Seedling Potential Attributing Ecological Variables: Trees Species Diversity along an Elevation Gradient in the Temperate Hill Forest, Central Nepal

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Research Article

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Abstract

Present research examined the tree diversity and their regeneration patterns along an elevation gradient in the temperate hilly forest, Central Nepal. Data were collected from 300 sample plots of 10 x 10 m² each. A total of 10 elevation bands of 100 m difference sampled from 1365 to 2450 m asl. A random sampling method was used to collect information in three seasons, winter, pre-monsoon and post monsoon seasons. Circumference at breast height (CBH) was used to broadly categorize the plant species into trees, saplings and seedlings. Present study found nearly ninety percent tree species were at regenerating stage. The tree species richness ranged from 12 to 25 with density of 350 to 1200 individuals per hectare. Species richness of tree and sapling showed statistically significant unimodal pattern, peaked at mid-elevation. Elevation showed a strong and positive linear relationship with the seedling density (Deviance = 0.99, p < 0.001) and significant hump shaped relationship with sapling density (Deviance = 0.95, p < 0.001). Similarly, elevations showed statistically significant negative hump shaped relationship with all tree, sapling and seedling's Simpson indices (Deviances = 0.89, 0.87 and 0.57). The highest values of the Shannon-Weiner index and lowest value of the Simpson index were found at mid-elevation for all growth forms. In the study area, 49% tree species found in a good renewal status, 32% were in fair renewal, and 11% at a poor regenerating condition. Nevertheless, 4.3% tree species were reported as non-regenerating stage and 4.3% were newly introduced species. Hence, the regeneration status of the study area was considered as fairly good since sapling (78.5%) > seedling (10.6%) ≤ mature (10.9%). Among tested environmental variables elevation, annual mean rainfall, aspect, slopes, pH, N and annual mean temperatures were the most influential factors in regeneration of trees species.

Introduction

Mountain forests provide fundamental support to large variation of plant diversity. Their survival and sustainability are determined by natural regeneration. The regeneration process of the species guides the future community composition. The ability of each species to complete the life cycle with the development of adaptation features under the changing environmental conditions defines the potentiality of regeneration (Khumbongmayum et al., 2006). Survival, growth, and development of each seedling and sapling governs the successful regeneration potential (Good & Good, 1972) which gives the strength towards long-term sustainability of forests (Malik et al., 2014). The forest regeneration potential usually depends on climatic, topographical, edaphic factors (Ávila et al., 2016; Mishra et al., 2013; Mishra & Garkoti, 2014; Sharma et al., 2018; Schrumpf et al., 2011), and anthropogenic disturbances like biomass extraction and forest fire (Chapman & Chapman, 1996; Malik et al., 2018; Napit & Paudel, 2015).

Forest dynamics epitomized by regenerating, changing and adapting with change in environmental factors (Tripathi et al., 2019). Forest regeneration potential is decades old inherent phenomenon that may be either natural or artificial or both. Many theories have been progressing to explain the forest regeneration pattern. The mosaic theory of forest regeneration (Swaine & Hall,, 1988) explains and emphasizes the importance of gap that required between juvenile and adult populations of each tree species in a regenerating forest. Seeds germinate into seedlings and seedlings grow into saplings.
Saplings grow and develop along with others into large taller plants. Many seedlings or saplings lost their life cycle from seeds to mature individuals either by natural or by induced events (Malik & Bhatt, 2015; Yamamoto, 1992). Sufficient number of juveniles, their population and structure indicated the future course of plant regeneration (Odum & Barrett, 2005). The future composition of the plant community depends on the regeneration potential of a dominant plant species at the respective locality (Austin et al., 1996; Henle et al., 2004).

Nepalese Himalayan Mountains are unique due to wider and sharper elevation gradient. Plants have physiological, genetical as well environmental pressure to fit and adopt sharp elevation gradient at a short spatial displacement. Understanding regeneration pattern from stressful condition will help us to understand their ecological adaptation and to plan future conservation strategies. The study of natural forest regeneration in such a mountainous region is highly useful for understanding the development of large-scale restoration initiatives (Crouzeilles et al., 2017). Natural forest regeneration might be affected both by biotic and abiotic factors (Bose et al., 2016; Jiménez-Alfaro et al., 2014). The natural forest regeneration pattern along elevation gradient indicates effects of natural climatic factors and the forest status. Healthy regenerating forest enhances the forest diversity due to a sharp change in topography, climate, and edaphic factors. The change in elevation of the mountain region leads to change in precipitation, solar radiation, temperature, aspects, and direction of the wind (Dorji et al., 2014; López-Angulo et al., 2018). Hence, these ecological attributes ultimately affect the vegetation composition and their richness (Chawla et al., 2008). A reduction in precipitation in mountainous regions can lead to drought and limit the regeneration potential of seedlings (Crouzeilles et al., 2017; Fredericksen & Pariona, 2002; Vieira et al., 2007). Species regeneration potential in a forest varies with the rate of precipitation (Osem et al., 2009), temperature (Mok et al., 2012), canopy coverage (Bose et al., 2016), understory vegetation (Bucci & Borghetti, 1997) survivorship (Dickinson et al., 2000; Palik et al., 2003), and composition (Battles et al., 2001; Gilliam, 2007) of individual species. The process of regeneration in mountainous regions can also be influenced by natural calamities and anthropogenic factors (Kozlowski, 2002). Thus, the ecological responses of forests can be rendered after elevation gradient analysis. Due to discrepancy of ecological conditions at different spatial scales, insufficient regeneration has become a major issue in mountainous regions (Kräuchi et al., 2000).

The Himalayan temperate forest is witness to several anthropogenic activities and plays a critical role by providing livelihood opportunities to residents. Therefore, sustainable management of such forest is indispensable by their growth and development. The dependency of ecological resources for human activities is one of the most contributing factors for forest regeneration. An understanding forest regeneration mechanism is energetic in the development of good forest management practices (Eilu & Obua, 2005; Malik & Bhatt, 2015). Knowledge about forest dynamics and their composition is essential for the development of future conservation strategies. A healthy regenerating forests provide suitable habitat for other species and supports existence of species under wide harmonized environmental conditions (Elouard et al., 1997; Khaine et al., 2018). The survival of a species in a forest depends on the regeneration potential of the forest under changing ecological factors. The natural recovery of forests
depends on the capability of germination of seeds, growth of seedling, maturation of sapling, soil nutrients and natural or induced disturbances.

