

Article

Assessing Forest Structure and Composition along the Altitudinal Gradient in the State of Sikkim, Eastern Himalayas, India

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Abstract: Understanding the structure and composition of native forests is a prerequisite in developing an adaptive forest management plan for Himalayan forest ecosystems where climate change is rapid. However, basic information on forest structure and composition are still limited in many places of the Eastern Himalayas. In this study, we aimed to understand the diversity, structure, and composition of forests and their variations along an altitudinal gradient in Himalayan forests. The study was conducted in the Indian federal state of Sikkim, Eastern Himalayas. We carried out a comprehensive and comparative evaluation of species diversity, stand basal area, and stem density along the altitudinal gradient from 900 m a.s.l. to 3200 m a.s.l. We used stratified random sampling to survey eighty-three plots each 0.1 ha in forest communities that occurred along the altitudinal gradient: (a) lower (900–1700 m) altitude forest ($N = 24$), (b) mid (1700–2500 m) altitude forests ($N = 37$), and (c) higher (2500–3200 m) altitude forests ($N = 22$). We measured and identified all living trees with a >3 cm diameter at breast height in each plot. We counted 10,344 individual plants, representing 114 woody species belonging to 42 families and 75 genera. The family Fagaceae and its species *Lithocarpus pachyphyllus* (Kurz) Rehder. were reported as the most dominant forest trees with the highest Importance Value Index. The Shannon diversity index was recorded as being the highest for the low-altitude forests, whereas measures of structural diversity varied among forests along with altitude: the mid-altitude forests recorded the highest stem density and the high-altitude forests showed the highest mean stem DBH (diameter at 1.3 m height). One significant finding of our study was the disparity of the size class distribution among forests along the altitudinal gradient. Overall, we found a reverse J-shape distribution of tree diameter signifying the uneven-agedness. However, we showed, for the first time, a complete lack of large trees (>93 cm DBH) in the lower altitude forests. Our study highlights conservation concerns for the low-altitude forests that record high species diversity, although lacked large-diameter trees. We anticipate that our study will provide a comprehensive understanding of forest diversity, composition, and structure along the altitudinal gradient to design conservation and sustainable management strategies

Keywords: Eastern Himalaya; Sikkim; species diversity; size class distribution; uneven-aged forests

1. Introduction

1.1. Background

Quantitative assessment of the diversity, structure, and composition of forest trees are essential, not only to understand forest biodiversity and health but also for designing conservation strategies towards climate change [1], which is a significant threat to biodiversity in the Himalayas [2–5]. The Eastern Himalaya region is a confluence of multiple biogeographic origins such as the Indo–Malayan realm, Palearctic, and the Sino–Japanese region, and it is characterized by remarkable biodiversity of major ecological and global significance and represents one of the 34 global biodiversity hotspots [6,7]. It covers an extensive area of 524,190 sqkm, ranging from east of Nepal to northwest Yunnan Province in China, including the northeastern region of India [2]. The Himalayan forests stores abundant carbon in forest soil and vegetation, and thus, are of prime importance for the regional and global carbon cycles [8,9]. It supplies constant water and is the prime regulator of life [10]. Further, the forest-based biological resources are the chief source of livelihood for people living in the Himalayas [11]. Simultaneously, the Himalayas are one of the most fragile systems on earth [12], geologically young (45 million years), tectonically active, and highly susceptible to natural hazards [4]. Moreover, the Himalayas are reported as the prime site for changing climate [13], with forest vegetation notably vulnerable to climate change [14–16]. The degrading Himalayan forests not only affect the surrounding region but have global implications [17]. While the ecological fragility and the significance of Himalayan forests are much realized, basic knowledge on the structure and composition in Himalayan forests are still limited in many regions particularly in the remote eastern parts [16].

Forest trees are the dominant structural and functional component of the forest ecosystem [18]. Tree species diversity, size class distribution, stem density, and basal area are the essential attributes that describes a forest's ecosystem [19,20], and measuring these attributes are fundamental in designing conservation strategies. Species diversity is the most crucial descriptors, which not only captures information on species richness (number of species in a community) but the relative abundance of species in a forest. It also provides information on the rarity and the commonness of a species. The ability of species diversity to quantify forest composition has provided ecologist with the most prominent tool, often used as the scorecard to preserve and restore a forest. Likewise, the size class distribution of forest trees is the prime indicator of forest structure and dynamics, widely used to examine the forest's health, including regeneration [21]. Tree diameter is a statistically proven parameter to measure forest carbon stocks [22]. Furthermore, stem density and basal area are an excellent surrogate to estimate forest biomass and carbon [23,24]. A proper understanding of forest composition and structure allow foresters, national park rangers, and landowners to maximize forest ecosystem's goods and services by maintaining or conserving a desired structure and composition of the forest at stand and landscape level.

1.2. Past Studies in the Eastern Himalayas

Studies in the Eastern Himalayan forests outside of India were mainly carried out in Nepal [25,26], Bhutan [27–29], and China [30,31] to assess forest structure and composition. Within the Indian part of the Eastern Himalayas, studies were carried out in Arunachal Pradesh [32–34], Meghalaya [8,35,36], Darjeeling, West Bengal [37], and Assam [38,39]. The majority of these studies presented the structure and composition of different forests along altitudinal gradients with varying intensities of anthropogenic disturbance. However, we did not find similar studies from the Sikkim State of the Eastern Himalaya region in India. Studies on the forest of Sikkim have mostly been carried out as case studies with concentrated sampling on watershed [40], alpine forests [41,42], timberline forest [43], and trekking corridors [44], with narrow altitudinal range [42,43]. Albeit more recently, Acharya et al. [45] and Sharma et al. [46] performed research with samples from multiple locations but did not describe the composition and size class distribution of trees.

1.3. Aims of this Study

In this study, we aimed to fill the existing knowledge gap on the diversity, structure, and composition of forest tree species, using well-represented samples covering forests along the altitudinal gradient in Sikkim, a part of the Eastern Himalayas. Our study not only provides an overall assessment on the diversity, composition, and structure of forest tree communities but also evaluates how these attributes vary among forest communities which occur along the altitudinal gradient.

2. Materials and Methods

2.1. Study Area Description and Data Collection

Sikkim ($27^{\circ}07'$ to $28^{\circ}13'$ N and $88^{\circ}01'$ to $88^{\circ}92'$ E), a northeastern region of India, falls within the Eastern Himalayan biodiversity hotspot (Figure 1). It has a remarkable altitudinal gradient with only an area of 7096 km², ranging from 300 m a.s.l. to 8586 m a.s.l. with *Mount Kanchendzonga*—the third highest peak in the world. The complex topography and enormous altitude are characterized by 12 major vegetation types, from a tropical warm broad-leaved forest at the lowest altitude to alpine meadow at the highest altitude [47]. It has a subtropical to temperate climate, with annual rainfall between 2700 mm to 3200 mm, and the mean annual temperature (MAT) varies from 8.4 °C to 23.2 °C [48].

