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Tree diversity and regeneration patterns along stand-age gradients in the Swayambhu sacred forest

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A R T I C L E I N F O

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A B S T R A C T

Sacred or religious forests are one of the most important but difficult to manage forest types due to high human interferences. The Swayambhu Religious Forest was selected for this study. This sacred forest was divided into three strata based on the stand age, considering the species composition, including established forests, generally comprising broadleaved species (old forests), emerging forests or young (10 years or above) forests, generally dominated by pine trees five years or above, and regeneration forest (newly established, less than five years of age, with a few scattered trees, by using the stratified systematic sampling method for data collection from 29 circular sample plots established in the forest. The Permutation-based ANOVA test showed significant variation in tree diversity and regeneration diversity among the three forest strata, but the Shannon diversity index was higher in the broadleaved forest in comparison to the regeneration and pine forests. The Spearman correlation analysis showed positive correlations in canopy density and Shannon diversity, tree diversity and regeneration diversity, and tree density and regeneration diversity of tree species, but there was no strong positive correlation between tree density and Shannon diversity. There was a negative correlation between canopy density and regeneration diversity, demanding canopy opening to promote natural regeneration of the forest. Both regeneration diversity and tree diversity were higher in the broadleaved forest, where anthropogenic disturbance was moderate, with 10 of the 14 tree species regenerating. The study showed a decline in richness of species diversity by age of forest.

INTRODUCTION

Religious or sacred forests are one of the participatory conservation practices that has traditionally maintained a taboo or culturally prohibited environment with limited extraction activities due to religious norms. Such sites are traditionally governed through spiritual beliefs, cultural norms and customary institutions, which effectively regulate access and resource use, thereby contributing to long-term species and habitat conservation (Malhotra et al., 2007; Dudley et al., 2010; Ormsby & Bhagwat, 2010). In the Himalayan region, Special Areas for Conservations (SACs) play a particularly vital ecological role, as they often protect remnant old-growth forest patches, rare and endemic species, and critical ecosystem functions such as soil stability and water regulation (Wild et al., 2019).

Sacred forests often function as informal protected areas, complementing state-managed conservation systems and demonstrating how culturally-embedded governance can achieve conservation outcomes with minimal external enforcement.

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The communities consider these participatory and religious forest systems to be of great conservation significance on account of their value for identity, spiritual and ecological integrity (Malhotra et al., 2001; Ormsby and Bhagwat, 2010). The community-managed mid-hill forests in Nepal support greater bird species diversity, richness and density compared to government-managed protected areas, thereby establishing the effectiveness of community management for maintaining favourable habitat conditions (Baral and Heinen, 2007).

Despite growing body of research, a key ecological question remains poorly addressed: How does species composition vary across forest age gradients under participatory management regimes, particularly sacred forests? Temporal studies in the western Himalayas have shown that species richness and species composition can shift substantially over multi-decadal scales, with both naturally introduced and management-planted species contributing to compositional change and the relative contributions of dominant species declining over time, indicating dynamic community processes linked to stand development and disturbance history and management interventions (Chaturvedi et al., 2017).

Similarly, studies along altitudinal gradients in eastern Nepal have documented significant changes in forest structure, species richness and community composition across environmental gradients, underscoring the heterogeneous nature of forest biodiversity across spatial and environmental scales (Bhattarai and Vetaas, 2003). However, stand age gradients in religious forests are limited, particularly regarding how conservation-oriented participatory governance influences compositional trajectories over time.

The study had the assumption of no intervention for better conservation, whereas forest management involves the control of the composition and structure of the growing stock (Shrivastava, 1997). Tree diversity assessment is very important for conservation of tree species in religious forests. Religious forest management plays an important role in species richness and maintenance of diversity (Zegeye, et al., 2011). Understanding species composition patterns across forest age gradients in religious forests is, therefore, essential. It informs conservation planning, clarifies the long-term ecological outcomes of sacred forests and helps reconcile traditional forest governance with contemporary biodiversity science (Ormsby, 2013). This study aims to fill this gap by investigating species composition dynamics across distinct forest age classes in participatory and culturally-governed sacred forests, with a focus on community priorities and biodiversity outcomes.

MATERIALS AND METHODS

Study area

Located in Kathmandu, Nepal, at 27.17° N and 85.32 ° E, the Swayambhu Religious Forest (SRF) encompasses a total area of 31.38 hectares (ha), consisting of 24 ha of forested land and 7.38 ha of infrastructure. Situated within a hilly landscape, the site features an elevational gradient ranging from 1,350 m to 1,406 m above sea level. The region is characterized by a subtropical climate, with a maximum temperature of 37°C in June and a minimum temperature of 10°C in January. The average monsoon precipitation is 1,454 mm/year, with the relative humidity of 74%. The forest is rich in tree diversity, including both native and exotic plants. SRF is mainly composed of tree species such as Chilaune (*Schima wallichii),* Katus *(Castanopsis indica),* Phirphire *(Acer oblongum),* Punwale *(Ilex excelsa),* Khari *(Celtis australis),* and Vimal *(Grewia optiva*). The major associate trees include *Myrsine semiserrata Pyrus Phasia, Ziziyphus incurva, Diospyros tomentosa, Myrica esculenta* in the plantations of Chir pine (*Pinus roxburghii*) and exotic plant species like *Eucalyptus*, *Grevillea* and *Araucaria*.

