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Research Article

VEGETATION PATTERNS IN RELATION TO TOPOGRAPHY AND WATER AVAILABILITY IN DAPCHA WATERSHED OF KAVREPALANCHOWK, NEPAL

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ABSTRACT

Watersheds in the mid-hills of Nepal support diverse forest ecosystems and provide critical ecological services including water regulation and slope stabilization. Vegetation patterns in these watersheds are shaped by interactions among topographic and hydrological factors. This study examined vegetation structure and composition along gradients of aspect and distance from spring sources under the environmental variables such as aspect, elevation, canopy cover, invasive species coverage and human disturbance in the Dapcha Watershed, Kavrepalanchowk, Nepal. Nested quadrat sampling was used to measure vegetation structural parameters including tree height and diameter at breast height (DBH). Abundance of trees, saplings and seedlings were measured from elevations ranging from 887 to 1800 masl across the 37 km² watershed. Species composition pattern in terms of environmental variables was analysed using non-metric multidimensional scaling. The findings revealed significant differences between north- and south-facing slopes. North-facing slopes supported higher species richness (38 species) and Shannon diversity (H' = 2.76) compared to south-facing slopes (18 species, H' = 1.03). Tree density was significantly higher on north-facing slopes (350 stems/ha) compared to south-facing slopes (304 stems/ha). *Pinus roxburghii* dominated with the highest Importance Value Index (IVI) of 99.04 followed by *Schima wallichii* (41.07) and *Alnus nepalensis* (29.78). Distance from springs significantly influenced tree height with taller trees occurring near water sources. Similarly, PERMANOVA test was used to determine the significant drivers affecting vegetation which revealed elevation, canopy cover and invasive species coverage plays a significant role. Regeneration analysis showed that 49.15% of species exhibited fair regeneration while poor regeneration pattern was observed in 33.90%. This study concludes that microtopographic factors, particularly aspect gradient and proximity to water sources in watersheds are key determinants of forest structure and composition.

Keywords: Hydrology, Proximity to springs, Regeneration, Slope aspect, Species composition, Springs

INTRODUCTION

Site-specific environmental factors primarily influence the local vegetation pattern (Zellweger et al., 2016). Plants have been used as a good indicator of soil type, geology, water availability and its storage over a few decades (Goslee et al., 1997). The availability of water strongly determines the productivity and its sensitivity on every stage from gametophyte to seedling stage. It also regulates life span and shapes the morphological structures of vegetation (Bykova et al., 2019). Such vegetation in terrestrial ecosystems have pivotal functions that thrive human community to sustainability through biodiversity conservation, carbon sequestration, hydrological regulation and watershed protection (Ma et al., 2021). Various environmental conditions like topography, substrate type, disturbance and interactions play a vital role in shaping the vegetation pattern (Dahlin et al., 2014). In a way, vegetation dynamics are controlled by negligible yet paramount factors including invasion, soil moisture, microbial interaction, deforestation, urbanization and water availability (Pickett et al., 2009). Regardless of such global environmental changes, the ecosystem and its services must be balanced yet dynamic. Many researches have examined the relationship of vegetation diversity indices and ecosystem stability although it varies according to the landscape and study matrices (Craven et al., 2018; White et al., 2022). The productivity in a small region, has a significant impact on the financial and social crisis threatening food security, livestock marketing and ecological instability as well (White et al., 2022). Plant species with high richness are considered to be water-efficient and they have high biomass production as they can utilize high soil moisture (Vogel et al., 2012) concluding that the productivity of vegetations are influenced by water availability (De Boeck et al., 2006). The vegetation structure and pattern changes as the distance from the water source increases. Taller and denser vegetation are often found in the riparian zone while shorter and sparser vegetation occurs farther away from these water sources (Catterall et al., 2007). Water availability has been recognized as the major factor for the development of vegetation structure and patterns (Lu et al., 2023). A positive feedback mechanism can be experienced by the plants to improve their local growth condition by increasing the water availability (Keif et al., 2016). The low water availability areas enhance biomass accumulation affecting the stability of forest and its composition and structure (Marasco et al., 2014). Water availability is measured directly by presence or absence of water source or by co-variates like rainfall, soil moisture, evapotranspiration, soil drainage index, etc. Pausas and Austin (2001) argued the positive correlation between the plant species richness and rainfall in California, trees species richness and the annual rainfall in South Africa and soil moisture index with moss species richness.

The pattern of vegetation is shaped by complex interacting system that creates the distinct microclimatic conditions (Jia et al., 2024) affected by local topography (elevation, slope angle and aspects) since they alter the solar radiations, humidity, wind direction and velocity (Jucker et al., 2018). Slope aspect modulates the incoming solar radiation playing a decisive role in plant communities due to which the soil temperature and moisture changes. In the Northern hemisphere, the landscape facing north receives less direct solar radiation while more in south facing slopes (Geroy et al., 2011; Fan et al., 2020), resulting lower temperatures over a longer time and low evapotranspiration rates compared to their south-facing counterparts. The soil of North-facing slopes will have high moisture levels and support more diverse vegetation than the dry south facing slope (Elnaker & Zaleski, 2021). The slope aspect influences the soil characteristics which are necessary for availability of nutrients for vegetation growth and the forest development (Onwuka & Mang, 2018). The direct and indirect effect of water availability and vegetation pattern, respectively, shape the soil system which influences the overall structure of the ecosystem either by nutrient cycling, productivity, organism interaction, etc. There seems to have cascading effects of water availability on soil and then to vegetation (Zhang et al., 2023). However, different plant species have different water tolerant capacity, and respond accordingly exhibiting various plant growth, life span, abscission period and other traits (Wilcox et al., 2021) which may lead to vegetation shift as well. The interaction between slope orientation and water availability creates complex environmental conditions that shape vegetation patterns across landscapes (Yang et al., 2020; Zhang et al., 2023). Previous studies put less attention to the combined effects of slope and water availability on plant community characteristics rather focused on the factors independently (Zhang *et al*., 2022; Faiz *et al*., 2025). This is more crucial where terrain and water availability strongly interact and understanding these relationships is helpful for predicting vegetation responses to environmental change and planning conservation mechanism in mountainous regions (Yang et al., 2020). Thus, this study aims to address the change in vegetation dynamics with environmental variables like aspect gradient and distance from water source in Dapcha Watershed of Kavrepalanchowk District.

