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Influence of elevation and climate on vegetation structure of tropical Montane Forest of Brahmagiri Wildlife Sanctuary, Central Western Ghats

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Abstract

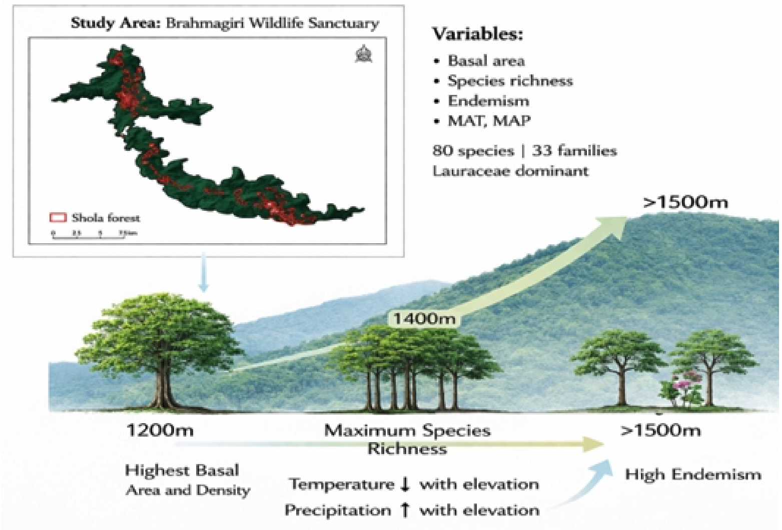
Aim: This study assessed the effects of elevation and climatic variability on species composition, endemism, and vegetation structure in the montane ecosystems of Brahmagiri Wildlife Sanctuary, within the Western Ghats biodiversity hotspot.

Methodology: Vegetation data were collected across elevation zones. Tree species were identified, and parameters such as species richness, density, basal area, and endemism were measured. Climatic variables, including mean annual temperature and precipitation, were analyzed. Kernel Density estimation and spearman's Rank correlation examined relationships between vegetation and climate.

Results: A total of 80 tree species from 33 families were documented, with Lauraceae being the most dominant. Species richness peaked at mid-elevations, aligned with the mid-domain effect. Basal area and density were higher at lower elevations, while endemism increased significantly at higher elevations.

Interpretation: Higher elevations characterised by lower temperatures support the presence of unique endemic species, highlighting a strong link between vegetation structure and climate. These findings underscore the sensitivity of montane ecosystems and emphasize on the need for targeted conservation strategies to protect endangered species amid ongoing climate change.

Key words: Climate variability, Elevation gradient, Species richness, Tropical Montane Forests



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Introduction

The Western Ghats, a globally renowned biodiversity hotspot and a major water source for Peninsular India, stretch parallel to the western coastline from the Tapi River in the north to Kanyakumari in the south (Myers *et al.,* 2000). This ancient mountain range, which originated after the Indian subcontinent separated from Madagascar (Pullaiah, 2024), plays a vital role in capturing the south-west monsoon, producing orographic rainfall that sustains its exceptional biological diversity. In recognition of its ecological significance, the region was designated a UNESCO World Heritage Site in 2012 (UNESCO, 2012; WGEEP,2011). The Western Ghats are characterized by significant topographic variation and a strong precipitation gradient, which together support a wide range of ecosystems and forest types, including evergreen, semi-evergreen, montane Shola forests and grasslands, moist deciduous, dry deciduous, and dry thorn forests (Bawa *et al.,* 2007, Shigwan *et al.,* 2024). Montane Shola forests are comprised by fragmented tropical evergreen forest patches, varying from less than a hectare to several hundred hectares, typically found in sheltered valleys or depressions juxtaposed with grasslands at elevations ranging from 1000 m to above 1500 m (Bunyan *et al.,* 2015; Robin and Nandini, 2012).

