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Variation of tree diversity, structure and composition in the different forest types of Eastern Himalaya, India

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ABSTRACT

Despite high biodiversity and endemism and decades of research, the tree diversity of the Eastern Himalaya remains poorly understood. To fulfill this gap, we examined the patterns of the alpha and beta diversity and tree community structure in the Darjeeling area of the Eastern Himalaya. We conducted primary vegetation sampling focused on the tree strata within 3 protected areas, including National Park (NP) and Wildlife Sanctuary (WLS) of the Darjeeling Himalaya, India. The study sites included Mahananda WLS, Neora Valley NP, and the lower and upper ranges of Singalila NP. A total of 32 sampling plots (each 200 m x 200 m) were established across these sites, within which 128 quadrats (20 m × 20 m) were laid out for detailed vegetation analysis. Within each quadrat, all trees with a girth at breast height (GBH) of ≥ 10 cm were measured and identified. We recorded a total of 2137 individuals belonging to 65 tree species, 47 genera and 31 families in our study. Out of all the recorded tree species, 5 species were found endemic to the Eastern Himalayan region, and 4 globally threatened as per the IUCN Red List. We observed the highest alpha and beta diversity in the temperate forests of lower Singalila NP. Tree basal area and the density were highest in the tropical moist deciduous forests of Mahananda WLS and the sub-alpine forests of upper Singalila NP, respectively. The study sites showed distinct tree community assemblages with high beta diversity determined by substitution components. We identified 27 indicator tree species (including 23 species from single sites) with significantly high Indicator Value (IndVal) across the different forest types of the Darjeeling Himalaya. We conclude that different forest types in the Darjeeling Himalaya support a high diversity and a unique assemblage of trees, including endemics. For efficient conservation of plant diversity in the Himalaya, there is an urgent need to create more protected areas.

1. Introduction

India, with approximately 2.4% of global geographical area, is one of the 12 mega biodiversity countries and harbours 4 biodiversity hotspots, namely the Himalaya, Indo-Burma, Western Ghats, and Sundaland (Mittermeier et al., 2011). The country harbours nearly 11% of the world's flora, with approximately 28–33% of the flora being endemic to the region (Chitale et al., 2014). However, environmental changes mainly driven by the increased rate of anthropogenic activities such as forest degradation, rampant and unplanned urbanization and other developmental activities are greatly threatening its endemic flora and fauna, especially in the biodiversity hotspots like the Himalaya (Pandit et al., 2014; Manish et al., 2016; Pandit, 2017). The published national-level status of the forest report shows a consistent increase in forest cover in India, but a closer scrutiny reveals an increase only in the case of moderately dense and open forests, and a decline in very dense forests, particularly in the Himalayan region (ISFR, 2019). Thus, there is an urgent need to document the existing biodiversity of the Himalayan region through on-the-ground sampling and to assess pragmatic ways to conserve the increasingly threatened biodiversity of the region.

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The tree community of the Himalaya has received considerable attention but most of the studies were either confined to a single protected area (PA) (Yam and Tripathi, 2016; Rawat et al., 2018; Sinha et al., 2018) or a single forest type (Sagar and Singh, 2005; Timilsina et al., 2007; Gautam et al., 2016; Singh et al., 2016). However, some studies have assessed tree communities across different forest types (Chettri et al., 2002; Chetri, 2010; Sharma et al., 2010; Acharya et al., 2011; Dar and Sundarapandian, 2016; Hanief et al., 2016; Pandey et al., 2016) or across a wide elevational gradient (Oommen and Shanker, 2005; Behera and Kushwaha, 2007; Acharya et al., 2011; Tashi et al., 2016). As compared to the Western Himalaya, the tree diversity and community structure of the Eastern Himalaya are poorly studied in spite of having higher biodiversity and endemic plant species (Behera et al., 2002).

Phytogeographically, Eastern Himalaya constitutes a distinct floristic region and is a meeting point of three biogeographic realms, Indo-Malayan, Afro-tropic and Indo-Chinese. It has also been recognised as a refuge of flowering plants and a centre of active speciation (Behera et al., 2002). Few studies have reported tree communities in the Eastern Himalaya (Acharya et al., 2011; Rawat et al., 2018; Sinha et al., 2018), but none have covered multiple PAs with different forest types. The tree communities of Darjeeling have also been studied, but were focused on a single protected area, such as Mahananda Wildlife Sanctuary (Shankar, 2001; Rai et al., 2008), Neora Valley National Park (Rawat et al., 2018) and Singalila National Park (Sinha et al., 2018). The present study aims to fulfil this knowledge gap by documenting tree diversity across different forest types and multiple PAs in the Darjeeling Himalaya (a part of the Eastern Himalaya biodiversity hotspot). Specifically, the present study aimed to assess tree (alpha and beta) diversity and community characteristics across different forest types and 3 PAs (Mahananda Wildlife Sanctuary, Neora Valley National Park and Singalila National Park) in the Darjeeling Himalaya, India. The specific objectives were: (a) to understand the alpha diversity and the beta diversity (including its partitioning) of the trees in the different PAs of Darjeeling Himalaya, (b) to understand the dominance, community structure and distribution pattern of trees in different forest types of the different PAs of Darjeeling Himalaya, and (c) to identify whether PAs in different forest types harbor high diversity of tree species in the Darjeeling Himalayan region.

2. Materials and methods

2.1. Study area

The study area was located in the Darjeeling Himalaya of the Eastern Himalaya in the Indian state of West Bengal (Fig. 1). The Darjeeling Himalaya is located between 27° 13' N to 26° 27' N and 88° 53' E to 87° 59' E and covers a total geographical area of 3149 km^2 (Fig. 1) across Darjeeling and Kalimpong districts. Its elevation ranges from approximately 30 m to 3636 m. The annual mean maximum temperature is about 14.9°C, and the annual mean minimum temperature is about 8.9°C, with monthly averages typically ranging from about 6°C to 18°C.