The study area represents the temperate forest, dominated by *Alnus-Schima* species at the lower elevation and *Berberis-Quercus* species towards upper elevation. This forest is at a high risk due to its location very close to the capital city, Kathmandu, Nepal. This landscape is increasingly fragmented by different developmental activities such as road constructions, cable cars development, development of recreation sites, hiking routes development, electrification and the installation of telephone towers. Thus, understanding the forest in the study area by means of its regeneration pattern is urgent in order to safeguard its biological diversity and natural integrity. Regeneration patterns in Nepalese forest have been infrequently studied. A few previous studies investigated from the same mountain that mainly focused on the species composition (Bania, 2001; Katuwal et al., 2020), and tree carbon potential (Dani & Baniya, 2019). Other studies (Chapagai et al., 2021; Chikanbanjar et al., 2020; Rautiainen & Suoheimo, 1997) failed to obtain data that allowed to assess the status of forest regeneration. Furthermore, there is a lack of studies that model factors affecting forest trees regeneration. Thus, this present study has been initiated.

We aim to investigate the regeneration dynamics of the temperate forest of the study area along the elevation gradient. We assume that the regeneration of tree species in the study area is mainly determined by elevation, rainfall and edaphic variables like soil nutrients, water holding capacity, etc. In a natural regeneration process, the juvenile and matured tree species replace the older and dead plants. Thus, the main objectives of this study were (i) to explore the status of the regeneration potential of tree species along the elevation gradient, and (ii) to determine the influential ecological factors that impact the regeneration potential most.

**Materials and methods**

**Study area**

The present study was conducted in the south to east facing aspects of Chandragiri Hill, at the western border of Kathmandu valley (Fig. 1) within coordinates 27°27.04' N to 27°49.15' N and 85°10.08' E to 85°32.24' E, covering an area of 11 km². The Chandragiri Hill is about 17 km far from the core of Kathmandu valley and represents a typical temperate vegetation with elevational ranges between 1365 m a.s.l. to 2540 m a.s.l. The study area has an annual mean temperature of 17.67°C and the annual rainfall 378 mm. About 80% precipitation cascades occur between June and September (CBS, 2019). This mid-hill forest is dominated by *Schima wallichii* and *Alnus nepalensis* at lower elevations, and by a *Quercus semecarpefolia* and *Berberis aristata* composition in the upper region. The Hill has both natural and planted trees with more than a dozen of community managed forests. There are six larger community forests across the complete elevation range occupying about 80% of the study area.

**Sampling design**
Field work was carried out on winter, pre-monsoon and post monsoon seasons of the year 2019–2020. Based on the availability of forest types, we selected six study sites with an elevation range from 1365 m a.s.l. to 2450 m a.s.l. in the east to south-facing temperate forest. At all study sites, we developed ten vertical grid quadrats of 1000 m² (50 x 20 m²) area with a distance of ca. 100 m between them. For every grid quadrat, five square quadrats (100 m²) were established for trees; single for every corner and one from centre. The 10 nested quadrats for sapling (25 m² each), and 32 for seedling (1 m² each) were designed. In total, 300 quadrats (10 x 6 x 5) for trees with nested for seedling and saplings were selected. The smaller sized quadrats for the counting of tree species were selected to ensure greater steepness of study area and availability of spaces for growth of the tree species.

The growth forms of each individual tree species that occurred inside each quadrat were categorized into three groups: trees, saplings, and seedlings based on circumference at breast height (CBH) measured at 1.37 m height for trees and saplings, and 10 cm above the ground for seedlings. Individuals having circumference ≥ 31.5 cm CBH were considered as trees, individuals with < 10.5 cm circumference were considered as seedling, and those with intermediate dimension (10.5–31.4 cm) as saplings (Knight, 1963).

The number of individuals and their life stages (adult, sapling, and seedling) of each species were counted in all quadrats and recorded. The plant materials were pressed, dried, mounted and preserved following standard methods (Forman and Bridson, 1989). Density of all tree seedlings, saplings, juveniles and adults were assessed within each quadrat. For counting regenerating tree species each quadrat was divided into four equal subplots in order to ease counting as well as avoid double counting. Tree species were identified in the field using field guides (Press et al., 2000; Rajbhandari & Rai, 2017; Raskoti, 2009; Shrestha et al., 2018; Watson et al., 2011, Polunin & Stainton, 1984). Identification of unknown specimens and validation of identified specimens was achieved by comparison of material deposited at National Herbarium and Plant Laboratories (KATH) and Tribhuvan University Central Herbarium (TUCH). Thus, collected data were managed properly to develop the data matrix for statistical analysis.

Soil samples were taken from each quadrat. About 200 gm soil in 10 cm depth was taken from four corners of each quadrat. These four samples were mixed together and half soil were used for determination of water holding capacity and soil pH. Remaining soil was then air dried by room temperature and finally stored in air tight polythene bags until laboratory analysis. Edaphic parameters were analyzed in the Soil Department of National Agriculture and Research Council (NARC), Kathmandu, Nepal. Soil pH was analyzed using a soil electrode. Soil nitrogen was measured by the Kjeldahl method (Barbano et al. 1990; Kjeldahl, 1883), soil organic carbon by the Walkley-Black rapid titration method (Walkley, 1934), soil phosphorus by the Olsen’s method (Olsen et al., 1982), and soil potassium by the ammonium acetate method (Normandin et al., 1998).

**Environmental and edaphic variables**

Elevation, aspect, slope, latitude, longitude, soil pH, nitrogen, phosphorus, potassium, soil organic carbon (SOC) and the Relative Radiation Index (RRI) were considered as explanatory variables in the present
study. We obtained the annual mean temperature (AMT) and annual mean rainfall (AMR) for every elevation band using QGIS 3.22 software (http://www.qgis.org) from the Worldclim database (http://www.worldclim.org/).

The RRI measures the dispersal of direct solar radiation of the specific studied area (Mamassis et al. 2012) and its values were calculated by following Baniya et al. (2010).

\[ RRI = \cos (180^\circ - \Omega) \cdot \sin \beta + \cos \beta \cdot \cos \phi, \] where \( \Omega \) is an aspect, \( \beta \) is the slope, and \( \Phi \) is the latitude of each plot. Its value ranges from +1 to −1.

**Vegetation composition and diversity indexes**

The composition and structure of the forest were determined by following Mueller-Dombois & Ellenberg (1974). Community composition, species diversity (species richness) and equitability (distribution of abundances among the species) as a measure of alpha diversity were calculated for each site by using Shannon-Wiener index (H, Shannon & Weaver, 1963) and Simpson index (D, Simpson, 1949).

