phylogenetic analyses, focusing on trees, shrubs, herbs, and Lauraceae species like *Cinnamomum verum*. The findings were expected to inform conservation strategies, emphasizing the protection of altitudinal gradients to preserve taxonomic, functional, and evolutionary diversity in the montane ecosystem.

CHAPTER III

3. Materials and Methods

3.1. Study area

The study was conducted in a protected area of Phawngpui National Park (Blue Mountain), situated in the easternmost extremity of the Indian Himalayas. It lies in the southeast corner of Mizoram between 93°0'0" to 93°6'0" E and 22°36'0" to 22°42'0" N. Phawngpui National Park is one of the Patkai Ranges, part of the North Arakan Yoma Mountain Chain, and its peak is 2157 m high. It is covered with diverse forest and vegetation types, including secondary forests and bamboo forests resulting from historical human use. The forest types of Phawngpui National Park can be classified into sub-tropical hill forest (Singh et al., 2002) with humid sub-tropical climates characterized by long winters. The study area receives monsoon-annual rainfall of approximately 2300 mm, with temperature ranges of 18°C–24°C in summer and 4°C–15°C in winter. *Quercus* species dominate some high-altitude forests above 1600 m. The Blue Mountain, being physically located at the junction of Eastern Himalayas and Indo-Burma biodiversity hotspot, harbour highly diverse plant groups and are known for their species richness, including the Lauraceae, *Rhododendrons*, Orchids, etc. Diverse epiphytic plant communities largely constitute Vacciniaceae, Ericaceae, and Zingiberaceae, forming a unique feature of the Blue Mountain Forest. Since Phawngpui National Park is limited in size (50 km²) and only includes elevations above 1000 m, we expanded our study area to include lower altitudes, starting from 273 m. Using ArcGIS version 9.3, the study boundaries were redefined to extend beyond the park, covering a broader range of altitudes (**Figure 3.1**). This adjustment allowed for a more comprehensive assessment of the influence of altitude on angiosperm diversity, structure, and composition; regeneration dynamics and canopy structure; aboveground biomass and carbon stocks; and the phylogenetic diversity of Lauraceae across different altitudinal gradients.

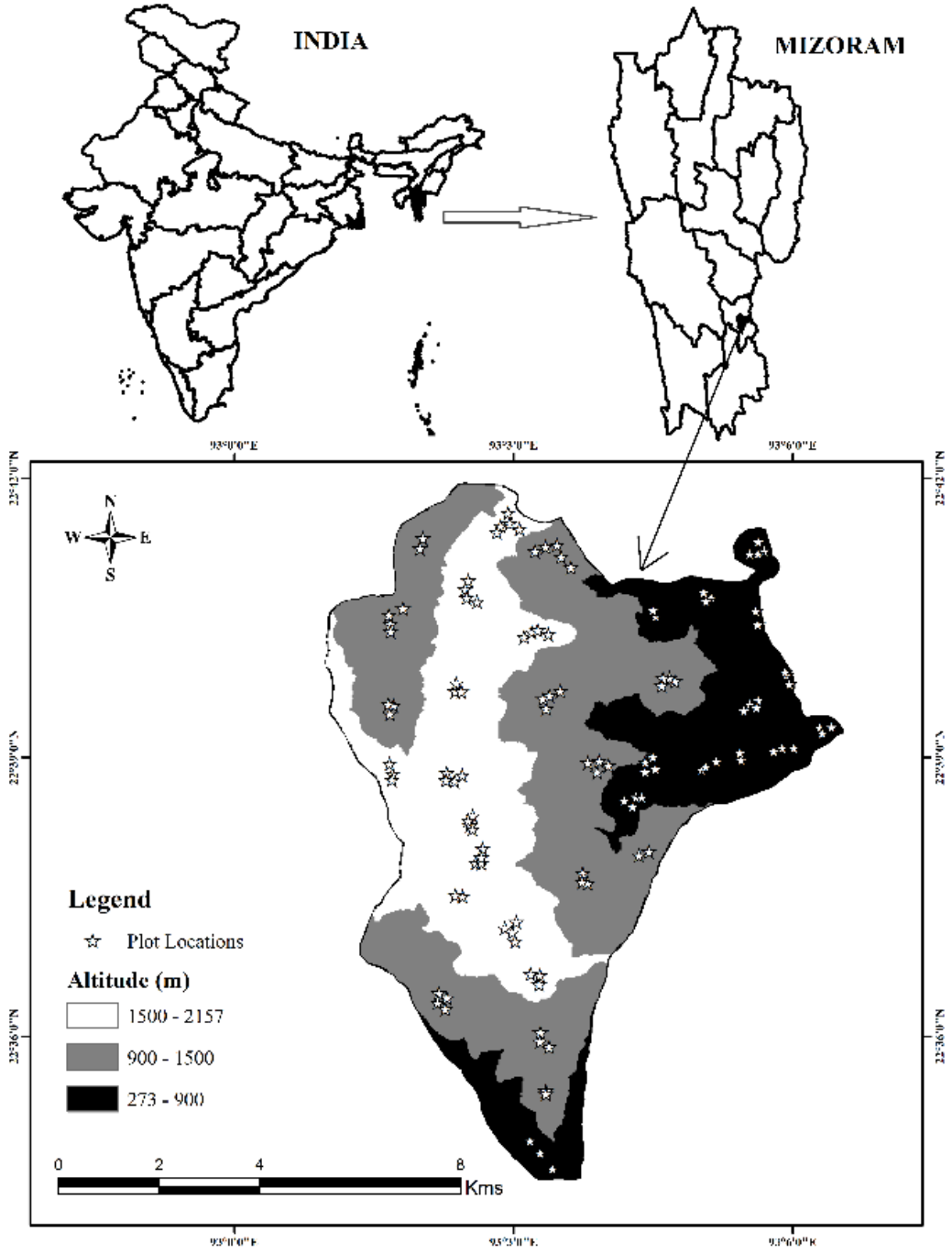


Figure 3.1. Study area showing sampling plot locations across three altitudinal zones in Phawngpui National Park, India.

3.2. Plot design, data collection and identification

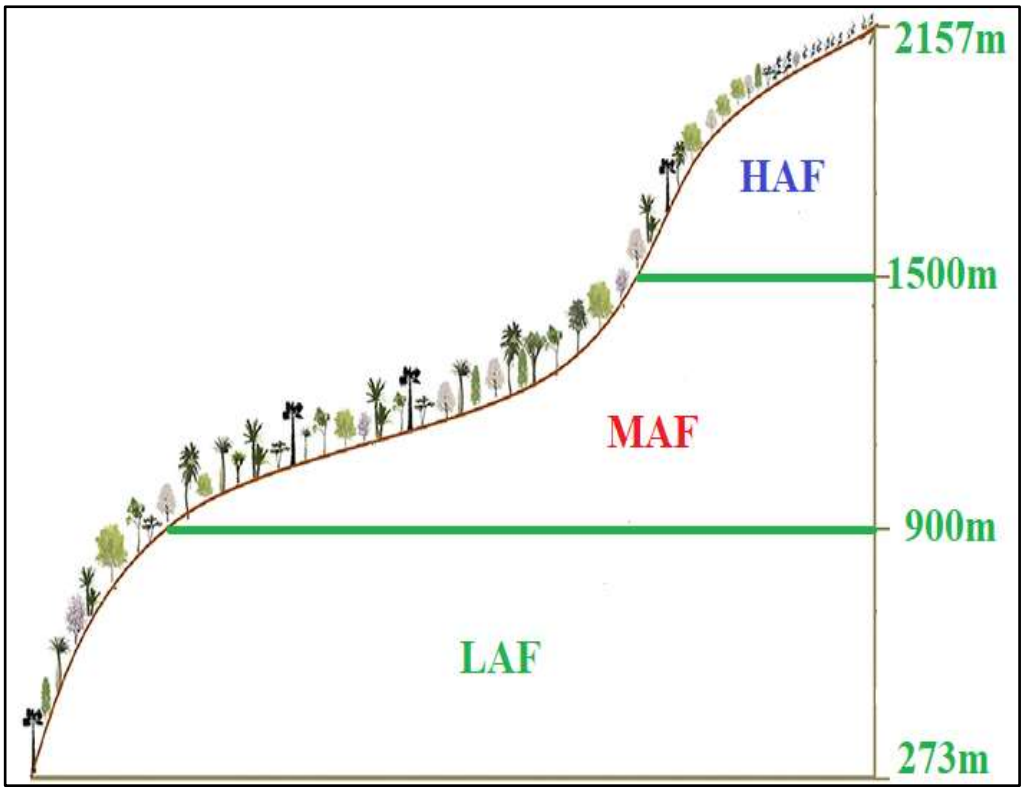


Figure 3.2. Schematic representation of the study site in Phawngpui National Park, showing altitudinal stratification into three forest zones: LAF (Low Altitude Forest, 273–900 m), MAF (Mid Altitude Forest, 900–1500 m), and HAF (High Altitude Forest, 1500–2157 m).

The study area was stratified into three altitudinal zones: Low Altitude Forest (LAF), ranging from 273–900 m; Mid Altitude Forest (MAF), ranging from 900–1500 m; and High Altitude Forest (HAF), ranging from 1500–2157 m (**Figure 3.2**). The zonation was defined based on observed shifts in forest structure, species composition, and ecological transitions along the elevational gradient. Changes in tree diversity, dominant species, and forest physiognomy provided a natural basis for delineating LAF, MAF, and HAF. The stratified random sampling approach was adopted to ensure that all elevation zones and associated vegetation types were adequately represented, while minimizing sampling bias across varied terrain and forest types. Due to the dominance of bamboo brakes in LAF, cliffs and rough terrain in the west, and subalpine meadows in HAF, site accessibility varied across the

altitudinal zones. Most plots were located on east- and southeast-facing slopes, as west-facing slopes were dominated by continuous cliffs, making them nearly impossible to sample. Although terrain accessibility influenced plot placement, a representative distribution was maintained along the elevational gradient. The plots were randomly placed in well-preserved forest patches, with an approximate gradual increase of 15 m from 273 m to 2157 m. A total of 120 plots, each measuring 10 m × 10 m, were established, with 40 plots in each of the three altitudinal zones randomly distributed along the elevational gradient. All individual trees having at least 10 cm of diameter at breast height (DBH, measured at 1.3 m above the ground), were recorded in the field for species identity, DBH and height.

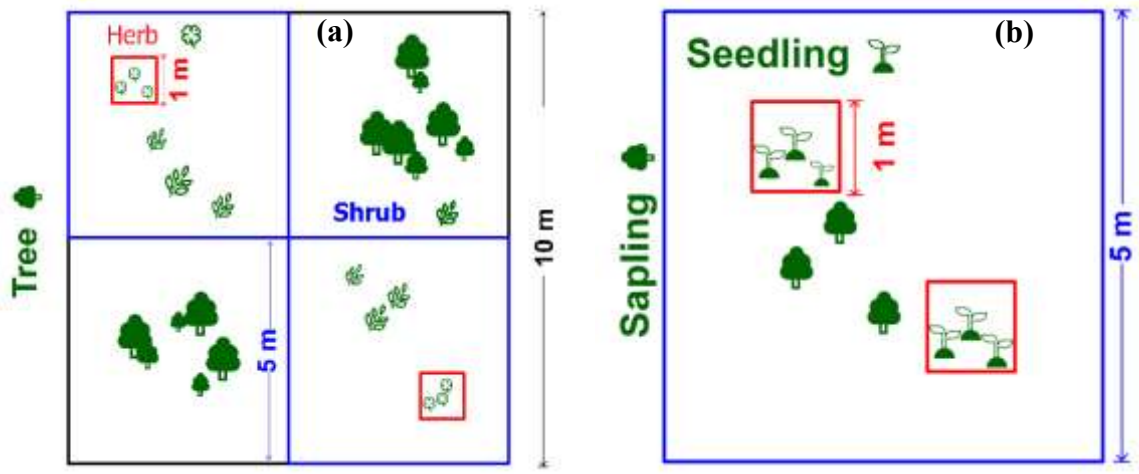


Figure 3.3. Plot design used for data collection along the altitudinal gradient: (a) Layout for the assessment of trees, shrubs, and herbs; (b) Layout for the assessment of seedlings and saplings.

To assess vegetation structure more comprehensively, understorey and regeneration data were also collected. For understorey vegetation, two 5 m × 5 m subplots were laid out diagonally within each 10 m × 10 m plot to record shrub species, and two 1 m × 1 m quadrats were laid out for herbaceous species (**Figure 3.3a**). Seedlings (Height < 1 m) and saplings (1 cm ≤ DBH < 10 cm) were recorded in each plot to examine regeneration dynamics (**Figure 3.3b**). All individuals were identified and counted.

In each 10 m × 10 m plot, environmental parameters such as canopy cover, soil moisture, soil organic carbon, soil pH, total nitrogen, available phosphorus, available potassium, relative humidity, air temperature, and light intensity were also measured to support further ecological analyses, including species-environment relationships. Canopy photographs were taken at the centre of each 10 m × 10 m plot using a hemispherical lens to estimate canopy cover and light availability.

Most plant species were identified directly in the field. Unidentified specimens were collected and later identified using regional floras (Sawmliana, 2013; Singh et al., 2002). Scientific names were validated using online resources such as the World Flora Online (WFO), Plants of the World Online (POWO), Royal Botanic Gardens, Kew, and JSTOR.

3.3. Data Analysis

All statistical analyses and graphical visualizations were performed using RStudio (v.4.2.2). The analyses included various biodiversity and community structure assessments to address the objectives of the study. Species diversity indices—such as Shannon, Simpson, Pielou's Evenness, species richness, and Whittaker's beta diversity—were calculated for each lifeform (trees, shrubs, and herbs) across the three altitudinal zones. Species and family Importance Value Indices (IVI and FIVI) were computed to identify dominant taxa. Species Accumulation Curves (SAC) were generated to evaluate sampling sufficiency.

Non-Metric Multidimensional Scaling (NMDS), based on Bray-Curtis dissimilarity, was used to assess species compositional differences along the altitudinal gradient. Indicator Species Analysis (ISA) was applied to identify indicator species for each zone. Canonical Correspondence Analysis (CCA) was used to relate species composition to environmental variables, while Principal Component Analysis (PCA) was employed to examine seedling survival in relation to environmental parameters. Regression analyses were conducted to examine the relationships between altitude and diversity indices, structural parameters (e.g., basal area, AGB), as well as between seedling and sapling densities.

To estimate Aboveground Biomass (AGB) and Carbon Stock (CS) of trees, allometric equations were applied using tree DBH, height, and wood specific gravity. A Biomass Importance Value (BIV) was also calculated to identify species contributing most to biomass.

For the evolutionary assessment of Lauraceae, DNA sequences of the matK chloroplast region were used. Sequences were aligned using MAFFT, and phylogenetic relationships were inferred using the Maximum Likelihood (ML) method in MEGA software. The best-fit substitution model was determined within MEGA. The resulting phylogenetic tree was used to calculate phylogenetic diversity indices, offering insights into evolutionary relationships among Lauraceae species in the region.

CHAPTER IV

4. Influence of altitude on the diversity, structure, and composition of Angiosperms.

4.1. Introduction

Altitude is a pivotal ecological driver, shaping plant communities through gradients in temperature, precipitation, soil chemistry, and light availability (Körner, 2007). These gradients influence species distributions, community assembly, and ecological interactions, making altitudinal studies critical for understanding the mechanisms underpinning biodiversity in montane ecosystems (Sundqvist et al., 2013). This chapter examines the intricate relationship between altitude and the diversity, structure, and composition of angiosperms in the subtropical forests of Phawngpui National Park, Mizoram, India, situated within the Indo-Burma biodiversity hotspot. Spanning an altitudinal gradient of nearly 2000 m, this study encompasses three distinct forest zones—low-altitude (LAF), mid-altitude (MAF), and high-altitude (HAF)—each characterized by unique environmental conditions.

Focusing on three angiosperm life forms—trees, shrubs, and herbs—this chapter investigates how altitudinal variation governs species diversity, structural attributes, and compositional dynamics. Trees provide the structural backbone of forests, shrubs contribute to understory complexity, and herbs reflect rapid responses to microclimatic changes, collectively offering a comprehensive view of community responses to environmental gradients (Getaneh et al., 2023). By exploring patterns of species richness, community organization, and species-environment interactions, this study aims to elucidate processes such as environmental filtering and niche differentiation that drive angiosperm distributions across altitudinal zones. Such insights are particularly relevant in subtropical montane forests, where high biodiversity faces increasing threats from climate change, habitat fragmentation, and anthropogenic pressures (Lu et al., 2023).

The findings are expected to highlight the adaptive strategies of angiosperms to varying ecological conditions, shedding light on the resilience of subtropical forest ecosystems. Moreover, this research seeks to inform conservation strategies for Phawngpui National Park by identifying key species and environmental drivers that sustain its ecological integrity. By addressing these objectives, this chapter aimed to contributes to the global discourse on altitudinal ecology and underscores the urgency of preserving montane biodiversity in the face of escalating environmental challenges (Sadia et al., 2025).

4.2 Methodology

4.2.1. Species accumulation and sampling adequacy

Species Accumulation Curves (SACs) were plotted for the entire plant community—including trees, shrubs, and herbs—and for each altitudinal zone to assess how species richness varies with sampling effort. The rarefaction method was applied to generate these curves, enabling comparison of richness accumulation across altitudes and vegetation layers. This approach provided insights into the adequacy and completeness of species sampling across the gradient and ensured that the sampling effort was sufficient to capture the majority of species present in each zone.

4.2.2. Species composition analyses

To examine changes in community composition along the altitudinal gradient, the following multivariate and indicator-based methods were applied:

4.2.2.1. Non-Metric Multidimensional Scaling (NMDS) and ANOSIM

The influence of altitude on species composition was examined using Non-Metric Multidimensional Scaling (NMDS) ordination. NMDS is a robust technique used to represent pairwise dissimilarities among sites in a lower-dimensional space as accurately as possible, facilitating the visualization of complex ecological data and the identification of patterns in community composition (Legendre & Legendre, 2012). The analysis began with the computation of the Bray-Curtis distance matrix from the abundance data, with species abundances in columns and sampling plots arranged in rows according to increasing altitude. A stress plot, derived from the

Shepard diagram, was used to evaluate the goodness-of-fit of the NMDS ordination (Legendre & Legendre, 2012), where lower stress values indicate a better representation of the data in the reduced-dimensional space. Analysis of Similarities (ANOSIM) was then performed to test for compositional differences among the three altitudinal zones, followed by pairwise comparisons (LAF vs. MAF, LAF vs. HAF, and MAF vs. HAF). R-statistic values > 0.75 indicate strong dissimilarity, 0.5–0.75 moderate, < 0.5 weak, and values near or below 0 suggest high similarity or random variation.

4.2.2.2. Importance Value Index (IVI) and Family IVI (FIVI)

The Importance Value Index (IVI) was calculated for both species (SIVI) and families (FIVI) to determine the dominant species and families within each altitudinal zone and across the entire community (Curtis, 1959). The relative components used to calculate the IVI are explained below:

Relative Density (RD): (Density of species) / (Total density of all species) × 100

Relative Frequency (RF): (Frequency of species) / (Total frequency of all species) × 100

Relative Dominance (Do): (Dominance of species) / (Total dominance of all species) × 100

Relative Abundance (RA): (Abundance of species) / (Total abundance of all species) × 100

For trees, the Species IVI (SIVI) was calculated as:

SIVI = Relative Density + Relative Frequency + Relative Dominance

For shrubs and herbs, where basal area-based dominance is not applicable, SIVI was calculated using:

SIVI = Relative Density + Relative Frequency + Relative Abundance

Family IVI (FIVI) was calculated as:

FIVI = Relative Density + Relative Dominance + Relative Diversity where, *Relative Diversity* is the number of species in a family divided by the total number of species studied (Mori et al., 1983).

For shrubs and herbs, FIVI was modified as:

FIVI = Relative Density + Relative Abundance + Relative Diversity

4.2.2.3. Indicator Species Analysis (ISA)

Indicator Species Analysis (ISA) was used to identify species strongly associated with specific altitudinal zones. This method determines which species are characteristic of each zone by assessing their abundance and occurrence (Cáceres & Legendre, 2009; Dufrene & Legendre, 1997). The Indicator Value (IndVal) was calculated as:

$IndVal = A \times B$

Where, A (specificity) is the mean abundance of a species in a given zone divided by its total mean abundance across all zones, and B (fidelity) is the number of plots where the species is present in a given zone divided by the total number of plots in that zone. A higher IndVal score (ranging from 0 to 1) indicates a species is both commonly found and largely restricted to a specific zone. ISA was performed using the indicspecies package (Cáceres & Legendre, 2009) in R (R Core Team, 2023), with significance assessed using a randomization test with 999 permutations ($p < 0.05$). Significant indicator species were reported in tabular format for each lifeform.

4.2.2.4. Environmental drivers of species distribution across altitudinal zones

Canonical Correspondence Analysis (CCA) was used to explore and visualize the relationship between species distribution and measured environmental variables, such as altitude, soil pH, soil moisture, light intensity, temperature, and nutrient availability. This constrained ordination technique helps to identify which environmental gradients are most strongly associated with species composition across the altitudinal zones.

CCA was particularly suitable for this study as it assumes unimodal species responses to environmental gradients, which is often the case in complex ecological datasets. The analysis was based on species abundance data from 120 plots and corresponding environmental measurements.

The top three indicator species from each altitudinal zone (as identified through Indicator Species Analysis) were highlighted in the CCA biplot to examine their ecological preferences and zone-level associations. Arrows representing environmental variables indicate the direction and strength of gradients, while the position of species and site scores in the ordination space reflects their relationship with these variables. CCA helped identify the key environmental drivers structuring tree communities along the altitudinal gradient and provided insights into species–environment interactions within each zone.

4.2.3. Analysis of diversity indices

The relationship between plant species diversity and elevation was assessed using multiple diversity indices: the Shannon diversity index, Simpson diversity index, Pielou's evenness index, and Whittaker's beta diversity index.

4.2.3.1. Shannon diversity index (H′)

As one of the most widely used indices in ecological research, the Shannon index was applied to assess alpha diversity across altitudinal zones (Jiménez-Paz et al., 2021). It was calculated for each plot and each zone using the formula (Shannon & Weaver, 1963):

$$H' = - \Sigma \, pi \ln(pi)$$

Where, H′ is the Shannon diversity value, S is the total number of species in the community, and pi is the proportion of the i^{th} species in the community.

The Shannon index captures both species richness and evenness.

4.2.3.2. Simpson diversity index (D)

The Simpson index (Simpson, 1949) measures the probability that two randomly selected individuals belong to different species. It is calculated as:

$$D = 1 - \Sigma (pi^2)$$

Where pi is the proportion of individuals belonging to species *i*. Lower values of D indicate lower diversity (dominated by few species), while higher values suggest higher diversity and evenness.

4.2.3.3. Pielou's evenness index (J′)

Pielou's Evenness Index (Pielou, 1966) quantifies how evenly individuals are distributed among the species present. It is expressed as:

$$J' = H' / \ln(S)$$

Where H′ is the Shannon index and S is the total number of species. This index complements richness and diversity by providing insight into community structure.

4.2.3.4. Beta diversity (β)

Beta diversity was calculated using Whittaker's formula (Whittaker, 1975) as described in Mena and Vázquez-Domínguez ((Mena & Vázquez-Domínguez, 2005)):

$$\beta = s / \alpha - 1$$

Where, s is the total number of species recorded in all plots, α is the average species richness per plot. Beta diversity reflects the turnover in species composition across altitudinal zones.

4.2.4. Forest structural analyses

The forest structure of tree communities was assessed using four primary attributes: stem density (stems ha^{-1}), basal area (m^2 ha^{-1}), median diameter at breast height (DBH), and size class distribution. These metrics provide insights into the composition, dominance, and maturity of tree populations across the altitudinal gradient.

To visualize and compare structural differences among the altitudinal zones, boxplots with jittered data points were employed. As the variables often exhibited non-normal distributions, the median was selected as the principal measure of central tendency.

Basal area, representing the cross-sectional area of trees per hectare, was used to indicate the relative dominance of tree species within a community. It was calculated using the formula:

$$BA = \pi / 4 \times (DBH)^2$$

Where BA is the basal area in square meters and DBH is the diameter at breast height in centimetres. This formula was applied to each tree, and values were aggregated to estimate total basal area per plot and per zone.

4.2.5. Environmental variables measurement and calculation

To assess the influence of abiotic variables on angiosperm diversity and composition across altitudinal zones, a comprehensive set of microclimatic and soil physicochemical parameters was measured in each of the 120 sampling plots (10 × 10 m). These variables were used in Canonical Correspondence Analysis (CCA) to explain species–environment relationships along the altitudinal gradient.

4.2.5.1. Microclimatic parameters

Microclimatic data were collected during the peak growing season under stable weather conditions to ensure consistency. Light intensity, air temperature, and relative humidity were recorded in each plot.

a) Light Intensity (µmol m^{-2} s^{-1})

A Quantum PAR light meter (Apogee MQ-500) was used to measure photosynthetically active radiation (PAR), which accurately represents the light available for plant photosynthesis. Readings were taken at 1 meter above the ground between 11:00 AM and 1:00 PM on cloud-free days. Three consecutive readings were taken per plot and averaged to represent light intensity (Montgomery & Chazdon, 2001).

b) Air Temperature (°C) and Relative Humidity (%)

A digital thermo-hygrometer (Extech 445815 Hygro-Thermometer) was used to record temperature and humidity at 1.5 meters above the ground at the same time as the light readings.

4.2.5.2. Soil Physico-chemical parameters

Composite soil samples were collected from each plot using a soil auger at a depth of 0–10 cm. Three subsamples were taken per plot and combined into one representative sample. Samples were air-dried, sieved (2 mm), and analysed using standard laboratory procedures.

a) Soil Moisture Content (SMC, %)

To determine soil moisture content, 10 g of freshly collected soil samples were placed in a hot air oven at 105 °C for 24 hours. After drying, the samples were weighed again to obtain the oven-dried weight. Three replicates were maintained for each sample to ensure accuracy. The percentage moisture content was calculated using the following formula:

$$\text{Moisture Content (\%)} = \frac{\text{Fresh Weight} - \text{Dry Weight}}{\text{Fresh Weight}} \times 100$$

b) Soil pH

Soil pH was measured by mixing 10 g of freshly collected soil with 50 mL of distilled water in a beaker. The soil-water suspension was stirred for 20 minutes using a magnetic stirrer to ensure proper mixing. The mixture was then allowed to settle overnight. The pH of the supernatant was measured the following day using a calibrated pH meter (SYSTRONICS-335).

c) Soil Organic Carbon (SOC, %)

Soil organic carbon was determined using the Walkley and Black (Walkey & Black, 1934) wet oxidation method. 1 gram of air-dried, sieved soil sample was placed in a 500 ml conical flask. To this, 10 ml of 1 N potassium dichromate ($K_2Cr_2O_7$) solution and 20 ml of concentrated sulfuric acid (H_2SO_4) were added. The mixture was swirled gently and allowed to stand for 30 minutes. After the oxidation period, 200 ml of distilled water, 10 ml of orthophosphoric acid, and 1 ml of diphenylamine indicator were added. The solution was titrated with 1 N ferrous ammonium sulphate

(FAS) until the colour changed from violet-blue to green. A blank titration (without soil) was also performed.

The percentage of soil organic carbon was calculated using the following formula:

$SOC\ (\%) = [(V_{blank} - V_{sample}) \times N \times 0.003 \times 100] / \text{Weight of soil sample (g)}$

Where,

V_{blank} = Volume of FAS used for the blank titration (ml)

V_{sample} = Volume of FAS used for the soil sample titration (ml)

N = Normality of ferrous ammonium sulphate

0.003 = Amount of carbon oxidized by 1 ml of 1 N $K_2Cr_2O_7$ (g)

Weight of soil sample = Weight of soil used (g)

d) Total Nitrogen (N, %)

Total nitrogen in the soil was estimated using the Kjeldahl digestion method. Approximately 1 gram of air-dried, sieved soil sample was placed in a Kjeldahl digestion flask. To this, a digestion mixture consisting of 10 ml concentrated sulfuric acid (H_2SO_4) and a catalyst (usually a mixture of potassium sulfate and copper sulfate or selenium) was added. The mixture was heated gently until the solution became clear, indicating complete digestion of organic matter.

After digestion, the sample was cooled and diluted with distilled water. The digested sample was then made alkaline by adding sodium hydroxide (NaOH), and the liberated ammonia was distilled into a flask containing a known volume of standard boric acid solution with a mixed indicator (e.g., methyl red and bromocresol green). The collected ammonia was titrated with standard hydrochloric acid (HCl) or sulfuric acid (H_2SO_4) until a color change indicated the endpoint. The percentage of total nitrogen was calculated using the following formula:

Total Nitrogen (%) = [(V_{sample} - V_{blank}) × N × 14.01 × 100] / Weight of soil sample (mg)

Where,

V_{sample} = Volume of acid used for titration of the sample (ml)

V_{blank} = Volume of acid used for titration of the blank (ml)

N = Normality of standard acid

14.01 = Atomic weight of nitrogen

Weight of soil sample = in milligrams (usually 1000 mg for 1 g sample)

e) Available Phosphorus (mg/kg)

Available phosphorus in the soil was estimated using the Olsen method, which is suitable for neutral to alkaline soils. A known weight (usually 2.5 g) of air-dried soil was extracted with 50 mL of 0.5 M sodium bicarbonate ($NaHCO_3$) solution at pH 8.5. The soil-extractant mixture was shaken for 30 minutes and then filtered. The phosphorus content in the filtrate was determined colorimetrically using the ascorbic acid method, where a blue colour develops upon the addition of molybdate and ascorbic acid reagents. The intensity of the blue colour was measured using a spectrophotometer at 882 nm.