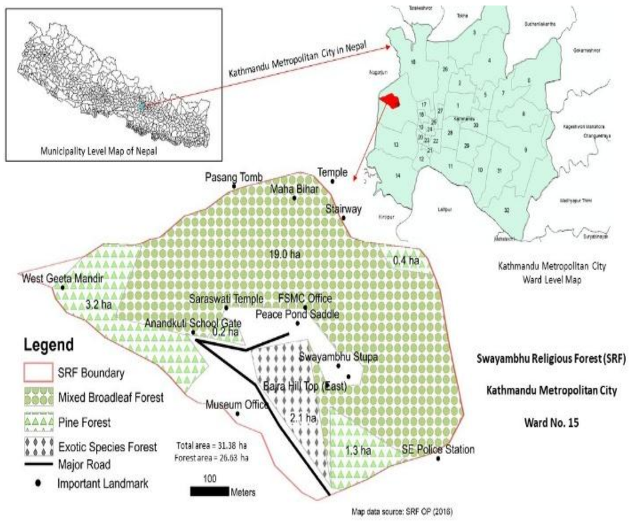

Figure 1: Location map of the study site

SRF was handed over to the Federation of Swayambhu Management and Conservation (FSMC) by the District Forest Office (DFO), Kathmandu, in 2010 and its operational plan was reviewed in 2016. Since time immemorial, the forest was a pristine natural forest, covering the hilly landscape of Swayambhu, which is noted as a major tourist attraction by the National Biodiversity Strategy 2002. The religious forest has contributed to the conservation of tree diversity, which is relatively less disturbed due to the legal restriction on tree-cutting. SRF is a cultural heritage inscribed in the world heritage site of Swayambhu by UNESCO in 1979 (UNESSCO, 1979). The forest was handed over to the FSMC for management as a religious forest in 2010 by the DFO Kathmandu (MoFSC, 2015).

Data collection

The primary data were collected from the field, while secondary information was collected through the content analysis of the minutes, operation plan and literature review. Stratified systematic sampling was carried out in the religious forest, establishing 29 nested circular sample plots for data collection of seedlings, saplings, poles and trees (Table 1). Trees > 10 cm dbh over bark were measured at 1.37 m above the ground. Tree height was measured by Suunto

Table 1: Sampling design

Strata	Area (ha)	Sample Size (ha)	Radius (m)	Area (m^2)	Total Plot	Distance between Plots (m)	Remarks
Broadleaved forest	20	0.4	12.62	500	13	149	Tree
Pine forest	3	0.06	5.64	100	8	65	Pole
Regeneration forest	1	0.02	2.82	25	8	33	Regeneration

Crown density was measured by using a convex spherical densiometer following the standard canopy assessment protocols (Lemmon, 1956). Measurements were taken at the centre of each sample plot. The observer faced each of the four cardinal directions, ie north, south, east and west, in which the number of grid intersections occupied by the canopy cover was recorded. The measurements of the four directions were averaged and converted into percentages.

Field observation was done with the participation of the FSMC members to assess the implementation of the forest operational plan. Interactions were held with key informants such as FSMC members, *Guthi* members (who are indigenous group of Newar communities group to manage their resources) and local stakeholders, including forest staffs, residing in the vicinity of the forest. Forest inventory data were collected following the sampling design as prescribed in the Community Forestry Inventory Guidelines 2004 (Table 1).

Data analysis

The Shannon diversity indices of tree and the regeneration diversities in the forest strata of the broadleaved, pine and regeneration forests were calculated. Spearman correlation analysis was done to evaluate the relationship between tree diversity and regeneration diversity in the three forest strata. Shannon Diversity index was calculated using the following formula (Shannon & Weaver, 1963):

Shannon Diversity index (H') = $-\Sigma$ (pi (ln pi)

Where:

> $p\ i$ = the proportion of individuals of species i in the sample

The crown density of the forest was determined by calculating the value given by the densitometer. The corner gap points were counted in the north, east, west and south directions at every sample plot, and the average count was multiplied by the factor 1.04 for the value which was deducted to 100 for crown density in the three forest strata. The crown density was classified as closed in between 0.75 and 1.0, thin in between 0.5 and 0.75 and open under 0.5 (Chaturvedi and Khanna, 2004). Anthropogenic disturbance on tree diversity was assessed with respect to regeneration diversity through observation of obvious signs of human disturbance and monitoring of the impact area based on access, impact area and anthropogenic stress. Broadleaved forest with controlled access, pine forest with open access and regeneration forest with restricted access were categorized as medium, high and low disturbance regimes respectively. Forest management practices were evaluated with the participation of the FSMC members.

A permutation-based analysis of variance (PERMANOVA) (Anderson, 2001; Legendre & Legendre, 2012), performed in the adonis2 function of the vegan package in R (Oksanen et al., 2025), was used to evaluate the differences in Shannon diversity among forest age classes. Euclidean distance was employed and 999 permutations were utilized to determine significance. Pairwise comparisons were carried out using permutation-based ANOVA when the global test was significant, and the Benjamini-Hochberg technique was used to modify p-values.

Non-metric multidimensional scaling (NMDS) (McCune and Grace, 2002; Legendre and Legendre, 2012) based on the Bray–Curtis dissimilarities was used to examine the regeneration diversity composition across forest age classes. A community matrix was created using species abundance information from each sampling plot. To obtain stable ordination, NMDS was carried out in R, using the metaMDS function from the vegan package (Oksanen et al., 2025) with two dimensions (k = 2) and 100 iterations (trymax = 100). To determine goodness-of-fit, stress values were analysed. Plots were colour-coded in accordance with the forest age classes, which were utilized as categorical grouping variables for display.

One-way analysis of variance (ANOVA) (Zar, 2010; Gotelli & Ellison, 2013), using location as a fixed factor, was used to examine variations in canopy density between the forest age gradient. A continuous response variable was used to measure canopy density. The significance of the model was assessed at $\alpha = 0.05$. Tukey's honestly significant difference (HSD) test was used for post-hoc pairwise comparisons between sites when a significant site effect was found. R was used for all analyses.

RESULTS

Tree diversity of the three forest strata was evaluated with Shannon diversity index (H'), calculating mean standard deviation, indicated by lowercase letters (a, b), signifying the differences between the strata. The coefficient of variation (CV) revealed no significant variation in Shannon diversity between the pine and regeneration forests, but there was significant variation in the broadleaved forest (Table 2).