Shannon-Wiener index (Shannon & Weaver, 1963) emphasizes the randomness of every species present at the respective site and denotes both species richness and equitability. It was calculated by the following formula:

\[ \text{Shannon-Wiener index (H)} = -\sum_{i=1}^{s} p_i \ln p_i \]

Simpson's index (Simpson 1949), represents the concentration of dominance and considered more as a dominance index as it accounts proportion of a species in each sample. It was calculated by following the following formula:

\[ \text{Simpson index (D)} = \frac{1}{\sum_{i=1}^{s} p_i^2} \]

In both indexes, \( p \) is the proportion \((n/N)\), \( n \) = total number of individuals of a species, \( N \) = total number of individuals of all species, \( \ln \) is natural log and is the sum of calculation, \( s \) is the number of species

**Regeneration status**

The regeneration grade of each tree species was derived by analysis of the density of mature trees and their juvenile stages by following literature (Khan et al., 1986; Khumbongmayum et al., 2006; Shankar, 2001). Regeneration status was considered as:

i. good generation (GR) = number of seedlings > saplings > trees;
ii. fair regeneration (FR) = number of seedlings > saplings ≤ adults;
iii. poor regeneration (PR) = species survives only at sapling stage, but not seedlings (number of saplings may be less or equal to adults);
iv. none regeneration = species is present only in adult form (no seedling and sapling stages) and
v. new regeneration = species has no adults, only represented by juvenile stages (only seedlings or saplings present)

**Statistical analyses**

Statistics were used to discover the relationships among seedling species abundance, density, their composition and environmental variables. The mean values of the response variables were tested by using one-way ANOVA with post hoc Tukey HSD test; the level of significance was fixed as $\alpha = 0.05$. To evaluate the correlation between species density with climatic and edaphic factors, we calculated the Pearson’s correlation coefficient.

Most significant predictors from the dataset were isolated by using the best fit model selection procedure. The possibility of multicollinearity among predictors were examined through the `vif.cca` function in the `car` package (Fox & Weisberg, 2019). The variation inflation factor (VIF) value of 1 shows no correlations, 1 to 5 shows moderate correlation and > 5 indicates potentially high correlation between considered predictor variable and other predictor variables. Predictor variables with a VIF value $\geq 6$ were considered as redundant, i.e., collinear by this ordination study (Zuur, Ieno, & Elphick, 2010). Thus, such explanatory variables were no entertained by this study during ordination.

Alternately, we also used *Leaps* package to select the best predictor variable after exhaustive searching of the predictors (Lumley, 2020). The `regsubsets` function of *leaps* package were used to identify different best models disrespecting the size of variables (*nvmax*). The best predictors were selected after by assessing the combination of AIC score and adjusted $r^2$ values. The most significant response variable, seedling density was regressed with all predictors variables by giving `nbest = 5, nvmax = 13`, and method = exhaustive. The adjusted $r^2$ values of competing models were used for comparisons in the context of best-subsets regression (Hahs-Vaughn & Lomax, 2012). The adjusted $r^2$ served here as an index of explanatory power while also penalizing models based on their complexity in relation to sample size. After selection of best predictors, conventional regression model for a continuous response variables, generalized linear model (GLM) (Hastie & Pregibon, 1992) and package *ggplot2* for visualization (Wickham, 2016) were used. The best regression model was selected after using 'Deviance' method. According to Hastie & Pregibon, (1992), deviance is:

\[
\text{Deviance} = 1 - \frac{\text{Residual Deviance}}{\text{Null Deviance}}
\]

A Detrended Correspondence Analysis (DCA, Hill & Gauch, 1980) was applied to examine variance and gradient length present in the sample by species data matrix. The length of the gradient by the DCA axis I was found as 8.62 standard deviation unit and the Eigenvalues for same axis was 0.76. Hence unimodal application of ordination method, Canonical Correspondence Analysis (CCA) was justified according to Leps & Smilauer (2003).

A canonical correspondence analysis (ter Braak, 1986) was used to visualize effects of ecological factors on tree species composition. The CCA biplot was used to explain relationships among different tree
species composition and most influential selective environmental variables. All statistical analysis for species composition and model selection were performed by using *vegan* package (Oksanen et al., 2020) through R programs (R Core Team, 2022). Only most significant explanatory variables are plotted in graphs.

**Results**

**Species composition, richness and density**

We identified a total of 47 tree species; 45 individual trees were at adult stage, 38 at sapling stage, and 42 at seedling stage. Across all elevation ranges species of 40 genera and 24 families were found with the regeneration of only 34 genera of 22 families in sapling form and 35 genera of 22 families in seedling forms. Rosaceae was the most species-rich family with 7 species (14.9%) followed by Fagaceae with 5 species (10.6%), and 16 families (61.5%) were represented by a single species.

The tree and sapling species richness gradually increases with increasing elevation up to mid-elevation (Fig. 2a), and later decreased with further increasing or decreasing elevation. The maximum modeled trees species richness (23) and sapling species richness (18) were found both at the middle elevation at 1900 respectively. For seedlings, the highest number of species richness (17) was found at higher (2300) elevations (Fig. 2a).

Species richness was least at the lowest elevation (1500 m) for all trees ranging between 9 (seedling stage) and 12 (adult stage). Species life form density per hectare for trees, sapling, and seedling species increased with increasing elevation in the study area on lower regions. The highest trees density per hectare (983 individuals) was found at middle elevation, lower density was found at upper and lower edges (447 and 350 individuals per hectare). A similar pattern was also observed for sapling species with higher density at middle elevation (776 individuals) and lesser at the upper (660 individuals) and lower (447 individuals) elevation. In seedlings, the life form density also increased from bottom to top starting from 2865 to 7679 individuals per hectare (Fig. 2b).

The Shannon Diversity Index (H index) was found highest at the middle elevation, and lowest for lower and the highest elevations for all both trees and saplings (2.9 for trees and 2.7 for a sapling Fig. 3a). Seedlings showed non-significant relation with elevation.

Similarly, the lowest value for D was observed for mid-elevations for all life forms, and the highest at lowest and highest elevations (Fig. 3b).

**Regeneration status in the forest**

Forests at higher elevation (> 2100 m a.s.l.) and lower elevation (< 1500 m a.s.l.) showed good regeneration, while the regeneration of tree species at middle elevation was low. The forests at an
elevation range between 1600 and 2000 m a.s.l. had higher tree species diversity but lower regeneration potential (Fig. 4a).

Among the 4001 individuals of seedlings and saplings belonging to 47 species, 48.9% were woody species with a good regeneration status, 31.9% showed only a fair regeneration, and 10.6% were characterized by a poor regeneration status (Fig. 4b). However, 4.3% of the woody species were found at non-regenerating stage (without seedling stage), and 4.3% were newly introduced species. Overall, the regeneration status of forests in the study area was considered fairly good with sapling (78.5%) > seedling (10.6%) ≤ mature (10.9%).