The term 'Shola' originates from the Tamil word 'cholai,' meaning grove. The shola forests are recognized globally as ‘Cloud Forests’ because of their persistent cloud cover, which enhances moisture availability (Mohandass and Davidar, 2010). These forests are known for their high endemism, with many species restricted to narrow elevation bands, making them highly vulnerable to climate change hence were referred as ‘Living fossil’ (Arceivala, 2012). Recent studies have highlighted that altitudinal variation plays a crucial role in shaping species composition and forest structure in the Western Ghats, with mid-elevations often supporting higher species richness (Zhang *et al.,* 2012; Jaiswal and Jayakumar, 2024). Structurally, Shola trees are evergreen, robust, and branchy, with dense, umbrella-shaped crowns composed of coriaceous leaves. They are often covered with epiphytes, mosses, ferns, lichens, and orchids, contributing to their ecological complexity (Jose *et al.,* 1996). The fringe trees are generally dwarf-sized to withstand high winds, while those in the core are relatively taller. Global change significantly shapes species distributions and alters the functional dynamics and ecosystem services of forest systems (Wang *et al.,* 2022) Despite this, tree species exhibit varied responses to climate factors (O'Sullivan *et al.,* 2020), because their distributions depend on both abiotic and biotic influences.

However, previous studies have mainly concentrated on the roles of abiotic factors like climate, topography and soil properties, whereas the influence of biotic factors particularly plant functional traits has received insufficient attention. (O'Sullivan *et al.,* 2020; Wang *et al.,* 2022). Yet, plant functional traits are known to mediate species performance in varying environments (Bruelheide *et al.,* 2018; Wang *et al.,* 2022), and widespread trait climate relationships suggest that functional traits could provide important predictive strategy for understanding species distribution shifts in a changing climate (Kemppinen *et al.,* 2021; Wang *et al.,* 2022). Therefore, unravelling the relative contributions of climate and functional traits to species distributions is essential for effective forest management and informed decision-making. Addressing this research gap is particularly important in montane forests, where complex topography and interacting climatic gradients shape vegetation structure. In this regard, the present study examines species diversity, endemism patterns and vegetation structural changes across an elevation gradient in Brahmagiri Wildlife Sanctuary. It also analyses temperature and precipitation to understand how climate affects biodiversity patterns. This research provide a significant knowledge on how vegetation in shola forest responds to varied environmental factors and helps in suggesting the practical steps for conservation, management and climatic adaptation measures in these montane areas. In light of this, we hypothesized that vegetation structure, species composition, and endemism vary along the elevation gradient. Mid-elevations should show highest species richness and structural complexity due to optimal climate conditions. Temperature and precipitation variations also play a major role in shaping Shola Forest structure and composition

Materials and Method

Study area: The study was undertaken in Brahmagiri Wildlife Sanctuary (BWS), situated in Karnataka's Kodagu district within the Central Western Ghats biodiversity hotspot. The sanctuary located between 11^0 55' to 12^0 19' N latitude and 75^0 44' to 76^0 04' E longitude covers an area of 181.29 km². The Eco-Sensitive Zone (ESZ) spans approximately 136.60 km² and extends 1 to 15 km beyond the sanctuary boundary (Neikha and Nagaraja, 2019). The average rainfall for this region varies between 2,500 to 6,000 mm. Significantly, Laxmanthirtha and Ramthirtha rivers are the major tributaries of the Cauvery River, originate within this sanctuary. The region encompasses a variety of forest types, including tropical wet evergreen, semi-evergreen, moist deciduous forests, as well as montane Shola forests and grasslands (Champion and Seth, 1968). Brahmagiri Wildlife Sanctuary was designated as a protected area in 1974, following its delineation from two reserve forests: Brahmagiri Ghat and Urti Reserve Forest. It maintains ecological connectivity with Talacauvery Wildlife Sanctuary through the adjoining Kerti and Padinalknad Reserve Forests. The sanctuary supports a wide diversity of flora and fauna, encompassing taxa from insects and small mammals to large herbivores, such as Indian elephants and endemic birds like the Malabar hornbill. The landscape is characterized by undulating topography with elevations ranging from 65 to 1,618 m above sea level, including Brahmagiri Peak, the highest point in the sanctuary (Neikha and Nagaraja, 2019).

Data collection and Species identification: Vegetation sampling was conducted between January to March, 2025. A standard transect method (Misra, 1968; Sutherland, 2006) was adopted along an elevation gradient of 1,200 to above 1,500 m. At