Table 2: Tree diversity across the forest age gradient

Forest age gradient	Shannon Diversity Index (H')	Coefficient of Variation (CV)	No. of Species per plots	Remarks
Broadleaved forest	0.91 (0.53)[b]	0.58	3.23 (1.24)[a]	Natural Forest
Pine forest	0.25 (0.35)[a]	1.38	1.38 (0.74)[b]	Pine Plantation
Regeneration forest	0.14 (0.27)[a]	1.98	1.38 (0.74)[b]	Regeneration

Table 3: Permutation-based ANOVA (PERMANOVA) testing the effect of forest age gradient on Shannon diversity

Source	Degree of Freedom	Sum of Square	R2	F statistics	p-value
Forest age	2	3.76	0.44	10.28	0.003
Residual	26	4.76	0.56		
Total	28	8.51	1.0		

Table 4: Shannon diversity pairwise variations along the forest age gradient using permutation-based ANOVA (999 permutations). Benjamini–Hochberg (BH) adjusted p-values, explained variance (R^2) and F-statistics are presented.

Comparison	F	R^2	p (BH-adjusted)
Regeneration vs pine	0.57	0.04	0.570
Regeneration vs broadleaved	9.63	0.34	0.011
Pine vs broadleaved	14.57	0.43	0.002

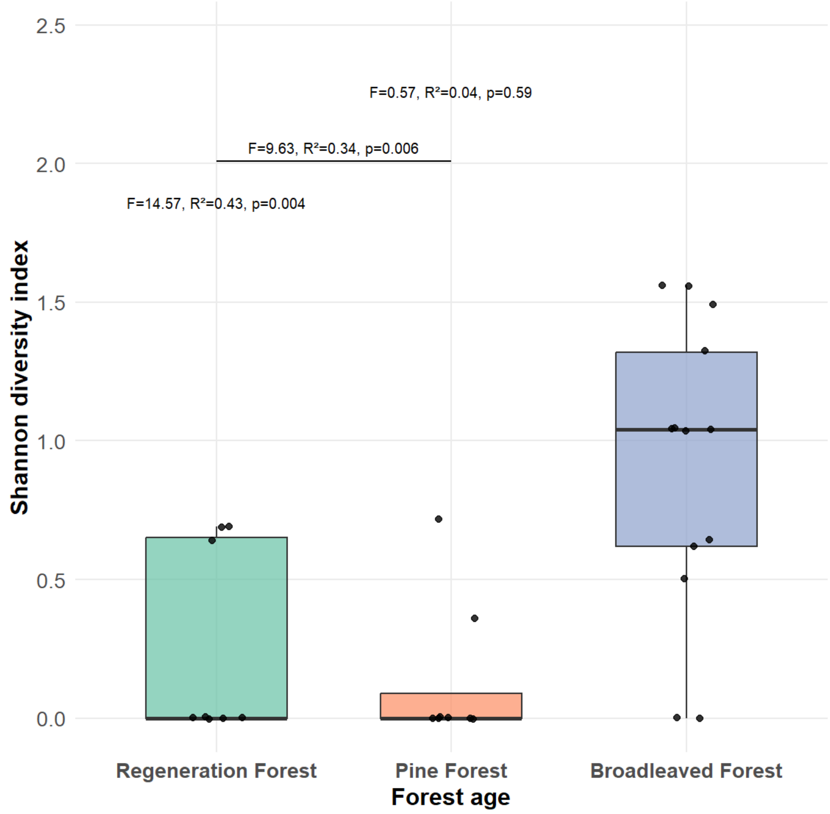

Figure 2: Shannon diversity variation along a gradient of forest age. Points show individual plots, whiskers show 1.5 × IQR, and boxplots show the median and interquartile range. Permutation-based ANOVA (999 permutations) was used to assess differences between age groups. F-statistics, explained variance (R^2) and BH-adjusted p-values are shown above the boxplots for pairwise comparisons

Table 5: Regeneration diversity across the forest age gradient

S.N.	Forest Strata	Shannon Diversity (H')	Coefficient of Variation (CV)	Remarks
1	Broadleaved forest	0.19 (0.30) [b]	1.57	Natural forest
2	Pine forest	0.07 (0.20) [a]	2.83	Pine forest
3	Regeneration forest	0.08 (0.20) [a]	2.83	Regenerated forest