The available phosphorus content was calculated from the absorbance values by referencing a standard curve prepared using known concentrations of KH_2PO_4. The final phosphorus concentration in the soil was calculated using the following formula:

$$\text{Available P (mg/kg)} = \frac{C \times V}{W}$$

Where,

C = Concentration of phosphorus obtained from the standard curve (mg/L)

V = Volume of the extract (mL)

W = Weight of the soil sample (g)

f) Available Potassium (mg/kg)

Available potassium in the soil was estimated using the Flame Photometric Method after extraction with neutral normal ammonium acetate (1N NH_4OAc). A known quantity of air-dried soil (5 g) was extracted with 25 mL of 1N NH_4OAc solution (pH 7.0). The mixture was shaken for 30 minutes on a mechanical shaker and then filtered.

The potassium content in the filtrate was measured using a flame photometer, which detects the intensity of the flame emission from potassium ions. The readings were compared against a calibration curve prepared from standard KCl solutions of known concentrations.

The available potassium was expressed in mg/kg (or ppm) using the formula:

$$\text{Available P (mg/kg)} = \frac{C \times V}{W}$$

Where,

C = Concentration of potassium from the standard curve (mg/L)

V = Volume of the extract (mL)

W = Weight of soil sample (g)

4.2.6. Statistical analyses

All statistical analyses were performed using R packages such as 'ggplot2' (Wickham, 2016), 'dplyr' (Wickham et al., 2023), 'vegan' (Okasen et al., 2020), 'indicspecies' (Cáceres & Legendre, 2009) with built-in functions including 'vegdist', 'specaccum', 'metaMDS', 'adonis', 'diversity', 'multipatt' all within RStudio version 4.2.2.

4.3. Results

4.3.1. Species Accumulation Curves (SAC)

4.3.1.1. Species accumulation curve for tree community

The species accumulation curve analysis revealed that the overall tree community was adequately sampled, as indicated by the gentle slope of the curve beyond approximately 90 plots (**Figure 4.1**). This suggests that most tree species were captured with the current sampling effort. For the altitudinal zones (each based on 40 plots), distinct accumulation patterns were observed. The low-altitudinal forest (LAF) and high-altitudinal forest (HAF) curves showed signs of saturation, indicating that additional sampling would likely yield few new species in these zones. In contrast, the mid-altitudinal forest (MAF) curve continued to rise without reaching a clear asymptote, suggesting ongoing species accumulation and higher tree diversity at mid-elevations. These patterns highlight both adequate sampling coverage overall and a peak in species richness at mid-altitudes.

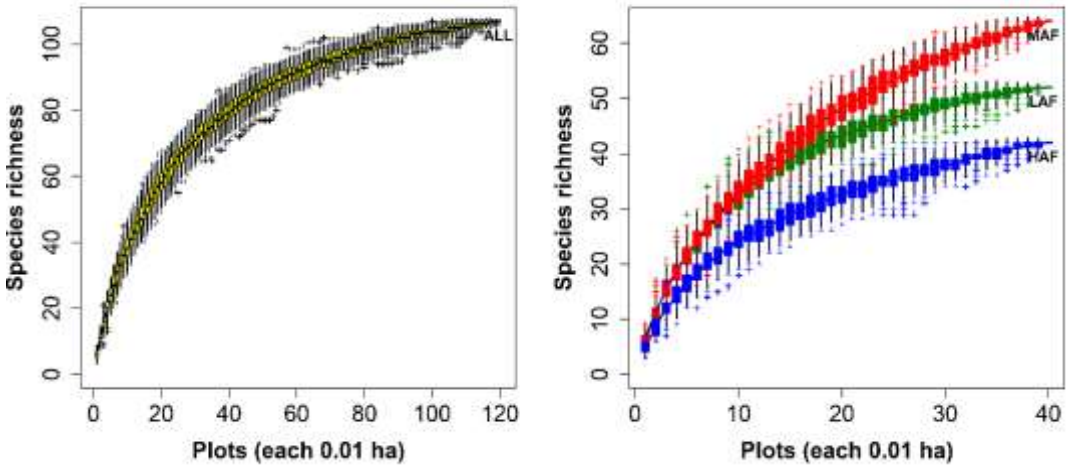


Figure 4.1. Species accumulation curve based on the rarefaction method for tree community: (a) Overall forest community; (b) Three altitudinal forest communities: LAF = Low Altitude Forest, MAF = Mid Altitude Forest, HAF = High Altitude Forest.

4.3.1.2. Species accumulation curve for shrub community

The species accumulation curve analysis for the shrub community revealed that sampling was relatively effective but not exhaustive, as indicated by a gradual yet ongoing rise in the curve even after approximately 90 plots (**Figure 4.2**). This suggests that while most common shrub species were captured, some rare species may not have been fully recorded. For the altitudinal zones, distinct accumulation patterns were evident. The mid-altitudinal forest (MAF) exhibited the highest species richness, with an accumulation curve that continued to rise without reaching a clear asymptote, indicating incomplete sampling and the potential for discovering additional shrub species. The low-altitudinal forest (LAF) displayed intermediate richness, with the curve beginning to flatten after 30–35 plots, suggesting near-complete sampling. In contrast, the high-altitudinal forest (HAF) curve saturated quickly, reflecting lower species richness and effective sampling at higher elevations.

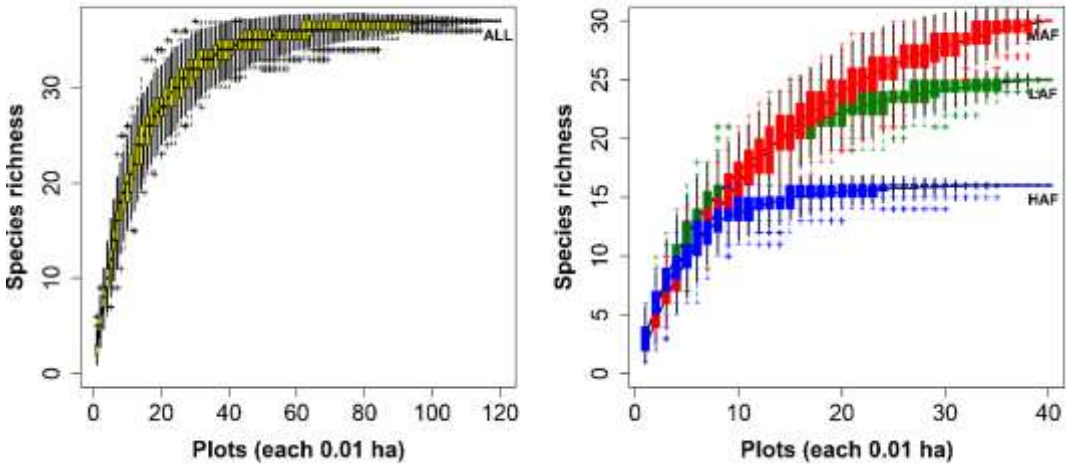


Figure 4.2. Species accumulation curve based on the rarefaction method for shrub community: (a) Overall forest community; (b) Three altitudinal forest communities: LAF = Low Altitude Forest, MAF = Mid Altitude Forest, HAF = High Altitude Forest.

4.3.1.3. Species accumulation curve for herbaceous community

The species accumulation curve analysis for the herbaceous community indicated that, while most common herbaceous species were sampled, complete saturation was not achieved (**Figure 4.3**). The overall curve exhibited a gradual rise even after 100 plots, suggesting that some rare herbaceous species may remain unsampled. Among the altitudinal zones, the mid-altitudinal forest (MAF) and high-altitudinal forest (HAF) demonstrated higher herbaceous species richness, with both curves showing continuous upward trends without reaching clear asymptotes. This suggests incomplete sampling and the possibility of encountering additional species with further sampling. In contrast, the low-altitudinal forest (LAF) displayed lower species richness and a curve that began to flatten earlier (~30 plots), indicating near-saturation at lower elevations.

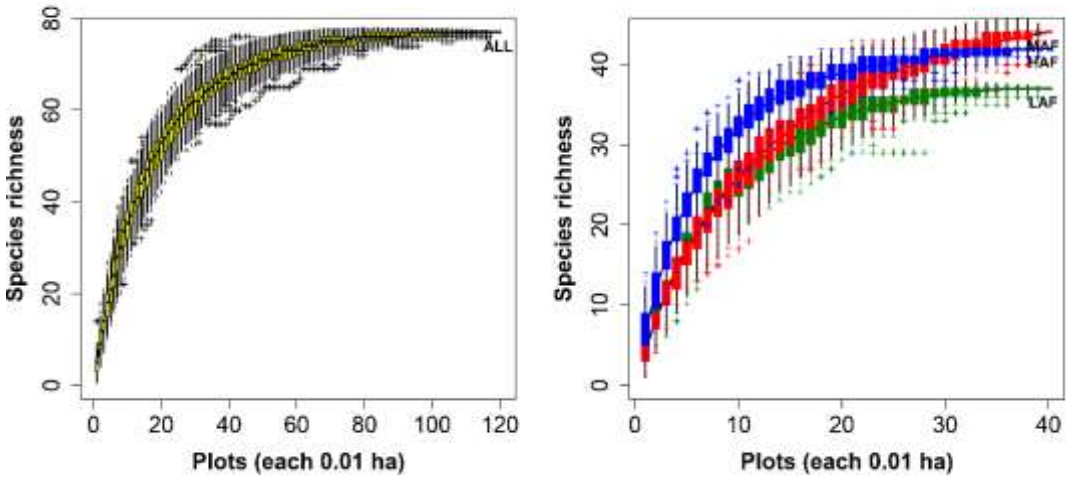


Figure 4.3. Species accumulation curve based on the rarefaction method for herbaceous community: (a) Overall forest community; (b) Three altitudinal forest communities: LAF = Low Altitude Forest, MAF = Mid Altitude Forest, HAF = High Altitude Forest.

4.3.2. Tree community composition

Within the 1.2 ha studied area, a total of 1339 individual trees, representing 107 species, 77 genera, and 38 families were recorded (**Table 4.1**). Lauraceae, recorded

as the most diverse family with 12 species, exhibited the highest amplitude and was found along the entire altitudinal gradient.

Table 4.1. Altitude range, sample area, basal area, stem density, dominant taxa, and diversity indices for all forest communities along the altitudinal gradient for tree community.

Parameters	**ALL**	**LAF**	**MAF**	**HAF**
Altitude (m)	273–2157	273–900	900–1500	1500–2157
Total number of stems	1339	463	466	410
Total sampled area (ha)	1.2	0.4	0.4	0.4
Total species	107	52	64	42
Total genus	77	40	54	34
Total family	38	19	31	22
Total basal area (m^2ha^{-1})	40.85 ± 13.12	42.71 ± 10.93	43.83 ± 11.36	30.75 ± 12.88
Shannon (H')	4.07	3.43	3.51	3.05
Simpson Index (D)	0.79 ± 0.06	0.81 ± 0.03	0.82 ± 0.03	0.74 ± 0.09
Pielou's Evenness (J')	0.94 ± 0.04	0.95 ± 0.03	0.96 ± 0.02	0.92 ± 0.07
Beta diversity (β)	15.36	7.36	7.97	7.13
Dominant family	Fagaceae	Fabaceae	Fagaceae	Fagaceae
Dominant species	*Castanopsis tribuloides*	*Macaranga denticulata*	*Castanopsis tribuloides*	*Engelhardia spicata*

4.3.2.1. Non-Metric Multidimensional Scaling (NMDS)

The NMDS ordination plot showed three ecologically distinct forest communities along the altitudinal gradient, each characterized by a unique species composition, indicating weak overlap among the three altitudinal zones with a stress value of 0.13 (**Figure 4.4a**). The Shepard diagram and goodness-of-fit tests confirmed the results, with a high R-squared value indicating a strong correlation between the observed and predicted values (**Figure 4.4b**). ANOSIM results validated significant differences in species composition among communities (Global R = 0.62, p = 0.001). Pairwise comparisons between altitudinal zones also showed significant variations: LAF-MAF

(R = 0.63, p = 0.001), LAF-HAF (R = 0.74, p = 0.001), while MAF-HAF showed moderate differences (R = 0.36, p = 0.001).

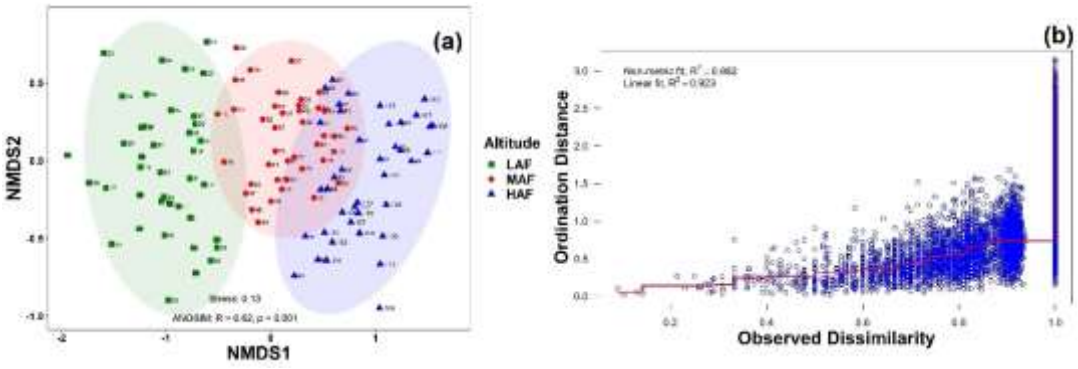


Figure 4.4. Non-metric multidimensional scaling (NMDS) ordination based on Bray–Curtis distances estimated from abundance data for tree community: (a) NMDS ordination with stress and ANOSIM values, where more similar plots are grouped closer together. (b) Shepard diagram assessing the goodness of fit for the NMDS ordination.

4.3.2.2. Dominance distribution pattern for tree community

The overall forest community was dominated by the Fagaceae family, with *Castanopsis tribuloides* showing the highest IVI. In the low-altitude forest (LAF), *Macaranga denticulata* was the most dominant species, followed by *Duabanga grandiflora* and *Albizzia chinensis*. In the mid-altitude forest (MAF), *Castanopsis tribuloides*, *Engelhardia spicata*, and *Schima wallichii* had the highest IVI values, while the high-altitude forest (HAF) was dominated by *Engelhardia spicata*, along with *Quercus floribunda* and *Castanopsis tribuloides* (**Figure 4.5**).

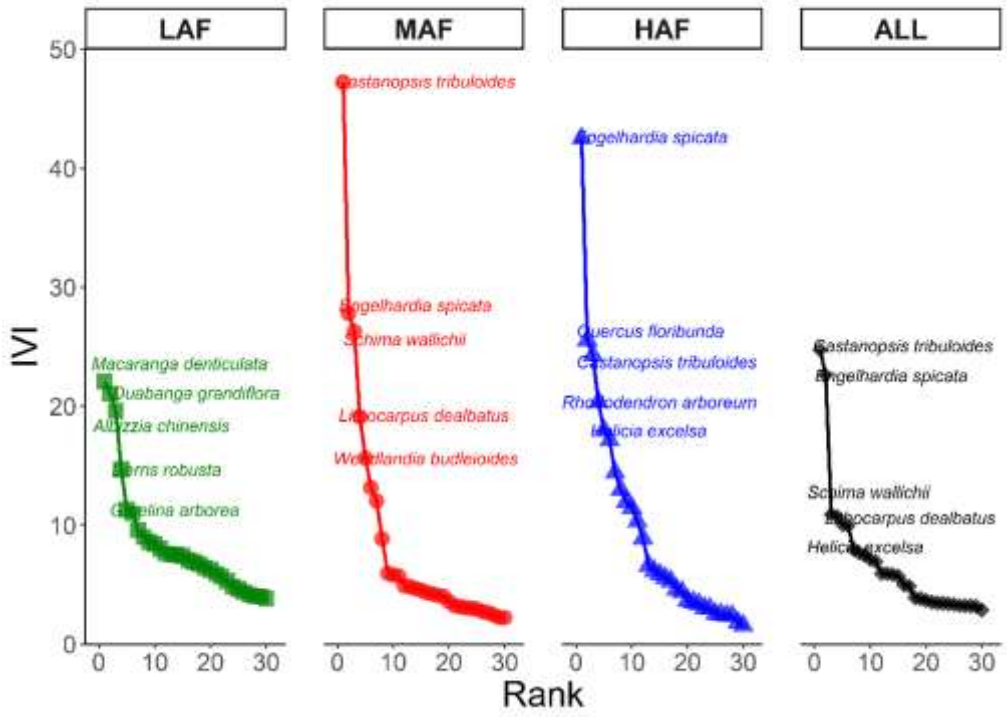


Figure 4.5. The Importance Value Index (IVI) of the top five tree species across three altitudinal zones.

At the family level, Fagaceae was the most dominant across the entire forest, followed by Fabaceae and Lauraceae. In LAF, Fabaceae and Moraceae were the leading families, whereas MAF and HAF were predominantly dominated by Fagaceae, with Lauraceae and Juglandaceae also contributing notably to community composition (**Figure 4.6**).

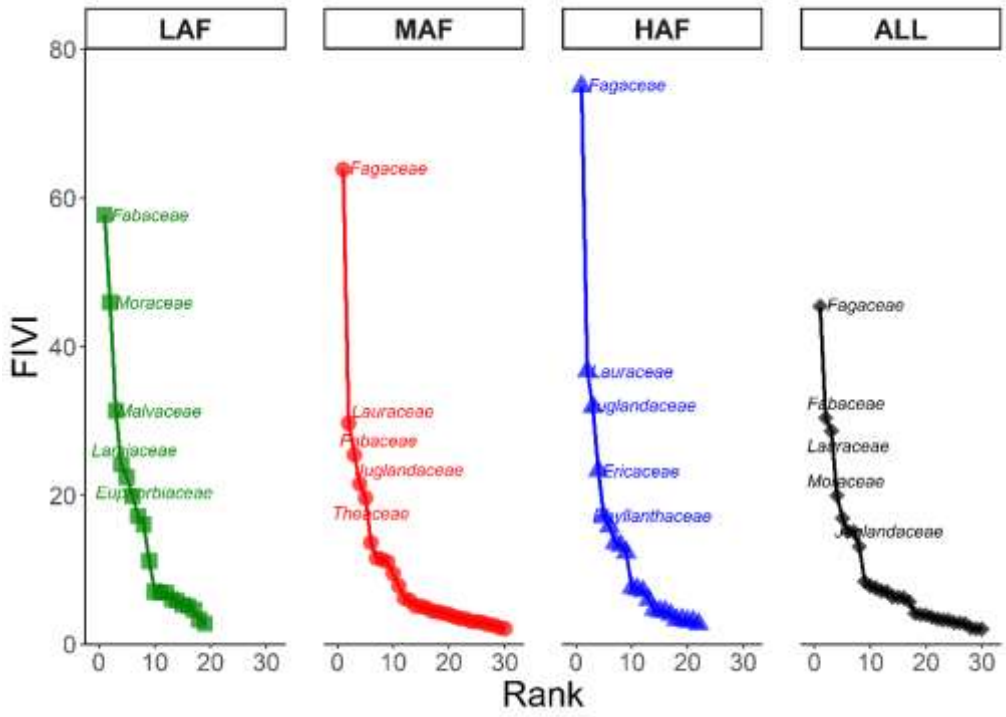


Figure 4.6. The Family Importance Value Index (FIVI) of the top five tree family across three altitudinal zones.

4.3.2.3. Indicator species analysis for tree species

Indicator Species Analysis (ISA) identified tree species significantly associated with altitudinal zones and their combinations. In LAF, *Macaranga denticulata* (IndVal = 0.57, p = 0.001) and *Duabanga grandiflora* (IndVal = 0.52, p = 0.001) were the strongest indicators. For MAF, *Schima wallichii* (IndVal = 0.52, p = 0.001) and *Wendlandia budleioides* (IndVal = 0.51, p = 0.001) showed high fidelity and specificity. In HAF, *Rhododendron arboreum* (IndVal = 0.44, p = 0.001) and *Staphylea cochinchinensis* (IndVal = 0.41, p = 0.001) were prominent indicators. Combinations of zones revealed strong indicators such as *Engelhardia spicata* (IndVal = 0.78, p = 0.001) for HAF+MAF and *Callicarpa arborea* (IndVal = 0.56, p = 0.001) for LAF+MAF (**Table 4.2**). HAF had the highest number of indicator species, reflecting its distinct environmental conditions. Only species with significant p-values ($p < 0.05$) were reported, confirming robust associations with their respective zones.

Table 4.2. Indicator Species Analysis for tree species across altitudinal zones.

Zone	Species	IndVal	P_Value
LAF	*Macaranga denticulata* Müll.Arg.	0.57	0.001***
LAF	*Duabanga grandiflora* Walp.	0.52	0.001***
LAF	*Derris robusta* (Roxb. ex DC.) Benth.	0.39	0.001***
LAF	*Ficus semicordata* Buch. -Ham. ex Sm.	0.38	0.002**
LAF	*Gmelina arborea* Roxb.	0.36	0.001***
LAF	*Pterospermum acerifolium* (L.) Willd.	0.34	0.001***
MAF	*Schima wallichii* (DC.) Korth.	0.52	0.001***
MAF	*Wendlandia budleioides* Wall. ex Wight & Arn.	0.51	0.001***
MAF	*Diospyros glandulosa* Lace	0.46	0.001***
MAF	*Machilus gamblei* King ex Hook.f.	0.31	0.004**
MAF	*Lithocarpus pachyphyllus* Rehder	0.28	0.004**
MAF	*Phoebe lanceolata* (Nees) Nees	0.28	0.008**
HAF	*Rhododendron arboreum* Sm.	0.44	0.001***
HAF	*Staphylea cochinchinensis* (Lour.) Byng & Christenh.	0.41	0.001***
HAF	*Quercus floribunda* Lindl. ex A.Camus	0.40	0.001***
HAF	*Heteropanax fragrans* Seem.	0.39	0.001***
HAF	*Lithocarpus xylocarpus* Markgr.	0.35	0.001***
HAF	*Olea dioica* Roxb.	0.34	0.001***
HAF	*Neolitsea umbrosa* (Nees) Gamble	0.33	0.002**
HAF	*Macropanax dispermus* Kuntze	0.25	0.038*
HAF+MAF	*Engelhardia spicata* Lechen ex Blume	0.78	0.001***
HAF+MAF	*Castanopsis tribuloides* A.DC.	0.72	0.001***
HAF+MAF	*Helicia excelsa* Blume	0.59	0.001***
LAF+MAF	*Callicarpa arborea* Roxb.	0.56	0.001***
LAF+MAF	*Albizia chinensis* (Osbeck) Merr.	0.51	0.002**
LAF+MAF	*Litsea monopetala* Pers.	0.45	0.005**
HAF + LAF	*Cinnamomum verum* J.Presl	0.47	0.004**

Significance levels are indicated by * ($p \leq 0.05$), ** ($p \leq 0.01$), and *** ($p \leq 0.001$).

4.3.2.4. Tree species–environment associations

Canonical Correspondence Analysis (CCA) revealed a clear separation of tree community composition among the three altitudinal zones (LAF, MAF, HAF) based on the measured environmental variables (**Figure 4.7**). The first two axes explained 74.7% of the total variance in the species–environment relationship, with CCA1 accounting for 51.3% and CCA2 for 23.4%. To avoid plot overcrowding, only the top indicator species from Indicator Species Analysis (ISA) for each zone were labelled. LAF plots clustered predominantly on the right side of the ordination, associated with higher soil pH, potassium, phosphorus, temperature, and moderate light intensity. Top indicator species such as *Duabanga grandiflora*, *Macaranga denticulata*, and *Derris robusta* aligned closely with these environmental gradients. Plots from the MAF zone were positioned toward the upper left quadrant, strongly associated with higher relative humidity, soil moisture content, organic carbon, and nitrogen, with indicator species like *Wendlandia budleioides*, *Diospyros glandulosum*, and *Schima wallichii* dominating this group. HAF plots clustered toward the lower center and lower left, primarily influenced by higher altitude and light intensity, characterized by species such as *Symplocos cochinchinensis*, *Rhododendron arboreum*, and *Quercus floribunda*. Overall, the ordination indicated that distinct environmental gradients contributed to variations in species composition across the zones.

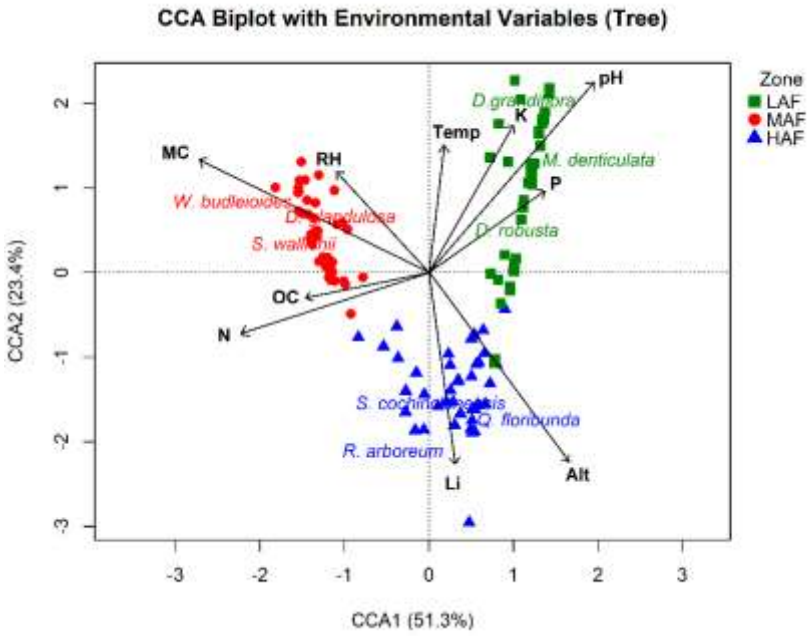


Figure 4.7. CCA biplot illustrating the relationship between tree species composition and key environmental variables across altitudinal zones. Arrows indicate significant environmental gradients, and labelled species represent top indicators based on IndVal scores.

4.3.3. Shrub community composition

Within the 0.6 ha studied area, a total of 618 individual herb, representing 37 species, 33 genera, and 17 families were recorded (**Table 4.3**). Fabacae family was recorded as the most diverse family.

Table 4.3. Altitude range, sample area, density, dominant taxa, and diversity indices for all forest communities along the altitudinal gradient for shrub community.

Parameters	**ALL**	**LAF**	**MAF**	**HAF**
Altitude (m)	273–2157	273–900	900–1500	1500–2157
Total number of individuals	618	201	175	242
Total sampled area (ha)	0.6	0.2	0.2	0.2
Total species	37	25	30	17
Total genus	33	21	23	10
Total family	17	15	15	9
Shannon (*H'*)	2.37	2.31	1.89	2.45
Simpson Index (D)	0.89	0.87	0.81	0.92
Pielou's Evenness (*J'*)	0.92	0.91	0.88	0.94
Beta Diversity (β)	9.87	6.50	9.05	4.29
Dominant family	Fabaceae	Fabaceae	Fabaceae	Acanthaceae
Dominant species	*Strobilanthes fimbriata* Nees	*Chromolaena odorata* (L.) R.M.King & H.Rob.	*Melastoma malabathricum* L.	*Ardisia macrocarpa* Wall

4.3.3.1. Non-Metric Multidimensional Scaling (NMDS)

The NMDS ordination (Stress = 0.08) showed clear separation in shrub species composition across the three altitudinal zones, with LAF and MAF communities overlapping substantially, while HAF formed a more distinct group (**Figure 4.8a**). The ordination fit was strong (Non-metric $R^2 = 0.992$; Linear $R^2 = 0.965$) (**Figure 4.8b**). ANOSIM confirmed significant differences among zones (global R = 0.24, p =

0.001), with the greatest dissimilarity between LAF and HAF (R = 0.45, p = 0.001), moderate separation between MAF and HAF (R = 0.26, p = 0.001), and a smaller but significant difference between LAF and MAF (R = 0.07, p = 0.001), indicating an increasing turnover of shrub species with altitude.

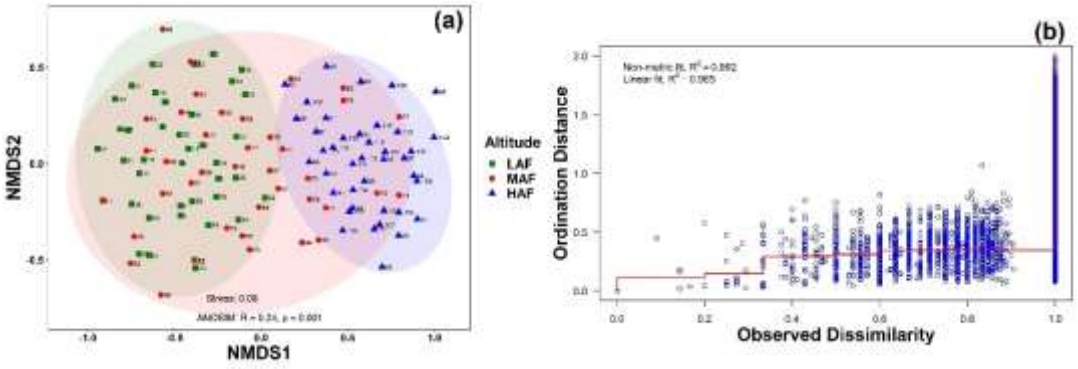


Figure 4.8. Non-metric multidimensional scaling (NMDS) ordination based on Bray–Curtis distances estimated from abundance data for shrub community: (a) NMDS ordination with stress and ANOSIM values, where more similar plots are grouped closer together. (b) Shepard diagram assessing the goodness of fit for the NMDS ordination.