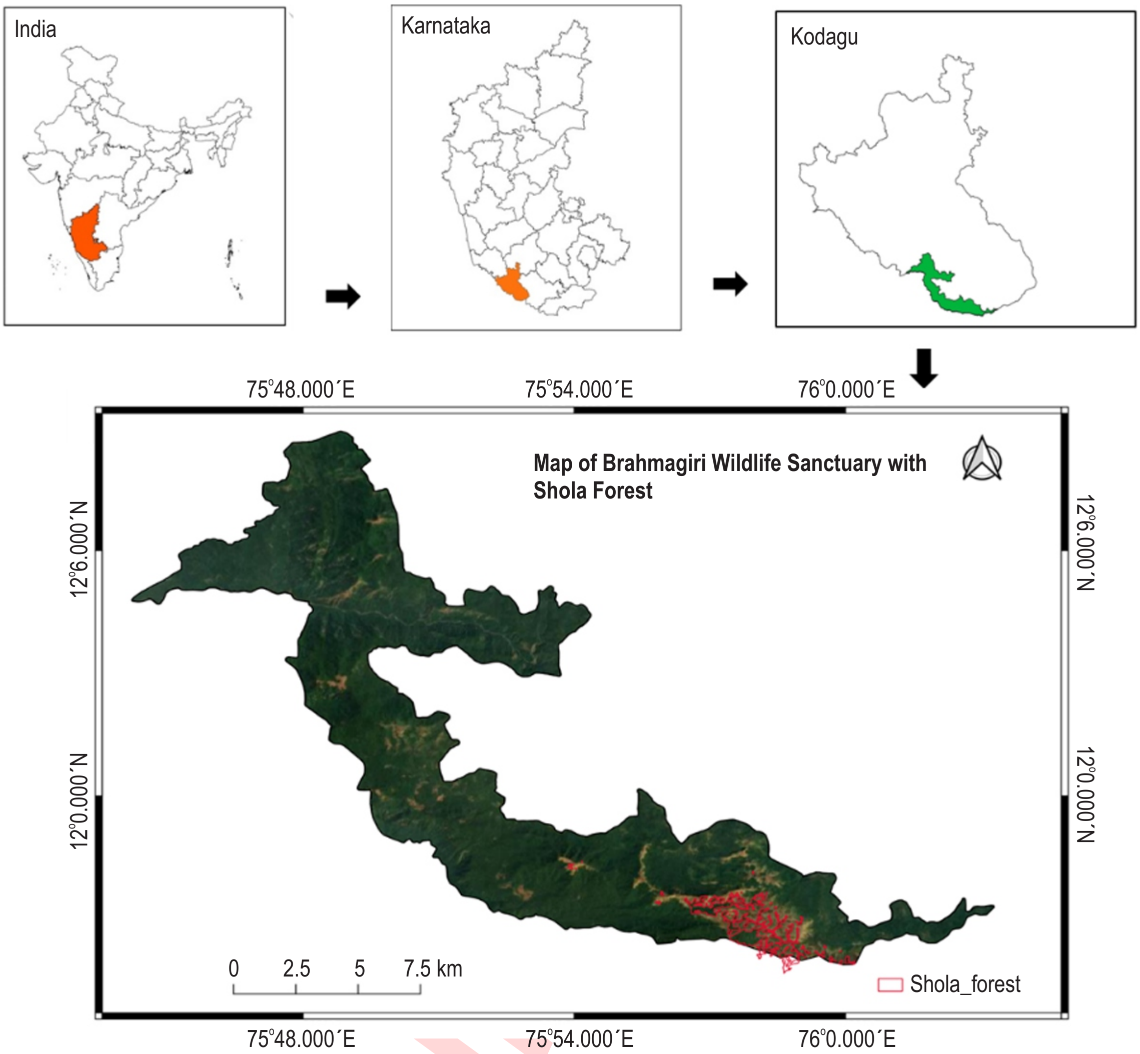

Fig. 1: Study area map of Brahmagiri Wildlife Sanctuary, Kodagu region of Western Ghats.

each elevation level, belt transects measuring 100m x 50 m were established within the Shola forests. These transects comprised multiple 20m x 20m plots, each separated by a 10 m gap. In total, 24 plots encompassing an area of one hectare were systematically surveyed. Tree species were identified using local expertise and reference floras (Pascal and Ramesh, 1987; Neginhal, 2020). Girth at Breast Height (GBH) was measured carefully to avoid disturbance. For each species, density, frequency, abundance, basal area, and Importance Value Index (IVI) were calculated (Curtis and McIntosh, 1951), along with Family Importance Value (FIV). Species were classified by endemism and IUCN conservation status.