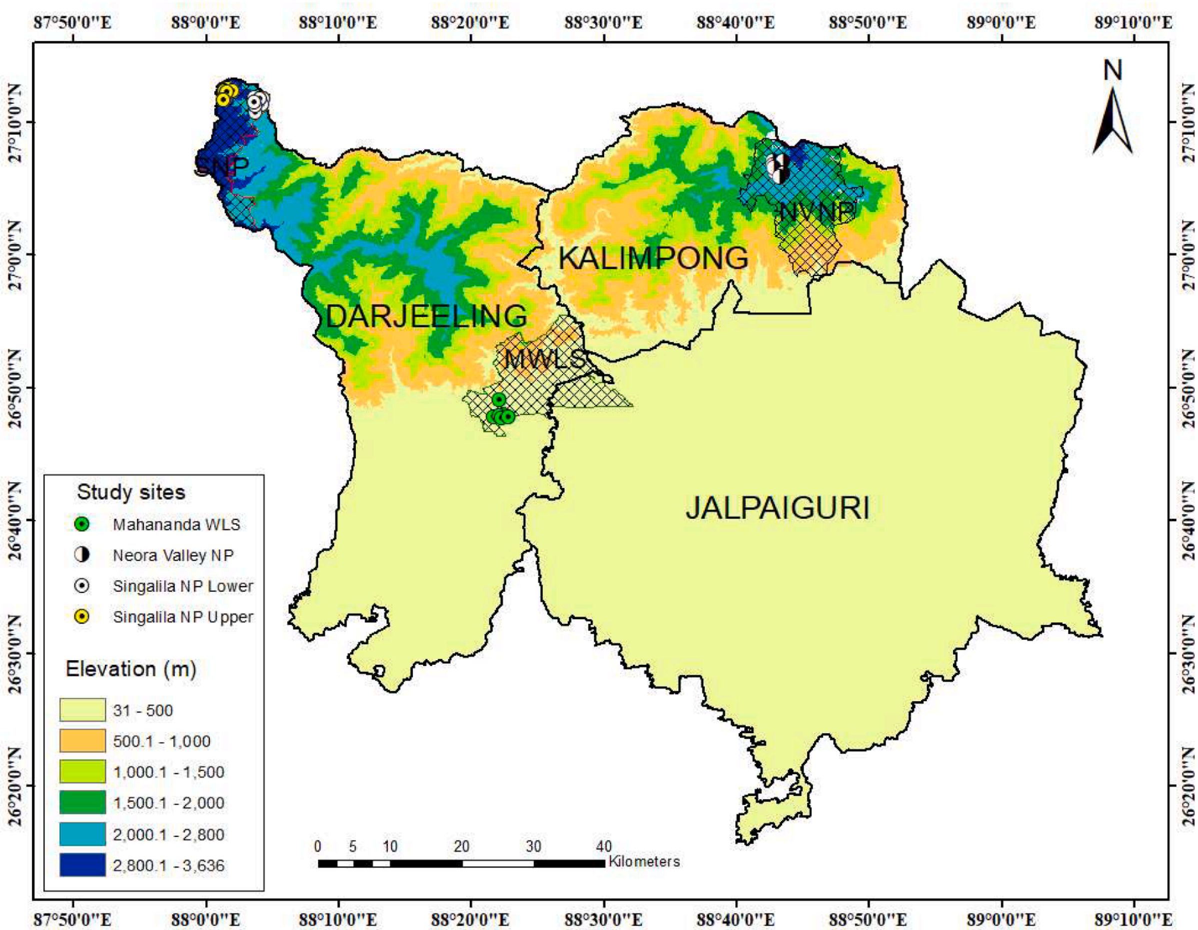

Fig. 1. Map showing the location of the study plots in the three protected areas of Darjeeling Himalaya: the Mahananda Wildlife Sanctuary (MWLS); the Neora Valley National Park (NVNP) and the Singalila National Park (SNP). The SNP was divided into the lower Singalila National Park (Singalila NP Lower) and the upper Singalila National Park (Singalila NP Upper). While NVNP and SNP lie within Kalimpong and Darjeeling districts respectively, the boundaries of MWLS extend into both Darjeeling and Jalpaiguri districts of West Bengal, India.

The region receives heavy precipitation from the summer monsoon, with an average annual rainfall of about 3092 mm (Government of West Bengal, 2026). Overall, the forests in the area above 2000 m are in relatively pristine state but the forests in the area below 2000 m (mostly sub-tropical forests) have been heavily disturbed in the past because of extensive conversion of forests for agriculture and tea plantations. The Darjeeling Himalaya has impressively high forest cover with 75.19%, as compared to 19.04% for the state of West Bengal, and 21.67% for India as a whole (ISFR, 2019). The Darjeeling Himalayan region comprises five major protected areas - Singalila National Park, Neora Valley National Park, Senchal Wildlife Sanctuary, Mahananda Wildlife Sanctuary, and Jorepokhri Wildlife Sanctuary (Das et al., 2008).

2.2. Field sampling

Sampling of tree species and phyto-sociological surveys were conducted across four study sites in the study area. These study sites were located in 3 different forest types in the 3 PAs of Darjeeling Himalaya (Fig. 1). Necessary permission for field sampling was obtained from the West Bengal Forest Department (Letter No. 349/2-44 dated 21.07.2014). The different forest types were East Himalayan Sal Forest in the Mahananda Wildlife Sanctuary (Mahananda WLS), Northern Montane Wet Temperate Forest/High level Oak Forest in the Neora Valley National Park (Neora Valley NP) and the lower range of Singalila National Park (lower Singalila NP) and the East Himalayan Sub-alpine Birch/Fir Forest in the upper range of Singalila National Park (upper Singalila NP) (Champion and Seth, 1968). The elevational gradient of different study sites spanned across 154–200 m for Mahananda WLS (Panchanai range), 2250–2600 m for Neora Valley NP (Rachella range), 2300–2500 m in lower Singalila NP (lower Phalut range) and 3035–3170 m in the upper Singalila NP (upper Phalut range). While Neora Valley NP and Singalila NP lie within Kalimpong and Darjeeling districts respectively, the boundaries of Mahananda WLS extend into both Darjeeling and Jalpaiguri districts of West Bengal (Fig. 1).

Sampling in the study sites was conducted during the monsoon (July-August) and post-monsoon (September-October) seasons in 2014–2015 by using a stratified random sampling method. We selected sampling plots (of size 200 m x 200 m) in the different forest stands (of size 2000 m x 1000 m) including from Mahananda WLS (7 plots in Panchanai range), Neora Valley NP (9 plots in Rachela range), lower Singalila NP (9 plots in lower Phalut), and upper Singalila NP (7 plots in upper Phalut range) within Darjeeling and Kalimpong districts. The selected study plots in all the study sites were located more than 200 m from each other. In all the 32 study plots, 4 quadrats of 20 m × 20 m were placed per sampling plots for optimal coverage of the vegetation (Majila and Kala, 2010). Thus, we sampled 28 quadrats (= 7 plots x 4 quadrats) each from Panchanai range of Mahananda WLS and upper Phalut range of Singalila NP; and 36 quadrats (= 7 plots x 9 quadrats) each from lower Phalut range of Singalila NP and Rechila range of Neora Valley NP. In total, we sampled 128 quadrats (5.12 hectares) across the study sites. In each quadrat, the girth at breast height (GBH; i.e. at 1.37 m above ground level) of each tree were measured. In the present study, trees with a minimum GBH of ≥ 10 cm were considered for measurement and analysis. Correct identification of tree taxa specimens was done by referring to the regional flora (Hara, 1971; Grierson and Long, 1983-2001), and by consulting herbarium of Llyod Botanical Garden, Darjeeling, West Bengal, India. The taxonomic validity of species and their family names were confirmed based on WFO Plant List database (https://wfoplantlist.org/).

2.3. Data analysis

2.3.1. Diversity indices

We calculated the different diversity, richness and evenness indices for each of the four study sites based on the standard formulas (Simpson, 1949; Shannon and Weaver, 1963; Pielou, 1969). Alpha diversity was calculated as species richness in a quadrat (Crist and Veech, 2006). Additionally, Shannon-Wiener diversity index (H') (Shannon and Weaver, 1963), species richness (S), Simpson's diversity index (Cd) or species dominance index (Simpson, 1949) and Pielou's evenness (J) (Pielou, 1969) were calculated for each of the 128 quadrats and visually represented using "vegan" package (Oksanen et al., 2017) in R 3.1.3 (R Development Core Team, 2015).

Beta diversity was calculated for both the species presence-absence data (Baselga, 2012) and abundance data (Baselga, 2017). To identify the ecological processes that determined beta diversity patterns (in terms of species composition), the beta diversity was partitioned into components of spatial turnover and nestedness-resultant component (Baselga, 2010, 2012, 2017) and also into balanced variation in abundance and abundance gradients (Baselga, 2013a, 2017). Such an approach of multiple measures of beta diversity has been recommended and employed previously for robust analysis (Si et al., 2015; Baselga, 2017). Using incidence-based (Sorensen index) and abundance-based indices (Bray-Curtis index), the partitioning of the beta diversity was done to quantify both the multiple site dissimilarity (Baselga, 2017) and pair-wise site dissimilarity (Baselga, 2013a, b). To quantify overall species assemblage heterogeneity explainable by beta diversity and its components in datasets comprising more than two sites, we assessed multiple-site dissimilarity rather than pairwise measures, as recommended for heterogeneous communities (Baselga, 2013b). We calculated multiple-site Bray-Curtis dissimilarity (β_{BRAY}) and partitioned it into balanced variation in abundance ($\beta_{BRAY.BAL}$) and abundance gradients ($\beta_{BRAY.GRA}$) following Baselga (2017). In addition, multiple-site Sørensen dissimilarity (β_{SOR}) was computed and decomposed into turnover (β_{SIM}) and nestedness-resultant (β_{SNE}) components. The relative contributions of nestedness and abundance gradients were evaluated using $\beta ratio_S = \beta_{SNE}/\beta_{SOR}$ (Dobrovolski et al., 2012; Si et al., 2015) and $\beta ratio_B = \beta_{BRAY.GRA}/\beta_{BRAY}$ (Baselga et al., 2017). Values of $\beta ratio_B$ or $\beta ratio_S < 0.5$ indicate dominance of substitution processes (species turnover or balanced abundance variation), whereas values > 0.5 indicate dominance of nestedness or abundance gradients (Dobrovolski et al., 2012; Si et al., 2015).

