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Forest community compositions and soil properties association in the Moist Temperate Forest across Northwestern Himalayan

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Abstract

Forests play a critical role in climate mitigation strategies and act as a carbon sink. Complex ecological cycles play significant roles in balancing ecological forces and shaping species habitat, consequently community patterns and structure. The community compositions and their relationship with soil have not yet been fully understood. We studied vegetation structure, community patterns, regeneration dynamics, soil physicochemical properties including soil organic carbon (SOC) in 14 forest communities at an elevational gradient (2400–3290 m) of Tarla Wildlife Sanctuary, India. Community structure and species diversity were quantified across 50 sites, and soil samples from 0–15 cm and 15–30 cm depths were analyzed to determine nutrient status. It was found that a conifer-mixed community dominated by *Abies pindrow* and *Picea smithiana* had the highest species richness. In contrast, a pure *Quercus semecarpifolia* community was rich in soil nutrients and showed positive associations with soil moisture and nutrient availability, thereby supporting greater SOC storage. While Surface soils had higher SOC % and key macronutrients (NPK) than subsurface soils, bulk density and coarse fragments increased with depth, negatively influencing carbon storage. Collectively, current findings revealed that the vegetation–soil relationship is very important for shaping forest structure and soil carbon dynamics across altitude gradients, and that mixed forests play an important role in sustaining nutrient cycling, carbon sequestration, and the path towards ecosystem resilience.

Key words: Climate change; Soil health; Soil organic dynamics; Vegetation study

1. Introduction

The high-altitude regions of the Himalaya are fascinating ecosystems that provide favorable conditions and habitats for numerous endemic species [1]. Plant growth in these high-altitude regions depends on environmental limiting factors that regulate or restrict species distribution [2]. To comprehend the ecosystem forces, species structure, and function, it is essential to understand the relationship between biotic and abiotic factors [3;4]. Species interact with each other in both biotic and abiotic ways, subsequently transferring energy and nutrients from one trophic level to another [5;6]. Therefore, to understand vegetation structure and function, it is equally important to understand their relationships with other edaphic factors [7]. Plant growth is influenced by multiple ecological drivers, including altitudinal gradients, microbial activity, climatic conditions, vegetation, topography, and soil nutrients [8].

Multiple ecological factors, including different geographical features and topographical constraints, create distinct habitats and niches of the species [9]. These environmental conditions in the ecosystem form different forest community compositions and structures, with some having mixed forest stand structures while some are single-individual dominant [10;11;12]. Hence, these different community compositions across habitats and at altitude gradient are due to environmental filtering [13;14]. Plants maintain physiological homeostasis under harsh environmental conditions by regulating nutrient, water, and biochemical levels to survive [15;16]. Under adverse environmental conditions, plants generally follow a conservative approach for survival and tissue preservation (17). Plant traits vary according to environmental conditions, as was also described by Liu et al. [18]. Likewise, Thakur and Chawla [19] observed an essential role of altitude and aspect in the variation of plant functional traits. They also found that parental soil materials significantly influence plant species abundances along altitudinal gradients and exhibit a non-linear relationship.

Vegetation-soil coupling is a reciprocal relationship in which soil micro- and macronutrients regulate vegetation dynamics; litterfall, root microbial activity, and nutrient uptake occur through biogeochemical cycling in the forest ecosystem [20;21]. Soil pH, bulk density, moisture %, and EC, as well as primary macronutrients such as nitrogen, phosphorus, and potassium, determine vegetation and soil health [22;23]. However, different forest types, including coniferous and broadleaf forests, regulate soil fertility through their community compositions [24]. Soil

properties generally vary due to litterfall deposition, understory biomass, and organic matter accumulation, as well as biotic and abiotic factors [25]. This reciprocal relationship between vegetation and soil biota forms a coupling mechanism that regulates soil biogeochemical properties [26]. Understanding the combined influence of elevation and soil factors on plant diversity is crucial for understanding forest dynamics and species responses to climate change [27;28].

Various studies have characterized floristic diversity across different altitudinal gradients and focused on understanding the impacts of climate change in sub-temperate forest regions [28;29]. However, due to remote and rough terrain, community composition and soil health information in Tarla Wildlife Sanctuary have not been reported in the literature [30]. Therefore, the current study was performed to understand the relationship between vegetation structure and soil physicochemical properties, with key objectives of understanding species diversity across different forest stands, spatial variation in soil physicochemical properties, and the relationships between species composition and soil characteristics using multivariate statistical approaches. The current study hypothesized that Forest community composition and soil properties also play a key role, rather than elevation alone.

2. Materials and methods

2.1 Study area

The Talra Wildlife Sanctuary (TWS) situated in the Jubbal and Chopal tehsils of District Shimla, Himachal Pradesh (India), in the Pabbar Valley. The Sanctuary lies at an altitude of 30° 57’ N to 31° 03’ N Latitude, 77° 43′ E to 77° 48′ E Longitude, and an elevation of 1,395–3392 m (Fig. 1). The present study is performed in the different forest stands including broad and conifer forest dominated by *Abies pindrow, Picea smithiana,* and *Quercus semecarpifolia* forest at an altitudinal range of 2400 to 3300 m asl in the TWS [12]. The TWS forest stands are characterized by broad, mixed coniferous stands, small alpine pastures, and cold climatic conditions, with cold winters and seasonal snowfall at higher elevations [30].

