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RESEARCH ARTICLES

Forest structure and tree diversity along an altitudinal gradient in Sikkim Himalaya

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Abstract
The vegetation types of Sikkim Himalayas more particularly Southern Sikkim has not been studied before. This study is the first comprehensive one on the tree species diversity and composition across four forest types (Tropical semi evergreen forest (TSEF), Sub-tropical broad mixed leaved hill forest (STBLHF), Himalayan wet temperate forest (HWTF) and Sub alpine Forest (SAF) in the region. We employed quadrat sampling and all the trees > = 10 cm DBH at 1.37m height were considered for the purpose. A total of 130 tree species belonging to 91 genera and 52 families were recorded in the study sites of which Moraceae and Lauraceae represented the highest number of species (8 each). The tropical semi evergreen forest (TSEF) harboured 61 species, followed by sub-tropical broad mixed leaved hill forest (STBLHF) (59), Himalayan wet temperate forest (HWTF) (43) and sub-alpine forest (SAF) (25). The Shannon-Weiner diversity index (H') in TSEF, STBLHF, HWTF and SAF was 3.31, 2.92, 2.82, and 2.34 respectively. The H' showed a linear relation with elevation ($R^2 = 0.9265$, $p < 0.05$) and the Margalef's species richness (S) indicated a significant quadratic relation ($R^2 = 0.9996$, $p < 0.05$) with elevation. A hump-shaped pattern was observed for tree species richness while the DBH size class showed a reverse J shaped pattern. It concluded that tree species diversity in South Sikkim Himalayas is primarily influenced by elevation, showing a linear decline in H′ and a hump-shaped pattern for species richness, peaking at mid-elevations. The reverse J-shaped DBH distribution indicates active regeneration, further supporting the observed diversity pattern.

Keywords Eastern Himalaya · Elevation gradient · Woody taxa · Forest types · Conservation

Introduction

Forests are the vital source of life ensuring the flow of a wide range of ecosystem service. Species diversity, floristic composition and forest structure are important ecological features that correlate significantly with prevailing environmental components (Lalfakawma et al. 2009; Sahoo and Lalfakawma 2010; 2013; Thakur et al. 2021). Quantification of these attributes has played a pivotal role in understanding the biodiversity and forest

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health (Behera et al. 2023, 2024) and is the basis of sustainable forest management (Musa and Sahoo 2023). The conservation of biodiversity and sustainable use are priority agenda of Sustainable Development Goals of the United Nations Framework Convention on Climate Change (Rees et al. 2018; Pettorelli et al. 2021). Tree diversity differ from place to place due to variation in habitat, ecology and disturbance (Naidu and Kumar 2016). Besides, climate change, land degradation, fragmentation of habitat, change in land use and gaps in the forest canopy due to deforestation have potential influence on tree diversity and its population in the forest (Behera et al. 2023; Lalfakawma et al. 2009; Lilabati et al. 2018). Amongst the different forest types tropical forest contributes significantly in regulating climate dynamics on Earth (Lewis et al. 2009) contributing about 25% of the total terrestrial carbon stock and serving as a major sink (Ahirwal et al. 2021; Gogoi et al. 2020, 2022; Sahoo et al. 2019; Singh et al. 2018). More specifically, the diversity of woody taxa can be utilized to forecast the patterns of plant species diversity across all forest ecosystems (Giorgini et al. 2015). The woody taxa contribute to habitat maintenance and resource provision for all other connected species, and their richness in some way reflects the biodiversity of the relevant forest types (Bhat et al. 2020). Elevation is one of the crucial element which affect the distribution of trees because it has a direct impact on micro climate of habitat (Shaheen et al. 2012) and it has been reported that the number of species decrease with increasing altitude (Laing et al. 2019), similarly the density of trees is higher in lower altitude than the higher altitude (Saha et al. 2016).

The Himalayas possess a distinctive and richest ecosystem with a varied range of forests, These forests greatly differ in their characteristic features due to wide range of altitudinal and climatic changes from lowlands to alpine peaks. A review of literature reveal that studies on species diversity, composition and forest structure along the elevation gradient have been done in adjacent hill ranges of Nepal (Gachhadar et al. 2023; Nepali et al. 2021), and Bhutan (Tenzin et al. 2016; Thorne et al. 2022), while a very limited number of studies on the above aspects have been carried to on the Indian Eastern Himalayas such as Arunachal Pradesh (Bharali et al. 2011; Dash et al. 2021), Meghalaya (Pao and Upadhaya 2017; Shankar and Tripathi 2017) and Assam (Buragohain et al. 2023; Dutta and Devi 2013; Gogoi and Sahoo 2018). Sikkim one of the East Himalayan Indian state that is known for its biodiversity hotspot gives a tremendous scope in research area for studying the phytodiversity along the elevation (Sharma et al. 2019; Bhutia et al. 2019), the vegetation inventory of South Sikkim has not been attempted so far.

South Sikkim is located in the Eastern Himalayas and is regarded as a rich biodiversity hotspot. A check list of species in Mamlay and Sumbuk (Myers 1988; Subba et al. 2020) and Maenam wildlife sanctuary (Hynniewta and Chhetri 2013) has been reported, however, these studies do not account a detailed vegetation inventory and there is also limited understanding to species diversity, distribution, floristic composition and forest structure of woody taxa in the major forest types and elevation gradient (500–3200 m asl) in this part of Eastern Himalayas. Through this study, we investigated to find out (i) what is the tree species composition, and how are they distributed in the major forest types/ along the wide elevation gradient in South Sikkim, (ii) quantify the phytosociological attributes and (iii) find out the relationship between elevation and species richness. Addressing these research gaps may help in sustainable management of forests and can significantly contribute in planning and policy making to forest managers in this area.

