Patterns of Regeneration Along an Altitudinal Gradient in a Montane Forest, Eastern Himalaya

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Abstract: - Plant population structure and regeneration status are crucial for understanding forest ecosystem dynamics. Assessment of population structure and regeneration status is essential for effective planning, conservation, and sustainable management of forest resources. Tree seedling recruitment, growth, and survival are influenced by microclimatic, biotic and edaphic factors. Elevation is a complex combination of climatic and edaphic variables contributing to altitudinal variation. The present study investigates into the patterns of recruitment and regeneration in a montane forest from Eastern Himalaya along altitudinal gradient. It is concluded that population dynamics are influenced by a history of disturbance regimes, including small-scale disturbances from gap creation or temperature change.

Key-Words: - Population structure, Regeneration status, Altitude. Montane forest, disturbance, pyramids

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1 Introduction

Plant population structure and regeneration status is significant to understand the dynamics of vegetation. Regeneration is a vital part of any forest ecosystem dynamics as it regulates the existence of species and restoration of degraded forest land [1]. The population structure indicates the continuity and stability of a population. The population dynamics of seedlings, saplings, and tree can reveal the regeneration profile of a specific species. The regeneration status of a species is poor if the number of seedlings and saplings is much less than mature individuals [2]. The floristic composition and distribution across tropics are determined by topography, local climatic regime, and edaphic features [3]. Natural regeneration in forest ecosystems facilitate the establishment and development of indigenous flora, improving the stability, adaptability, and species heterogeneity [4]. The assessment of population structure and regeneration status is necessary for the effective planning, forest conservation, and sustainable management of forest resource base [5], [6]. Studies on population behavior of tree seedlings in different forests have shown that their recruitment, growth and survival are influenced by a variety of microclimatic and edaphic factors [7]. It is influenced by disturbances because patterns of regeneration rely greatly on interactions between disturbance regimes (i.e., intensity, frequency, and scale) [8].

Elevation and climatic factors are the governing factors for regional differences in species composition [9] impacting distribution of the species. Elevation itself represents a complex combination of related climatic variables closely correlated with numerous other environmental properties, i.e, soil texture, nutrients and substrate stability [10]. Tropical mountain forests, located at altitudes between 1,200 and 3,500 m, [11] are among the world's most species-rich ecosystems. They are sensitive to extreme erosion due to steep relief, and are dwindling rapidly due to population pressure and resource use like firewood, mineral resources, pastures, agriculture. The neotropical montane region is ranked among the 12 major crop-gene centers globally, according to Churchill et al [12]. Typically found in Latin America and Southeast Asia, with outposts in tropical Africa [13] their regeneration process remains poorly understood.

Discriminant analysis is a mathematical technique used when the dependent variable is categorical and the independent variables are metric. It aims to reduce data dimensions and maximize observed variation among pre-established groups, providing significance levels for differentiation that other multivariate exploratory analysis techniques lack [14].

Principal component analysis, one of the most

popular multivariate statistical techniques widely used in the areas of pattern recognition is utilized to extract the important information from the data on a number of edaphic and vegetational variables so as to express this information on principal components.

Projection matrix analysis was combined with simulations for seedling recruitment reduction and elasticity analysis and relevant management implications are discussed.

The aim is to find out variables that impact recruitment and pattern development in the tree population along altitudinal gradient. The present contribution deals with patterns of tree regeneration in a Montane Forest along an altitudinal gradient and factors contributing to the altitudinal variation with the following objectives.

1) To investigate into the community characteristics in a montane forest along altitudinal gradient
2) To explore into the patterns of regeneration in a montane forest along altitudinal gradient driving the regeneration
3) To generate a Canonical discriminant model for verifying differences along altitudinal gradient in Montane Forest
4) To apply Principal Component Analysis for exploring recruitment and regeneration pattern development along altitudinal gradient
5)To simulate and analyse Seedling Recruitment Reduction across altitudinal gradient

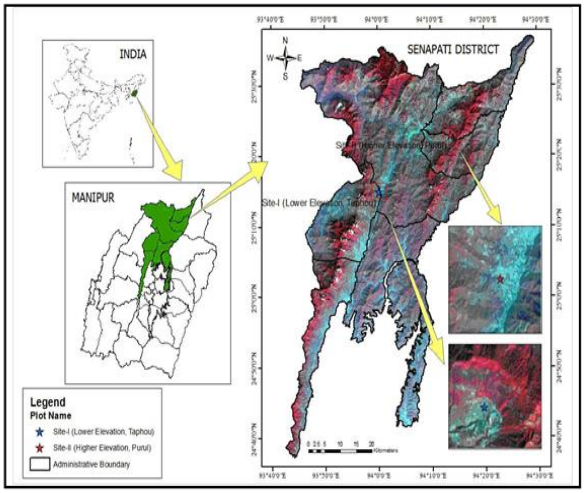


Fig. 1: Location of Study Sites Taphou and Purul in Montane forest,Manipur,Eastern Himalaya

2 Study Area and Methods

2.1 Study Area

Montane forests from Manipur in the Eastern Himalaya located at 25°14 52.7"N latitude and 94°00 10.0"E longitude at an altitude of 1160 m called Taphou whereas the other located at 25°22 57"N latitude and 94°13 41.7"E longitude at an elevation of 1810 m above the mean sea level called Purul were selected. There is a difference of about 50 km. between the two study sites (Fig.1).

The climate of the area is monsoonic with warm moist summer and cold dry winter. The site enjoys humid subtropical to temperate climate and as per the nearest meteorological station, it gets an average annual rainfall of 1450 mm. The air temperature ranges from a minimum of 4° C in winter to a maximum of 29.57^0 C in summer. Texture of soil was found to be sandy clay loam and clay loam at lower and higher elevations respectively. Soil Temperature decreased with elevation. The forest is Subtropical moist with characteristic Schima-Albizzia-Quercus community at Taphou and comprised of Temperate Forest with Castanopsis-Lithocarpus-Engelhardtia community at Purul along the altitudinal gradient. The attributes for the two study sites are given in Table1. The table provides the location, elevation, topography, Community types, average values of various Richness, Diversity and Evenness Indices and Soil Attributes of the two sites along the altitudinal gradient.

Fig. 1: Map of Study Area showing Sites Taphou and Purul along altitudinal gradient in a Montane Forest, Manipur, Eastern Himalaya

Table 1. Some significant attributes of study sites from a Montane Forest along altitudinal gradient

ATTRIBUTES	SITES	
LOCATION	TAPHOU	PURUL
Latitude	25°14 52.7"N	25°22 57"N
Longiude	94°00 10.0"E	94°13 41.7"E
Elevation mmsl	1160	1810
Dominant Forest Type	Subtropical moist	Temperate
Dominant community	Schima-Albizzia-Quercus	Castanopsis-Lithocarpus-Engelhardtia
VEGETATION ATTRIBUTES		
Species richness	27	21
Genus	23	19
Family	25	14
Stem density (ha^{-1})	1100	1760
Total basal cover (m^2 ha^{-1})	53.36	72.83
Simpson index	0.055	0.76
Shannon–Wiener index	3.094	2.823
Species evenness	0.939	0.937
SOIL ATTRIBUTES		
Soil Temperature ^{0}c	18.8	16.1
Soil Moisture %	21.31	28.73
pH	5.7	5.9
Texture	Sandy clay loam	Clay loam
Total Nitrogen %	0.19	0.25
Available phosphorus %	0.0013	0.0015
Exchangeable Potassium %	0.054	0.061

A

B

C

D

Fig. 2: Dominant trees from Montane Forest Ecosystem, Manipur, Eastern Himalaya (A) Schima wallichii (B) Alnus nepalensis (C) Engelhardtia spicata (D) Castanopsis hystrix