4.3.3.2. Dominance distribution pattern for shrub community

The overall shrub community across the altitudinal gradient was dominated by *Strobilanthes fimbriata*, which exhibited the highest Importance Value Index (IVI) across all plots. In the low-altitude forest (LAF), *Chromolaena odorata* was the most dominant species, followed by *Bridelia montana* and *Buddleja asiatica*. In the mid-altitude forest (MAF), *Melastoma malabathricum*, *Boenninghausenia albiflora*, and *Duhaldea eupatorioides* recorded the highest IVI values. In the high-altitude forest (HAF), *Strobilanthes fimbriata* was the dominant shrub species, with *Ardisia macrocarpa* and *Nostolachma khasiana* contributing significantly to the community composition (**Figure 4.9**).

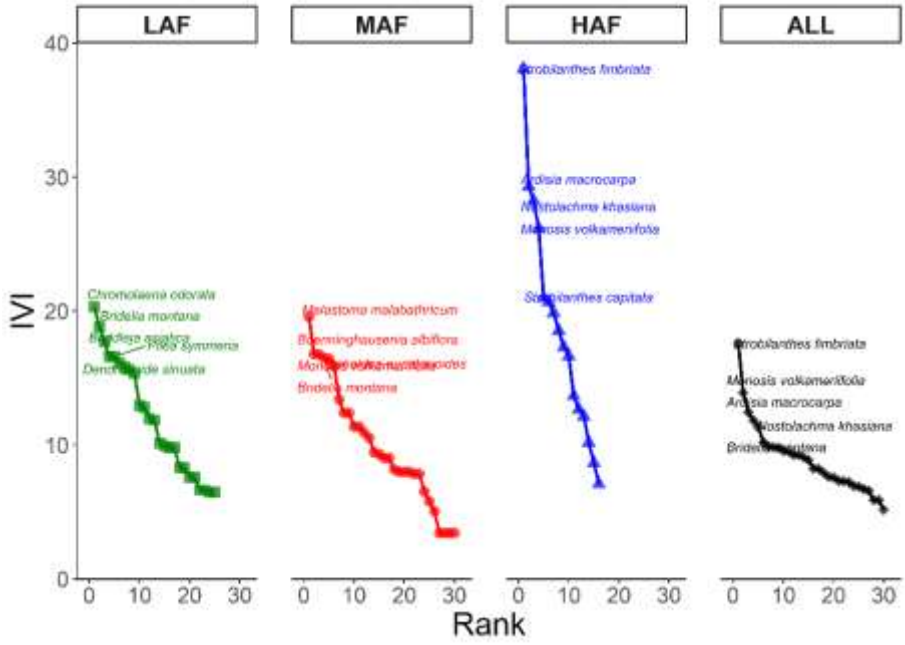


Figure 4.9. The Importance Value Index (IVI) of the top five shrub species across three altitudinal zones.

At the family level, Fabaceae emerged as the most dominant family across the entire shrub community, followed by Acanthaceae and Asteraceae. In LAF, Fabaceae and Urticaceae were the predominant families, whereas MAF was characterized by the dominance of Fabaceae and Acanthaceae. In HAF, Acanthaceae was the leading family, with Rosaceae and Asteraceae also playing substantial roles in shaping the shrub community structure (**Figure 4.10**).

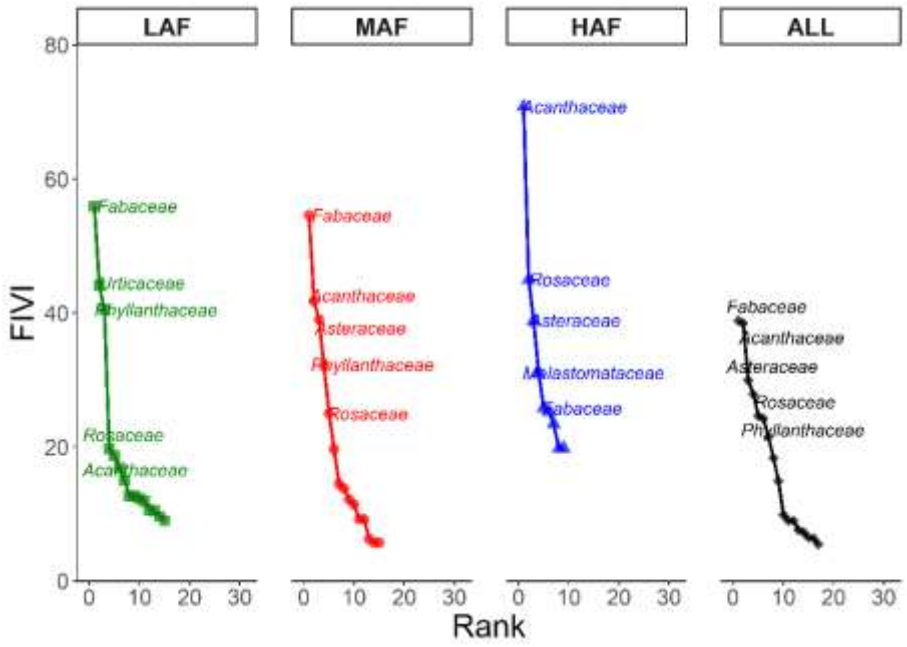


Figure 4.10. The Family Importance Value Index (FIVI) of the top five shrub family across three altitudinal zones.

4.3.3.3. Indicator species analysis for shrub species

Indicator Species Analysis (ISA) identified shrub species significantly associated with altitudinal zones and zone-wise combination. In LAF, *Clerodendrum infortunatum* (IndVal = 0.33, p = 0.001) and *Pilea symmeria* (IndVal = 0.32, p = 0.003) were the strongest indicators. For MAF, *Melastoma malabathricum* (IndVal = 0.24, p = 0.030) was the only significant indicator. In HAF, *Nostolachma khasiana* (IndVal = 0.43, p = 0.001) and *Strobilanthes fimbriata* (IndVal = 0.42, p = 0.001) showed the highest associations, with eight additional species also significant ($p < 0.05$). For the LAF+MAF combination, *Bridelia montana* (IndVal = 0.25, p = 0.011) and *Indigofera heterantha* (IndVal = 0.22, p = 0.034) were notable indicators (**Table 4.4**). HAF exhibited the most indicator species, likely due to its unique high-altitude conditions.

Table 4.4. Indicator Species Analysis for shrub species across altitudinal zones.

Zone	Species	IndVal	P-value
LAF	*Clerodendrum infortunatum* L.	0.331	0.001***
LAF	*Pilea symmeria* Wedd.	0.32	0.003**
LAF	*Buddleja asiatica* Lour.	0.312	0.001***
LAF	*Elatostema lineolatum* Wight	0.299	0.004**
LAF	*Chromolaena odorata* (L.) R.M.King & H.Rob.	0.265	0.015*
MAF	*Melastoma malabathricum* L.	0.241	0.030*
HAF	*Nostolachma khasiana* (Hook.f.) Deb & Lahiri	0.433	0.001***
HAF	*Strobilanthes fimbriata* Nees	0.42	0.001***
HAF	*Osbeckia chinensis* L.	0.4	0.001***
HAF	*Ardisia macrocarpa* Wall.	0.38	0.001***
HAF	*Leucosceptrum canum* Sm.	0.34	0.002**
HAF	*Osbeckia stellata* Buch.-Ham. ex D.Don	0.305	0.008**
HAF	*Rubus niveus* Thunb.	0.281	0.009**
HAF	*Baliospermum calycinum* Müll.Arg.	0.276	0.007**
HAF	*Monosis volkameriifolia* (DC.) H.Rob. & Skvarla	0.252	0.016*
HAF	*Strobilanthes parryorum* C.E.C.Fisch.	0.222	0.048*
HAF	*Strobilanthes capitata* T.Anderson	0.221	0.039*
LAF+MAF	*Bridelia montana* Woodrow ex J.J.Sm.	0.252	0.011*
LAF+MAF	*Indigofera heterantha* Wall. ex Brandis	0.224	0.034*
LAF+MAF	*Bridelia tomentosa* Blume	0.213	0.035*

Significance levels are indicated by * ($p \leq 0.05$), ** ($p \leq 0.01$), and *** ($p \leq 0.001$).

4.3.3.4. Shrub species–environment associations

The CCA biplot for shrub species, with CCA1 and CCA2 explaining 41.5% and 19.7% of the variance respectively, illustrated distinct ecological patterns across altitudinal zones. Top indicator species from ISA were labelled in the ordination to represent each zone (**Figure 4.11**). Shrubs from LAF, including *Buddleja asiatica*, *Pilea symmeria*, and *Clerodendrum infortunatum*, were associated with higher pH, temperature, and potassium levels, indicating a preference for warmer, alkaline, nutrient-rich conditions. The MAF zone was characterized by *Melastoma malabathricum*, linked to elevated moisture content and relative humidity, suggesting

adaptation to humid mid-elevation environments. HAF shrubs such as *Nostolachma khasiana*, *Osbeckia chinensis*, and *Strobilanthes fimbriata* were associated with higher altitude, nitrogen, organic carbon, and light intensity, reflecting specialization for cooler, high-altitude habitats.

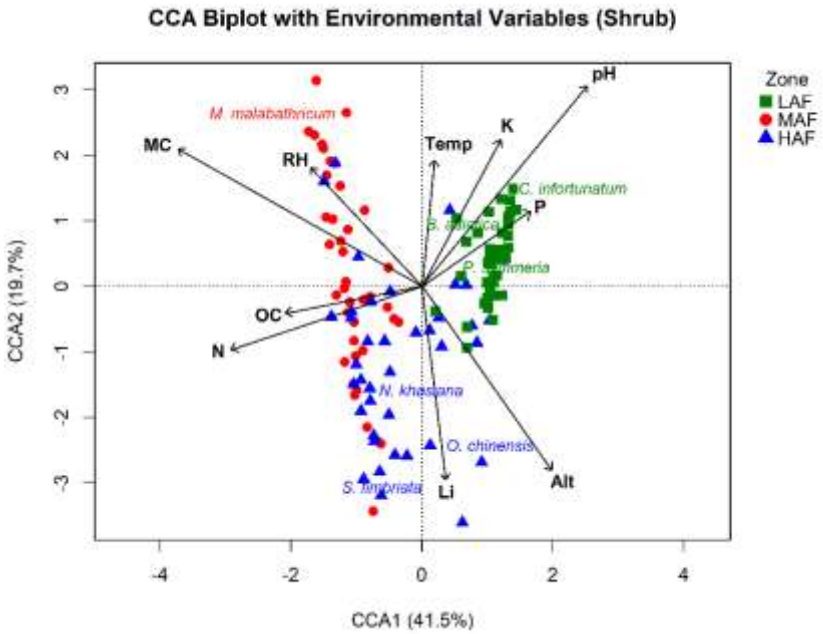


Figure 4.11. CCA biplot illustrating the relationship between shrub species composition and key environmental variables across altitudinal zones. Arrows indicate significant environmental gradients, and labelled species represent top indicators based on IndVal scores.

4.3.4. Herb community composition

Within the 0.024 ha studied area, a total of 1185 individual herb, representing 77 species, 47 genera, and 33 families were recorded (**Table 4.5**). Asteraceae family was recorded as the most diverse family across all zones.

Table 4.5. Altitude range, sample area, density, dominant taxa, and diversity indices for all forest communities along the altitudinal gradient for herbaceous community.

Parameters	**ALL**	**LAF**	**MAF**	**HAF**
Altitude (m)	273–2157	273–900	900–1500	1500–2157
Total number of individuals	1185	358	310	517
Total sampled area (ha)	0.024	0.008	0.008	0.008
Total species	77	37	41	45
Total genus	47	26	31	36
Total family	33	13	15	21
Shannon (*H'*)	2.43	1.83	2.14	2.89
Simpson Index (D)	0.86	0.82	0.85	0.89
Pielou's Evenness (*J'*)	0.94	0.91	0.94	0.97
Beta Diversity (β)	12.98	7.07	8.21	5.88
Dominant family	Asteraceae	Asteraceae	Poaceae	Asteraceae
Dominant species	*Eragrostis nutans* Nees ex Steud.	*Ageratina adenophora* (Spreng.) R.M.King &	*Eragrostis nutans* Nees ex Steud.	*Scleria levis* Retz.

4.3.4.1. Non-Metric Multidimensional Scaling (NMDS)

The NMDS ordination revealed that herb communities of LAF and MAF overlapped moderately, with a significant but relatively low ANOSIM R value (R = 0.34, p = 0.001; **Figure 4.12a**). In contrast, LAF and HAF showed a strong separation with a high R value (R = 0.67, p = 0.001), indicating distinctly different herb assemblages at lower and higher altitudes. Similarly, MAF and HAF also showed a considerable

separation (R = 0.52, p = 0.001). The overall ANOSIM global R was 0.43, suggesting moderate but significant structuring of herb communities along the altitudinal gradient. The NMDS stress value was 0.13, and the Shepard diagram indicated a good ordination fit (non-metric R^2 = 0.983, linear R^2 = 0.922) (**Figure 4.12b**).

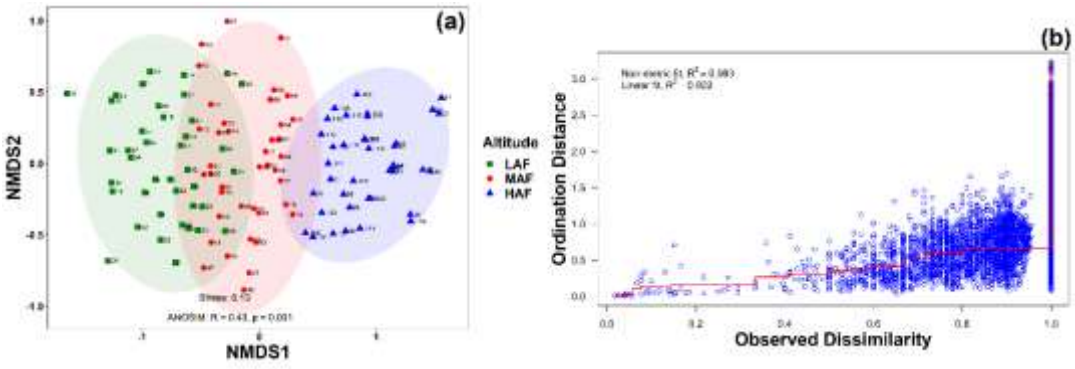


Figure 4.12. Non-metric multidimensional scaling (NMDS) ordination based on Bray–Curtis distances estimated from abundance data for herbaceous community: (a) NMDS ordination with stress and ANOSIM values, where more similar plots are grouped closer together. (b) Shepard diagram assessing the goodness of fit for the NMDS ordination.

4.3.4.2. Dominance distribution pattern for herb community

The overall herb community across the altitudinal gradient was dominated by *Scleria levis*, which exhibited the highest Importance Value Index (IVI) across all plots. In the Low Altitude Forest (LAF), *Ageratina adenophora* emerged as the most dominant species, followed by *Eragrostis nutans* and *Ageratum houstonianum*. In the Mid Altitude Forest (MAF), *Curculigo capitulata* recorded the highest IVI value, with *Scleria levis* and *Ageratina latifolia* also contributing significantly. In the High Altitude Forest (HAF), *Ainsliaea latifolia* was the dominant herb species, with *Drymaria cordata* and *Scleria levis* playing notable roles in the community composition (**Figure 4.13**).

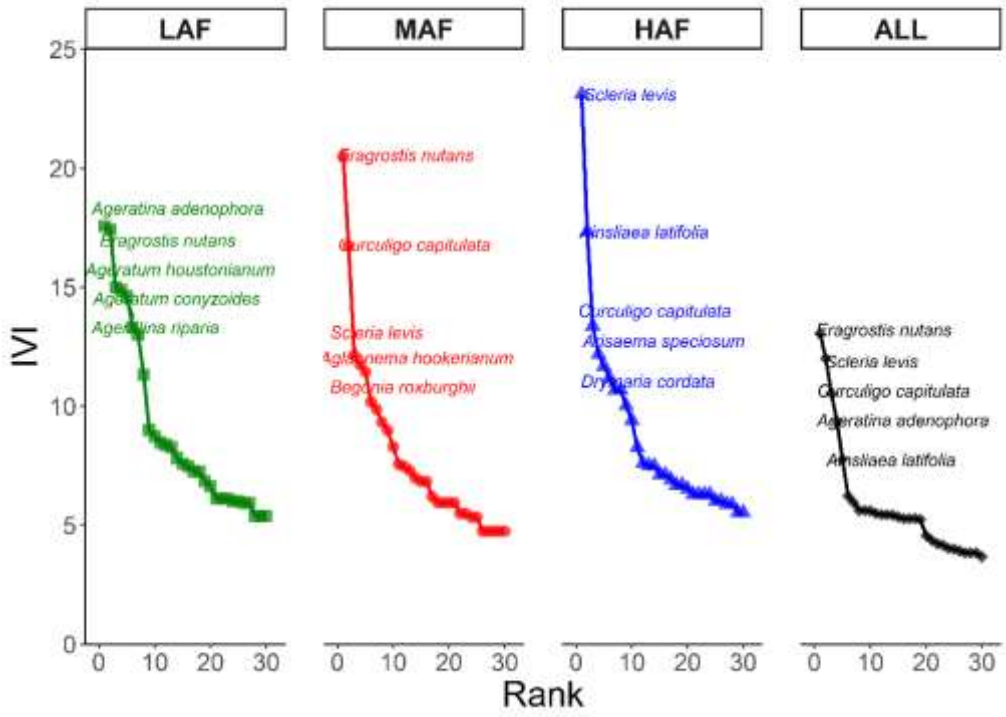


Figure 4.13. The Importance Value Index (IVI) of the top five herbaceous species across three altitudinal zones.

At the family level, Asteraceae emerged as the most dominant family across the entire herb community, followed by Poaceae and Zingiberaceae. In LAF, Asteraceae and Poaceae were the predominant families, whereas MAF was characterized by the dominance of Poaceae and Zingiberaceae. In HAF, Asteraceae was the leading family, with Violaceae and Poaceae also contributing substantially to the herb community structure (**Figure 4.14**). The Family Importance Value Index (FIVI) further reinforced these patterns, with Asteraceae maintaining a high rank across all zones, particularly in HAF, while Poaceae showed significant influence in MAF and LAF, and Zingiberaceae and Violaceae gained prominence in HAF and MAF, respectively.

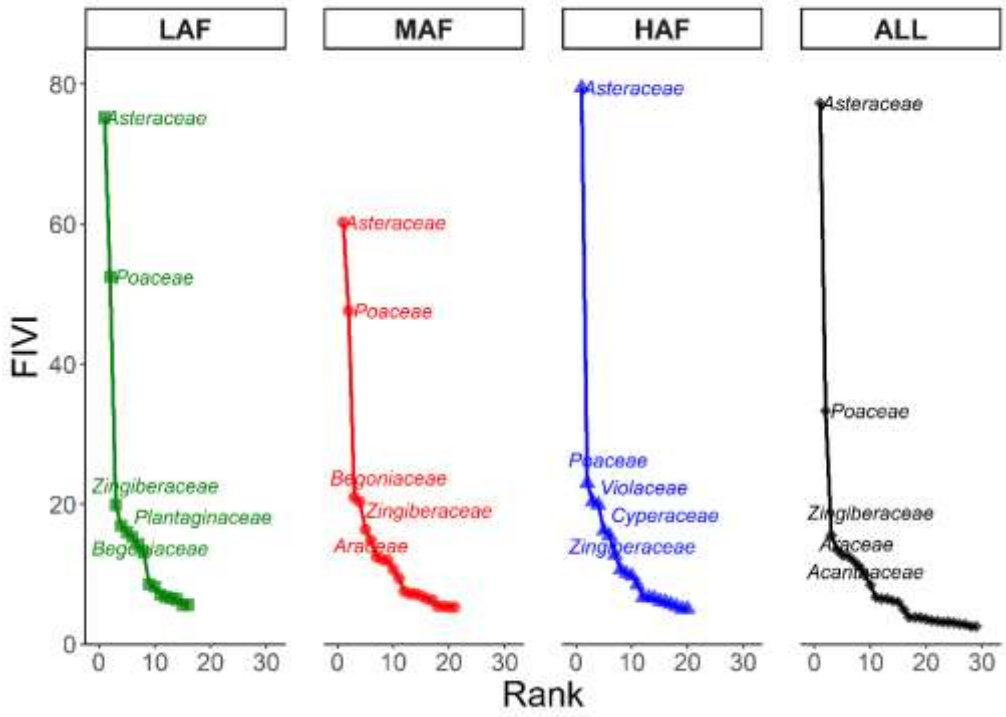


Figure 4.14. The Family Importance Value Index (FIVI) of the top five herbaceous family across three altitudinal zones.

4.3.4.3. Indicator species analysis for herbaceous species

Indicator Species Analysis (ISA) revealed herb significant species associated with altitudinal zones and zone combinations. In LAF, *Ageratina riparia* (IndVal = 0.34, p = 0.002) and *Galinsoga parviflora* (IndVal = 0.34, p = 0.003) were the strongest indicators. For MAF, *Amorphophallus bulbifer* (IndVal = 0.29, p = 0.005) and *Dracaena spicata* (IndVal = 0.28, p = 0.016) showed significant associations. In HAF, *Scleria levis* (IndVal = 0.42, p = 0.001) and *Drymaria cordata* (IndVal = 0.40, p = 0.001) were the most prominent indicators, with 17 additional species also significant ($p < 0.05$). For zone combinations, *Curculigo capitulata* (IndVal = 0.27, p = 0.012) was notable for HAF+MAF, and *Plantago major* (IndVal = 0.25, p = 0.031) for LAF+MAF (**Table 4.6**). HAF had the highest number of indicator species, reflecting its diverse and specialized herbaceous flora.

Table 4.6. Indicator Species Analysis for herbaceous species across altitudinal zones.

Zone	Species	IndVal	P-value
LAF	*Ageratina riparia* (Regel) R.M.King & H.Rob.	0.341	0.002**
LAF	*Galinsoga parviflora* Cav.	0.34	0.003**
LAF	*Ageratum conyzoides* L.	0.319	0.003**
LAF	*Bidens pilosa* L.	0.298	0.002**
LAF	*Crassocephalum crepidioides* S.Moore	0.268	0.019*
LAF	*Ageratum houstonianum* Mill.	0.264	0.010**
LAF	*Senecio vulgaris* L.	0.256	0.024*
LAF	*Justicia procumbens* L.	0.247	0.032*
LAF	*Boehmeria virgata* (G.Forst.) Guill.	0.239	0.029*
MAF	*Amorphophallus bulbifer* Blume	0.29	0.005**
MAF	*Dracaena spicata* Roxb.	0.278	0.016*
MAF	*Setaria palmifolia* Stapf	0.228	0.038*
HAF	*Scleria levis* Retz.	0.417	0.001***
HAF	*Drymaria cordata* Willd. ex Schult.	0.403	0.001***
HAF	*Ainsliaea latifolia* (D.Don) Sch.Bip.	0.393	0.001***
HAF	*Arisaema speciosum* (Wall.) Mart.	0.381	0.001***
HAF	*Artemisia vulgaris* L.	0.363	0.001***
HAF	*Hypericum elodeoides* Choisy	0.355	0.001***
HAF	*Laggera alata* (DC.) Sch.Bip. ex Oliv.	0.347	0.001***
HAF	*Isodon repens* (Wall.) Murata	0.346	0.002**
HAF	*Hemisteptia lyrata* Bunge	0.34	0.001***
HAF	*Dicliptera paniculata* (Forssk.) I.Darbysh.	0.314	0.003**
HAF	*Duhaldea nervosa* (Wall. ex DC.) Anderb.	0.31	0.005**
HAF	*Swertia cordata* Wall.	0.305	0.002**
HAF	*Viola pilosa* Blume	0.303	0.005**
HAF	*Senecio scandens* (L.) Buch. -Ham.	0.295	0.002**
HAF	*Cirsium interpositum* Petr.	0.284	0.010**
HAF	*Amomum dealbatum* Roxb.	0.271	0.012*
HAF	*Potentilla lineata* Trevir.	0.258	0.040*
HAF	*Eulalia trispicata* (Schult.) Henrard	0.247	0.037*
HAF	*Notoseris khasiana* (C.B.Clarke) N.Kilian	0.246	0.029*
HAF	*Viola betonicifolia* Sm.	0.243	0.031*

HAF	*Viola hamiltoniana* D.Don	0.239	0.039*
HAF	*Digitaria sanguinalis* (L.) Scop.	0.238	0.032*
HAF+MAF	*Curculigo capitulata* Kuntze	0.268	0.012*
HAF+MAF	*Scleria terrestris* (L.) Fassett	0.221	0.046*
LAF+MAF	*Plantago major* L.	0.246	0.031*
LAF+MAF	*Etlingera linguiformis* (Roxb.) R.M.Sm.	0.237	0.032*
LAF+MAF	*Eragrostis nutans* Nees ex Steud.	0.235	0.032*
LAF+MAF	*Aglaonema hookerianum* Schott	0.22	0.047*

Significance levels are indicated by * ($p \leq 0.05$), ** ($p \leq 0.01$), and *** ($p \leq 0.001$).

4.3.4.4. Herb species–environment relationships

The CCA biplot for herbaceous species, with CCA1 and CCA2 explaining 43.2% and 19.3% of the variance respectively, similarly revealed distinct ecological affinities across zones. Top indicator species selected from ISA were labelled for clarity (**Figure 4.15**). LAF herbs such as *Ageratum conyzoides*, *Ageratina riparia*, and *Galinsoga parviflora* were strongly associated with higher pH, temperature, and potassium, favouring warmer, lowland conditions. MAF herbs, notably *Amorphophallus bulbifer*, *Dracaena spicata*, and *Setaria palmifolia*, were linked to higher moisture content and relative humidity. HAF species including *Ainsliaea latifolia*, *Drymaria cordata*, and *Selaginella levis* were associated with higher altitude, nitrogen, organic carbon, and light intensity, reflecting adaptation to cooler, nutrient-rich environments. The analysis underscored the role of environmental gradients, particularly altitude, soil properties, and moisture availability, in shaping herb community structure.

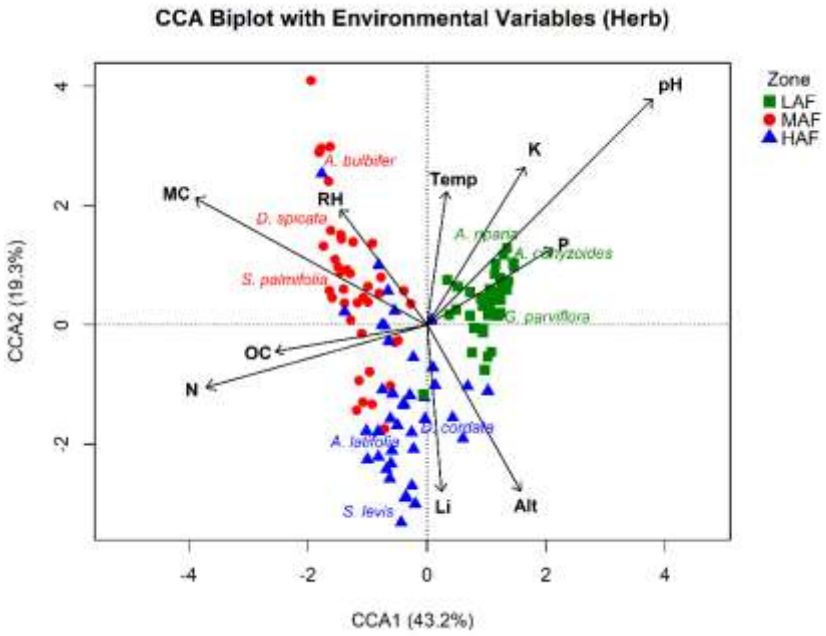


Figure 4.15. CCA biplot illustrating the relationship between herbaceous species composition and key environmental variables across altitudinal zones. Arrows indicate significant environmental gradients, and labelled species represent top indicators based on IndVal scores.

4.3.5. Diversity patterns across altitudes

4.3.5.1. Tree Diversity

The relationship between tree diversity indices and altitude followed a significant quadratic trend ($P < 0.001$ for all indices). Shannon diversity index among plots were found maximum at 1500 m (2.14) and minimum at 2000 m (0.85) (**Figure 4.16a**). Similarly, the Simpson diversity index among plots exhibited a comparable hump-shaped pattern, with higher diversity observed at intermediate altitudes (**Figure 4.16b**). Pielou's evenness among plots showed a slight but significant decline with increasing altitude, indicating that tree communities at higher elevations were less evenly distributed compared to those at lower elevations (**Figure 4.16c**). Shannon diversity across the altitudinal zones ranged from 3.05 to 3.51, while the overall Shannon index value was notably high at 4.07 (**Table 4**). The Simpson diversity index valued from 0.74 to 0.82, with the highest value for the MAF zone. The

Pielou's evenness index varied from 0.92 to 0.96, with MAF had highest score while HAF scored the lowest (**Table 4.1**). The alpha diversity indices were found to increase with altitude up to 1500 m but then decreased above this mid-altitude threshold. Beta diversity decreased initially with increasing altitude, reaching a minimum point at MAF zone and then started increasing again at higher altitudes (**Figure 4.16d**). This pattern contrasted with alpha diversity, as beta diversity was relatively high in LAF and HAF but declined in MAF.