Materials and methods

Study area

The study was conducted in South district of Sikkim of India (Fig. 1) conducted during December 2022 to May 2023. The total forest cover of South Sikkim is 750 sq. km (76.15%) of the state's total geographical area wherein four forest types (based on Champion and Seth 1968) viz. (a) Tropical semi-evergreen forest, (b) Sub-tropical mixed broad leaved hill forest, (c) Himalayan wet temperate forest and (d) Sub alpine forest were selected for vegetation inventory along an elevation gradient of 500–3200 m above mean sea level (Table 1). South Sikkim is located in the Eastern Himalayas, experiences a humid subtropical to temperate climate, depending on altitude. However, low elevations (below 1500 m) experience warm summers and mild winters, while higher elevations (above 1500 m) coolor summers and cold winters (Singh et al. 2018). The average temperature ranges from 5 °C (in winter) to 25 °C (in summer). Additionally, the area experiences heavy rainfall due to the influence of the south monsoon (June to September) and the average annual rainfall ranges between 2000 mm and 3500 mm (Gupta et al. 2024; Kakkar et al. 2022). The study site is characterized by four seasons viz. summer (March to mid June (moderate), wet rainy (mid June to September), Autumn (October to November) and winter (December to Febraury) (Sharma and Shrestha, 2016). Moreover, the geographical composition of South Sikkim is part of Himalayan orogenic belt, characterized by metamorphic

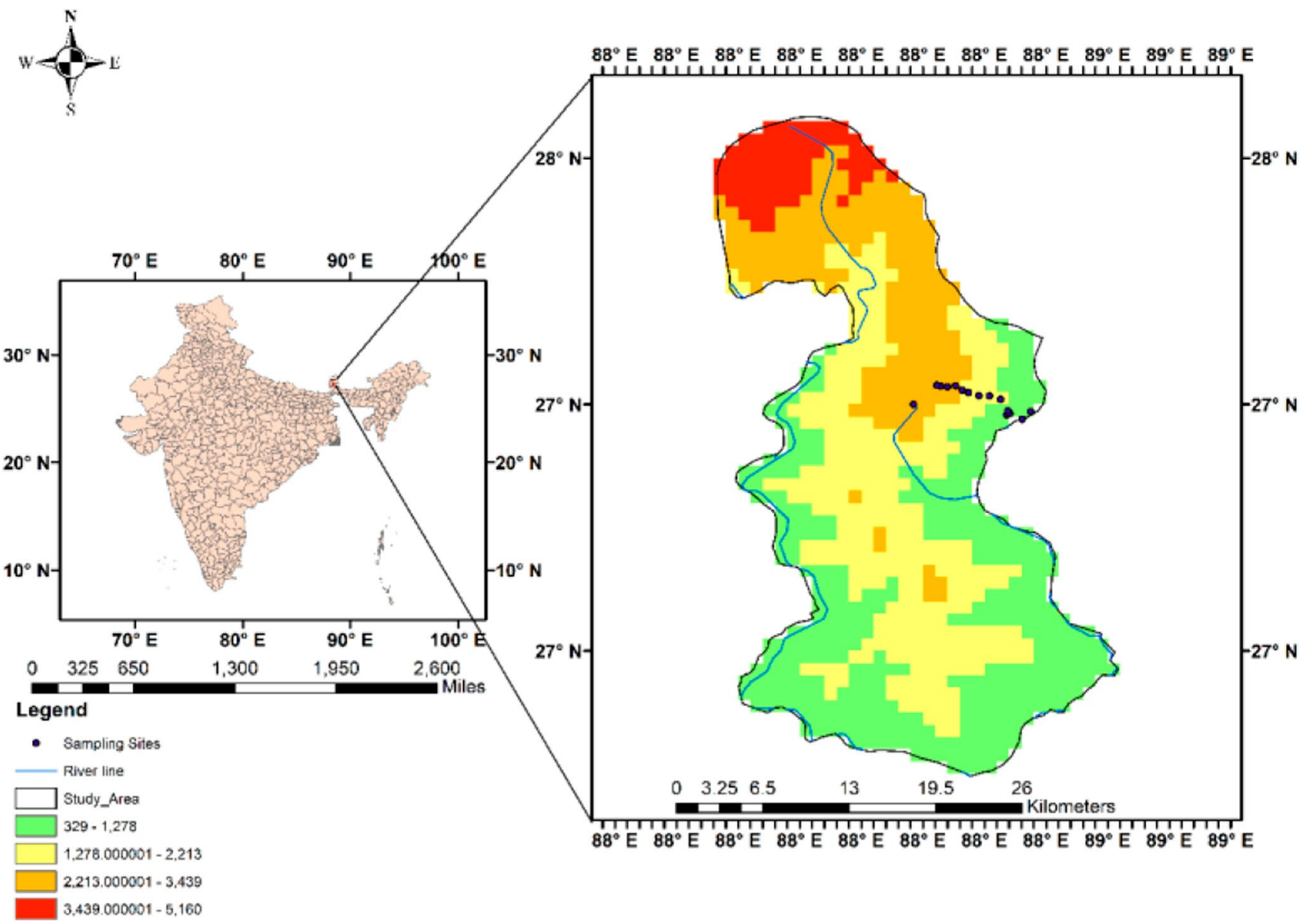

Fig. 1 Study area map showing the sampling location along the elevation

Table 1 Forest types, elevation range, management status and disturbance level

Forest name	Area sampled (ha)	Elevation Range (m)	Management status	Causes of disturbance	Disturbance
TSEF	0.45	300–900	Un reserved	Less settlement, landslide	Medium
STBLHF	0.6	1000–1800	Un reserved	More settlement, wood extraction	Highly
HWTF	0.75	1800–2700	Reserved	less anthropogenic factors	Low
SAF	0.45	2800–3500	Reserved	less anthropogenic factors	Low

TSEF-Tropical semi evergreen forest; STBLHF- Sub-tropical broad mixed leaved hill forest; HWTF- Himalayan wet temperate forest; SAF-Sub alpine Forest

rocks such as schists, gneisses, quartzites, and phyllites, although, these rocks are part of the daling group and Darjeeling gneissic complex (Jha and Sharma 2022). Furthermore, the soil type in the site mostly include loamy to clay rich in organic matter, however, red loam and brown forest soils are also typical (Gangopadhyay and Bhattacharyya 2022). Simultaneously, South Sikkim lies within a seismically active zone due to the collision of the Indian plate with the Eurasian plate (Singh et al. 2007).

Sampling

Quadrat samplings were employed for enumerating woody stems of size ≥ 10 cm diameter at breast height (DBH) (1.37 m from the ground). Three replicated plots of 0.1 ha (50 m × 20 m) was laid in each elevation band and in each 0.1 ha plot, five 10 m × 10 m quadrats were laid down for the vegetation survey. Every individual woody plant species was identified with the help of regional floras (Rai 2018; Gogoi et al. 2021). A measuring tape was used for DBH measurement while ocular estimate was done for tree height. A total of 45 quadrats in tropical semi-evergreen forest (TSEF), 60 quadrats in sub-tropical broad mixed leaved hill forest (STBLHF), 75 quadrats in Himalayan wet temperate forest (HWTF) and 45 quadrats in sub-alpine forest (SAF) were sampled (Table 1). Tree density, basal area and girth class were estimated from 0.45 ha area, 0.60 ha and 0.75 and 0.40 ha area respectively and extrapolated on per ha basis. The management and disturbance level of the forests are shown in Table 1.