2.2 Method

Quadrat sample plot method was adopted for analysing the community characteristics and regeneration status of the of all the tree species. The individual greater than 31.5 cm gbh (girth at breast height i.e.1.37m above the ground) were considered as trees whereas between 10.5-31.5 cm gbh as sapling and less than 10.5 cm as seedlings [15]. Various community parameters such as density ,basal area and Importance Value Index (IVI) were computed using standard methods given by Misra [16] by random sampling using 100 quadrats of 10 m × 10 m size in each study site. Diversity index H′, index of co-dominance and evenness index (E) were calculated from density data after Shannon and Wiener [17], Simpson [18] and Pielou [19]. To assess the status of seedling and saplings of each tree species encountered, within selected twenty-five 10 m × 10 m quadrates, four sub plots of size $1m^2$ quadrates were randomly laid out at each site. Within the marked quadrates all the regenerating individuals were identified and counted and the data were subjected to computation and analysis for results to know regeneration status across altitudinal gradient. The density of seedlings and saplings is considered as an indicator of the regeneration potential. The status of regeneration of tree species was determined based on population size of seedlings, saplings and adults [20].The regeneration status is considered as (a)'good', if seedlings > or < saplings > adults; (b) 'fair', if seedlings > or ≤ saplings ≤ adults; (c)'poor', if a species survives only in sapling stage, but has no seedlings (though saplings may be or = adults); (d) 'none', if it is absent both in sapling and seedlings stages, but found only in adults and (e) 'new', if a species has no adults, but present only as saplings and/or seedlings.

3 Statistical Analysis and Simulation exercise

SPSS Software version 26 was used for applying multivariate statistical techniques viz Discriminant and Principal Component Analysis to assess the differences between sites along altitudinal gradient for understanding trends in natural regeneration, the impact of edaphic variables and forest overstorey and understory attributes of density, diversity and dominance on regeneration pattern in a Montane Forest Ecosystem .

3.1 Discriminant Analysis

This study employs Canonical Discriminant Analysis Model to verify differences among two Montane forests along the altitudinal gradient for sites Taphou and Purul using fifty-three variables comprising structural and edaphic attributes (five and forty-eight structural and edaphic respectively) for each site categorized in two classes. The goal is to apply known multivariate statistical technique to assess and describe differences among sites for understanding the process of natural regeneration in a Montane Forest Ecosystem by providing

indications of probable group differences. Discriminant Analysis builds a predictive model for groups and is composed of a discriminant function based on linear combinations of the predictor variables that provide the best discrimination between the groups. Given two groups of observations with measurements on five interval variables in vegetational group and forty-eight interval variables in edaphic group, canonical discriminant analysis derives a linear combination of the variables that has the highest possible multiple correlation with the groups. This maximal multiple correlation is called the first canonical correlation. With Pre-discriminant analysis (DA) tests assumptions like Log Likelihood ratio, Box's M, five attributes in vegetational in Forty-eight in Environmental groups were considered per site and considered satisfactory for a discriminant model.

3.2 Principal Component Analysis

Principal component analysis (PCA) after Hotelling [21] is applied to dataset that transforms a set of variables into principal components, also known as EOFs (empirical orthogonal functions) when spatial patterns are concerned as per Perry and Niemann [22]. Information is extracted via principal component analysis as a collection of summary indices known as principal components or EOFs (empirical orthogonal functions). Much of the variance of the original dataset as feasible is described by the first EOF, which is a linear combination of the original variables that are orthogonal (linearly independent) to one another. The goal was to apply it on an array of edaphic and vegetational variables to assess how the recruitment and regeneration pattern along the altitudinal gradient are impacted by them.

3.3 Simulation exercise

To assess the impact of Seedling Recruitment Reduction ,stage-structured model over an elevation gradient was applied using field observations as the initial population densities.The study assessed demographic performance under both observed and disturbed regeneration situations inorder to pinpoint the significance of life stages in long-term forest resilience.Projection matrix analysis was combined with simulations for seedling recruitment reduction and elasticity analysis and relevant management implications are discussed.

4 Results and Discussion

4.1 Community Characteristics along Altitudinal gradient

A total of the 41 tree species were recorded along the altitudinal gradient, 27 and 21 tree species were reported from lower and upper elevation respectively. The total tree density was found to be recorded higher (1760 individuals ha^{-1}) at higher elevation as compared to lower elevation (1100 individuals ha^{-1}). Tree species like Schima wallichii, Quercus serrata, Albizia procera, Flacourtia janggomas, Litsea monopetala etc. contributed maximum density at lower elevation while, Castanopsis hystrix, Lithocarpus fenestratus, Engelhardtia spicata, Ziziphus oenoplia etc. showed maximum density at higher elevation.The total basal area of tree species was found to be higher at higher elevation (72.83 m^2 ha^{-1}) than at lower elevation (53.36 m^2 ha^{-1}). Tree species like Schima wallichii, Albizia procera, Quercus serrata and Alnus nepalensis contributed maximum basal area at lower elevation. At higher elevation species like Castanopsis hystrix, Engelhardtia spicata, Lithocarpus fenestratus and Alnus nepalensis contributed maximum basal area.Dominance of species was assigned based on the calculated IVI values. Maximum IVI was exhibited by Schima wallichii (38.29) at lower altitude whereas the maximum IVI was contributed at higher altitude by Castanopsis hystrix (58.61) The Shannon-Weiner diversity index and evenness index for the trees showed higher value of 3.094 and 0.939 at lower altitude compared to 2.823 and 0.927 at higher altitude repectively. The Simpson's dominance index for species varied , as 0.055 at lower and 0.077 at higher altitude. The species common to lower and upper elevations were- Alnus nepalensis D.Don, Diospyros glandulosa Lace,Engelhardtia spicata Lechen ex, Lithocarpus fenestratus (Roxburgh), Melia azedirach Linnaeus Rehder, Schima wallichii Choisy and Ziziphus oenopolia (Linnaeus) P.Miller. Trees have only 29.1%, similarity in their floristic composition between the two sites, revealing less similarity between the two sites for floristic composition.

Tables 2 and 3 exhibit Regeneration and Community characteristics of Woody Species from Montane Forest at Lower Elevation-Taphou and at Upper Elevation Purul.

Table 2. Regeneration and Community characteristics of Woody Species from Montane Forest at Lower Elevation - Taphou

SN	Name of the species	Family	Seedlings ha^{-1}	Saplings ha^{-1}	Trees ha^{-1}	BA $m^2 ha^{-1}$	IVI	Regeneration Status
1	*Alangium chinense* (Loureiro) Harms	Alangiaceae	340	160	60	0.94	14.22	Good
2	*Albizia procera* (Roxburgh) Bentham	Leguminosae	100	20	120	2.04	27.01	Fair
3	*Alnus nepalensis* D.Don	Betulaceae	80	20	40	3.97	14.59	Fair
4	*Antidesma bunius* (Linnaeus) Sprengel	Euphorbiaceae	-	10	10	0.84	4.24	Poor
5	*Bauhinia variegata* Linnaeus	Leguminosae	60	10	10	2.52	7.38	Fair
6	*Bombax ceiba* Linnaeus	Bombacaceae	-	10	10	3.56	9.34	Poor
7	*Celtis australis* Linnaeus	Ulmaceae	-	10	10	0.36	3.34	Poor
8	*Cordia grandis* Roxburgh	Boraginaceae	20	10	10	1.61	5.68	Fair
9	*Dillenia pentagyna* Roxburgh	Dilleniaceae	-	20	30	0.55	7.28	Poor
10	*Diospyros glandulosa* Lace	Ebenaceae	160	170	20	3.47	11.83	Good
11	*Engelhardtia spicata* Lechen ex	*Juglandaceae*	-	-	10	5.01	12.05	None
12	*Ficus hispida* Linnaeus	Moraceae	-	-	10	1.07	4.67	None
13	*Ficus semicordata* Buch.-Hamilton ex J.E. Smith	Moraceae	-	-	10	4.09	10.32	None
14	*Flacourtia janggomas* (Loureiro) Raeuschel	Flacourtiaceae	40	30	70	0.72	12.96	Fair
15	*Gmelina arborea* Roxburgh	Verbenaceae	-	20	20	1.64	8.43	Poor
16	*Lithocarpus fenestratus* (Roxburgh) Rehder	Fagaceae	80	80	20	2.19	9.43	Good
17	*Litsea monopetala* (Roxburgh) Persoon	Lauraceae	400	60	70	1.91	15.2	Fair