MATERIALS AND METHODS

Study area

The Dapcha Watershed, watershed area of Dapcha Stream before the confluence with Roshi River in middle mountainous region of Nepal, covers an area of 37 km^2 with an average elevation 1314 masl ranging from 887 to 1800 masl (ICIMOD, 2025). The boundary of the watershed extends between 27° 30 '58" to 27° 35' 13" N latitude and 85° 35 '36.34 " to 85° 40' 57.44” E longitude. The watershed falls within the subtropical climatic region and annual average rainfall was observed to be approximately 1300 mm, as measured from the rainfall stations (Fig. 1). The Dapcha Stream within the watershed receives the water from the nine wards (Ward 1-9) of Namobuddha Municipality, one ward (Ward 11) of Dhulikhel Municipality and one ward (Ward 7) of Roshi Rural Municipality. The stream network along with the vegetation surveyed locations are illustrated in the Figure 1.

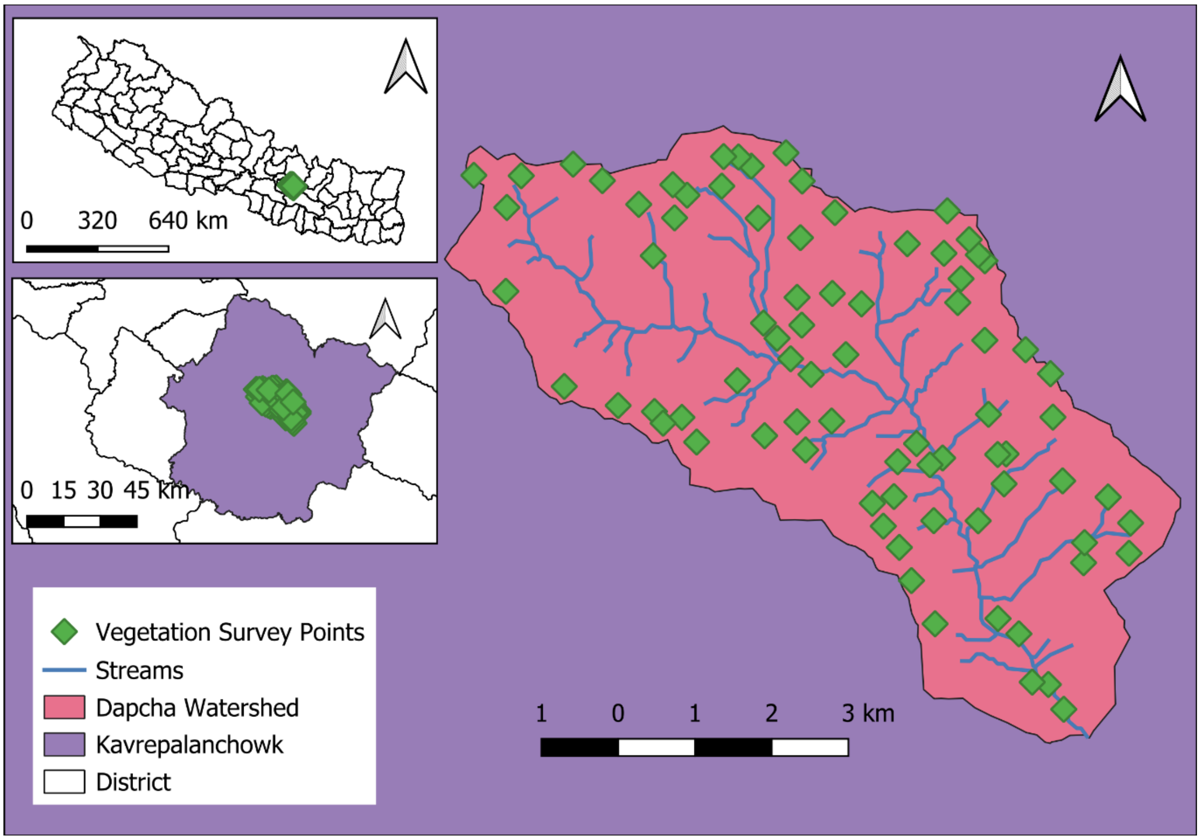

Figure 1. Map showing the streams and sampling plots distributed in Dapcha Watershed