Data analysis

The data collected in the field was analysed following standard ecological methods (Misra 1968). Frequency, density and basal area were determined for each species following Ellenberg and Mueller-Dombois (1974). The importance value index (IVI) was calculated by the summation of relative values of frequency, density and basal area. The Abundance to Frequency ratio (A/F) of each species was calculated to study the population distribution pattern. The ranges of values for determining distribution pattern were: regular (<0.025), random (0.025–0.05) and contiguous (>0.05) as given by Curtis and McIntosh (1951). Population structure of tree species was analysed using girth and height classes. Plant classification was done following APG classification using plant list (World Flora Online). The Shannon-Wiener diversity index (H') was calculated following Shannon and Wiener (1963), Simpson's dominance index was calculated following Simpson (1949), Simpson and Pielou's index of evenness was calculated following Pielou (1975) and species richness calculated using Margalef (1957). Species richness was determined as the total number of species in sampled area for different life forms. Linear regression analysis was used to determine the linear/quadratic relationship between diversity and tree richness with elevation gradients in different forest types of Sikkim Himalaya. The population structure of sampled tree species was assessed based on the data on individuals' ≥10 cm DBH. The data were analysed using RStudio (Version 2023.06.0) and Microsoft excel (version 2019).

Results

Species composition, density and dominant woody taxa in four forest types

The composition of woody taxa varied significantly between the forest types. The composition of species was in the order of TSEF (61 species,46 genera and 29 families) > STBLHF (59 species, 48 genera and 34 families) > HWTF (43 species, 33 genera and 27 families) > SAF (25 species,18 genera and 16 families) (Table 2). The total number of woody individuals (≥ 10 cm DBH) similarly, varied extensively between the sampled sites (798 woody individuals in TSEF, 1136 individuals in STBLHF, 1277 individuals in HWTF and 2584 individuals in SAF). The dominance of species also differed from forest to forest (Suppl. Table 1). While *Ostodes paniculata* (IVI-36.89) was the dominant species at TSEF, the co-dominant species in TSEF were *Schima wallichii* (IVI-33.21), *Engelhardia spicata* (IVI-25.90) and *Ailanthus integrifolia* (IVI-24.82). In STBLHF, the dominant species was *Engelhardia spicata* (IVI-50.59) and the co-dominant species were *Ostodes paniculata* (IVI-19.60) and *Lyonia ovalifolia* (IVI-15.38). In HWTF, the dominant species was *Sympocos dryphila* (IVI-39.93) and the co-dominant species were *Machilus odoratissimum* (IVI-39.08), *Viburnum erubescens* (31.87) and *Lithocarpus pachyphyllus* (28.93). In SAF, the dominant species was *Lyonia ovalifolia* (IVI-47.99) and the co-dominant species were *Rhododendron falconeri*

Table 2 Diversity indices of all four forest types of South Sikkim

Attributes	All	TSEF	STBLHF	HWTF	SAF
Number of species	130	61	59	43	25
Genera	91	46	48	33	18
Families	52	29	34	27	16
No. of individuals	3158	359	678	958	1163
Density (ha^{-1})	5789.54	797.8	1130	1277.3	2584.44
Basal area (m^2 ha^{-1})	183.16	28.66	25.17	76.53	52.8
Shannon -Weiner's diversity index (H′)	11.39	3.31	2.92	2.82	2.34
Evenness index	3	0.81	0.72	0.74	0.73
Simpson's diversity index (D)	3.6	0.93	0.89	0.91	0.87
Simpson's reciprocal index (1/D)	4.43	1.07	1.12	1.1	1.14
Concentration of dominance (Cd)	0.34	0.06	0.11	0.07	0.1
Margalef's richness index (R)	28.91	10.2	8.9	6.41	3.4

TSEF-Tropical semi evergreen forest, STBLHF-Subtropical mixed broad leaved hill forest, HWTF-Himalayan wet temperate forest, SAF-Subalpine forest

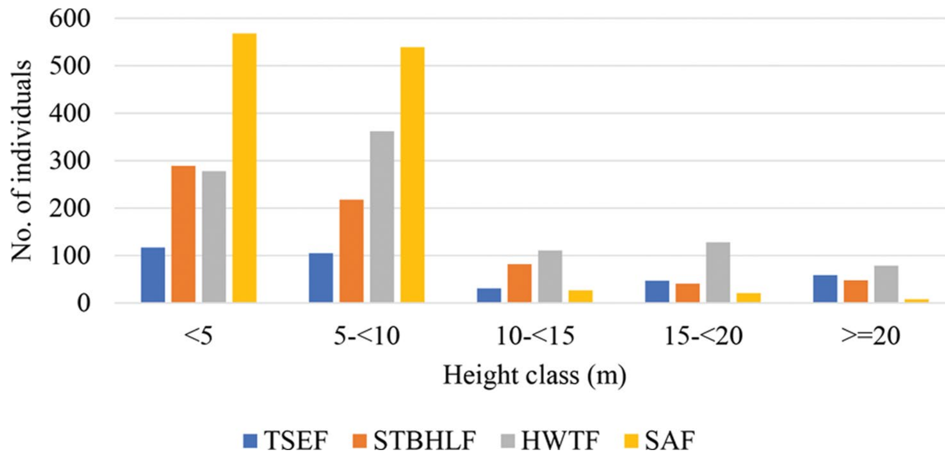

Fig. 2 Population structure of four different forest types in different height classes

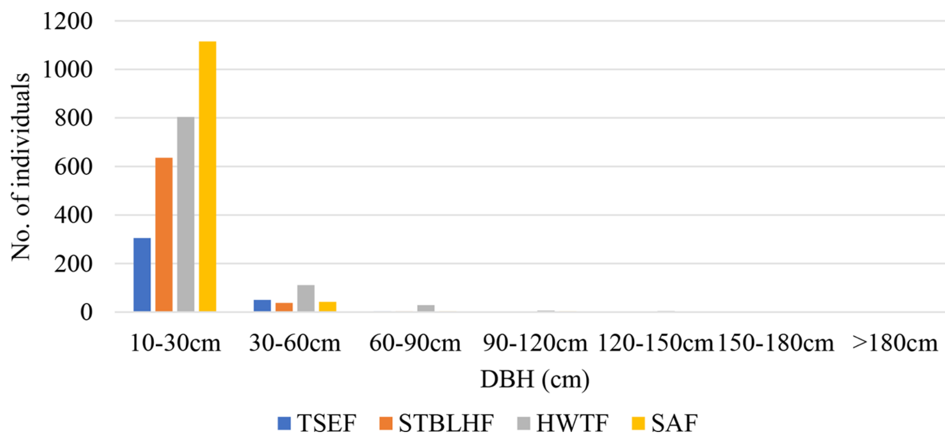

Fig. 3 Population structure of four different forest types in different DBH classes

(IVI-43.96), *Lithocarpus pachyphyllus* (IVI-38.60) and *Daphniphyllum himalense* (IVI-25.48).