18	*Magnolia hodgsonii* (Hooker f. & Thomson) H. Keng	Magnoliaceae	-	-	10	5.23	12.47	None
19	*Melia azedirach* Linnaeus	Meliaceae	100	10	20	1.27	5.95	Fair
20	*Phyllanthus emblica* Linnaeus	Phyllanthaceae	60	30	30	1.54	10.88	Fair
21	*Quercus griffithii* Hooker f. & Thomson ex Miquel	Fagaceae	40	30	50	1.62	12.85	Fair
22	*Quercus serrata* Murray	Fagaceae	40	30	170	1.10	22.78	Fair
23	*Rhus chinensis* P. Miller	Anacardiaceae	80	90	10	0.64	3.86	Good
24	*Schima wallichii* Choisy	Theaceae	60	110	250	1.75	38.29	Fair
25	*Toona ciliata* M. Roemer	Meliaceae	20	50	10	0.34	3.3	Good
26	*Wendlandia glabrata* DC.	Rubiaceae	20	-	10	3.07	8.42	Fair
27	*Ziziphus oenopolia* (Linnaeus) P.Miller	Rhamnaceae	-	-	10	0.29	3.2	None

Table 3. Regeneration and Community charateristics of Woody Species from Montane Forest at Upper Elevation-Purul

SN	Name of the species	Family	Seedlings ha^{-1}	Saplings ha^{-1}	Trees ha^{-1}	BA m^2 ha- ¹	IVI	Regeneration Status
1	*Albizia lebbeck* (Linnaeus) Bentham	Leguminosae	40	10	20	6.0	11.85	Fair
2	*Alnus nepalensis* D.Don	Betulaceae	40	30	40	9.51	20.27	Fair
3	*Castanopsis hystrix* Hooker f. & Thomson ex A.DC.	Fagaceae	240	360	740	3.07	58.62	Fair
4	*Cinnamomum verum* J. Presl	Lauraceae	160	20	60	2.48	12.99	Fair
5	*Diospyros glandulosa* Lace	Ebenaceae	-	60	20	4.07	9.20	Poor
6	*Elaeocarpus lanceifolius* Roxburgh	Elaeocarpaceae	-	40	50	3.21	10.95	Poor
7	*Engelhardtia spicata* Lechen ex Blume	Juglandaceae	60	20	100	7.63	21.09	Fair
8	*Juglans regia*	Juglandaceae	180	10	50	5.43	13.99	Fair

	Linnaeus							
9	*Lindera pulcherrima* (Nees) Hooker f.	Lauraceae	-	-	20	0.70	4.57	None
10	*Lithocarpus fenestratus* (Roxburgh) Rehder	Fagaceae	80	40	160	2.55	22.47	Fair
11	*Lyonia ovalifolia* (Wallich) Drude	Ericaceae	-	-	30	2.36	7.41	None
12	*Magnolia campbellii* Hooker f. & Thomson	Magnoliaceae	-	10	30	1.01	5.56	Poor
13	*Magnolia montana* (Blume) Figlar	Magnoliaceae	80	10	20	1.51	5.69	Fair
14	*Malus baccata* (Linnaeus) Borkhausen	Rosaceae	-	20	60	1.49	10.39	Poor
15	*Melia azedirach* Linnaeus	Meliaceae	-	10	40	3.15	11.54	Poor
16	*Phoebe hainesiana* Brandis	Lauraceae	-	20	20	4.99	10.46	Poor
17	*Pinus kesiya* Royle ex Gordon	Pinaceae	-	-	10	0.88	3.01	None
18	*Prunus nepalensis* Linnaeus	Rosaceae	-	10	60	3.90	13.71	Poor
19	*Prunus rufa* Wallich ex Hooker f.	Rosaceae	60	10	40	4.65	13.6	Fair
20	*Schima wallichii* Choisy	Theaceae	40	20	90	2.59	17.3	Fair
21	*Ziziphus oenopolia* (Linnaeus) P.Miller	Rhamnaceae	80	70	100	1.65	15.36	Fair

Vegetation patterns provide valuable insights into the health and dynamics of ecosystems [23], as well as the impacts of environmental changes and human activities [24]. Montane systems show spatial variations in species richness and composition due to eco-physiological factors along altitudinal gradients.

Mountain vegetation changes in vegetation structure and composition due to increasing elevation,also anthropogenic activities cause changes in structural attributes [25]. It has been observed that there is a considerable difference between the two study sites in species composition, diversity and community structure. Elevational gradients significantly influence biota's ecological and evolutionary responses to geophysical influences [26].

According to Whitmore [27], in tropical rain

forests the tree species range from 20 to a maximum of 223 ha $^{-1}$, the recorded species richness was within the range exhibited by tropical rainforests worldwide. Lower elevations have high species richness due to gaps in vegetation and facilitative interactions [28]. Tree density in tropical forests varies from 245 to 859 for trees of ≥30 cm gbh [29] and the recorded values of the present study lie within this range. Reduction of plants in higher altitude may be attributed to eco-physiological constraints, such as low temperature, precipitation and solar radiation which results in short growing season paving way for plant species tolerant to extreme conditions, a phenomenon known as "ecological filtering." These fluctuations also influence soil texture, nutrients and stability of substrate which in turn are responsible for maintaining vegetation composition [30]. Understanding factors influencing forest density and basal area is crucial for effective forest management which include altitudinal variation, species composition, age structure, successional stage, and disturbance, and are influenced by community succession and stand growth timing. The basal area is mainly influenced by community succession and the timing of stand growth [31] The elevational gradient pattern of the basal area also varies in different climatic zones [32]. Environmental conditions significantly influence plant occurrence and composition in mountain systems, as noted by Körner [26] and Rawal et al [33]. Higher IVI indicates high ecological abundance and it is a reflection of better regeneration status. Thus, on the basis of IVI, Schima wallichii in lower elevation and Castanopsis hystrix in higher elevation were recorded as dominant tree species. Higher values of IVI of these species indicated their good regeneration power, wide ecological amplitude and more adaptability in respective sites. Changes in dominance (based on IVI) in the examined sites represented the most evident floristic distinction caused by disturbance.

The Shannon-Weiner diversity index normally varies from 1.5 to 3.5 and rarely exceeds 4.5 [34]. The Shannon-Wiener index recorded in the present study site lies within the range and it reflects high tree diversity in the study site. The concentration of dominance of the study site corresponds well with the reported range for tropical forest and the average value is 0.06 as reported by Knight [35]. Environmental factors like temperature, precipitation, solar radiation, and wind speed change along an altitude gradient, affecting plant diversity and composition [36], [37]. Temperature and precipitation also have a strong negative correlation with altitude. The higher IVI values and dominance of Schima wallichii and Castanopsis hystrix, as well as other co-dominant tree species, suggest that these species have a stronger potential and competitive power to survive and outcompete other tree species in the community. These tree species may have been more competent depending on their morpho-physio-phenological traits [38].