Experimental design and sampling procedures

The preliminary survey was carried out in March 2024, for inventory of total springs available in the Dapcha Watershed and then a total of 80 plots were considered to assess the impacts of springs on plant community assemblages. The vegetation survey was carried out in November 2024. The number of quadrats laid were classified among 11 wards of Dhulikhel Municipality, Namobuddha Municipality and Roshi Rural Municipality using proportionate sampling based on the availability of springs in each ward. The number of quadrats laid in each ward of the Namobuddha Municipality is presented in Table 1. The quadrats were, then, laid in such a way that the distance between each quadrat was taken to be at least 300 m to maintain independence between sampling sites near and far from spring sites. All tree species having diameter >10 cm at breast height were measured in a 20 m × 20 m plots. Two nested quadrats of 5 m × 5 m and 1 m × 1 m were laid at the top left corner of the plot for saplings and seedlings, respectively (Mishra et al., 2013; Chapagain et al., 2021). The names of tree species, diameter at breast height measured with a DBH tape, height measured using a clinometer, type of disturbance and any other visible marks were noted. Saplings were defined as woody individuals with a height ≥ 1.37 m and a diameter at breast height (DBH) < 10 cm while seedlings were defined as individuals with a height < 1.37 m (Shahi et al., 2022). As part of tree species information collection, sapling and seedling diameter (in mm measured using a digital Vernier calliper) and height (in m measured with a 1.5 m tape) were noted. Method suggested by Kent *et al*. (2012) was followed as a reference for field sampling for plants. Of the 80 sampled plots, 17 plots located within 50 m of streams were excluded from the distance-based vegetation analysis to avoid confounding effects of riparian influence. Consequently, only 63 plots were examined for analysis in distance relationship to vegetation from spring sources. Similarly, plot that were either east facing or with 0 degree (facing upward) were avoided from the analysis for aspect relation to vegetation structure.

Table 1. Vegetation sampling plot distribution in ward level

S.N.	Municipality	Ward	No. of sampling plots
1	Namobuddha	1	9
2	Namobuddha	2	20
3	Namobuddha	3	7
4	Namobuddha	4	11
5	Namobuddha	5	2
6	Namobuddha	6	4
7	Namobuddha	7	13
8	Namobuddha	8	3
9	Namobuddha	9	7
10	Roshi	7	2
	Total		80

Data analysis

Vegetation metrics including abundance, richness, species diversity (Shannon diversity index, Simpson's dominance index and Pielou's evenness index) and Importance Value Index (IVI) were analysed. Normality was tested using Shapiro-Wilk test and the data were found to be skewed, and a non-parametric test was proceeded. Then, nonmetric multidimensional scaling (NMDS) was used to understand the patterns of tree species composition on north- and south-facing slopes as well as in near and far plots from springs.

Similarly, the regeneration was classified on five classes with good, fair, poor, none and new. If seedling > sapling > adult, its categorized as good; if seedling > sapling < adult, it's categorized as fair (Sarkar & Devi, 2014; Gebirehiwot et al., 2023). Poor resembles only if species survives in only sapling stage while none refers to the state where species is absent in both sapling and seedling but present in adults. If species has no adults but has only seedling and saplings, it's categorized as new regeneration state (Shankar, 2001; Dhaulkhandi et al.,2008). Field data were collected and statistical analyses were performed using RStudio (version 4.3.1). The packages used were vegan, ggplot2, dplyr, ggrepel, etc. All analyses were conducted with a significance level of $p<0.05$.

RESULTS

A total of 46 trees species, 40 sapling species and 40 seedlings were recorded indicating substantial plant community richness in the Dapcha Watershed.

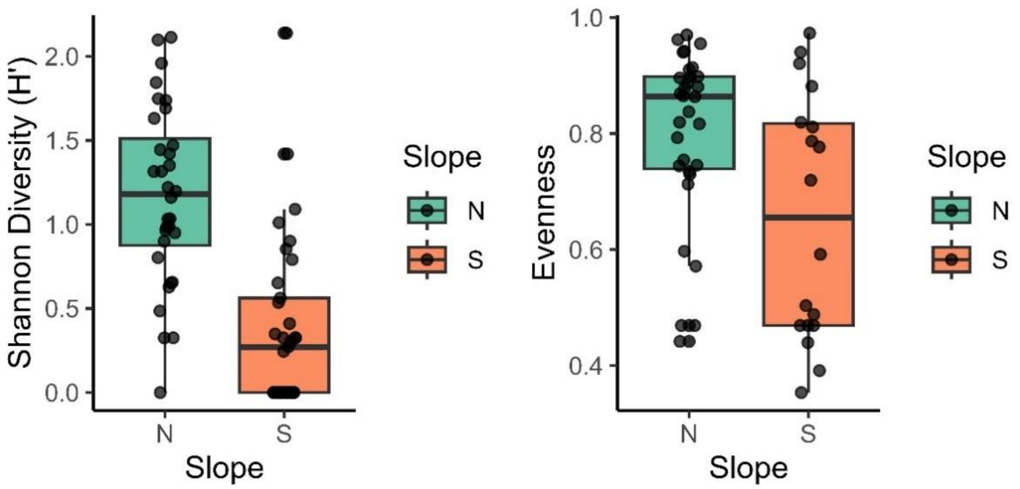

Figure 2. Shannon diversity and evenness across north and south facing slopes in Dapcha Watershed

Species diversity along north- and south-facing slopes

The contrasting structural heterogeneity were observed between north (NW-N-NE) and south-facing slopes (SW-S-SE) across Dapcha Watershed (Fig. 2). North-facing slopes supported higher species richness (38 species) and overall Shannon diversity of 2.76 with greater evenness of 0.76 representing structurally complex assemblages. In contrast, south-facing slopes harboured significantly lower richness of 18 species and Shannon diversity of 1.03 with reduced evenness of 0.36, which suggest dominance by a few well-adapted species. The saplings on north-facing slopes exhibited consistently higher Shannon diversity (2.94), richness (32) and evenness (0.85) compared to south-facing slopes (H' = 2.12, J = 0.72, richness = 17). The index values showed higher Shannon diversity, richness and evenness on north-facing slopes (H' = 2.79, J=0.88, S=24) than on south-facing slopes (H' = 2.69, J=0.86, S=23) considering the seedlings. Wilcoxon rank-sum test was used as a non-parametric test, where slope gradient i.e. North-facing and south facing slope significantly influence tree diversity ($p<0.001$) and evenness ($p<0.05$).

