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Diversity and Structural Assessment of Tree Species in Sacred Groves of Kodagu

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Aims: The present study was undertaken to assess the structure, diversity and regeneration status of tree species, with special emphasis on RET species, in the sacred groves of Kodagu representing evergreen and deciduous vegetation types.
Study Design: A stratified random sampling approach was adopted.
Place: The study was conducted in 19 sacred groves representing the semi-evergreen and moist deciduous vegetation types of Kodagu district, Karnataka, India.
Methodology: A stratified random sampling design was adopted using 4 m-wide belt transects laid perpendicular to a baseline until 500 trees (GBH ≥10 cm) were recorded per sacred grove. Tree species, GBH, height, and basal area were documented for floristic analysis, including diversity and similarity indices. Regeneration was assessed in 4 × 4 m subplots at 25 m intervals. Differences in floristic attributes and regeneration between vegetation types and grove sizes were analysed using appropriate statistical tests.

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Results: The study revealed that semi-evergreen sacred groves supported greater overall tree species richness (143 species) and a higher diversity of rare, endangered, and threatened (RET) species than moist deciduous groves, although mean species richness and stand structural attributes were comparable between vegetation types. Larger groves consistently exhibited significantly greater tree density, basal area, species richness, and regeneration diversity than smaller groves, highlighting the importance of grove size in maintaining ecological integrity. An inverse J-shaped girth-class distribution indicated healthy regeneration and stable population structure. Semi-evergreen groves also supported higher RET regeneration, emphasising their critical role in long-term biodiversity conservation.

Conclusion: Sacred groves in Kodagu effectively conserve tree diversity and support regeneration, with larger semi-evergreen groves supporting higher species richness, threatened taxa, and ecosystem resilience, underscoring their conservation importance.

Keywords: Sacred groves; rare; Endangered and Threatened (RET) tree species; diversity; regeneration.

1. Introduction

Conservation of nature and natural resources is a fundamental requirement for sustaining life and ensuring ecological stability. India, endowed with a rich cultural heritage and vast natural wealth, is globally recognised as one of the megadiverse countries, harbouring over 20,000 flowering plant species with a high proportion of endemism. This exceptional biodiversity is concentrated mainly within four global hotspots—the Himalayas, Western Ghats, Indo-Burma region and Sundaland—making conservation efforts in these regions critically important. Among them, the Western Ghats, a 1,600-km-long mountain chain along the western coast of India, is one of the world's most significant biodiversity hotspots. Known for its ancient geological origin, high species richness and remarkable endemism, the Western Ghats support unique non-equatorial tropical evergreen forests (Hrdina & Romportl, 2017). However, rapid land-use changes, population pressure and intensive resource exploitation have severely threatened this fragile ecosystem, placing many endemic and threatened tree species at risk (Warrier et al., 2020).

Kodagu district, located in the central Western Ghats, represents a unique landscape mosaic of forests, coffee plantations, spice gardens and sacred groves. With exceptionally high forest and tree cover, Kodagu is also renowned for its large number of sacred groves—traditionally protected forest patches dedicated to local deities (Kushalappa & Bhagwat, 2001). These groves function as repositories of biodiversity, traditional ecological knowledge and cultural heritage, often harbouring rare, endangered and threatened (RET) plant species (Prasad & Thomas, 2021; Maheswarappa & Vasudeva, 2018). Beyond biodiversity conservation, sacred groves contribute to carbon sequestration, microclimate regulation and long-term ecosystem resilience (Prasad & Bharathi, 2016).

Recent studies continue to document the conservation value of sacred groves for woody-plant diversity and stand structure in India, including evidence from the Shivalik foothills and the Western Ghats (Chettri et al., 2025; Shigwan et al., 2026). In the Western Ghats, sacred groves have also been associated with greater recruitment of zoochorous saplings beneath large trees, supporting the relevance of regeneration-based assessments alongside adult-tree structure (Pai et al., 2026). More broadly, recent vegetation assessments from Karnataka and sacred groves elsewhere in India indicate that tree composition, anthropogenic disturbance and regeneration can vary among sites, supporting the need for site-specific ecological evaluation (Gowda et al., 2026; Tirkey et al., 2025).

Trees, as keystone components of forest ecosystems, play a vital role in maintaining ecological balance, supporting diverse life forms and regulating climate. Understanding tree species diversity, structure and natural regeneration is therefore essential for assessing forest health and sustainability. Despite their importance, long-term studies on vegetation dynamics and regeneration patterns in sacred groves of Kodagu remain limited (Malik & Bhatt, 2016). Hence, the present study was undertaken to assess the tree species diversity, stand structure and regeneration status, with special emphasis on RET species, in the sacred groves of Kodagu representing evergreen and deciduous vegetation types. The study further compared diversity and structural parameters across vegetation types and different size classes of sacred groves.

2. Materials and Methods

The study was conducted in 19 sacred groves representing the semi-evergreen and moist deciduous vegetation types of Kodagu district, Karnataka, India (Fig. 1). Semi-evergreen forests occur in the western and central parts of the district, whereas moist deciduous forests are distributed in the central-eastern region (Pascal & Ramesh, 1997). The selected sacred groves were categorised as large (≥2.5 ha) and small (<2.5 ha). The region experiences a tropical humid climate, with mean annual rainfall of 2699.44 mm in semi-evergreen groves and 2269.69 mm in moist deciduous groves. Minimum temperatures ranged from 12–13°C (Fig. 2a) and maximum temperatures from 29.99–36°C (Fig. 2.b); data were collected from the weather station of KVK, Gonikoppa.