4.2 Regeneration in the study area

The population structure in terms of proportion of seedlings, saplings, and adults of tree species varied in the two study sites along the altitudinal gradient. The findings of the present study revealed the regeneration trends in both the study sites, Taphou (lower elevation) recorded the number of seedling, sapling and trees respectively as 1700 individuals ha^{-1} 980 individuals ha^{-1}and 1100 stems ha^{-1} whereas at Purul (higher elevation),the density of seedling, sapling and trees respectively recorded were 1060 individuals ha^{-1} ,770 individuals ha^{-1}and 1760 stems ha^{-1} . Tables 2 and 3 reveal that lower elevation (Taphou) had higher seedling and sapling population. The presence of higher number of seedling than that of sapling was recorded at the two study sites.

Basal area recorded above 31.5 cm gbh was 53.36 m^{2}ha^{-1} at lower elevation and 72.83 m^2 ha^{-1} at higher elevation (Tables 2,3).

4.2.1 Patterns of Regeneration Along Altitudinal Gradient

Trends in Seedling, Sapling and Tree population

From the total population of the studied sites, the percentage contributions of dominant species to the seedlings pool were calculated. At Taphou (lower altitude) the maximum density of seedlings was represented by Litsea monopetala (23.53%), followed by Alangium chinense (20%), Albizia procera (5.89%) and Melia azedirach (5.89%). The recruitment of these species was 55.29% to the total pool of established seedlings. At Purul (higher altitude), the maximum density of seedling was exhibited by Castanopsis hystrix (22.64%), Juglans regia (16.67%), Cinnamomum verum (15.10%). These species contributed 54.71% to the total established seedlings (Tables 2,3).

The maximum density of sapling were represented by Diospyros glandulosa (17.35%) followed by Alangium chinense (16.32%), Schima wallichii (11.22%). The contribution of these trees in the sapling pool from lower elevation (Taphou) was 44.89%. From higher elevation (Purul), the density

of sapling was recorded for Castanopsis hystrix, Ziziphus oenoplia and Diospyros glandulosa as 46.75%, 9.09%, and 7.80% contributing 63.64% to the total pool of established seedlings(Tables 2,3).

Overall at lower elevation Taphou ,the population exhibited the total density of seedlings (1700 individual ha-^{1}) that was higher than the saplings (980 individuals ha-^{1}) and adults (1100 individuals ha-^{1}), thus exhibiting 'fair' regeneration . At higher elevation Purul, the population exhibited that the total density of adult trees (1760 individuals ha-^{1}), outnumbered the density of seedlings (1060 individuals ha-^{1}) and saplings (770 individuals ha-^{1}) also exhibiting 'fair' regeneration status of tree species.

Each species illustrated different regeneration status with respect to their respective population size, at lower elevation .18.52% of tree species illustrated 'Good' regeneration status, 40.74% showed 'Fair' condition and 18.52% showed 'Poor' regeneration condition**.** A total of 18.52% of tree species without any individuals of seedling and sapling did not exhibit regeneration whereas 3.70 % reflected new recruit. (Table-2)

At higher elevation, Purul, 52.39% of tree species exhibited 'Fair' regeneration status, 33.34% exhibit 'Poor' condition and 14.29 % reflected 'Not' regenerating status (Table 3).

The species with good regeneration status were Alangium chinense, Diospyros glandulosa, Lithocarpus fenestratus, Rhus chinensis and Toona ciliata at lower altitude. However**,** at higher altitude none of the species exhibited 'good' regeneration status. Lack of good regeneration was accounted to insufficient saplings of most of the species. While, Albizia procera, Alnus nepalensis, Bauhinia vareigata, Cordia grandis, Flacourtia janggomas, Litsea monopetala, Melia azedirach, Phyllanthus emblica, Quercus griffithii, Q. serrata,, Schima wallichii and Wenlandia glabrata were the species illustrating 'Fair' regeneration at lower altitude Taphou while Albizia lebbeck, Alnus nepalensis, Castanopsis hystrix, Cinnamomum verum, Engelhardtia spicata, Juglans regia, Lithocarpus fenestratus, Magnolia montana, Prunus rufa, Schima wallichii and Ziziphus oenoplia reflected 'Fair' regeneration at Purul (higher elevation). The species illustrating 'Poor' regeneration status were reported as Antidesma bunius,Bombax ceiba,Celtis australis,Dillenia pentagyna,Gmelina arborea at lower altitude Taphou while, Diospyros glandulosa, Elaeocarpus lanceifolius, Magnolia campbelli, Malus baccata, Melia azedirach, Phoebe hainesiana and Prunus nepalensis at higher altitude Purul . The species without seedling and sapling were Engelhardtia spicata, Ficus hispida, Ficus semicordata, Magnolia hodgsonii and Ziziphus oenoplia at lower altitude Taphou. At higher altitude Purul, Lindera pulcherrima, Lyonia ovalifolia and Pinus kesiya were the species illustrating 'None' or not regenerating category.

Seedling density is a key indicator of regeneration potential, as the probability of seedling establishment is closely related to its size [39]. The study found that seedlings contribute the most to tree populations at lower elevations, while adults contribute the most at higher elevations. Lower elevations have a higher proportion of seedlings followed by saplings and adults, suggesting reverse J-shaped density- girth class curve for Alangium chinense suggesting stable regeneration status for species.

Seedling recruitment is crucial for plant regeneration and forest restoration [40] but environmental filtering by abiotic and biotic stress causes plant mortality [41]. Understanding biotic and abiotic factors that limit seedling survival ecology, is crucial to understand in mountain environments to what extent environmental filtering limits seedling establishment [42].

Species richness in lower elevations (Taphou) is high due to anthropogenic disturbances and facilitative interactions [28]. Lower density of saplings and seedlings in Purul is due to reduced disturbance which did not allow creating gaps and opening of canopies.

Lower elevations have higher seedling and sapling density due to biotic pressure, solar radiation, and reduced competition from upper canopy trees; the gaps created may also contribute to tree species regeneration. Canopy openness influences the survival rate of seedlings [43]. Natural phenomena like light gaps [44] and biotic pressure [45], [46] also affect species regeneration.

The study suggests that lower density of saplings and seedlings at higher altitudes may be due to reduced disturbance which did not allow for the creation of gaps and opening of canopies, limiting species' ability to regenerate. This could lead to local extinction of some species in future as high-altitude species have no further place to move upward/migrate to regenerate [47]. The reduced temperature at higher altitudes also affects regeneration rates impacting seedling growth. Cierjacks et al. [48] also have reported a lower number of seedlings at higher altitudes. However, Miihlenberg et al. [49] reported greater tree regeneration at higher elevations.

Seedling recruitment in the northern temperate forests of British Columbia was a reflection of the interaction between the abundance of seed and substrate favourability; however, the relative importance of these factors varied significantly with canopy structure [50].

Seasonal variation in seedling recruitment was observed, with maximum seedlings in the rainy season and least in winter, with soil nitrogen content positively influencing species composition and regeneration. Seedling survival rates increased during wet seasons [51] positively correlated with soil nitrogen content. Brandani et al. [52] suggested that the nutritional differences in soil influence the species composition and regeneration in Costa-Rican rain forest. Within medium and large gaps, saplings were heterogeneously distributed along gradients from opening to closed forest canopy, suggesting gap partitioning of saplings [53].