Vegetation comparison with respect to distance from water source (spring)

Out of 1060 individual trees recorded in the sampling sites of the watershed, 245 individuals representing 23 species were recorded near the spring sources, whereas 619 individuals representing 41 species far from the spring sources. Tree communities near the springs exhibited lower Shannon diversity (H'=2.27) but higher evenness (0.73) than the trees far from the springs. Similar structure can be observed in seedlings with low Shannon diversity but high evenness near the springs (H'=2.65, J=0.90) rather than far from the springs (H'=3.04, J=0.88). In contrast, the saplings have higher Shannon diversity and evenness far from the springs (H'=2.93, J= 0.89; Fig. 3) which suggests that proximity to spring source strongly influences vegetation composition and regeneration of species. Wilcoxon rank-sum test showed that the distance gradient (far and near) from springs has not significantly influenced tree diversity ($p>0.05$) and evenness ($p>0.05$).

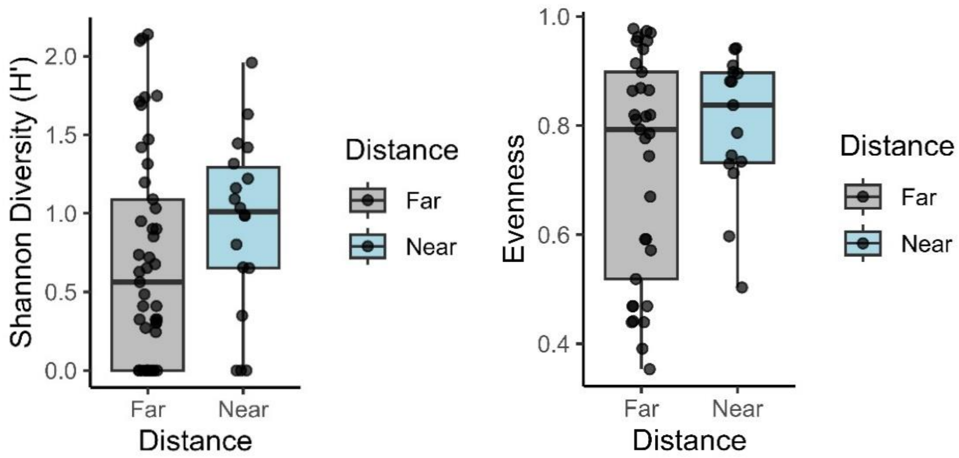

Figure 3. Shannon diversity and evenness based on distance from the spring source in Dapcha Watershed

Species composition along north and south facing slopes

Among the 46 species of trees, *Pinus roxburghii* (Khote Salla) was the dominant species with the highest IVI (99.04) followed by *Schima wallichii* (Chilaune) and *Alnus nepalensis* (Utis) in Dapcha Watershed. Phytosociological attributes of the vegetations are presented in Table 2. Species composition varied markedly between north and south facing slopes, with 38 species occurring on the north-facing slope and 18 species on the south facing slopes, differing in relative density, relative frequency, and relative basal area. On the north-facing slope, *S. wallichii* was the dominant species IVI of 59.22 followed by *A. nepalensis* and *P. roxburghii*. Conversely, in the South facing slope, *P. roxburghii* was the dominant species with an IVI value of 194.32. The second and third most ecologically important species was *S. wallichii* and *A. nepalensis* with an IVI 34.46 and 20.09, respectively. On the south-facing slope, *S. wallichii* was dominating seedling whereas *P. roxburghii* was dominating sapling. In contrast, *Litsea monopetala* and *S. wallichii* were the dominant seedling species on the north-facing slope within the Dapcha Watershed.

Table 2. Top 10 tree species with highest IVI in Dapcha Watershed

Species	Density (stems/ha)	Frequency (%)	Dominance (m^2/ha)	RD (%)	RF (%)	RDo (%)	IVI (%)	Ranks
Pinus roxburghii	228.80	45	19.217	39.754	17.241	42.052	99.048	1
Schima wallichii	82.61	33	6.434	14.353	12.644	14.079	41.076	2
Alnus nepalensis	57.61	25	4.659	10.009	9.579	10.195	29.783	3
Engelhardia spicata	14.13	15	1.369	2.455	5.747	2.995	11.198	4
Castanopsis indica	20.65	10	1.668	3.588	3.831	3.649	11.069	5
Choerospondias axillaris	14.67	14	1.383	2.55	5.364	3.027	10.94	6
Pinus patula	17.93	2	1.562	3.116	0.766	3.417	7.300	7
Lyonia ovalifolia	9.24	9	0.658	1.605	3.448	1.440	6.493	8
Prunus cerasoides	9.78	8	0.476	1.700	3.065	1.043	5.807	9
Prunus pashia	6.52	7	0.742	1.133	2.682	1.624	5.439	10

In plots located farther from spring sources, *S. wallichii* was the dominant species with IVI = 62.54 followed by *P. roxburghii* (59.26) and *A. nepalensis* (53.25). In contrast, *P. roxburghii had the highest dominance* (IVI=109.7) followed by *S. wallichii* (IVI=41.05) and *A. nepalensis* (IVI=23.63) near the springs. For saplings and seedlings, *S. wallichii* was the dominant vegetation near the springs while *P. roxburghii* and *Litsea monopetala* are the dominant species far from the spring within the watershed.

Tree height did not differ significantly between the north and south facing slopes with median height of 11.0 m on both aspects (p>0.05; Table 3). However, tree height differed significantly (p<0.05) between plots near and far from the spring source with median height 12 m and 11 m, respectively. Total tree density, basal area and DBH varied significantly between the south and north-facing slopes (Table 4).