2.1 Sampling Design

A stratified random sampling approach was adopted. In each sacred grove, 4 m-wide belt transects were laid perpendicular to a baseline established along a natural or man-made linear feature (Fig. 3). Transects were placed at randomly generated intervals until 500 tree individuals with GBH ≥10 cm was recorded from each grove (Raghavendra, 2003). A minimum girth at breast height (GBH) of >10 cm was adopted as the inclusion criterion for trees to ensure consistent sampling of established woody individuals while excluding very young seedlings and saplings that are better represented in regeneration assessments. All tree species were identified using standard floras (Pascal & Ramesh, 1997), and their girth at breast height (GBH), total height, and basal area were recorded.

2.2 Floristic Analysis

The basal area of individual trees in each transect was calculated and summed to get the basal area of the transect. The frequency distribution of the various girth classes of stems was determined and compared between large and small groves in both vegetation types. Species richness, species evenness/Pielou's index and the Shannon–Wiener diversity index were calculated to assess floristic diversity (Colwell, 2009; Magurran & Henderson, 2003). Species similarity (β-diversity) between vegetation types and grove size classes was assessed using Jaccard's similarity index in Biodiversity Pro (Version 2).

2.3 Regeneration Assessment

Within the belt transect, 4 m × 4 m subsample plots were laid out at 25 m intervals along the transect. All regenerates within the subplots were identified and categorised into different life forms such as herbs, climbers, shrubs, tree species and RET tree species. Regenerates were classified based on their height. They were assigned to the respective regeneration classes for further analysis (Sathish et al., 2013).