Several species were widely adapted along all their distributional elevational ranges (Table 1) like *Alnus nepalensis, Castanopsis indica, Castanopsis tribuloids, Fraxinus floribunda, Gaultheria fragrantissima, Grewia oppositifolia, Hydrangia aspera, Lindera pulcherrima, Lyonia ovalifolia, Myrsine semiserata, Quercus glauca, Quercus semecarpefolia, Rhododendron arboreum,* and *Schima wallichii.* Besides that, *Acer oblongum, Cinnamomum camphora, Eriobotrya dubia, Eurya acuminata, Ligustrum confusum, Litsea oblong, Myrsine capitelata, Pinus roxburghii, Pinus wallichiana, Prunus cerasoides, Pyracantha cranulata, Quercus lanuginosa, Salix denticulata, Sarcococca coriacea, Syzygium cumini,* and *Woodfordia fruticosa* showed good or fair regeneration in their distributional ranges of elevation.
<table>
<thead>
<tr>
<th>Name of plant species</th>
<th>Nature of regeneration in elevational ranges (elevation in m asl)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1400</td>
</tr>
<tr>
<td><em>Acer oblongum</em> Wall. ex DC.</td>
<td>PR</td>
</tr>
<tr>
<td><em>Alnus nepalensis</em> D.Don</td>
<td>GR</td>
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<tr>
<td><em>Berberis aristata</em> Roxb.</td>
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<tr>
<td><em>Camellia kissi</em> Wall.</td>
<td>PR</td>
</tr>
<tr>
<td><em>Caryopteris foetida</em> (D.Don) Thellung</td>
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</tr>
<tr>
<td><em>Castanopsis indica</em> (Roxb.) A.DC.</td>
<td>FR</td>
</tr>
<tr>
<td><em>Castanopsis tribuloids</em> (Sm.) A. DC</td>
<td>GR</td>
</tr>
<tr>
<td><em>Cinnamomum camphora</em> (L.) J.Presl</td>
<td>GR</td>
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<tr>
<td><em>Elaeagnus latifolia</em> L</td>
<td>PR</td>
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<tr>
<td><em>Eriobotrya dubia</em> (Lindl.) Decne.</td>
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<tr>
<td><em>Eurya acuminata</em> DC.</td>
<td>PR</td>
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<tr>
<td><em>Fraxinus floribunda</em> Wall.</td>
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<tr>
<td><em>Gaultheria fragrantissima</em> Wall. Wall.</td>
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<tr>
<td><em>Grewia oppositifolia</em> Ham.-D.Don</td>
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(GR = good regeneration, FR = fair regeneration, PR = poor regeneration, NN = none regeneration, NR = new regeneration)
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<td>Hydrangea aspera D.Don</td>
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<tr>
<td>Lecoceptrum canum Sm.</td>
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<td>Ligustrum confusum Dene</td>
<td>NN</td>
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<tr>
<td>Lindera pulcherrima (Nees.) Benth. ex Hook. F.</td>
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<tr>
<td>Litsea oblong (Wall.) Hook. F.</td>
<td>PR</td>
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<tr>
<td>Luculia gratissima (Wall.) Sweet</td>
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<tr>
<td>Lyonia ovalifolia (Wall.) Drude</td>
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<tr>
<td>Maclura cochiachinensis (Lour.) Corner</td>
<td></td>
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<tr>
<td>Maesa chisia Buch.-Ham. ex D.Don</td>
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<tr>
<td>Mahonia nepaulensis DC.</td>
<td>NN</td>
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<tr>
<td>Myrica esculenta Buch.-Ham. ex D.Don</td>
<td>GR</td>
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<tr>
<td>Myrsine capitelata Wall.</td>
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<tr>
<td>Myrsine semiserata Wall.</td>
<td>GR</td>
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<tr>
<td>Pinus roxburghii Sargent</td>
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<td>1400 1500 1600 1700 1800 1900 2000 2100 2200 2300</td>
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<tr>
<td><em>Pinus wallichiana</em> A.B. Jack</td>
<td>GR  FR  GR</td>
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<tr>
<td><em>Princepia utilis</em> Royle</td>
<td>NN  NN</td>
</tr>
<tr>
<td><em>Prunus cerasoides</em> D.Don</td>
<td>GR  GR  NN  NN  PR</td>
</tr>
<tr>
<td><em>Pyracantha cranulata</em> (D.Don) Roem</td>
<td>PR  PR  GR  GR</td>
</tr>
<tr>
<td><em>Pyrus pashia</em> Buch.-Ham. ex D.Don</td>
<td>GR  NN</td>
</tr>
<tr>
<td><em>Quercus glauca</em> Thunb.</td>
<td>GR  GR  GR  GR  GR</td>
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<tr>
<td><em>Quercus lanuginosa</em> D.Don</td>
<td>GR  PR  GR  GR</td>
</tr>
<tr>
<td><em>Quercus semecarpfelia</em> Sm.</td>
<td>GR  GR  GR</td>
</tr>
<tr>
<td><em>Rhododendron arboreum</em> Sm.</td>
<td>GR  GR  GR  GR  GR  GR  GR  GR</td>
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<tr>
<td><em>Salix denticulata</em> And.</td>
<td>GR  NN  PR  NN  NN</td>
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<tr>
<td><em>Sapium insigne</em> (Royle) Benth</td>
<td>PR  PR  FR</td>
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<tr>
<td><em>Sarcococca coriacea</em> (Hook.f.) Sewwt</td>
<td>FR  GR  GR  GR  PR</td>
</tr>
<tr>
<td><em>Schima wallichii</em> (DC.) Kortch.</td>
<td>GR  GR  GR  GR  GR  GR  GR  GR</td>
</tr>
<tr>
<td><em>Syzygium cumini</em> (L.) Skeels</td>
<td>GR  PR  PR  PR  PR  PR  PR</td>
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<tr>
<td>Wendlandia puberula DC.</td>
<td>NN</td>
</tr>
<tr>
<td>Woodfordia fruticosa (L.) Kurz</td>
<td>GR    NN    PR    NN    PR</td>
</tr>
<tr>
<td>Zanthoxylum armatum DC.</td>
<td>PR    PR    PR</td>
</tr>
<tr>
<td>Aesculus indica (Wall. ex Cambess.) Hook</td>
<td>NR</td>
</tr>
<tr>
<td>Taxus wallichiana Zucc.</td>
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</table>

(GR = good regeneration, FR = fair regeneration, PR = poor regeneration, NN = none regeneration, NR = new regeneration)

Some species like Acer oblongum, Elaeagnus latifolia, Eurya acuminata, Ligustrum confusum, Litsea oblong, Ligustrum confusum, and Mahonia nepaulensis were found to regenerate less in a few elevational ranges. On the other hand, Salix denticulata (1500–1800), Prunus cerasoides (1800–2000), Mahonia nepalensis (1800–1900), Princepia utilis (2100–2200), Woodfordia fruticosa (1600–1800), Wendlandia puberula (2100) showed no regeneration at a certain elevation of their distributional ranges.