Table 3. Tree measurements sampled at the north-facing and south-facing slopes Dapcha Watershed (n =65). DBH = Diameter at Breast Height (1.37 m), SD = Standard Deviation and p-value is from Kruskal-Wallis rank sum test

Parameters	**North-facing forest stands**				**South-facing forest stands**				**p-value**
Tree measurements	Min	Max	Median	Mean ± SD	Min	Max	Median	Mean ± SD	
Total tree density (stems/ha)	67.93	298.91	190.22	190.22±53.79	67.93	380.43	163.04	165.10±54.15	<0.05
Basal Area (m^2/ha)	55.39	7159.40	248.72	414.34±590.2	78.5	3492.38	349.49	458.78±416.83	<0.01
Height (m)	3.00	32.80	11.20	11.66±4.54	3	28.10	11.20	11.36±4.08	>0.05
DBH (cm)	8.40	95.50	17.80	20.46±10.47	10	66.70	21.10	22.34±9.24	<0.01

*DBH and height in above table represent measurements taken from all standing trees within each forest stand

Except height of trees, other trees measurements such as total tree density, basal area, and DBH didn't vary among the plots near and far from the spring source (p>0.05).

Table 4. Tree measurements in forest stands sampled at the near and far from the springs of Dapcha Watershed (n = 63). DBH = Diameter at Breast Height (1.37 m), SD = Standard Deviation and p-value is from Kruskal-Wallis rank sum test

Parameters	**Near from springs**				**Far from springs**				**p-value**
Tree measurements	Min	Max	Median	Mean ± SD	Min	Max	Median	Mean ± SD	
Total tree density (stems/ha)	122.28	271.74	183.42	184.93±43.75	67.93	394.02	176.63	186.89±12.54	>0.05
Basal Area (m^2/ha)	39.57	7159.40	262.89	454.07±668.11	30.18	3737.39	277.45	431.02±448.68	>0.05
Height (m)	1.80	32.80	12.00	12.46±5.07	1.30	27.10	11.00	11.37±4.21	0.01
DBH (cm)	7.10	95.50	18.30	21.33±11.14	6.20	69.00	18.80	21.35±9.65	>0.05

* The DBH and height data in the table represent measurements of all standing trees within sample plots categorized by their proximity i.e. near or far from the spring sources.

Regeneration patterns

Out of 46 recorded tree species in the Dapcha Watershed, the majority of 49.15% showed fair regeneration, 33.90% of species depict poor while only 5.08% of species showed good regeneration. New regeneration was observed in 11.86% of species. This illustrates the dominance of fair and poor regeneration indicating challenges for the vegetation community.

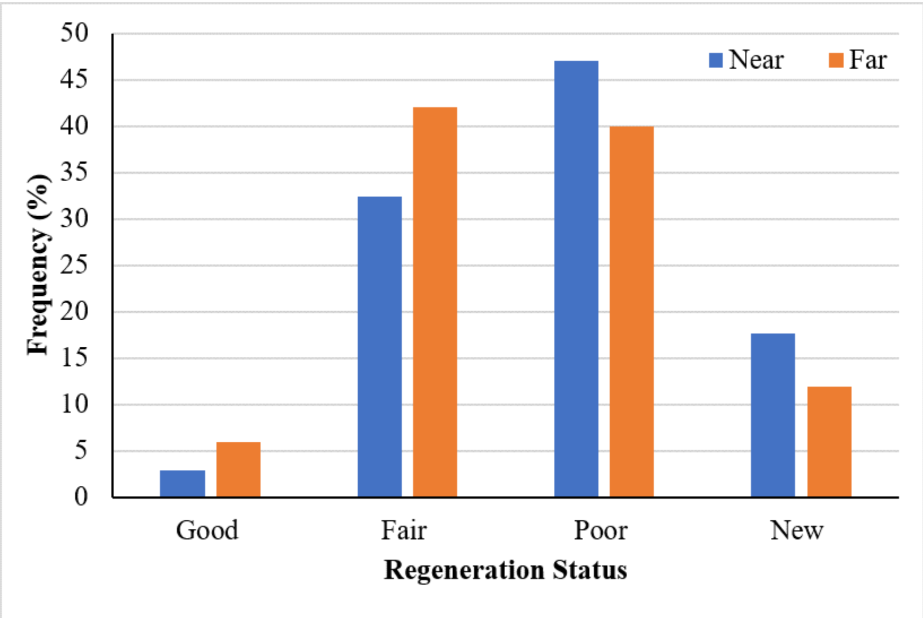

Figure 4. Regeneration status based on distance from springs

The findings reveal distinct trends in regeneration status along spatial gradients based on distance from springs (Fig. 4). Sites near water sources were characterized by a higher proportion of poor regeneration (47.06%) indicating only saplings are present followed by fair regeneration with 32.35% of species. 17.65% species resemble new regeneration patterns indicating absence of adult but presence of only seedlings and saplings. Sites farther from water show greater percentages of good and fair regeneration than the regeneration rate of near plots which suggest more stable and balanced regeneration dynamics in the sites far from water source.

Similarly, north-facing slopes are characterized by poor (46.67%) and fair regeneration (42.22%) whereas south-facing slopes exhibited the highest level of poor regeneration (36.10%) followed by new regeneration pattern (Fig. 5).