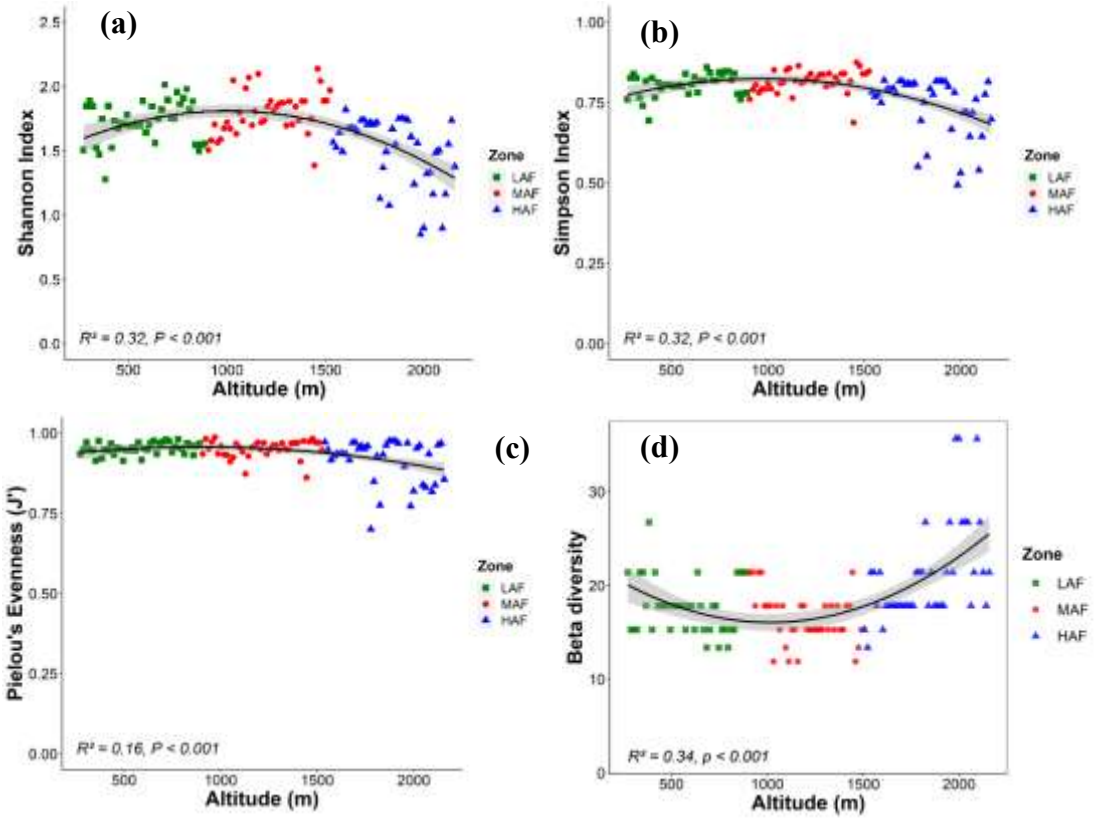


Figure 4.16. Quadratic regression analysis for tree community: (a) Between Shannon diversity and altitude, (b) Between Simpson diversity and altitude, (c) Between Pielou's Evenness index, (d) Between beta diversity and altitude. R^2 and p-values are displayed on the bottom left corner of each plot.

4.3.5.2. Shrub Diversity

The quadratic regression models showed that shrub diversity indices among plots varied significantly with altitude. Shannon diversity exhibited a U-shaped pattern along the altitudinal gradient, with lower diversity values at mid-elevations and

higher values at both low and high elevations ($R^2 = 0.28$, $P < 0.001$) (**Figure 4.17a**). Similarly, Simpson diversity also followed a U-shaped relationship with altitude ($R^2 = 0.21$, $P < 0.001$), with diversity declining at mid-altitudes (**Figure 4.17b**). In contrast, Pielou's evenness did not display a significant relationship with altitude ($R^2 = 0.018$, $P = 0.98$), indicating that the uniformity of species distribution among shrubs remained relatively constant across the gradient (**Figure 4.17c**). Among altitudinal zones, Shannon diversity was found to be maximum at HAF (2.45) and minimum at MAF (1.89). The overall shrub's species diversity was 2.37. Similarly, Simpson diversity index and Pielou's evenness index followed the same pattern with higher values at LAF and HAF but dip at the mid altitude zone. Beta diversity displayed a hump-shaped pattern, with the highest compositional dissimilarity observed at mid-elevations ($R^2 = 0.19$, $P < 0.001$) (**Figure 4.17d**).

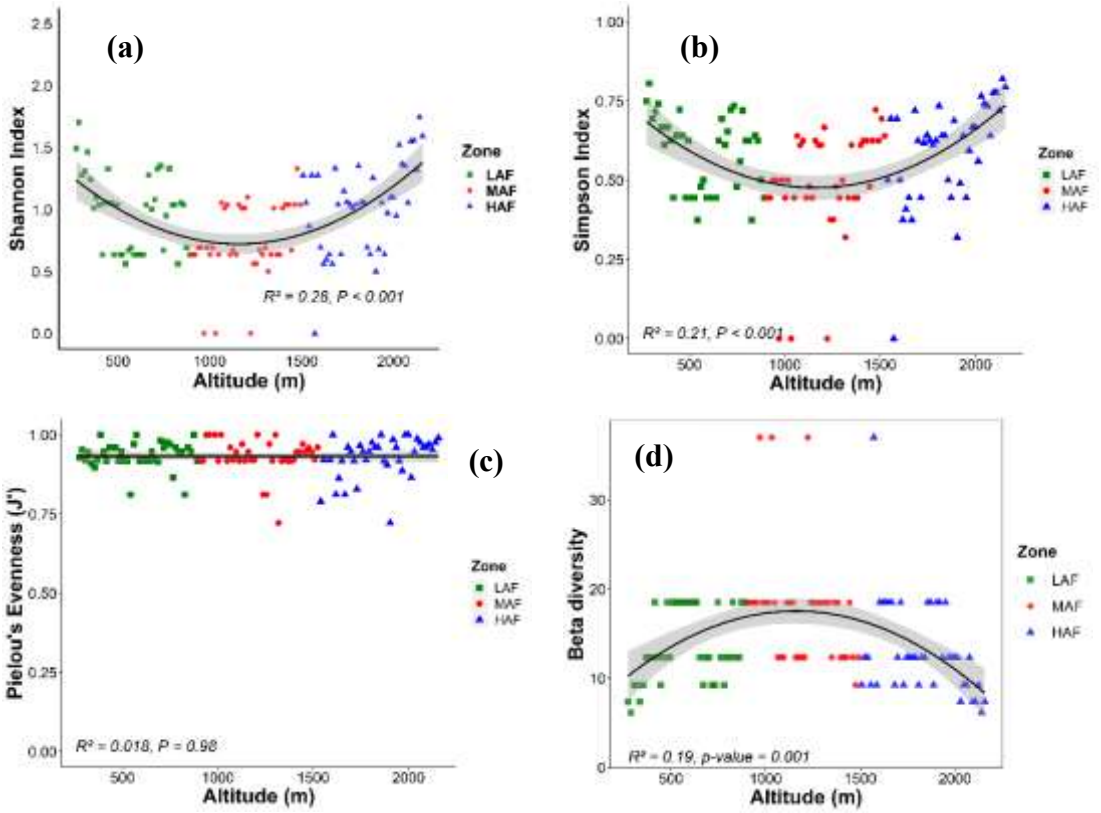


Figure 4.17. Quadratic regression analysis for shrub community: (a) Between Shannon diversity and altitude, (b) Between Simpson diversity and altitude, (d) Between beta diversity and altitude. Linear regression analysis: (c) Between Pielou's Evenness index. R^2 and p-values are displayed on each plot.

4.3.5.3. Herbaceous Diversity

The quadratic regression models indicated that herbaceous diversity among plots varied significantly with altitude. Shannon diversity exhibited a positive linear trend, with diversity increasing toward higher elevations ($R^2 = 0.30$, $P < 0.001$) (**Figure 4.18a**). Similarly, Simpson diversity also increased with altitude, although with a lower explanatory power ($R^2 = 0.17$, $P < 0.001$) (**Figure 4.18b**). Pielou's evenness showed a slight but significant positive relationship with altitude ($R^2 = 0.04$, $P = 0.02$), suggesting a marginal increase in the uniformity of herb species distribution at higher elevations (**Figure 4.18c**). In contrast, beta diversity demonstrated a hump-shaped pattern, with compositional dissimilarity peaking at mid-elevations and declining toward higher altitudes ($R^2 = 0.26$, $P < 0.001$) (**Figure 4.18d**). The herbaceous Shannon diversity among the altitudinal zones found to be highest at HAF (2.89) and lowest at LAF (1.83). The overall Shannon diversity was 2.43. Likewise, Simpson index and Pielou's evenness followed a similar pattern.

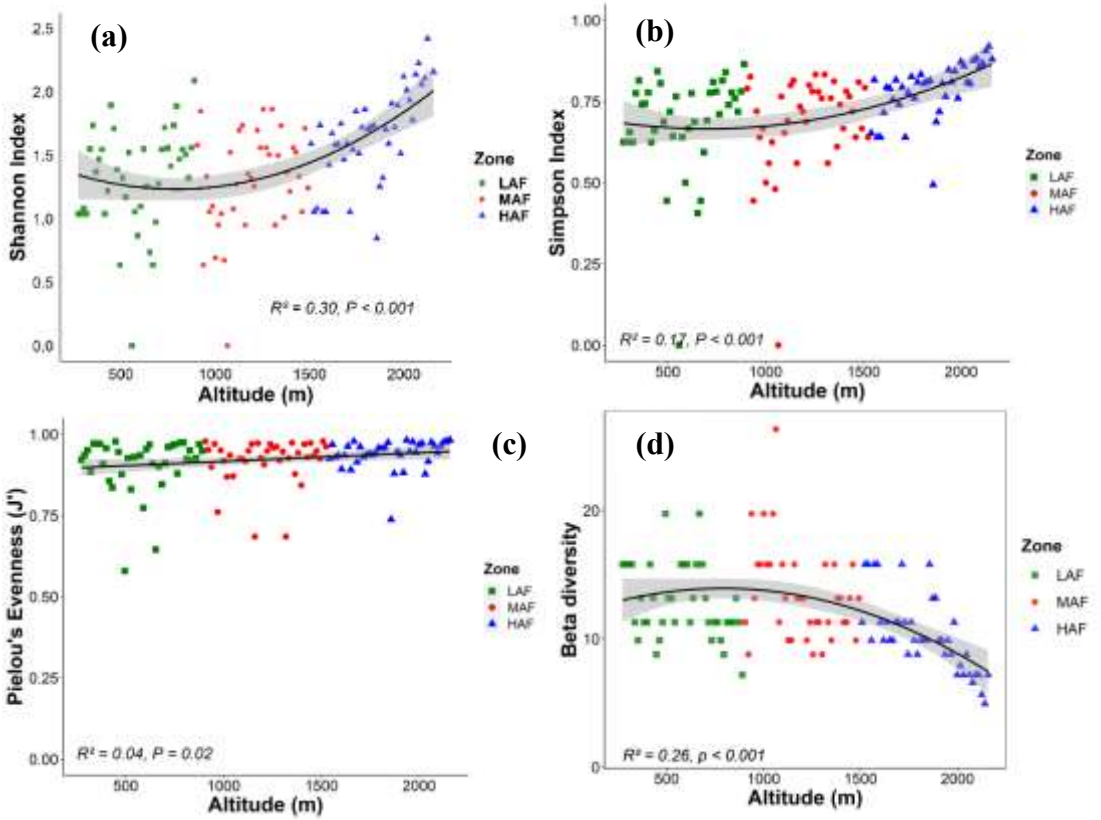


Figure 4.18. Quadratic regression analysis for herbaceous community: (a) Between Shannon diversity and altitude, (b) Between Simpson diversity and altitude, (d) Between beta diversity and altitude. Linear regression analysis: (c) Between Pielou's Evenness index. R^2 and p-values are displayed on each plot.

4.3.6. Forest structure

The size class distribution, basal area, and stem density of tree species together constitute the forest structure. The recorded values for stem density, basal area, and median of stem DBH from overall communities were 1100 ha^{-1}, 40.85 m^2 ha^{-1}, and 19.33 cm, respectively (**Figure 4.19a-c**). The MAF had the highest stem density (1200 stem ha^{-1}), basal area (43.83 m^2 ha^{-1}), and stem DBH (21.6 cm) among the forest communities. However, the HAF recorded the lowest for both basal area (30.75 m^2 ha^{-1}) and stem DBH (18.59 cm).

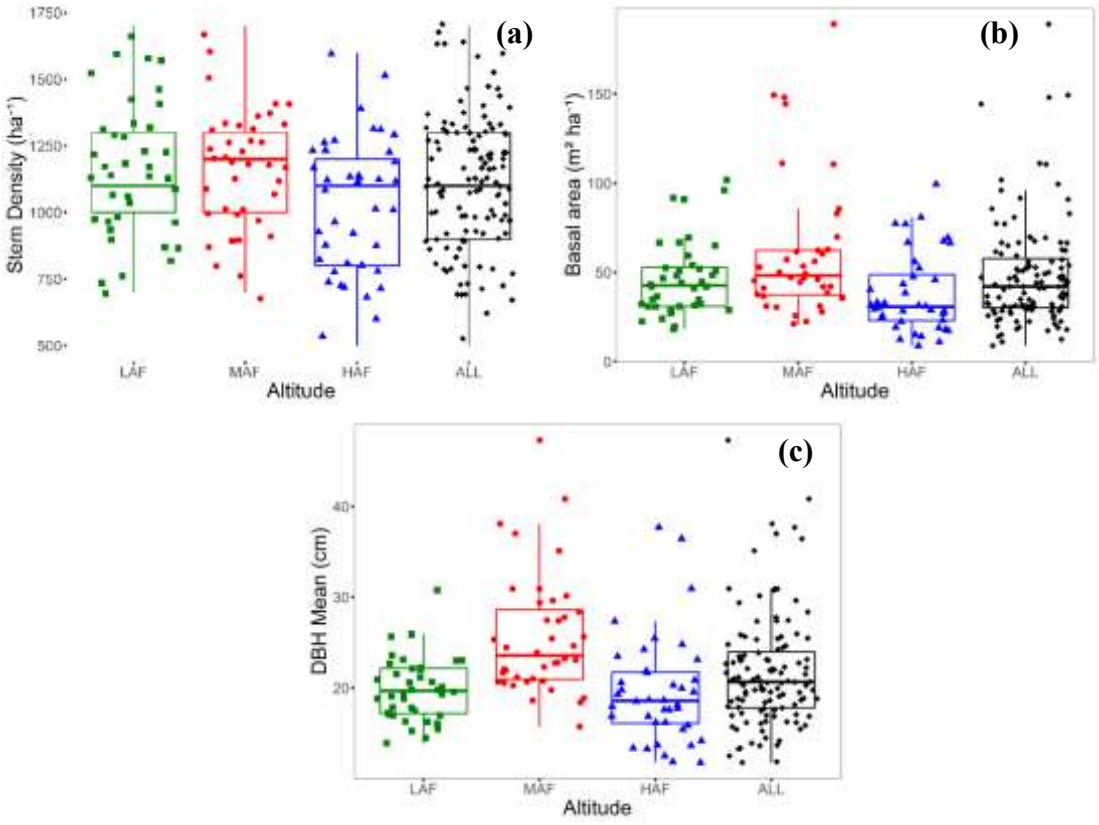


Figure 4.19. Boxplot with jittered data points showing the distribution of: (a) stem density, (b) basal area, and (c) stem DBH. The horizontal line inside the box

represents the median, while the box encompasses the 25th and 75th percentiles. The vertical line outside the box indicates the minimum and maximum values.

On the basis of stem density per hectare, the size class distribution showed a reverse J-shaped curve, with the highest number of stems in the 10 to 20 cm DBH class and the lowest in the 110 to 120 cm DBH class (**Figure 4.20**). The altitudinal zones exhibited a similar pattern, but the LAF and HAF did not have any trees with a diameter of more than 100 cm. The MAF zone had the highest DBH classes, with the largest tree being *Engelhardia spicata* with a diameter of 110.83 cm DBH.

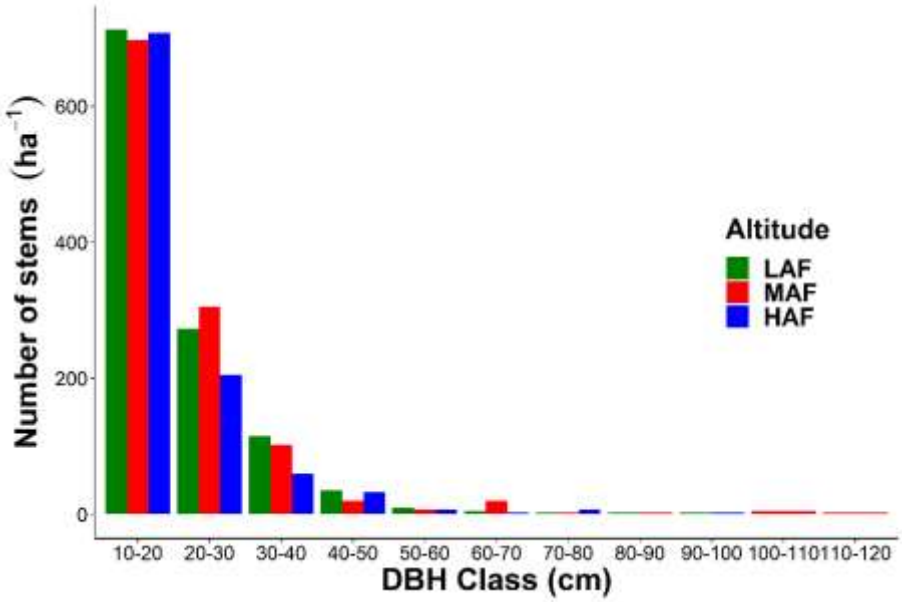


Figure 4.20. Size class distribution of tree DBH recorded in the study across the three altitudinal zones: LAF = Low Altitude Forest, MAF = Mid Altitude Forest, HAF = High Altitude Forest.

4.4. Discussions

The species accumulation curves (SAC) demonstrated that tree, shrub, and herb communities were adequately sampled overall, with saturation beyond 90–100 plots, reflecting comprehensive coverage of common species (Gotelli & Colwell, 2011). Trees and shrubs showed saturation in LAF and HAF, indicating stable species pools at lower and higher altitudes, while MAF exhibited ongoing accumulation, suggesting a diversity peak driven by transitional habitats (Bhattarai & Vetaas, 2006).

Herbs followed a similar trend, with LAF nearing saturation but MAF and HAF showing continuous rises, highlighting higher richness and potential rare species at mid- to high altitudes (Chao et al., 2014). These patterns underscored altitude's role as a key driver of species richness, likely influenced by climatic and edaphic gradients in the Himalayas (Krömer et al., 2013). The incomplete sampling in MAF and HAF across lifeforms suggested that rare species, possibly adapted to niche microhabitats, remained underrepresented, aligning with findings from montane ecosystems (Colwell et al., 2012). This richness gradient supported the use of these communities for biodiversity monitoring, with future studies needed to assess rare species contributions to altitudinal diversity.

The NMDS ordinations revealed distinct community structures for trees, shrubs, and herbs across LAF, MAF, and HAF, with altitude acting as a primary driver of species composition, consistent with eastern Himalayan studies (Bhutia et al., 2019). Trees showed the strongest separation (global R = 0.62), with high LAF-HAF divergence (R = 0.74), reflecting niche specialization (Jiménez-Paz et al., 2021). Shrubs exhibited moderate structuring (global R = 0.24), with HAF's distinctness (LAF-HAF: R = 0.45) suggesting adaptation to high-altitude conditions, while MAF overlapped with LAF (R = 0.07) as a transitional zone (Körner, 2007). Herbs displayed intermediate separation (global R = 0.43), with significant LAF-HAF differences (R = 0.67), likely due to sensitivity to climatic gradients (Bhattarai & Vetaas, 2006). The low overlap between zones, particularly for trees and herbs, indicated strong niche adaptation, with species like *Rhododendron arboreum* (HAF) and *Duabanga grandiflora* (LAF) restricted to their altitudes. These patterns reflected the influence of climatic, topographic, and edaphic factors along the Himalayan gradient (Krömer et al., 2013). The communities' altitudinal structuring highlighted their potential as bioindicators for climate change, warranting further trait-based studies.

The IVI and FIVI analyses revealed distinct dominance patterns across tree, shrub, and herb communities along the altitudinal gradient, reflecting ecological adaptations to varying conditions. Trees showed *Macaranga denticulata* dominating LAF, *Castanopsis tribuloides* in MAF, and *Engelhardia spicata* in HAF, highlighting niche

specialization driven by altitude and disturbance (Sprent, 2009). Shrubs exhibited *Chromolaena odorata* in LAF, *Melastoma malabathricum* in MAF, and *Strobilanthes fimbriata* in HAF, suggesting resilience to altitudinal stressors (Bhattarai & Vetaas, 2006). Herbs were led by *Ageratina adenophora* in LAF, *Curculigo capitulata* in MAF, and *Ainsliaea latifolia* in HAF, indicating sensitivity to climatic shifts (Krömer et al., 2013). At the family level, Fagaceae dominated trees in MAF and HAF, Fabaceae in LAF trees and shrubs, and Asteraceae in herbs across zones, reflecting their adaptive roles in soil fertility and climatic tolerance (Manos & Stanford, 2001). These patterns underscored the influence of altitudinal gradients, including temperature and moisture, on community structure (Körner, 2007). The dominance shifts highlighted these species and families as potential indicators of environmental change, warranting further studies on their functional traits and responses to disturbance.

The Indicator Species Analysis (ISA) revealed distinct tree, shrub, and herb species associated with Lowland Altitudinal Forest (LAF, 500–1000 m), Mid-Altitudinal Forest (MAF, 1000–1500 m), High Altitudinal Forest (HAF, >1500 m), and their combinations, indicating strong altitudinal structuring of plant communities. HAF exhibited the highest number of indicator species across all lifeforms, with eight tree species (e.g., *Rhododendron arboreum*, IndVal = 0.44, p = 0.001), ten shrub species (e.g., *Nostolachma khasiana*, IndVal = 0.43, p = 0.001), and 19 herb species (e.g., *Scleria levis*, IndVal = 0.42, p = 0.001). This pattern suggested that HAF's unique environmental conditions, such as lower temperatures and higher moisture, fostered specialized flora, consistent with findings on altitudinal gradients (Körner, 2007). In contrast, MAF had the fewest indicator species, particularly for shrubs (*Melastoma malabathricum*, IndVal = 0.24, p = 0.030) and herbs, suggesting a transitional zone with less distinct species associations (Dufrene & Legendre, 1997).

High IndVal scores for species in zone combinations, such as *Engelhardia spicata* (IndVal = 0.78, p = 0.001) for HAF+MAF (trees) and *Curculigo capitulata* (IndVal = 0.27, p = 0.012) for HAF+MAF (herbs), highlighted species with broader ecological tolerances across altitudes. These findings aligned with previous work, which noted that ISA could identify species bridging multiple ecological conditions (Cáceres &

Legendre, 2009). The predominance of significant p-values ($p < 0.05$) across all lifeforms supported the use of these species as bioindicators for monitoring altitudinal shifts under climate change (Chowdhury et al., 2023; Dinca et al., 2024). Future studies could investigate functional traits of these indicator species to elucidate their ecological roles across altitudinal gradients.

The Canonical Correspondence Analysis (CCA) results demonstrated strong associations between environmental gradients and plant community composition across altitudinal zones, consistent with recent ecological research on species distribution patterns. For tree species, the distinct separation of low-altitude (LAF), mid-altitude (MAF), and high-altitude (HAF) zones, with 74.7% of variance explained by the first two axes, highlighted the critical role of altitude, soil nutrients, and microclimatic factors such as temperature and humidity. LAF species, including *Duabanga grandiflora* and *Macaranga denticulata*, were associated with warmer, nutrient-rich conditions, aligning with findings from lowland tropical forests. MAF species, such as *Schima wallichii*, were linked to higher humidity and organic carbon, reflecting mid-elevation adaptations (Getaneh et al., 2023). HAF species like *Rhododendron arboreum* were associated with cooler, high-light environments, consistent with high-altitude ecological patterns (Bharali et al., 2012).

Shrub and herb communities showed comparable patterns, with CCA axes explaining 61.2% and 62.5% of variance, respectively, reinforcing the influence of environmental gradients. LAF shrubs (e.g., *Buddleja asiatica*) and herbs (e.g., *Ageratum conyzoides*) were tied to alkaline, potassium-rich soils, corroborating studies on lowland species preferences (Dibaba et al., 2022). MAF shrubs like *Melastoma malabathricum* and herbs like *Amorphophallus bulbifer* were associated with humid conditions, consistent with mid-elevation moisture-driven ecosystems (He et al., 2023). HAF shrubs (e.g., *Strobilanthes fimbriata*) and herbs (e.g., *Ainsliaea latifolia*) were adapted to high-altitude, nutrient-rich conditions, supporting research on alpine plant specialization (Kumar et al., 2024).

These results underscored that altitude, soil properties, and microclimatic factors were primary drivers of plant community structure across trees, shrubs, and herbs,

indicating robust environmental filtering processes (Dibaba et al., 2022). The consistency of these patterns across life forms suggested strong ecological niche differentiation, as observed in similar montane studies (Shrestha et al., 2012). Future research could investigate temporal dynamics or anthropogenic disturbances to further clarify these relationships, particularly in the context of climate change impacts on altitudinal gradients (Maren et al., 2014).

The range of tree species diversity among plots along the altitudinal gradient was similar to the reported range from the subtropical Himalayas (Bhutia et al., 2019; Negi et al., 2024; Tomar et al., 2024b). Shannon diversity index (H') among altitudinal zones was comparable with previous studies (Hrahsel et al., 2019; Nohro & Jayakumar, 2020; Reang et al., 2025; Wapongnungsang et al., 2021). The overall forest community's high Shannon diversity index of 4.07, which is notably high for a subtropical forest, can be attributed to its unique location at the biogeographic intersection of the Eastern Himalayas and Indo-Burma hotspot, coupled with its wide altitudinal gradient, habitat heterogeneity, and ecological stability. This high diversity index reflects not only the richness and evenness of species but also the region's potential for supporting a complex array of species across different elevations. This is strongly supported by the Pielou's Evenness Index (J' = 0.94), indicating an almost uniform distribution of individuals among species, which increases diversity. Although the Simpson's Index (D = 0.79) is slightly lower, it still highlighted low species dominance and contributed to the overall richness and balance in the community, supporting the high diversity. This finding aligned with recent studies that reported a Shannon Index value above 4 in various parts of the Eastern Himalayan region (Devi et al., 2018; Gogoi et al., 2020; Suchiang et al., 2020). However, those studies were conducted in tropical forests, whereas our study focuses on a subtropical forest, differing in both altitudinal range and forest type. One potential factor for high diversity could be the presence of secondary forests in the LAF zone. Many secondary forests recovered quickly owing to the observed diversity of the woody species present and have tree species richness, often surpassing old-growth forests (Amani et al., 2021). This phenomenon aligned with the intermediate disturbance hypothesis (Bongers et al., 2009), which suggested that

biodiversity reaches its peak in mid-successional forests. This is attributed to the coexistence of pioneer species established immediately after disturbance and late-successional, shade-tolerant species that thrived in the shade of the pioneers (Norden et al., 2009).

In this study, the total number of shrub species recorded (37 species) matched the findings of a previous study (Sangry et al., 2024), which also reported 37 species and observed a similar increasing trend in shrub diversity with elevation. However, contrasting patterns have been documented in other regions, which may reflect differing ecological and climatic conditions. For example, in the East African mountains, shrub diversity was found to decrease with increasing altitude (Cirimwami et al., 2019), while a similar decreasing trend was also reported in the West Himalaya (Sekar et al., 2024). These findings suggested that factors such as temperature, precipitation, and local climatic conditions may play a significant role in shaping shrub diversity along altitudinal gradients in different mountain regions. On the other hand, a hump-shaped pattern, where diversity peaks at mid-elevations, was observed in other study (Sharma & Kala, 2022), suggesting that intermediate altitudes may provide an optimal combination of environmental conditions (e.g., temperature, moisture, and nutrient availability) that supports the highest levels of shrub diversity. These contrasting and varied patterns across regions highlight the complex interplay of environmental variables that influence plant community structure and diversity in mountainous ecosystems.

The herbaceous species diversity in this study showed an increasing trend with altitude, which is consistent with findings from other studies (Cirimwami et al., 2019; Sangry et al., 2024), where herbaceous diversity was also observed to increase at higher altitudes from subtropical to subalpine forests. However, contrasting patterns have been reported in other regions. For instance, a decreasing trend in herbaceous species with increasing altitude was found in the West Himalaya (Sekar et al., 2024). The fact that several herbaceous species are shade intolerant (Grytnes, 2000) explains their increase in species richness in high elevations where light availability increases even if other factors related to soil, climate, topography, density of herbivores, etc. may also influence their elevational distribution patterns of

diversity (Belalong et al., 1995; Jiang et al., 2016). Therefore, the diversity pattern of herbs along the elevation gradient may be shaped by the interaction between altitude and canopy density which controls light availability in the understory (Zhang et al., 2016). Herb lifeforms benefit both from fewer competition with woody lifeforms and also from more available light (Körner, 2007).