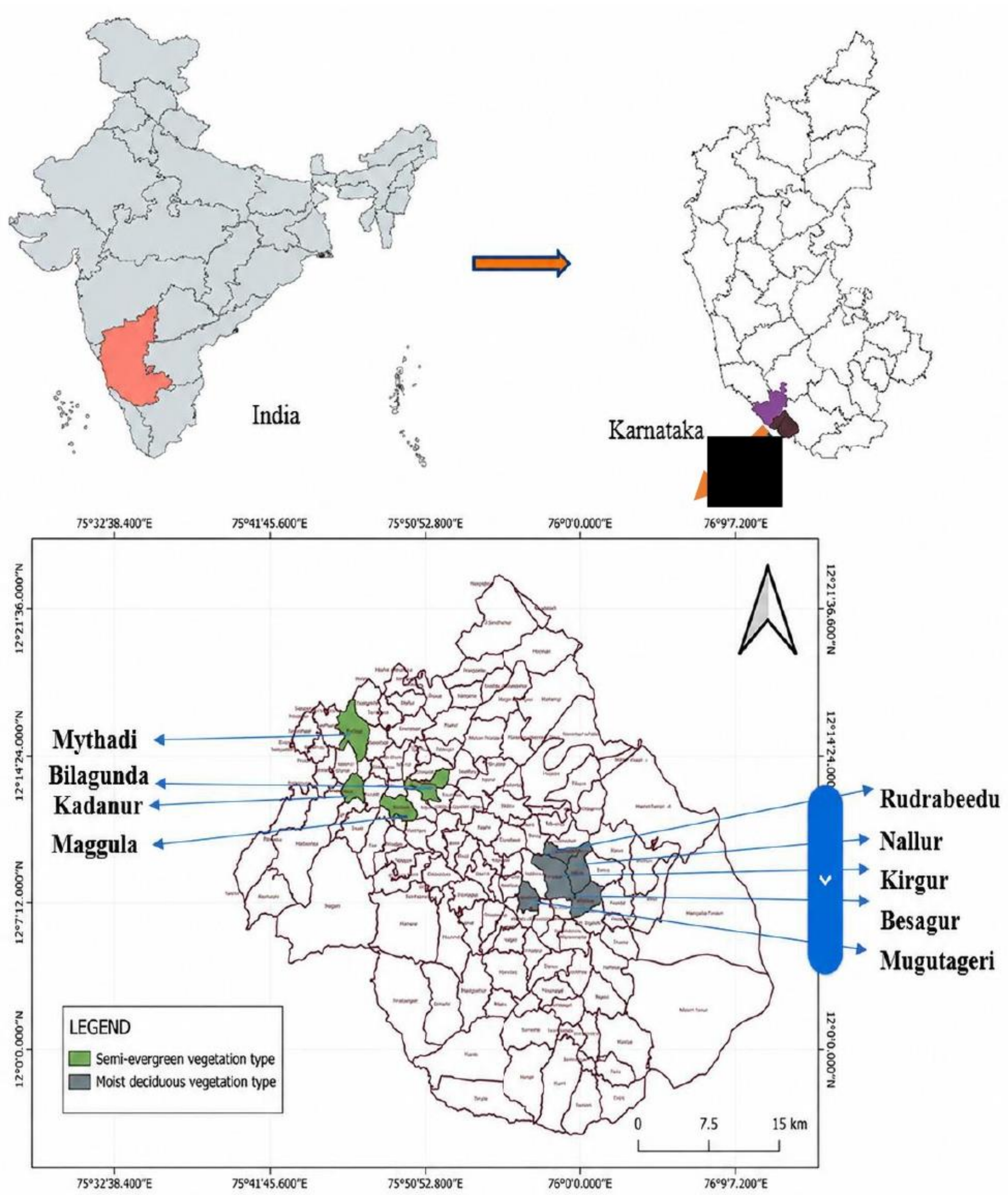


Fig. 1 Map of the study area

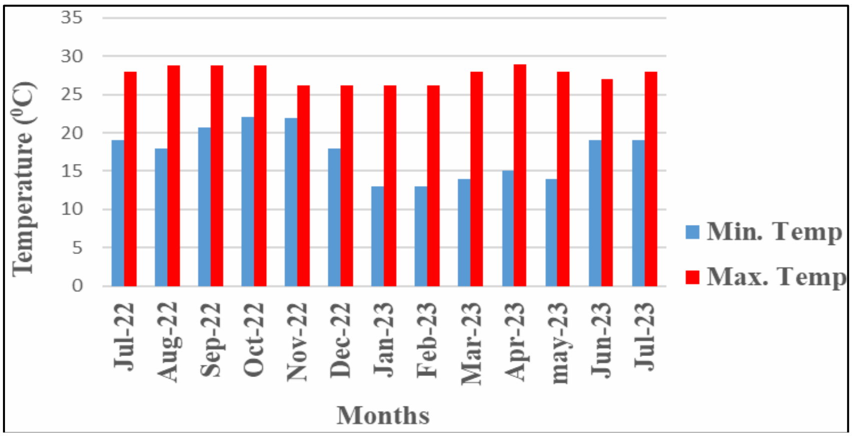


Fig. 2a. Mean monthly maximum and minimum temperature during the study period in sacred groves of semi-evergreen vegetation

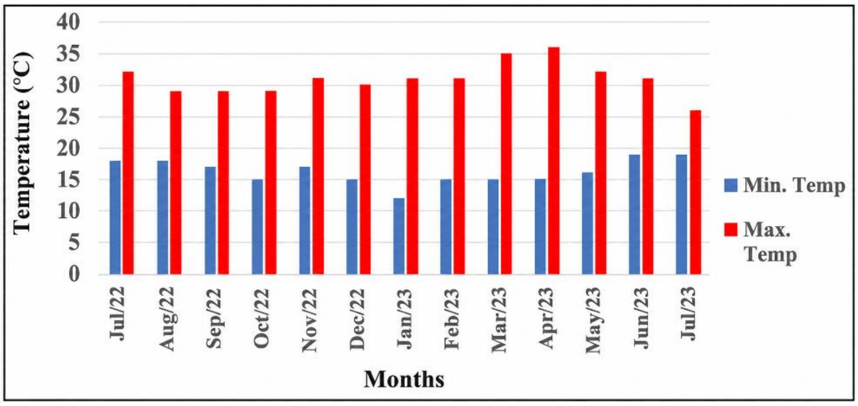
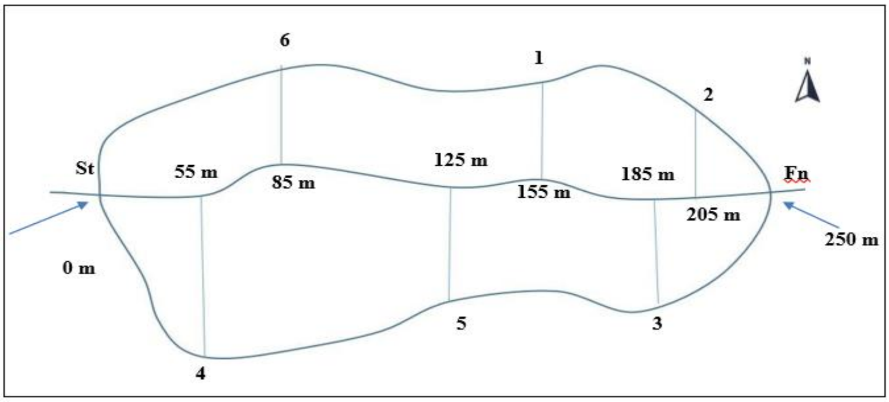


Fig. 2b. Mean monthly maximum and minimum temperature during the study period in sacred groves of moist deciduous vegetation



Legend:

- St, Fn – Start & Finish of the base line
- 55, ... 205m – Distance in meters of random point from starting point
- 1,6 – Transect numbers in sequence ofmeasurement

Fig. 3. Sampling design: Sampling locality with a baseline running across the patch and framework of transects placed at random points along the baseline, on a randomly chosen side

2.4 Statistical Analysis

Differences in species richness, density, and basal area between vegetation types and grove size classes were analysed using Student's t-test. Girth class distributions were compared using the Kolmogorov–Smirnov two-sample test (Ludwig & Reynolds, 1988). All statistical analyses were performed using Microsoft Excel (2016) and Biodiversity Pro (Version 2).

3. Results

3.1 Diversity Attributes across Vegetation Types

Pooled analysis of large and small sacred groves revealed higher overall tree species richness in semi-evergreen vegetation (143 species) compared to moist deciduous vegetation (130 species). However, mean species richness did not differ significantly between semi-evergreen (53.30 ± 3.61) and moist deciduous groves (53.11 ± 3.41). Tree species diversity, measured using the Shannon–Wiener index, was marginally higher in semi-evergreen groves ($H' = 3.91$) than in moist deciduous groves ($H' = 3.85$). Species evenness was identical (0.79) in both vegetation types, indicating a comparable and equitable distribution of individuals among species (Table 1).

Rare, endangered and threatened tree species richness was higher in semi-evergreen groves (17 species) than in moist deciduous groves (11 species). RET species accounted for 11.89 per cent of total tree richness in semi-evergreen groves and 8.46 per cent in moist deciduous groves. Mean RET species richness did not differ significantly between vegetation types (8.30 ± 0.81 in semi-evergreen and 6.56 ± 0.56 in moist deciduous groves). RET tree diversity was higher in semi-evergreen groves ($H' = 2.22$) than in moist deciduous groves ($H' = 1.90$), while evenness values were comparable (0.78–0.79) (Table 1).