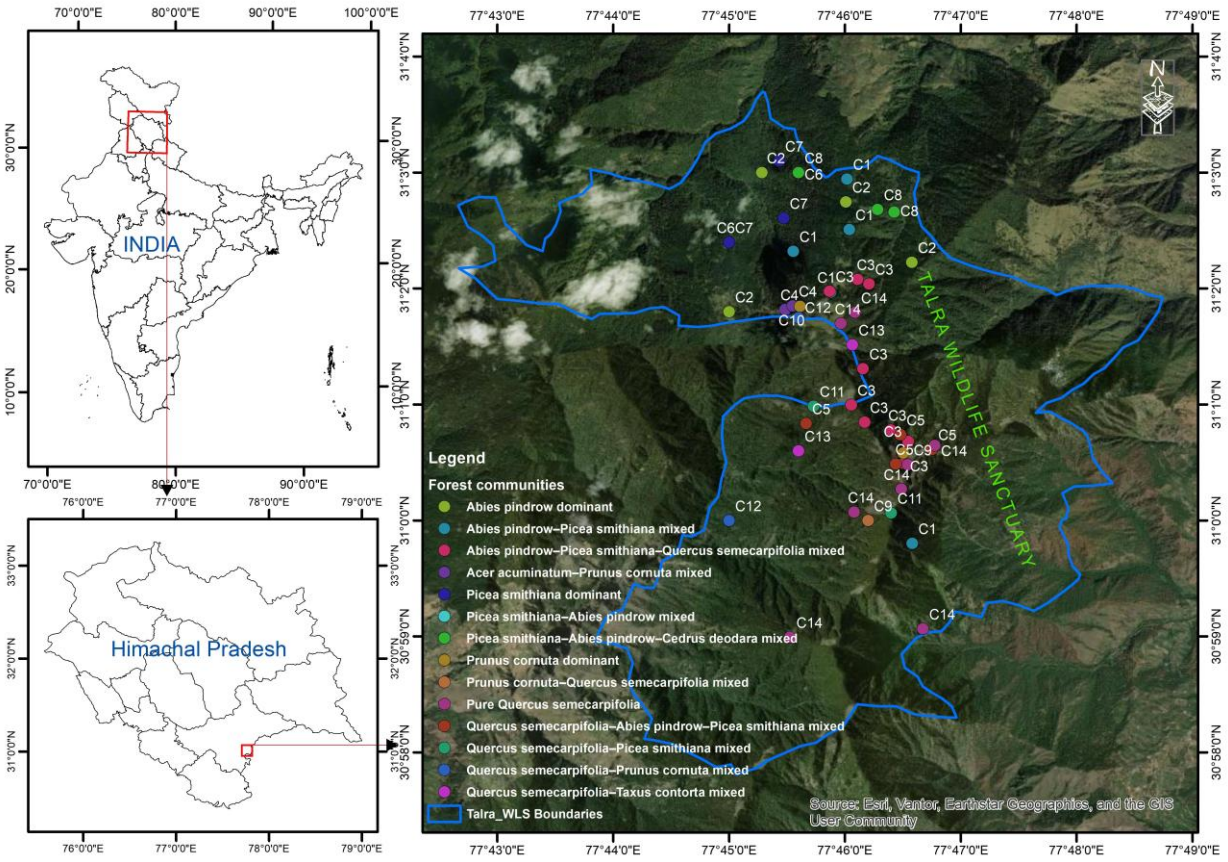


Fig.1 Tarla Wildlife Sanctuary

2.2 Sampling design

A qualitative stratified random sampling was performed across forests dominated by different tree species. A total of 50 different forest sites were selected along the elevational gradient of temperate forest communities. At those sites, 50 × 50 m-sized plots were laid to assess the ecological parameters. For vegetation, a total of 10 sub-quadrats (10 × 10 m) were established for tree sampling, 10 quadrats (5 × 5 m) for shrubs, and 20 quadrats (1 × 1 m) for herbs; following standard phytosociological methods [31;32;33].

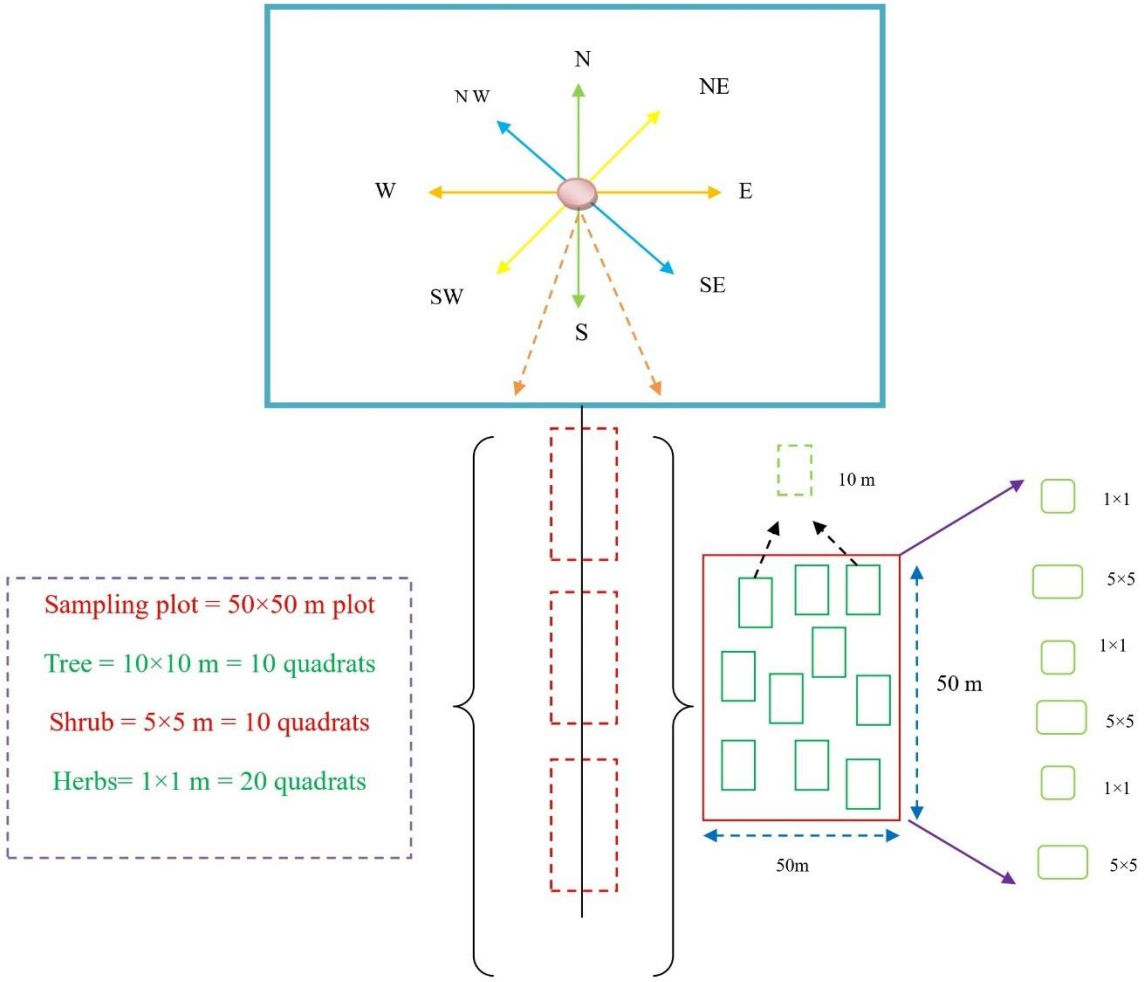


Fig.1 Sampling design for data collection in the

2.3 Vegetation analysis

The phytosociological study of each site was computed using tree density, frequency, dominance, and the Important Value Index (IVI), following Curtis and McIntosh [33] and Mueller-Dombois and Ellenberg [34]. Community structure was based on the Important Value Index. Moreover, Species diversity was calculated using the Shannon–Wiener and Simpson diversity indices [35;36]. All forest communities were classified by performing phytosociological analysis, following the calculation of the Importance Value Index (IVI) for all species at each site. The analysis was performed using Microsoft Excel 2016 [37]. In the dataset, species with an IVI of more than 150 out of 300 were considered representative of the that communities [33;34]

Similarly, sites with two or more species collectively forming an IVI of 150 or above were specified as mixed communities. In contrast, sites where a single species with an IVI of 300 was present were characterized as pure communities. For each identified community with their representative sites were selected, and descriptive statistics were computed in PAST after data entry to characterize the structural and ecological properties of each forest community [38].