Diversity indices and species richness

The diversity indices differed between forest types (Table 2). Shannon-Weiner' diversity index (H′) was 3.31, 2.92, 2.82, and 2.34 in TSEF, STBLHF, HWTF and SAF respectively (Table 2). The species richness was in the order of TSEF,> STBLHF > HWTF > SAF.

Tree height and DBH distribution

There was a distinct variation in tree height between the forest types. A majority of tree species were of < 5 m and 5-<10 m height found in SAF. There was a distinct and gradual decline in tree height in the order of SAF > HWTF > STBHLF > TSEF for 5-<10 m height class (Fig. 2). The larger height trees (10-<15 m, 15-<20 m and > = 20 m) were found in HWTF. The stem diameter in four forest types of Sikkim was divided into seven classes (Fig. 3), the highest class was recorded by 10–30 cm in four forest types, and shown J shaped, DBH class distribution decreased with the increase in diameter of trees, but the lack of big diameter class also could be due to disturbance or cutting of big tree by local community or local people around forest (Fig. 4).

Relationship between elevation with diversity and species richness

A strong relationship was observed between the elevation with diversity ($R2 = 0.9265$) and species richness ($R2 = 0.9996$) in the study area (Fig. 5).

Discussion

Species composition, density of woody taxa

The forest types differed from one another with respect to tree species composition, density, and diversity. As expected, the altitude-induced climatic variation along with forest management and anthoropogenic disturbances, these factorsmay influence tree growth and species composition. The HWTF and SAF are reserved forests with minimal anthropogenic disturbances while TSEF and STBLHF are unreserved and therefore, the latter two forest types were