We did not find matured tree stages of Aesculus indica and Taxus wallichiana in the study area, but sapling and seedling stages only, indicating that the two taxa may have been recently newly introduced. Princepia utilis and Wendlandia puberula were present at matured stage only suggesting no regenerating of these species in the study area.

### Ecological variables selection

Among the environmental variables studied, elevation, AMT, and K were found statistically significant with higher F-values and lower p-values (elevation, $F = 14.95$, $p = 0.0003$, AMT, $F = 10.86$, $p = 0.002$ and K, $F = 3.37$, $p = 0.007$). These variables showed the environmental scores with −1.00, 0.82 and 0.07 for the first axis, and 0.05, 0.06 and −0.04 for second axis, respectively.

Present study did not reveal an influence of any ecological variables on tree seedling species richness. After removal of elevation, latitudes and longitudes due to higher VIF scores, Annual mean temperature and Aspect were best fitted for the regeneration potentiality of tree seedling species (Table 2) based on higher adjusted $R^2$ values, least Akaike Information Criteria (AIC) values and lower Bayesian Information...
Criteria (BIC) values. Other environmental variables were unable to justify the potentiality of forest regeneration.

Table 2
Regression analysis LM between response variable seedling densities with bested fitted predictor variables

<table>
<thead>
<tr>
<th>Model</th>
<th>Predictors</th>
<th>$R^2$</th>
<th>C(p)</th>
<th>AIC</th>
<th>$\Delta$AIC</th>
<th>BIC</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AMT</td>
<td>0.35</td>
<td>1.45</td>
<td>355.50</td>
<td>0.62</td>
<td>213.81</td>
<td>&lt; 0.01*</td>
</tr>
<tr>
<td>2</td>
<td>Asp AMT</td>
<td>0.36</td>
<td>1.02</td>
<td>354.88</td>
<td>0.00</td>
<td>213.62</td>
<td>&lt; 0.01*</td>
</tr>
<tr>
<td>3</td>
<td>Asp AMT SOC</td>
<td>0.35</td>
<td>1.63</td>
<td>355.30</td>
<td>0.43</td>
<td>214.53</td>
<td>0.23</td>
</tr>
<tr>
<td>4</td>
<td>Asp AMT SOC N</td>
<td>0.34</td>
<td>2.49</td>
<td>355.98</td>
<td>1.11</td>
<td>215.79</td>
<td>0.28</td>
</tr>
<tr>
<td>5</td>
<td>Asp AMT AMR SOC N</td>
<td>0.33</td>
<td>3.47</td>
<td>356.76</td>
<td>1.89</td>
<td>217.25</td>
<td>0.38</td>
</tr>
<tr>
<td>6</td>
<td>Asp AMT pH SOC N P</td>
<td>0.31</td>
<td>4.71</td>
<td>357.85</td>
<td>2.97</td>
<td>219.04</td>
<td>0.49</td>
</tr>
<tr>
<td>7</td>
<td>Asp AMT AMR pH SOC N P</td>
<td>0.28</td>
<td>6.04</td>
<td>359.01</td>
<td>4.14</td>
<td>220.98</td>
<td>0.39</td>
</tr>
<tr>
<td>8</td>
<td>Asp AMT AMR pH SOC N K P</td>
<td>0.26</td>
<td>7.21</td>
<td>359.96</td>
<td>5.08</td>
<td>222.87</td>
<td>0.49</td>
</tr>
<tr>
<td>9</td>
<td>Slp Asp AMT AMR pH SOC N K P</td>
<td>0.19</td>
<td>9.02</td>
<td>361.72</td>
<td>6.84</td>
<td>225.30</td>
<td>&lt; 0.03*</td>
</tr>
<tr>
<td>10</td>
<td>Slp Asp AMT AMR pH SOC N K P</td>
<td>0.16</td>
<td>11.00</td>
<td>363.70</td>
<td>8.82</td>
<td>227.85</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Generalized estimation of the equation for selection of the best fitted model for response variable with predictor variables based on highest $R^2$ values, lowest AIC (Akaike Information Criteria), low $\Delta$AIC and lowest BIC (Bayesian Information Criteria) values. According to AIC, $R^2$ and BIC values, model 2 is best fitted with additional supporting models are 1 and 3. (AMT = Annual Mean Temperature, Asp = Aspect, SOC = Soil Organic Carbon, N = Nitrogen, AMR = Annual Mean Rainfall, P = Phosphorus, Slp = Slope, K = Potassium, RRI = Relative Radiation Index)

**Community composition**

The DCA revealed higher Eigenvalues of the DCA1 (0.76; Table 3) and confirmed a unimodal response pattern of seedling species composition along the environmental gradient. The scores on the first CCA axis ranged between 2.238 and −1.25. Species such as *Woodfordia fruticosa* (2.23), *Aesculus indica* (2.11), and *Taxus wallichiana* (2.09) had higher scores, while plants like *Lecoceptrum canum* (-1.25), *Lyonia ovalifolia* (-1.23) and *Maesa chisia* (-1.23) and showed the lowest species scores. The Eigenvalues of the second CCA axis ranged from 3.16 to -1.563 with the lowest scores for *Pyrus pashia* (-1.56), *Luculia gratissima* (-1.00), and *Quercus lanuginosa* (-0.69), and the highest scores for *Woodfordia fruticosa* (3.16), *Aesculus indica* (2.55), and *Taxus wallichiana* (2.23) (Table 4).
Table 3
DCA summary

<table>
<thead>
<tr>
<th></th>
<th>DCA1</th>
<th>DCA2</th>
<th>DCA3</th>
<th>DCA4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalues</td>
<td>0.7649</td>
<td>0.4305</td>
<td>0.3728</td>
<td>0.3082</td>
</tr>
<tr>
<td>Decorana values</td>
<td>0.8363</td>
<td>0.4162</td>
<td>0.328</td>
<td>0.2316</td>
</tr>
<tr>
<td>Axis lengths</td>
<td>8.6194</td>
<td>3.6802</td>
<td>4.0285</td>
<td>1.3928</td>
</tr>
</tbody>
</table>
### Table 4
Species with their CCA score in the study area