Their strong presence in mountains can also be explained by the structure of their flowers looking like a daisy (Belalong et al., 1995), which could enable them to be easily dispersed by mountain winds. The Asteraceae family, in particular, is abundant in these regions, and its characteristic flower structure may contribute to its widespread distribution at high altitudes.

Size class distribution, stem density, basal area, and DBH collectively describe forest structure. These forest structural attributes showed a significant altitudinal variation. The size class distribution of trees provides the population structure of forests (Forrester et al., 2017; Saxena & Singh, 1984), and is widely employed to assess regeneration status and dynamics (Veblen et al., 1981). The reverse J-shaped forest structure in this study suggested tree species were in the most dominant form in the stand and indicated a good regeneration pattern, as shown in recent studies (Negi et al., 2024). This distribution pattern is a characteristic of uneven-aged forests (Vetaas, 2000), with a sufficient number of young trees to replace the old mature stands. The total basal area in this study was similar to previous reports from the Eastern Himalayan region, ranging from 10.88-56.9 m^2 ha^{-1} (Bhutia et al., 2019; Negi et al., 2024; Suchiang et al., 2020). The MAF zone recorded the highest stem density, basal area, and stem DBH, suggesting that mid-altitudes provide optimal conditions for tree growth. This finding supported the 'mid-domain effect' theory (Colwell & Lees, 2000), which suggested that intermediate elevations offered optimal environmental conditions, including light, soil nutrients, and moisture, thereby promoting higher complexity of forest structural attributes. The absence of trees exceeding 100 cm DBH in the LAF and HAF zones was remarkable. In the LAF zone, this may be attributed to shifting cultivation practices and the selective harvesting of valuable timber-yielding species, including *Gmelina arborea*, *Magnolia champaca*, *Duabanga grandiflora*, *Toona ciliata*, and certain Lauraceae species like *Phoebe attenuata*.

Furthermore, the dominance of bamboo brakes in the LAF zone may have contributed to the absence of large trees. In the HAF zone, the lower stem diameter and basal area may be attributed to a higher density of young individuals and the impact of cold and harsh climatic conditions (Negi et al., 2024). The high number of large-sized trees of *Engelhardia spicata* and *Castanopsis tribuloides* in the MAF zone emphasized their ecological value and highlighted their potential role in carbon storage under changing climate conditions. These structural variations underscore the importance of studying elevational patterns in forest structure, as they provide insights into ecosystem stability, regeneration dynamics, and conservation planning in montane forests.

CHAPTER V

5. Regeneration dynamics and canopy structure along altitudinal gradient.

5.1. Introduction

Understanding how regeneration processes respond to environmental variation is central to forest ecology, especially in topographically complex landscapes such as Phawngpui mountain with its unique location at the biogeographic intersection of the Eastern Himalayas and Indo-Burma hotspot. Forest regeneration plays a pivotal role in maintaining the structure, diversity, and long-term resilience of forest ecosystems (Gairola et al., 2011; Tesfaye et al., 2002). In subtropical montane systems, such as those found in the Eastern Himalayas, regeneration dynamics are shaped by steep environmental gradients that influence species composition, seedling establishment, and growth (Sun et al., 2020). Altitude, in particular, acts as a surrogate for multiple abiotic factors—temperature, soil moisture, and light availability—thereby creating distinct regeneration niches along elevational transects (Grubb, 1977; Xie et al., 2024).

Canopy structure is a key determinant of regeneration success, as it modulates the forest microclimate and controls light penetration to the forest floor (Montgomery & Chazdon, 2001; Tafesse et al., 2025). Variations in canopy openness and leaf area index (LAI) across altitudinal zones can significantly affect seedling density and growth performance, especially in light-sensitive early life stages (Gairola et al., 2011; Moser et al., 2007). Subtropical forests, in particular, exhibit complex canopy dynamics that influence both the spatial and temporal heterogeneity of understorey regeneration.

Given the ecological significance of the Indo-Burma biodiversity hotspot and the altitudinal variability of Phawngpui National Park, understanding how regeneration and canopy cover respond to elevation is critical. This chapter explores regeneration dynamics—measured through seedling and sapling densities—and examines canopy characteristics along an altitudinal gradient. Additionally, it considers how

environmental variables shape seedling survival and trait performance across distinct microhabitats, offering insights into forest renewal processes in a subtropical montane ecosystem.

5.2. Methodology

5.2.1. Assessment of regeneration dynamics

To examine regeneration dynamics along the altitudinal gradient in Phawngpui National Park, both sapling and seedling densities were quantified across 120 plots, evenly distributed among three altitudinal forest zones: Low Altitude Forest (LAF), Mid Altitude Forest (MAF), and High Altitude Forest (HAF). These subplots for regeneration attributes were established within the 10 m × 10 m tree plots described in Chapter 3 (Section 3.2), maintaining spatial consistency across datasets.

5.2.1.1. Sapling density

Sapling density was assessed using 120 subplots of 5 m × 5 m (25 m² each), with 40 subplots allocated to each of the three zones. All saplings (1 cm ≤ DBH < 10 cm) falling within these subplots were counted to estimate density per zone.

5.2.1.2. Seedling density

For seedling density, a total of 120 subplots of 1 m × 1 m (1 m² each) were established within the same sampling plots, again with equal representation across LAF, MAF, and HAF. Seedlings (Height < 1 m) within these microplots were counted to determine density and assess forest floor regeneration.

5.2.2. Canopy cover analysis

Canopy structure was evaluated to investigate its influence on regeneration. At the centre of each 120 10 m × 10 m tree plot, hemispherical photographs were captured using a digital camera fitted with a fisheye lens under uniform diffuse light conditions.

These images were processed using Gap Light Analyzer (GLA) software version 2.0, which provided two key metrics:

(a) Canopy Openness (%): The proportion of sky visible through the canopy.

(b) Leaf Area Index (LAI): A dimensionless value representing leaf area per unit ground area.

These values were averaged per zone to describe variation in canopy structure along the altitudinal gradient.

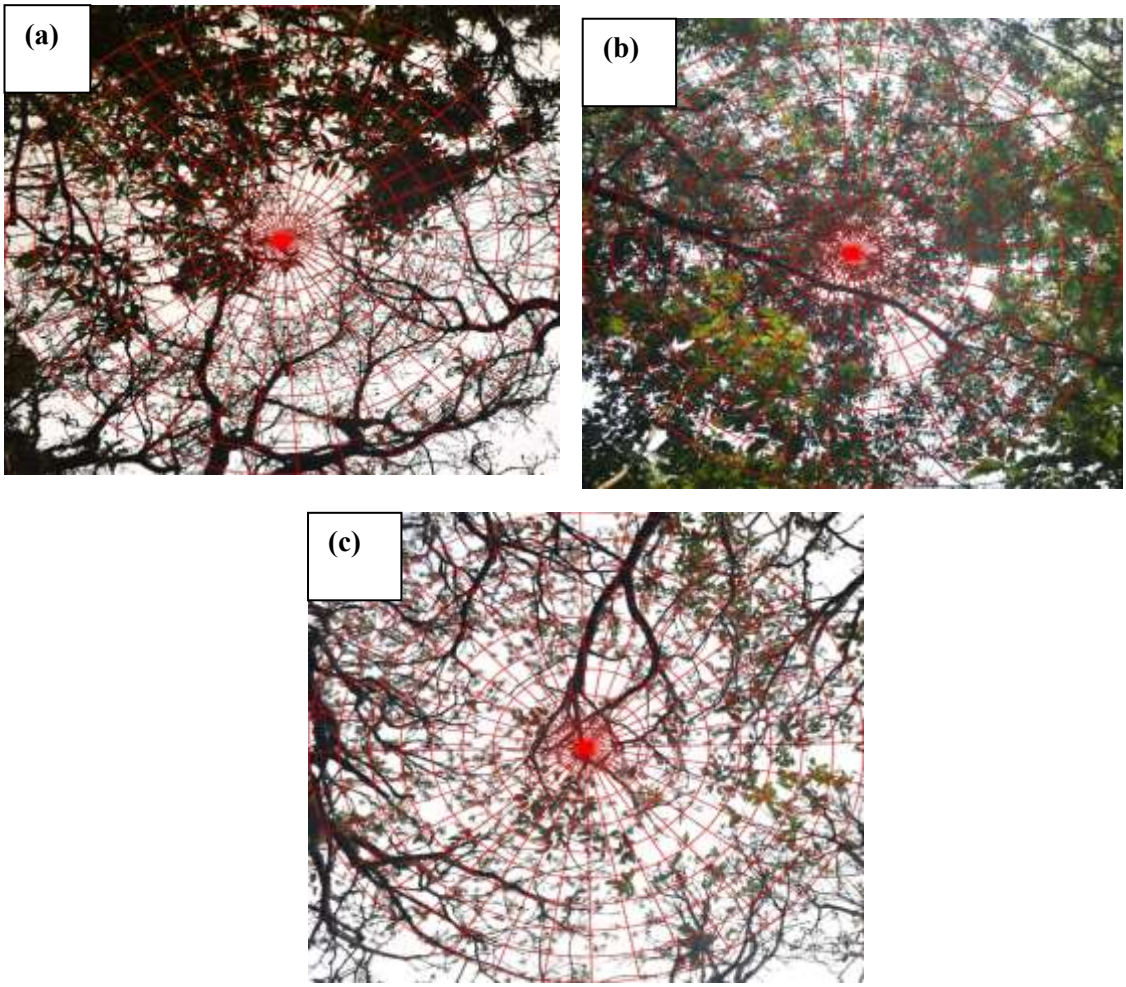


Figure 5.1. Canopy openness analysis using Gap Light Analyzer (GLA): (a) LAF; (b) MAF; (c) HAF

5.2.3. Environmental and seedling trait measurements

To evaluate how environmental conditions influence seedling performance, a suite of microclimatic and edaphic parameters was recorded, as described in Chapter 4

(Section 4.2.5). These included: light intensity, air temperature, relative humidity, soil moisture content (SMC), soil pH, soil organic carbon (SOC), total nitrogen (N), available phosphorus (P), and available potassium (K).

Measurements were conducted during the peak growing season in three microhabitats—open, edge, and closed canopy—within each altitudinal zone. In each microhabitat, 10 replicate plots (1 m × 1 m) were established, resulting in 90 plots in total. Environmental variables were recorded using appropriate instruments (e.g., PAR sensor, thermo-hygrometer), and soil samples (0–10 cm depth) were analysed using standard protocols detailed in Chapter 4.

In addition, three morphological traits of *Cinnamomum verum* seedlings were recorded to assess growth performance under varying conditions:

(a) Plant Height (cm): Average final height of all seedlings per plot, measured at the last census.

(b) Number of Leaves: Counted per seedling at the final census and averaged per plot.

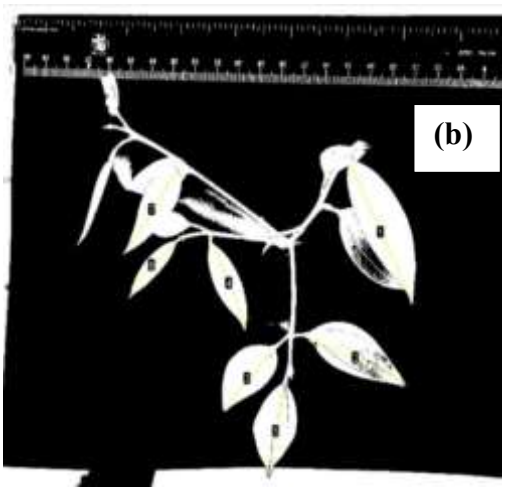
(c) Leaf Area (cm^2): A mature leaf from each seedling was scanned and analyzed using ImageJ software (v1.54k). The mean leaf area per plot was calculated.

Trait data were collected quarterly over a two-year period (June 2022 to June 2024). All seedlings in the 90 plots were tagged, and one representative value per trait per plot was used for analysis.

5.2.4. Seedling survival monitoring

To assess persistence across different microhabitats, seedling survival of *Cinnamomum verum* was monitored in 90 plots (10 plots per site × 3 microhabitats × 3 zones). Tagged seedlings were tracked quarterly for two years (June 2022 – June 2024).

Survival data were expressed as percentages per site and zone, and survival curves were constructed to visualize temporal and habitat-specific trends in seedling persistence.



(c)

Results

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	Label	Area	Mean	Min	Max	Angle	Length
1		0.073	250.326	0.000	255	-65.336	6.877
2		0.052	235.796	0.000	255	-24.567	4.908
3		0.035	255.000	255.000	255	-129.523	3.307
4		0.040	255.000	255.000	255	-67.834	3.719
5		0.038	229.753	0.000	255	-101.514	3.514
6		0.028	246.494	0.000	255	-135.971	2.661
7		0.045	255.000	255.000	255	-121.264	4.178
8	Mean	0.044	246.767	109.286	255	-92.287	4.166
9	SD	0.015	10.214	136.303	0	41.089	1.386
10	Min	0.028	229.753	0.000	255	-135.971	2.661
11	Max	0.073	255.000	255.000	255	-24.567	6.877

Figure 5.2. Leaf area (cm^2) measured using Image J (v.1.54k): (a) *Cinnamomum verum* seedling density recorded in the field; (b) Processed image; (c) Result

5.2.5. Statistical analyses

To examine the relationship between regeneration and altitude, quadratic regression analyses were performed separately for seedling and sapling densities. This allowed the detection of non-linear responses to elevation.

To explore the influence of environmental variables on seedling traits and survival, Principal Component Analysis (PCA) was conducted. PCA is a multivariate technique that transforms correlated variables into uncorrelated components, capturing maximum variance (Legendre & Legendre, 2012). PCA helped identify

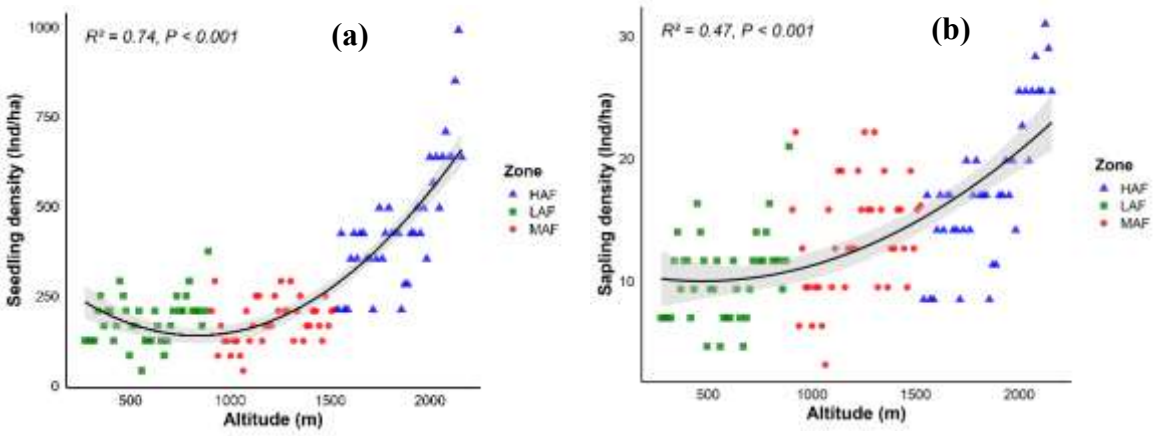
dominant environmental gradients and visualize site clustering, indicating how microsite conditions shape seedling performance across zones.

5.3. Results

5.3.1. Altitudinal variation in sapling and seedling density

Variation in sapling and seedling densities along the altitudinal gradient followed significant quadratic relationships (**Figure 5.3**). Sapling density initially remained relatively stable at lower altitudes (LAF and MAF) but increased markedly towards higher elevations (HAF), with a significant positive quadratic trend ($R^2 = 0.47$, $P < 0.001$) (**Figure 5.3a**). Seedling density exhibited a similar pattern, showing a slight decline from lower to mid elevations, followed by a pronounced increase at higher altitudes, with a stronger quadratic relationship ($R^2 = 0.74$, $P < 0.001$) (**Figure 5.3b**).

Figure 5.3. Quadratic regression analysis between altitude and density: (a) Seedlings, (b) Saplings.



5.3.2. Canopy structure across altitudinal zones

Canopy openness and leaf area index (LAI) showed significant variation across altitudinal zones (ANOVA, $p < 0.001$ for both). Post-hoc comparisons indicated that canopy openness was significantly higher at HAF ($59.20 \pm 2.14\%$) than at LAF ($41.86 \pm 1.89\%$) and lowest at MAF ($26.52 \pm 1.65\%$). In contrast, LAI was highest at MAF (1.86 ± 0.03), followed by LAF (1.18 ± 0.07), and lowest at HAF (0.59 ± 0.02),

suggesting denser canopies at mid-elevation and increasingly open canopies at higher altitudes.

Table 5.1. Mean (± SE) values of canopy openness (%) and leaf area index (LAI) across altitudinal zones.

Parameter	HAF	MAF	LAF
Canopy Openness (%)	59.20 ± 2.14^{a}	26.52 ± 1.65^{c}	41.86 ± 1.89^{b}
Leaf Area Index (LAI)	0.59 ± 0.02^{c}	1.86 ± 0.03^{a}	1.18 ± 0.07^{b}

5.3.3. Seedling survival trends of *Cinnamomum verum* across altitudinal zones and habitat types

Seedling survival of *Cinnamomum verum* decreased steadily over the 24-month period across all altitudinal zones and forest habitat types (**Figure 5.4**). In each zone, open habitats consistently recorded the highest survival rates, followed by edge and closed canopy sites. Final survival percentages in the High Altitude Forest (HAF) were 51% in open, 32% at the edge, and 24% in closed habitats. In the Mid Altitude Forest (MAF), survival reached 38%, 28%, and 21%, respectively. The Low Altitude Forest (LAF) showed comparable values, with final survival rates of 37% (open), 28% (edge), and 21% (closed). While all sites exhibited a similar pattern of decline, open sites retained relatively higher survival throughout the study period.

5.3.4. Seedling traits and environmental variation across altitude and microhabitats

Table 5.2. Mean (± SD) values of seedling survival, morphological traits, microclimatic factors, and soil properties across three altitudinal zones (LAF, MAF, HAF) and microhabitats (Open, Edge, Closed). Superscript letters indicate significant differences ($p < 0.05$) among altitudes within each microhabitat type based on Tukey's HSD test (n = 10 per site).

Seedling traits and Microclimate							
Altitude	**Seedling Survival (%)**	**Plant Height (cm)**	**No. of Leaves (per plant)**	**Leaf Area (cm^2)**	**Li (µmol m^{-2} s^{-1})**	**RH (%)**	**Air Temp. (°C)**
LAF_Open	37.54 ± 1.15^{a}	32.38 ± 1.13^{a}	10.48 ± 0.26^{a}	177.34 ± 6.00^{b}	3098.63 ± 60.83^{a}	53.13 ± 1.59^{a}	27.44 ± 0.98^{a}
MAF_Open	38.46 ± 1.62^{b}	36.01 ± 0.94^{b}	12.30 ± 0.36^{b}	208.55 ± 6.47^{a}	3004.24 ± 84.35^{b}	52.04 ± 1.05^{ab}	24.16 ± 0.58^{b}
HAF_Open	51.04 ± 1.60^{ab}	33.51 ± 0.95^{c}	15.18 ± 0.50^{c}	198.66 ± 8.04^{c}	3139.33 ± 107.15^{ab}	50.31 ± 1.08^{b}	20.94 ± 0.60^{c}
LAF_Edge	28.87 ± 0.37^{a}	29.85 ± 0.81^{a}	8.83 ± 0.28^{a}	76.55 ± 1.69^{a}	2444.90 ± 66.92^{a}	54.32 ± 1.76^{a}	24.53 ± 0.71^{a}
MAF_Edge	24.19 ± 0.77^{b}	32.98 ± 1.10^{b}	11.77 ± 0.24^{b}	88.38 ± 2.13^{b}	2259.55 ± 57.45^{ab}	52.77 ± 1.32^{b}	23.46 ± 0.73^{b}
HAF_Edge	32.07 ± 0.46^{c}	24.57 ± 0.59^{c}	13.14 ± 0.39^{c}	69.44 ± 2.11^{c}	2335.61 ± 70.12^{b}	50.35 ± 1.50^{c}	20.45 ± 0.54^{c}
LAF_Closed	21.89 ± 0.28^{a}	22.35 ± 0.74^{a}	7.14 ± 0.25^{a}	55.48 ± 1.60^{a}	791.06 ± 19.06^{a}	54.96 ± 1.81^{a}	23.26 ± 0.59^{a}
MAF_Closed	18.33 ± 0.40^{b}	23.41 ± 0.67^{b}	7.40 ± 0.23^{b}	62.72 ± 1.67^{b}	705.75 ± 19.74^{b}	53.62 ± 1.53^{ab}	23.24 ± 0.81^{b}
HAF_Closed	24.05 ± 0.28^{c}	13.78 ± 0.43^{c}	9.18 ± 0.27^{c}	46.09 ± 0.79^{c}	761.80 ± 22.11^{c}	51.01 ± 1.57^{b}	20.15 ± 0.43^{c}
Soil nutrients and Soil chemical properties							
Altitude	**SOC (mg g^{-1})**	**Total N (%)**	**Avail. P (µg g^{-1})**	**K (µg g^{-1})**	**Soil pH**	**SMC (%)**	
LAF_Open	5.73 ± 0.16^{a}	0.72 ± 0.02^{a}	5.98 ± 0.16^{a}	381.67 ± 10.36^{a}	4.82 ± 0.15	16.47 ± 1.09^{a}	
MAF_Open	5.03 ± 0.14^{b}	0.62 ± 0.01^{b}	6.03 ± 0.19^{a}	371.48 ± 10.71^{ab}	4.85 ± 0.17	14.79 ± 1.03^{b}	

HAF_Open	4.20 ± 0.09^{c}	0.59 ± 0.02^{c}	5.51 ± 0.15^{b}	366.94 ± 11.15^{b}	4.80 ± 0.15	13.26 ± 1.02^{c}
LAF_Edge	5.86 ± 0.15^{a}	0.76 ± 0.02^{a}	6.71 ± 0.22^{a}	394.49 ± 11.47	4.91 ± 0.15	16.31 ± 1.07^{a}
MAF_Edge	5.63 ± 0.16^{b}	0.73 ± 0.02^{a}	6.49 ± 0.23^{a}	383.71 ± 14.63	4.96 ± 0.13	14.63 ± 1.08^{b}
HAF_Edge	5.22 ± 0.12^{c}	0.63 ± 0.02^{b}	5.66 ± 0.16^{b}	384.41 ± 7.04	4.81 ± 0.18	13.10 ± 1.01^{c}
LAF_Closed	5.99 ± 0.21^{a}	0.89 ± 0.03^{a}	6.80 ± 0.21^{a}	399.93 ± 9.32	4.95 ± 0.16^{a}	16.05 ± 1.10^{a}
MAF_Closed	5.91 ± 0.18^{b}	0.89 ± 0.03^{a}	6.81 ± 0.16^{a}	397.51 ± 11.32	4.98 ± 0.15^{ab}	14.44 ± 1.04^{b}
HAF_Closed	5.94 ± 0.16^{c}	0.72 ± 0.02^{b}	5.82 ± 0.14^{b}	397.09 ± 10.38	4.88 ± 0.13^{b}	12.91 ± 1.02^{c}

Seedling traits, microclimatic factors, and soil characteristics varied notably across altitudinal zones (LAF, MAF, HAF) and site types (Open, Edge, Closed) (**Table 5.2**). In open sites, seedling survival was highest at HAF (51.04 ± 1.60%), followed by MAF and LAF (**Figure 5.4**). MAF seedlings were tallest (36.01 ± 0.94 cm) with the largest leaf area (208.55 ± 6.47 cm²), while HAF seedlings had the most leaves (15.18 ± 0.50). Light intensity remained high (>3000 µmol m^{-2} s^{-1}) across all zones, slightly higher at HAF. Relative humidity declined with altitude, and temperature dropped from LAF (27.44 °C) to HAF (20.94 °C).

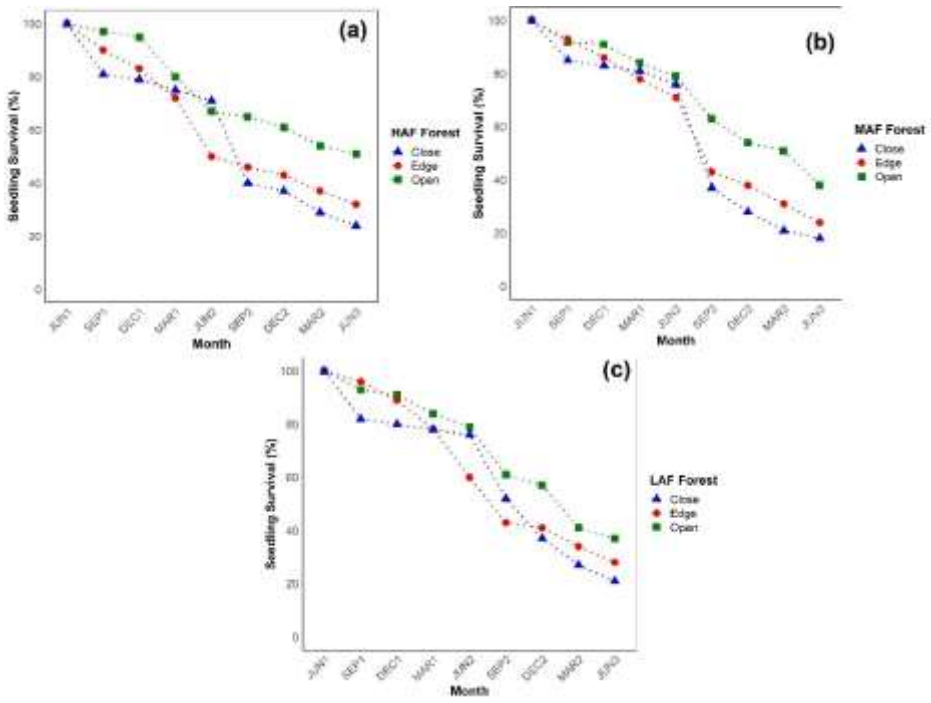


Figure 5.4. Seedling survival curves across different altitudinal zones: (a) HAF, (b) MAF, (c) LAF and microhabitats (open, edge, closed). Survival rates are shown over the monitoring period of 2 years, highlighting differences in mortality patterns along environmental gradients.

At forest edges, survival again peaked at HAF ($32.07 \pm 0.46\%$) and was lowest at MAF. Seedlings at MAF were taller with larger leaves, while HAF seedlings produced more leaves. Both light and temperature declined with altitude, with HAF being the coolest and dimmest.

In closed canopy sites, HAF maintained the highest survival ($24.05 \pm 0.28\%$), followed by LAF and MAF. MAF seedlings were tallest and had the largest leaves, whereas HAF seedlings had more leaves—potentially a response to low light (700–800 $\mu mol\ m^{-2}\ s^{-1}$). Temperature under canopy decreased with altitude, reaching ~20.15 °C at HAF.

Soil organic carbon, nitrogen, and moisture content declined with altitude in open and edge sites but remained relatively high in closed sites across zones, with slightly lower values at HAF. Phosphorus and potassium levels were stable but marginally lower at HAF. Soil pH was acidic (4.80–4.98).

Overall, HAF exhibited the highest seedling survival across site types, even under cooler and drier conditions. In contrast, MAF supported more vigorous growth, likely due to moderate temperature, light, and higher nutrient availability.

PCA clarified these patterns, with the first two axes explaining 68.7% of variance (PC1: 52.5%, PC2: 16.2%). PC1 aligned positively with temperature, moisture, nutrients (N, P, K), and SOC—separating MAF_edge and MAF_closed plots toward favorable resource conditions. LAF_open and LAF_edge clustered negatively along PC1, indicating lower soil and thermal quality (**Figure 5.5**).

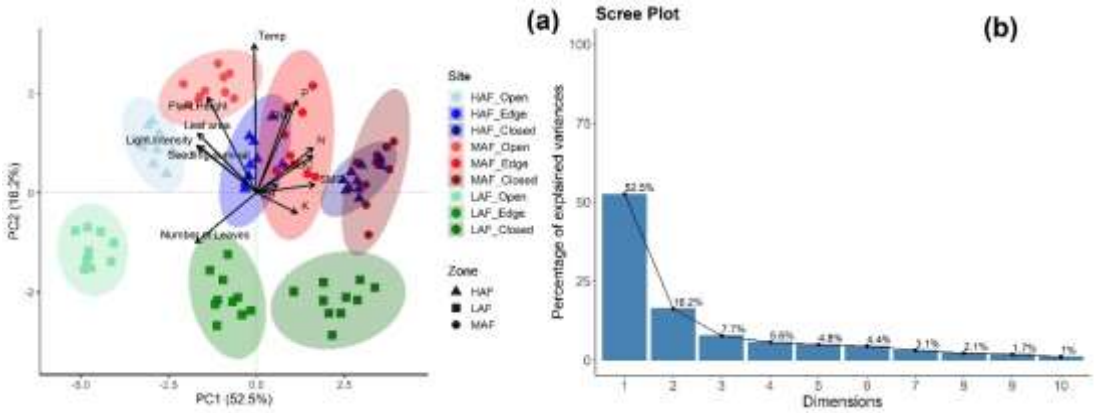


Figure 5.5. Principal Component Analysis (PCA): (a) biplot showing the relationship between seedling traits, microclimatic variables, and soil properties across altitudinal zones (LAF, MAF, HAF) and microhabitats (Open, Edge, Closed). Ellipses represent 95% confidence intervals for each group. (b) Scree plot showing the percentage of explained variance by each principal component, with PC1 and PC2 explaining 52.5% and 16.2% of the variance, respectively.