We calculated the pair-wise beta diversity (dissimilarity), in order to understand how the pattern of beta diversity differed within different study sites. We calculated pair-wise Bray-Curtis dissimilarity (β_{bray}) and its partition due to balanced variation in abundance ($\beta_{bray.bal}$) and due to abundance gradients ($\beta_{bray.gra}$) with original abundance-based community data matrix, and pair-wise Sorensen dissimilarity (β_{sor}) and its components of turnover (β_{sim}) and nestedness-resultant (β_{sne}) using transformed (presence: ≥1/absence: 0) matrix. For both the dissimilarity indices (i.e., Sorensen index and Bray-Curtis index), we carried out betadisper analysis to compare the beta diversities of the tree communities aggregated by the four study sites and visualized the same through a PCoA plot. We also prepared box and whisker plot to observe the homogeneity (i.e., the distance of beta diversity values in relation to their respective centroids) in each study site. The multiple-site and pair-wise beta diversity and their components for both the dissimilarity indices were calculated by "betapart" package (Baselga et al., 2017) and plots were prepared by "vegan" package (Oksanen et al., 2017) in R 3.1.3 (R Development Core Team, 2015).

2.3.2. Dominance of tree species and families

Before proceeding with the analysis of different measures of dominance for tree species and families, GBH was converted to diameter at breast height (DBH) using DBH = GBH/3.14. The dominance of tree species and families were evaluated using the standard measures of Importance Value Index (IVI), Family Importance Value Index (FIV), frequency, density, abundance, basal area, total basal area, relative frequency, relative density, relative dominance and relative diversity (Curtis and McIntosh, 1951; Mishra, 1968; Greig-Smith, 1983; Mori et al., 1983).

2.3.3. Tree structural composition and distribution pattern

The structural composition of tree communities for all the study sites were analyzed by examining the distribution of the tree diameter classes (using diameter classes) of <10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, 50–60 cm, 60–70 cm, 70–80 cm and >80 cm with respect to the tree density (trees ha^{-1}) and basal area (m^{2}ha^{-1}) following Borah et al. (2019). For tree communities in different study sites, we also examined the density-dominance distribution curves (for IVI) following Whittaker (1965) and distribution patterns explored following Whitford (1949) based on Abundance/Frequency (A/F) ratio: regular if the A/F ratio is (< 0.025), random (0.025–0.050) and contagious (> 0.050).

2.3.4. Indicator value analysis

It is important to identify indicator species for different habitats including those associated with more than one habitat. One of the most widely accepted methods of identifying indicator species for the different habitat is through analysis of species indicator value (IndVal) which is product of specificity (A) and fidelity (B) of species to the habitat (Dufrêne and Legendre, 1997; De Cáceres et al., 2010). IndVal analysis help to evaluate the association of tree species to not only a particular habitat but also to group of habitats (Dufrêne and Legendre, 1997; De Cáceres et al., 2010). To identify indicator tree species for the different studied forest stands of three protected areas in the Darjeeling Himalaya, we used 'multipatt' function (with association index IndVal. g, duleg = FALSE, nperm = 999, P < 0.05) of 'indicspecies' package (De Cáceres and Jansen, 2016) in R 3.1.3 (R Development Core Team, 2015).

3. Results

3.1. Alpha diversity and other community measures

We recorded a total of 2137 individuals belonging to 65 tree species, 47 genera and 31 families in our study. The tree species richness was observed to be highest in the lower Singalila NP and lowest in upper Singalila NP (Table 1). Lower Singalila NP also had the highest number of genera and family (shared with Mahananda WLS). The lowest values of species richness, genera and family were recorded in upper Singalila NP (Table 1). Lower Singalila NP also recorded the highest values overall and per quadrat values for Shannon-Weiner diversity index (Fig. 2a), species richness (Fig. 2b), Simpson's diversity index (Fig. 2c), and Pielou's evenness (Fig. 2d) followed by Neora Valley NP, Mahananda WLS and upper Singalila NP.

Table 1
The tree diversity and community characteristics in different forest types of the three protected areas: Mahananda Wildlife Sanctuary (MWLS); Neora Valley National Park (NVNP), lower ranges of Singalila National Park (SNPL) and upper ranges of Singalila National Park (SNPU) of the Darjeeling Himalaya, India.

Indices/parameters	MWLS	NVNP	SNPL	SNPU
Total species richness (SR)	24	22	26	11
No. of genera	20	16	22	7
No. of families	15	11	15	5
Shannon-Weiner index (H')	1.75	2.06	2.61	1.31
Simpson Diversity index (Cd)	0.71	0.82	0.90	0.63
Evenness/Equitability (J)	0.55	0.66	0.80	0.55
Total sampled area (ha)	1.12	1.44	1.44	1.12
Abundance	296	791	429	621
Density (trees ha^{-1})	264.3	549.3	297.9	554.46
Basal area (m^2 ha^{-1})	42.28	19.76	28.25	36.38
βbray	0.52	0.54	0.56	0.38
βsor	0.47	0.47	0.49	0.37
Endemic species	0	4	3	2
IUCN Red List status				
Endangered	0	0	1	0
Near Threatened	1	1	1	0
Least concern	22	17	19	5
Not Evaluated	1	4	5	6
Indicator species	6	9	10	6

3.2. Beta diversity

We observed very high and comparable multiple site beta diversity (β_{BRAY} = 0.988; β_{SOR} 0.985). The substitution component, i.e. the balanced variation in abundance and spatial turnover, contributed the largest fraction of beta diversity for Bray-Curtis dissimilarity and Sørensen dissimilarity, respectively ($\beta_{BRAY.BAL}$ = 0.976 and β_{SIM} = 0.972). The βratio for both the indices were very low (βratio$_B$ = 0.016 and βratio$_S$ = 0.009), which indicated that variations of tree community compositions were predominantly related to the substitution components, i.e., balanced variation in abundance and spatial turnover, when considering abundance-based dissimilarity and incidence-based dissimilarity, respectively.

The pair-wise beta diversity for both the indices was highest in lower Singalila NP (βbray = 0.56; βsor = 0.49) followed by Neora Valley NP, Mahananda WLS and upper Singalila NP (Fig. 3a, b). Analysis of tree community assemblage based on both indices revealed that the quadrats belonging to the study sites representing the temperate forests (Neora Valley NP and lower Singalila NP) and sub-alpine forests (upper Singalila NP) showed some overlap and aggregated together, but the quadrats from Mahananda WLS formed a distinct assemblage (Fig. 3c, d).