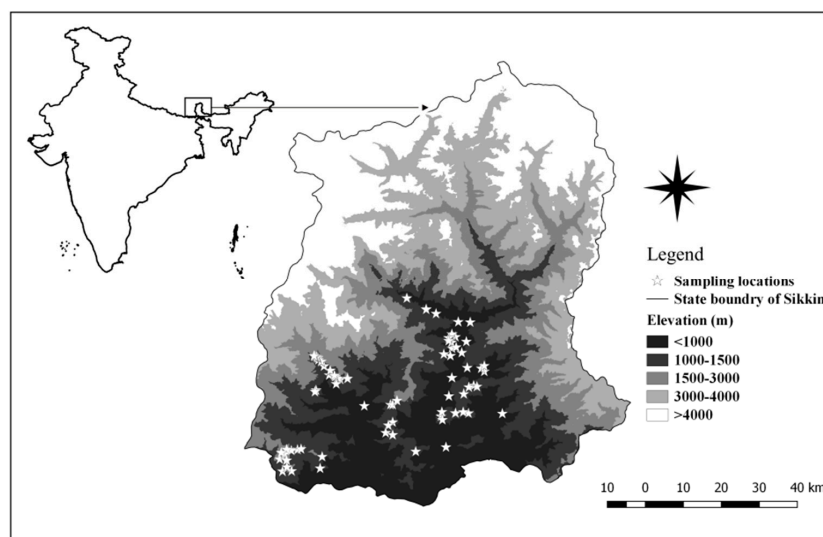


Figure 1. Study area with sampling locations along an altitude gradient in Sikkim, India.

The field study was conducted over 3 years (2013–2015), during the dry winter seasons from the beginning of October to late May to avoid challenges caused by understory growth of thick shrubs and herbs during the monsoon season. Stratified random sampling was used to sample plots along the altitudinal gradients, from 900 m a.s.l. to 3200 m a.s.l. The forests were selected because, forests within the range has undergone significant loss in forest cover [47]. Thus, quantitative assessment of these forests is imperative to plan conservation strategies. The forests were stratified into three altitudinal zones: low-altitude forest (LF), ranging from 900 m a.s.l. to 1700 m a.s.l., the mid-altitude forest (MF), ranging from 1700 m a.s.l. to 2500 m a.s.l., and the high-altitude forest (HF) ranging from 2500 m a.s.l. to 3200 m a.s.l. Plots were randomly installed at different locations for each altitude zone. Altogether, we installed 83 plots of 100 m × 10 m (each 0.1 ha), covering a total area of 8.3 ha. The number of plots varied across forests, and were distributed as LF = 24, MF = 37, and HF = 22 plots among three forest communities along the altitudinal gradient. Within each plot, all living woody trees with >3 cm diameter at breast height (DBH, or trunk diameter at 1.3 m above ground level) were measured and identified. Voucher specimens were collected for individuals challenging to identify in the field, and was used later for further identification.

2.2. Data Analysis

The analysis included quantitative data on the abundance, DBH, taxonomic, and geo-coordinate details for all sites. Prior to the quantification of forest attributes, we conducted cluster analysis and ordination to examine and validate the presence of ecologically meaningful clusters among our sampled plots designed for the study. First, we computed the Bray–Curtis distance matrix using the abundance data, with species in the columns and sites in ascending order of altitude in rows. Then, we performed hierarchical Ward’s minimum variance clustering on the Bray–Curtis distance matrix. This method is based on the least squares linear model criteria, and forms cluster with the least variance [49]. Secondly, we performed the Nonmetric multidimensional scaling method (NMDS), an indirect gradient analysis approach to ordinate our sampled sites using the same distance matrix. Nonmetric multidimensional scaling represents the pairwise dissimilarity among sites in a low dimensional space as closely as possible [49]. We also estimated the goodness of fit measured as “stress” from the Shepard diagram to evaluate the appropriateness of the NMDS result [49].

We plotted the species accumulation curve to determine the sampling effectiveness for the entire sample installed in our study. Further, we plotted sample-based rarefaction curve for different forest communities. It computes the average richness by randomly drawing 1,2,3,...n samples representing a community, without replacement [50]. The richness estimated from the sample-based rarefaction curves was also used to compare the richness for different forest communities with distinct sampling effort.

Shannon’s diversity index (H') was estimated by multiplying the proportion of each species to their natural log. Shannon Index ($H' = -\sum p_i \log(\ln)p_i$), where, p_i is the proportion (n/N) of individuals of a particular species found (n) divided by the total number of individuals recorded (N), \ln is the natural log, and Σ is the sum of the calculations.

Shannon diversity provides information on both species richness and relative abundance among plots, and thus are sensitive to the sampling effort or the number of individuals sampled. To avoid bias, we estimated other indices, namely, the rarefied richness for forest communities and compared richness among subsets using a fixed sample size. Further, we estimated the Fisher alpha, a parametric richness estimate, which compares richness among samples with varying individuals. Pielou’s J was also estimated to check for differences in evenness among communities with different sample size. Apart from these, we estimated observed species richness, genus richness, and family richness for the overall forest community and three forest communities along the altitudinal gradient.

Additionally, we estimated four essential stand structural parameters: the median DBH, stem density (ha^{-1}), basal area ($\text{m}^2 \text{ha}^{-1}$), and size class distribution of forest trees. We mostly used the median as a measure of central tendency because variables often did not follow a Gaussian distribution. We calculated the Important Values Index (IVI) both for species(SIVI) and families(FIVI). We followed the equations by Keel et al. [51] and Ganesh et al. [52] for IVI estimation. Diversity analysis, clustering, and ordination were conducted using the R package “vegan” and “BiodiversityR” V 2.9-2, and the built-in function “decostand”, “vegdist”, “hclust”, “ward.D2” and “metaNMDS” in R Studio (version 1.1383).

3. Results

3.1. Distinct Forest Communities along the Altitude Gradient from 900 m to 3200 m

The cluster analysis revealed that three forest communities could be formed based on the composition of tree species at different sites, although few plots deflected from its designated categories (Figure 2a). The NMDS result superimposed with a cluster dendrogram also showed similar groups (Figure 2b). The Shepard diagram and the goodness of fit also supported our result with high R^2 value (Figure 3). It can be stated that both the cluster analysis and NMDS suggested the presence of three ecologically meaningful forest communities along the altitudinal gradient with distinct species composition. These three forest communities corresponded to the altitudinal gradient, hence, reiterated the importance of altitude as a covariate to determine the composition of tree species in the Himalayas.