<table>
<thead>
<tr>
<th>SN</th>
<th>Abbreviation</th>
<th>Species name</th>
<th>CCA1</th>
<th>CCA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ace.obl</td>
<td><em>Acer oblongum</em></td>
<td>0.41</td>
<td>-0.30</td>
</tr>
<tr>
<td>2</td>
<td>Aln.nep</td>
<td><em>Alnus nepalensis</em></td>
<td>0.95</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>Ber.ari</td>
<td><em>Berberis aristata</em></td>
<td>-1.12</td>
<td>0.54</td>
</tr>
<tr>
<td>4</td>
<td>Cam.kis</td>
<td><em>Camellia kissi</em></td>
<td>0.98</td>
<td>0.06</td>
</tr>
<tr>
<td>5</td>
<td>Car.foe</td>
<td><em>Caryopteris foetida</em></td>
<td>-0.99</td>
<td>-0.26</td>
</tr>
<tr>
<td>6</td>
<td>Cas.ind</td>
<td><em>Castanopsis indica</em></td>
<td>0.33</td>
<td>-0.48</td>
</tr>
<tr>
<td>7</td>
<td>Cas.tri</td>
<td><em>Castanopsis tribuloids</em></td>
<td>-0.11</td>
<td>-0.45</td>
</tr>
<tr>
<td>8</td>
<td>Cin.cam</td>
<td><em>Cinnamomum camphora</em></td>
<td>1.42</td>
<td>-0.65</td>
</tr>
<tr>
<td>9</td>
<td>Eri.dub</td>
<td><em>Eriobotrya dubia</em></td>
<td>-0.71</td>
<td>0.40</td>
</tr>
<tr>
<td>10</td>
<td>Eur.acu</td>
<td><em>Eurya acuminata</em></td>
<td>-0.41</td>
<td>-0.41</td>
</tr>
<tr>
<td>11</td>
<td>Fra.flo</td>
<td><em>Fraxinus floribunda</em></td>
<td>-1.15</td>
<td>0.82</td>
</tr>
<tr>
<td>12</td>
<td>Gau.fra</td>
<td><em>Gaultheria fragrantissim</em></td>
<td>-1.01</td>
<td>0.69</td>
</tr>
<tr>
<td>13</td>
<td>Gre.opp</td>
<td><em>Grewia oppositifolia</em></td>
<td>-1.20</td>
<td>1.19</td>
</tr>
<tr>
<td>14</td>
<td>Hyd.asp</td>
<td><em>Hydrangia aspera</em></td>
<td>1.94</td>
<td>2.33</td>
</tr>
<tr>
<td>15</td>
<td>Lec.can</td>
<td><em>Lecoceptrum canum</em></td>
<td>-1.25</td>
<td>0.99</td>
</tr>
<tr>
<td>16</td>
<td>Lig.con</td>
<td><em>Ligustrum confusum</em></td>
<td>-0.52</td>
<td>0.10</td>
</tr>
<tr>
<td>17</td>
<td>Lin.pul</td>
<td><em>Lindera pulcherrima</em></td>
<td>-0.40</td>
<td>-0.68</td>
</tr>
<tr>
<td>18</td>
<td>Lit.obl</td>
<td><em>Litsea oblong</em></td>
<td>0.52</td>
<td>-0.40</td>
</tr>
<tr>
<td>19</td>
<td>Luc.gra</td>
<td><em>Luculia gratissima</em></td>
<td>-0.16</td>
<td>-1.00</td>
</tr>
<tr>
<td>20</td>
<td>Lyo.ova</td>
<td><em>Lyonia ovalifolia</em></td>
<td>-1.23</td>
<td>0.75</td>
</tr>
<tr>
<td>21</td>
<td>Mac.coc</td>
<td><em>Maclura cochichinensis</em></td>
<td>-1.04</td>
<td>1.34</td>
</tr>
<tr>
<td>22</td>
<td>Mae.chi</td>
<td><em>Maesa chisia</em></td>
<td>-1.23</td>
<td>1.09</td>
</tr>
<tr>
<td>23</td>
<td>Myr.esc</td>
<td><em>Myrica esculenta</em></td>
<td>0.94</td>
<td>-0.16</td>
</tr>
<tr>
<td>24</td>
<td>Myr.cap</td>
<td><em>Myrsine capitelata</em></td>
<td>0.96</td>
<td>0.28</td>
</tr>
<tr>
<td>25</td>
<td>Myr.sem</td>
<td><em>Myrsine semiserata</em></td>
<td>0.02</td>
<td>-0.05</td>
</tr>
<tr>
<td>26</td>
<td>Pin.rox</td>
<td><em>Pinus roxburghii</em></td>
<td>0.48</td>
<td>-0.56</td>
</tr>
<tr>
<td>27</td>
<td>Pin.wal</td>
<td><em>Pinus wallichiana</em></td>
<td>-0.98</td>
<td>0.64</td>
</tr>
</tbody>
</table>
According to CCA scores, *Aesculus indica*, *Taxus wallichiana*, *Hydrangia aspera* found statistically significant preference of regeneration towards samples with higher concentration of Phosphorus, Nitrogen, and soil organic compound. Likewise, a regeneration of these species was further significantly supported by a moderate value of AMT, and lower values of AMR. Abundance of *Schima wallichii*, *Sarcococca coriacea*, *Camellia kissi Myrsine capitelata* species were significantly supported with higher annual mean temperature and Potassium, and moderate annual mean rainfall and negatively affected by elevation and increasing slopes. The regeneration of *Pyrus pashia*, *Luculia gratissima*, *Lindera pulcherrima*, and *Quercus lanuginosa* species were significantly supported in plots with higher values of annual mean rainfall, aspect and Potassium, a moderate annual mean temperature elevation, and low values of Phosphorus. The regeneration of *Quercus semecarpefolia*, *Berberis aristata*, *Eriobotrya dubia* are strongly supported by increasing slope and elevation while increasing degree of aspect supported the regeneration of *Quercus lanuginosa*, *Luculia gratissima Castanopsis tribuloids*. Potassium plays active role in regeneration of *Acer oblongum*, *Litsea oblong Castanopsis indica* (Fig. 5, Table 5).
Table 5
Biplot scores for constraining significant variables of study area

<table>
<thead>
<tr>
<th>SN</th>
<th>Variables</th>
<th>CCA1</th>
<th>CCA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Elevation (Elv)</td>
<td>-1.00</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>Slope (Slp)</td>
<td>-0.41</td>
<td>0.09</td>
</tr>
<tr>
<td>3</td>
<td>Aspect (Asp)</td>
<td>-0.08</td>
<td>-0.35</td>
</tr>
<tr>
<td>4</td>
<td>Annual Mean Temperature (AMT)</td>
<td>0.82</td>
<td>0.06</td>
</tr>
<tr>
<td>5</td>
<td>Annual Mean Rainfall (AMR)</td>
<td>-0.58</td>
<td>-0.70</td>
</tr>
<tr>
<td>6</td>
<td>Potassium (K)</td>
<td>0.07</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

The regeneration of *Luculia gratissima, Lindera pulcherrima, Quercus glauca* and *Caryopteris foetida* is supported by higher mean rainfall and aspect values and lowering Phosphorus, annual mean temperature. Similarly, *Lecoceptrum canum, Grewia oppositifolia, Maesa chisia, Sapium insigne* and *Maclura cochiachinensis* seems to be promoted by a higher elevation and by a lower of potassium. *Ligustrum confusum, Quercus semecarpefolia, Berberis aristata, Fraxinus floribunda* regeneration is stroked by higher elevation with lower annual mean temperature. Higher values of Potassium promote the regeneration of *Litsea oblong, Myrica esculenta,* and *Acer oblongum.* The regeneration of *Schima wallichii, Sarcococca coriacea, Myrsine capitellata, Alnus nepalensis,* *Camellia kissi* were found highly supported by a higher AMT, and P, as well as by a lower degree of Aspect and AMR. (Fig. 5, Table 5).