3.3. Dominance of tree species and families

We observed distinct community structure of trees in the four study sites, based on FIV (Tables S1, S2), as well as dominance (m^2 ha^{-1}), density (stems ha^{-1}), and IVI (Table S3). A total of 24 tree species belonging to 20 genera and 15 families were observed in the Mahananda WLS. The maximum FIV was observed for Dipterocarpaceae (130.1) followed by Theaceae (31.95) and Fabaceae (24.84) (Table S1). *Shorea robusta* C.F.Gaertn. had the highest IVI followed by *Schima wallichii* (DC.) Choisy and *Magnolia champaca* (L.) Baill. ex Pierre which together contributed about 75% of the total IVI (226.07 out of 300). The remaining 21 species contributed only one-fourth to the total IVI (range: 1.42–12.89). *Shorea robusta* C.F.Gaertn. (33.23 m^2 ha^{-1}) was the most dominant followed by *Magnolia champaca* (L.) Baill. ex Pierre (4.71 m^2 ha^{-1}) and *Schima wallichii* (DC.) Choisy (1.89 m^2 ha^{-1}), which also had highest density (Table S3).

A total of 22 tree species belonging to 16 genera and 11 families were observed in the Neora Valley NP. In Neora Valley NP, the highest FIV was observed for Ericaceae (98.36) followed by Pinaceae (59.69), Fagaceae (35.57) (Table S1). The most dominant tree species were *Rhododendron arboreum* Sm. followed by *Tsuga dumosa* (D. Don) Eichler and *Rhododendron falconeri* Hook. f.. These 3 species together contributed nearly half of the total IVI (147.6 out of 300). The basal area was highest for *Tsuga dumosa* (D. Don) Eichler (8.83 m^2 ha^{-1}), but the density was the highest for *Rhododendron arboreum* Sm. (186.11 ha^{-1}; Table S3).

A total of 26 tree species belonging to 22 genera and 15 families were observed in the lower Singalila NP. In the lower Singalila NP, the highest FIV was observed for Fagaceae (75.88), followed by Cupressaceae (58.31), and Pinaceae (39.83) (Table S1). *Cryptomeria japonica* (Thunb. ex L.) D. Don had the maximum IVI (61.13) followed by *Lithocarpus pachyphyllus* (Kurz) Rehder (IVI=36.81) and *Tsuga dumosa* (D.Don) Eichler (IVI = 35.19), which together contributed 44.37 % of the total IVI. *Cryptomeria japonica* (Thunb. ex L.) D. Don (11.37 m^2 ha^{-1}) was the most dominant species but the density was highest for *Rhododendron arboreum* Sm. (47.22 ha^{-1}) dominated by individuals of small diameter (Table S3).

Only 11 tree species belonging to 7 genera and 5 families were observed in the upper Singalila NP. The highest FIV was observed for Ericaceae (148.88) followed by Pinaceae (111.07) (Table S1), while the most dominant species were *Abies densa* Griff. (IVI=123.20), followed by *Rhododendron arboreum* Sm. (IVI =97.89) and *Rhododendron barbatum* Wall. ex G. Don (IVI=34.95), which together contributed to 85.35 % of the total IVI. The other 21 species contributed only 14.65 % to the

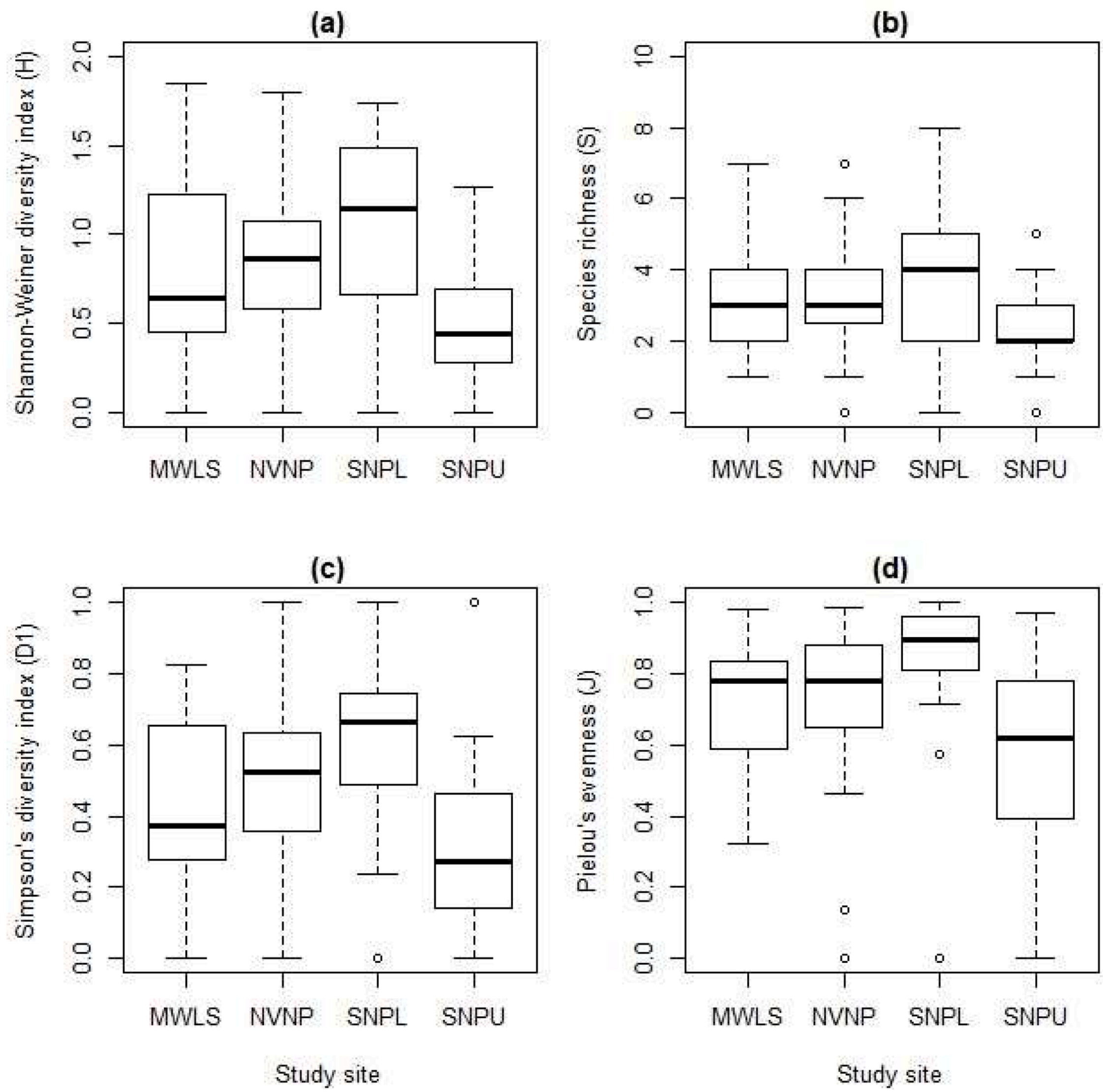

Fig. 2. Box and whisker plot showing pattern of: (a) Shannon-Weiner diversity index (H'), (b) species richness (S), (c) Simpson's diversity index (Cd), (d) Pielou's evenness (J) per quadrat in the different forest types of the three protected areas in the Darjeeling Himalaya: the Mahananda Wildlife Sanctuary (MWLS), the Neora Valley National Park (NVNP), the lower Singalila National Park (SNPL) and the upper Singalila National Park (SNPU).

total IVI (range: 1.69–14.60). The dominance was the highest for *Abies densa* Griff. (31.95 m^2 ha^{-1}), and the highest density was observed for *Rhododendron arboreum* Sm. (310.71 ha^{-1}; Table S3).

3.4. Tree density, basal area and density diameter class distribution

The tree density in the present study was the highest in upper Singalila NP (mean = 554.46 trees ha^{-1}), followed by Neora Valley NP, lower Singalila NP and Mahananda WLS (Table 1). The basal area in the present study was highest in Mahananda WLS (mean = 42.28 m^2 ha^{-1}) followed by upper Singalila NP, lower Singalila NP and Neora Valley NP (Table 1).