PC2 was driven by light intensity and seedling traits (survival, height, leaf area, leaf number). HAF_open and LAF_open clustered positively along this axis, associated with higher light and seedling performance. In contrast, HAF_closed and MAF_closed plotted lower on PC2, reflecting shaded conditions and reduced growth. These results highlighted how both altitude and microhabitat openness jointly influenced seedling performance through variations in light, temperature, and soil conditions.

5.4. Discussions

The observed quadratic increase in sapling and seedling densities with elevation aligned with patterns reported in other montane forest ecosystems. Similar trends had been documented, where species richness and diversity exhibited quadratic relationships along elevation gradients (Negi et al., 2024; Tomar et al., 2024). The increase in sapling density at higher altitudes could have been attributed to reduced competition and favourable microclimatic conditions that supported regeneration.

The forest structure above 1500 m exhibited expansion, characterized by higher seedling and sapling densities but a decline in larger tree size classes. This pattern suggested an upward movement of tree species along the altitudinal gradient, potentially as an adaptive response to changing climatic conditions where species adjusted their distribution to maintain optimal growth environments. This finding was aligned with previous study in the Eastern Himalayas (Negi et al., 2024).

Significant variation in canopy openness and leaf area index (LAI) across altitudinal zones underscored the influence of elevation on forest structure. Higher canopy openness at high-altitude forests (HAF) suggested a more open forest structure, possibly due to environmental stressors such as wind or reduced tree density. In contrast, the higher LAI at mid-altitude forests (MAF) indicated denser foliage, which likely affected light penetration and microclimatic conditions beneath the canopy (Condit et al., 2004). These denser canopies may have created moderated temperature and humidity conditions, facilitating diverse understory communities, whereas the more open canopies at HAF could have exposed understory plants to more extreme environmental conditions, affecting species composition and growth patterns.

The consistent decline in seedling survival over the 24-month period across all altitudinal zones and habitat types highlighted the challenges faced by *Cinnamomum verum* during early establishment. Higher survival rates in open habitats indicated that light availability played a crucial role in seedling persistence. Conversely, reduced survival in closed canopy sites pointed to limited light and possibly increased competition or herbivory as major constraints to seedling growth (Belalong

et al., 1995; Jiang et al., 2016; Sharma et al., 2009; Zhou et al., 2023). The variation in survival rates across altitudes and habitat types underscored the importance of microhabitat heterogeneity in conservation strategies. Tailored management interventions enhancing light availability in targeted microhabitats could improve regeneration outcomes.

Seedling traits, microclimatic factors, and soil characteristics varied considerably across altitudinal zones and site types, emphasizing the complex interplay between environment and seedling development. Higher seedling survival at HAF, despite cooler and drier conditions, suggested facilitative effects such as reduced competition or microclimatic buffering. In contrast, the vigorous growth observed at MAF, characterized by taller seedlings and larger leaf area, indicated that moderate temperatures and higher nutrient availability supported robust development (Pérez-Harguindeguy et al., 2013). The decline in soil organic carbon, nitrogen, and moisture content with increasing altitude in open and edge sites, compared to more stable levels in closed sites, highlighted the role of canopy cover in modulating soil properties. These dynamics were critical for predicting ecosystem responses to environmental change.

The principal component analysis (PCA) revealed significant associations between environmental variables and seedling traits. The alignment of PC1 with temperature, moisture, and nutrient availability emphasized their central roles in shaping seedling performance. The clustering of MAF_edge and MAF_closed plots under favourable resource conditions implied that mid-altitude environments offered optimal conditions for growth. PC2's association with light intensity and seedling traits further highlighted light as a crucial factor. The placement of HAF_open and LAF_open plots along this axis indicated that open habitats, regardless of altitude, provided favourable conditions for seedling survival and growth (Muñoz Mazón et al., 2022; Sharma et al., 2009). These results reinforced the importance of integrated approaches in ecological research and the utility of multivariate analysis for predicting forest responses under shifting climatic regimes.

CHAPTER VI

6. Estimation of Aboveground Biomass and Carbon Stock across altitudinal zones.

6.1. Introduction

Natural forests, acting both as carbon sources and sinks, draw significant global attention for their role in maintaining ecological balance and mitigating climate change. The sustainable management of these forests, in terms of both quality and quantity, has become a global priority. Accurate inventory and regular monitoring of carbon stock changes, along with forest area dynamics and land-use transitions, are essential for improving our understanding of the global carbon budget.

Forest ecosystems, particularly those in mountainous and subtropical regions, play a critical role in carbon sequestration. However, they are increasingly vulnerable to pressures from land-use change and climate variability. Globally, the total carbon stock in forests decreased from 668 gigatonnes in 1990 to 662 gigatonnes in 2020, while carbon density slightly increased from 159 to 163 tonnes per hectare over the same period (FAO, 2020).

In temperate forest ecosystems, aboveground biomass and carbon stocks are known to vary along altitudinal gradients due to differences in forest composition, stem size distribution, soil fertility, topography, and disturbance regimes (Ali et al., 2019; Joshi et al., 2021; Kumar et al., 2013; Urquiza-Haas et al., 2007; Weizhong, 2012). Several environmental factors change systematically with altitude, resulting in variation in the distribution and abundance of biomass and carbon stocks. Typically, forest biomass and carbon stocks along long altitudinal gradients in temperate regions exhibit a consistent increase, peaking at mid-elevations before declining at higher altitudes (Dar et al., 2017; Gairola et al., 2011). This decline is attributed to climatic constraints on photosynthesis, transpiration, and nutrient uptake at higher elevations (Kitayama & Aiba, 2002; Reich et al., 2006; Sharma et al., 2020). Additionally, the decreasing availability of soil nitrogen has been suggested as a limiting factor for tree

height and biomass accumulation with elevation (Cánovas et al., 2018; Wang et al., 2014).

Variation in biomass and carbon stocks may also result from differences in forest composition types along the altitudinal gradient. For instance, broad-leaved forests tend to support greater biomass production compared to mixed-wood forests, which comprise diverse species assemblages (Baral et al., n.d.; Gao et al., 2014; Raha et al., 2020).

Monitoring the dynamics of forest aboveground biomass and carbon stocks along altitudinal gradients is therefore essential for evaluating ecosystem productivity and informing sustainable forest management. Altitudinal gradients offer a valuable natural laboratory for examining how forest vegetation responds to environmental changes, making them ideal for ecological and evolutionary studies. Understanding how carbon stocks vary with elevation also enhances our ability to predict regional and global carbon cycle responses to climate change.

However, in remote and rugged landscapes like Phawngpui National Park, data on carbon storage remain limited due to accessibility challenges. In the context of global warming, it is crucial to adopt non-destructive methods for estimating biomass and carbon sequestration based on standing trees. Therefore, this study employs a non-harvest approach to assess the spatial distribution of aboveground biomass and carbon stock across an altitudinal gradient in this subtropical forest ecosystem. Such assessments are vital for enhancing conservation strategies and supporting climate change mitigation efforts.

6.2. Methodology

6.2.1. Aboveground Biomass (AGB) estimation

Aboveground biomass (AGB) and carbon stock were estimated using data collected from 120 vegetation plots of size 10 × 10 m, distributed evenly across three altitudinal forest zones: 40 plots each in Lower Altitudinal Forest (LAF), Middle Altitudinal Forest (MAF), and Higher Altitudinal Forest (HAF). Within each plot, all

individual trees with a diameter at breast height (DBH) ≥10 cm were measured for DBH and total height.

Aboveground biomass (AGB) for all tree individuals was estimated using the species-specific allometric equation developed by Nath et al. (2019), which was designed for tropical forests in Northeast India. The model integrates tree diameter, height, and wood specific gravity to provide accurate biomass predictions:

$$AGB_{est} = 0.32(D^2 H\delta)^{0.75} \times 1.34$$

Where:

AGB_{est} = Estimated Aboveground Biomass (in kg)

D = Diameter at Breast Height (DBH, in cm)

H = Total height of the tree (in m)

δ = Wood specific gravity (g/cm³)

Wood density (δ) values were extracted from the Global Wood Density Database (Zanne et al., 2009) for the corresponding species. When species-specific values were unavailable, genus-level averages were used.

6.2.2. Carbon stock estimation

The carbon content in the aboveground biomass was estimated by applying the carbon conversion factor of 0.47, following Chave et al. (2005):

$$\text{Carbon Stock} = AGB \times 0.47$$

The total AGB and corresponding carbon stock were computed for each 10 × 10 m plot and then scaled to per hectare values (Mg ha^{-1}) to allow comparison across the three altitudinal forest zones: LAF, MAF, and HAF.

6.2.3. Biomass Importance Value (BIV)

A Biomass Importance Value (BIV) was calculated as the average of relative density, relative basal area, and relative AGB values, following the method of Torres et al.

(2020). This composite index provides insight into the ecological dominance of species based on their contribution to stand structure and biomass

$$BIV = \frac{\text{Relative Density} + \text{Relative Basal area} + \text{Relative AGB}}{3}$$

6.2.4. Statistical Analyses

To evaluate the relationship between aboveground biomass (AGB) and altitude, a quadratic regression analysis was conducted using plot-wise AGB values. In addition, boxplots were generated to visualize the variation in DBH, basal area, and AGB across the three altitudinal forest zones.

Prior to statistical comparisons, the Shapiro-Wilk test was performed to assess the normality of the data. Based on the results, non-parametric tests were employed due to the lack of normal distribution. A Kruskal-Wallis test was used to examine differences among the three altitudinal zones, followed by Dunn's post hoc test for pairwise comparisons where significant differences were found.

6.3. Results

6.3.1. Aboveground Biomass and Carbon Stock Distribution Across Altitudes

Aboveground biomass (AGB) varied significantly along the altitudinal gradient, with the highest mean recorded in the MAF at 223.0 ± 77.5 Mg ha^{-1}, followed by the LAF with 146.0 ± 60.7 Mg ha^{-1}, and the lowest in the HAF at 109.0 ± 63.5 Mg ha^{-1}. Carbon stock values followed a similar pattern, with MAF recording the highest value at 104.8 Mg C ha^{-1}, LAF at 68.6 Mg C ha^{-1}, and HAF the lowest at 51.2 Mg C ha^{-1} (**Table 6.1**). This clear altitudinal pattern reflects variation in biomass accumulation and carbon storage across zones.

Table 6.1. Aboveground biomass (AGB) and estimated carbon stock across three altitudinal forest zones in Phawngpui National Park, Mizoram. Values are presented as mean AGB (± SD), along with minimum and maximum recorded AGB per zone.

Altitudinal Zone	AGB (Mg/ha ± SD)	Min. AGB (Mg/ha)	Max. AGB (Mg/ha)	Carbon Stock (Mg C/ha)
LAF	146.0 ± 60.7	45.3	341.0	68.6
MAF	223.0 ± 77.5	99.9	411.0	104.8
HAF	109.0 ± 63.5	27.2	306.0	51.2

6.3.2. Variation in AGB with Altitude

A significant non-linear relationship was observed between aboveground biomass (AGB) and altitude (**Figure 6.1**). The quadratic regression model explained 28% of the variation in AGB across the 120 plots ($R^2 = 0.28$, $p < 0.001$). AGB increased with altitude up to the middle elevation range (MAF) and declined thereafter at higher elevations (HAF), forming a hump-shaped pattern. This trend highlights the peak AGB values in the middle altitudinal zone, consistent with the mean AGB values reported in **Table 6.1**.

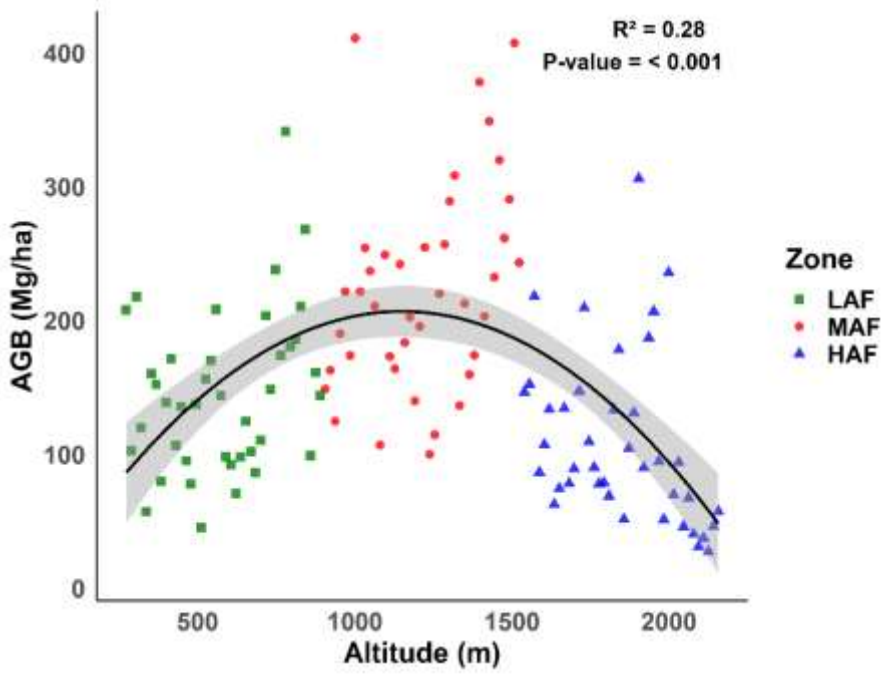


Figure 6.1. Relationship between aboveground biomass (AGB; Mg/ha) and altitude (m) across three altitudinal forest zones (LAF, MAF, HAF) in Phawngpui National Park, Mizoram. AGB shows a unimodal trend with altitude, peaking at mid-altitudes (MAF). The fitted curve represents a quadratic regression ($R^2 = 0.28$, $P < 0.001$), and the shaded area indicates the 95% confidence interval.

6.3.3. Structural Attributes Across Zones

Tree structural attributes, including diameter at breast height (DBH), height, and aboveground biomass (AGB), showed significant variation across the three altitudinal forest zones (**Figure 6.2**). Mean DBH was highest in the MAF, followed by HAF and LAF, with significant differences observed between MAF and the other two zones (**Figure 6.2a**). Similarly, tree height was significantly greater in MAF compared to both LAF and HAF (**Figure 6.2b**), which did not differ significantly from each other. In terms of AGB per plot, MAF again recorded the highest values, while HAF had the lowest. The differences in AGB between MAF and HAF were statistically significant (**Figure 6.2c**), indicating that structural attributes contributing to biomass accumulation peak at mid-elevation.

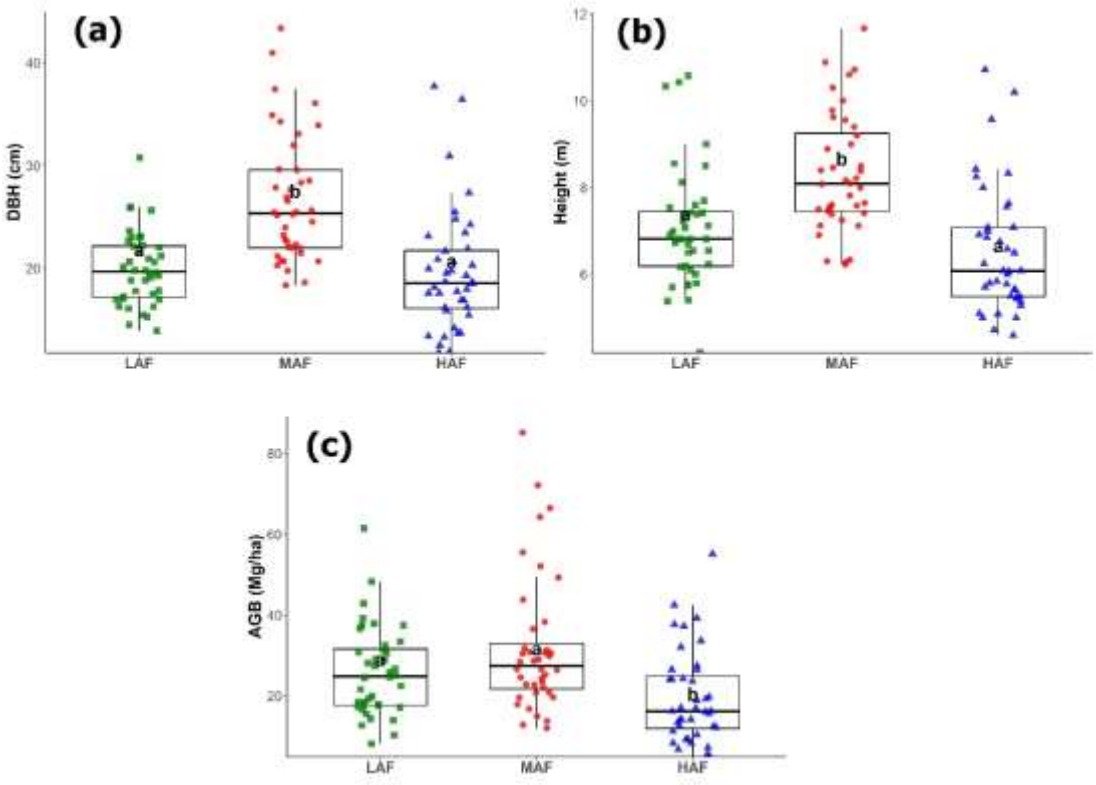


Figure 6.2. Boxplots showing variation in tree structural attributes across three altitudinal forest zones (LAF, MAF, HAF) in Phawngpui National Park, Mizoram: (a) Diameter at breast height (DBH; cm), (b) Tree height (m), and (c) Aboveground biomass (AGB; Mg/ha). Data are presented per plot, with individual jittered points overlaid. Different lowercase letters indicate statistically significant differences among zones ($p < 0.05$) based on Dunn's post hoc comparisons.

To assess the variation in structural attributes—aboveground biomass (AGB), diameter at breast height (DBH), and tree height—across the three altitudinal zones, normality of the data was first tested using the Shapiro-Wilk test (**Table 6.2**). The results indicated that the assumption of normality was violated for multiple variables, particularly AGB in the MAF and HAF zones ($p < 0.001$ and $p = 0.003$, respectively), and height in LAF ($p = 0.008$) and HAF ($p = 0.001$). Consequently, non-parametric methods were employed for further analyses.

Table 6.2. Shapiro-Wilk test for normality of AGB, DBH, and Height across altitudinal zones.

Variables	LAF	MAF	HAF
AGB	0.045	<0.001	0.003
DBH	0.25	0.0067	<0.001
Height	0.008	0.093	0.001

The Kruskal-Wallis test (**Table 6.3**) revealed statistically significant differences among the three altitudinal zones for all three variables. AGB differed significantly across zones ($\chi^2 = 17.42$, $p < 0.001$), as did DBH ($\chi^2 = 36.2$, $p < 0.001$) and height ($\chi^2 = 33.22$, $p < 0.001$), indicating a marked variation in forest structure along the altitudinal gradient.

Table 6.3. Kruskal-Wallis Test for Differences among Zones.

Variables	N	df	χ^2	p-value	Significance
AGB	40	2	17.42	<0.001	***
DBH	40	2	36.2	<0.001	***
Height	40	2	33.22	<0.001	***

Posthoc comparisons using Dunn's test with Bonferroni-adjusted p-values (**Table 6.4**) further identified the specific zone pairs contributing to these overall differences. AGB was significantly different between HAF and MAF ($p < 0.001$), and between HAF and LAF ($p = 0.0048$), while the comparison between LAF and MAF was not statistically significant ($p = 0.21$). For DBH, significant differences were observed between MAF and LAF, and between MAF and HAF (both $p < 0.001$), whereas no significant difference was found between HAF and LAF ($p = 0.44$). In the case of

height, significant differences occurred between MAF and both LAF and HAF ($p < 0.001$), while the difference between HAF and LAF was not significant ($p = 0.065$).

Table 6.4. Dunn's Posthoc Test with Bonferroni-adjusted p-values

Variables	Zone Comparison	p (adjusted)	Significance
AGB	HAF vs LAF	0.0048	*
	HAF vs MAF	<0.001	***
	LAF vs MAF	0.21	ns
DBH	HAF vs LAF	0.44	ns
	HAF vs MAF	<0.001	****
	LAF vs MAF	<0.001	****
Height	HAF vs LAF	0.065	ns
	HAF vs MAF	<0.001	****
	LAF vs MAF	<0.001	***

These statistical results demonstrate that structural parameters vary across the altitudinal zones, with several pairwise comparisons showing clear distinctions in biomass accumulation, stem size, and tree height.

6.3.4. Biomass Importance Value (BIV) Across Altitudinal Zones

The ten most important tree species contributing to biomass in each altitudinal zone were identified using their Relative Density, Relative Basal Area, and Relative Aboveground Biomass, which together informed their Biomass Importance Value (**Table 6.5**).

Table 6.5. Relative density, relative basal area, and relative AGB of the ten most important trees across altitudinal zones.

LAF					
Family	**Species**	**Rel.D (%)**	**Rel.BA (%)**	**Rel.AGB (%)**	**BIV (%)**
Lythraceae	*Duabanga grandiflora*	4.97	9.22	11.15	8.44
Fabaceae	*Albizia chinensis*	4.10	10.67	10.39	8.39
Euphorbiaceae	*Macaranga denticulata*	9.94	2.87	2.37	5.06
Lamiaceae	*Gmelina arborea*	2.81	5.26	5.01	4.36
Fabaceae	*Derris robusta*	7.13	3.13	2.79	4.35
Moraceae	*Ficus rumphii*	0.43	6.37	3.95	3.59
Malvaceae	*Bombax insigne*	0.86	4.60	4.97	3.48
Sterculiaceae	*Sterculia villosa*	1.73	3.67	4.39	3.27
Fabaceae	*Albizia odoratissima*	2.59	3.32	3.47	3.12
Lauraceae	*Litsea monopetala*	4.54	2.42	2.19	3.05
MAF					
Family	**Species**	**Rel.D (%)**	**Rel.BA (%)**	**Rel.AGB (%)**	**BIV (%)**
Fagaceae	*Castanopsis tribuloides*	11.16	25.60	24.88	20.55
Juglandaceae	*Engelhardia spicata*	7.51	12.46	12.10	10.69
Theaceae	*Schima wallichii*	7.08	11.00	11.12	9.73
Fagaceae	*Lithocarpus dealbatus*	8.80	4.71	4.16	5.89
Rubiaceae	*Wendlandia budleioides*	7.73	1.93	1.74	3.80

Proteaceae	*Helicia excelsa*	4.94	2.99	2.86	3.60
Fabaceae	*Albizia chinensis*	2.15	3.73	3.87	3.25
Lamiaceae	*Callicarba arborea*	4.51	1.93	1.97	2.80
Betulaceae	*Betula alnoides*	1.72	2.61	2.98	2.43
Lauraceae	*Alseodaphnopsis petiolaris*	1.29	1.84	2.16	1.76
HAF					
Family	**Species**	**Rel.D (%)**	**Rel.BA (%)**	**Rel.AGB (%)**	**BIV (%)**
Juglandaceae	*Engelhardia spicata*	12.20	17.34	19.50	16.34
Fagaceae	*Castanopsis tribuloides*	4.88	13.15	14.01	10.68
Fagaceae	*Quercus floribunda*	13.17	6.62	6.17	8.65
Ericaceae	*Rhododendron arboreum*	8.78	4.84	4.51	6.05
Proteaceae	*Helicia excelsa*	7.07	4.17	3.94	5.06
Lauraceae	*Cinnamomum verum*	1.95	6.13	6.99	5.03
Staphyleaceae	*Staphylea cochinchinensis*	7.56	3.32	3.08	4.65
Fagaceae	*Lithocarpus dealbatus*	4.88	4.74	4.00	4.54
Fagaceae	*Quercus helferiana*	2.20	4.77	3.77	3.58
Phyllanthaceae	*Glochidion sphaerogynum*	5.61	2.56	2.22	3.46

In the LAF, *Duabanga grandiflora* (Lythraceae) had the highest BIV (8.44%), followed closely by *Albizia chinensis* (Fabaceae) with a BIV of 8.39%. These two species exhibited high relative basal area and AGB, indicating their significant structural contribution to biomass in LAF. Other notable contributors included *Macaranga denticulata* (Euphorbiaceae) and *Gmelina arborea* (Lamiaceae), both

with moderate density and basal area values, reflecting a mix of pioneer and secondary species contributing to the forest structure.

In the MAF, *Castanopsis tribuloides* (Fagaceae) emerged as the most dominant species, with a high BIV of 20.55%, attributed to its substantial basal area (25.60%) and AGB (24.88%). *Engelhardia spicata* (Juglandaceae) and *Schima wallichii* (Theaceae) also displayed high BIVs of 10.69% and 9.73%, respectively, due to their strong representation in both basal area and biomass. These species indicate a shift toward more massive, mature tree forms in MAF. Additional contributors with moderate BIVs included *Lithocarpus dealbatus* (Fagaceae), *Wendlandia budleioides* (Rubiaceae), and *Helicia excelsa* (Proteaceae), highlighting a structurally diverse forest community at mid elevations.

In the HAF, *Engelhardia spicata* again ranked highest with a BIV of 16.34%, suggesting its wide ecological amplitude across zones. It was followed by *Castanopsis tribuloides* (10.68%) and *Quercus floribunda* (Fagaceae; 8.65%), both contributing considerably to the structural biomass at higher elevations. Species such as *Rhododendron arboreum* (Ericaceae) and *Cinnamomum verum* (Lauraceae) showed intermediate BIVs, indicating the prominence of temperate elements in the upper zone. The presence of multiple Fagaceae members in HAF, including *Quercus helferiana* and *Lithocarpus dealbatus*, underscores the dominance of this family in structuring biomass at higher altitudes.

Overall, the biomass contribution patterns showed distinct species dominance in each zone, with *Castanopsis tribuloides* and *Engelhardia spicata* being consistently important in both mid and high elevations. These patterns reflect changes in species composition and forest structure along the altitudinal gradient, likely influenced by variations in climatic and edaphic factors.

6.4. Discussion

The results of this study revealed clear and statistically significant patterns in forest structure, aboveground biomass (AGB), and species-level biomass contribution along the altitudinal gradient in Phawngpui National Park. These findings

highlighted how elevation influenced forest composition, functional structure, and biomass distribution in subtropical montane ecosystems.

The observed hump-shaped distribution of AGB, with peak values of 223.0 ± 77.5 Mg/ha in the mid-altitudinal forest (MAF), aligned with established patterns reported in tropical and subtropical montane forests (Alves et al., 2010; Spracklen & Righelato, 2014). This pattern reflected the optimal growing conditions often found at intermediate altitudes, where temperature, moisture availability, and soil fertility were most favourable for tree growth and biomass accumulation (Fehse et al., 2002). In comparison, the reported AGB ranged from 46.5–144.2 Mg/ha in Manipur's subtropical forests (Gogoi et al., 2020), with higher values at lower to mid altitudes, while AGB of 187–293 Mg/ha was estimated in Meghalaya's forests, closely matching the MAF's 223.0 Mg/ha (Chaudhury & Upadhaya, 2016). Globally, AGB carbon stocks peaked at mid altitudes (77.90–92.44 Mg C/ha) in Andean montane forests, slightly lower than the MAF's 104.8 Mg C/ha, suggesting Phawngpui's mid-altitude forests supported robust carbon storage (de la Cruz-Amo et al., 2020). In contrast, the lower (LAF) and higher (HAF) zones exhibited reduced AGB of 146.0 ± 60.7 Mg/ha and 109.0 ± 63.5 Mg/ha, respectively, and carbon stocks of 68.6 Mg C/ha and 51.2 Mg C/ha. These values aligned with findings from secondary forests in Mizoram (Hrahsel et al., 2019), which reported carbon stocks of 71.20–77.47 Mg C/ha, and tropical forests in Assam (Borah et al., 2013), which estimated AGB of 71.20–77.47 Mg/ha, indicating similar constraints in disturbed lowlands and high altitudes. In the LAF, these limitations included anthropogenic disturbance or competition from fast-growing pioneer species (Bongers et al., 2009), as also noted in Manipur's lowland forests (Thong et al., 2020), while in HAF, reduced temperature, shorter growing seasons, and nutrient-poor soils limited biomass accumulation (Moser et al., 2007).

Structural attributes such as diameter at breast height (DBH) and tree height also peaked in the mid-altitudinal forest, supporting the interpretation that the MAF represented a structurally mature and stable forest zone with AGB ranging from 99.9–411.0 Mg/ha. The significant differences in DBH and height between MAF and the other two zones underscored how mid-elevation forests served as ecological

transition zones with high resource use efficiency and competitive dynamics favouring taller, thicker-stemmed individuals. These findings corroborated the hypothesis that forest structure changed predictably with altitude and that structural complexity was maximized at intermediate elevations in montane forests (Culmsee et al., 2010; Homeier et al., 2010). In the Central Himalaya, subtropical forests showed AGB of 227.23–577.16 Mg/ha, slightly higher than the MAF's maximum of 411.0 Mg/ha, driven by larger DBH and height at mid altitudes, reinforcing the structural maturity of MAF zones (Joshi et al., 2021).