Table 1 Community types, distribution, and major associates in Talra Wildlife Sanctuary

Communities	**Abbreviation used**	**Elevational range (m)**	**SR**	**Lat °N**	**Long °E**	**Habitat**	**Aspect**	**Major associated species**
Abies pindrow- Picea smithiana mixed	*Ap-Ps* mixed	2638-2946	5	31.03-31.04	77.76-77.77	Sm, Ex, Ma, Ri	NW, N, SE, NE, SE	*Abies Pindrow, Picea smithiana*, *Quercus floribunda,*
Abies pindrow dominant	*Ap* dominant	2549-2998	4	31.03-31.05	77.75-77.77	Sm, Ex	N, SE, NW, W	*Abies Pindrow, Picea smithiana, Juglans regia*
Abies pindrow- Picea smithiana -Quercus semecarpifolia mixed	*Ap-Ps-Qs* mixed	2677-2874	9	31.03-31.04	77.75-77.76	Dg, Sm, Ri	N, SE, NW, W, NE	*Abies pindrow- Picea smithiana -Quercus semecarpifolia*
Acer acuminatum-Prunus cornuta mixed	*Aa-Pc* mixed	3097-3129	2	31.03-31.04	77.75-77.76	Dg, Sm	S, E, SE, NW	*Acer acuminatum, Prunus cornuta, Abies pindrow-*
Quercus semicarpifolia-Abies pindrow- Picea smithiana mixed	*Qs-Ap-Ps* mixed	3099-3190	4	31.0-31.01	77.76-77.77	Sm, Dg, Ex	NS, E, SE, NW	*Quercus semicarpifolia-Abies pindrow- Picea smithiana,*
Picea smithiana-Abies pindrow mixed	*Ps-Ap* mixed	2436-3099	2	31.04-31.05	77.75-77.76	Ri, Sm, Ma	N, NE	*Picea smithiana, Abies pindrow, Asculus indica*
Picea smithiana Dominant	*Ps* Dominant	2434-2765	3	31.04-31.05	77.75-77.76	Sm	N, NE, NW	*Picea smithiana, Abies pindrow, Asculus indica*
Picea smithiana-Abies pindrow- Cedrus deodara mixed	*Ps-Ap-Cd* mixed-	2772-2841	3	31.04-31.05	77.76-77.77	Dg, Ri, Sm,	NE, SE, NW	*Picea smithiana, Abies pindrow, Cedrus deodara*
Prunus cornuta- Quercus semicarpifolia mixed	*Pc-Qs* mixed	3204-3330	2	31.00-31.01	77.77-77.78	Dg, Bd	N, NE	*Prunus cornuta, Quercus semicarpifolia, Picea smthiana*
Prunus cornata dominant	*Pc* dominant	3090-3210	2	31.01-31.0	77.77-77.7	Dg, Sm	N, NW	*Prunus cornata*

				2	8			
Quercus semecarpifolia Picea smithiana mixed	*Qs-Ps* mixed	2752-3099	2	31.00-31.02	77.76-77.77	Sm	NE, NW,	*Quercus semicarpifolia, Acer acuminatum, Prunus cornata*
Quercus semicarpifolia-Prunus cornata mixed	*Qs-Pc* mixed	3031-3201	2	31.00-31.03	77.75-77.76	Sm.	N, NW	*Quercus semicarpifolia, Prunus cornata, Picea smithiana*
Quercus semecarpifolia-Taxus contorta mixed	*Qs-Tc* mixed	3090-3181	2	31.01-31.03	77.76 77.77	Sm	SE, NW	*Quercus semecarpifolia, Taxus wallchiana*
Quercus semecarpifolia Pure	*Qs* pure	3140-3390	8	30.98-31.03	77.76. 77.78	Dg, Ms	N, SE, NW	*Quercus semecarpifolia*

Abbreviations used: - Bd: Bouldary; **Dg**: Degraded; **Ms**: Moist slope; **Ri**: Riverine; **Rk**: Rocky; and **Sm**: Shady moist, **SE**: South East; **SW**: South West; **W**: West; **E**: East; **NE**: North East; **NW**: North West; **S**: South

2.4 Soil sampling and laboratory analysis

To analyze soil health, the composite soil samples at depths of 0–15 and 15–30 cm were collected from each site [39]. The five subsamples, one from the center and four from the corners, were mixed to obtain representative samples from each site [40; 41]. After the samples were brought to the laboratory, the soil was air-dried and sieved through a 2-mm mesh for further physicochemical analysis [42]. The pH, EC, moisture content (%), bulk density (BD), coarse fragments (CF), available nitrogen (N), available phosphorus (P), available potassium (K), soil organic carbon (SOC), and soil organic carbon stock were determined using standard protocols [43]. Soil pH and electrical conductivity (EC) were calculated from a 1:2.5 soil-to-distilled water suspension using digital pH and conductivity meters, respectively [44]. Afterwards, fresh soil samples were dried at 105°C in the laboratory until a constant weight was reached to determine the soil moisture % [45;46]. Bulk density (BD) was measured using the standard core method and calculated as the ratio of oven-dry soil mass to core volume (g cm^{-3}) [47]. Simultaneously, coarse fragments (CF) were calculated as the % of the oven-dry soil fraction retained on a 2-mm sieve relative to the total oven-dry soil mass [44]. Moreover, total soil nitrogen was determined using the Kjeldahl method [48], available phosphorus using the Bray and Kurtz method [49],

which is suitable for acidic soils, available potassium using the Hanway and Heidel method [50], and soil organic carbon using the Walkley–Black wet oxidation method [51].

2.5 Statistical analysis

All statistical analyses were performed using R software (version 4.5.3) [52]. Data management and descriptive statistics were conducted using the base package. Data visualization was performed using the ggplot2 package [53]. Pearson correlation analysis was visualized using the corrplot package [54] Community diversity analyses and ordination were conducted using the vegan package [55]

3. Results

3.1 Species richness across forest communities

The result indicated the species diversity in the range of 33 to 108 across all the forest community (Fig. 2). The highest species richness was recorded in the *Abies pindrow–Picea smithiana* community (108 species), followed by the *Picea smithiana* dominant community (107 species) and the *Abies pindrow* dominant (100 species) respectively. In contrast, the *Prunus cornuta–Quercus semecarpifolia* forest community had the lowest species richness (33 species), followed by the *Quercus semecarpifolia–Taxus wallichiana* mixed community (34 species) and the *Quercus semecarpifolia-Abies pindrow–Picea smithiana* mixed (38 species), which were at a higher altitude. The synthesis of the results found that mixed forest stands have greater species richness, followed by pure-dominated forest stands. However, in the intermediate zone of the sanctuary, species richness was observed relatively stable in the *Picea smithiana–Abies pindrow* mixed (71 species), followed by *the Picea smithiana–Abies pindrow–Cedrus deodara* mixed (68 species), and *Quercus semecarpifolia–Prunus cornuta* mixed (59 species), respectively.