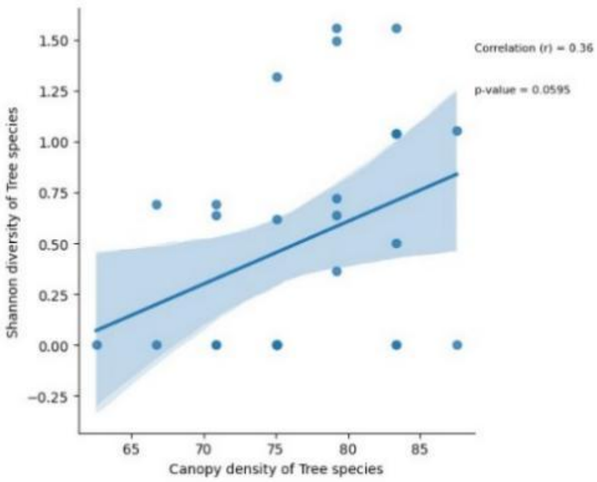

Figure 3: Canopy density and Shannon diversity

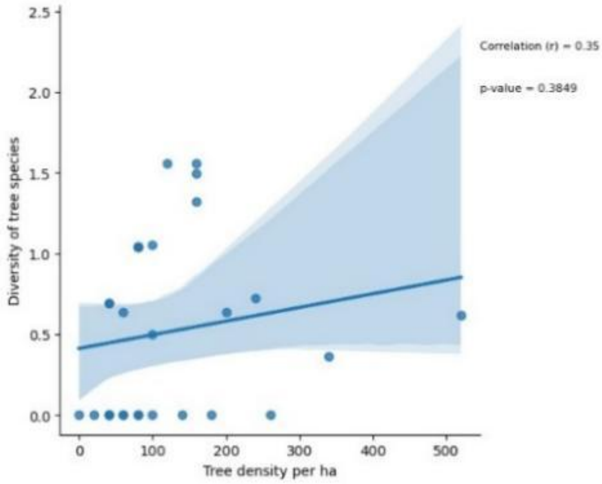

Figure 4: Tree density and Shannon diversity

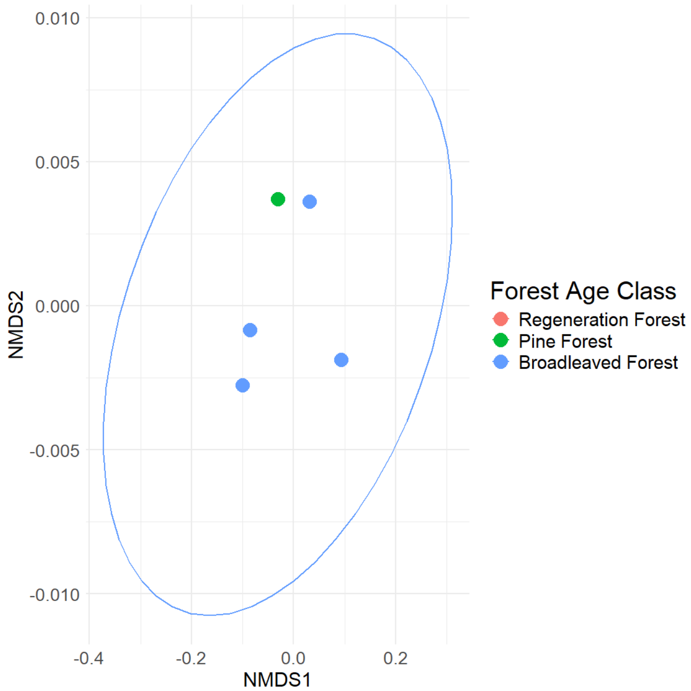

Figure 5: The regeneration composition's NMDS ordination (Bray–Curtis distance) across forest age classes. A sampling plot, colored by forest age class, is represented by each point. For every forest age class, ellipses display 95% confidence intervals. Plots of broadleaved and pine forests are shown; however, regeneration forest plots were left out because no regeneration species were found. Stress value = 0.01, which shows that the differences in two dimensions are well represented. Weak compositional differentiation between forest age classes is indicated by overlap between ellipses.

The forest age gradient significantly affected Shannon diversity, according to a permutation-based analysis of variance (PERMANOVA) ($F = 10.28$, $R2 = 0.44$, $p = 0.003$; 999 permutations). Total 44.1% of the variation in tree diversity was explained by forest age, suggesting significant compositional variations between the broadleaved, pine and regeneration forests.

Pairwise permutation-based ANOVA revealed that Shannon diversity varied significantly along the forest age gradient. In terms of Shannon diversity, the regeneration and pine forests did not differ significantly (F = 0.57, R2 = 0.04, p = 0.57). The regeneration forests, on the other hand, showed far less diversity than the broadleaved forests (F = 9.63, R2 = 0.34, p = 0.011). Similarly, Shannon diversity was considerably lower in the pine forests than in the broadleaved forests (F = 14.57, R^2 = 0.43, p = 0.002). From early successional stands to mature broadleaved forests, Shannon diversity generally grew significantly (Figure 2; Table 4).

The result of the Spearman correlation analysis (Spearman R = 0.36) showed a positive correlation between canopy density and Shannon diversity (Figure 3). There was no stronger positive correlation (r = 0.35, P > 0.05) between tree density and Shannon diversity (Figure 4). There might be other environmental factors such as light, soil and aspects affecting Shannon diversity.

The coefficient of variation revealed no significant variation between the pine and regeneration forests, but regeneration diversity was higher in the broadleaved forest. The mean standard deviation (a, b) indicated significant difference among the forest age gradient.

Forest age class did not significantly affect regeneration diversity composition, according to the permutation-based ANOVA (F = 0.76, R2 = 0.06, p = 0.51). Only approximately 5.5% of the difference in regeneration data was explained by forest age; residual factors accounted for the majority of the variation. This suggests that the composition of regeneration was essentially the same for all forest age classes.

Table: 6. Permutation-based ANOVA (PERMANOVA) testing the effect of forest age gradient on regeneration diversity composition

Source	Degree of Freedom	Sum of Square	R^2	F statistics	p-value
Forest age gradient	2	0.101	0.055	0.76	0.508
Residual	26	1.738	0.945		
Total	28	1.839	1.00		

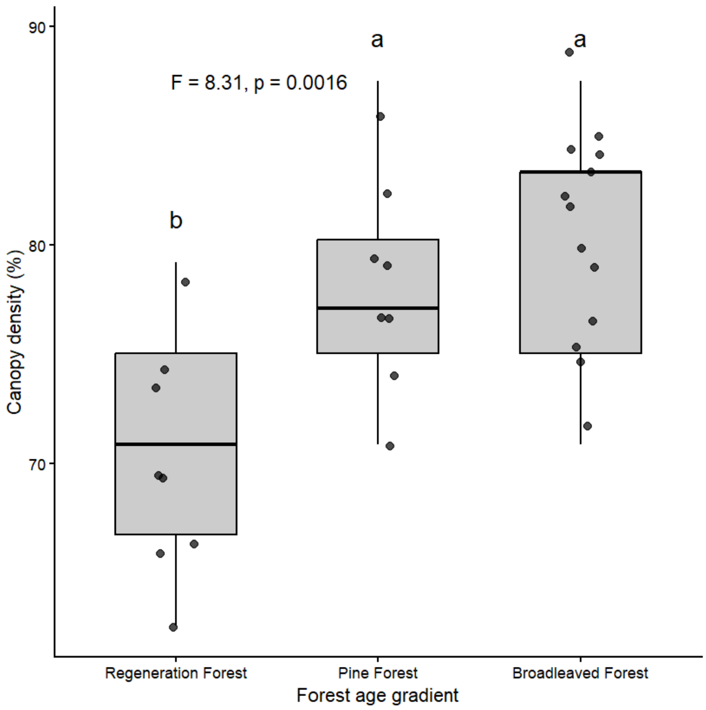

Figure 6: The differences in canopy density along the forest age gradients. Interquartile ranges are represented by boxes, medians are shown by horizontal lines, and individual plots are displayed by points.