Based on the Species Importance Value Index and a proportion of stem density and basal area (see Table 3), all forests can be classified as mixed-broadleaf forests but with distinct communities at different altitudes. The lower altitude (LF) forests can be classified as the association of *Schima wallichii* Choisy., *Castanopsis tribuloides* Smith., *Engelhardtia spicata* Blume., and *Gynocardia odorata* R.Br. (Figure 4). The mid-altitude (MF) forests can be classified as the association of *Symplocos ramosissima* Wall. ex G. Don, *Castanopsis hystrix* Hook.f. & Thomson ex A.DC., *Viburnum erubescens* Wall., and *Quercus lamellosa* Sm. (Figure 5). Whereas, high-altitude (HF) forests can be classified as the association of *Lithocarpus pachyphyllus*, *Rhododendron arboreum* Sm., *Magnolia campbellii* Hook.f. & Thomson, and *Symplocos heishanensis* Hayata. (Figure 6).

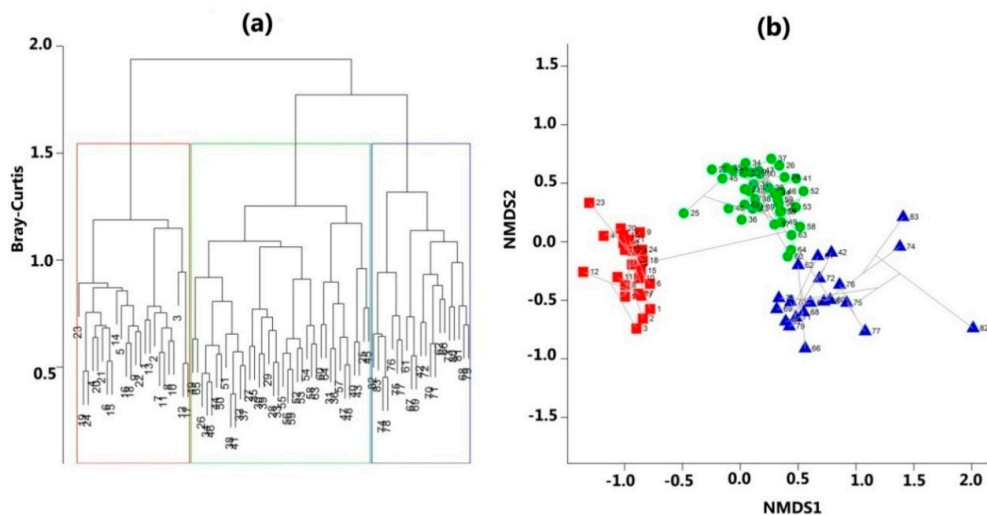


Figure 2. Hierarchically clustered dendrogram and Nonmetric multidimensional scaling (NMDS) ordination on the Bray–Curtis distance estimated using abundance data. (a) Hierarchical clustering was done using Ward’s algorithm, the y -axis represents the Bray–Curtis distance shared among each cluster; (b) NMDS ordination superimposed with the result of the cluster analysis, more similar plots are grouped closer to another. The red, green and blue dots and lines correspond to the low-altitude forest (LF), mid-altitude forest (MF), and high-altitude forest (HF), forest categories in our study.

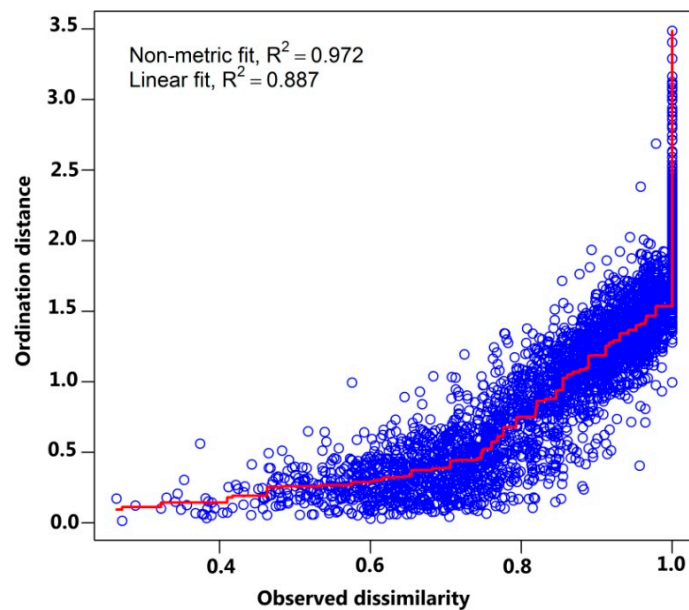


Figure 3. Shepard diagram with the goodness of fit (R^2) from the NMDS result presented in Figure 2.

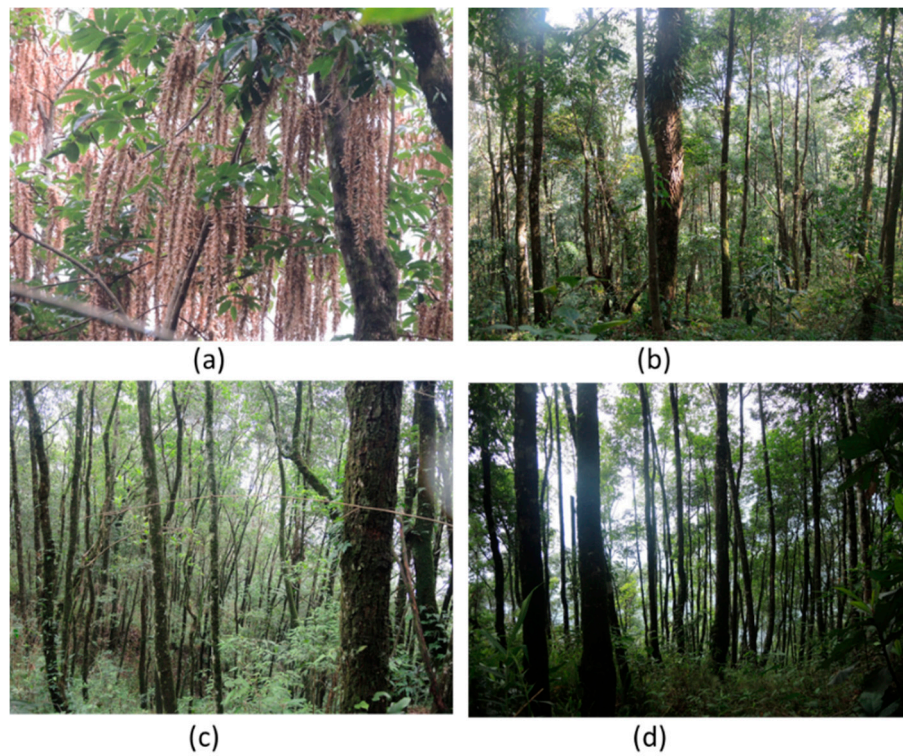


Figure 4. The low-altitude forest (LF): (a) *Engelhardtia spicata*, one of the dominant trees in flowering; (b) *Schima wallichii*, *Symplocos*, and *Castanopsis* mixed forest; (c–d) even sized *Castanopsis* and *Schima wallichii* trees recorded at 1400 m a.s.l.