3.2 Diversity Attributes across Grove Size Classes

In semi-evergreen vegetation, large groves supported higher tree species richness (120 species) than small groves (91 species), with mean richness significantly greater in large groves (61.20 ± 4.27) compared to small groves (45.40 ± 3.00). Tree species diversity was also higher in large groves ($H' = 3.95$) than in small groves ($H' = 3.70$), whereas evenness remained similar (0.82–0.83). RET tree richness was slightly higher in large groves (14 species) than in small groves (13 species), although mean richness did not differ significantly (Table 1). RET diversity was higher in large groves ($H' = 2.22$), while the proportional contribution of RET species was greater in small groves (14.29%) than in large groves (11.67%).

In moist deciduous vegetation, large groves supported higher tree species richness (113 species) than small groves (81 species), with significantly greater mean richness in large groves (59.80 ± 3.89) compared to small groves (44.75 ± 1.60). Tree species diversity was higher in large groves ($H' = 3.87$) than in small groves ($H' = 3.56$), with minimal variation in evenness (0.81–0.82). RET tree richness was higher in large groves (11 species) than in small groves (8 species), though mean richness was not significantly different (Table 1). RET diversity and evenness were marginally higher in large groves ($H' = 1.89$; $E = 0.79$), while the relative contribution of RET species was slightly higher in small groves (9.87%).

3.3 β-Diversity (Species Similarity)

Species composition exhibited high similarity between large and small groves of semi-evergreen vegetation (72.70%), indicating strong floristic overlap. Lower similarity (60.49%) was observed between large groves of semi-evergreen and moist deciduous vegetation. RET tree species showed the highest similarity between large and small semi-evergreen groves (73.18%), while the lowest similarity (55.30%) occurred between large semi-evergreen and small moist deciduous groves (Table 2).

3.4 Structural Attributes

Mean tree density did not differ significantly between semi-evergreen (1316.62 ± 338.06 stems ha^{-1}) and moist deciduous groves (1280.17 ± 225.58 stems ha^{-1}). Similarly, RET tree density was comparable between semi-evergreen (443.57 ± 143.04 stems ha^{-1}) and moist deciduous groves (423.27 ± 141.04 stems ha^{-1}). Mean basal area of both total trees and RET trees did not differ significantly between vegetation types, indicating broadly similar stand structure. Large groves consistently exhibited significantly higher tree density and basal area than small groves across both vegetation types. A similar trend was observed for RET tree density, although basal area of RET trees did not differ significantly between grove size classes, underscoring the structural importance of larger sacred groves in maintaining mature forest characteristics. Within semi-evergreen vegetation, significant differences were observed between large and small forest patches. Large groves recorded significantly greater tree density (1899.45 ± 110.09 individuals ha^{-1}) and basal area (116.88 ± 28.03 m^2 ha^{-1}) than small groves (660.89 ± 158.45 individuals ha^{-1} and 28.99 ± 7.57 m^2 ha^{-1}, respectively). Likewise, RET tree density was substantially higher in large groves (768.27 ± 195.34 individuals ha^{-1}) compared to small groves (118.87 ± 34.67 individuals ha^{-1}).

In moist deciduous vegetation, large forest groves exhibited significantly higher tree density (2045.99 ± 324.00 individuals ha^{-1}) and basal area (110.99 ± 20.74 m^2 ha^{-1}) compared to small groves (404.90 ± 109.56 individuals ha^{-1} and 12.86 ± 2.22 m^2 ha^{-1}, respectively). RET tree density and basal area were also markedly greater in large groves (713.37 ± 155.27 individuals ha^{-1} and 41.49 ± 13.65 m^2 ha^{-1}) than in small groves (60.65 ± 16.51 individuals ha^{-1} and 5.86 ± 1.59 m^2 ha^{-1}). Large forest groves supported greater tree abundance and higher RET tree populations, emphasising their ecological importance for biodiversity conservation and long-term persistence of threatened tree species (Table 3).

Table 1. Tree diversity among different vegetation types and sizes of sacred groves

Sl No	Diversity parameter	Vegetation type		Semi-evergreen		Moist- deciduous	
		Semi-evergreen	Moist- deciduous	Large	Small	Large	Small
01	Species richness of trees	143	130	120	91	113	81
02	Richness of tree species	53.30 ± 3.61	53.11 ± 3.41	61.20 ± 4.27	45.40 ± 3.00	59.80 ± 3.89	44.75 ± 1.60
03	Shannon's index of trees (*H'*)	3.91	3.85	3.95	3.70	3.87	3.56
04	Evenness index of tree species	0.79	0.79	0.83	0.82	0.82	0.81
05	Species richness of RET trees	17	11	14	13	11	8
06	Percentage of RET tree species	11.89	8.46	11.67	14.29	9.73	9.87
07	Shannon's index of RET tree species (*H'*)	2.22	1.90	2.22	2.02	1.89	1.62
08	Evenness index of RET tree species	0.78	0.79	0.84	0.79	0.79	0.78
09	Richness of RET trees	8.30 ± 0.81	6.56 ± 0.56	9.60 ± 0.81	7.00 ± 1.22	7.40 ± 0.40	5.50 ± 0.96

*(± SEm - Standard error of mean, RET - Rare, Endangered and Threatened trees, * Significant at 0.05 % level and .95 % confidence interval, ** Significant at 0.01% level and 99% confidence interval)*

Table 2. Similarity of tree species (Above half) and RET trees (Below half) in sacred groves of Kodagu

	Semi-evergreen Large	Semi-evergreen Small	Moist deciduous Large	Moist deciduous Small
Semi-evergreen Large	*	72.70	60.49	61.99
Semi-evergreen Small	73.18	*	61.29	60.81
Moist deciduous Large	68.03	69.29	*	65.30
Moist deciduous Small	55.30	65.87	68.87	*