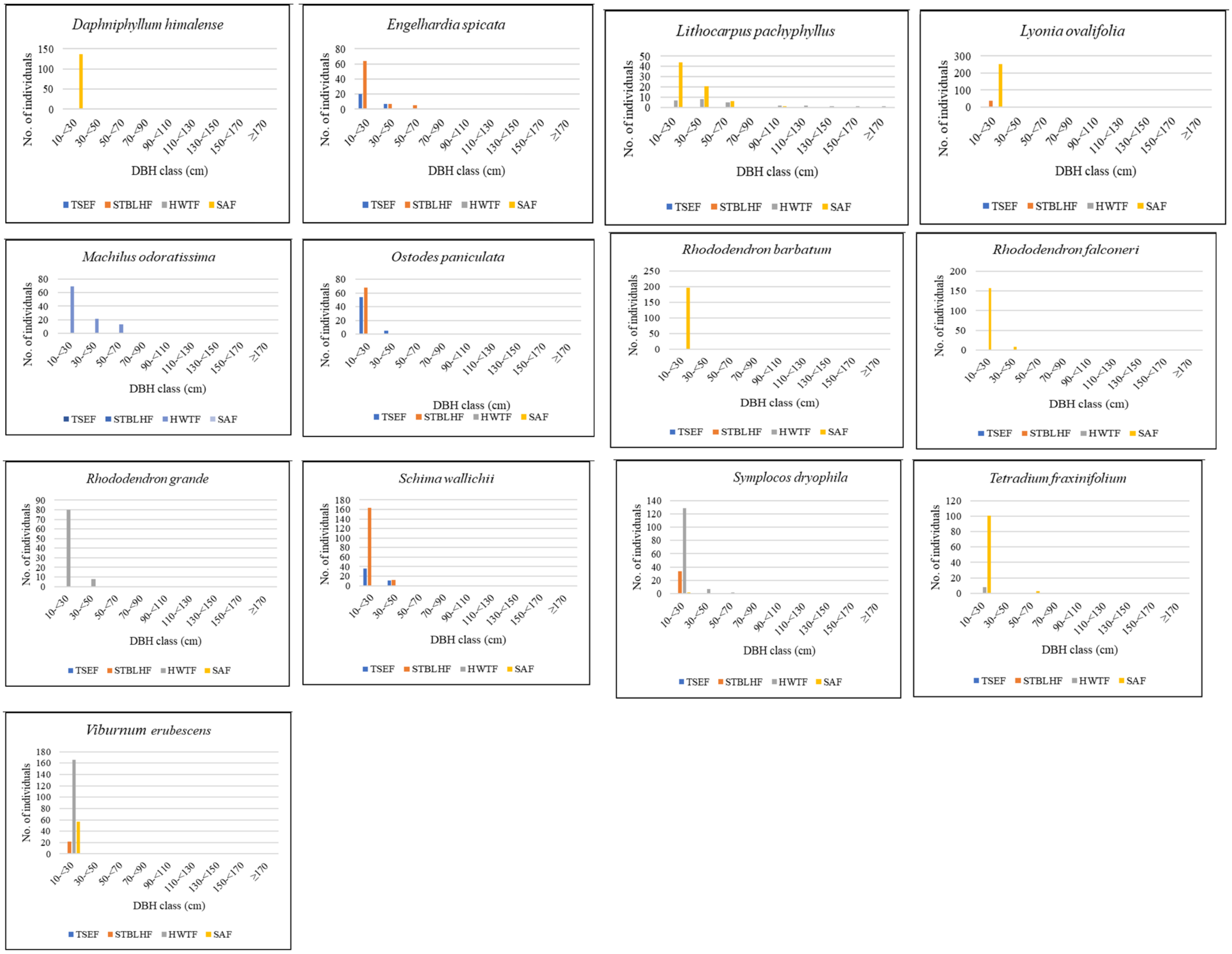

Fig. 4 DBH classes distribution of dominance species in four forest type

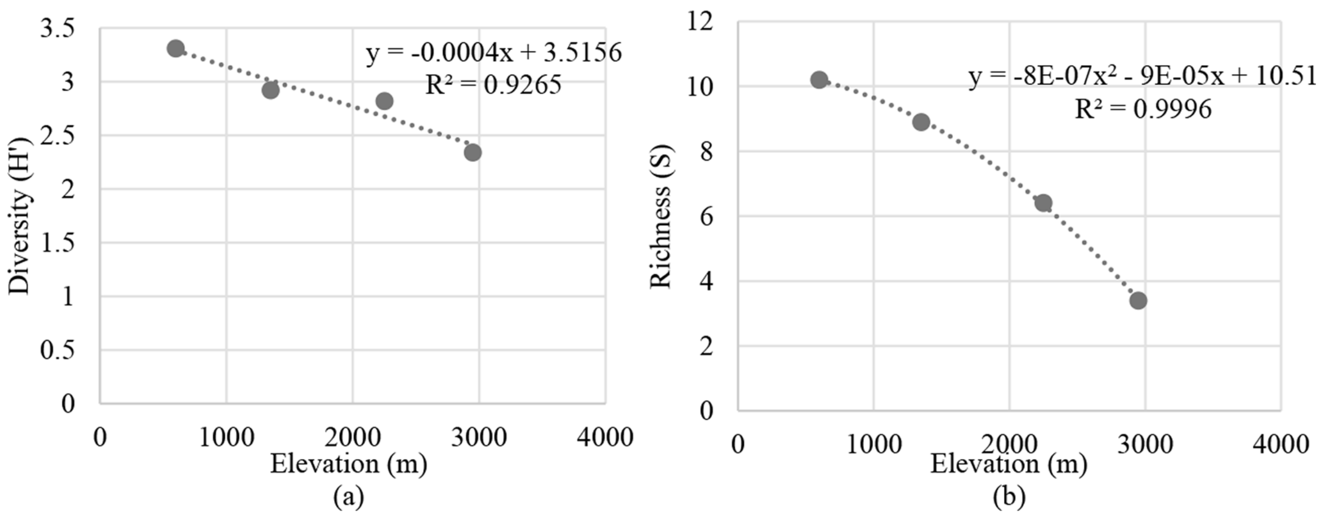

Fig. 5 Relationships between elevation and tree species composition (**a**) Shannon Index of Diversity (H'), (**b**) Margalef's Index of species richness

subjected to higher level of anthropogenic disturbances (Table 1). The species richness in TSEF, STBLHF, HWTF and SAF was 61, 59, 43, and 25 respectively. This clearly suggested that the altitude played an important role in determining species richness. Many authors also have reported that species richness decreases with increase in altitude and also from high to low-rainfall regions (Rahbek 1995; Pandey et al. 2016; Bhutia et al. 2019; Mohandass et al. 2016). The higher number of individuals per unit area in HWTF and SAF reflect that the forest with low human disturbances and forest protection towards illegal felling and encroachment (Table 1). Various authors have reported that the vegetation composition and functional traits of plant communities are influenced by a variety of environmental processes including topography, disturbance, and edaphic factors (Sahoo et al. 2009; Thakur et al. 2021). Besides, global climate change, land degradation, habitat fragmentation, land-use change and gaps in the forest canopy due to logging have potential influence on diversity and tree population in the forest (Gachhadar et al. 2023; Gogoi and Sahoo 2018; Gogoi et al. 2020).

A total 130 species belonging to 82 genera and 51 families were recorded in four forest types of south Sikkim. This result indicate that the species richness reported in the present study is highest compared to other studies in India. For example, 97 species of a mid-elevation tropical montane evergreen forests (sholas) of the Western Ghats, Southern India (Mohandass et al. 2016), 122 species in Western Himalayan Moist Temperate Forest in Kashmir (Shaheen et al. 2012), 118 tree species were recorded in sub-tropical forest of Nagaland, Northeast India (Ao et al. 2021). The dominant families reported in the forests are Moraceae and Anacardiaceae in STEF, Anacardiaceae in STBLHF, Araliaceae and Ericaceae in HWTF, and Ericaceae in SAF. The overall dominant families are Moraceae (8) Lauraceae (8) followed by Anacardiaceae (7), Ericaceae (6) and Araliaceae (4). Similarly recorded by Pandey et al. (2016) reported that Ericaceae was the most dominant family while Lauraceae was reported to be the dominant family (Mohandass et al. 2016). The dominant families reported in a mid-elevation Tropical Montane Evergreen Forests (sholas) of the Western Ghats, Southern India are Rubiaceae, Euphorbiaceae, Myrtaceae and Symplocaceae (Mohandass et al. 2016). These findings suggest that the dominance of a particular or group of families are specific to a location and the micro environmental factors operating in the ecosystem.

Dominance and diversity of tree species

Importance value index is a reliable measure to assess the relative importance of a species since it takes into account several properties of the species in the vegetation (Myer 1988; Nayak and Sahoo 2020). The highest IVI species indicate the dominance of species in given forest, density per unit area and frequency. As discussed by Padalia et al. (2004) and Naidu and Kumar (2016) diversity of tree species in a forest is attributed mainly to the variation in habitat, biogeography and disturbance. The distribution of species has been found to be strongly correlated with climatic variation (Khaine et al. 2017). We found increase in H′ with the increase in number of species in forest type as well as decrease with increase of elevation or richness of species decline with increase in altitude. As mentioned earlier the reduction in tree species diversity is also arising due to the high dependency on forest resources by the surrounding local villages for fuel wood, medicine, and shifting cultivation (Ao et al. 2021). Species diversity and structural complexity of a forest nevertheless could also be influenced by rainfall and other environmental factors that help in the development of vegetation (Khaine et al. 2017). Therefore, the higher value of diversity reveal a forest with high tree species diversity and abundance, and species diversity can be very useful tool in forestry and/or plant ecology to compare the composition of different tree species (Naidu and Kumar 2016). Moreover, altitude is one of important factors of tree distribution due to its direct impact on habitat microclimate (Shaheen et al. 2012). The H′ value in STBLHF is higher than western Himalayan moist temperate forest in Kashmir which ranged from 0.75 to 2.27 (Shaheen et al. 2012), Dhanaulti of Garhwal Himalaya ranged from 0.84 to 2.13 for trees (Saha et al. 2016), different sites of tropical forest in Myanmar the species diversity (H) ranged from 2.03 to 3.20. Likewise, H′ value in our study was found less than the sub-tropical forest of Nagaland, Northeast India that ranged from 2.95 to 3.88 (Ao et al. 2021), 3.40 in a mid-elevation tropical montane evergreen forests (sholas) of the Western Ghats, Southern India (Mohandass et al. 2016).