Stem density increases along the altitudinal gradient, possibly due to higher organic matter content and soil moisture. Altitude is linked to ecological factors like temperature, humidity, and soil [48]. Stem density impacts seedling and sapling densities and the dense canopy adversely impacts seedlings and saplings. Environmental conditions vary along physiographic and ecological gradients within a species' geographical range leading to spatial heterogeneity in growth-limiting factors and tree establishment and regeneration [54]. Variations in the number of individuals in different stages may be attributed to environmental factors and disturbance. Bazzaz [55] suggests that seedling and sapling densities in forest understories are dynamic and may vary among species. Elevation gradient is the best factor for evaluating species' correspondence to habitat patterns and predicting the effects of environmental change on species diversity [56] , increase with increasing elevation [57] and have a hump-shaped pattern at the highest mid-elevation [58] .Whether there is a generalized relationship between species diversity and altitude is unclear [59] Therefore, the mechanisms and factors influencing the altitude gradient pattern of species diversity need to be further investigated in depth.

The study in a subtropical forest at Nagaland, India by Ao et al [60]showed that about 41–57% of the tree species exhibited good regeneration followed by 23–30% as fair, 6–16% as poor, whereas 6–21% species did not show regeneration along the altitudinal gradient.

Our study found that 40.70% and 52.39% tree species in the study sites at Taphou and Purul showed fair regeneration, with a lower sapling population density than seedlings and adults.

The low density of saplings at Taphou of Litsea monopetala and Melia azedirach indicates issues with seedling establishment due to higher mortality from anthropogenic impacts like trampling and grazing; the forest site being close to settlement. Low density of sapling of the species like Cinnamomum verum and Juglans regia at Purul indicates unfavourable microclimatic conditions. The vegetation structure and composition in mountains are expected to change gradually due to environmental conditions as elevation increases, anthropogenic activities causing changes in structural attributes [25].

18.52% species revealed poor regeneration status at Taphou while33.34% exhibited poor status at Purul.Species that did not regenerate comprised of 18.52% of Species at Taphou and 14.29 % at Purul respectively. 3.70% of species at Taphou were new recruits.

Although species with poor or no regenerati on are regarded as of secondary importance, the demands on the dominant species will grow if they perish as a result of population pressure. Non
regenerating potential may also be influenced by local factors and temperature fluctuations. Predicting how forest ecosystems will react to the climate change requires measuring colonization rates [61]. Inadequate regeneration is a common issue in Indian forests [62], [20]due to factors like grazing, fire and cultivation.

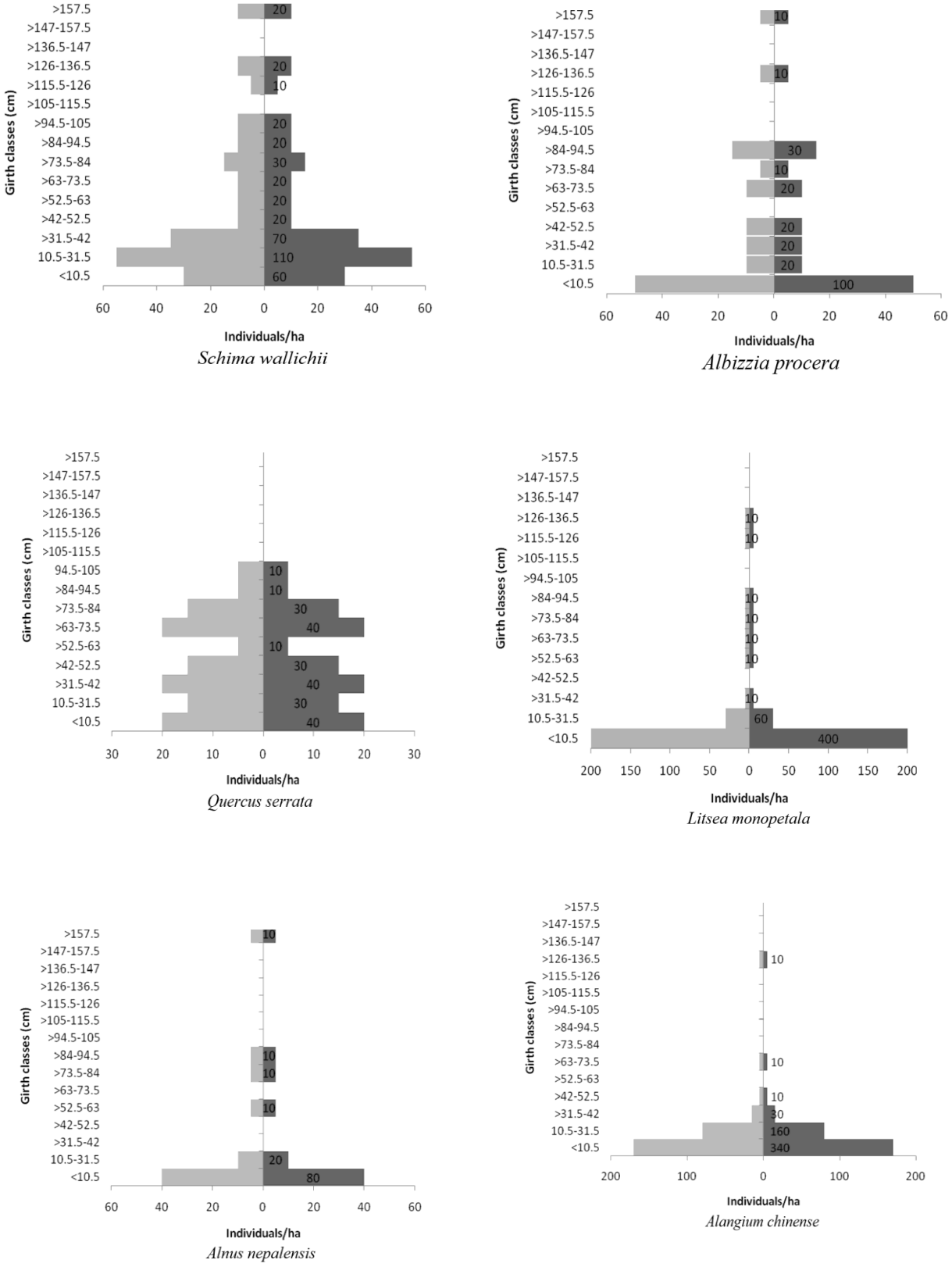


Fig. 3: Population Structure of Six Dominant Species at Lower Elevation Taphou in a Montane Forest