The F and p values are derived from the one-way ANOVA ($F_{2, 22}$ = 8.31, p = 0.0016). As a result of variations in stand structure and management history, this figure shows that canopy density varies considerably between the forest age gradients

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There is a significant group overlap in the NMDS ordination of regeneration diversity composition across forest age classes (Figure 5). Points show sampling plots with 95% confidence ellipses for each group, coloured by forest age class. Plots of broadleaved and pine forests are well represented; however, the plots of the regeneration forests were left out because no regeneration species were found. The low stress value (stress = 0.01) suggests that the differences in regeneration composition are sufficiently represented by the two-dimensional NMDS. The ordination shows minimal compositional heterogeneity throughout the forest age classes, indicating that the composition of regeneration species is generally consistent throughout the locations that were sampled.

Effect of canopy density in diversity across the forest age gradient

The forest age gradient had significantly different canopy densities (one-way ANOVA: $F_{2, 22}$ = 8.31, p = 0.0016). A significant amount of the variance in canopy density was explained by the forest age gradient, suggesting significant site-level variations in the structural features of the forest. The mean canopy density varied continuously between locations, indicating that local stand characteristics and management history are related to different canopy closure.

The forest age gradient impact was considerable (η^2 = 0.39), meaning that site differences accounted for over 40% of the total variation in canopy density.

The Spearman correlation analysis showed negative correlation (r = - 0.17, P > 0.05) between canopy density and regeneration diversity of tree species in the sacred forest (Figure 7). On the contrary, there was a positive (r = 0.35, P < 0.05) correlation between regeneration diversity and tree density, indicating higher number of individuals with increasing number of tree species (Figure 7). There might be other environmental factors affecting regeneration diversity of trees in the forest.

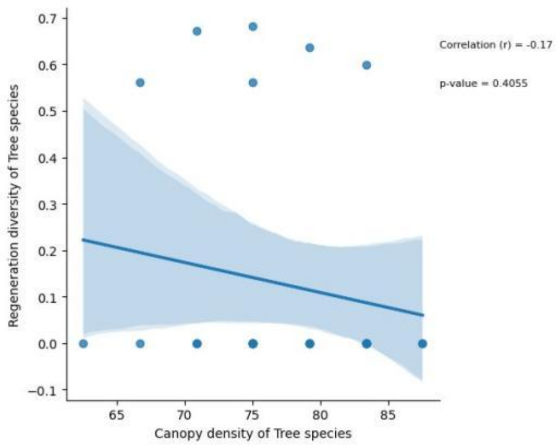

Figure 7: Regeneration diversity and canopy density

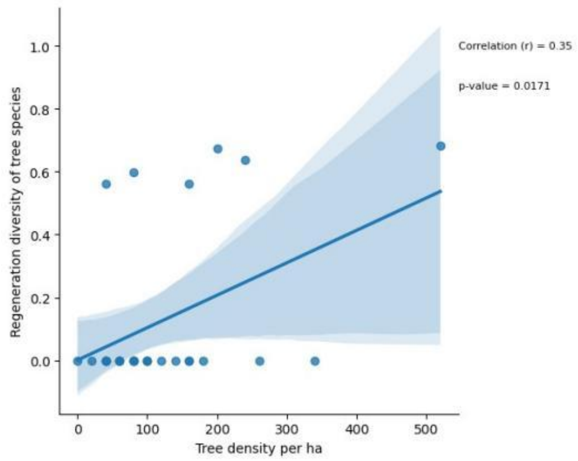

Figure 8: Regeneration diversity and tree density

The Spearman correlation analysis showed a weak positive correlation (r = 0.35, P > 0.05) between tree diversity and regeneration diversity of tree species, indicating increase in regeneration diversity with increase in tree diversity (Figure 9).

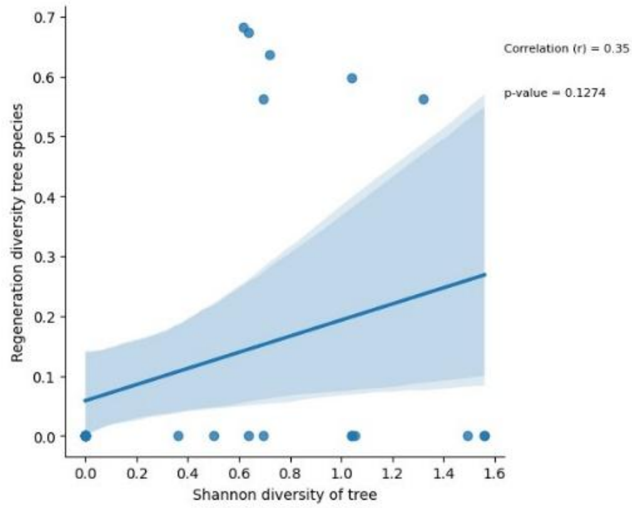

Figure 9: Tree diversity and regeneration diversity

The Importance Value Index (IVI) summed the percentage of relative values of density, frequency and basal area with respect to the tree species of the forest. *Chilaune* (*Schima wallichii)*, *Kalikath* (*Myrsine semiserrata*) and *Ritha* (*Sapindus mukorossy*) were the dominant tree species in the broadleaved forest, whereas *Khote Salla* (*Pinus roxburghii*) was dominant in the pine forest and *Chilaune* (*Schima wallichii*), *Masala* (*Eucalyptus Spps*) and *Khari* (*Celtis australis*) were dominant in the regeneration forest.