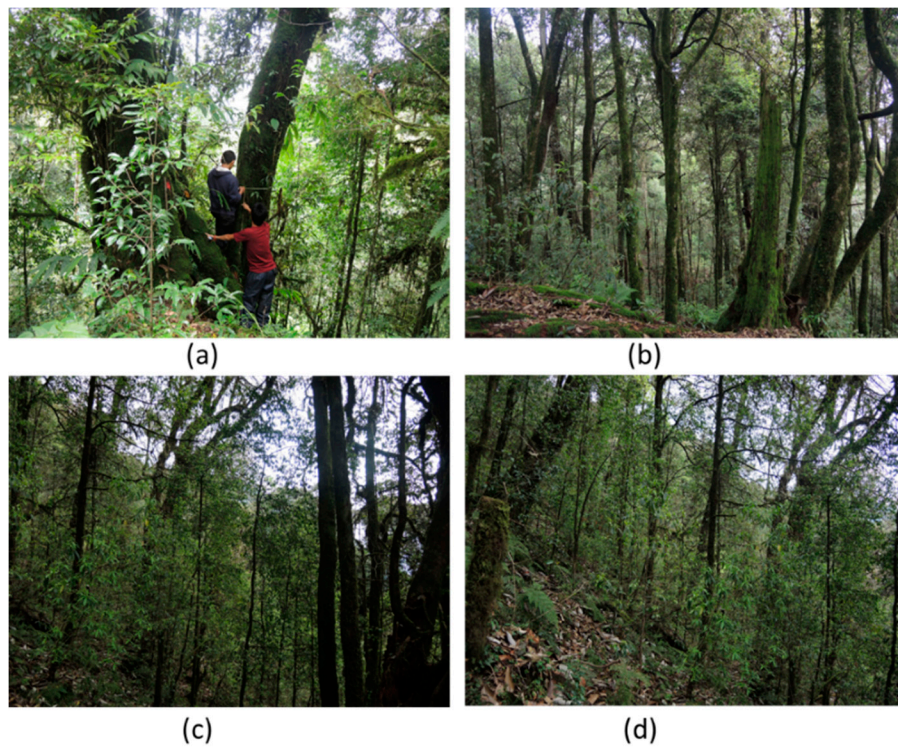


Figure 5. Mid-altitude forest (MF): (a) *Castanopsis hystrix* with 82cm DBH recorded at 2100 m a.s.l.; (b) forests dominated by *Castanopsis tribuloides* at 2000 m a.s.l.; (c–d) forests dominated by *Symplocos* species at 2300 m a.s.l.

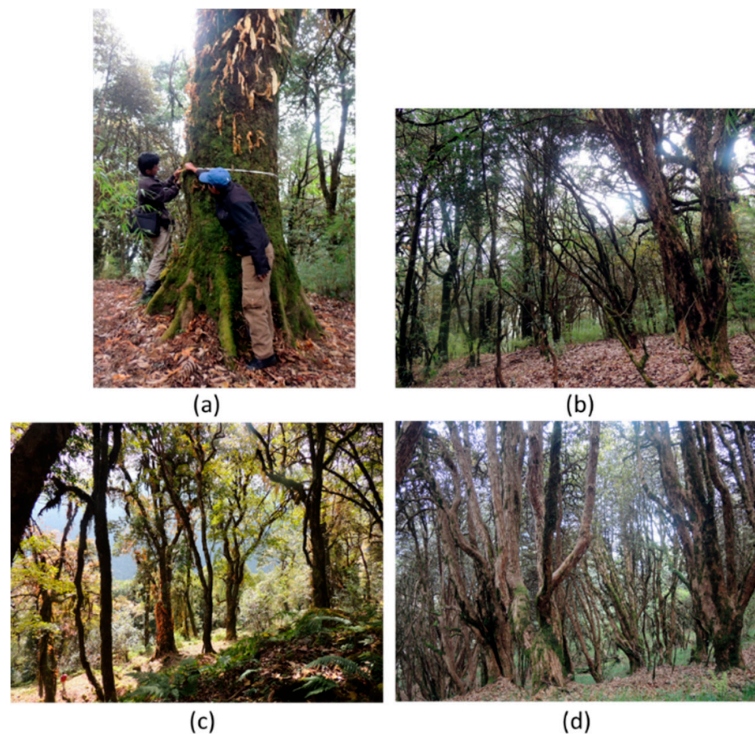


Figure 6. High altitude forest (HF): (a) *Lithocarpus pachyphyllus* with 110 cm DBH recorded at 2860 m a.s.l.; (b) *Lithocarpus pachyphyllus* and *Rhododendron* mixed forest 2875 m a.s.l.; (c) Open forest at 2792 m a.s.l., where *Lithocarpus pachyphyllus*, *Magnolia campbellii* and *Acer campbellii* Hoof.f.& Thomson ex Hiern., were reported as the major tree species; (d) a *Rhododendron* forest stand at 3200 m a.s.l.

3.2. Diversity and Composition of Tree Species in Three Forest Communities

Overall, the study recorded 10,344 individuals from 8.3 ha (83 sample plots of each 0.1 ha in size), including 87 unidentified individuals, with the observed richness of 114 species from 42 families and 75 genera (Table 1). The species accumulation curve for the entire tree community showed a gentle slope for the cumulative species richness after the sample size of 70 indicating an adequate number of plots (Figure 7a). However, for different forest communities, the species accumulation curve showed an increasing asymptote (Figure 7b). Nevertheless, the curve clearly recorded the highest species richness (77) for the MF, followed by LF (68) and HF(51). However, for the same sample size of 20, the LF recorded the highest average species richness of 65.36 (Figure 7b). The Shannon (H) diversity varied from 1.71 ± 0.40 to 2.10 ± 0.35 , with the highest value for the LF (Table 1), and the Pielou's evenness (J) varied from 0.46 ± 0.7 to 0.35 ± 0.10 , with the highest value for the LF (Table 1).

Tables 2 and 3 show the results for the Importance Value Index (IVI), estimated for both species (SIVI) and families (FIVI), along with species richness, families, stem density, basal area, their proportion to the contribution for the overall forest community, and different forest communities. We found *Lithocarpus pachyphyllus* (9.30%), *Symplocos ramosissima* (8.72%), *Castanopsis hystrix* (8.23%), *Castanopsis tribuloides* (4.99%), and *Schima wallichii* (4.46%) to be the five most important species with the highest Species Importance Value Index (SIVI). Similarly, we recorded Fagaceae (27.86%), Symplocaceae (12.26%), Theaceae (8.04%), Ericaceae (7.70%), and Lauraceae (6.62%), as the top five families. Lauraceae was also recorded as the most diverse family with 13 species (Table 2).