The four study sites across the three protected areas in the Darjeeling Himalaya showed a distinct pattern of density-diameter class distribution for the tree density (Fig. 4a) and the basal area (Fig. 4b). The tree density declined with increasing diameter class in all the sites except in the Mahananda WLS and the lower Singalila NP (where the tree density did not show a clear trend). Highest density for the trees with greater diameter classes was observed for the Mahananda WLS (50–60 cm & 60–70 cm) and the upper Singalila NP (> 60 cm), whereas higher density for lower diameter class (<10 cm and 10–20 cm) was found for the Neora Valley NP and the upper Singalila NP (Fig. 4a), signifying good regeneration. In the Mahananda WLS and the lower Singalila NP, trees across the whole range of diameter classes were fairly distributed, indicating the healthy nature of these forest stands. Distribution of basal area cover in different diameter size classes indicated a reverse trend as compared to that of the stand density in the upper Singalila NP and the Neora Valley NP. However, basal area cover showed positive increase with increasing diameter size class in the Mahananda WLS and the lower Singalila NP. Tree stems belonging to higher DBH class (with intermediate and higher DBH) contributed greatly to the overall basal area in case of the studied forest plots from Mahananda WLS (DBH = 40–50 cm, 50–60 cm, 60–70 cm, and 70–80 cm), lower Singalila NP (DBH = 30–40 cm, 40–50 cm, 60–70 cm, and 70–80 cm), upper Singalila NP (DBH = 60–70 cm, 70–80 cm, and >80 cm), and Neora Valley NP (60–70 cm, 70–80 cm, and >80 cm) (Fig. 4b). Thus, DBH class-based tree density exhibited bell-shaped pattern for Mahananda WLS and lower Singalila NP, but reverse J-shaped curve in case of NVNP and upper Singalila NP. On the contrary, DBH class-based basal area exhibited nearly bell-shaped and J-shaped patterns in the different study sites.

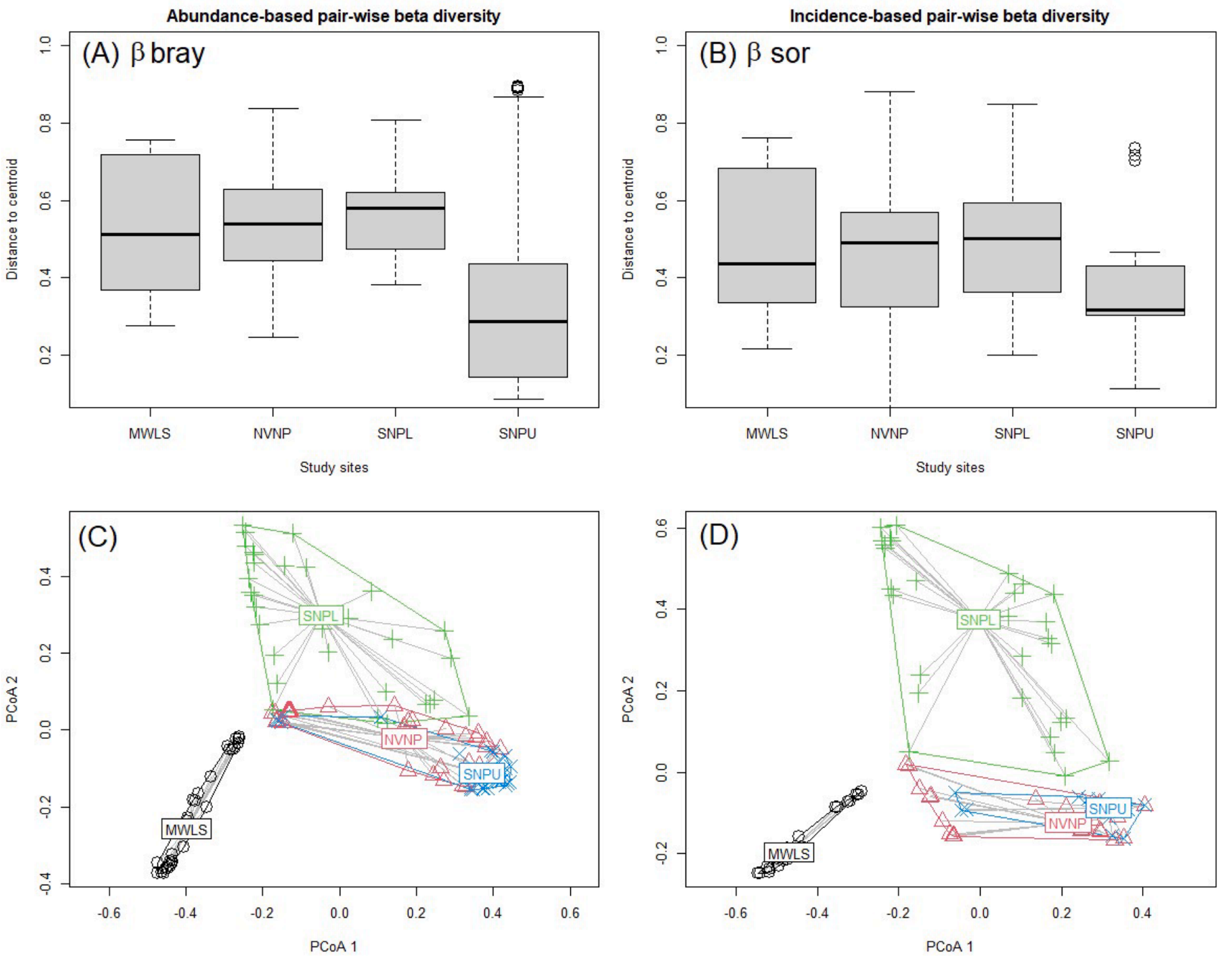

Fig. 3. Box and whisker plot representing the distance to centroid (a, b) and plot showing PCoA (c, d) for the pair-wise dissimilarity computed respectively by: incidence-based dissimilarity index (Sorensen index) and abundance-based dissimilarity index (Bray Curtis index) in the species composition of tree communities in the 128 transects across the four forest types in the different forest types of the three protected areas in the Darjeeling Himalaya: the Mahananda Wildlife Sanctuary (MWLS), the Neora Valley National Park (NVNP), the lower Singalila National Park (SNPL) and the upper Singalila National Park (SNPU).

3.5. Density-dominance and distribution pattern

The density-dominance curve of trees in three sites namely representing East Himalayan Sal Forest (in Mahananda WLS), and montane wet temperate forests (in Neora Valley NP and lower Singalila NP) showed log normal pattern, whereas geometric pattern was observed in the East Himalayan sub-alpine forests (in upper Singalila NP) (Fig. 5). Across the four study sites, maximum tree species showed contagious pattern (11–24 species), very few species showed random pattern (0–2 species) and none showed regular distribution pattern based on A/F ratio. The dominance of contagious distribution pattern of trees ranged from 100 % (all 11 species) in upper Singalila NP, followed by 95.45 % (21 out of 22 species) in Neora Valley NP, 92.31% (24 out of 26 species) in lower Singalila NP, and 91.67% (22 out of 24 species) in Mahananda WLS. On the other hand, percentage of trees showing random distribution was only 8.33 % in Mahananda WLS, 7.69% in lower Singalila NP, 4.55 % in Neora Valley NP, and 0% in upper Singalila NP.

The species showing random pattern were *Aphanamixis polystachya* (Wall.) R.Parker and *Schima wallichii* (DC.) Choisy in the Sal forest of Mahananda WLS; *Quercus lineata* Blume in the montane wet temperate forest of Neora Valley NP; *Lithocarpus pachyphyllus* (Kurz) Rehder and *Tsuga dumosa* (D.Don) Eichler in the lower Singalila NP; and none in the sub-alpine forests of upper Singalila NP (Table S2).