Table 3. Comparison of density and basal area of trees and RET trees

Vegetation		Density of trees	Basal area of trees	Density of RET Species	Basal area RET Species
Vegetation type	Semi-evergreen	1316.62 ± 338.06	72.94 ± 20.05	443.57 ± 143.04	36.73 ± 8.94
	Moist deciduous	1280.17 ± 225.58	67.38 ± 20.43	423.27 ± 141.04	25.65 ± 9.56
	t-value	0.09	0.19	0.10	0.85
	*p-value	0.93	0.85	0.92	0.41
Semi-evergreen	Large	1899.45 ±110.09	116.88± 28.03	768.27± 195.34	45.48±16.19
	Small	660.89 ± 158.45	28.99 ±7.57	118.87±34.67	27.97± 7.68
	t-value	6.42	3.02	3.27	0.98
	*p-value	0.002	0.03	0.03	0.37
Moist deciduous	Large	2045.99 ± 324.00	110.99 ±20.74	713.37±155.27	41.49±13.65
	Small	404.90±109.56	12.86± 2.22	60.65 ±16.51	5.86±1.59
	t-value	4.80	4.70	4.18	2.59
	*p-value	0.05	0.01	0.01	0.06

*(SEm - Standard error of mean, RET - Rare, Endangered and Threatened trees, * Significant at 0.05 % level and .95 % confidence interval, ** Significant at 0.01% level and 99% confidence interval)*

3.5 Girth Class Distribution

Girth class distribution was similar across vegetation types and grove sizes, with a predominance of individuals in lower girth classes (0–0.3 m), forming an inverse 'J'-shaped curve indicative of healthy regeneration. RET tree species followed a comparable pattern, with higher representation in lower to mid-girth classes, suggesting stable recruitment and population persistence (Fig. 4).

3.6 Regeneration Status

Regeneration was observed across all life forms. The comparison of species richness and density of regenerates between semi-evergreen and moist deciduous vegetation indicated variations across life forms, although most parameters did not differ significantly. Shrub regeneration differed significantly between vegetation types, while climbers, shrubs and trees were more abundant in moist deciduous groves. Among climbers, moist deciduous vegetation recorded comparatively higher species richness (3.66 ± 0.71) and density (4184.02 ± 855.92 individuals ha^{-1}) than semi-evergreen vegetation (3.00 ± 0.33 and 2367.93 ± 637.83 individuals ha^{-1}, respectively). However, these differences were not statistically significant ($p > 0.05$). Shrub species richness was significantly higher in moist deciduous vegetation (10.88 ± 1.23) than in semi-evergreen vegetation (7.60 ± 0.47) ($t = 2.59$, $p = 0.01$). Nevertheless, shrub density did not vary significantly between vegetation types, although moist deciduous vegetation recorded comparatively greater density (10401.59 ± 2802.50 individuals ha^{-1}) than semi-evergreen vegetation (8571.48 ± 1190.70 individuals ha^{-1}) (Table 4). Tree regenerates had the highest species richness among all life forms, with moist deciduous vegetation showing slightly greater richness (26.00 ± 2.56) than semi-evergreen vegetation (23.70 ± 1.35). In contrast, tree regeneration density was marginally higher in semi-evergreen vegetation (18064.10 ± 2641.80 individuals ha^{-1}) than in moist deciduous vegetation (16418.05 ± 1952.00 individuals ha^{-1}). However, these differences were not statistically significant. RET tree regenerates showed relatively higher species richness (4.70 ± 0.56) and density (3555.96 ± 894.85 individuals ha^{-1}) in semi-evergreen vegetation than in moist deciduous vegetation (3.88 ± 0.48 and 734.29 ± 414.60 individuals ha^{-1}, respectively).

The Shannon diversity index of regenerates revealed moderate to high diversity across life forms, with trees exhibiting the highest diversity values in both vegetation types. Tree regenerates recorded the highest diversity index in moist deciduous vegetation (3.66), followed closely by that in semi-evergreen vegetation (3.53), indicating a highly diverse and evenly distributed tree regeneration pattern. Among shrubs, diversity was relatively high and comparable between semi-evergreen (2.19) and moist deciduous vegetation (2.13), reflecting a stable shrub community structure. Herb diversity was higher in moist deciduous vegetation (1.16) than in semi-evergreen vegetation (0.83), while climbers also exhibited greater diversity in moist deciduous vegetation (0.66) compared to semi-evergreen vegetation (0.47). RET tree regenerates showed higher diversity in semi-evergreen vegetation (1.75) than in moist deciduous vegetation (1.37), indicating relatively greater heterogeneity and distribution of threatened tree species in semi-evergreen sacred groves (Table 5). At the grove-size level, large groves generally exhibited higher diversity values than small groves across vegetation types. In semi-evergreen vegetation, large groves recorded higher diversity of shrubs (2.23), trees (3.55), and RET trees (1.91) than small groves. Similarly, in moist deciduous vegetation, large groves exhibited greater diversity of climbers (0.78), herbs (1.44), trees (3.63), and RET trees (1.44) than small groves. This suggests that larger groves support more diverse regenerative communities due to greater habitat heterogeneity and lower ecological disturbance (Table 5).