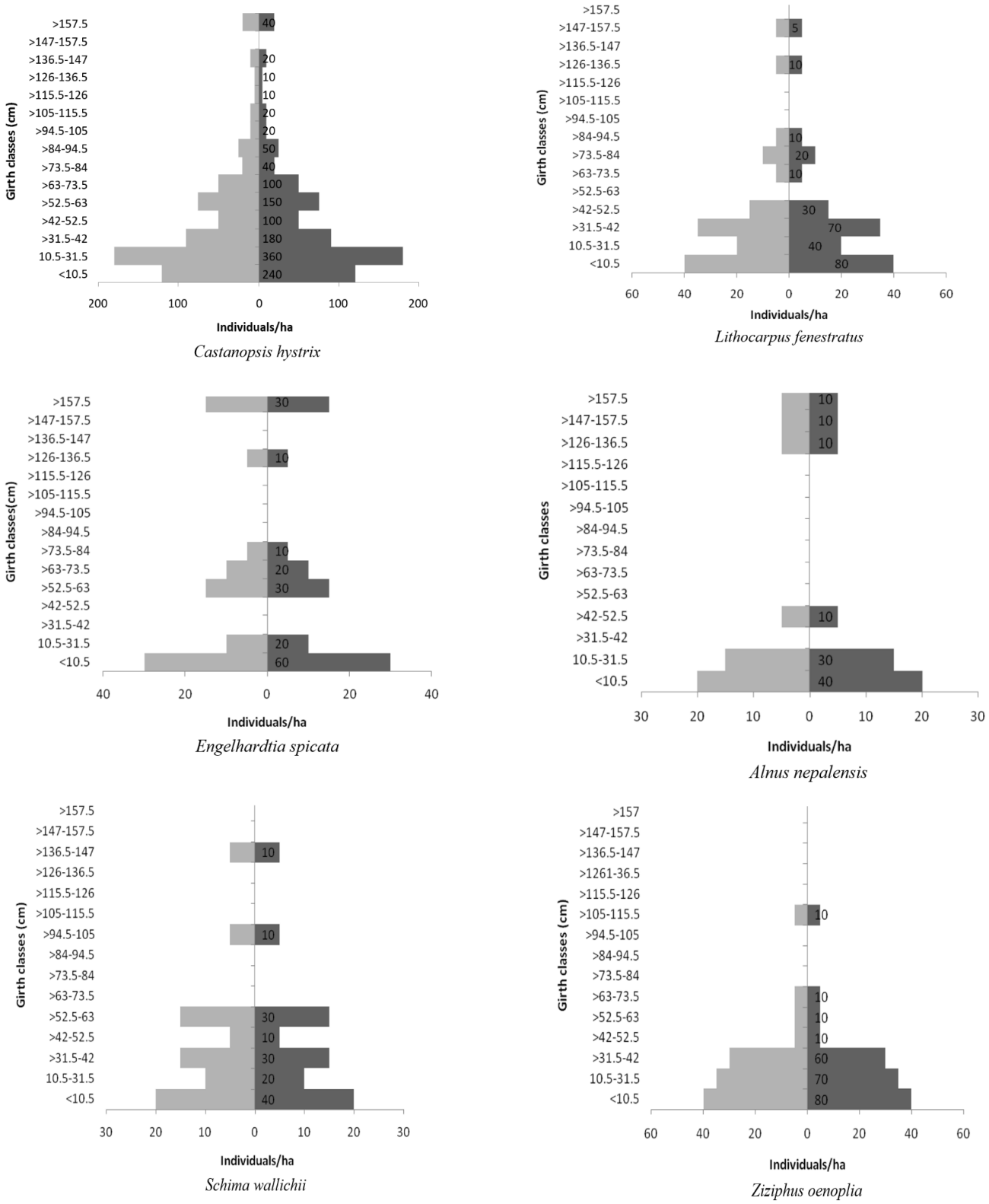


Fig. 4: Population Structure of Six Dominant Species at Higher Elevation Purul in A Montane Forest

4.2.2 Population Structure of Dominant Species

Figure 3 and Figure 4 represented the population structure of six dominant species at each site viz. Schima wallichii (IVI- 38.29), Albizia procera (IVI-27.09), Quercus serrate(IVI-22.78), Litsea monopetala (IVI-15.2)Alnus nepalensis (IVI-14. 59) and Alangium chinense (IVI -14.59) from Taphou and from Purul viz. Castanopsis hystrix (IVI-

58.62), Lithocarpus fenestratus (IVI- 22.47), Engelhardtia spicata (IVI- 21.09), Alnus nepalensis (IVI -20.27), Schima wallichii (IVI- 17.3) and Zizyphus oenoplia (IVI- 15.36) were studied and represented through pyramids.

In the pyramid diagrams, successive vertical columns represent the distribution of the stem girth classes within each species at a particular site. Thus, each of the vertical column represents absolute densities (no. of stems from base to top) of seedlings, saplings and adult stems of trees of six dominating species from each of the sampling sites. The absolute numbers of stems counted at each site is also listed in the centre of each column.

At Taphou, five dominant species viz Schima wallichii **,** Albizia procera , Quercus serrate , Litsea monopetala, Alnus nepalensis recorded fair regeneration,only Alangium chinense recorded good regeneration, while all the six dominant species viz Castanopsis hystrix , Lithocarpus fenestratus , Engelhardtia spicata, Alnus nepalensis , Schima wallichii , and Zizyphus oenoplia reflected 'Fair' regeneration at Purul. Increasing global temperatures may alter tree growth rates, recruitment and mortality, creating new tree assemblages [63], [64], [65].

One of the codominants at Taphou, Ziziphus oenoplia, does not regenerate and represented only in the tree layer, suggesting that the species has not reproduced in the past nor reproducing in the present, making its long-term persistence doubtful**.** Kräuchi et al. [66] suggested that the lack of sufficient regeneration is a major problem of mountain forests.

Absence of gaps in the size classes indicate that regeneration is adequate and has been for some time whereas obvious gaps in size class distribution of species occur at both the elevations as a result of past disturbances.

When saplings are less as in species Albizia procera, Litsea monopetala, Alnus nepalensis at Taphou and Lithocarpus fenestratus and Schima wallichii at Purul then it is indication of past disturbance with a much larger impact on tree saplings as noted by Pinard et al [67]. Lopez et al [68] in eastern Bolivia reported from a large wildfire that occurred toward the end of the dry season. Baker et al. [69] from a study on tropical forest demonstrated that low-intensity fires can generate a landscape-scale pulse of canopy gap formation. It seems that irregular tree age distributions observed in the Montane Forest may be due to combination of rare and abundant disturbances. Irregular tree-diameter distributions in intact tropical forest stands have been earlier reported by Poorter et al [70] and Bunyavejchewin et al [71]. The role of disturbances in influencing the dynamics of tropical forests is becoming more widely acknowledged [72].

Sustained regeneration and growth of all species in older plants are crucial for the growth of the plant community.Species distribution along altitudinal gradients is directly con-trolled by ecophysiological processes of temperature tolerance [26]. Species from warmer lower elevational vegetation belts took advantage of the improved growing conditions to extend their leading edges to the temperate belts at the expense of cold- adapted species already occurring there like Alnus nepalensis and Schima wallichii both showing fair regeneration along altitudinal gradient.

Thus, it appears that a complex history of disturbance regimes varying in scale and intensity, together with small-scale disturbances arising from gap creation caused by single treefall gaps or temperature change govern the population structure affecting forest dynamics.

5. Statistical Analysis and Simulation Exercise

5.1 Discriminant Analysis

The dataset for Discriminant analysis contains 53 observations, with 5 in the Class 00 termed as vegetational and 48 in Class 1.00 termed as Edaphic. Here, the default weight of 1 for each observation in the dataset is used , so the weighted number of observations in each class is equal to the unweighted number of observations in that class. There were significant differences in vegetational Class 00) being 976.0 and 1070 for Taphou and Purul. Similarly in edaphic (Class 1.00) means were obtained as 7.94 and 30.53 respectively for sites Taphou and Purul. The total means of differences of, vegetational and Environmental variables were 99.27 and 128.5 ,thus allowing for the use of these predictors to distinguish observations along the elevational gradient..

Log Determinants and Box's M Test help to verify whether the assumptions of discriminant analysis are satisfied, the difference in log determinants is 24.729-14.924= 9.805 , indicating that the spread of data is quite different between class 00 and 1.00,however smaller p value (<0.05) indicates that Box's M test verifies that the assumptions of discriminant analysis are satisfied.