The forest regeneration condition was poor in the three forest strata. Regeneration included 277 seedlings/ha and 1,385 saplings/ha of 10 tree species and 1,262 seedlings/ha of seven shrub species in the broadleaved forest. In the pine forest, regeneration was 57 seedlings/ha and 171 saplings/ha of three tree species and 1,943 seedlings/ha of five shrub species. In the regeneration forest, it was 100 seedlings/ha and 250 saplings/ha of four tree species and 2,000 seedlings/ha of five shrub species (Table 5). Regeneration was very poor in the pine and regeneration forests due to lack of seedlings and saplings due to invasions by shrubs like *Banmara* (*Lantana camara*), *Sisnu* (*Urtica dioica*) and *Asuro* (*Adhatoda vasica*).

The crown density in the forest strata of the broadleaved, pine and regeneration forests was classified as closed (80.16%), dense (78.16%) and thin (70.88%) respectively based on Champion and Seth (1968), DoF (2017) and FAO (2018), whereas the average crown density of the religious forest was dense, with 76.4% (Table 6).

Forest Strata	Crown Density	Condition	Remarks
Broadleaved forest	80.16%	Closed	Average Crown Density 76.4% dense
Pine forest	78.16%	Dense	
Regeneration forest	70.88%	Thin	

The Spearman correlation analysis showed negative correlation ($r = -0.17$, $P > 0.05$) between crown density and regeneration diversity of tree species (Figure 7). The strata of pine, broadleaved and regeneration forests were categorized into high, medium and low anthropogenic disturbance regimes, evaluating access, frequency and impact of human activities in the forest strata. The broadleaved forest had foot trails whereas the pine forest had access to roads and trails for visitors, however, the regeneration forest was restricted for visitors with fencing in the boundary. The pine forest was highly disturbed by human activities such as jungle walks, videography and photography. The broadleaved forest had moderate anthropogenic disturbance caused by collectors of minor forest produce such as leaf litter, firewood and fruit, which had higher regeneration density of 277 seedlings/ha and 1,385 saplings/ha, as shown in Figure 10.

Jungle walk was most frequent in the pine forest, frequent in the broadleaved forest and infrequent in the regeneration forest due to easy access to foot stairs and road access to the three forest strata. In the three forest strata, non-timber forest products such as *Lapsi* (*Choerospondias axillaris*), *Rithha* (fruit of the *Sapindus* tree) and *sisnu* were collected. Fire-damaged patches were observed in the broadleaved, pine and regeneration forests. Waste materials such as plastics, glasses and stale foods were deposited along the foot trails, creating disturbance to regeneration, growth and development of trees in the forest. Human activities for recreation and collection of firewood, fruits and flowers had moderate effects in the broadleaved forest, high impact in the pine forest and low impact in the regeneration forest.

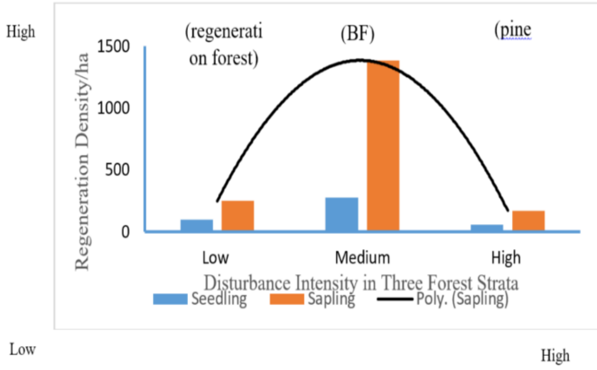

Figure 10: Anthropogenic disturbance on regeneration

The Swayambhu Sacred Forest was handed over to the user committee in 2010, and its forest management plan was reviewed in 2016 for ten years. Forest management records were not maintained, but official minutes, along with annual fiscal report, were available. Uprooted and broken trees were utilized, but record was not maintained. Shrub cutting was done to clear *Lantana camara* in the pine and regeneration forests to reduce fire hazard. Forest offences were not reported. Public awareness was limited to installing hoarding boards. Cleaning campaigns were done for trash collection and management. Watchmen were deployed for forest protection with priority to biodiversity conservation.

Forest condition was evaluated based on the regeneration condition and growing stock criteria as prescribed in the Community Forest Inventory Guidelines 2004. The average growing volume of poles and trees was 277.3 stands/ha with volume of 168.6 m^3/ha and mean annual increment accounted for 3% for good forest with medium growth of 5.058 m^3/ha. The average growing stock density of regeneration in the forest was 144.66 seedlings/ha, 602 saplings/ha, 400.66 poles/ha and 145.43 trees/ ha, whereas shrub species included 1,135 seedlings/ha (Table 8). The overall forest condition was good but natural regeneration was poor in the pine and regeneration forests.

Table 8: Forest condition

Forest Strata	Regeneration Density /ha					Growing Stock/ha				Forest Condition
	Seedling		Sapling		Condition	Pole		Tree		
	Tree	Shrub	Tree	Shrub		Density	Volume (m^3/ha)	Density	Volume (m^3/ha)	
Broadleaved forest	277	1262	1385	0	Good	87.69	15.68	60	166	Good
Pine forest	57	1943	171	0	Poor	614.29	147	314.29	261	Good
Regeneration forest	100	200	250	0	Poor	500	133	62	154	Good
Average	**144.6**	**1135**	**602**	**0**	Poor	**400.66**	**98.56**	**145.43**	**193.66**	Good

DISCUSSION

Forest Diversity across the forest age gradient

We assessed tree diversity with respect to regeneration diversity, analysing forest condition, limiting factors of crown density and anthropogenic disturbance, including forest management practices in the SRF. Statistical analysis was done with the results of a permutation-based analysis of variance (PERMANOVA) and Spearman correlation analysis of vegetation parameters in broadleaved, pine and regeneration forests. The increasing Shannon diversity along the forest age gradient shows that tree diversity and vegetation composition are mainly shaped by the stand development of the forest. The higher diversity was significantly supported by mature broadleaved forests than the regeneration and pine forests, likely due to greater structural complexity, niche differentiation and stable microclimatic conditions that develop with succession (Odum, 1969; Spies, 1998). Similar trends have been seen in temperate and subtropical forests, where a few pioneer species frequently dominate early successional stands, whereas later successional stages encourage the coexistence of late-successional and shade-tolerant taxa (Connell, 1978; Chazdon, 2008). Regeneration and pine forests appear to be very early or simple structural stages with little species turnover, based on the absence of discernible differences between the two. All things considered, these results are consistent with the succession theory and empirical research demonstrating favourable correlations between the forest age, habitat heterogeneity and tree variety (Paillet et al., 2010; Poorter et al., 2015). The growing stock volume of mature trees was higher than the volume of poles in the forest. Removal of hazard trees, including dead, dying, diseased and deformed trees, would reduce competition for space, nutrient and water. Competition is usually intense between the individuals of the same species as their demands are similar for food, light and moisture (Khanna and Chaturvedi, 2000).