Tree Species **RET Species**

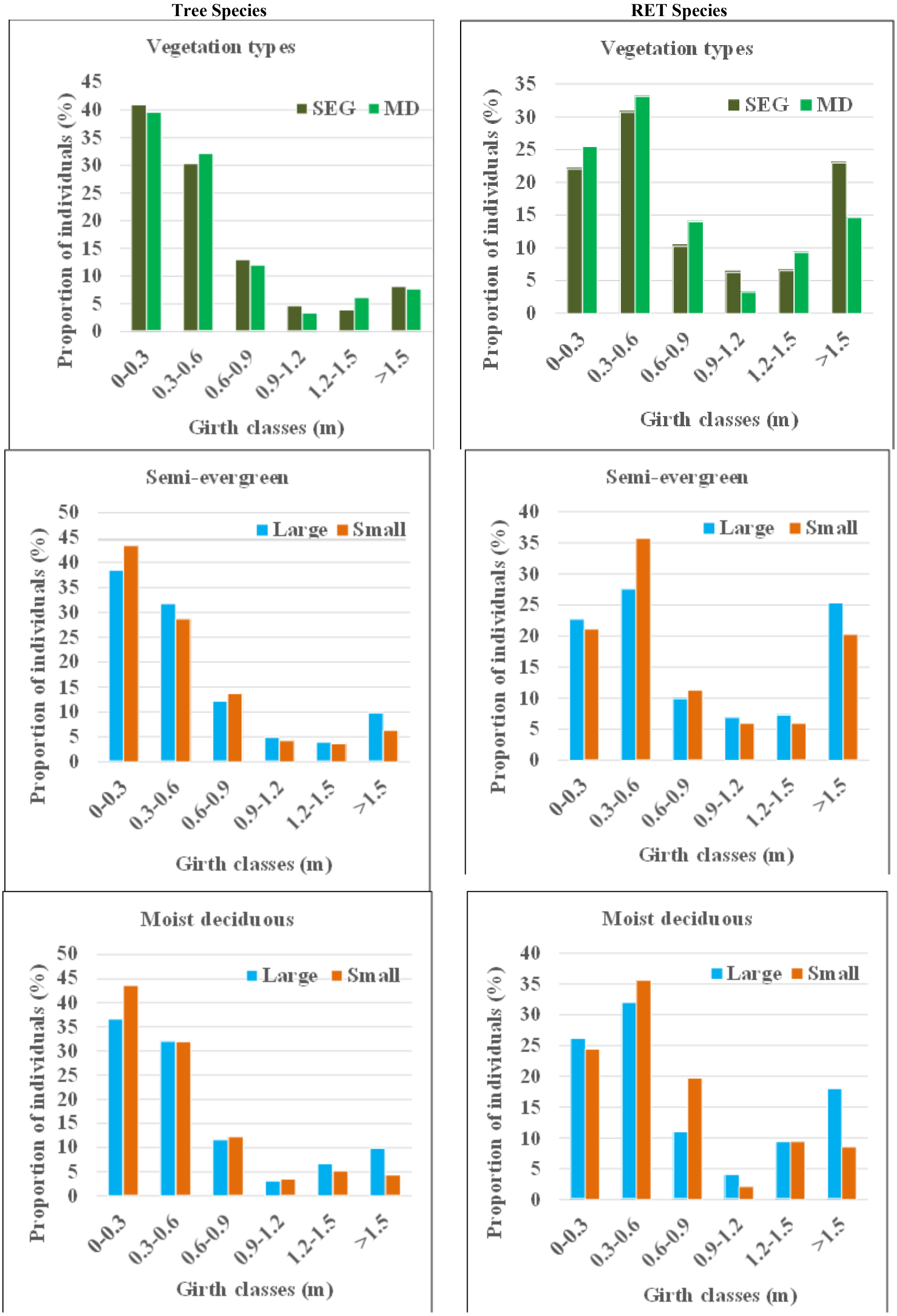


Fig. 4. Girth class distribution of Tree and RET trees in sacred groves (SEG- Semi-evergreen, MD- Moist deciduous vegetation and RET - Rare, Endangered and threatened trees)

3.7 Density and Species Richness of Regenerates in Large and Small Groves

Within semi-evergreen vegetation, tree regenerates exhibited significantly greater species richness in large groves (26.80 ± 1.39) than in small groves (20.60 ± 1.21)) ($p = 0.01$). Similarly, RET tree species richness was significantly higher in large groves (5.80 ± 0.73) than in small groves (3.60 ± 0.51) ($p = 0.04$). However, the density of regenerates across life forms did not vary significantly between large and small groves, although tree and RET tree densities were comparatively higher in large groves (Table 6).

In moist deciduous vegetation, climber species richness was significantly greater in large groves (5.00 ± 0.84) than in small groves (2.00 ± 0.41) ($p = 0.02$). Shrub density was significantly higher in small groves (16203.12 ± 4861.67 individuals ha^{-1}) than in large groves (5760.36 ± 1405.79 individuals ha^{-1}) ($p = 0.04$), indicating shrub dominance in smaller patches. No significant differences were observed for herbs, tree regenerates, or RET tree richness and density between grove sizes ($p > 0.05$) (Table 6).

4. Discussion

4.1 Species Richness and Diversity between Vegetation Types

Understanding changes in species composition is one of the primary objectives of forest ecology, as it helps infer past ecological conditions and predict future forest dynamics (Read et al., 1995). Tree species richness forms an essential component of tropical forest biodiversity because trees provide habitat, food, and ecological support to numerous life forms. The present study recorded higher tree species richness in semi-evergreen sacred groves (143 species) than moist deciduous groves (130 species). The greater richness in semi-evergreen vegetation may be attributed to relatively stable environmental conditions, higher habitat heterogeneity, favourable microclimates, and lower anthropogenic disturbances that collectively support species coexistence. Differences in geographical setting, disturbance regimes, climatic variability, and habitat fragmentation could also explain variations in species richness between vegetation types (Pradhan et al., 2019). Similar observations were reported by Prasad and Bharathi (2016), who documented 132 tree species in the sacred groves of Virajpet taluk, Kodagu district. Likewise, Biradar (2021) reported 145 tree species in the sacred Kaans of Soraba taluk in the Central Western Ghats of Karnataka.