Table 4. Eigen Value,Wilk's Lambda and Canonical Correlation and Significance Values

	Discriminant Function 1
Eigenvalue	5.174[a]
% of variance	100
Cumulative %	100
Canonical Correlation	0.915
Equality covariance matrices	
Wilks' Lambda	0.162
Chi Square	91.017
df	2
Significance	0.000

Table 5. Standardized Canonical Discriminant Function Coefficients and Discriminant Loading

		Taphou	Purul
Standardized Canonical Discriminant Function Coefficients	Function1	0.785	0.431
Discriminant Loading	Function1	0.911	0.660

The results generated by analysis are presented in Tables 4 and 5. Table 4 presents the salient findings of the Discriminant analysis viz.Eigen value, Canonical correlation, Wilk's Lambda, Chi-square, Degrees of Freedom and Significance whereas Table 5 presents the Standardized Canonical Discriminant Function Coefficients and Discriminant Loading.

Discriminating the Sites along altitudinal gradient

The eigenvalues of a matrix with a magnitude of 5.174 represent the discriminating ability of a function.The eigenvalue is related to the canonical correlation and describe how much discriminating ability a function possesses. The percentage of variance represents the proportion of discriminating ability of two continuous variables in a given function. This proportion is calculated as the proportion of the function's eigenvalue to the sum of all the eigenvalues. The cumulative proportion of discriminating ability was 100%. The canonical correlation is 0.915 between predictor variables (vegetational and environmental) and the categorical variables of Taphou and Purul sites.

The test of function(s) involves examining the canonical correlations of a function with the null hypothesis that the canonical correlations associated with the functions are all equal to zero. In our case, we have two functions, the first test presented t both canonical correlations ("1 through 2") and the second test presented the second canonical correlation alone. The Wilks' Lambda is a multivariate statistic and product of the values of (1-canonical correlation^2). As our canonical correlation is 0.915 , so the Wilks' Lambda is (1-0.915^2) = 0.162 .Its lower value indicates the better discriminating ability.The Chi-square statistic is used to test the null hypothesis that a function has no discriminating ability, indicating that its canonical correlation is zero . Our value of Chi- Square Statistics was obtained as 91.027. at dF =2 as the effect degrees of freedom (df) is based on the number of groups in the categorical variable and the number of continuous discriminant variables. As the p-value (0.000), was less than alpha (0.05), hence, the null hypothesis (a given function's canonical correlation is equal to zero and the function has no discriminating ability) is rejected as it is proved that the function has discriminating ability.

Discriminant Score

The score is calculated using coefficients, with the magnitude of the discriminating variables indicating their impact on the score. For instance, standardized coefficient z for Taphou in the function is greater (0.785) in magnitude than the coefficient (0.431) z Purul. The discriminant function score Z is calculated as

Discriminnant Score = 0.785* zTaphou+ 0.431 * zPurul.

Thus, the lower elevation Taphou which is more diverse and richer will have the greatest impact on the discriminating score.

Standardized Canonical Discriminant Function Coefficients calculate discriminant scores, indicating the impact of discriminating variables. For instance, Taphou's magnitude is greater than Purul's, indicating its maximum influence on the discriminating score1.

The canonical structure of the discriminant function in the Structure Matrix is also known as canonical loading or discriminant loading, of the discriminant function. It indicates the correlation between observed variables (the two continuous discriminating environmental and vegetational variables) and unobserved dimensions (created with the unobserved discriminant functions). The largest correlation between discriminating variables and function was found at Taphou as 0.911 and correlation was 0.660 at Purul along the altitudinal gradient.

5.2 Principal Component Analysis (PCA)

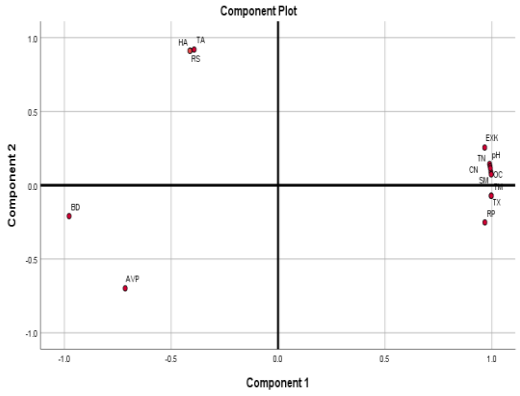
Principal component analysis (PCA) was used to extract the most important patterns (PCs) of the underlying spatiotemporal variability. It separated the overall variance into important patterns yielding a clear separation of the variables with respect to the principal components (PC).

Table 6. Eigenvectors for Principal Components 1 and 2 for Sites Taphou and Purul for Edaphic and Vegetational variables

	TAPHOU			PURUL		
Sl. No.	Variables	PCI	PCII	Variables	PCI	PCII
1	TX	0.997	-0.072	TX	0.795	-0.607
2	TM	0.997	-0.072	TM	0.795	-0.607
3	BD	-0.978	-0.209	BD	-0.915	-0.403
4	SM	0.996	0.091	SM	0.964	0.264
5	pH	0.990	0.144	pH	0.997	0.075
6	OC	0.997	0.074	OC	0.927	0.375
7	TN	0.992	0.128	TN	0.968	0.250
8	C:N	0.993	0.115	C:N	-0.167	0.986
9	AVP	-0.715	-0.699	AVP	-0.720	-0.694
10	EXK	0.967	0.255	EXK	0.903	0.430
11	TA	-0.393	0.920	TA	-0.555	0.832
12	HA	-0.412	0.911	HA	-0.563	0.826
13	RP	0.968	-0.252	RP	-0.159	-0.987
14	RS	-0.412	0.911	RS	-0.958	0.288

EDAPHIC VARIABLES-TX-Texture, TM-Temperature, BD-Bulk Density, SM-Soil Moisture, pH, OC-Organic Carbon, TN-Total Nitrogen, CN-C:N Ratio,AVP-Available PhosphorusEXK-Exchangeable Potassium VEGETATIONAL VARIABLES-TA- Overstorey, HA-Understorey, RP-Regeneration Potential, RS- Regeneration Status

(A)



(B)

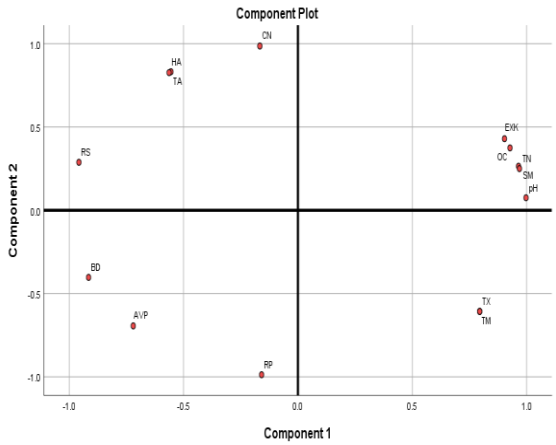


Fig. 5: 2D Plot for Principal Components 1 and 2 for (A) Taphou and(B) Purul with loading of Edaphic and Vegetational variables

According to the PCA result, 76.84% and 23.15 % of the total variation, respectively, is explained by the first and second principal components at the lower elevation at Taphou. Texture, Soil Temperature, Organic C, Moisture, C:N ratio, TN, pH and Ex K showed positive loadings at lower elevation, on first PC whereas BD, AVP had negative effects. Overstorey and understorey structural variables did not impact on the regeneration potential (RP). Regeneration status (RS) exhibited a favorable effect at the lower elevation on PCII, with overstorey and understory structures demonstrating their influence on the patterns exhibited by the species. The highly loaded values based on PCA suggests that Soil Moisture, Soil Temperature, Organic Carbon and Total Nitrogen are the most sensitive soil factors in PC1 impacting Regeneration potential i.e., seedling emergence, sapling establishment at Taphou.