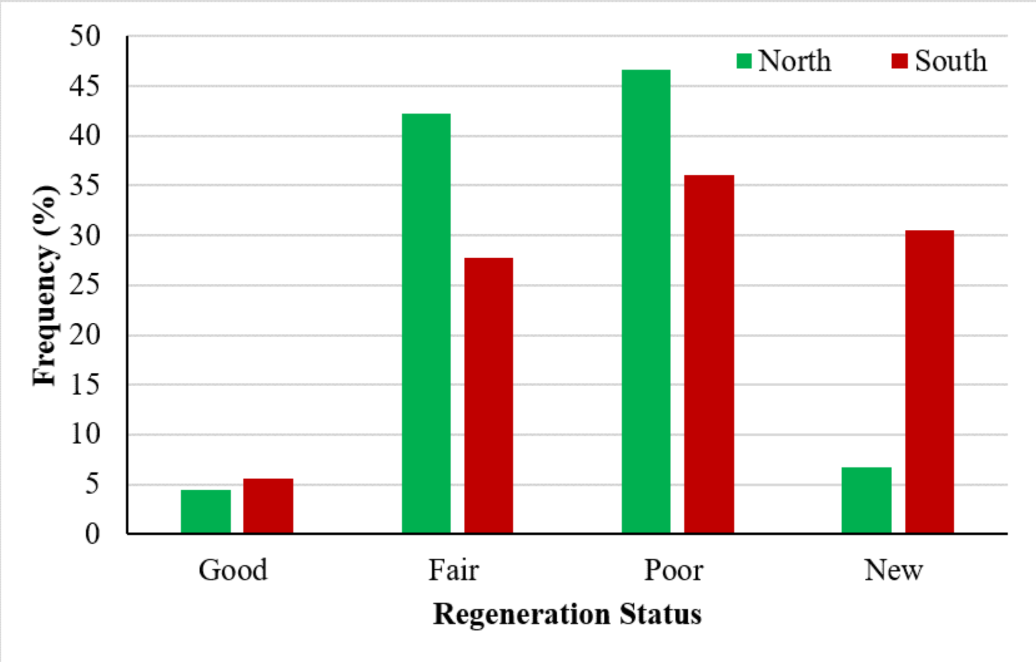

Figure 5. Regeneration status based on north and south facing slopes

NMDS ordination revealed a moderate (stress value = 0.123) but distinct ecologically clustering patterns between near and far sites, with some overlap indicating shared taxa between distance from spring sources. The results of the PERMANOVA analysis revealed that north and south facing slopes has a significant influence on tree species composition across the sampled plots. Specifically, the analysis showed that slope explains 19.4% of the variation in species composition, with a highly significant result ($F = 15.19$, $p < 0.05$), indicating strong differences in species assemblages between north and south-facing slopes. In contrast, the PERMANOVA test confirmed this visual pattern, showing a significant effect of distance on the vegetation community composition ($F_{1,\ 76} = 2.65$, $p<0.05$). However, distance from springs explained only 3.37% of the total variation in vegetation structure, relatively minor compared to slope. This suggests that proximity to springs acts as a secondary driver of community assembly, influencing species distribution at a microhabitat scale while other environmental variables play more dominant roles in structuring overall vegetation patterns within the watershed. Similarly, among ten environmental variables tested, canopy coverage, distance from the springs, aspect and elevation ($p<0.05$) only depict the significant differences among the vegetation structure and composition (Fig. 6).

A non-metric multidimensional scaling (NMDS) ordination was performed to visualize differences in tree community composition across north- and south-facing slopes in the Dapcha area. The ordination yielded a stress value of 0.137, indicating a satisfactory two-dimensional representation of the compositional dissimilarity among plots based on Bray-Curtis distances. Environmental vector fitting revealed several significant variables shaping community structure (Fig. 7). Elevation ($p<0.05$) and canopy coverage ($p<0.05$) showed strong correlations with the ordination axes which indicates as key drivers of variation. Other relevant factors included litter cover, aspect, invasive coverage, average basal area of trees, disturbance class and distance from human disturbance showed patterns of clustering that further explain variability among plots.

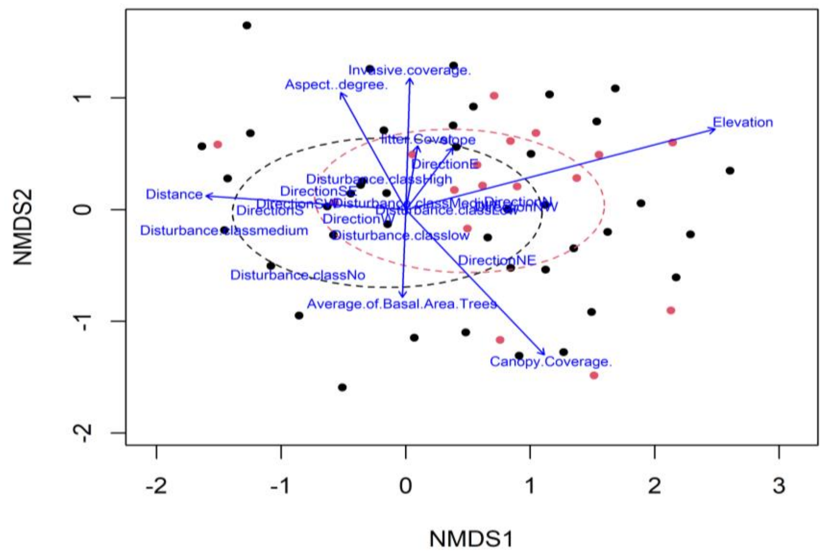

Figure 6. Bi-plots from NMDS ordination of species abundance data with environmental variables representing significant difference based on distance from the springs. Black and red dots indicate far and near distanced plots from springs