The present investigation further revealed slightly higher tree species diversity in semi-evergreen sacred groves (Shannon's index: 3.91) compared to moist deciduous groves (3.85), indicating greater heterogeneity in species composition. Semi-evergreen forests generally support diverse ecological niches, favourable moisture conditions, and reduced environmental fluctuations, thereby facilitating species persistence and diversity. Similar diversity values ranging from 3.02 to 3.63 were reported by Prasad and Bharathi (2016) in sacred groves of Virajpet taluk. However, Kanade et al. (2008) reported contrasting findings, observing higher Shannon's diversity in moist deciduous forests (3.2) than in evergreen forests (3.1) in Chandoli National Park, Maharashtra. According to Condit et al. (2006), tropical forests maintain high diversity through varied demographic niches characterised by differential growth and mortality rates among species. The evenness index remained similar (0.79) in both semi-evergreen and moist deciduous sacred groves, indicating an equitable distribution of individuals among species and reduced dominance by a few taxa. The findings align with Pradhan et al. (2019), who reported evenness values ranging between 0.72 and 0.84 in sacred forests. Similarly, Maheswarappa (2019) observed higher evenness in sacred groves (0.97) compared to coffee plantations (0.77), emphasising the ecological stability of sacred forests.

Table 4. Plant species richness of regenerates in semi-evergreen and moist deciduous vegetation

Life forms	Species richness				Density (Individuals ha^{-1})			
	Semi-evergreen	Moist deciduous	t value	P value	Semi-evergreen	Moist deciduous	t value	p-value
Climbers	3.00 ± 0.33	3.66 ± 0.71	0.88	0.39	2367.93 ± 637.83	4184.02 ± 855.92	1.72	0.10
Herbs	1.40 ± 0.16	1.22 ± 0.28	0.56	0.57	1988.61 ± 733.08	696.68 ± 377.60	1.51	0.14
Shrubs	7.60 ± 0.47	10.88 ± 1.23	2.59	0.01*	8571.48 ± 1190.70	10401.59 ± 2802.50	0.62	0.54
Trees	23.70 ± 1.35	26.00 ± 2.56	0.81	0.42	18064.10 ± 2641.80	16418.05 ± 1952.00	0.49	0.62
RET Tree	4.70 ± 0.56	3.88 ± 0.48	1.08	0.29	3555.96 ± 894.85	734.29 ± 414.60	0.32	0.74

*(± SEm - Standard error of mean, RET - Rare, Endangered and Threatened trees, * Significant at 0.05 % level and .95 % confidence interval, ** Significant at 0.01% level and 99% confidence interval)*

Table 5. Shannon's diversity index of regenerates in sacred groves

Life forms	Semi- evergreen	Moist deciduous	SEG Large	SEG Small	MD Large	MD Small
Climbers	0.47	0.66	0.21	0.66	0.78	0.39
Herbs	0.83	1.16	1.09	0.37	1.44	0.35
Shrubs	2.19	2.13	2.23	1.94	2.11	1.88
Trees	3.53	3.66	3.55	3.35	3.63	3.37
RET trees	1.75	1.37	1.91	1.36	1.44	1.17

SEG – Semi-evergreen vegetation, MD – Moist deciduous vegetation

Sacred groves are well recognised for harbouring endemic, rare, endangered and threatened (RET) species due to traditional conservation practices and reduced disturbances (Prasad & Thomas, 2021). The present study recorded greater RET tree species richness in semi-evergreen groves (17 species), constituting 11.89 per cent of the total tree species, compared to moist deciduous vegetation. This higher representation of RET species may result from favourable microclimatic conditions, habitat continuity, and lower anthropogenic pressure in semi-evergreen forests. Biradar (2021) similarly reported 8.4 per cent RET species in sacred Kaans of Soraba taluk. Vijay (2006) also documented higher RET richness (17 species) and diversity in semi-evergreen sacred groves than in moist deciduous groves, suggesting that vegetation type strongly influences the persistence of threatened tree species.

Table 6. Density of regenerates in large and small groves of semi-evergreen and moist deciduous vegetation

Vegetation types	Life forms	Density (Individuals ha^{-1})				Species richness			
		Large	Small	t value	*p- value	Large	Small	t value	*p- value
Semi-evergreen	Climbers	3001.48 ± 981.91	1734.37 ± 816.92	0.99	0.35	3.20 ± 0.37	2.80 ± 0.58	0.57	0.58
	Herbs	1666.86 ± 799.98	2310.36 ± 1314.01	0.418	0.69	1.60 ± 0.24	1.20 ± 0.20	1.26	0.24
	Shrubs	7914.34 ± 1882.49	9228.63 ± 1618.72	0.52	0.61	7.20 ± 0.58	5.60 ± 0.75	1.68	0.13
	Trees	19560.62 ± 5153.69	16567.57 ± 1930.22	0.54	0.60	26.80 ± 1.39	20.60 ± 1.21	3.36	0.01*
	RET trees	4449.79 ± 1728.18	2662.12 ± 466.20	0.99	0.34	5.80 ± 0.73	3.60 ± 0.51	2.46	0.04*
Moist deciduous	Climbers	4593.75 ± 1068.16	3671.87 ± 1528.60	0.51	0.62	5.00 ± 0.84	2.00 ± 0.41	2.95	0.02*
	Herbs	450.90 ± 141.10	1003.90 ± 875.06	0.70	0.50	1.60 ± 0.40	0.75 ± 0.25	1.68	0.13
	Shrubs	5760.36 ± 1405.79	16203.12 ± 4861.67	2.29	0.04*	7.60 ± 0.51	6.00 ± 0.82	1.73	0.12
	Trees	13741.03 ± 2219.61	19764.32 ± 2816.41	1.70	0.13	28.60 ± 3.93	22.75 ± 2.72	1.15	0.28
	RET trees	3079.96 ± 611.95	5011.72 ± 1385.60	1.37	0.21	4.20 ± 0.58	3.50 ± 0.87	0.69	0.51