**Discussion**

**Species composition and structure**

There was a unimodal richness pattern for species richness of tree seedlings with a high richness at mid-elevation. This high richness at mid-elevation would be due to the mid-domain effect (Colwell & Lees, 2000) as constrained by the geometry of the landscape. Seedling species showed greater diversity at the upper elevation. The higher species richness of seedlings and lower species diversity of saplings and tree species on the top ridge of the hill might be caused by a development of microclimatic habitats due to anthropogenic activities. Invasion toward lower elevation may be another cause of decreasing species diversity (Austin et al., 1996; Burns 1995; Choler et al., 2001). Tree species and sapling species showed greater diversity at middle elevation due to the mid-domain effect. The pattern of species regeneration along the elevation gradient is also affected by species richness.

There was a gradual increase of saplings and seedlings densities toward the top ridge of the hills. Elevation showed a strongly positive correlation with the seedling density, seedling species richness, sapling density, and tree species richness. The density of trees showed unimodal pattern with peak at middle elevations as found in study in the Western Ghats (Parthasarathy & Karthikeyan, 1997), and
temperate forests of the Himalaya (Samant & Pant, 2003), the Dolpa district (Kunwar & Sharma, 2004), and the eastern Himalaya (Borah & Garkoti, 2011).

**Species richness and diversity indices**

The result of regression showed that elevation and annual mean rainfall had a significant effect on species density but not on species richness. The diversity indexes were positively correlated with elevation. The lowest D and highest H was found at mid-elevations for all life forms prevailed that greater diversity in the study area. A greater diversity index for seedlings the top ridge indicates their least diversity. Higher diversity and lower dominance on the top of the hill may be due to the formation of microclimates by moderate disturbance induced by anthropogenic recreational activities and settlement practices.

The higher the value of Simpson's index designates the diversity. Simpson index and species richness of trees were negatively related to elevation as defined by Choler et al. (2001). The value of the Shannon index increases as diversity increases. Middle elevation supported a higher density and species richness of trees. Similar result were reported for different life forms in Himalayan forests (Durak, 2012). Greater species richness at middle elevation is due to the effect of climate change which obliges to change by adapting to the more appropriate conditions or by shifting upwards or downwards from their predictable range of distribution of species (Sharma et al., 2014).

Seedling species showed a heterogenous response in Simpson index with a sharp decline at the top of the mountain, and higher values at mid elevational ranges, consistent with previous results (Kharkwal et al., 2005; Sharma et al., 2009) obtained in temperate forests of Himalayan regions. Contrasting results have been provided by (Austin et al., 1996; Burns 1995; Rosbakh et al., 2014) showing the highest species richness at lower elevations.

**Regeneration status**

The regeneration potential of a tree species indicates forest sustainability. The regeneration potential of existing tree species defines the future composition of forests, coexistence, dominancy, and wealth of forests (Jones et al., 1994). The number of different life stages like trees, saplings, and seedlings can assist in predicting future changes, the status of regeneration, and floral diversity (Malik & Bhatt, 2016).

A good regeneration status of trees can be assessed by the presence or density of trees in the mature, sapling, and seedling stage in the order of seedlings > saplings > trees (Rawat et al., 2018; Rocky & Mligo, 2012). The present study showed that the status of the forest in the study area have a good regenerating status since the proportion of total saplings (78.5%) is much higher than that of total seedlings (10.5%) and matures (10.9%). As the seedling population ranged between 71 to 87% of the total population of tree species indicating a good regenerating status. For normal replacement of forest, the value of seedling to total population should be ≥ 50% (Sagar & Singh, 2004).
The number of mature tree individuals of all species is not equally regenerating in all elevations. The mid-elevation shows a poor regeneration while the upper and lower elevation ranges possess a good regeneration potential. Good regeneration at upper elevations may be attributed to the lower biotic activities existing there. The low regeneration at middle elevation may be due to the larger number of trees with a higher canopy covering which prevents sufficient light intensity for a maximum survival rate of seedlings (Benzing, 2004; Chaturvedi et al., 2016; Chesson, 2000; Marimon et al., 2012).

Trees found at the top ridges, including *Berberis aristata*, *Pinus wallichiana*, *Pyracantha cranulata*, *Quercus glauca*, *Q. semecarpfolia*, *Q. lanuginose*, and *Rhododendron arboreum*, show a good regeneration. Similarly, trees found in the bottom region of hills, e.g., *Maesa chisia*, *Alnus nepalensis*, *Lyonia ovalifolia*, *Schima wallichii*, *Syzygium cumini* showed a good regeneration. *Caryopteris foetida*, *Elaeagnus latifolia*, *Maclura cochichinensis*, *Mahonia nepaulensis*, and *Zanthoxylum armatum* have a very poor regeneration. *Aesculus indica* and *Taxus wallichiana* were not present in adult form but in the sapling or seedling stage only, at lower elevations near agricultural fields. They might have been recently introduced by humans for medicinal and aesthetic purposes. Only matured stages are reported for *Princepia utilis* and *Wendlandia puberula* indicating no regenerating of these species in the study area. Species found in natural vegetation in the matured stage only indicate the susceptible condition for local extermination (Taye et al., 2011).

In the present study, some tree species were found in the non-regenerating stage while the majority of species were found in all growth stages. Forest regeneration is governed by more than a single factor. Canopy density, soil properties, grazing, light intensity, shade tolerance, intra and interspecific competition, niche isolation, dormancy ability, recruiting potential of growth forms, and fire resistance greatly affect species regeneration in the Himalayan region (Behera et al., 2012; Bose et al., 2016; Saikia et al., 2017). Abiotic factors like temperature, precipitation, soil fertility, and biotic factors such as richness, diversity, and composition of forests greatly affect the regeneration potential of natural forests (Khaine et al., 2018).