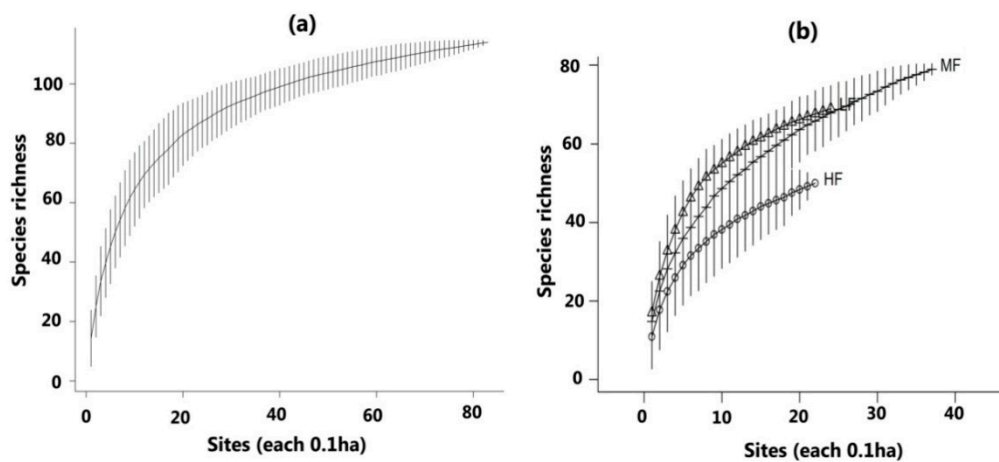


Figure 7. Species accumulation curve based on the rarefaction method: (a) whole tree population; (b) three forests: LF = low-altitude forest, MF = mid-altitude forest, HF = high-altitude forest.

Table 1. Richness, species diversity, stem densities, and basal area for different forest communities along an altitude gradient. The table provides the median and its standard error since richness showed a right-skewed distribution. LF = low-altitude forest, MF = mid-altitude forest, HF = high-altitude forest.

Parameters	ALL	LF	MF	HF
Altitude (m)	900–3200	900–1700	>1700–2500	>2500–3200
Total sampled area (ha)	8.3	2.4	3.7	2.2
Total species richness	114	68	77	51
Total genus richness	75	52	54	37
Total family richness	42	33	35	25
Median of species' richness \pm SE	14 \pm 4.34	16 \pm 4.43	14 \pm 3.04	10 \pm 4.50
Median of genus' richness \pm SE	12 \pm 3.96	15.50 \pm 4.06	12 \pm 2.72	10 \pm 3.51
Median of families' richness \pm SE	10 \pm 2.89	13 \pm 2.94	9 \pm 1.95	9 \pm 2.81
Total individual counted	10344	2591	5463	2290
Shannon index (H') \pm SD	1.87 \pm 0.44	2.10 \pm 0.35	1.71 \pm 0.40	1.78 \pm 0.48
Fisher's alpha richness	4.44 \pm 1.84	5.68 \pm 2.00	4.14 \pm 1.35	3.51 \pm 1.64
Pielou's evenness (J)	0.39 \pm 0.39	0.46 \pm 0.7	0.35 \pm 0.10	0.38 \pm 0.13
Dominant family	Fagaceae	Fagaceae	Fagaceae	Fagaceae
Dominant species	<i>Lithocarpus pachyphyllus</i>	<i>Schima wallichii</i>	<i>Symplocos ramosissima</i>	<i>Lithocarpus pachyphyllus</i>

Species such as *Schima wallichii* (18.90%), *Castanopsis tribuloides* (17.91%), *Engelhardtia spicata* (6.72%), *Gynocardia odorata* (6.05%), and *Eurya acuminata* (4.83%) were recorded as the five most dominant species with higher species Important Value Index (SIVI) for LF. Similarly, *Symplocos ramosissima* (15.09%), *Castanopsis hystrix* (14.99%), *Viburnum erubescens* (7.09%), *Quercus lamellosa* (6.85%) and *Eurya acuminata* (4.42%) were reported as the most dominant species for the MF. The HF was dominated by species such as *Lithocarpus pachyphyllus* (24.37%), *Rhododendron arboreum* (16.78%), *Magnolia campbellii* (4.54%), *Symplocos heishanensis* (4.14%), and *Symplocos ramosissima* (3.96%) with the highest SIVI (Table 3).

Table 2. Species richness, density, basal area, Species Importance Value Index (SIVI), Families Importance Value Index (FIVI), and their proportion to the contribution for the top ten species and families for the overall forest community recorded in the study.

Species	Family	Stem Density (ha ⁻¹)	Stem Density%	Basal Area (m ² ha ⁻¹)	Basal Area%	SIVI%
<i>Lithocarpus pachyphyllus</i>	Fagaceae	51.20	4.11	12.31	21.07	9.30
<i>Symplocos ramosissima</i>	Symplocaceae	248.07	19.19	1.61	2.76	8.72
<i>Castanopsis hystrix</i>	Fagaceae	62.05	4.98	9.91	16.97	8.23
<i>Castanopsis tribuloides</i>	Fagaceae	62.41	5.01	4.22	7.23	4.99
<i>Schima wallichii</i>	Theaceae	78.19	6.27	2.40	4.11	4.46
<i>Rhododendron arboreum</i>	Ericaceae	85.54	6.86	2.54	4.35	4.33
<i>Viburnum erubescens</i>	Adoxaceae	103.98	8.34	0.38	0.64	4.16
<i>Eurya acuminata</i> DC.	Pentaphylacaceae	60.96	4.89	0.81	1.39	3.91
<i>Quercus lamellosa</i>	Fagaceae	9.88	0.79	4.95	8.49	3.86
<i>Symplocos heishanensis</i>	Symplocaceae	49.40	3.96	0.38	0.65	2.93

Families	Richness	Stem Density (ha ⁻¹)	Stem Density%	Basal Area (m ² ha ⁻¹)	Basal Area%	FIVI%
Fagaceae	9	20.88	16.75	33.61	57.19	27.86
Symplocaceae	4	33.55	26.92	2.18	3.71	12.26
Theaceae	2	13.90	11.16	3.20	5.45	8.04
Ericaceae	7	14.76	11.84	3.81	6.48	7.70
Lauraceae	13	4.63	3.71	4.97	8.45	6.62
Adoxaceae	2	10.41	8.35	0.38	0.64	4.64
Magnoliaceae	4	1.12	0.90	2.09	3.64	2.70
Betulaceae	4	1.93	1.55	0.99	1.69	2.19
Primulaceae	3	2.28	1.83	0.41	0.23	2.10
Sapindaceae	1	0.69	0.55	1.23	2.10	1.89

Table 3. Stem density, basal area, Family (FIVI) and Species Importance Value Indexes (SIVI) and their proportion to the contribution of the ten dominant species for three forest communities: LF, MF, and HF.