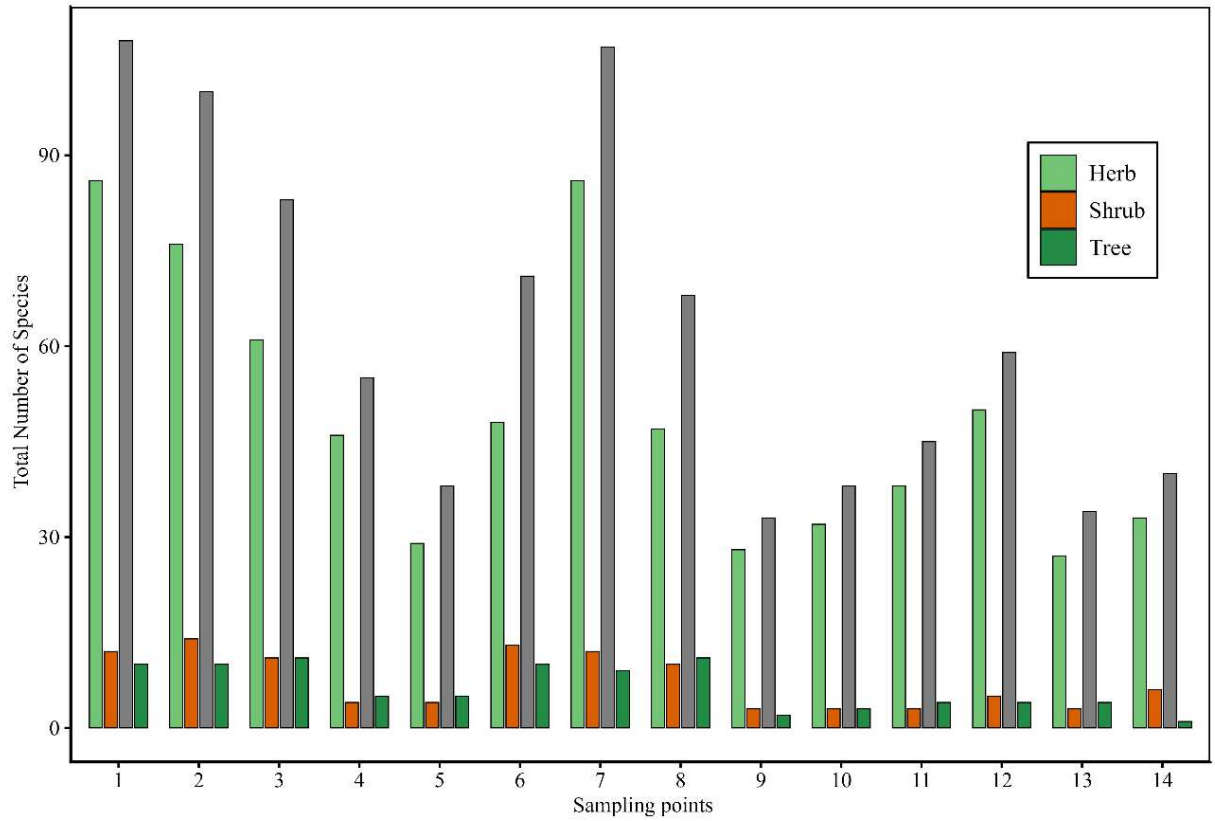


Fig. 2 Total number of species richness from each site at TWS

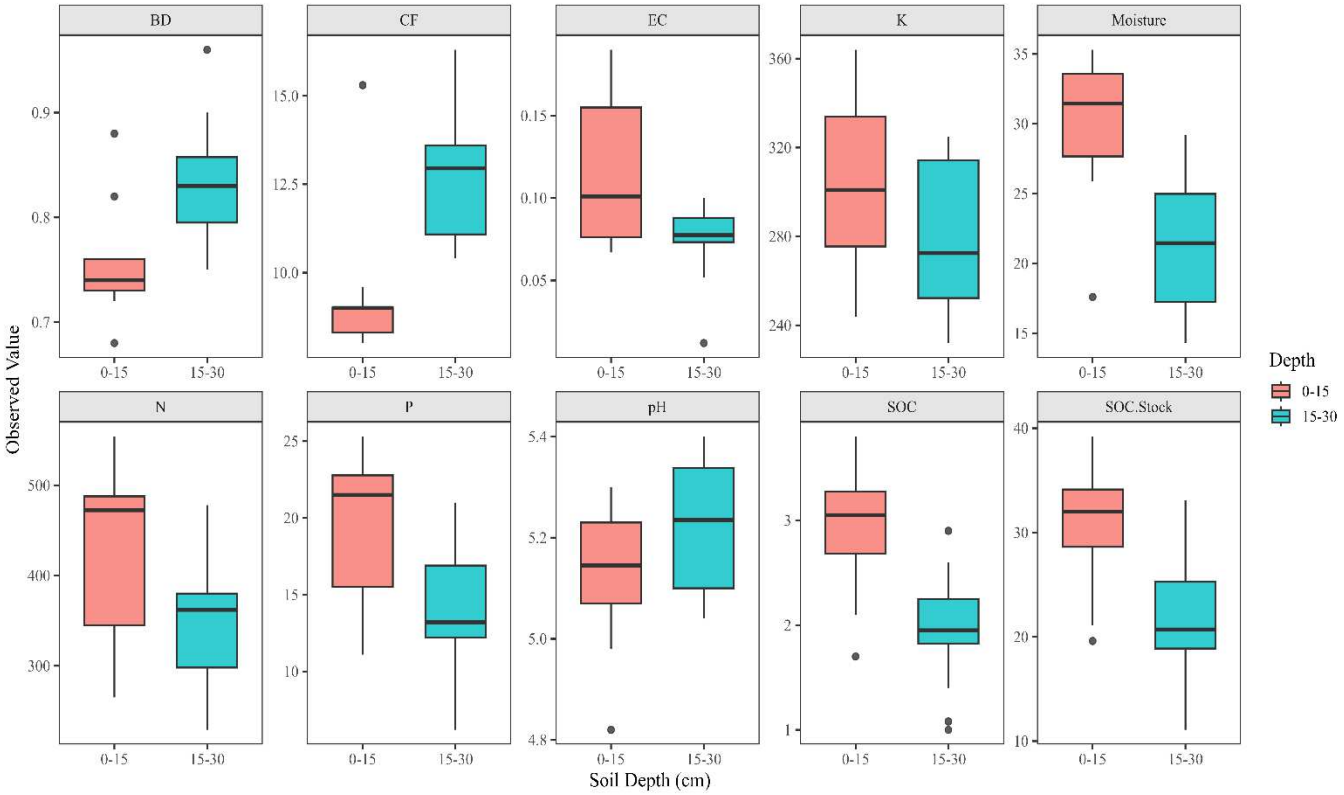
3.2 Site-wise characteristics and variation in ecological attributes

The physicochemical properties of the soil showed notable trends in different forest communities (Table 1). The altitude range of the sampling sites was from 2400 to 3290 m (avg. 2949.79 ± 301.74 m). The soil was mostly acidic, with a pH range of 4.96 to 5.34 respectively. The electrical conductivity (EC) was in the range of 0.06 to 0.15 dS m^{-1} (avg. 0.10 ± 0.03 dS m. The key physicochemical properties of soil, including SOC, carbon stock, soil moisture, bulk density (BD), and coarse fragments (CF), varied considerably from site to site in the Tarla Wildlife Sanctuary. Depth-wise analysis revealed that both SOC and soil carbon stock were maximum in the *Qs* pure forest community at the 0–15 cm and 15–30 cm soil layers. The corresponding SOC% were 3.8 ± 0.8% and 2.9 ± 0.49%, while soil carbon stocks were 35.6 ± 7.19 Mg ha^{-1} and 33.1 ± 5.9 Mg ha^{-1}, respectively. In contrast, the *Pc* dominant community had the lowest SOC% (1.7 ± 0.7% and 1.08 ± 0.5%) and carbon stock (19.6 ± 10.2 Mg ha^{-1} and 13.5 ± 7.7 Mg ha^{-1}) at

the respective soil depths (Table 1). Available nitrogen (N) also showed notable variation among forest stands (Fig. 3).