**Community analysis and variables selection**

Many abiotic and biotic factors influence plant species distribution and abundance (Hall et al., 1992), and species richness. Plant species composition and elevation are scale dependent (Nogués-Bravo et al., 2008). Our regression analysis did not reveal an influence of ecological variables on tree seedling species richness. However, tree seedling density was found most significantly influenced by elevation ($r^2 = 0.70$, $p < 0.001$), annual mean rainfall ($r^2 = 0.35$, $p < 0.004$) and Phosphorus ($r^2 = -0.56$, $p < 0.20$). Several studies also proved aspect (Bangroo et al., 2018; Yang et al., 2020), pH (Saeed et al. 2014), Nitrogen (Bhandari et al., 2019), water holding capacity, crown coverage, and ground vegetation coverage (Giweta, 2020) as influencing factors, which we could not reproduce in the present study.

Elevation is a decisive ecological factor (He et al., 2016) for other ecological parameters like rainfall, temperature, humidity, aspects, slopes, and directly affects the plant species richness and species
composition (Shimoto et al., 2010; Zhu et al., 2019). Elevation also plays a key role in determining water holding capacity, soil nutrients, and solar light intensity.

The lesser the atmospheric temperature also the lowering the soil temperature. The soil temperature decreases along increasing elevation and showed a significant inverse relationship to nitrogen stocks (Vieira et al., 2011) and soil water content. It decreases mineralization or decomposition of litter (Zhang et al., 2012). Similarly, there is a negative correlation with available Phosphorus (Khadka et al., 2016) and species density. High availability of Phosphorus also suits a competitive species which expels less productive species (Hautier et al., 2009).

**Environment species composition**

In CCA, seedling species density of several trees showed a close relationship to different ecological variables, although these effects differed between species. Sites having higher N, P and soil organic carbon contents were represented at sites towards the lower values of aspect, pH, annual mean rainfall and RRI values and moderate values of elevation and slope. The regeneration potential of *Lecoceptrum canum*, *Grewia oppositifolia*, *Pyracantha cranulata*, *Pinus wallichiana*, *Maesa chisia*, *Gaultheria fragratissima*, etc. were higher in the sites having higher values of N, P and soil organic carbon contents and lower values of soil pH, aspect, annual mean rainfall and RRI. Similarly, the higher regeneration potential of *Pyrus pashia*, *Luculia gratissima* and *Lindera pulcherrima* were found at region having higher values of pH, RRI, aspect and annual mean rainfall and lower values of N, P, SOC and WHC had lower values. It signified that N, P, soil organic carbon and pH greatly impact on the regeneration potential of seeds but not uniform correlation with every seeds. Whereas Potassium does not find significant role at species composition as strong as nitrogen and phosphorus. Plant species usually have independent range of tolerance of soil nutrients and other ecological factors which cannot be generalized.

Soil nutrients alters the biological diversity and ecosystem services (Smith et al., 1999). Plant growth and development might be diminished by low availably of both N and P in terrestrial environments (Vitousek & Howarth, 1991). Energy metabolism and foliar development need Phosphorus (Mokwunye et al., 1986). Soil pH controls the relative abundance of inorganic Phosphorus in soil (Schachtm et al., 1998). In the majority of cases, poor phosphorus is found in high elevation rangelands and forest which decrease the soil fertility (Brown et al., 2000). Soil pH showed negative values at both CCA axes and opposite relation with litter coverage, water holding capacity indicating that the soil pH has positive roles at low water holding capacity and litter coverage towards lower elevation. The plant species such as *Lindera pulcherrima* had a high species score towards sites with higher pH values and RRI values indicating positive effects. Chapagain et al. (2021) found a significant positive effect of RRI on the distribution of juvenile and adult stages of plant species in the Himalaya region of Nepal.

The species occurrences, their abundances and plant communities also depend on environmental variables (Bernard-Verdier et al., 2012). Environmental variables not only establish the relationship but also determine the pathway of regeneration patterns. The elevation, aspect, soil nutrients, soil pH, RRI, and other predictors have impulsive effects on plant species. The knowledge of the relationship between
plant regeneration and environmental variables help to develop a better strategic plan of restoration of forest by implementing good and suitable therapeutics.

**Conclusion and recommendation**

The present study revealed that the tree species richness in the mature and sapling growth stage and their density showed a hump shaped structure with a mid-domain effect along elevational gradients. Ridge effects were observed in the regeneration of tree species as well. Regeneration also followed the same pattern with good regeneration between 1400–1500 m asl. and 2100–2300 m asl. with poor regeneration at mid-elevation (1700–2100 m asl.). Seedlings showed increasing species richness and stand density with increasing elevation. Half of the individuals of tree species were noticed in all growth forms along elevation gradient while another half showed either fair or poor regenerating status. The spatial distribution patterns of tree species showed contagious, clumped, scattered, irregular, and regular distribution patterns along different elevational ranges. During modelling, elevation, annual mean rainfall, aspects, slope and annual mean temperature revealed the greater influences on regeneration potential of tree species in the study area. Anthropogenic activities like the constructions of roads, hiking trails, cottages and shelters in the study area were also noticed which may represent a major negative impact on the potential of regeneration of the forest.

**Declarations**

**Acknowledgments**

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**Author contributions**

Both authors agree to be liable for the contents of the work. The first author innately contributed to the research design, data assembly, data analysis, and manuscript writing; the second author contributed to data analysis and supervision of study, editing manuscript.

**Availability of data and material**

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Conflicts of interests

We both authors declared that we have no conflict of interests.

References


**Figures**
Figure 1

Map showing study area showing sampling plots
Figure 2

a. Regression between tree species richness and elevation, saplings species richness and elevation and seedling species richness with elevations. Each fitted line is the significant model after `glm`. Model statistics have been represented in term of Deviance.

b. Regression between tree density and elevation, saplings density and elevation and seedling density with elevations. Each fitted line is the significant model after `glm`. Model statistics have been represented in term of Deviance. Seedling density was divided by 10 during regression but normal while representation.
Figure 3

a. Regression between Shannon Diversity index of tree, sapling and seedling with elevation. Each fitted line is the significant model after glm. Model statistics have been represented in term of Deviance. The species richness showing lower diversity at top and bottom of forest with highest diversity at middle elevation

b. Regression between Simpson index of tree, sapling and seedling with elevation. Each fitted line is the significant model after glm. Model statistics have been represented in term of Deviance. The species richness showing lower diversity at top and bottom of forest with highest diversity at middle elevation

Figure 4

a. Regeneration status of the forest: good regeneration at lower and upper elevation with low regeneration at middle elevation

b. Regeneration status of the forest: nearly half of tree species are regenerating (49%), very few are non-regenerating (4%), new regeneration (4%) and one third (32%) are in the stage of good regeneration and poor regeneration (11%)
Figure 5

CCA biplot of plant species with the most significant predictor variables in the study area (full forms of environmental variable and species names with CCA score were given in Table 4).