Forest regeneration diversity across the forest age gradient

Regeneration composition did not differ significantly along the forest age gradient, suggesting that early regeneration processes are weakly linked to stand age. Similar patterns have been reported in subtropical and Himalayan forests, where regeneration is often governed by microsite conditions, seed availability and disturbance, rather than overstorey age alone (Sharma et al., 2012; Pandey and Shrestha, 2016). In Nepalese Sal and pine forests, regeneration composition has been shown to be strongly influenced by grazing pressure and canopy openness sometimes overriding successional effects (Gautam et al., 2008). In contrast, studies from less disturbed Asian forests have reported clear age-related shifts in their regeneration compositions, particularly under closed-canopy conditions (Chazdon, 2008; Poorter et al., 2015). The lack of a significant age effect in the present study likely reflects site-level disturbances and environmental heterogeneity across plots.

A total of 14 of the 25 tree species recorded in the study were regenerated. The forest strata of the broadleaved, pine and regeneration forests had 15, 3 and 4 tree species regenerated respectively (Shrestha, 2024). The broadleaved forest had the highest number of 277 seedlings/ha and 1,385 saplings/ha of 15 tree species. The pine forest had the lowest number of 57 seedlings/ha and 171 saplings/ha but the highest number of shrub species (1,943 seedlings/ha). The regeneration forest had 100 seedlings/ha and 250 saplings/ha (Table 5). There was no regeneration in the forest areas colonized by invasive shrubs, including Lantana (*Lantana camara*), *Banmara* (*Ageratina adenophora)* and *Ashuro* (*Adhatoda vasica*). Lantana and *Ageratina* were obnoxious weeds suppressing and killing young plants, affecting natural regeneration and increasing fire hazards (Khanna and Chaturvedi, 2000). Shrub cutting creates favourable conditions for regeneration (Khanna and Chaturvedi, 2000). Shrub cutting should be carried out during rains as shrubs impede regeneration (Khanna, 1996).

Effects of canopy density on diversity across the forest age gradient

Significant changes in forest structural conditions are indicated by notable variance in canopy density between sites, which is probably due to differences in stand growth, disturbance intensity and management history. In Nepal, disparities in canopy closure are frequently linked to different community forest management strategies, selective harvesting and grazing pressure, all of which have a direct impact on light availability and stand structure (Adhikari et al., 2017; Poudel and Devkota, 2022). Similar site-level variation in canopy density has been documented from northern Indian *Shorea robusta* forests, where disturbance regimes and management intensity are reflected in the canopy closure (Tripathi and Singh, 2009).

Canopy density is widely acknowledged as a crucial structural characteristic that controls regeneration niches, understorey microclimate and forest successional routes on a global scale (Muscolo et al., 2014; Zellweger et al., 2020). These results are in line with the study's strong site effect, which lends credence to the theory that the canopy structure serves as a significant biological filter affecting forest dynamics. Even in cases where overall regeneration diversity does not change considerably between the forest age gradient, the observed variations in canopy density are likely to contribute to site-specific regeneration assemblages when they are taken into account in conjunction with the NMDS results of regeneration composition.

Crown density in the forest strata of the broadleaved, pine and regeneration forests was classified as closed (80.16%), dense (78.16%) and thin (70.88%) respectively (Table 4). The average crown density of the sacred forest was 76.4%, indicating a dense canopy condition. Crown density showed a negative correlation with regeneration diversity (Figure 6). Similar findings in previous studies have reported high crown density reflecting negative effects on regeneration (Connell, 1978; Poorter et al., 2010). In contrast, intermediate crown densities provided optimal conditions for a diverse range of tree species in the Shivpuri National Park (Adhikari and Skutsch, 2016). Higher crown density reduced light availability, limiting seedling establishment and growth, particularly for shade-intolerant species, as observed in mixed broadleaf conifer forests (Martinez Pastur, Peri, & Piquilloud, 2011; Kitao et al., 2023).

This is consistent with the findings of a study on a Sal (*Shorea robusta)* forest of Nepal, where regeneration density was higher under open canopies and negatively correlated with crown cover percentage (Baral and Ghimire, 2020). However, some studies suggest that certain shade-tolerant species may regenerate even under closed or dense canopies, indicating that the effects of crown density on regeneration can be species-specific (Chazdon et al., 2006). Thus, crown thinning by removing hazardous and unhealthy trees would enhance regeneration as well as growth and development of forest stands due to availability of sunlight. In full light, plants grow greater vigour to flowering and fruiting and temperature affects survival, growth and development of plants (Khanna and Chaturvedi, 2000).

Anthropogenic disturbances can play an important role in maintaining plant diversity, influencing stand structure and impacting regeneration of forest ecosystems (Chapagain et al., 2021). Similarly, anthropogenic disturbance 'alter the habitat gradually changing vegetation in the forest' (Khanna and Chaturvedi, 2000). Moreover, cultural operations like climber cutting and controlled burning would assist regeneration. Tending operations of weeding in seedling stage, cleaning of unwanted growth in sapling stage and thinning, pruning in pole and tree stages would maintain biotic potential of the forest for forest renewal. The operations would have positive impacts of moderate disturbance on regeneration (Chapagain et al., 2021).