At the 0–15 cm depth, the highest available N was recorded in the *Ap–Ps–Qs* mixed community (554 ± 18.3 kg ha^{-1}), followed by the *Ps–Ap–Cd* mixed community (553± 10.7 kg ha^{-1}), *Qs pure* community (510 ± 21.3 kg ha^{-1}), *Qs–Tc* mixed community (490 ± 12.3 kg ha^{-1}), and *Ap* dominant (481 ± 9.5 kg ha^{-1}), Qs–Pc mixed community (371 ± 6.1 kg ha^{-1}) and *Aa–Pc* mixed community (289 ± 13.3 kg ha^{-1}) (Table 1). At the 15–30 cm depth, available N was maximum in the *Qs* pure community (478 ± 17.1 kg ha^{-1}), while minimum in the *Aa–Pc* mixed community (232 ± 2.1 kg ha^{-1}). Available phosphorus (P) also differed substantially among forest communities. At the 0–15 cm depth, the highest P concentration was recorded in the *Qs–Ps* mixed community (25.3± 2.1 kg ha^{-1}), followed by the *Qs pure* community (25.0±1.4 kg ha^{-1}), *Ps* dominant (23.5 ± 0.8 kg ha^{-1}), *Qs–Tc* mixed (23.0 ± 1.2 kg ha^{-1}), *Qs–Pc* mixed (22.1 ± 0.8 kg ha^{-1}), *Ap–Ps–Qs* mixed (22.0 ± 2.9 kg ha^{-1}), and *Qs–Ap–Ps* mixed (21.0 ± 4.2 kg ha^{-1}) communities.

Moreover, at the 15–30 cm depth, the maximum available P was present in the Qs pure community (21.0 ± 1.2 kg ha^{-1}), whereas the lowest value occurred in the *Ps–Ap* mixed community (6.2 ± 1.2 kg ha^{-1}). Available potassium (K) followed a similar pattern. At the 0–15 cm soil depth, the highest K concentration was observed in the *Ap-Ps-Qs* mixed community (364±45.1 kg ha^{-1}); followed by *Qs pure* community (360 ± 23 kg ha^{-1}), *Ps–Ap–Cd* mixed community (356 ± 53.7 kg ha^{-1}), *Qs–Ps* mixed community (341 ± 15.2 kg ha^{-1}), and *Ap–Ps–Qs* mixed community (320 ± 45.3 kg ha^{-1}) stands. At the 15–30 cm depth, the corresponding K concentrations were 325 ± 13 kg ha^{-1} in the *Qs* pure community, 320±45.3 in the *Ap-Ps-Qs* mixed community, and 317 ± 51.4 kg ha^{-1} in the *Ps-Ap-Cd* mixed community, respectively. (Table 1). Variations in the physicochemical properties of the soil were observed with increasing depth (Fig. 3). Moisture, available nitrogen, phosphorus, potassium, SOC, and SOC stock were higher in the upper soil layer (0–15 cm), while in the 15–30 cm layer, they decreased with depth. Conversely, bulk density and coarse particle content increased with depth, while a slight rise in pH was observed in the subsoil. Electrical conductivity remained consistently low at both depths, indicating that the soil across the study area was non-saline.



200

201 Fig. 3 Cumulative overview of soil physicochemical properties across all forest communities
202 representing the TWS forest ecosystem

203 Table 1 Soil physico-chemical properties in all communities

Forest types	Depth (cm)	pH	EC dS/m	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Moisture (%)	BD (cm^3)	CF (%)	SOC (%)	SOC stock (Mg ha^{-1})
Ap-Ps mixed	0-15	5.07±0.50	0.18±0.03	472.9±13.1	18±2.2	265.8±9.1	25.9.±8.1	0.72±0.03	9±1	3.3±0.5	32.5±6.4
	15-30	5.04±0.44	0.074±0.02	370±11.2	13±3.1	252±5.2	17.7±4.01	0.77±0.06	13.3±2.9	2.1±0.3	21.2±4.2
Ap dominant	0-15	4.98±0.45	0.19±0.07	481±9.5	22±2.1	298±13.5	32.5±10.5	0.76±0.07	9.3±2.08	3.3±1.05	34.8±14
	15-30	5.23±0.51	0.10±0.05	361±7.2	17.2±3.4	267±19.2	22.6±0.5	0.85±0.01	14±2.6	2.4±0.60	26.4±7.6
Ap-Ps-Qs mixed	0-15	5.18±0.57	0.13±0.04	554±18.3	22±2.9	364±45.1	29.6±2.2	0.75±0.1	8.33±1.52	3.5±0.91	39.2±11.76
	15-30	5.22±0.64	0.012±0.05	380±25.1	16±4.2	320±45.3	19.6±8.01	0.77±0.08	13.6±2.3	1.9±0.73	19.4±9.1
Aa-Pc mixed	0-15	5.25±0.55	0.14±0.03	289±13.3	11.1±3	245±4.3	30.4±9.7	0.73±0.06	9.6±1.5	2.1±0.8	21.1±9.2
	15-30	5.33±0.65	0.077±0.04	229±8.1	8.1±2.1	232±2.1	17.1±5.1	0.84±0.03	13.3±2.08	1.0±0.53	11.08±6.3
Qs-Ap-Ps mixed	0-15	5.20±0.55	0.067±0.08	336.1±8.1	21±4.2	303.8±5.1	35.3±11.5	0.74±0.05	8.01±2.01	3.1±0.5	31.9±7.7
	15-30	5.34±0.63	0.055±0.02	298±7.2	18.6±2.1	253±3.4	25.3±6.3	0.86±0.2	13.6±1.5	2.6±0.76	31.2±12.2
Ps-Ap mixed	0-15	5.24±0.57	0.16±0.06	477±16.2	12.3±0.9	289±6.2	33.5±8.5	0.73±0.06	9.01±1.02	3±1.1	32.1±11.4