Species	Family	Stem Density (ha ⁻¹)	Stem Density%	Basal Area (m ² ha ⁻¹)	Basal Area%	SIVI%
LF (900 m to 1700 m a.s.l.)						
<i>Schima wallichii</i>	Theaceae	259.17	24.01	7.08	26.73	18.90
<i>Castanopsis tribuloides</i>	Fagaceae	202.50	18.76	7.68	29.00	17.91
<i>Engelhardtia spicata</i>	Juglandaceae	60.42	5.60	2.35	8.86	6.72
<i>Gynocardia odorata</i>	Achariaceae	92.50	8.57	1.23	4.63	6.05
<i>Eurya acuminata</i>	Pentaphylacaceae	66.67	8.57	0.76	2.86	4.83
<i>Betula alnoides</i>	Betulaceae	21.25	6.18	0.99	3.75	2.57
Buch.-Ham.ex.D.Don						
<i>Macaranga denticulata</i>	Euphorbiaceae	18.08	1.97	0.39	1.48	2.43
Blume						
<i>Albizia lebbek</i> (L.) Benth.	Leguminosae	17.08	1.58	1.23	4.64	2.31
<i>Alnus nepalensis</i> D.Don	Betulaceae	12.08	0.66	1.00	3.77	2.21
<i>Brassaiopsis hispida</i> Seem.	Araliaceae	36.25	3.36	0.19	0.53	1.87

Families	Richness	Stem Density (ha ⁻¹)	Stem Density%	Basal Area (m ² ha ⁻¹)	Basal Area%	FIVI%
Theaceae	2	9.42	30.18	7.84	29.60	22.54
Fagaceae	6	6.73	21.57	8.23	31.09	20.17
Juglandaceae	3	1.80	5.75	2.38	8.99	7.42
Achariaceae	1	2.67	8.57	1.23	4.63	6.58
Betulaceae	3	1.04	3.32	2.09	7.89	5.26
Euphorbiaceae	5	1.23	3.94	0.59	2.22	4.34
Araliaceae	3	1.57	5.02	0.17	0.66	3.53
Leguminosae	3	0.30	0.96	1.27	4.80	2.90
Anacardiaceae	3	0.59	1.89	0.48	1.81	2.76
Lauraceae	6	0.63	2.01	0.09	0.35	2.64

Table 3. Cont.

Species	Family	Stem Density (ha ⁻¹)	Stem Density%	Basal Area (m ² ha ⁻¹)	Basal Area%	SIVI%
MF (>1700 m to 2500 m a.s.l.)						
<i>Symplocos ramosissima</i>	Symplocaceae	501.89	33.99	3.36	4.67	15.09
<i>Castanopsis hystrix</i>	Fagaceae	132.43	8.97	21.72	30.15	14.99
<i>Viburnum erubescens</i>	Adoxaceae	211.89	14.35	0.75	1.05	7.09
<i>Quercus lamellosa</i>	Fagaceae	20.54	1.39	10.67	14.81	6.85
<i>Eurya acuminata</i>	Pentaphragaceae	83.78	5.67	1.23	1.71	4.42
<i>Lithocarpus pachyphyllus</i>	Fagaceae	48.92	3.31	5.17	7.18	4.32
<i>Symplocos heishanensis</i>	Symplocaceae	73.78	5.00	0.56	0.78	4.07
<i>Castanopsis tribuloides</i>	Fagaceae	8.65	0.59	4.49	6.23	2.78
<i>Quercus glauca</i>	Fagaceae	14.32	0.97	3.09	4.29	2.70
<i>Elaeocarpus sikkimensis</i> Mast.	Elaeocarpaceae	10.54	0.71	2.21	3.07	2.52
Families	Richness	Stem Density (ha ⁻¹)	Stem Density%	Basal Area (m ² ha ⁻¹)	Basal Area%	FIVI%
Fagaceae	7	10.82	16.44	45.70	45.70	30.12
Symplocaceae	4	28.90	43.91	4.33	4.33	20.14
Lauraceae	11	3.08	4.69	9.60	9.60	9.22
Adoxaceae	2	9.46	14.37	0.75	0.75	8.07
Theaceae	2	3.95	6.00	1.71	1.71	5.73
Elaeocarpaceae	2	0.48	0.73	2.23	2.23	3.17
Ericaceae	5	2.49	3.79	0.49	0.49	2.72
Sapindaceae	1	0.40	0.60	1.50	1.50	2.60
Primulaceae	3	1.24	1.89	0.16	0.16	2.60
Magnoliaceae	4	0.59	0.90	1.75	1.75	2.43
Species	Family	Stem Density (ha ⁻¹)	Stem Density%	Basal Area (m ² ha ⁻¹)	Basal Area%	SIVI%
HF (2500 m to 3200 m a.s.l.)						
<i>Lithocarpus pachyphyllus</i>	Fagaceae	110.91	10.66	7.88	54.56	24.37
<i>Rhododendron arboreum</i>	Ericaceae	310.00	29.78	7.47	13.08	16.78
<i>Magnolia campbellii</i>	Magnoliaceae	16.82	1.62	5.39	6.62	4.54
<i>Symplocos heishanensis</i>	Symplocaceae	61.82	5.94	5.81	0.69	4.14
<i>Rhododendron hodgsonii</i> Hook.f.	Ericaceae	54.55	5.24	2.90	3.15	3.76
<i>Corylus ferox</i> Wall.	Betulaceae	26.82	2.58	4.15	1.33	2.68
<i>Viburnum erubescens</i> Wall.	Adoxaceae	35.91	3.45	4.15	0.21	2.60
<i>Acer campbellii</i>	Sapindaceae	10.91	1.05	3.73	2.98	2.59
<i>Rhododendron falconeri</i> Hook.f.	Ericaceae	39.55	3.80	2.07	1.86	2.58
Families	Richness	Stem Density (ha ⁻¹)	Stem Density%	Basal Area (m ² ha ⁻¹)	Basal Area%	FIVI%
Fagaceae	4	3.33	90.11	40.96	57.16	79.21
Ericaceae	7	11.82	29.63	13.47	18.79	72.16
Symplocaceae	3	4.64	2.07	0.94	1.31	26.02
Magnoliaceae	2	0.48	10.90	4.95	6.91	16.03
Lauraceae	6	0.92	5.51	2.51	3.50	15.24
Betulaceae	2	0.76	2.16	0.98	1.37	9.91
Theaceae	2	0.53	1.46	0.67	0.93	9.69
Berberidaceae	2	1.39	0.37	0.17	0.24	9.47
Adoxaceae	1	0.95	0.33	0.15	0.21	9.92
Sapindaceae	1	0.29	4.70	2.14	2.98	8.77

3.3. Forest Structure

Overall, we recorded the median stem DBH of 15.42 ± 1.11 cm, stem density of 1246.27 ± 568.28 ha⁻¹, and the basal area of 54.35 ± 4.44 m² ha⁻¹ (Figure 8). Among forest communities, the HF recorded the highest median stem DBH (20.89 ± 3.09 cm) but showed the lowest stem density. Similarly, MF recorded the highest stem density of about 1320 ± 119.72 ha⁻¹, with the second highest

value for the stem DBH and basal area. However, the LF recorded the second highest value for median stem density and the minimum value for the median DBH and basal area.