Statistical analyses: For each species, density, frequency, abundance, Basal area (BA), Importance Value Index (IVI), and Family Importance Value (FIV) were calculated by the standard equations (Mishra, 1968; Curtis and McIntosh, 1951). Data analysis included Bray-Curtis Cluster Analysis using BioDiversity Pro 2.0 to assess species similarity across elevations (Bray and Curtis, 1957). Density plots and correlation heatmaps were generated with RStudio (v4.4.1), and Kernel Density Estimation (KDE) was used to compare species richness and ecological metrics independent of sample size (Seaman & Powell, 1996). Spearman's Rank Correlation tested relationships among elevation, species richness, basal area, endemism, diversity indices (Shannon, Simpson, Evenness), and climatic variables (mean annual temperature and precipitation), with significance levels set at $p < 0.05$, 0.01, and 0.001.

Results and Discussion

A total of 80 tree species belonging to 33 families were recorded along the elevational gradient of Brahmagiri Wildlife Sanctuary. Among these, Lauraceae was the most dominant family, comprising 215 individuals across 15 species, followed by Rubiaceae with 92 individuals from 2 species, and Moraceae, as reflected by the Family Importance Value (FIV) percentages of 64.49, 27.21 and 20.88%, respectively. The dominance of Lauraceae aligns with global and regional studies showing that a few families significantly shape forest community composition (Gentry, 1995). *Canthium dicoccum* was the most abundant species with 90 individuals, followed by *Litsea floribunda* and *Cinnamomum sulphuratum*. Among which the species such as *Canthium dicoccum, Cinnamomum sulphuratum, Cryptocarya wightiana, Dysoxylum binectariferum* and *Myristica dactyloides* listed under IUCN threatened category, underscoring the conservation value of this montane ecosystem. Tree density varied from 375 to 1112 stems/ha across elevations, notably higher than densities reported for similar forest types in the Western Ghats (Neikha and Nagaraja, 2019). Diversity indices Shannon's diversity index (H' = 3.25), Simpson's dominance index (D = 0.05), and Evenness (E = 0.87) indicate robust species richness and well-balanced community structures likely reflecting effective protection and management efforts (Utkarsh *et al.,* 1998) in the sanctuary (Table 1).

The rank-abundance distribution observed in this study followed a power-law pattern, highlighting a strong dominance of a few families in shaping species richness. The results revealed that Lauraceae, Rubiaceae, and Symplocaceae were the most dominant families, with Lauraceae exhibiting the highest species richness. This aligns with global and regional studies, which report that specific families tend to dominate in distinct ecological zones (Gentry, 1995). The fitted power-law equation ($y = 224.54x^{-1.339}$, $R^2 = 0.9828$) suggests a steep decline in species richness as family rank increases, reflecting a typical ecological pattern, where a few families contribute disproportionately to overall diversity. (Fig. 2). Similar trends have been reported in tropical and montane forest ecosystems. where habitat specificity, dispersal mechanisms, and evolutionary adaptations drive species abundance (Mohandass & Davidar, 2010; Ashton and LaFrankie *et al.,* 2000). The high coefficient of determination ($R^2 = 0.98$) further supports the robustness of distribution, reinforcing the hypothesis that species richness in these forests is largely controlled by a few ecologically dominant families. The results provide critical insights into community assembly rules, biogeographic influences, and conservation priorities in montane ecosystems, emphasizing the need for targeted conservation of dominant taxa to maintain ecological stability. Bray-Curtis similarity indices reflect moderate species compositional overlap, with 31.6% similarity between mid- and high-elevation communities, reflecting both continuity and distinct altitudinal zonation. These patterns imply that elevation-driven environmental gradients, especially temperature and moisture, strongly influence the community composition and turnover (Fig. 3).

Montane ecosystems exhibit spatial variations in species composition, ecological metrics, and climatic conditions across elevation gradients. Factors such as temperature fluctuations, precipitation, and habitat, shape the biodiversity patterns. The analysis illustrates the distribution of ecological and climatic parameters such as, species richness, endemism, diversity indices, evenness, basal area, mean annual temperature (MAT), and mean annual precipitation (MAP)—across four elevation ranges (1200–1600 m) (Fig 4). The Kernel Density Estimation (KDE), reveals probability density, ensuring fair comparisons across elevations regardless of sample size (Seaman and Powell, 1996). This approach reveals underlying trends, providing insights into species distribution and the role of climate in structuring montane vegetation.