	15-30	5.40± 0.63	0.09±0 .07	362±5. 8	6.2±1. 2	278±8. 3	23.3±5. 5	0.75±0 .05	13.6± 0.5	1.9±0. 65	18.7± 7.4
Ps dominant	0-15	5.17± 0.56	0.18±0 .08	336±1 3.2	23.5± 0.8	313±1 9.4	33.6±5. 3	0.76±0 .06	9.01± 1.01	2.61± 0.44	28.4±6.7
	15-30	5.24± 0.60	0.078± 0.05	298±7. 9	13.2± 2.3	316±1 7.2	20.3±2. 5	0.81±0 .06	12.6± 1.5	1.9±0. 49	20.4±6.9
Ps-Ap-Cd mixed	0-15	5.30± 0.67	0.092± 0.05	553±1 0.7	15.3± 0.7	356±5 3.7	27.01±3 .3	0.82±0 .08	8.01± 2.01	2.9±1. 0	33.6±15.10
	15-30	5.34± 0.60	0.075± 0.03	437±2 1.44	8.8±1. 1	317±5 1.4	17.01±3 .3	0.90±0 .07	10.6± 2.8	1.4±0. 52	16.6±6.8
Pc-Qs mixed	0-15	5.30± 0.74	0.089± 0.06	440±8. 5	16.2± 2.1	305±8	27.02±7 .5	0.76±0 .09	8.01± 1.01	3.2±0. 7	34.3±11.4
	15-30	5.38± 0.62	0.073± 0.01	362±6. 2	12.2± 0.8	280±1 1	14.3±3. 8	0.79±0 .07	12±2. 6	2.0±0. 5	21±6.07
Pc dominant	0-15	5.07± 0.50	0.086± 0.01	265±3. 9	14.2± 0.6	243.7± 6.9	17.6±5. 2	0.88±0 .09	15.3± 2.08	1.7±0. 7	19.6±10.2
	15-30	5.04± 0.44	0.096± 0.02	239±3. 2	12.2± 2	234.8± 5.2	14.3±3. 8	0.96±0 .1	16.3± 2.08	1.08± 0.5	13.5±7.7
Qs-Ps mixed	0-15	4.82± 0.50	0.072± 0.04	472±7. 2	25.3± 2.1	341±1 5.2	34.01±5 .8	0.74±0 .04	8.3±2. 08	3.1±0. 9	31.7±10.2
	15-30	5.10± 0.49	0.084± 0.03	380±3. 2	19±2. 3	309± 16.9	24.02±4 .2	0.82±0 .02	11.3± 1.5	2±0.6	21.9±7.2
Qs-Pc mixed	0-15	5.03± 0.48	0.11±0 .06	371±6. 1	22.1± 0.8	271±3. 7	29.6±4. 1	0.72±0 .07	8.4±1. 5	2.5±1. 3	25.4±14.8
	15-30	5.10± 0.45	0.052± 0.02	249±4. 1	13.2± 1.2	240±7. 1	26.3±4. 4	0.82±0 .06	10.6± 2.08	1.8±0. 59	20.0±7.9
Qs-Tc mixed	0-15	5.12± 0.57	0.073± 0.04	490±1 2.3	23±1. 2	290±1 5	34.3±7. 3	0.73±0 .09	9.01± 2.01	2.9±0. 7	29.3±9.8
	15-30	5.24± 0.65	0.089± 0.01	388±8. 4	16±0. 8	265±1 1	27.6±7. 5	0.89±0 .3	11.01 ±2.6	2.3±0. 8	26.9±16.6
Qs pure	0-15	5.07± 0.50	0.068± 0.08	510± 21.3	25±1. 4	360± 23	32.5±10 .02	0.68±0 .007	9.01± 1.02	3.8±0. 8	35.6±7.19
	15-30	5.04± 0.44	0.085± 0.06	478±1 7.1	21±1. 2	325±1 3	29.18±1 0.1	0.85±0 .02	10.4± 2.08	2.9±0. 49	33.1±5.9

3.3 Communities wise vegetation diversity indices

The Shannon's index (H) was highest in *the Ap-Ps-Qs* (1.98) mixed community, followed by the *Ps-Ap* mixed (1.81), *Ps*-dominant (1.62), and *Ps-Ap-Cd* mixed (1.61) communities. On the other hand, the *Qs* pure forest community showed no tree diversity due to single-species stand forests. The value of Simpson (1-D) was also low in the *Qs* pure stand, but high in the *Ap-Ps-Qs* (0.82) mixed community. The *Qs* pure forest stand was highly dominated by a single species, with a dominance index (D) of 1, whereas it was lower in the *Ap-Ps-Qs* (0.18) mixed forest community. However, with increasing altitude, single-species stands showed relatively high dominance, particularly in the *Quercus semecarpifolia* stand. In addition, Fisher's alpha, Brillouin's index, Menhinick, and Margalef were higher in the *Ap-Ps-Qs* mixed forest community, with values of 3.92, 1.74, 1.41, and 2.43, respectively.

Furthermore, Equitability (J) and Berger–Parker dominance ranged between (0.35- 0.86) and (0.31- 1.00) across all the forest communities in the TWS (Table 4.3).

Shrub Layer In the case of the shrub layer, the diversity of the species was higher in the *Ps* dominant forest community with Shannon's index (H) of 2.23, followed by the *Ap-Ps Qs* mixed (2.17) and *Ap-Ps* mixed (2.06) communities, respectively. The results showed that the *Pc-Qs* mixed community had lower diversity (0.42). However, the dominance (D) of all the shrub layers in all forest communities lies between 0.12 in the Ps and 0.80 in the *Pc-Qs* mixed forest community. Similarly, Simpson's index (1–D) was also greater in the *Ap-Ps-Qs* and *Ps* forest communities (0.87 each), followed by the rest of the forest communities (Table 2). Evenness (e^H/S) was lower in the *Ps-Ap-Cd* mixed (0.37) while greater in the *Ap-Ps-Qs* (0.90) mixed forest community. The Brillouin index showed trends similar to those of the Shannon index. Menhinick and Margalef indices had the highest species richness in the *Ps* and *Ps-Ap-Cd,* with values of 1.16 and 2.35, respectively. Furthermore, *Ps* had 81 a higher Fisher's alpha (3.47). Equitability (J) showed that the *Pc-Qs* (0.38) mixed community shrubs were unevenly distributed, while the *Aa-Pc* mixed community shrubs were evenly distributed (0.93). Despite this, *Ap-Ps-Qs* had a lower Berger-Parker index (0.20), and the *Qs* mixed forest community was highest (0.89), respectively (Table 2).

The *Ap-Ps* mixed community showed greater herb diversity, as indicated by Shannon's index (H) (3.60), followed by the *Ap*-dominant and *Ps*-dominant Forest communities (3.44 each), respectively. In the herb layer across all forest communities, Simpson's index (1–D) was high, ranging from 0.85 to 0.96. The maximum value was found in the *Ap-Ps* mixed community (0.96), and the minimum value was 0.85 in the *Qs-Tc* mixed community. Another diversity index, Shannon's (H), was also highest in the *Ap-Ps* mixed forest community (3.60) and lowest in the *Qs-Tc* mixed community (2.38). Moreover, Evenness (e^H/S) of herb species in the forest community ranged from 0.32 to 0.49, indicating an uneven distribution. At the same time, Brillouin's index, as well as Menhinick and Margalef's results, showed similar patterns in the in the herbs layer respectively.