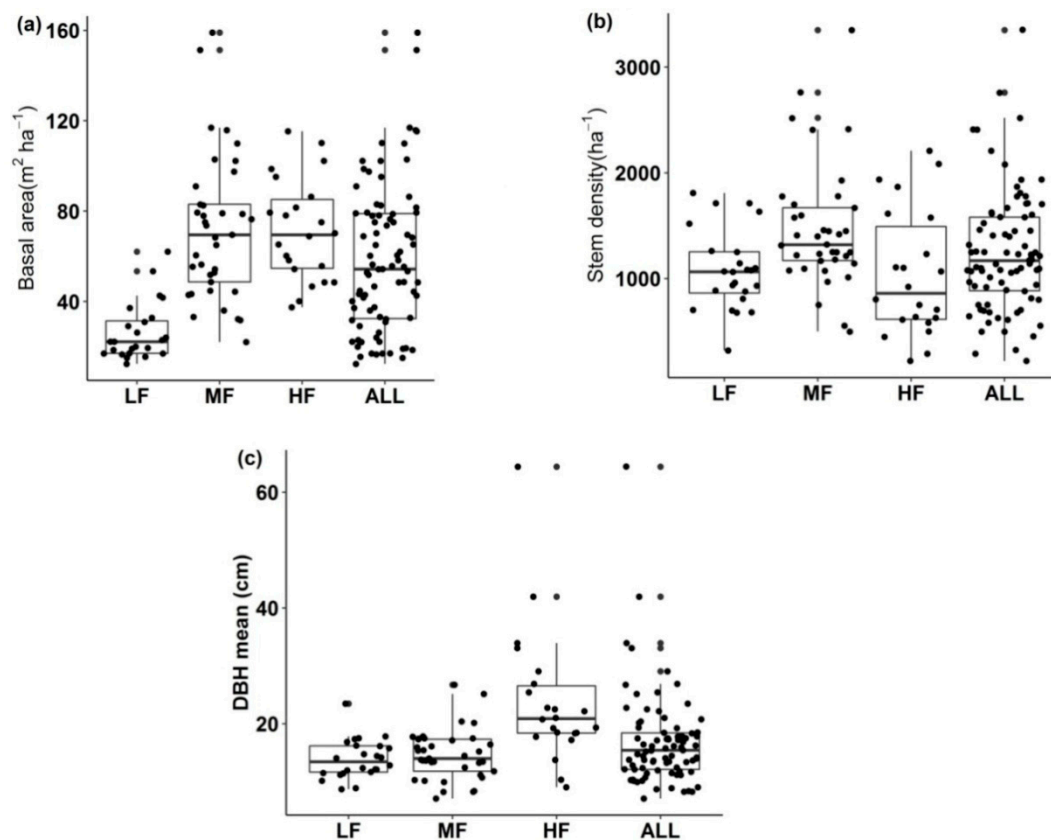


Figure 8. Boxplot with jittered data points showing the distribution of (a) basal area, (b) stem density, and (c) DBH. The horizontal line crossing the box in the center represents the median, the box represents the 25th and the 75th percentiles. The vertical line outside the box represents the minimum and maximum values. ALL = total forest community, LF = low-altitude forest, MF = mid-altitude forest, HF = high-altitude forest.

The overall size class distribution showed a reverse “J”-shaped pattern (Figure 9), with the highest number of individuals in the smallest DBH class between 3 to 13 cm (Figure 9a), and the least number of individuals in the largest DBH class between 293–303 cm (Figure 9b). A similar distribution was documented for different forest communities. However, they differed in the number of DBH classes: MF recorded the maximum number of DBH classes with the biggest tree of 295 cm DBH recorded in the study; LF and MF lacked comparable DBH trees. The LF recorded the least number of DBH classes and completely lacked trees above 93 cm DBH.

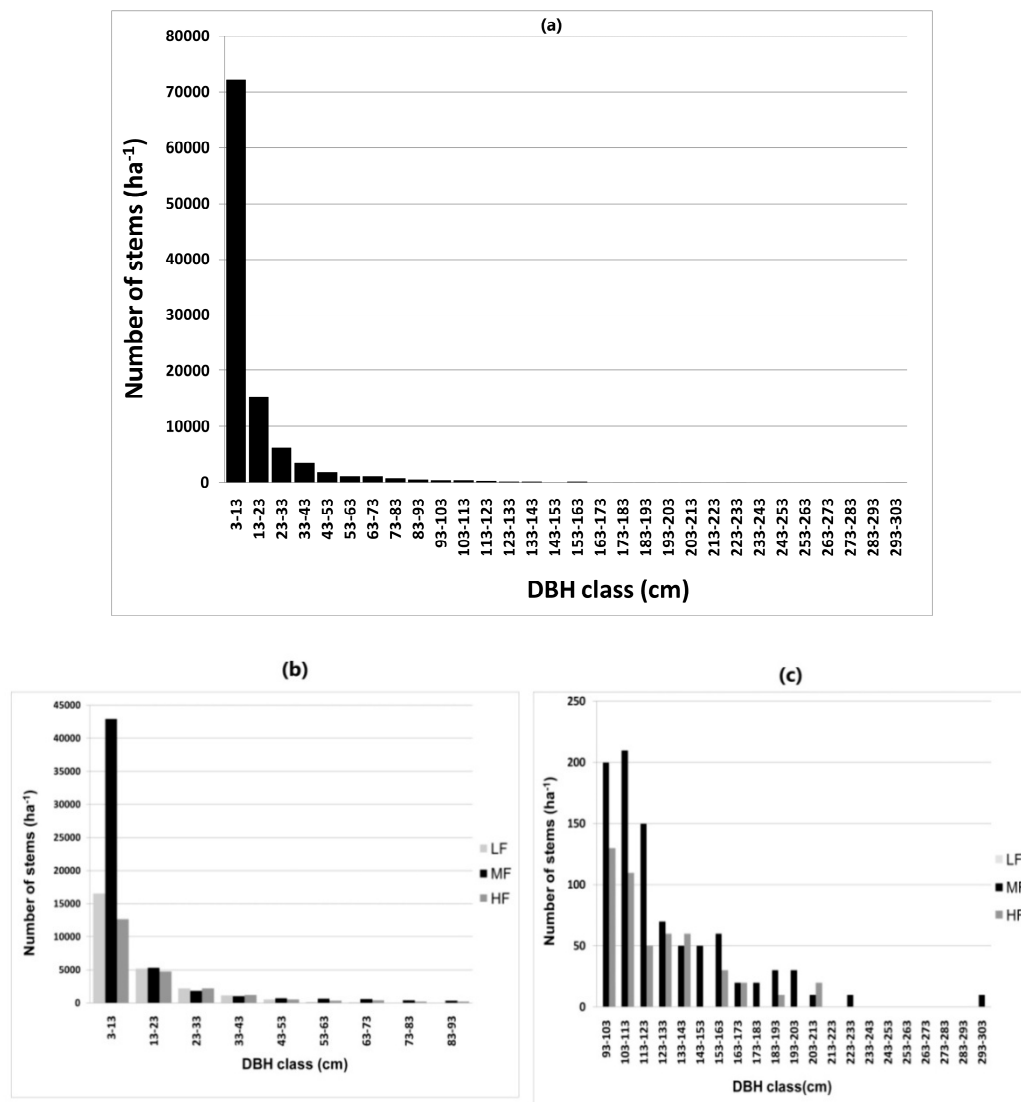


Figure 9. Class distribution of trees with >3 cm DBH recorded in the study. (a) Overall stems recorded in the study, (b) DBH ranging from >3 to 93 cm among three forest communities, and (c) DBH ranging from >93 cm to 303 cm. LF = low-altitude forest, MF = mid-altitude forest, HF = high-altitude forest.