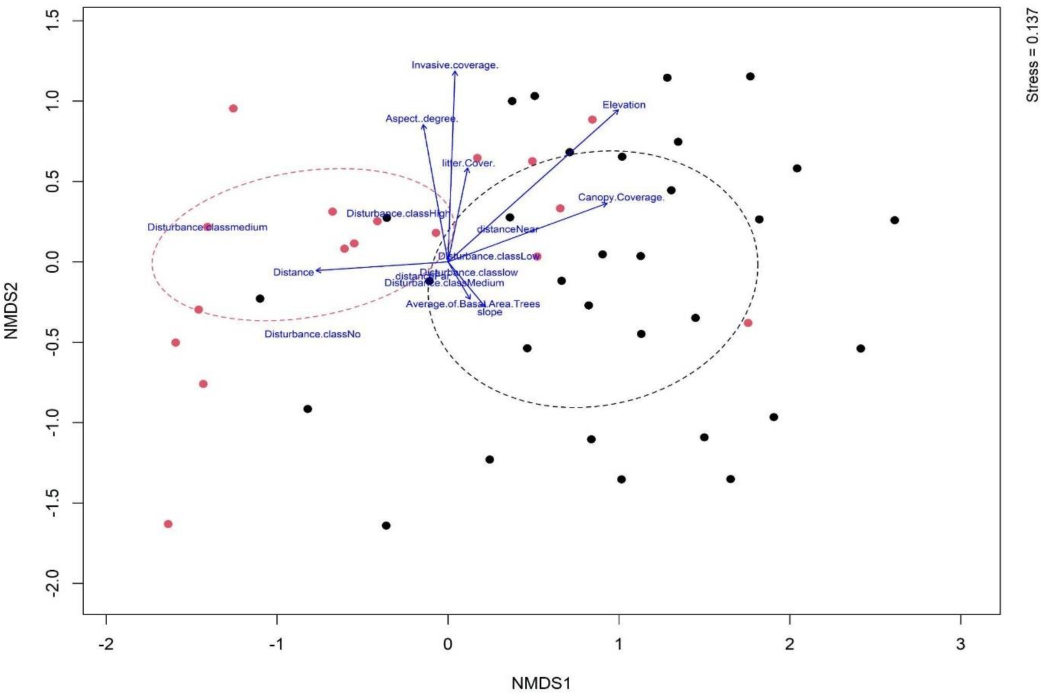

Figure 7. Bi-plots of site species from two-dimensional NMDS ordination of species abundance data with environmental variables fitted in the ordination spaces representing significant difference based on North and south facing slope

DISCUSSION

This study indicates that vegetation structure and diversity were profoundly influenced by proximity to spring sources. Species near to the spring source exhibited fewer species with lower diversity compared to sites farther away from the spring source. Species evenness was lower near springs, suggesting that fewer species are present, but they distributed more fairly. This could be indicating dominance by a few highly competitive species in these moisture-rich microhabitats (Breshears et al., 2008). Furthermore, proximity to springs did not significantly influence tree density, basal area, or DBH; nevertheless, tree height was significantly greater near springs. This indicates that higher moisture content in the soil surface favours vertical growth compared to DBH growth of the trees (Lopez et al., 2019).

Water availability has a significant impact on plant communities by influencing seed germination, growth, and competitive interactions (Chapin et al., 2011). Water stress and inadequate nutrient availability often lead to a decrease in species richness as distance from water source increases (Bedford et al., 1999). Higher species richness and diversity were observed near spring sources, potentially associated with increased water availability that influences plant distribution and survival. In riparian plant communities, proximity to a water source enhances the growth of plants as well as the community structure (Tsheboeng et al., 2017). Conversely, the higher species diversity and richness found farther from the springs indicate that water stress might lead to niche diversification and species coexistence by reducing competitive pressure (Chesson, 2000). Higher the soil moisture level near the spring source creates favourable condition for moisture-loving species and increase diversity, whereas areas farther from the water source support xerophytic plant that are adapted to low water availability (Van Rooyen et al., 1994; Vijayaragavan et al., 2025). The comparatively high evenness of seedlings and saplings far from the springs reflects the presumption that early stages are more susceptible to hydrological gradients, as previous observations in montane and subtropical ecosystems (Bhattarai & Vetaas, 2003).

North-facing slope exhibited higher species richness, diversity, and evenness compared to south- facing slopes. In the same way, the north-facing slope had higher tree density but smaller DBH and basal area, whereas the south-facing slope exhibited fewer but thicker trees. These findings align with previous research suggesting that north-facing slopes provide more suitable microclimatic conditions for a greater number of species due to lower solar radiation, leading to cooler surface temperatures and higher soil moisture availability (Bhardwaj et al., 2021; Schaefer et al., 2024). On contrary, the harsher, drier conditions of south-facing slope favour drought-tolerant and stress resilient species reducing diversity and richness (Måren et al., 2015). Although tree height was consistent across the slopes, possibly due to species composition or stand age than aspect (Long et al., 2020). The pivotal role of microclimatic factors, particularly moisture availability and thermal stress may be the reason in shaping vegetation composition (Nagy et al., 2003; Chen et al., 2016). The cooler, mesic conditions of north-facing slopes facilitate niche differentiation and species coexistence whereas the dry environment of south-facing slopes imposes physiological constraints. This leads to reduced diversity and increased species dominance (Bennie et al., 2006; Li et al., 2011). The patterns observed in seedlings and saplings emphasize the importance of aspect-mediated environmental filters in the early life stage. Higher diversity among seedlings and saplings on north-facing slopes indicate greater recruitment success under cooler, moisture conditions (Dearborn & Danby, 2017).

The species composition of Dapcha Watershed clearly demonstrates strong environmental filtering attributed to the north- and south-facing slopes. North-facing slopes provide cooler and moisture microclimates helping the dominance of broadleaved species like *Schima wallichii* and *Alnus nepalensis* both of which are known for their tendency for humid, shady environments and their relevance in mid-hill succession process (Ra, 2022; Dwivedi et al., 2025). On the other hand, south-facing slopes received intense sunlight and dry conditions. Such area is dominated mainly by *Pinus roxburghii*, a species that is well-adapted to water scarcity and frequent disturbances like fire (Auslander et al., 2003; Ayer et al., 2024). The shift in dominant species composition emphasises resilient capacity of species matters.