244

245 **Table 2 Comparison of Species Diversity, Evenness, Richness, and Dominance Indices for**
246 **Tree, Shrub, and Herb Layers across 14 Forest communities at TWS**

Communities	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Tree														
Dominance_D	0.33	0.43	0.18	0.29	0.29	0.22	0.30	0.31	0.88	0.68	0.44	0.61	0.37	1
Simpson_1-D	0.67	0.57	0.82	0.71	0.71	0.78	0.71	0.69	0.12	0.32	0.56	0.38	0.63	0
Shannon_H	1.47	1.40	1.98	1.39	1.33	1.81	1.62	1.61	0.24	0.60	1.06	0.76	1.12	0
Evenness_e^H/S	0.44	0.40	0.66	0.80	0.75	0.56	0.56	0.50	0.64	0.61	0.72	0.53	0.76	1
Brillouin	1.37	1.24	1.74	1.22	1.20	1.66	1.47	1.45	0.20	0.46	0.98	0.65	1.02	0
Menhinick	0.82	1.08	1.41	0.83	0.70	1.09	0.96	1.07	0.37	0.75	0.49	0.64	0.53	0.16
Margalef	1.80	2.02	2.43	1.12	1.02	2.16	1.79	2.01	0.29	0.72	0.71	0.81	0.75	0
Equitability_J	0.64	0.61	0.83	0.86	0.82	0.76	0.74	0.70	0.35	0.55	0.77	0.55	0.80	
Fisher_alpha	2.42	2.93	3.92	1.58	1.37	3.13	2.52	2.90	0.48	1.09	0.93	1.11	0.99	0.19
Berger-Parker	0.49	0.64	0.31	0.39	0.35	0.36	0.49	0.51	0.93	0.81	0.62	0.76	0.48	1
				Shrub										
Dominance_D	0.16	0.22	0.13	0.30	0.30	0.19	0.12	0.36	0.80	0.52	0.46	0.27	0.40	0.35
Simpson_1-D	0.84	0.78	0.87	0.70	0.70	0.81	0.87	0.64	0.20	0.48	0.54	0.73	0.60	0.65
Shannon_H	2.06	1.84	2.17	1.28	1.27	1.93	2.23	1.57	0.42	0.84	0.92	1.45	1.00	1.31
Evenness_e^H/	0.65	0.45	0.7	0.9	0.8	0.6	0.77	0.3	0.5	0.7	0.8	0.8	0.9	0.6

S			9	0	9	9		7	1	7	3	5	0	2
Brillouin	1.94	1.82	2.13	1.22	1.23	1.83	2.05	1.47	0.39	0.79	0.85	1.37	0.94	1.22
Menhinick	0.91	0.39	0.39	0.39	0.29	0.71	1.16	0.90	0.25	0.31	0.40	0.47	0.33	0.60
Margalef	2.13	1.81	1.50	0.64	0.57	1.70	2.35	2.24	0.40	0.44	0.50	0.85	0.45	1.08
Equitability_J	0.83	0.70	0.90	0.93	0.92	0.84	0.89	0.61	0.38	0.76	0.84	0.90	0.91	0.73
Fisher_alpha	2.92	2.19	1.81	0.82	0.72	2.21	3.47	3.06	0.53	0.59	0.68	1.07	0.61	1.40
Berger-Parker	0.29	0.33	0.20	0.44	0.41	0.33	0.21	0.57	0.89	0.68	0.63	0.41	0.53	0.52
Herbs														
Dominance_D	0.044	0.05	0.08	0.08	0.11	0.09	0.05	0.07	0.11	0.09	0.09	0.07	0.14	0.11
Simpson_1-D	0.956	0.95	0.92	0.92	0.89	0.91	0.95	0.93	0.89	0.90	0.91	0.93	0.85	0.89
Shannon_H	3.604	3.44	2.97	2.91	2.58	2.85	3.44	2.92	2.57	2.75	2.85	3.05	2.38	2.61
Evenness_e^H/S	0.427	0.41	0.32	0.40	0.46	0.37	0.36	0.39	0.47	0.49	0.45	0.42	0.40	0.41
Brillouin	3.581	3.42	2.95	2.89	2.56	2.83	3.41	2.91	2.55	2.72	2.82	3.03	2.36	2.59
Menhinick	0.841	0.74	0.62	0.69	0.52	0.63	0.96	0.50	0.52	0.66	0.64	0.71	0.47	0.55
Margalef	9.183	8.09	6.54	5.35	3.49	5.34	9.45	5.16	3.39	4.00	4.53	5.75	3.22	3.90
Equitability_J	0.809	0.80	0.72	0.76	0.77	0.74	0.77	0.75	0.77	0.79	0.78	0.78	0.72	0.75
Fisher_alpha	12.820	11.05	8.70	7.14	4.43	7.06	13.45	6.65	4.29	5.25	5.95	7.72	4.05	5.01
Berger-Parker	0.105	0.10	0.19	0.18	0.20	0.17	0.12	0.14	0.22	0.19	0.18	0.18	0.23	0.19

247 Abbrebration; *Abies pindrow-Picea smithiana* mixed (*Ap-Ps*) (1), *Abies pindrow* dominant(Ap)
248 (2), *Abies pindrow-picea smithiana-Quercus semecarpifolia* mixed (*Ap-Ps-Qs*) (3), *Acer*

acuminatum-Prunus cornuta mixed (*Aa-Pc*) (4), *Quercus semicarpifolia-Abies pindrow-Picea smithiana* mixed (*Qs-Ap- Ps*)(5), *Picea smithiana-Abies pindrow* mixed (*Ps-Ap*) (6), and *Picea smithiana* dominant(Ps) (7), *Picea smithiana-Abies pindrow-Cedrus deodara* mixed (*Ps-Ap-Cd*) (8), *Prunus cornuta- Quercus semecarpifolia* mixed (*Pc-Qs*) (9), *Prunus cornata* dominant (*Pc*) (10), *Quercus semecarpifolia-Picea smithiana (Qs-Ps*) (11), *Quercus semecarpifolia-Prunus cornata* mixed (*Qs-Pc*) (12), *Quercus semecarpifolia-Taxus contorta* (*Qs-Tc*) (13), and *Quercus semecarpifolia* (*Qs*) (14)