Interestingly, although AGB declined at higher elevations (HAF) to 109.0 ± 63.5 Mg/ha, some large, high-wood-density species such as *Engelhardia spicata* and *Castanopsis tribuloides* maintained strong biomass contributions in both MAF and HAF. The Biomass Importance Value (BIV) analysis revealed that these species consistently dominated in terms of relative basal area and AGB, indicating their crucial role in maintaining carbon stocks of 51.2 Mg C/ha in the HAF. This suggested a degree of ecological plasticity and altitudinal adaptability in these species, which may be critical under scenarios of climate change (Fadrique et al., 2018; Malhi et al., 2017). Comparable species dominance was observed in Mizoram's subtropical forests, where high-wood-density species contributed to carbon stocks of 109–172 Mg C/ha (Hauchhum, 2017), highlighting their regional importance in sustaining biomass across altitudes.

The species-specific contributions to AGB, as revealed by the BIV, also reflected shifts in forest composition along the gradient. The LAF, with AGB ranging from 45.3–341.0 Mg/ha, was characterized by light-demanding species such as *Duabanga grandiflora* and *Albizia chinensis*, typical of secondary forests and disturbed lowland areas (Slik et al., 2008). In contrast, the MAF and HAF showed increasing dominance of Fagaceae, Juglandaceae, and Lauraceae, families associated with mature, closed-canopy montane forests (Ashton, 2014). This transition pointed to a compositional and functional turnover with elevation, driven by climate, soil conditions, and successional stage (Sundqvist et al., 2013). Similar compositional shifts were reported in Assam's tropical to subtropical forests, where carbon stocks

varied from 84.74–163.56 Mg C/ha, with Fagaceae dominating at higher altitudes (Borah et al., 2013).

The presence of temperate taxa such as *Rhododendron arboreum* and *Cinnamomum verum* in the HAF suggested the floristic influence of Sino-Himalayan elements in the upper montane belt (Bharali et al., 2012). Their structural contributions, though less than those of Fagaceae, indicated the integration of temperate elements into subtropical montane forest structure, a characteristic feature of the Eastern Himalayas and Indo-Burma region (Bharali et al., 2012).

Continued research integrating belowground biomass, long-term monitoring, and remote sensing would be valuable for capturing the full dynamics of carbon storage and forest structure across elevational gradient. Moreover, the consistent dominance of species like *Engelhardia spicata* and *Castanopsis tribuloides* suggested their potential as indicator species for biomass-rich zones and possible targets for conservation and reforestation efforts in similar montane systems.

CHAPTER VII

7. Assessing the phylogenetic diversity of Lauraceae in Phawngpui National Park through molecular insights.

7.1. Introduction

The Lauraceae, or laurel family, is one of the most ecologically and evolutionarily significant families of flowering plants in tropical and subtropical forests. With more than 2,500 species distributed globally, the family is particularly diverse in Southeast Asia, southern China, and the Himalayas (Li et al., 2025; Rohwer, 1993; van der Werff, 2001). Lauraceae species are often dominant components of forest canopies and play critical roles in ecosystem functioning, including biomass accumulation and ecological interactions (Chanderbali et al., 2001). Despite their ecological importance, the phylogenetic relationships among many Lauraceae species remain unresolved, especially in biogeographically complex and underexplored regions such as Northeast India.

Phawngpui National Park, located in Mizoram in the Eastern Himalayan foothills, is part of the Indo-Burma biodiversity hotspot—one of the most biologically rich yet threatened regions globally (Myers et al., 2000). Positioned at the interface of the Southeast Asian and Sino-Himalayan floristic realms, this region is thought to act as a transitional zone for numerous plant lineages (Ohsawa, 1991). It is thus an ideal setting to investigate the evolutionary history and biogeographic affinities of Lauraceae species.

This chapter presents a molecular phylogenetic analysis aimed at elucidating the evolutionary relationships of 12 Lauraceae species documented from Phawngpui National Park. The analysis employs the chloroplast *matK* gene, a widely accepted DNA barcode for plants, known for its effectiveness in resolving relationships at the genus and species levels (Yu et al., 2011). Sequence data generated from locally collected samples were analyzed alongside 45 reference sequences retrieved from GenBank, representing Lauraceae taxa primarily from Southeast Asia and China. This comparative approach enables the identification of phylogenetic clustering

patterns and lineage affinities among the regional species, especially with regard to well-established groups such as *Persea*, *Cinnamomum*, and *Litsea*.

In addition to phylogenetic reconstruction, this chapter also quantifies the phylogenetic diversity (PD) of the Lauraceae community using indices such as Faith's PD, abundance-weighted PD, mean pairwise distance (MPD), and mean nearest taxon distance (MNTD). These insights complement the earlier findings on structural and taxonomic diversity across the altitudinal gradient and contribute to a more comprehensive understanding of community assembly and biogeographic history in this ecologically critical region.

7.2. Methodology

7.2.1. Marker selection and study context

In this study, the chloroplast gene *matK* was used to construct a phylogenetic tree of 12 Lauraceae species from Phawngpui National Park, a subtropical montane forest located in the Indo-Burma biodiversity hotspot and forming part of the Eastern Himalayan region of Northeast India. The primary objective was to assess the evolutionary relationships of these species with Lauraceae taxa from Southeast Asia and China.

This comparison is ecologically and biogeographically significant, as the Indo-Burma region shares strong floristic affinities with Southeast Asia and southern China—regions considered important centres of origin and diversification for Lauraceae (Rohwer, 2000; Chanderbali et al., 2001). Understanding the phylogenetic placement of species from Phawngpui may shed light on historical biogeographic patterns and dispersal pathways.

Although multilocus datasets (e.g., *ITS*, *rbcL*) are typically recommended for robust phylogenetic inference, only *matK* was used in this study due to limitations in publicly available sequence data for other markers across all target species. *matK* remains the most consistent and widely represented chloroplast marker for Lauraceae in GenBank and is known to provide sufficient resolution at the genus and species level. Since the goal was to explore phylogenetic clustering and regional affinities—

rather than formal species delimitation—*matK* was deemed appropriate for this analysis.

7.2.2. DNA isolation and amplification

Fresh young leaves of each Lauraceae species were collected in the field and stored under cold conditions prior to processing. Total genomic DNA was extracted using the CTAB method (Doyle & Doyle, 1987), optimized for Lauraceae. DNA quality and concentration were verified using spectrophotometry and gel electrophoresis.

PCR amplification of the *matK* region was performed using the following primers (Yu et al., 2011):

Forward: CGTACAGTACTTTTGTGTTTACGAG

Reverse: ACCCAGTCCATCTGGAAATCTTGGTTC

Amplified products were visualized via agarose gel electrophoresis and subsequently sent for bidirectional sequencing to Eurofins Genomics (Bangalore, India).

7.2.3. Sequence analysis and alignment

The raw sequences obtained were manually edited for quality and trimmed using Geneious Prime, and aligned using MAFFT v7 (Katoh & Standley, 2013), a high-accuracy multiple sequence alignment tool. The G-INS-i algorithm was selected due to its suitability for aligning homologous sequences with global homology, such as chloroplast *matK* regions. Identification of each sequence was confirmed through BLAST searches against the NCBI GenBank database. Reference sequences for closely related Lauraceae species from Southeast Asia and China were retrieved from GenBank for inclusion in the phylogenetic analysis.

7.2.4. Phylogenetic tree construction

Phylogenetic reconstruction was carried out using the Maximum Likelihood (ML) method implemented in MEGA version 12. All sequences were aligned using MUSCLE. The most suitable nucleotide substitution model was selected using the model test function in MEGA based on BIC scores.

To properly root the phylogenetic tree and provide evolutionary context, *Parkia timoriana* (Fabaceae) was used as an outgroup. The resulting ML tree was evaluated with 1,000 bootstrap replicates to assess the robustness of clades. The final tree provided insights into evolutionary clustering among Lauraceae species across subtropical Asia.

7.2.5. Phylogenetic diversity analysis

To assess the evolutionary diversity of Lauraceae species along the altitudinal gradient in Phawngpui National Park, several phylogenetic diversity indices were calculated using species abundance data and a molecular phylogeny based on matK gene sequences.

The complete tree was exported in Newick format to facilitate subsequent computational analyses. The tree was then pruned to retain only the 12 study species observed in the field plots, ensuring that the topology corresponded directly to the community abundance data. Phylogenetic diversity was assessed using the following indices, computed with the R packages 'picante', 'ape', and 'ggtree'.

7.2.5.1. Faith's Phylogenetic Diversity (PD):

Faith's PD (Faith, 1992) quantifies the total branch length of the phylogenetic tree connecting all species within a community:

$$PD=\sum L$$

Where, L is the sum of branch lengths forming the minimum spanning subtree.

7.5.2.2. Abundance-weighted Phylogenetic Diversity (PDw):

To incorporate species abundance, PDw was calculated as:

$$PDw=\sum(Li\times Ai)$$

Where, Li is the branch length associated with species i, and Ai is its abundance.

7.5.2.3. Mean Pairwise Distance (MPD):

MPD represents the average phylogenetic distance between all pairs of species in a community:

$$MPD=\sum_{i<j}^{dij}/(S(S-1)/2)$$

Where, dij is the phylogenetic distance between species i and j; S is species richness.

7.5.2.4. Mean Nearest Taxon Distance (MNTD):

MNTD measures the mean phylogenetic distance from each species to its nearest relative:

$$MNTD=\sum_{i}\min(dij)/S$$

Where, min (dij) is the shortest phylogenetic distance between species i and any other species j.

These indices were computed separately for each altitudinal zone (LAF, MAF, and HAF) to explore variation in phylogenetic diversity and evolutionary structure across environmental gradients.

7.3. Results

7.3.1. Phylogenetic relationships among Lauraceae species

The Maximum Likelihood (ML) phylogenetic tree based on matK sequences elucidates the evolutionary relationships among 57 Lauraceae taxa, including 12 species collected from Phawngpui National Park (**Figure 7.1**). The tree topology recovers three well-supported major clades within Lauraceae: the Persea clade, the Litsea clade, and the Cinnamomum clade. These results are consistent with prior molecular phylogenetic studies (Chanderbali et al., 2001; Li et al., 2025; Rohwer, 2000), and most clades are supported by bootstrap values above 85, indicating high reliability.

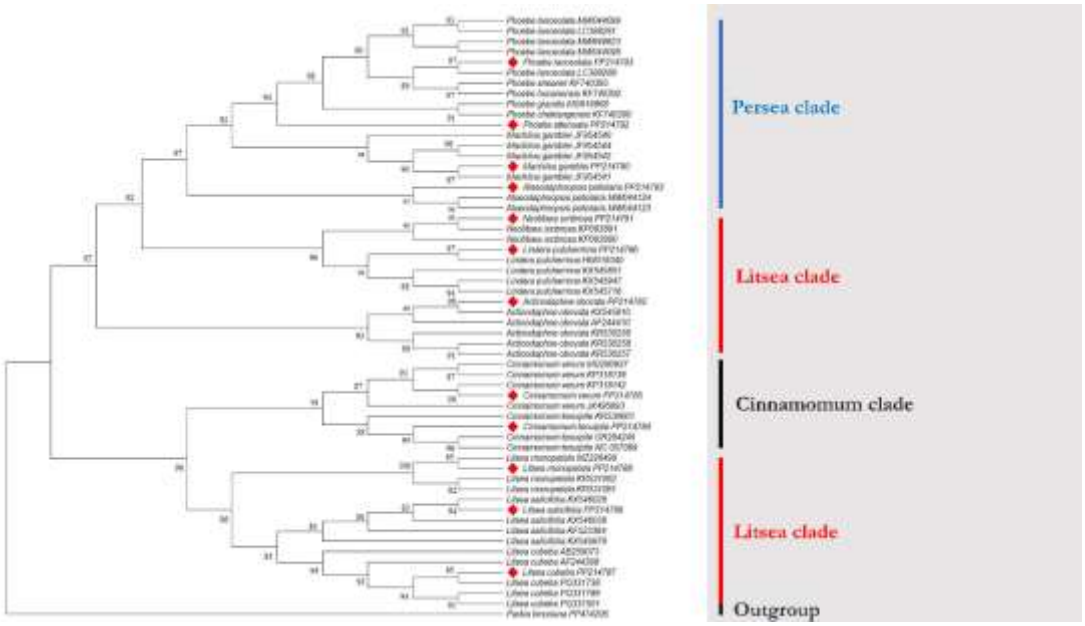


Figure 7.1. Maximum Likelihood (ML) phylogenetic tree of Lauraceae species from Phawngpui National Park, Mizoram, along with reference sequences based on the **matK** gene region. Red diamonds indicate sequences generated in the present study. Bootstrap support values are shown at major nodes.

7.3.1.1. Persea Clade

The Persea clade, often referred to as the "old laurel group" (Rohwer, 2000), includes the genera *Phoebe*, *Machilus*, and *Alseodaphne*. This lineage is considered one of the more ancient and basal groups within Lauraceae (Chanderbali et al., 2001; Rohwer & Rudolph, 2005), typically found in tropical Asia and parts of Central America. In the current phylogeny, species such as *Phoebe lanceolata* (PP214793) and *Machilus gamblei* (PP214790) from Phawngpui clustered tightly with their respective reference sequences, with bootstrap support ranging from 87 to 99. The grouping of these taxa with other *Phoebe* and *Machilus* accessions strongly supports their placement within the Persea clade and aligns with taxonomic expectations.

7.3.1.2. Litsea Clade

The Litsea clade exhibited two distinct subclades, suggesting polyphyly or deep genetic divergence within the genus *Litsea*. This clade includes taxa from *Litsea*, *Lindera*, *Neolitsea*, and *Actinodaphne*, and is widely distributed throughout

subtropical and tropical Asia. *Neolitsea umbrosa* and *Lindera pulcherrima* from Phawngpui aligned closely with conspecific sequences from GenBank, with bootstrap values ranging from 95–97, confirming both their identity and regional affinity. Other species, including *Litsea monopetala*, *L. salicifolia*, and *L. cubeba*, also formed well-supported clusters (bootstrap 91–94). This structure is consistent with previous findings that suggest complex evolutionary histories within the Laureae tribe (Li et al., 2004).

7.3.1.3. Cinnamomum Clade

The genus *Cinnamomum* formed a monophyletic clade distinct from the other groups, with bootstrap support values ranging from 85 to 93. Species such as *C. verum*, *C. tenuipe*, and *C. tamala* grouped together with high confidence, affirming their genetic cohesion and taxonomic integrity. The clarity of this grouping reflects the unique evolutionary lineage of *Cinnamomum*, which is increasingly treated as separate from the core Laureae based on both molecular and morphological data (Yang et al., 2022).

7.3.1.4. Outgroup

The phylogeny was rooted using *Parkia timoriana* (Fabaceae) to provide evolutionary context for divergence within Lauraceae. The use of this outgroup enabled appropriate rooting of the tree and inference of directional evolutionary relationships among the ingroup taxa.

7.3.2. Phylogenetic diversity patterns across altitudinal zones

The assessment of phylogenetic diversity (PD) of Lauraceae across the three altitudinal zones of Phawngpui National Park yielded distinct patterns corresponding to changes in altitude.

Table 7.1. Altitudinal distribution of Lauraceae species recorded in Phawngpui National Park, Mizoram. Values represent the number of individuals recorded per species in each altitudinal zone.

Species Name	**LAF**	**MAF**	**HAF**
Actinodaphne obovata	11	7	0
Alseodaphnopsis petiolaris	7	9	0
Cinnamomum tenuipile	0	0	7
Cinnamomum verum	8	12	11
Lindera pulcherrima	0	0	7
Litsea cubeba	9	13	0
Litsea monopetala	33	0	0
Litsea salicifolia	0	0	11
Machilus gamblei	12	0	0
Neolitsea umbrosa	0	0	13
Phoebe attenuata	0	17	12
Phoebe lanceolata	0	13	5

At the Low Altitudinal Forest (LAF, 273–900 m), a total of six Lauraceae species were recorded with a cumulative abundance of 88 individuals (**Table 7.1**). This zone exhibited the highest phylogenetic diversity (PD = 12.5), alongside a Mean Pairwise Distance (MPD = 0.85) and Mean Nearest Taxon Distance (MNTD = 0.63) (**Table 7.2**). These metrics indicated a random phylogenetic structure, where species were more distantly related than would have been expected under clustering scenarios, consistent with patterns observed in lowland tropical forests of Northeast India (Manish & Pandit, 2018).

In the Mid Altitudinal Forest (MAF, 900–1500 m), six Lauraceae species were recorded (N = 71 individuals), but PD decreased to 9.2, with MPD and MNTD declining to 0.57 and 0.42, respectively (**Table 7.2**). These values suggested moderate phylogenetic clustering, where species were more closely related compared

to the LAF, aligning with findings in mid-altitude Himalayan forests (Sharma et al., 2017).

Table 7.2. Phylogenetic Diversity (PD) of Lauraceae species across three altitudinal zones.

Altitude Zone	Species Richness (S)	Total Abundance (N)	Phylogenetic Diversity (PD)	Mean Pairwise Distance (MPD)	Mean Nearest Taxon Distance (MNTD)	Phylogenetic Structure
LAF	5	88	12.5	0.85	0.63	Random phylogenetic structure
MAF	5	71	9.2	0.57	0.42	Moderate Phylogenetic clustering
HAF	9	66	6.8	0.34	0.17	Strong phylogenetic clustering (close relatives dominate)

At the High Altitudinal Forest (HAF, 1500–2157 m), species richness increased to seven species (N = 66 individuals). However, PD decreased further to 6.8, with the lowest MPD (0.34) and MNTD (0.17) values across all zones (**Table 7.2**). These metrics indicated strong phylogenetic clustering, where species were predominantly close relatives, similar to patterns reported in high-altitude montane forests of South China (Zhang et al., 2016).

The HAF displayed higher species richness but lower PD, MPD, and MNTD compared to LAF and MAF, indicating that the additional species were closely

related and contributed minimal novel evolutionary history to the community. This pattern aligned with observations in Southeast Asian Lauraceae communities, where high-altitude zones exhibited reduced phylogenetic diversity (He et al., 2023).

Overall, the PD metrics revealed an altitudinal trend from random phylogenetic structure in the LAF to moderate clustering in the MAF and strong clustering in the HAF, reflecting shifts in the relatedness of Lauraceae species across the elevational gradient.

7.4. Discussion

The phylogenetic reconstruction of 12 Lauraceae species in Phawngpui National Park revealed distinct evolutionary patterns consistent with global phylogenetic frameworks for the family. The Maximum Likelihood (ML) tree, constructed using matK sequences, resolved three major clades—*Persea*, *Litsea,* and *Cinnamomum*—corroborating earlier studies that delineated these groups based on morphological and molecular evidence (Li et al., 2025; Trofimov et al., 2022). High bootstrap support values across clades (>85%) reinforced the robustness of the phylogenetic relationships inferred in this study. The inclusion of 45 additional Lauraceae species from South China and Southeast Asia strengthened these findings, as the resolved clades aligned with regional phylogenetic studies, such as those in the Sino-Himalayan region, where similar matK-based groupings were reported (Rohwer, 2000).

The placement of *Phoebe*, *Machilus*, and *Alseodaphne* within the Persea clade aligned with previous findings that characterized these genera as part of an ancient lineage with a predominantly tropical Asian distribution (Li et al., 2011). Similarly, the clustering of *Litsea*, *Neolitsea*, *Lindera*, and *Actinodaphne* within the Litsea clade reflected the complex evolutionary history of the Laureae tribe, known for frequent polyphyly and rapid diversification (Li et al., 2004; Trofimov et al., 2022). The monophyletic grouping of *Cinnamomum* species corroborated prior molecular analyses that emphasized the distinct evolutionary trajectory of this economically important genus, particularly in the Eastern Himalayas and Indo-Burma region (Yang et al., 2022). The phylogenetic relationships among the 12 species, when compared

with the 45 South China and Southeast Asian species, suggested a shared evolutionary history, with Phawngpui's Lauraceae exhibiting closer affinity to Sino-Himalayan lineages than to Southeast Asian ones.

The phylogenetic diversity (PD) analyses across altitudinal gradients provided critical ecological insights. In the Low Altitudinal Forest (LAF), the random phylogenetic structure, characterized by relatively high PD, MPD, and MNTD values, indicated that the assemblage comprised evolutionarily distant lineages. This pattern suggested a wide range of ecological strategies and minimal environmental filtering, consistent with findings in lowland tropical forests of Northeast India (Gogoi et al., 2020; Swenson et al., 2012).

Conversely, the Mid Altitudinal Forest (MAF) exhibited moderate phylogenetic clustering, implying that environmental filtering played a more significant role as elevation increased (He et al., 2023). The reduction in PD, MPD, and MNTD suggested that species at mid-elevations were more closely related, likely due to adaptations to cooler temperatures and reduced moisture availability. This pattern resonated with studies in the Eastern Himalayas, where mid-altitude forests showed phylogenetic clustering due to abiotic constraints (Sharma et al., 2019).

At the High Altitudinal Forest (HAF), despite the highest species richness among the three zones, phylogenetic diversity metrics (PD, MPD, and MNTD) were lowest. This strong phylogenetic clustering indicated that high-elevation environments imposed stringent environmental filters, favouring closely related taxa with similar functional traits (He et al., 2023; Myers et al., 2013).

The decoupling of species richness and phylogenetic diversity at HAF underscored the importance of incorporating evolutionary metrics to understand biodiversity patterns across environmental gradients (Tucker et al., 2017). While higher richness suggested greater taxonomic diversity, the strong phylogenetic clustering revealed that evolutionary novelty was diminished at higher elevations, a pattern also noted in Southeast Asian Lauraceae communities (Luo et al., 2023). This finding emphasized the need to consider phylogenetic diversity alongside species richness in conservation planning, particularly in montane ecosystems.

Overall, the altitudinal trend from phylogenetic overdispersion at low elevations to increasing clustering at higher elevations aligned with theoretical expectations of community assembly under environmental filtering (Swenson et al., 2012). The 12 Lauraceae species exhibited a gradient of phylogenetic diversity that reflected the interplay between evolutionary history and ecological processes in shaping montane forest communities. These findings highlighted the conservation importance of protecting elevational gradients in Phawngpui National Park to preserve both taxonomic and phylogenetic diversity.

CHAPTER VIII

8. Conclusions

This study investigated plant community dynamics, forest structure, aboveground biomass (AGB), and phylogenetic diversity across altitudinal gradients in Phawngpui National Park, providing critical insights into the ecological and evolutionary processes that shaped subtropical montane ecosystems. The findings highlighted the interplay of environmental gradients, structural attributes, and evolutionary history, offering a robust framework for conservation and climate change adaptation.

By examining species richness, community composition, and environmental drivers across altitudinal gradients, the study's significance lay in its comprehensive assessment of trees, shrubs, and herbs, which revealed altitude as a primary driver of biodiversity patterns. The high Shannon diversity index (H' = 4.07) and Pielou's Evenness Index (J' = 0.94) underscored exceptional species richness and evenness, particularly in MAF, attributed to the biogeographic confluence of the Eastern Himalayas and Indo-Burma hotspot. This diversity peak at mid-elevations supported the intermediate disturbance hypothesis, where moderate disturbance fostered coexistence of pioneer and late-successional species, enhancing ecosystem resilience.

The Indicator Species Analysis (ISA) was particularly significant, as it identified species strongly associated with specific altitudinal zones, with HAF hosting the most indicators (e.g., *Rhododendron arboreum*, IndVal = 0.44, p = 0.001). ISA's value lay in its ability to pinpoint species that reflected unique ecological niches, making them robust bioindicators for monitoring environmental changes, such as climate-induced altitudinal shifts. For instance, HAF's indicator species, adapted to cooler, high-moisture conditions, served as potential signals of changes in temperature or precipitation patterns, critical for climate change adaptation strategies. ISA's precision in identifying niche-specific species simplified conservation targeting, enabling prioritization of species like *Nostolachma khasiana* (shrub, HAF) or *Scleria levis* (herb, HAF) for protection, which enhanced ecosystem stability. The Canonical Correspondence Analysis (CCA) further reinforced the role of

environmental gradients (altitude, soil nutrients, microclimate) in shaping community structure, providing a predictive tool for assessing climate change impacts on species distributions.

The significance of this study extended to its utility in biodiversity monitoring. The distinct community structures across altitudinal zones, coupled with dominant families (e.g., Fagaceae in MAF/HAF, Asteraceae in herbs), highlighted their potential as ecological indicators for tracking habitat alterations. These findings were vital for conservation planning, as they identified biodiversity hotspots (e.g., MAF) and vulnerable zones (e.g., HAF with rare species) that required targeted protection to mitigate climate change effects, such as upward species migration or habitat loss.

The forest structure, regeneration patterns, and seedling dynamics revealed how altitudinal gradients influenced ecosystem stability and resilience. The reverse J-shaped size class distribution, indicative of uneven-aged forests, signified robust regeneration, particularly in MAF, where high stem density, basal area, and diameter at breast height (DBH) aligned with the mid-domain effect. This structural complexity at mid-elevations enhanced ecosystem services, including carbon sequestration and habitat provision, critical for mitigating climate change impacts.

The quadratic increase in sapling and seedling density with elevation, peaking in HAF, suggested an upward movement of species, likely an adaptive response to warming temperatures. This finding was significant for predicting forest responses to climate change, as it indicated potential range shifts that could alter community compositions. The study of *Cinnamomum verum* seedling survival highlighted the critical role of light availability in open habitats, emphasizing microhabitat heterogeneity as a determinant of regeneration success. This insight was invaluable for conservation, as tailored interventions (e.g., enhancing light in specific microhabitats) could bolster regeneration of key species, ensuring forest persistence under changing climatic conditions. Moreover, Seedling survival rate of *C. verum* along altitudinal gradient provides optimum condition for plantation success, higher yields, and supporting sustainable economic benefits through agroforestry.

The Principal Component Analysis (PCA) linked seedling traits to environmental variables (temperature, moisture, light), underscoring MAF's optimal conditions for growth. These findings informed restoration strategies by identifying altitudinal zones and microhabitats conducive to reforestation, particularly for species vulnerable to climate-induced stressors. The significance of this objective lay in its contribution to understanding forest dynamics, providing a basis for adaptive management to sustain regeneration and structural integrity in montane ecosystems facing climate change.

Estimation of AGB and carbon storage, revealed a hump-shaped pattern with MAF as the biomass hotspot (223.0 ± 77.5 Mg/ha, 104.8 Mg C/ha), driven by optimal environmental conditions. This finding was significant for climate change mitigation, as MAF's high carbon storage capacity positioned it as a priority for conservation to maximize carbon sequestration. The lower AGB in LAF (146.0 ± 60.7 Mg/ha) and HAF (109.0 ± 63.5 Mg/ha) reflected anthropogenic disturbances and abiotic constraints, respectively, highlighting the need for targeted restoration in these zones. The dominance of high-wood-density species like *Engelhardia spicata* and *Castanopsis tribuloides* in MAF and HAF underscored their ecological plasticity and role in carbon storage, making them ideal candidates for reforestation initiatives. The presence of temperate taxa (e.g., *Rhododendron arboreum*) in HAF indicated Sino-Himalayan influences, enhancing the region's floristic uniqueness. The Biomass Importance Value (BIV) analysis clarified species-specific contributions, guiding conservation by identifying key species for maintaining carbon stocks.

This study significance lay in its alignment with global carbon sequestration goals. By quantifying AGB and carbon stocks, the study provided data for regional and global carbon inventories, essential for climate change mitigation strategies. The identification of MAF as a structural and biomass hotspot informed land-use policies, prioritizing its protection to preserve carbon sinks and biodiversity under climate change pressures.

Assesment of phylogenetic diversity (PD) of Lauraceae species, revealed an altitudinal trend from overdispersion in LAF to strong clustering in HAF. The

phylogenetic reconstruction of 12 species into three clades (*Persea*, *Litsea*, *Cinnamomum*) affirmed their evolutionary affinity with Sino-Himalayan lineages, enhancing the region's biogeographic significance. The decreasing PD with altitude, despite high species richness in HAF, indicated environmental filtering, where abiotic stressors (e.g., low temperatures, nutrient limitations) favoured closely related taxa.

The importance of this study lies in its integration of evolutionary metrics into biodiversity assessment. The low PD in HAF, despite high taxonomic diversity, highlighted the risk of losing evolutionary novelty, critical for ecosystem resilience under climate change. The overdispersion in LAF suggested diverse ecological strategies, supporting ecosystem adaptability, while MAF's moderate clustering indicated a balance between filtering and diversity. These insights guided conservation by prioritizing altitudinal gradients to preserve both taxonomic and phylogenetic diversity, ensuring long-term ecosystem stability.

The decoupling of species richness and PD in HAF emphasized the need for phylogenetic metrics in conservation planning. Protecting phylogenetically distinct lineages in LAF and clustered taxa in HAF enhanced resilience to climate-induced changes, such as altered precipitation or temperature regimes. This objective's findings positioned Phawngpui National Park as a critical site for conserving evolutionary diversity in the Eastern Himalayas.

The study faced several limitations. The incomplete sampling of rare species in MAF and HAF, as indicated by species accumulation curves, suggested that additional surveys were needed to capture their contributions to diversity. The focus on aboveground biomass omitted belowground biomass, limiting the full assessment of carbon stocks. Temporal dynamics, such as seasonal variations or long-term climate impacts, were not explored, potentially overlooking transient ecological responses. The phylogenetic analysis was restricted to Lauraceae, and expanding to other families could have provided a broader evolutionary perspective. Anthropogenic disturbances, particularly in LAF, were noted but not quantified, warranting further investigation into their impacts on biodiversity and biomass.