Distance from spring source also influenced community vegetation structure across the watershed. The dominance of *S. wallichii*, *P. roxburghii*, and *A. nepalensis* was comparatively more uniformly distributed farther from springs, indicating that moderate moisture limitation encourages coexistence by reducing competitive asymmetry (Tang et al., 2020; Singh & Thadani, 2023). *Pinus roxburghii* maintained a strong ecological advantage despite being in the moist area. This suggests that *P. roxburghii* is highly tolerant species found in both moisture availability and drier environments (Singh et al., 2006). Higher recruitment of *S. wallichii* was seen in seedling and sapling layers near springs indicating its shade tolerance and competitive ability during early establishment phase under moist conditions (Thapa & Sharma, 2023).

In the other hand, the species composition is strongly shaped by north - south facing slopes and distance from springs and has direct implications for base flow regulation. Broadleaved species such as *S. wallichii* and *A. nepalensis* are dominant on moist north-facing slopes and near springs. This enhances the infiltration and soil moisture retention which thereby sustain the base flow. Similarly, dry south-facing slopes are dominated by *P. roxburghii* that has very high-water repellent soil and low infiltration rate than broadleaf (Piyaruwan et al., 2020; Zhang et al., 2023). It can be generalized as central and eastern Nepal has its south-facing slopes dominated by *P. roxburghii* (Tiwari et al., 2020; Dahal & Mandal, 2023).

The dynamics of regeneration in the watershed indicate that recruitment success is limited across species likely due to anthropogenic disturbances and environmental stress (Amlin et al., 2012; Hishe et al., 2021; Thapa & Sharma, 2023). Periodic flooding, waterlogging and increased human exploitation may be the reasons behind poor regeneration in the areas near water bodies. This might have diminished the survival of seedlings and slow down the regeneration cycle (Shankar, 2001; Malik & Bhatt, 2016; Choudhury et al., 2022). On the other hand, good regeneration on south-facing slopes indicates favourable microclimatic conditions due to higher exposure to intense sunlight supporting seedling development and early growth. This is consistent with findings that aspect-driven microenvironmental differences have a major impact on regeneration (Erefur, 2010; Marler & Del Moral, 2018). Seed predation by animals, unfavourable soil conditions, lack of suitable light levels, competition from existing vegetation, herbivory of young seedlings and environmental stressors like drought are some challenges that affect the regeneration (McKee, 1995; Eriksson & Ehrlén, 2008). The findings show that different life stages of plants in the Dapcha Watershed reveal important patterns about how forests can regenerate depending on hydrology and topography (Lamb et al., 2005; Holl & Aide, 2011). The number of species stays fairly consistent as plants grow from seedlings to mature trees but the diversity metrics change significantly between these stages. This points towards the complex ecological processes that helps in shaping the plant community.

The contrasting dominance of *Pinus roxburghii* on south-facing slopes and near the springs while *Schima wallichii* on north-facing slopes and far from springs has important implications for watershed hydrology in the Dapcha Watershed. Pine-dominated areas generally produce needle-based litter that decomposes slowly which often lower soil organic matter (SOM), and poorer macro-pore development (Sachithanantham & Jindujaha, 2026). Such environment can limit the infiltration and enhance surface runoff, not supporting growth of other species (Zhang et al., 2023). In contrast, broadleaved species such as *A. nepalensis* and *S. wallichii* generate more labile litter that decomposes rapidly enriching SOM which stimulates the present soil biota including earthworms (Prescott et al., 2000). These allows to easily decompose such leaves and connect macropore networks promoting percolation and sustained soil moisture (Ilstedt et al., 2016). These species-specific effects align with your finding that trees were taller near springs, suggesting that greater soil moisture availability in *Alnus–Schima* dominated microsites favors vertical growth and continuous water supply (Kuželková et al., 2024). Collectively, these patterns indicate that vegetation composition with more than proximity to water alone can shape hydrological functioning of the watershed (Jačka et al., 2021), with height of these trees affected significantly rather than their stem size.

CONCLUSION

This study demonstrates that vegetation structure and composition in the Dapcha Watershed are influenced by environmental factors such as slope, proximity to spring sources, elevation, invasive species coverage and canopy cover. However, slope aspect emerged as the dominant driver while distance from springs exerted a comparatively weak influence. North-facing slopes exhibited higher tree density and basal area suggesting denser and potentially more productive forest stands. In contrast, south-facing slopes were characterized by trees with larger DBH indicating a possible dominance of fewer but larger individuals. Distance from springs had a significant effect only on tree height with trees closer to water sources being taller likely due to enhanced moisture availability. Elevation and canopy cover in both North-South facing slopes as well as far and near the distance from the springs are significant environmental drivers for determining vegetation assemblages. These patterns highlight the importance of topography and moisture gradients in shaping forest structure in the Dapcha Watershed. From a conservation perspective, spring-associated zones play an important role in maintaining forest structural complexity and local microhabitats particularly under increasing climatic and anthropogenic pressures. Integrating spring-shed management into slope-sensitive forest planning along with invasive species control and canopy conservation can serve as an effective nature-based strategy for sustaining watershed functions and ecological resilience.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article.

ETHICAL STATEMENT

This study is the original work and has not been previously published or submitted for publication elsewhere.

DATA AVAILABILITY STATEMENT

The authors declare that the data supporting the findings of this study are available within the paper. Should any raw data files be needed in another format that they are available from the corresponding authors upon request.

SUPPLEMENTARY INFORMATION

None

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