Stand structure: stem diameter, stem density, and basal area

Tree height, dbh are commonly used to measure the tree growth and tree height and species richness are both essential to character a forest structure. Higher densities of the trees in medium to lower girth classes suggest that the forests are still in the evolving stage. The 1st two dbh classes (10–30 and 30–60 cm) represented more than 98% of total tree density while the 1st dbh class (10–30 class) represented more than 70% total tree density (Fig. 3). From this observation, it can be inferred that the forest is a very young one and undergoing regeneration that require various degree of forest protection. Forest structure may also show variation among continents as well as countries (Khaine et al. 2017). The frequency and density distribution of trees contributes to the forest structure (Yam and Tripathi 2016; Pandey et al. 2016). The biotic factors e.g. seed quality, seedling survivorship and recruitment are important in sustaining the tree composition of forest (Naidu and Kumar 2016). Likewise, altitude and slope strongly affect the species structure and composition. The dbh distribution in Sikkim Himalayan is conformity with others (Mohandass et al. 2016; Yam and Tripathi 2016). In this study, we found the population density, the diameter of tree and/or size classes showing a reverse J-shaped distribution which mean that the trees having the lower DBH class are more in the population than the higher DBH classes. The lower DBH class often indicates the presence of regenerating tree species within the forest. However, increased disturbance can lead to variations in forest cover, resulting greater light availability. This enhanced sunlight penetration can promote the regeneration and growth of light-demanding tree species. Contrary to this many scientists (Pandey et al. 2016; Sharma et al. 2019; Bhutia et al. 2019) reported that tree species follow a hump-shaped pattern with elevation. Many others have argued that the tree density and diversity is higher in small DBH classes compared to the large DBH (Mohandass et al. 2016; Aye et al. 2014; Gogoi et al. 2020), likewise the basal area (BA) was increased with the increasing DBH (Mohandass et al. 2016).

Stem density was in the order of TSEF < STBLHF < HWTF < SAF which indicated that with the increase of elevation the density of trees species increased. The lower elevation forests were subjected to higher degree of human-disturbances and thus this trend of stem density. The highest number of stem density was recorded in SAF is highest compare to Dhanaulti of Garhwal Himalaya tree density ranged from 850 to 1210 per hectare (Saha et al. 2016), 804 per hectare in dry evergreen forest to 1293 per hectare in dry dipterocarp forest (Aye et al. 2014). Mohandass et al. (2016) recorded 1290 stem per hectare in a mid-elevation Tropical Montane Evergreen Forests (sholas) of the Western Ghats, Southern India. As has been reported by Ao et al. (2021) increasing human population can negatively affect the forest wealth. Therefore, the tree density and compositional variations along the altitudes are reflection to the factors of anthropogenic activities, natural calamities and also to soil properties (Naidu and Kumar 2016; Mohandass et al. 2016). Further, stand density are reported to be influenced by aspects and slopes (Pandey et al. 2016), besides, to other factors such as dispersal ability, stand history, habitat suitability, disturbance and ecological interactions. The forest community type, age, site history and site conditions too could influence the composition, diversity and density of tree species (Kumar et al. 2006; Parthasarathy 2001). As expected, the basal area of a species was influenced by the DBH and therefore with the increase of DBH, the highest basal area per hectare was recorded in HWTF (76.53 m^2 ha^{-1}) (Table 2) compared to other three forest types.

Conclusions

This study gives information on woody taxa diversity, composition and structure among the different forest types. A total of 130 tree species that belonged to 82 genera and 51 families were recorded and Moraceae and Lauraceae were represented by the highest number of species (8 each). Lower altitude offered a more diverse range of habitats and microclimates, allowing the coexistence of a greater number of tree species. As elevation increased a gradual decline in tree species richness was observed. Overall, the Himalayan wet temperate forest was the stable ecosystem having individuals from all the diameter classes. The study depicts the important role played by the altitude in influencing species diversity, composition and forest structure.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42535-024-01154-1.

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Data availability The data will be available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethical approval Not applicable.

Consent for publication Not applicable.

Consent to participate Not applicable.

Conflict of interest The authors declare that they have no conflict of interest.

References

Ahirwal J, Nath A, Brahma B, Deb S, Sahoo UK, Nath AJ (2021) Patterns and driving factors of biomass carbon and soil organic carbon stocks in the Indian himalayan region. Sci Total Environ 770:113972

Ao A, Changkija S, Tripathi SK (2021) Stand structure, community composition and tree species diversity of sub-tropical forest of Nagaland, Northeast India. Trop Ecol 62(4):549–562. https://doi.org/10.1007/s42965-021-00170-5

Aye YY, Pampasit S, Umponstira C, Thanacharoenchanaphas K, Sasaki N (2014) Floristic composition, diversity and stand structure of tropical forests in Popa Mountain Park. J Environ Prot 5(17):1588. https://doi.org/10.4236/jep.2014.517150

Behera MC, Sahoo UK, Mohanty TL, Prus P, Smuleac L, Pascalau R (2023) Species composition and diversity of plants along human-induced disturbances in tropical moist Sal forests of Eastern Ghats, India. Forests 14(10):1931. https://doi.org/10.3390/f14101931

Behera MC, Sahoo UK, Mohanty TL, Nayak S (2024) Sal-dominated forest influence the floristic composition, diversity and distribution pattern with special focus on the associated trees in the eastern ghats of Odisha. Int J Ecol Env Sci 50:711–726

Bharali S, Paul A, Khan ML, Singha LB (2011) Species diversity and community structure of a temperate mixed Rhododendron forest along an altitudinal gradient in West Siang District of Arunachal Pradesh, India. Nat Sci 9(12):125–140

Bhat JA, Kumar M, Negi AK, Todaria NP, Malik ZA, Pala NA, Kumar A, Shukla G (2020) Species diversity of woody vegetation along altitudinal gradient of the Western Himalayas. Global Ecol Conserv 24:e01302. https://doi.org/10.1016/J.GECCO.2020.E01302