3.6. Endemic, threatened and indicator species

Five out of the total 65 tree species (one-thirteenth) observed in the present study were found to be endemic to the Eastern Himalaya: *Abies densa* Griff. (in Neora Valley NP, lower Singalila NP, upper Singalila NP), *Brassaiopsis mitis* C.B.Clarke (in Neora Valley NP, lower Singalila NP), *Machilus clarkeana* King ex Hook.f. (lower Singalila NP), *Rhododendron falconeri* Hook.f. (in Neora Valley NP, upper Singalila NP), *Micromeles vestita* (Wall. ex G.Don) Mezhenskyj (in Neora Valley NP) (Table S2). Among the four study sites, Neora Valley NP harbored the maximum endemic species (4 species), followed by lower Singalila NP (3 species), upper Singalila NP (2 species), but Mahananda WLS lacked any endemic species (Table 1; Table S2).

Categorization of observed tree species according to IUCN Red List status revealed presence of four globally protected species, which included an 'Endangered' species *Taxus wallichiana* Zucc. (in lower Singalila NP), and three 'Near Threatened' species: *Shorea robusta* C.F. Gaertn. (in Mahananda WLS), *Quercus lamellosa* Sm. (in Neora Valley NP), *Cryptomeria japonica* (Thunb. ex L.) D. Don (in lower Singalila NP) (Table S2). Among the study sites, East Himalayan montane wet temperate forest of lower Singalila NP harbored two of these IUCN Red List species (one each of 'Endangered' and 'Near Threatened' species), whereas both the East Himalayan sal forests of Mahananda WLS and the East Himalayan montane wet temperate forest of Neora Valley NP harbored one 'Near Threatened' species each. On the other hand, there

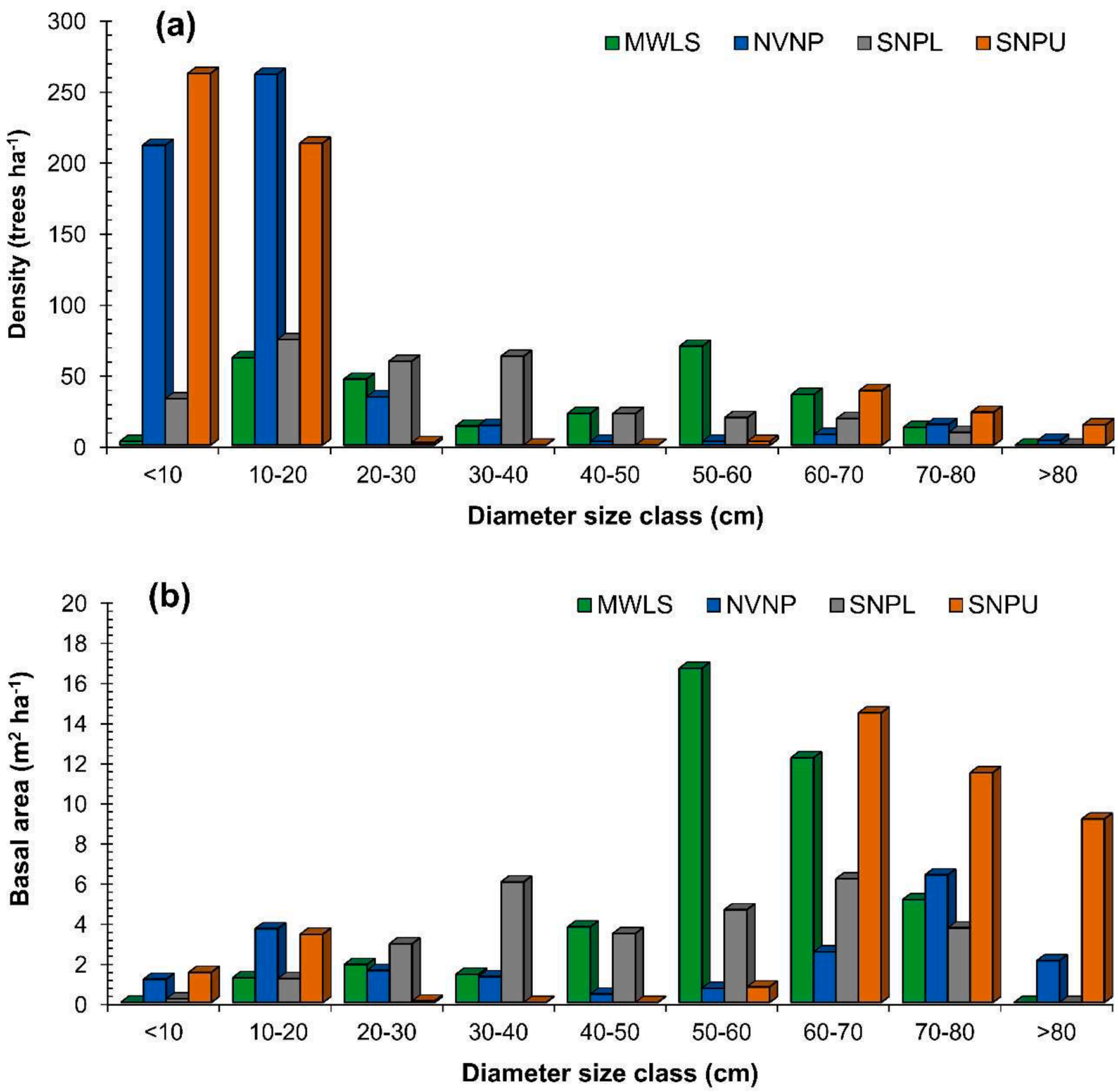

Fig. 4. Diameter size class distribution (cm) of (a) density (trees ha^{-1}) and (b) basal area (m^2 ha^{-1}) for tree communities in the different forest types of the three protected areas in the Darjeeling Himalaya: the Mahananda Wildlife Sanctuary (MWLS), the Neora Valley National Park (NVNP), the lower Singalila National Park (SNPL) and the upper Singalila National Park (SNPU).

were 48 'Least concern' tree species, and 13 species 'Not Evaluated' yet by the IUCN (Table S2). The 'Least concern' species also included two species (*Abies densa* Griff. and *Brassaiopsis mitis* C.B.Clarke) endemic to the Eastern Himalaya. Similarly, the 'Not Evaluated' species included three Eastern Himalayan endemic tree species namely *Rhododendron falconeri* Hook. f., *Micromeles vestita* (Wall. ex G.Don) Mezhenskyj, *Machilus clarkeana* King ex Hook.f.

We also identified a total of 27 most important and unique indicator tree species for the different study sites based on significantly ($p < 0.05$) high values of IndVal (Table S4). 23 of these indicator species were indicators for single site of which 8 species were associated with the East Himalayan montane wet temperate forest of lower Singalila NP followed by 6 for both the East Himalayan Sal forest of Mahananda WLS and the East Himalayan montane wet temperate forest of Neora Valley NP and 3 for the East Himalayan sub-alpine forests of upper phalut range of Singalila NP (Table S4). These indicator tree species were mostly the dominant species as revealed by their high values of IVI in all 4 different forest types of the three protected areas of the Darjeeling Himalaya (Tables S3, S4). The indicator species were represented by three of the five observed Eastern Himalaya endemics namely *Abies densa* Griff., *Machilus clarkeana* King ex Hook.f., and *Rhododendron falconeri* Hook.f. (Tables S2, S4). They also included all three observed IUCN 'Near Threatened' species: *Shorea robusta* C.F.Gaertn., *Cryptomeria japonica* (Thunb. ex L.) D.Don, and *Quercus lamellosa* Sm. (Tables S2, S4). Four species were also associated with two sites: *Rhododendron arboreum* Sm. and *Rhododendron barbatum* Wall. ex G.Don (each for NVNP and SNPU), *Quercus lineata* Blume (for NVNP and SNPL), and *Lyonia ovalifolia* (Wall.) Drude (for SNPL and SNPU) (Table S4). Hence, given their high dominance, with well representation by the Eastern Himalaya endemics and globally protected species in the different forest stands, these identified indicator tree species have high suitability for long-term ecological monitoring in the Eastern Himalaya.