Species richness in the montane Shola forests exhibits a distinct unimodal pattern along the elevational gradient. At lower elevations (1200–1300 m), richness peaks at approximately 10–15 species, likely driven by favorable microclimates and moderate resource availability (Rahbek, 1995; Grytnes and McCain, 2007). Mid-elevations (1300–1500 m) show slightly higher richness (10–17 species), which can be attributed to habitat heterogeneity and overlapping species ranges characteristic of ecotonal zones (Grytnes and Vetaas, 2002;

Table 1: Vegetation characteristics of trees across the elevation of Brahmagiri Wildlife Sanctuary, Kodagu region of Western Ghats

Vegetation characteristics	**Elevation(m)**				**Total**
	1200-1300	**1301-1400**	**1401-1500**	**>1501**	
No. of Species	40	40	55	32	80
No. of Genera	13	24	27	15	49
No. of Families	10	18	21	16	33
No. of Endemic species	4	10	11	10	24
No. of IUCN (Vulnerable Species)	-	2	4	3	4
Density (ha^{-1})	908	742	786	1017	3452
Basal area (m^{2}ha^{-1})	119.3	126.67	61.79	121.58	429.37
Shannon- Wiener Diversity index (H)	3.33	3.41	3.18	3.08	3.25
Simpson's Dominance index (D)	0.04	0.04	0.06	0.05	0.05
Pielou's Evenness index (E)	0.90	0.92	0.77	0.88	0.87
Fisher Alpha Diversity index (α)	8.721	30.87	10.65	10.79	15.25

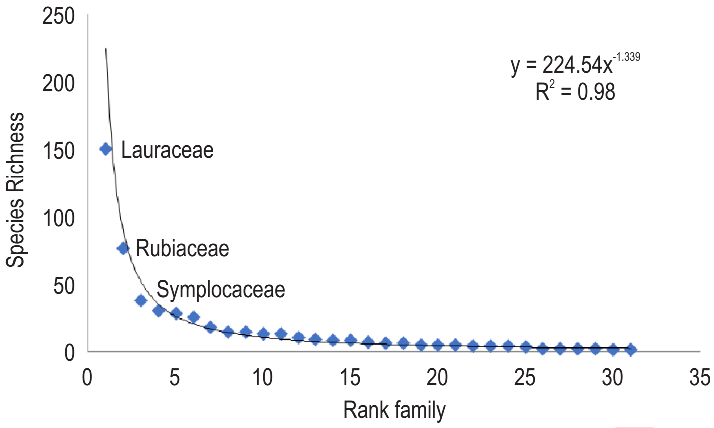

Fig. 2: Rank family and Species richness correlation in Brahmagiri Wildlife Sanctuary, Kodagu region of Western Ghats.

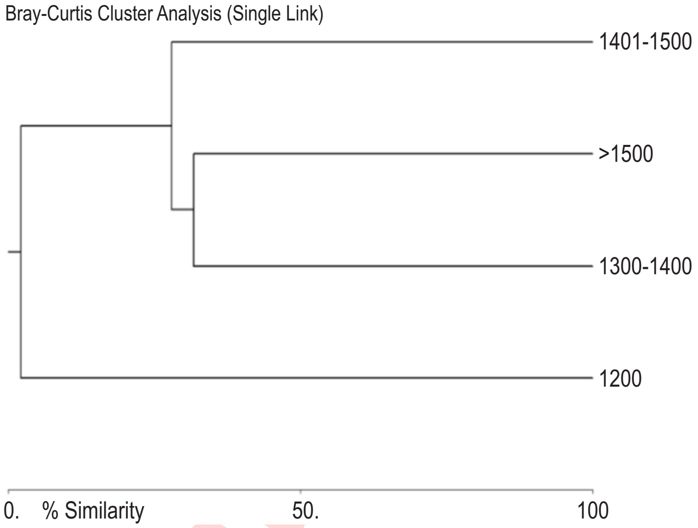

Fig. 3: Bray-Curtis Similarity of species across the elevation in Brahmagiri Wildlife Sanctuary, Kodagu region of Western Ghats.

Bhattarai and Vetaas, 2003). However, species richness declines at higher elevations (1500–1600 m), with 6–10 species, constrained by reduced energy availability and increased environmental stress (Korner, 2007; Currie et al., 2004). This unimodal pattern, visually represented in Fig. 4, supports the mid-domain and species-energy hypotheses and aligns with global montane biodiversity patterns (Colwell and Lees *et al.,* 2000; Rahbek, 1995).