In agreement, the silviculture practice is concerned with conserving, protecting and improving the forest as well as controlling the exploitation of forest (Shrivastava, 1997). However, still fire had damaged seedlings, saplings and poles in the broadleaved and pine forests in 2010 and 2019, where cleaning of trails would act as fire lines. Based on the average growing stock of poles and tree (277.3 stands/ha with volume 168.6 m^3/ha, which was higher than the national average growing stock of 164 m^3/ha, the forest condition was good (FRA, 2015). The average regeneration density of tree species in the forest included 144.66 seedlings/ha, 602 saplings/ha, 400.66 poles/ha and 145.43 trees/ ha, whereas shrub species had 1,135 seedlings/ha (Table 5). Nevertheless, the proportions of seedlings, saplings, poles and trees were abnormal due to lower density of seedlings and trees in comparison to higher density of saplings and poles, and showed ill J-shaped exponential growth of the forest. Therefore, the forest would be normal if trees of various ages occupy equal areas (Khanna and Chaturvedi, 2000).

Forest management is essential for regulating forests by controlling growing stock with forest management cycle of regenerating seedlings of valuable trees, through a combination of tending young crops and select harvesting of hazardous and unhealthy trees in the forest (FAO, 2021; Baral et al., 2018). Consistent with recent studies, moderate management intervention with moderate disturbance is necessary for regeneration and maintenance of wildlife habitat in the forest (Pokhrel et al., 2017; Ghimire & Lamichhane, 2021). The Swayambhu Religious Forest Operational Plan 2016 was partially implemented, executing shrub cutting, cleaning and burning of trash. Tending operations, like weeding, pruning and thinning, prescribed in the operational plan were not executed in the forest. Contrary to recommended practices, the management focused on forest protection against adverse impact of monkey and human activities, leaving old trees in Chautari with the nostalgic assumption of no intervention for better protection for self-sustaining of the forest with natural recovery, lthough maintaining a large number of trees would contribute to ecological stability (Baral et al., 2018).

There was no felling due to legal ban on tree cutting in sacred forests. However, fallen trees were utilized without record in religious activities as per the demand of the local *Guthis*. Silvicultural management of forest would ensure conservation of tree diversity in the forest. Through silvicultural treatments, forests are tended, harvested and replaced by new crops of distinctive form (Khanna and Chaturvedi, 2000). Silvicultural treatments would prevent tree diseases root rot and heart rot. Intra-specific competition was serious in pine trees because of their 'same requirements for growth and development' (Khanna, 1999). Silvicultural forest management under the selection system would promote natural regeneration of tree species diversity, enhancing the aesthetic value of the forest. The forest is a wild habitat of Rhesus monkey, providing shelter for more than 600 individuals (Shrestha et al., 2019). Monkeys do considerable damage by eating fruits, seeds and apical buds of forest trees and pulling out seedlings in artificial regeneration areas (Khanna and Chaturvedi, 2000). The monkeys face food scarcity in the wild, creates troubles in search of food, giving rise to human–wildlife conflicts in the world heritage site of Swayambhu.

Planting of fruit tree species like Jamun (*Syzyzium cumini*), Kafal (*Myrica esculenta*), Guava (*Psidium guyava*), Mayal (*Pyrus phasia*), and Lapsi (*Chorespondias axillaris*) would provide seasonal fruits with maintenance of wildlife habitat in the forest. Artificial regeneration is important for restoration of tree diversity in the forest by sowing, planting or other artificial means (Khanna and Chaturvedi, 2000). There is no way of improving the quality of trees in Chir pine in the forest except through artificial regeneration (Khanna, 1999). Initial plantation was done in 1982 by planting exotic plants of Monkey Pojal (*Araucaria species*), Eucalyptus (*Eucalyptus species*) and Kangio (*Grevelia robusta*) in the barren hilltops of the forest. Later, ceremonial plantations were done, but they could not survive due to lack of protection and management. Thus, proper selection of site and plant species is essential for successful planting in the forest with an action plan for protection and management. Plant species should be selected keeping in view the stage of development which the soil has reached

(Khanna, 1999). Plantation with tree guard and gabion wire net was successful in the pine forest for rewilding through Miyawaki plantation in 2023.

CONCLUSION

Swayambhu Religious Forest (SRF) is rich in tree diversity. A total of 45 plant species (25 tree species, 18 shrub species and 2 herb species) were recorded in the sacred forest (Shrestha, 2024). The positive correlations in regeneration diversity and tree density, tree diversity and regeneration diversity of tree species. On the contrary, there was a negative correlation between canopy density and regeneration diversity of tree species, demanding canopy opening to promote natural regeneration in the forest. Tree and regeneration diversity was higher in mixed broadleaved forest, with a record of 18 tree species, which was moderately influenced by anthropogenic disturbances for recreation and collection of firewood, fruits, flowers and shoots. Important Value Index showed dominant tree species of Chilaune (*Schima wallichii)* in the broadleaved forest, Chir pine (*Pinus roxburghii*) in the pine forest and Masala (*Eucalyptus Spps)* in the regeneration forest. The study revealed a huge decline in tree species diversity in comparison to the historical record of 208 plant species with the study record of 25 tree species, whereas 14 tree species were regenerated in the forest. The majority of tree species are light demanders, requiring adequate sunlight for germination, growth and development of forest stands. Dense crown density, anthropogenic disturbance and adverse impacts of shrubs and monkeys are the major causes of decline in tree diversity. Regeneration scarcity indicated regeneration gap posing a serious threat to the loss of tree diversity. SRF management was only focused on forest protection with partial implementation of the operational plan. An integrated action plan is required for managing venue, vegetation and visitors in the Swayambhu Religious Forest for sustainable tree diversity conservation in the forest. Only forest protection is not enough for tree diversity conservation, but it is essential to sensitize the FSMC members and policymakers for realization of the urgent needs for silvicultural management of the religious forest.

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