The first and second Principal Components, respectively, explain 62.51% and 37.58% of the overall variation, according to the PCA analysis at Purul. The first PC exhibited positive loadings at the higher elevations of pH, TN, Moisture, Organic Carbon, and Ex K, while C:N AVP, and BD displayed negative loadings. Overstorey or understorey structural elements and Regeneration Potential (RP)and regeneration status (RS) exhibited negative loadings on PCI. The C:N ratio showed positive loading on PCII, whereas texture, soil temperature, BD and AVP had negative effects. The overstorey and understorey structural variables have positive effects, whereas the regeneration potential (seedling sapling recruitment and establishment) exhibited negative effects.Regeneration Status (RS) exhibited positive but low association with PCII. RS (Regeneration Status) in Purul is negatively impacted by temperature (r=-.936) resulting in pattern development at the higher elevation.

5.3 Simulation exercise

Model of Population Projection

A Lefkovitch matrix was used to project population dynamics over a 50-year period. Initial densities used were, 1700 seedlings, 980 saplings, 1100 adults at lower elevation and 1060 seedlings, 770 saplings, 1760 adults at Upper elevation. To guarantee biological realism, conservative vital rates (fecundity, transitions, and survival) were set to published values [73], [74]based on forest demographic syntheses. The values of Vital rates applied were 0.35,0.40 0.97 and 1.2 respectively for Seedling-to-sapling transition, Sapling-to-adult transition, adult survival and Fecundity (as per the effective seedling recruitment per adult).

Matrix Structure

$$\begin{bmatrix} N_{s,t+1} \\ N_{j,t+1} \\ N_{a,t+1} \end{bmatrix} = \begin{bmatrix} 0 & 0 & F \\ P_{sj} & 0 & 0 \\ 0 & P_{ja} & P_{aa} \end{bmatrix} \begin{bmatrix} N_{s,t} \\ N_{j,t} \\ N_{a,t} \end{bmatrix}$$

where:

- N_s, N_j, N_a are seedling, sapling, and adult abundances
- F is fecundity (seedling recruitment per adult)
- P_{sj} is seedling-to-sapling transition
- P_{ja} is sapling-to-adult transition

P_{aa} is adult survival

Observed Vs Reduced Regeneration

Population projections over 50 years showed positive growth under observed regeneration (lower elevation $\lambda \approx 1.05$; upper elevation $\lambda \approx 1.07$). Growth was driven mainly by adult survival (>70% elasticity). Disturbance was simulated by 50%, reducing the seedling recruitment (fecundity) however at the same time, sapling and adult survival were kept constant. With 50% reduced seedling recruitment, growth slowed (lower elevation $\lambda \approx 1.02$; upper elevation $\lambda \approx 1.04$) but remained above replacement. Elasticity shifted further toward adult survival (>80%).

Elasticity Analysis

Elasticity quantified stage contributions to growth (lambda).

$$\text{Elasticity matrix:E} = \begin{bmatrix} 0 & 0 & 0.099 \\ 0.099 & 0 & 0 \\ 0 & 0.099 & 0.702 \end{bmatrix}$$

Adult survival accounted for the majority of elasticity, highlighting demographic inertia.

Elasticity Patterns

Adult survival contributed ~70–83% of λ, seedling recruitment contributed <10%., sapling transitions ~15–18%, showing populations persist mainly through longevity. Under 50% reduced regeneration, seedling contribution declined sharply, reinforcing dependence on adult longevity.

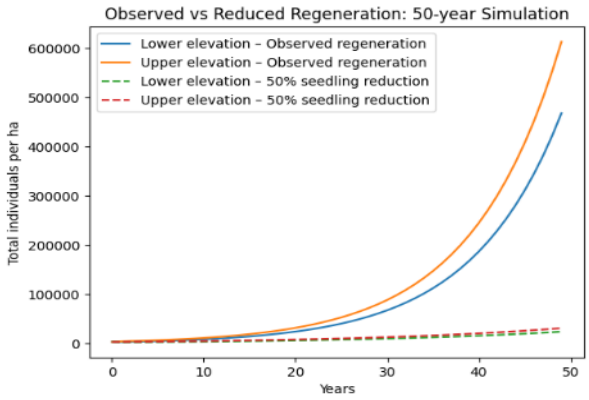


Fig. 6: Growth trajectories under observed and Reduced Regeneration

The simulation graph (Figure 6) showed slower growth trajectories under reduced regeneration. Populations at higher elevations remained adult-dominated, reflecting demographic inertia rather than resilience.

Longevity vs. Resilience

Although populations appeared stable in the face of decreased regeneration, this was more due to adult longevity than inherent resilience. Forests that heavily rely on adult survival are susceptible to mortality caused by disturbances or climate stress.

Forest Tree Regeneration under Climate Stress

The long reproductive lifespan, low turnover

accompanied by high adult survival rates of forest trees can temporarily hide recruitment failure. This apparent stability is unstable since any increase in adult mortality, particularly in the context of climate change, might lead to a rapid drop. Despite reduced regeneration, population growth is a time-lagged demographic vulnerability that indicates hidden risk rather than resilience. Such expansion should be seen as an indication of unsustainable recruitment and increased vulnerability to future disturbance driven mortality or the climate stress.

The Himalayan Vegetation is being significantly impacted by climate change [75], leading to vegetation movement towards higher elevations and altering plant life history [76]. Climate change is expected to alter vegetation distribution, disrupt ecological relationships, alter plant life history, and shift species distributional ranges due to rising temperatures [77]. Elevation is a complex combination of climatic variables closely correlated with various environmental properties like soil texture, nutrients, and substrate stability [10]. Factors like topography, aspect, and slope inclination also impact forest composition [78]. Solar radiation distribution affects microclimate and water balance, affecting plant community growth [79]. Topographical and soil factors play a significant role. The middle slope's steeper gradient may enhance drainage, making it more favourable for seed germination when water is abundant. Our study aligns with Liang et al's [80] findings that regeneration is more effective at lower slopes, with stand density negatively affecting upper slopes. Topographical and soil factors play a significant role, with water scarcity potentially shifting dominant factors. The study aimed to understand regeneration status and future compositional trends in Manipur's montane forests.

6 Conclusion

The discriminant analysis aimed to determine the influences of various factors on natural regeneration in forest sites along an altitudinal gradient.

Species richness in lower elevation (Taphou) is high due to anthropogenic disturbances and facilitative interactions; thus, the discriminant score had more magnitude than Purul reflecting lower density of saplings and seedlings due to reduced disturbance which did not allow creating gaps and opening of canopies.The loadings on PCA revealed how natural regeneration is influenced by biotic and abiotic factors, which affect resource availability and conditions.

Lower altitude exhibits stronger short-term regeneration signal due to high seedling density.At higher elevation higher demographic inertia noted due to an adult-dominated structure .However, as λ is determined by transition probabilities rather than raw densities, both altitudes are equally vulnerable to recruitment collapse over time. This is consistent with the research on montane forests, where, elasticity is dominated by adult survival, long-term persistence is controlled by recruitment. Rather than adult mortality, elevational stress frequently first appears as seedling bottlenecks.

Soil characteristics interact with climate, topography, and vegetation to shape plant communities. The analysis found that forest regeneration characteristics varied between sites along the gradient. Regeneration status, and recruitment had significant effects on differences between forests along the gradient. Site characteristics, overstorey structure, and site conditions were considered significant vegetation factors.

Management Implications

For long-term resilience, early life stages (seedlings and saplings) must be restored as adult survival promotes short-term growth. Particularly at higher elevations, conservation initiatives should prioritize microhabitat restoration, seedling establishment, and sapling survival. Thus, adult survival maintains short-term growth, but restoring early life stages is essential for long-term forest resilience. The study emphasizes how the forest populations appear stable due to adult lifespan and the restoration of early life stages is required for true resilience. The importance of conservation strategies lies in enhancing the seedling establishment and sapling survival so as to ensure the long-term health of forests.

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