Basal area is higher at lower elevations (1200–1400 m) due to warmer temperatures, resource availability, deeper soil profiles, and favourable growth conditions (Kumar *et al.,* 2014). These factors support greater tree growth and biomass accumulation. Lower elevations also experience less environmental stress and benefit from longer growing seasons. In contrast, higher elevations (1500–1600 m) face cooler temperatures, shallow soil profiles, and increased exposure to wind and frost, which limit tree growth and result in lower basal area; hence, species in these zones tend to grow slower and remain smaller. Maza *et al.* (2022) reported a significant decline in the aboveground biomass with elevation, from 310.26 ± 81.59 Mg ha^{-1} at 1421–1826 m, with notably higher values at lower altitudes. These findings highlight that elevation act as a pivotal role in forest structure and productivity (Dar and Sundarpandian, 2015).

The endemic pattern indicates the strong multimodal distribution ranges from 1200 to 1600 m. where highest endemism documented at higher elevation (1500-1600m) followed by mid elevation 1300-1500 m. This distribution aligns with the hypothesis that, stable climatic conditions and unique edaphic environments support long-term ecological isolation and speciation (Myers *et al.,* 2000). Species belonging to families

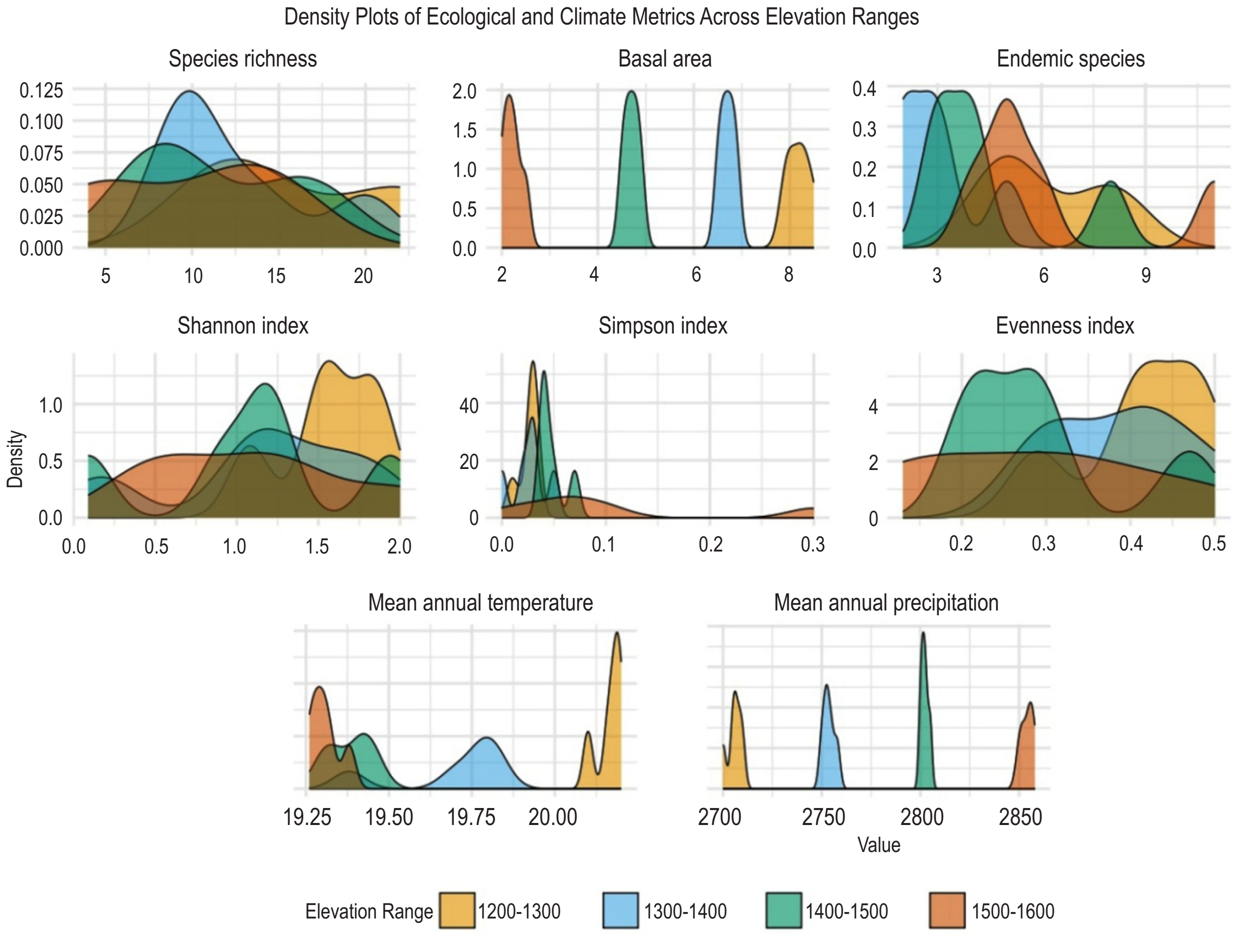

Fig. 4: Ecological and climate metrics across elevation.