Bhutia Y, Gudasalamani R, Ganesan R, Saha S (2019) Assessing forest structure and composition along the altitudinal gradient in the state of Sikkim, Eastern Himalayas, India. *Forests*, *10*(8), p.633

Buragohain MK, Dar AA, Babu KN, Parthasarathy N (2023) Tree community structure, carbon stocks and regeneration status of disturbed lowland tropical rain forests of Assam, India. Trees Forests People 11:100371. https://doi.org/10.1016/j.tfp.2023.100371

Champion HG, Seth SK (1968) A revised survey of the forest types of India. Manager of

Curtis JT, McIntosh RP (1951) An upland forest continuum in the prairie-forest border region of Wisconsin. Ecology 32(3):476–496. https://doi.org/10.2307/1931725

Dash SS, Panday S, Rawat DS, Kumar V, Lahiri S, Sinha BK, Singh P (2021) Quantitative assessment of vegetation layers in tropical evergreen forests of Arunachal Pradesh, Eastern Himalaya, India. Curr Sci, pp.850–858

Dutta G, Devi A (2013) Plant diversity, population structure, and regeneration status in disturbed tropical forests in Assam, northeast India. J Forestry Res 24(4):715–720. https://doi.org/10.1007/s11676-013-0409-y

Ellenberg D, Mueller-Dombois D (1974) Aims and methods of vegetation ecology. Wiley, New York, p 547

Gachhadar PK, Mandal TN, Baniya CB (2023) Forest structure and biodiversity patterns along elevational gradients in Eastern Nepal. Sci World 16(16):106–127. https://doi.org/10.3126/sw.v16i16.57298

Gangopadhyay SK, Bhattacharyya T (2022) Mollisols of Sikkim: the unique soils of the humid temperate zone of India. Clay Res 41(1):13–35. https://doi.org/10.5958/0974-4509.2022.00002.X

Giorgini D, Giordani P, Casazza G, Amici V, Mariotti MG, Chiarucci A (2015) Woody species diversity as predictor of vascular plant species diversity in forest ecosystems. For Ecol Manag 345:50–55. https://doi.org/10.1016/j.foreco.2015.02.016

Gogoi A, Sahoo UK (2018) Impact of anthropogenic disturbance on species diversity and vegetation structure of a lowland tropical rainforest of eastern Himalaya, India. J Mt Sci 15(11):2453–2465

Gogoi A, Sahoo UK, Saikia H (2020) Vegetation and ecosystem carbon recovery following shifting cultivation in Mizoram-Manipur-Kachin rainforest ecoregion, South Asia. Ecol Process 9:1–13

Gogoi R, Sherpa N, Benjamin F, Agrawala JH, Rai DK, S.K., Dash SS (2021) Flora of Sikkim - A Pictorial Guide. Botanical Survey of India, Kolkata and Forest & Environment Department, Sikkim, p 566

Gogoi A, Sahoo UK, Ahirwal J (2022) Evaluation of ecosystem carbon storage in major forest types of eastern Hmalaya: implications for carbon sink management. J Environ Manage 302:113972

Gupta B, Jose MM, Aggarwal S, Ranjan O (2024) A comprehensive analysis of long-term trends in temperature and rainfall patterns in Sikkim, India. J Clim Change 10(4):1–8

Hynniewta TM, Chhetri G (2013) A checklist of dicot flora of Maenam Wildlife Sanctuary and its adjacent areas, South Sikkim, India. Pleione 7(2):376–400

Jha V, Sharma R (2022) Formation of polymetallic ores in the metasedimentary rocks of Rangpo area, Sikkim Lesser Himalaya, India: mineralogical and geochemical attributes. Geol J 57(12):5061–5082

Kakkar A, Rai PK, Mishra VN, Singh P (2022) Decadal trend analysis of rainfall patterns of past 115 years & its impact on Sikkim, India. Remote Sens Applications: Soc Environ 26:100738

Khaine I, Woo SY, Kang H, Kwak M, Je SM, You H, Lee T, Jang J, Lee HK, Lee E, Yang L (2017) Species diversity, stand structure, and species distribution across a precipitation gradient in tropical forests in Myanmar. Forests 8(8):282. https://doi.org/10.3390/f8080282

Kumar A, Marcot BG, Saxena A (2006) Tree species diversity and distribution patterns in tropical forests of Garo Hills. Curr Sci, pp.1370–1381

Laing RS, Ong KH, Kueh RJH, Mang NG, King PJH, Sait M (2019) Stand structure, floristic composition and species diversity along altitudinal gradients of a bornean mountain range 30 years after selective logging. J Mt Sci 16(6):1419–1434. https://doi.org/10.1007/s11629-018-5219-4

Lalfakawma; Sahoo UK, Roy S, Vanlalhriatpuia K, Vanlalhluna PC (2009) Community composition and tree population structure in undisturbed and disturbed tropical semi-evergreen forest stands of North-East India. Appl Ecol Environ Res 7(4):303–318

Lewis SL, Lloyd J, Sitch S, Mitchard ET, Laurance WF (2009) Changing ecology of tropical forests: evidence and drivers. Annu Rev Ecol Evol Syst 40:529–549. https://doi.org/10.1146/annurev.ecolsys.39.110707.173345

Lilabati L, Sahoo UK, Thangjam U (2018) Floristic composition and regeneration status of *Emblica officinalis* Gaertn. In two semi-evergreen forest stands of Manipur, India. J Experimental Biology Agricultural Sci 6(3):563–571. https://doi.org/10.18006/20186(3)563571

Margalef DR (1975) Information theory in ecology Mem. Real Acad ciencias y artes de Barcelona 32:374–559. https://cir.nii.ac.jp/crid/1571980074889553536

Misra R (1968) Ecology workbook. Scientific

Mohandass D, Hughes AC, Mackay B, Davidar P, Chhabra T (2016) Floristic species composition and structure of a mid-elevation tropical montane evergreen forests (sholas) of the western ghats, southern India. Trop Ecol 57(3):533–543

Musa FI, Sahoo UK (2023) Role of sustainable forest management in poverty reduction and livelihood improvement in Sudan: a review. Int J Ecol Env Sci 49:449–456

Myers N (1988) Threatened biotas: hot spots in tropical forests. Environmentalist 8(3):187–208. https://doi.org/10.1007/BF02240252