4. Discussion

4.1. Tree alpha and beta diversity

The tree species richness and diversity (alpha and beta diversity) in the present study showed the highest values for temperate regions (lower Singalila NP, Neora Valley NP) representing the East Himalayan montane wet temperate forest, followed by tropical regions (Mahananda WLS) representing East Himalayan Sal forests and declined in the subalpine regions (upper Singalila NP). These results are consistent with existing studies on elevational gradients of plant diversity in the

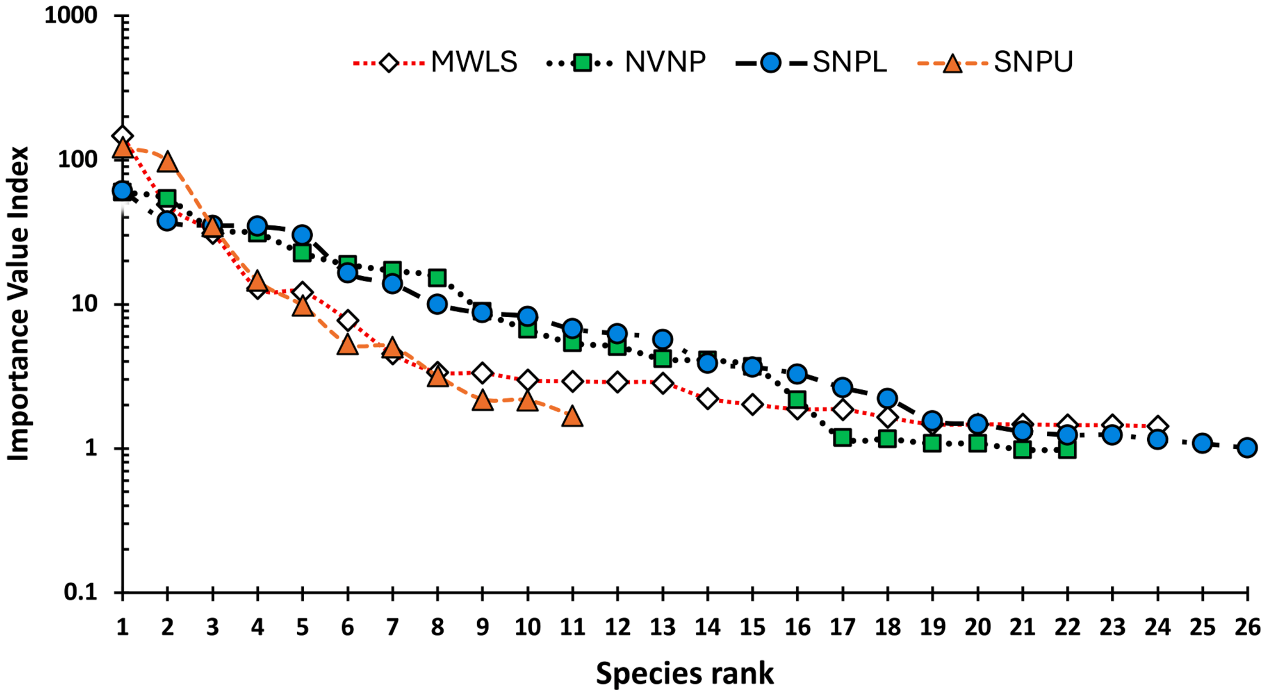

Fig. 5. Dominance distribution pattern of tree communities in the different forest types of the three protected areas in the Darjeeling Himalaya: the Mahananda Wildlife Sanctuary (MWLS), the Neora Valley National Park (NVNP), the lower Singalila National Park (SNPL) and the upper Singalila National Park (SNPU).

Himalayan ecosystems. The temperate regions (mid-elevations) in the Himalaya are reported to harbour higher diversity and species richness because of favourable climates such as optimum temperature, moisture, longer growing season, higher productivity and higher availability of ecological niches (Manish et al., 2017). The tropical forests (low elevations), on the other hand, have less environmental heterogeneity, less productivity and greater anthropogenic disturbances (Manish et al., 2017). The alpine and sub-alpine zones experience harsh climatic conditions, including low temperatures, a short growing season, and reduced productivity. These conditions act as strong environmental filters, allowing only species adapted to the harsh climate to survive in the alpine and subalpine zones (Manish and Pandit, 2018). This results in low diversity and species richness in the alpine and sub-alpine zones in the Himalaya.

Beta diversity was high across all study sites, though lower in the lower Singalila NP. The tree species richness in the study area is consistent with previous studies from the Eastern Himalayan region (Chettri et al., 2002; Chetri, 2010; Rawat et al., 2018; Sinha et al., 2018). The partitioning of pair-wise beta diversity in the present study revealed a distinct community assemblage in the different forest types in the present study with some overlap between East Himalayan montane wet temperate forests (lower Singalila NP, Neora Valley NP) and East Himalayan sub-alpine forests (upper Singalila NP), whereas the tropical East Himalayan Sal forests (Mahananda WLS) formed a very distinct assemblage. The multiple site beta diversity revealed that the variation of tree community compositions among the different forests from the 3 protected areas of the Darjeeling Himalaya is predominantly related to the substitution component (balanced variation in abundance and species turnover), which is a general trend in areas with the high biodiversity and landscape heterogeneity (Dobrovolski et al., 2012; Si et al., 2015). The higher beta diversity (both pair wise dissimilarity and multiple site dissimilarity) across the four study sites in the 3 protected areas of the Darjeeling Himalaya may be ascribed to presence of different forest types (East Himalayan tropical forests in the Mahananda WLS, montane temperate forests in the Neora Valley NP and the lower Singalila NP and sub-alpine forest in the upper Singalila NP) (Das et al., 2008), as well as low species similarity and narrow elevational range of many tree species in the Eastern Himalaya (Acharya et al., 2011).

4.2. Dominance of tree species and families

Dominance and density of *Shorea robusta* C.F.Gaertn. in the East Himalayan tropical Sal forests of the Mahananda WLS with IVI > 146 revealed that these forests are progressing towards mature stands in the succession and the results are comparable to those obtained in previous studies in the tropical sal-dominated forests of the Eastern Himalaya (Shankar, 2001; Baishya et al., 2009) and the Central and the Western Himalaya (Timilsina et al., 2007; Chauhan et al., 2008; Sharma et al., 2010). In the East Himalayan montane temperate forests of the lower Singalila NP, the tree community was co-dominated by species from different genera and families with no clear dominant species, suggesting that vegetation succession has not yet reached the climax stage. Climax forests are typically dominated by a limited range of competitive, shade-tolerant species (Odum, 1969). Our observed pattern of mixed dominance, however, suggests an earlier successional stage in which species replacement is still in progress and a stable competitive hierarchy has not yet been established. Similarly, in the East Himalayan montane temperate forests of the Neora Valley NP and in the sub-alpine forests of upper Singalila NP, the species of Ericaceae and Pinaceae dominated the tree communities. In the Neora Valley NP, dominance of two species of Rhododendrons (*Rhododendron arboreum* Sm. and *Rhododendron falconeri* Hook.f.) and *Tsuga dumosa* (D.Don) Eichler suggested that these two genera are generally dominant in temperate forests of Eastern Himalaya. In the East Himalayan Sub-alpine forests of upper Singalila NP, dominance of *Abies densa* Griff. (IVI=123.20), suggests that it has edged out Rhododendrons in the succession process and the tree community is being slowly replaced with the coniferous species. This can be as a result of the climate change-induced range shift in tree species (Telwala et al., 2013) or some forms anthropogenic disturbances. Similar results have been previously reported from the temperate forests (Yam and Tripathi, 2016; Rawat et al., 2018; Sinha et al., 2018) and sub-alpine forests in the Himalaya (Chettri et al., 2002; Chetri, 2010; Pandey et al., 2016; Tashi et al., 2016; Sinha et al., 2018).