such as Lauraceae, Oleaceae, and Melastomataceae exhibit adaptive traits like thick, leathery leaves, compact growth forms, and reduced height, enabling them to conserve moisture and thrive in low-temperature, low-light, and mist-laden conditions (Pascal, 1988). These functional adaptations, coupled with limited dispersal ability and synchronized phenology, restrict these species to specific elevational zones (Korner, 2007). The mid-elevation peak supports the ecotone and transition zone hypotheses, where overlapping species ranges and microhabitat heterogeneity foster diversification (Rahbek, 1995; Grytnes and McCain, 2007). This trait-based endemism also underscores the vulnerability of montane taxa to climate change and habitat disturbance (Ramesh *et al.,* 2010; Rahbek *et al.,* 2019).

Shannon diversity index displays a multimodal distribution across elevation ranges, with the highest peak at 1200–1300 m (~2.3), reflecting elevated species diversity likely driven by favorable microclimatic conditions and habitat heterogeneity (Whittaker, 1972; Rahbek, 2019). Notably, the 1300–1400 m range exhibits three distinct peaks (~1.8, ~2.0, and ~2.2), suggesting ecotonal transitions or species turnover zones where communities from adjacent elevations overlap (Grytnes and McCain, 2007). Simpson index, which gives more weight to dominant species, showed peaks at 1200–1300 m (~0.87), indicating a balanced community with low dominance. In contrast, the 1500–1600 m elevation range showed a primary peak at ~0.78 and a secondary peak at ~0.26, the latter suggesting strong dominance by a few stress-tolerant species under harsher conditions, likely due to environmental filtering (Korner, 2007; Gairola *et al.,* 2009). Evenness index further supports these trends, showing higher values at 1200–1400 m (~0.87–0.90), reflecting equitable species distribution, while declining at 1500–1600 m (~0.82), indicative of uneven community structures. Together, these diversity metrics highlight the ecological richness and community balance at lower to mid-elevations and emphasize their conservation significance.

The mean Annual Temperature (MAT) revealed that a clear decline with increasing elevation, consistent with the adiabatic lapse on the other hand, the relatively warmer conditions at 1200–1300 m can enhance metabolic activity and rate, where temperature decreases with altitude (Barry and

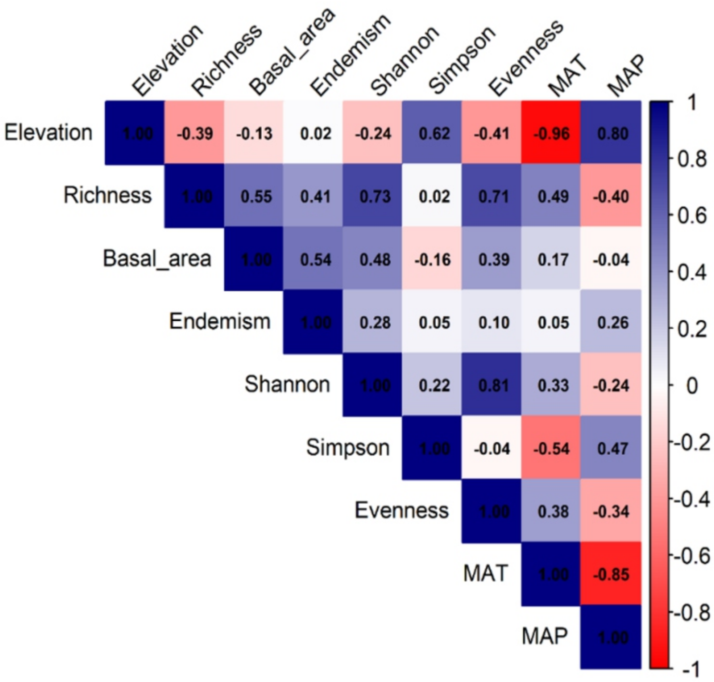

Fig. 5: Spearman's Correlation with vegetation structure and climatic variable across elevation gradient in BWS.