4. Discussion

4.1. Forest Communities and Species Composition

The cluster analysis highlighted the significance of altitude in driving compositional change of forest tree species recorded in the Himalayan forests, like Sikkim. The finding could be related to the close association of altitude with climatic variables: temperature and precipitation [53], and thus draws attention towards the susceptibility of Himalayan forests to climate change.

Additionally, cluster analysis also implied the presence of three distinct forest communities between 900 m a.s.l. and 3200 m a.s.l. Moreover, according to the Grierson and Long [54] classification, our study resembles three forest types, i.e., LF forest as the warm broad-leaved forest, MF as the evergreen oak forest, and HF as the temperate mixed forests [54]. Nevertheless, we recorded some differences in species recorded for high-elevation forests. For example, Grierson and Long's [54] classification reported *Tsuga dumosa* (D. Don) Eichler., *Larix griffithii* Hook. f., and *Picea smithiana* (Wall.) Boiss. as the major trees for high-elevation forests; however, we did not report similar findings. A reason in the change in species composition in these three forest types compared to the 1960s and

1970s could be related to increasing anthropogenic pressure, such as open grazing, tree felling for its use as scaffolding, timber for construction of houses, firewood, and clearing for forest for agriculture practice, as well as climate change effects; however, warrants more investigation. Future research should focus on documentation of forest trees for a detailed description of the Himalayan forest and revision of forest type classifications if needed.

4.2. Tree Species Richness and Diversity

Species accumulation curves are especially useful to decide sampling completeness and also to compare richness for communities with different sample sizes [50]. In the current analysis, the accumulation curves did not record saturation when plotted for different communities, which implies finding more species with increasing sampling effort. Nevertheless, it is clear that low-altitude forests record the highest number of species richness and evenness, and the disparity between the observed and rarified richness in the MF was the mere result of the sampling size differences. The varied species richness between forests covering different altitudes can be associated with numerous factors. Broadly, we assumed the widely reported climatic variables, namely, precipitation, temperature, and their interaction, as the prime factor for varied richness along the altitudinal gradient of the Himalayan system [46,55,56]. Another crucial factor could be anthropogenic disturbance and its intensity [27,38]. Future research could explore these variables to explain the difference in richness recorded in our study. The LF recorded not only the highest number of species but recorded more uniformly distributed tree species. However, the region lacks comparable literature to discuss optimum richness and evenness. We recommend long-term monitoring of permanent plots, which is completely lacking in the Indian Eastern Himalayas.

One of the important findings of our study was the significance of the family Fagaceae. It was recorded as having the highest FIVI and SIVI and dominated the forest along the altitudinal gradient between 900 m and 3200 m a.s.l. in Sikkim. The reasons should be further investigated because ecological and silvicultural knowledge of Fagaceae and its species are very limited for the Eastern Himalayan forests. Furthermore, we also showed for the first time the existence of huge trees of *Lithocarpus pachyphylls* (>1.5 m DBH) in high number, which implies that this species was the remnant of the old growth primary forests in the altitude from 2500 to 3200 in Sikkim Himalayas. These old-growth trees should be marked, registered, monitored, and conserved as habitat trees by the forest department.

However, not all forest communities were dominated by the Fagaceae species. For example, *Schima wallichii* and *Castanopsis tribuloides* dominated the lower altitude forests, whereas species like *Symplocos ramosissima* and *Castanopsis hystrix* dominated the mid-altitude forests. Different physiological and climatic adaptation of a species may have caused distinct species to dominate different altitude, resulting in three unique clusters of our samples. Moreover, the Himalayas are renowned for the pronounced variation in climatic, topographic and edaphic factors along the altitudinal gradient. Apart from these, the anthropogenic disturbance is a widely discussed factor for the dominance of fast-growing pioneer species like the *Symplocos racemose* [57]. Future research could explore the role of anthropogenic disturbance and different climatic and topographic factors on species dominance and composition along the altitudinal gradient.

4.3. Forest Structure: Stem Diameter, Stem Density, and Basal Area

Size class distribution of trees provides the population structure of forest [58], and are extensively used to understand regeneration status [59]. The present assessment presented a reverse J-shaped distribution, suggesting uneven-aged forests for sustainable reproduction and regeneration [60], with a sufficient number of young individuals to replace the old mature stand. However, between forest types, the low-altitude forests completely lacked trees above 93 cm diameter, a scenario undesirable for a sustainable forest. The finding could be associated with forest degradation and deforestation reported by earlier studies [47,61]. One potential factor for the absence of large trees could be the practice of

cardamom cultivation mainly in the low-altitude forest of Sikkim. Cardamom is a high-valued cash crop and it is intensively cultivated in the low- and mid-altitude forests, where forests are partially cleared for its cultivation [61]. Furthermore, the drying of cardamom demands a substantial supply of fuelwood, often generated from the nearby forests. Moreover, until 2004, Sikkim produced the highest among of large cardamom (*Amomum subulatum* Roxb.) in India, with the largest share in the world's market [62], number of trees felled must be profound.

5. Conclusions

Our study provides a comprehensive and quantitative understanding of diversity, structure, and composition of forest trees along the altitudinal gradient, ranging from 900 m a.s.l. to 3200 m a.s.l. in the Sikkim Himalayas. The study estimated high-species richness in the low-altitude forest occurring at 900 m a.s.l. to 1700 m a.s.l., whereas the high-altitude forest covering 2500 m a.s.l. to 3200 m a.s.l. recorded the highest mean stem DBH and stand basal area. Furthermore, we found that Fagaceae trees are the most significant, with a dominant contribution towards the total basal area and stem density. Hence, Fagaceae trees could prove as having a potential for carbon storage and climate change mitigation in the Himalayas. At the same time, large-sized Fagaceae trees may have very high biodiversity values which are yet to be quantified. One of the significant findings of our study was the disproportionate size class distribution within forests at different altitudes. The low-altitude forests completely lacked trees above 93 cm DBH. Overall, the study highlights the need to conserve low-altitude forests to maintain diversity and improve forest structure. We suggest further research to understand the factors associated with varied diversity, composition, and uneven forest structure recorded in the study.

Author Contributions: Y.B. conceptualized the research concept, methodology, collected field data, conducted all the statistical analyses, and wrote the original draft. S.S., R.G. (Ravikanth Gudasalamani), and R.G. (Rengaiyan Ganesan) supervised and reviewed the article. R.G. (Rengaiyan Ganesan) helped with plant identification. S.S. acquired funding for the Article Processing Charge.

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