*(SEm - Standard error of mean, RET - Rare, Endangered and Threatened trees, * Significant at 0.05 % level and 95 % confidence interval)*

The analysis of β-diversity revealed relatively lower similarity in overall tree species composition between semi-evergreen and moist deciduous vegetation, whereas similarity among RET tree species was comparatively higher. The lower similarity in overall tree composition may be attributed to differences in environmental conditions, disturbance regimes, moisture availability, and vegetation structure between the two vegetation types. Semi-evergreen groves supported greater tree richness, whereas moist deciduous groves experienced greater disturbance, leading to variation in species composition.

In contrast, higher similarity among RET species may result from the relatively lower number of RET species and their habitat specialisation. Factors such as niche specificity, dispersal limitation, habitat fragmentation, conservation practices, and historical ecological processes may collectively influence RET species distribution patterns. Similar findings were reported by Maheswarappa (2019), who observed greater similarity between sacred groves and coffee plantations than between natural forests and sacred groves, emphasising the role of habitat characteristics in determining species composition.

4.2 Species Richness and Diversity in Large and Small Groves of Semi-evergreen and Moist Deciduous Vegetation

Tree species richness varied considerably between grove size classes and vegetation types. Larger sacred groves consistently supported higher species richness than smaller groves, likely due to greater habitat area, reduced edge effects, and availability of diverse ecological niches. Bharathi and Prasad (2015) similarly reported higher species richness and evenness in larger sacred groves with moderate disturbance. Page et al. (2010) also established a positive relationship between species richness and habitat area.

In the present study, tree species richness ranged from 91 species in small semi-evergreen groves to 120 species in large groves, highlighting the ecological importance of grove size. However, RET tree species richness did not significantly differ between large and small groves in both vegetation types, indicating relatively similar rates of species accumulation and persistence. Similar findings were documented by Raghavendra (2003), who reported no significant differences in RET medicinal tree richness between grove sizes in Kodagu. Biradar (2021) further noted that larger and less disturbed Kaans supported more threatened species.

No major differences were observed in diversity and evenness indices between large and small semi-evergreen groves, possibly due to immigration of similar species and shared species pools under mild disturbance conditions. Interestingly, small groves recorded a slightly higher proportion of RET species than larger groves, suggesting that smaller sacred groves also contribute significantly to threatened species conservation. Boraiah et al. (2001) similarly observed that RET medicinal species constituted a small yet ecologically important proportion of sacred grove vegetation. In moist deciduous vegetation, larger groves recorded higher diversity values than smaller groves, likely due to lower disturbance and greater habitat heterogeneity. Similarly, RET diversity and evenness were comparatively higher in larger groves. Boraiah et al. (2001) and Tambat (2001) reported comparable trends, highlighting higher ecological stability and diversity in large, conserved sacred groves than in smaller disturbed patches.

The similarity of tree and RET tree species was highest between large and small semi-evergreen groves, reflecting the influence of the same vegetation type irrespective of grove size. Conversely, lower similarity was observed between semi-evergreen large groves and moist deciduous small groves, likely due to differences in vegetation composition, disturbance intensity, and ecological conditions. Smaller groves are more vulnerable to anthropogenic pressure, invasive species, and edge effects, leading to altered species composition. Boraiah et al. (2001) similarly reported wide variations in β-diversity among sacred groves, emphasising the unpredictable effects of disturbance on species sharing and composition.

5. Conclusion

The present study demonstrates that sacred groves of Kodagu continue to function as ecologically significant reservoirs of tree diversity and natural regeneration in the central Western Ghats. Semi-evergreen sacred groves supported greater overall tree richness, higher diversity of rare, endangered and threatened species, and better regeneration of threatened tree species than moist deciduous groves. While vegetation types exhibited comparable stand structure, larger sacred groves consistently maintained higher tree density, basal area, species richness, and regeneration diversity, emphasising the importance of grove size in sustaining ecological integrity. The inverse J-shaped girth-class distribution observed across all groves indicates a stable population structure and continuous recruitment, reflecting the effectiveness of traditional protection practices. The study highlights that both large and small sacred groves contribute to biodiversity conservation, although larger groves provide greater habitat heterogeneity and support the long-term persistence of threatened species. These findings reinforce the need to strengthen community-based conservation, prevent habitat degradation, and integrate sacred groves into regional biodiversity conservation strategies to ensure the continued protection of floristic diversity and ecosystem resilience in the Western Ghats.

6. Limitation

This assessment was confined to 19 sacred groves in Kodagu and therefore represents the sampled semi-evergreen and moist deciduous groves rather than all sacred groves of the Western Ghats. Tree structure was evaluated using individuals meeting the study's GBH inclusion criterion, while regeneration was assessed through subplots along the sampled transects. Accordingly, the findings should be interpreted within the spatial and sampling scope of the study. Broader comparisons across additional sacred groves and repeated assessments over time would strengthen understanding of variation in stand structure, diversity and regeneration.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests, non-financial interests, or personal relationships that could have appeared to influence the work reported in this paper.

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