4.3. Tree density, basal area and density diameter class distribution

The highest tree density observed in the East Himalayan sub-alpine forests (upper Singalila NP) than montane temperate forests (Neora Valley NP and lower Singalila NP) or tropical Sal forests (Mahananda WLS) was because of very high density shown by different *Rhododendron* spp. and presence of young tree stems showing good regeneration in the forest stands. This is in agreement with the previous studies (Acharya et al., 2011; Sinha et al., 2018). The highest basal area was observed in tropical Sal forests (Mahananda WLS) due to dominance of *Shorea robusta* C.F.Gaertn. (33.23 m^2 ha^{-1}). Surprisingly, sub-alpine forests of the upper Singalila NP had the second highest basal area due to high dominance of *Abies densa* Griff. (31.95 m^2 ha^{-1}) that was well represented by very high diameter trees reaching climax stage in ecological succession.

Regeneration seems to be excellent in case of the Neora Valley NP and the upper Singalila NP (due to dominance of small tree stems: <10 cm and 10–20 cm) and quite low in case of the Mahananda WLS and the lower Singalila NP. The poor density of trees in the intermediate (30–40 cm, and 40–50 cm, 50–60 cm) and high (60–60 cm, 70–80 cm, >80 cm) DBH classes in case of the upper Singalila NP and the Neora Valley NP suggests that the forest succession has not yet reached the climax stage. Trees with small diameter (DBH <10 cm and 10–20 cm) are generally dominant in the tree communities of tropical forest (due to high recruitment rate and regeneration), representing a high percentage of total density but low contribution to overall basal area.

In the present study, DBH-class distribution for tree density showed reverse J-shaped curve (due to dominance of small tree stems) in the forest plots of montane temperate moist forests (of Neora Valley NP) and sub-alpine forests (of upper Singalila NP), revealing excellent rates of seedling recruitment rates and forest regeneration, and relatively undisturbed nature of forest stands. However, tree density showed bell-shaped pattern of DBH class-based distribution in the Sal-dominated tropical deciduous forest (in Mahananda WLS) and montane temperate moist forests (in lower Singalila NP), revealing poor regeneration and seedling recruitment rates, and presence of maturing and old-growth forest stands progressing towards climax stage, and some form of environmental disturbances. Past studies in the forests from the Indian Himalayan region (Shrestha et al., 2007; Sharma et al., 2017; Borah et al., 2019; Negi et al., 2025), and elsewhere (Behera et al., 2025; Mansingh et al., 2025) have also reported reverse J-shaped as well as bell-shaped, and irregular/ J-shaped patterns for DBH class-based distribution pattern for tree density.

Tree stems from intermediate and higher DBH class contributed greatly to the overall basal area in case of the studied forest plots from Mahananda WLS (DBH = 40 to 80 cm), lower Singalila NP (DBH = 30–80 cm), as well as to lesser extent in Neora Valley NP upper Singalila NP and (DBH = 60–70 cm, to >80 cm, each for the latter two sites). Our findings of bell-shaped and J-shaped distribution patterns of DBH class-based basal tree population in the different study sites of Darjeeling Himalaya agrees with previous reports (Sharma et al., 2017; Borah et al., 2019; Mansingh et al., 2025), signifying moderately disturbed (but matured), and relatively disturbed (regenerating) forest stands, respectively.

4.4. Density-dominance and distribution pattern

The log normal pattern of density-dominance curve in three study sites representing East Himalayan Sal forest (in Mahananda WLS), and East Himalayan montane temperate forests (in Neora Valley NP and lower Singalila NP) signifies the heterogeneous nature of trees in the forest communities (Yam and Tripathi, 2016). On the other hand, geometric pattern shown by tree communities of the East Himalayan sub-alpine forests (in upper Singalila NP) are mostly seen for vascular plants having lower density (Whittaker, 1965) driven mainly due to dominance of *Rhododendron* spp. with small diameter stems and has been previously reported from the Himalaya (Kumar and Bhatt, 2006). The dominance of contagious pattern in the distribution pattern of trees agrees with the previous reports from the Himalaya (Yam and Tripathi, 2016; Rawat et al., 2018) and is a common pattern in nature (Odum, 1971). The high value of Simpson's diversity index (Cd) of tree communities in the study sites from two protected areas could be because of the dominance of a single species. *Shorea robusta* C.F.Gaertn. and *Abies densa* Griff. contributed about 50% and >40% of the total IVI in the Mahananda WLS and the upper phalut range of Singalila NP, respectively.

The analysis of distribution patterns of trees communities (based on A/F ratio) in the four study sites revealed that more than 91% of the observed tree species showed contagious pattern (range: 91.67 to 100%) and rest by random pattern (range: 0 to 8.33%), with absence of species with regular distribution pattern. These observations of distribution pattern of trees across the different forest types representing three protected areas in Darjeeling Himalaya, contrasts to a recent study along an elevational gradient in the East Himalaya (Negi et al., 2024), which reported dominance of trees showing random (47.3%) and contagious (42.9%) distribution patterns compared to regular distribution (10.8%) pattern of plant communities.

The observed dominance of contagious distribution pattern by the tree communities in the East Himalayan Sal forests (in Mahananda WLS), montane wet temperate forests (in Neora Valley NP, and lower Singalila NP), and sub-alpine forests (in upper Singalila NP) in Darjeeling Himalaya may be attributed to the characteristic dominance of this pattern in nature, specially tropical climatic regime (with temperature gradients), and lower tolerance of these species to environmental changes, or may be due to high recruitments of seedlings (Odum, 1971; Oommen and Shanker, 2005; Negi et al., 2024).

5. Conclusions

The present study aims to assess variation in tree community structure and composition across different forest types within the PAs of the Eastern Himalaya. The results revealed that temperate forests harbour higher alpha and beta tree diversity than tropical and subalpine forests in the Eastern Himalaya. The results also reveal distinct community assemblage patterns across the different forest types, albeit with a small overlap between the temperate and subalpine forests. Tropical forests form the most distinct assemblage in the Eastern Himalaya. The multiple-site beta diversity revealed that variation in tree community composition among forests was predominantly associated with balanced variation in abundance and species turnover. All the results indicate that differences in forest types in the Eastern Himalaya are responsible for distinct and diverse tree communities, including endemic and globally protected species, and that PAs help conserve these forests. PAs can play a pivotal and central role in the conservation of biodiversity in the Himalayan region. Policy makers can do well to increase the PA coverage in the Himalaya in the near future, especially in the temperate regions. The 27 identified indicator tree species, well represented by dominant species (based on IVI values), endemics, and globally protected species, can serve as suitable indicators for future ecological monitoring of different forest ecosystems in the Eastern Himalaya. The present study also highlights the need for more in-depth, on-the-ground field studies in the Eastern Himalaya, which remains one of the least-studied biodiversity hotspots in the world.

CRediT authorship contribution statement

Samjetsabam Bharati Devi: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Suratna Sur Shan Sher Sherpa:** Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Kumar Manish:** Writing – review & editing, Visualization, Validation, Formal analysis. **Kishor Sharma:** Writing –

review & editing, Visualization, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2026.101217.

Data availability

Data is available in the Supporting Information.

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