The findings had profound implications for conservation and climate change adaptation. The distinct altitudinal structuring of communities, with MAF as a biodiversity and biomass hotspot, underscored the need to prioritize its protection to safeguard carbon sinks and species diversity. ISA's identification of indicator species offered a practical tool for monitoring climate-induced shifts, enabling early detection of environmental changes. For example, HAF's indicator species tracked upward migrations driven by warming temperatures, informing adaptive conservation strategies.

The robust regeneration in MAF and HAF supported reforestation efforts, particularly using species like *Engelhardia spicata* and *Castanopsis tribuloides*, which enhanced carbon storage and ecosystem stability. The phylogenetic clustering in HAF highlighted the urgency of protecting evolutionarily distinct taxa to maintain resilience against climate change. Conservation strategies integrated microhabitat management, such as enhancing light availability for seedlings, to bolster regeneration under changing climatic conditions.

The study's alignment with global carbon sequestration goals positioned Phawngpui National Park as a model for montane forest conservation. Protecting altitudinal gradients ensured the preservation of ecological and evolutionary diversity, critical for adapting to climate change impacts like altered precipitation or habitat fragmentation. Policies focused on reducing anthropogenic pressures in LAF and promoting sustainable land-use practices enhanced ecosystem resilience.

Future studies should have addressed the identified limitations by conducting extensive surveys to capture rare species, particularly in MAF and HAF, to refine biodiversity assessments. Integrating belowground biomass and remote sensing would have provided a holistic view of carbon dynamics, enhancing climate change mitigation strategies. Long-term monitoring of temporal dynamics and anthropogenic impacts would have clarified ecosystem responses to climate change, informing adaptive management. Expanding phylogenetic analyses to other plant families would have broadened evolutionary insights, while functional trait studies of indicator species would have elucidated their ecological roles in climate adaptation.

Investigating climate change impacts, such as altered precipitation or temperature, on altitudinal shifts would have further refined conservation priorities.

Consequently, the present study provided a comprehensive understanding of altitudinal gradients in Phawngpui National Park, highlighting their ecological and evolutionary significance. The findings underscored MAF's role as a biodiversity and carbon hotspot, HAF's unique indicator species as climate change monitors, and the need to preserve phylogenetic diversity for ecosystem resilience. By addressing research limitations and leveraging these insights, conservation strategies could have enhanced the protection of montane ecosystems, ensuring their adaptability to climate change and contribution to global biodiversity and carbon sequestration goals.

APPENDICES

Appendix I

List of all tree species in the study area.

Tree Species	
Scientific Name	**Family**
Acrocarpus fraxinifolius Wight & Arn.	Fabaceae
Actinodaphne obovata (Nees) Blume	Lauraceae
Aglaia edulis (Roxb.) Wall.	Meliaceae
Alangium chinense (Lour.) Harms	Cornaceae
Albizia chinensis (Osbeck) Merr.	Fabaceae
Albizia lebbeck (L.) Benth.	Fabaceae
Albizia odoratissima (L.f.) Benth.	Fabaceae
Albizia lucidior (Steud.) I.C.Nielsen	Fabaceae
Alseodaphnopsis petiolaris (Meisn.) H.W.Li & J.Li	Lauraceae
Antidesma bunius (L.) Spreng.	Phyllanthaceae
Artocarpus chama Buch. -Ham.	Moraceae
Artocarpus lacucha Roxb. ex Buch. -Ham.	Moraceae
Balakata baccata (Roxb.) Esser	Euphorbiaceae
Bauhinia variegata L.	Fabaceae

Betula alnoides Buch. -Ham.	Betulaceae
Bombax insigne Wall.	Malvaceae
Callicarpa arborea Roxb.	Lamiaceae
Castanopsis tribuloides A.DC.	Fagaceae
Cinnamomum glaucescens (Nees) Hand. -Mazz.	Lauraceae
Cinnamomum verum J.Presl	Lauraceae
Colona floribunda (Kurz) Craib	Malvaceae
Cordia dichotoma G.Forst.	Boraginaceae
Dalbergia obtusifolia (Baker) Prain	Fabaceae
Dalbergia stipulacea Roxb.	Fabaceae
Derris robusta (Roxb. ex DC.) Benth.	Fabaceae
Dillenia pentagyna Roxb.	Dilleniaceae
Diospyros glandulosa Lace	Ebenaceae
Duabanga grandiflora Walp.	Lythraceae
Dysoxylum gotadhora (Buch. -Ham.) Mabb.	Meliaceae
Dysoxylum mollissimum Blume	Meliaceae
Elaeocarpus lanceifolius Roxb.	Elaeocarpaceae
Elaeocarpus tectorius Poir.	Elaeocarpaceae
Engelhardia spicata Lechen ex Blume	Juglandaceae

Erythrina stricta Roxb.	Fabaceae
Eurya japonica Thunb.	Pentaphylacaceae
Ficus fistulosa Reinw. ex Blume	Moraceae
Ficus hispida L.f.	Moraceae
Ficus prostrata (Miq.) Buch. -Ham. ex Miq.	Moraceae
Ficus retusa L.	Moraceae
Ficus rumphii Blume	Moraceae
Ficus semicordata Buch. -Ham. ex Sm.	Moraceae
Ficus simplicissima Lour.	Moraceae
Ficus variegata Blume	Moraceae
Firmiana colorata (Roxb.) R.Br.	Malvaceae
Glochidion sphaerogynum (Müll.Arg.) Kurz	Phyllanthaceae
Gmelina arborea Roxb.	Lamiaceae
Haldina cordifolia (Roxb.) Ridsdale	Rubiaceae
Helicia excelsa Blume	Proteaceae
Heteropanax fragrans Seem.	Araliaceae
Homalium ceylanicum (Gardner) Benth.	Salicaceae
Itea macrophylla Wall.	Iteaceae
Kydia calycina Roxb.	Malvaceae

Lannea coromandelica (Houtt.) Merr.	Anacardiaceae
Lindera pulcherrima (Nees) Benth. ex Hook.f.	Lauraceae
Lithocarpus dealbatus Rehder	Fagaceae
Lithocarpus pachyphyllus Rehder	Fagaceae
Lithocarpus xylocarpus Markgr.	Fagaceae
Litsea cubeba Pers.	Lauraceae
Litsea monopetala Pers.	Lauraceae
Litsea salicifolia Hook.f.	Lauraceae
Macaranga denticulata Müll.Arg.	Euphorbiaceae
Macaranga peltata Müll.Arg.	Euphorbiaceae
Machilus gamblei King ex Hook.f.	Lauraceae
Macropanax dispermus Kuntze	Araliaceae
Magnolia champaca (L.) Baill. ex Pierre	Magnoliaceae
Magnolia doltsopa (Buch. -Ham. ex DC.) Figlar	Magnoliaceae
Mallotus macrostachyus Müll.Arg.	Euphorbiaceae
Mangifera sylvatica Roxb.	Anacardiaceae
Monosis volkameriifolia (DC.) H.Rob. & Skvarla	Asteraceae
Morus macroura Miq.	Moraceae
Myrica esculenta Buch. -Ham. ex D.Don	Myricaceae

Neolitsea umbrosa (Nees) Gamble	Lauraceae
Olea dioica Roxb.	Oleaceae
Oreocnide integrifolia (Gaudich.) Miq.	Urticaceae
Oroxylum indicum (L.) Benth. ex Kurz	Bignoniaceae
Ostodes paniculata Blume	Euphorbiaceae
Phoebe attenuata (Nees) Nees	Lauraceae
Phoebe lanceolata (Nees) Nees	Lauraceae
Phyllanthus emblica L.	Phyllanthaceae
Phyllanthus velutinus (Wight) Müll.Arg.	Phyllanthaceae
Pittosporum napaulense (DC.) Rehder & E.H.Wilson	Pittosporaceae
Pouzolzia rugulosa (Wedd.) Acharya & Kravtsova	Urticaceae
Premna milleflora C.B.Clarke	Lamiaceae
Prunus cerasoides D.Don	Rosaceae
Pterospermum acerifolium (L.) Willd.	Malvaceae
Quercus floribunda Lindl. ex A.Camus	Fagaceae
Quercus glauca Thunb.	Fagaceae
Quercus helferiana A.DC.	Fagaceae
Quercus lanata Sm.	Fagaceae
Rhododendron arboreum Sm.	Ericaceae

Rhododendron veitchianum Hook.	Ericaceae
Rhus chinensis Mill.	Anacardiaceae
Saurauia napaulensis DC.	Actinidiaceae
Schima wallichii (DC.) Korth.	Theaceae
Staphylea cochinchinensis (Lour.) Byng & Christenh.	Staphyleaceae
Sterculia villosa Roxb.	Malvaceae
Stereospermum tetragonum DC.	Bignoniaceae
Syzygium cumini (L.) Skeels	Myrtaceae
Syzygium grande (Wight) Walp.	Myrtaceae
Terminalia myriocarpa Van Heurck & Müll.Arg.	Combretaceae
Terminalia phillyreifolia (Van Heurck & Müll.Arg.) Gere & Boatwr.	Combretaceae
Toona ciliata M.Roem.	Meliaceae
Trema orientalis (L.) Blume	Cannabaceae
Trevesia palmata Vis.	Araliaceae
Vaccinium sprengelii (G.Don) Sleumer ex Rehder	Ericaceae
Vitex glabrata R.Br.	Lamiaceae
Vitex peduncularis Wall.	Lamiaceae
Wendlandia budleioides Wall. ex Wight & Arn.	Rubiaceae

APPENDIX II

List of all shrub species in the study area.

Shrub Species	
Scientific Name	**Family**
Ardisia macrocarpa Wall.	Primulaceae
Baliospermum calycinum Müll.Arg.	Euphorbiaceae
Boenninghausenia albiflora (Hook.) Meisn.	Rutaceae
Bridelia montana Woodrow ex J.J.Sm.	Phyllanthaceae
Bridelia tomentosa Blume	Phyllanthaceae
Buddleja asiatica Lour.	Scrophulariaceae
Chromolaena odorata (L.) R.M.King & H.Rob.	Asteraceae
Clerodendrum infortunatum L.	Lamiaceae
Crotalaria cytisoides DC.	Acanthaceae
Dendrocnide sinuata (Blume) Chew	Urticaceae
Duhaldea eupatorioides (DC.) Anderb.	Asteraceae
Elatostema lineolatum Wight	Urticaceae
Flemingia macrophylla (Willd.) Kuntze ex Merr.	Fabaceae
Flemingia stricta Roxb.	Fabaceae
Flueggea virosa (Roxb. ex Willd.) Royle	Phyllanthaceae
Grona heterocarpos (L.) H.Ohashi & K.Ohashi	Fabaceae
Indigofera heterantha Wall. ex Brandis	Fabaceae
Indigofera stachyodes Lindl.	Fabaceae

Leucosceptrum canum Sm.	Lamiaceae
Maesa montana A.DC.	Primulaceae
Melastoma malabathricum L.	Melastomataceae
Monosis volkameriifolia (DC.) H.Rob. & Skvarla	Asteraceae
Nostolachma khasiana (Hook.f.) Deb & Lahiri	Rubiaceae
Osbeckia chinensis L.	Melastomataceae
Osbeckia stellata Buch.-Ham. ex D.Don	Melastomataceae
Pilea symmeria Wedd.	Urticaceae
Rubus barberi H.E.Weber	Rosaceae
Rubus birmanicus Hook.f.	Rosaceae
Rubus ellipticus Sm.	Rosaceae
Rubus niveus Thunb.	Rosaceae
Solanum viarum Dunal	Solanaceae
Strobilanthes capitata T.Anderson	Acanthaceae
Strobilanthes fimbriata Nees	Acanthaceae
Strobilanthes parryorum C.E.C.Fisch.	Acanthaceae
Syzygium polypetalum (Wall. ex Wight) Merr. & L.M.Perry	Myrtaceae
Trichodesma khasianum C.B.Clarke	Boraginaceae
Woodfordia fruticosa Kurz	Lythraceae

APPENDIX III

List of all herbaceous species in the study area.

Herbaceous Species	
Scientific Name	**Family**
Ageratina adenophora (Spreng.) R.M.King & H.Rob.	Asteraceae
Ageratina riparia (Regel) R.M.King & H.Rob.	Asteraceae
Ageratum conyzoides L.	Asteraceae
Ageratum houstonianum Mill.	Asteraceae
Aglaonema hookerianum Schott	Araceae
Ainsliaea latifolia (D.Don) Sch.Bip.	Asteraceae
Amomum dealbatum Roxb.	Zingiberaceae
Amorphophallus bulbifer Blume	Araceae
Arisaema speciosum (Wall.) Mart.	Araceae
Artemisia vulgaris L.	Asteraceae
Begonia lushaiensis C.E.C.Fisch.	Begoniaceae
Begonia palmata D.Don	Begoniaceae
Begonia roxburghii (Miq.) A.DC.	Begoniaceae
Bergenia ciliata (Haw.) Sternb.	Saxifragaceae
Bidens pilosa L.	Asteraceae
Boehmeria virgata (G.Forst.) Guill.	Urticaceae
Centella asiatica (L.) Urb.	Apiaceae

Cirsium interpositum Petr.	Asteraceae
Crassocephalum crepidioides S.Moore	Asteraceae
Crotalaria albida B.Heyne ex Roth	Fabaceae
Curculigo capitulata Kuntze	Hypoxidaceae
Cyanotis cristata (L.) D.Don	Commelinaceae
Dicliptera paniculata (Forssk.) I.Darbysh.	Acanthaceae
Digitaria radicosa Miq.	Poaceae
Digitaria sanguinalis (L.) Scop.	Poaceae
Disporum cantoniense (Lour.) Merr.	Colchicaceae
Dracaena spicata Roxb.	Asparagaceae
Drosera peltata Thunb.	Droseraceae
Drymaria cordata Willd. ex Schult.	Caryophyllaceae
Duhaldea nervosa (Wall. ex DC.) Anderb.	Asteraceae
Eragrostis nutans Nees ex Steud.	Poaceae
Erigeron bonariensis L.	Asteraceae
Etlingera linguiformis (Roxb.) R.M.Sm.	Zingiberaceae
Eulalia trispicata (Schult.) Henrard	Poaceae
Galinsoga parviflora Cav.	Asteraceae
Galium elegans Wall.	Rubiaceae
Globba spathulata Roxb.	Zingiberaceae
Gynura bicolor DC.	Asteraceae
Hedychium villosum Wall.	Zingiberaceae

Hemisteptia lyrata Bunge	Asteraceae
Himalaiella deltoidea (DC.) Raab-Straube	Asteraceae
Hypericum elodeoides Choisy	Hypericaceae
Imperata cylindrica (L.) P.Beauv.	Poaceae
Isodon repens (Wall.) Murata	Lamiaceae
Justicia procumbens L.	Acanthaceae
Laggera alata (DC.) Sch.Bip. ex Oliv.	Asteraceae
Laggera crispata (Vahl) Hepper & J.R.I.Wood	Asteraceae
Lepidagathis incurva Buch. -Ham. ex D.Don	Acanthaceae
Melanoseris macrorhiza (Royle) N.Kilian	Asteraceae
Myriactis wallichii Less.	Asteraceae
Notoseris khasiana (C.B.Clarke) N.Kilian	Asteraceae
Ophiorrhiza treutleri Hook.f.	Rubiaceae
Peperomia pellucida (L.) Kunth	Piperaceae
Persicaria chinensis (L.) H.Gross	Polygonaceae
Persicaria wallichii Greuter & Burdet	Polygonaceae
Plantago asiatica L.	Plantaginaceae
Plantago major L.	Plantaginaceae
Potentilla lineata Trevir.	Rosaceae
Saccharum longisetosum Nayaran. ex Bor	Poaceae
Sanicula elata Buch. -Ham. ex D.Don	Apiaceae
Scleria levis Retz.	Cyperaceae

Scleria terrestris (L.) Fassett	Cyperaceae
Scutellaria discolor Colebr.	Lamiaceae
Senecio scandens (L.) Buch. -Ham.	Asteraceae
Senecio vulgaris L.	Asteraceae
Setaria palmifolia Stapf	Poaceae
Sonerila maculata Roxb.	Melastomataceae
Stachyphrynium placentarium (Lour.) Clausager & Borchs.	Marantaceae
Swertia cordata Wall.	Gentianaceae
Taraxacum officinale F.H.Wigg.	Asteraceae
Tetrataenium burmanicum (Kurz) Manden.	Apiaceae
Thysanolaena latifolia Honda	Poaceae
Urena lobata L.	Malvaceae
Urtica dioica L.	Urticaceae
Viola betonicifolia Sm.	Violaceae
Viola hamiltoniana D.Don	Violaceae
Viola pilosa Blume	Violaceae

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B.Sc	2013	Mizoram University	67.25	I
M.Sc	2015	Mizoram University	75.68	Dist.

List of Publications

1. Lalrinmuana, Lalbiaknunga, J., & Lalbiaknii, P. C. (2025). Influence of altitude on tree species diversity, structure and composition in a protected area of the Eastern Himalayas, Mizoram, India. *Flora* 327.

2. Lalbiaknii, P.C., Ngamlai E.V., Rinmuana L., Vanlalnunpuia P.C., Lalnunmawia F., Ralte V., (2023). In silico validation and pharmacological activity of potent anti viral and anti inflammatory ethnomedical plants used by traditional herbalists within Thorangtlang Wildlife Sanctuary. *International Journal of Pharmaceutical Sciences and Research* 14(5): 2385-2400.

3. Vanlalhruaia, L., Lalbiaknunga, J., & Ralte, L., Lalrinmuana (2021). A Study of Correlation between Morphology and Evolution of Euphorbiaceae sl using Taxonomic Congruence and Total Evidence. *Science and Technology Journal* 9(1): 49-55.

4. Malsawmtluanga, C. D., Lalbiaknunga, J., & Thangliankhup, K., Lalrinmuana (2023). Proximate Analysis, Mineral Contents, and Antioxidant Activities of Wild Edible Mushrooms from India. *International Journal of Medicinal Mushrooms*, *25*(8).

List of Presentations

1. Presented paper (poster) on "Diversity of wood-inhabiting polypores from Reiek and Hmuifang forests" at the 12th Annual Convention of Association of Biotechnology and Pharmacy (ABAP) & International Conference on Biodiversity, Environment and Human Health: Innovations and Emerging Trends (BEHIET 2018) organized by School of Life Sciences, Mizoram University, Aizawl and Association of Biotechnology and Pharmacy (ABAP), India on November 12-14, 2018.
2. Presented paper (oral) on "Analysis of Tree Diversity and Forest Structure in Thorang Wildlife Sanctuary, Mizoram" at the 2nd Annual Convention of North East (India) Academy of Science and Technology (NEAST) & International Seminar on Recent Advances in Science and Technology (IRSRAST) organized by NEAST, Mizoram University, Aizawl-796004, Mizoram (India) on 16th-18th November 2020 (Virtual).
3. Presented paper (oral) on "Quantitative analysis of indigenous medicinal plants used by surrounding inhabitants of Phawngpui National Park, Mizoram, India" at the National Seminar on Plant Taxonomy and Traditional knowledge in the Himalayas and Northeast India and Annual Conference of East Himalayan Society for Spermatophyte Taxonomy (EHHST). Jointly organized by Department of Botany, Rajiv Gandhi University, East Himalayan Society for Spermatophyte Taxonomy on February 21-22, 2022.
4. Presented paper (poster) on "The effect of altitude in shaping the distribution pattern of flora in a protected area of the Eastern Himalaya, Mizoram, India" at the Life Sciences discipline technical session in the 4th Mizoram Science Congress organized by Mizoram Science, Technology, and Innovation Council (MISTIC) in collaboration with Mizo Academy of Science (MAS), Mizoram Science Society (MSS), Science Teachers' Association, Mizoram (STAM), Geological Society of Mizoram (GSM), Mizoram Mathematics Society (MSS), Biodiversity and Nature Conservation Network (BIOCONE) and Mizoram Information & Technology Society (MITS) on November 24-25, 2022.

Conferences/ Seminars/ Workshops Attended

1. Participated in UGC STRIDE Workshop on "BASIC AND ADVANCED MOLECULAR TECHNIQUES" held from 1st June, 2021 to 5th June, 2021 at Mizoram University, Aizawl, Mizoram.
2. Participated in National Webinar on "Sunderlal Bahuguna and Environmentalism in India" organized by the Government Model College, Kaziranga on 5th June, 2021.
3. Participated in the Webinar on "Current scenario of ethnobotanical research in Jammu, Kashmir and Ladakh" organized by FRLH Herbarium and Raw Drug Repository of medicinal plants used in Indian system of Medicine, Centre for Conservation of Natural Resources, TDU on 31st May, 2022.

PARTICULARS OF THE CANDIDATE

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Approval Of Research Proposal	:
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Extension (If Any)	: Two years extention, No.16-2/MZU (Acad)/21/313-318

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ABSTRACT

DIVERSITY OF ANGIOSPERMS ALONG ALTITUDINAL GRADIENTS AND MOLECULAR PHYLOGENY OF LAURACEAE OF PHAWNGPUI NATIONAL PARK MIZORAM

AN ABSTRACT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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DEPARTMENT OF BOTANY
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MAY, 2025

DIVERSITY OF ANGIOSPERMS ALONG ALTITUDINAL GRADIENTS AND MOLECULAR PHYLOGENY OF LAURACEAE OF PHAWNGPUI NATIONAL PARK MIZORAM

BY

LALRINMUANA

Department of Botany

Supervisor

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Submitted

In partial fulfillment of the requirement of the Degree of Doctor of Philosophy in Botany of Mizoram university, Aizawl

Abstract

The Eastern Himalayas, a globally recognized biodiversity hotspot, harbour an extraordinary array of flora and fauna, shaped by complex environmental gradients and evolutionary processes. Phawngpui National Park, located in Mizoram, India, exemplifies this ecological richness, offering a unique opportunity to explore plant community dynamics and evolutionary diversity across altitudinal gradients. The present study entitled 'Diversity of Angiosperms along altitudinal gradient and molecular phylogeny of Lauraceae of Phawngpui National Park Mizoram', investigated the ecological and phylogenetic patterns of angiosperms in a subtropical montane ecosystem. By integrating field-based ecological assessments with molecular phylogenetic analyses, the study addressed four key objectives to elucidate the interplay of altitude, community structure, regeneration, biomass, and evolutionary history. The findings provided critical insights into biodiversity conservation and climate change adaptation, highlighting the park's ecological significance at the biogeographic junction of the Eastern Himalayas and Indo-Burma hotspot. Despite challenges, such as incomplete sampling of rare species, the study laid a robust foundation for future research and conservation strategies in montane ecosystems.

The study was structured in four main objectives, each addressing a distinct facet of ecological and evolutionary dynamics in Phawngpui National Park:

1. Influence of altitude on the diversity, structure, and composition of angiosperms.
2. Regeneration dynamics and canopy structure along altitudinal gradients.

3. Estimation of aboveground biomass and carbon stocks across altitudinal zones.
4. Assessing the phylogenetic diversity of Lauraceae through molecular insights.

Phawngpui National Park was selected due to its exceptional ecological and biogeographic attributes. Spanning nearly 2000 m in altitude, the mountain encompasses a wide range of climatic and edaphic conditions, fostering diverse plant communities across Low Altitude Forest (LAF), Mid Altitude Forest (MAF), and High Altitude Forest (HAF). Its unique geographic location at the intersection of the Eastern Himalayas and Indo-Burma biodiversity hotspot enhances its floristic richness, harbouring a complex array of angiosperms and evolutionary lineages. This setting provided an ideal natural laboratory to investigate altitudinal influences on biodiversity, forest dynamics, and phylogenetic patterns, with implications for conservation in a region increasingly vulnerable to climate change.

The study employed a multidisciplinary approach, integrating ecological field surveys, quantitative analyses, and molecular phylogenetic techniques to address the objectives. To assess angiosperm diversity and community structure, vegetation sampling was conducted across altitudinal zones, capturing data on trees, shrubs, and herbs. This approach ensured comprehensive representation of lifeforms and enabled robust statistical analyses, such as Non-metric Multidimensional Scaling (NMDS), Indicator Species Analysis (ISA), and Canonical Correspondence Analysis (CCA), to elucidate community patterns and environmental drivers. For regeneration and canopy structure, demographic surveys of seedlings and saplings of tree species,

combined with measurements of canopy openness and leaf area index (LAI), provided insights into forest dynamics. These methods were chosen for their ability to quantify structural and regenerative responses to altitudinal gradients. AGB and carbon stocks were estimated using allometric equations and field measurements of diameter at breast height (DBH) and tree height, selected for their accuracy in subtropical montane forests. Phylogenetic analyses utilized matK gene sequences to reconstruct evolutionary relationships of Lauraceae, complemented by phylogenetic diversity metrics (PD, MPD, MNTD) to assess community assembly. This molecular approach was critical for integrating evolutionary perspectives into ecological studies. The combination of these methods ensured a holistic understanding of ecological and phylogenetic patterns, tailored to the study site diverse altitudinal and biogeographic context.

Species accumulation curves indicated adequate sampling for trees, shrubs, and herbs, with MAF exhibiting ongoing accumulation, suggesting a diversity peak driven by transitional habitats. NMDS ordinations revealed distinct community structures, with trees showing the strongest altitudinal separation (global $R = 0.62$), followed by herbs ($R = 0.43$) and shrubs ($R = 0.24$), reflecting niche specialization. ISA identified HAF as hosting the most indicator species (e.g., *Rhododendron arboreum*, IndVal = 0.44, $p = 0.001$), underscoring its unique ecological conditions. CCA confirmed environmental filtering, with altitude, soil nutrients, and microclimate explaining 74.7%, 61.2%, and 62.5% of variance in tree, shrub, and herb communities, respectively. The high Shannon diversity index ($H' = 4.07$) and Pielou's Evenness Index ($J' = 0.94$) highlighted exceptional diversity, particularly in MAF, supporting the intermediate disturbance hypothesis.

A reverse J-shaped size class distribution indicated robust regeneration, with MAF showing the highest stem density, basal area, and DBH, aligning with the mid-domain effect. Sapling and seedling density increased quadratically with elevation, peaking in HAF, suggesting upward species movement in response to climatic shifts. *Cinnamomum verum* seedling survival was higher in open habitats, emphasizing light availability's role in regeneration. PCA linked seedling traits to temperature, altitude, and light, identifying HAF as optimal for growth. Higher canopy openness in HAF and denser LAI in MAF shaped understory communities, influencing ecosystem stability.

AGB and carbon stock followed a hump-shaped pattern, peaking in MAF (223.0 ± 77.5 Mg/ha, 104.8 Mg C/ha) due to optimal conditions, compared to LAF (146.0 ± 60.7 Mg/ha) and HAF (109.0 ± 63.5 Mg/ha). High-wood-density species like *Engelhardia spicata* and *Castanopsis tribuloides* dominated in MAF and HAF, contributing significantly to carbon storage. LAF's light-demanding species (e.g., *Duabanga grandiflora*) reflected secondary forest dynamics, while HAF's temperate taxa (e.g., *Rhododendron arboreum*) indicated Sino-Himalayan influences. These findings positioned MAF as a carbon sequestration hotspot, critical for climate change mitigation.

Phylogenetic reconstruction of 12 Lauraceae species resolved three clades (*Persea, Litsea, Cinnamomum*), aligning with Sino-Himalayan lineages. Phylogenetic diversity decreased with altitude, with LAF showing overdispersion, MAF moderate clustering, and HAF strong clustering due to abiotic stressors. Despite HAF's high species richness, its low PD indicated reduced evolutionary novelty, emphasizing the

need for phylogenetic metrics in conservation. The altitudinal trend from overdispersion to clustering reflected environmental filtering's role in community assembly.

The findings underscored Phawngpui National Park's ecological significance, offering actionable insights for conservation and climate change adaptation. The identification of MAF as a biodiversity and carbon hotspot suggested prioritizing its protection to preserve carbon sinks and species diversity. ISA's indicator species, particularly in HAF, served as bioindicators for monitoring climate-induced altitudinal shifts, informing adaptive conservation strategies. Reforestation efforts should have focused on species like *Engelhardia spicata* and *Castanopsis tribuloides* to enhance carbon storage and ecosystem stability. Protecting altitudinal gradients ensured the preservation of taxonomic and phylogenetic diversity, critical for resilience against climate change impacts, such as altered precipitation or habitat fragmentation. Policies should have aimed to reduce anthropogenic pressures in LAF, promoting sustainable land-use practices.

However, the study faced limitations. Incomplete sampling of species in MAF and HAF, as indicated by species accumulation curves, suggested that additional surveys were needed to capture their contributions. The focus on aboveground biomass omitted belowground biomass, limiting a comprehensive carbon assessment. Temporal dynamics, such as seasonal or long-term climate impacts, were not explored, potentially overlooking transient responses. The phylogenetic analysis was restricted to Lauraceae, and expanding to other families could have provided broader

evolutionary insights. Anthropogenic disturbances in LAF were noted but not quantified, warranting further investigation.

This thesis provided a comprehensive understanding of angiosperm diversity, forest dynamics, and phylogenetic patterns in Phawngpui National Park, highlighting the critical role of altitudinal gradients in shaping subtropical montane ecosystems. The findings emphasized MAF's significance as a biodiversity and carbon hotspot, HAF's unique indicator species as climate change monitors, and the importance of phylogenetic diversity for ecosystem resilience. By addressing limitations through future research—such as extensive rare species surveys, belowground biomass studies, and long-term monitoring—conservation strategies could enhance the park's adaptability to climate change, contributing to global biodiversity and carbon sequestration goals. Phawngpui National Park's unique altitudinal range and biogeographic position underscored its value as a model for studying and conserving montane ecosystems.