Table 2: Spearman's correlation matrix showing the relationship between vegetation structural attributes, climatic factors and elevation

Variables	Elevation	Richness	Basal area	Endemism	Shannon	Simpson	Evenness	MAT	MAP
Elevation	1								
Richness	-0.39	1							
Basal area	-0.13	0.55*	1						
Endemism	0.02	0.41	0.54*	1					
Shannon	-0.24	0.73***	0.48*	0.28	1				
Simpson	0.62**	0.02	-0.16	0.05	0.22	1			
Evenness	-0.41	0.71***	0.39	0.10	0.81***	-0.04	1		
MAT	-0.96***	0.49*	0.17	0.05	0.33	-0.54*	0.38	1	
MAP	0.80***	-0.40	-0.04	0.26	-0.24	0.47*	-0.34	0.85***	1

Chorley, 2009). Cooler temperatures at 1500–1600 m may impose physiological limitations on lowland species, leading to the establishment of distinct high-elevation assemblages adapted to colder conditions (Korner, 2007). productivity but may also increase evapotranspiration stress, potentially influencing species distribution and community composition (Colwell and Lees, 2000). The mean Annual Precipitation (MAP) increased with elevation due to orographic effects, where rising air cools and condenses, leading to higher rainfall (Barry and Chorley, 2009). However, despite greater moisture availability at 1500–1600 m, species richness declines, likely due to cooler temperature, shorter growing seasons, and nutrient limitations restrict plant survival (Korner, 2007). The mid-elevation peak hypothesis (Rahbek *et al.,* 2019) suggests that species richness was maximum at 1300–1400 m due to favourable climatic conditions, while lower elevations (1200–1300 m) experienced moisture stress, which may affect the species distribution. The ecological and climatic data across elevations show clear patterns in vegetation composition and structure (Körner, 2007). The mid-elevation zone serves as a biodiversity hotspot due to optimal environmental conditions (Rahbek, 1995; Grytnes and McCain, 2007). At higher elevations, harsher climate leads to decreased species richness and dominance by a few species (Korner, 2007). Basal area and biomass decrease with elevation because of lower temperature and poor soil (Moser *et al*., 2011). Thus, these findings highlight the need for targeted conservation efforts, particularly at mid-elevations zone.

In Spearman's correlation, the relationship between elevation, climate (MAT and MAP), and vegetation structure (species richness, basal area, endemism) were evaluated. Table 2 lists all correlation coefficients. Fig. 5 visually represents these relationships using color shadings blue indicates positive correlations and red indicates negative correlations. The intensity of colors reflect the strength of the correlations, ranging from –1 to +1. Elevation negatively correlates with species richness (r = −0.39), tree density (r = −0.36), and basal area (r = −0.13), indicating a decline in forest structural complexity at higher altitudes, likely due to harsher climatic conditions and resource limitations (Korner, 2007; Bruun *et al.,* 2006).

Temperature decrease sharply with elevation (r=−0.95***), making it the primary factor controlling vegetation patterns (Colwell and Lees, 2000). In contrast, MAP increased with elevation (r=0.79***), though its weak correlation with species richness and basal area suggested that precipitation alone does not govern forest structure (Givnish, 1999). Diversity Whittaker indices (Shannon, evenness, richness) exhibited strong positive correlations (r=>0.7***), supporting the idea that species-rich forests tend to have more even species distributions (Whittaker, 1972). Higher tree density positively influences species richness (r=0.78***) and basal area (r = 0.45*), suggesting that forests with greater biomass support higher biodiversity (Chave *et al.,* 2003). These findings align with global patterns of elevational biodiversity gradients, emphasizing the interplay of temperature, precipitation, and forest structure in shaping the mountain ecosystems.

This study highlights that mid-elevation zones in Brahmagiri Wildlife Sanctuary function as biodiversity hotspots characterized by high species richness, balanced community structures, and significant endemism. These patterns show the need to prioritize conservation in these zones to maintain ecosystem resilience. Moreover, understanding how climatic and edaphic factors influence vegetation dynamics provides a scientific basis for developing elevation specific conservation and restoration strategies tailored to the unique ecological conditions of tropical montane landscapes.

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Authors' contribution: S. Vidyashree: Conceptualization, Species identification, Manuscript writing, Conducting experiment and Statistical analysis; **K.P. Vijayananda:** Species identification, Conducting experiment; **B.C. Nagaraja:** Designing the experiment, Editing of the manuscript.

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Data availability: The data that support the findings of this study are available from the Corresponding author upon reasonable request.

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