Naidu MT, Kumar OA (2016) Tree diversity, stand structure, and community composition of tropical forests in Eastern Ghats of Andhra Pradesh, India. J Asia-Pacific Biodivers 9(3):328–334. https://doi.org/10.1016/j.japb.2016.03.019

Nayak S, Sahoo UK (2020) Tree diversity and ecological status of Madhuca latifolia (Roxb.) JF Macbr in forests of Odisha. Ind J Ecol 47(1):138–149

Nepali BR, Skartveit J, Baniya CB (2021) Impacts of slope aspects on altitudinal species richness and species composition of Narapani-Masina landscape, Arghakhanchi, West Nepal. J Asia-Pacific Biodivers 14(3):415–424. https://doi.org/10.1016/j.japb.2021.04.005

Padalia H, Chauhan N, Porwal MC, Roy PS (2004) Phytosociological observations on tree species diversity of Andaman Islands, India. Curr Sci, pp.799–806

Pandey KP, Adhikari YP, Weber M (2016) Structure, composition and diversity of forest along the altitudinal gradient in the Himalayas, Nepal. Appl Ecol Environ Res 14(2):235–251. https://doi.org/10.15666/aeer/1402_235251

Pao NT, Upadhaya K (2017) Effect of fragmentation and anthropogenic disturbances on floristic composition and structure of subtropical broad leaved humid forest in Meghalaya, Northeast India. Appl Ecol Environ Res 15(385):e407. https://doi.org/10.15666/aeer/1504_385407n

Parthasarathy N (2001) Changes in forest composition and structure in three sites of tropical evergreen forest around Sengaltheri, Western Ghats. *Current science*, pp.389–393

Pettorelli N, Graham NA, Seddon N, Maria da, Cunha Bustamante M, Lowton MJ, Sutherland WJ, Koldewey HJ, Prentice HC, Barlow J (2021) Time to integrate global climate change and biodiversity science-policy agendas. Journal of Applied Ecology, 58(11), pp.2384–2393

Pielou EC (1975) Ecological diversity. https://cir.nii.ac.jp/crid/1130000795048897920

Rahbek C (1995) The elevational gradient of species richness: a uniform pattern? Ecography 18(2):200–205

Rai P (2018) Common Flora of South Sikkim: a glance to ethnicity and diversity of common flora of South Sikkim. Notion

Rees SE, Foster NL, Langmead O, Pittman S, Johnson DE (2018) Defining the qualitative elements of Aichi Biodiversity Target 11 with regard to the marine and coastal environment in order to strengthen global efforts for marine biodiversity conservation outlined in the United Nations sustainable development goal 14, vol 93. Marine Policy, pp 241–250

Saha S, Rajwar GS, Kumar M (2016) Forest structure, diversity and regeneration potential along altitudinal gradient in Dhanaulti of Garhwal Himalaya. For Syst 25(2):e058–e058

Sahoo UK, Lalfakawma (2010) Population dynamics of *Schima Wallichii* in an undisturbed vs disturbed forest stands of northeast India. Int J Ecol Env Sci 36:157–165

Sahoo UK, Lalfakawma (2013) Population dynamics of Castanopsis tribuloides A.(DC) in an undisturbed and disturbed tropical forest stands of northeast India. J Exp Biol Agric Sci 1(6):454–463

Sahoo UK, Singh SL, Gogoi A, Kenye A, Sahoo SS (2019) Active and passive soil organic carbon pools as affected by different land use types in Mizoram, northeast India. PLoS ONE, 14(7), e0219969

Shaheen H, Ullah Z, Khan SM, Harper DM (2012) Species composition and community structure of western himalayan moist temperate forests in Kashmir. For Ecol Manag 278:138–145. https://doi.org/10.1016/j.foreco.2012.05.009

Shankar U, Tripathi AK (2017) Rainforests north of the Tropic of Cancer: physiognomy, floristics and diversity in 'lowland rainforests' of Meghalaya, India. Plant Divers 39(1):20–36. https://doi.org/10.1016/j.pld.2016.10.003

Shannon CE, Wiener W (1963) The Mathematical Theory of Communication. University of Illinois Presss, Urbana, IL, p 127

Sharma RK, Shrestha DG (2016) Climate perceptions of local communities validated through scientific signals in Sikkim Himalaya, India, vol 188. Environmental monitoring and assessment, pp 1–11

Sharma N, Behera MD, Das AP, Panda RM (2019) Plant richness pattern in an elevation gradient in the Eastern Himalaya. Biodivers Conserv 28:2085–2104. https://doi.org/10.1007/s10531-019-01699-7

Simpson EH (1949) Measurement of diversity. Nature 163(4148):688–688. https://doi.org/10.1038/163688a0

Singh SP, Gumber S (2018) Climate change in Himalayas: research findings and complexities. International Journal of Plant and Environment, 4(01)

Singh A, Kumar MR, Raju PS (2007) Mantle deformation in Sikkim and adjoining Himalaya: Evidences for a complex flow pattern. Phys Earth Planet Inter 164(3–4):232–241

Subba S, Gurung K, Subba S, Nepal S (2020) Quantitative analysis of vegetation structure, composition and species diversity of moist Sal bearing tropical forest of Sumbuk reserve forest in South Sikkim, India. Trop Plant Res 7(1):245–254. https://doi.org/10.22271/tpr.2020.v7.i1.030

Tenzin J, Hasenauer H (2016) Tree species composition and diversity in relation to anthropogenic disturbances in broad-leaved forests of Bhutan. Int J Biodivers Sci Ecosyst Serv Manage 12(4):274–290. https://doi.org/10.1080/21513732.2016.1206038

Thakur U, Bisth NS, Kumar A, Kumar M, Sahoo UK (2021) Regeneration potential of forest vegetation of Churdhar Wildlife Sanctuar of India: Implicaton for forest management. Water Air Soil Pollut 232:373. https://doi.org/10.1007/s11270-021-05315-9

Thorne JH, Choe H, Dorji L, Yangden K, Wangdi D, Phuntsho Y, Beardsley K (2022) Species richness and turnover patterns for tropical and temperate plants on the elevation gradient of the eastern Himalayan Mountains. Front Ecol Evol 10:942759. https://doi.org/10.3389/fevo.2022.942759

Yam G, Tripathi OP (2016) Tree diversity and community characteristics in Talle Wildlife Sanctuary, Arunachal Pradesh, Eastern Himalaya, India. J Asia-Pacific Biodivers 9(2):160–165. https://doi.org/10.1016/j.japb.2016.03.002