3.4 **Seedling and Sapling Density (Ind ha^{-1}) across the communities**

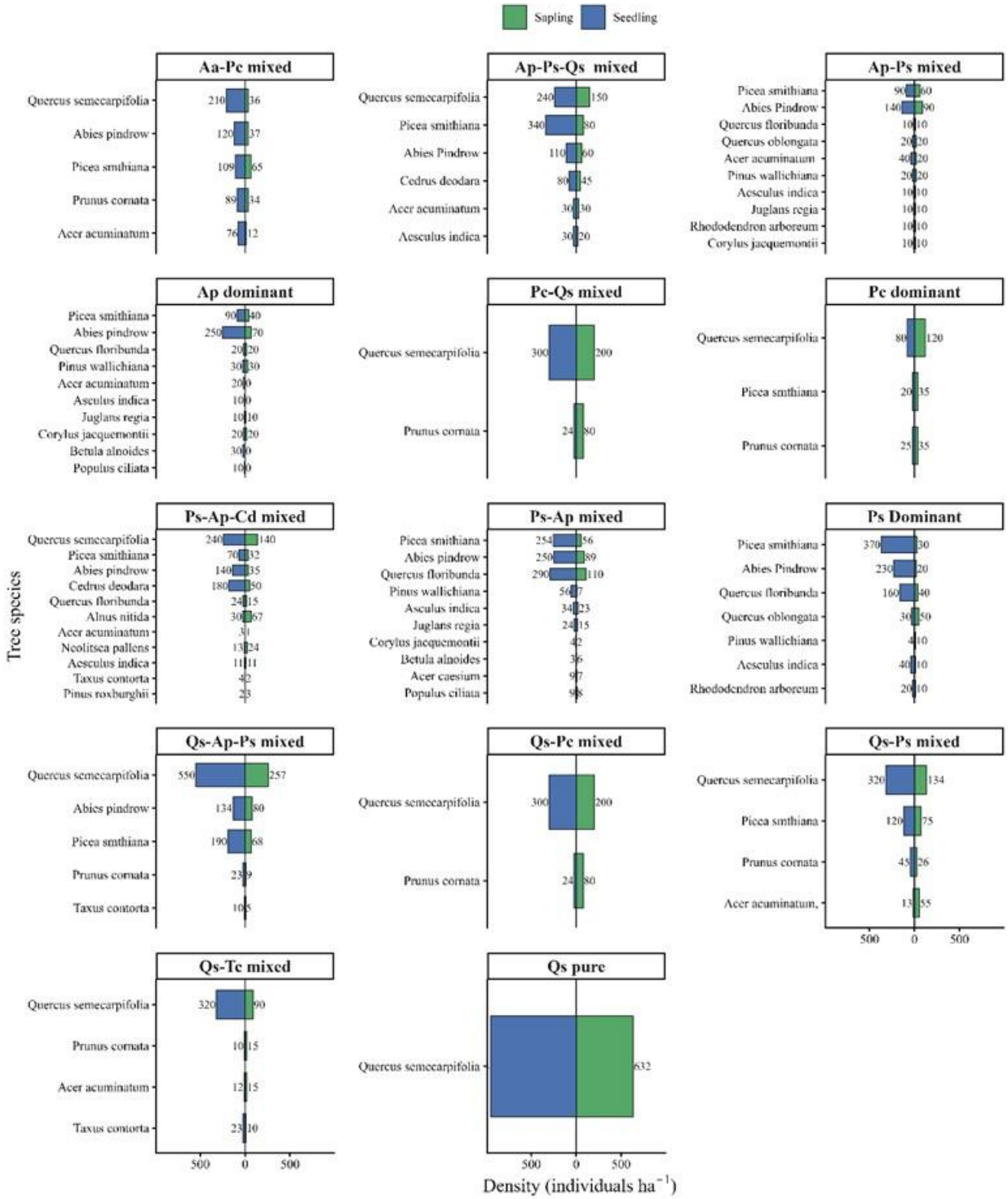
The statistical description of the regeneration profile status of the forest stands in the Talra Wildlife Sanctuary showed that the range of seedlings was observed from 125 ind. ha^{-1} to 954 ind. ha^{-1} (avg. 577.57 ±268.64 ind. ha^{-1}). In contrast, tree saplings were found in the range of 121 ind. ha^{-1}to 632 ind. ha^{-1}, with an average value of 279.43 ±136.53 ind. ha^{-1}, respectively.

In comparison, community-wise regeneration patterns showed that in the *Qs* pure forest community, seedling density was observed to be higher with a total of 954 ind. ha^{-1}and sapling density was 632 ind. ha^{-1} followed by the *Qs-Ap-Ps* mixed community of 907 seedlings ind. ha^{-1} and 449 saplings ind. ha^{-1}, *Ps* dominant of 854 ind. ha^{-1} seedlings and 170 ind. ha^{-1} saplings, and *Ps-Ap-Cd* mixed of 717 ind. ha^{-1} seedlings and 380 ind. ha^{-1} saplings. However, *Ps-Ap* was observed at 933 ind. ha^{-1} seedling and 323 ind. ha^{-1} sapling, followed by *Ap-Ps* with 538 ind. ha^{-1} seedling and 323 ind. ha^{-1} sapling. The *Qs-Ps* had 498 seedlings and 290 ind. ha^{-1} saplings. It was followed by *Ap-Ps-Qs*, 567 ind. ha^{-1} seedlings and 280 ind. ha^{-1} saplings.

The *Pc-Qs* mixed community had 324 ind. ha^{-1} seedlings and 280 ind. ha^{-1} saplings. In contrast, the *Ap* dominant forest community had 490 ind. ha^{-1} seedlings and 190 ind. ha^{-1} saplings. At the same time, the *Aa-Pc* mixed community had 604 ind. ha^{-1} seedlings and 184 ind. ha$^{-1.}$ Respectively. While in the case of the *PC*-dominant community, it was observed that of the 125 ind. ha^{-1} seedlings and 190 ind. ha^{-1} saplings, followed by *Qs-Tc* 365 ind. ha^{-1} seedlings and 130 ind. ha^{-1} saplings, and *Qs-Pc* with 210 ind. ha^{-1} seedlings and 121 ind. ha^{-1} saplings, respectively.

The *Quercus semecarpifolia* (*Qs*) pure community was higher regeneration patterns, followed by the *Quercus semicarpifolia-Abies pindrow-Picea smithiana* mixed (*Qs-Ap- Ps*), *Picea smithiana dominant* (*Ps*), *Picea smithiana-Abies pindrow-Cedrus deodara* mixed (*Ps-Ap-Cd*),

Acer acuminatum-Prunus cornuta mixed (*Aa-Pc*), *Abies pindrow-picea smithiana-Quercus semecarpifolia* mixed (*Ap-Ps-Qs*), *Abies pindrow-Picea smithiana* mixed (*Ap-Ps*), *Quercus semicarpifolia-Abies pindrow-Picea smithiana* mixed (*Qs-Ap-Ps*), *Quercus semecarpifolia-Taxus contorta* (*Qs-Tc*), *Prunus cornuta- Quercus semecarpifolia* mixed (*Pc-Qs*), *Quercus semecarpifolia-Prunus cornata* mixed (Qs-Pc) and, *Prunus cornata* dominant (*Pc*) respectively in the Talra Wildlife Sanctuary forest ecosystem (Fig. 5)



284

285 **Fig. 5** Seedling and sapling densities (individuals ha^{-1}) across forest sites

286

3.6 Relationships among vegetation and soil Variables

Pearson correlation analysis showed distinctive affinities among the ecological variables (Fig. 6). Soil organic carbon (SOC %) was positively associated with SOC stock (r = 0.98), available nitrogen (r = 0.70), phosphorus (r = 0.67), potassium (r = 0.57), and soil moisture (r = 0.53). Moreover, SOC was negatively correlated with bulk density (r = –0.56) and coarse fragments (r = –0.55). Simultaneously, soil nitrogen was also positively correlated with potassium (r = 0.75) and moderately correlated with phosphorus (r = 0.31). The correlation analysis showed that with increasing altitude, vegetation patterns, tree density, and species richness decreased, as shown by negative correlations with tree density (r = –0.74), species richness (r = –0.71), Shannon diversity (r = –0.74), Simpson diversity (r = –0.72), and inverse Simpson diversity (r = –0.75). Consequently, species richness and moisture were positively associated with soil nutrient availability and vegetation attributes, while bulk density, coarse fragments, and increasing altitude were associated with lower SOC and reduced vegetation diversity.

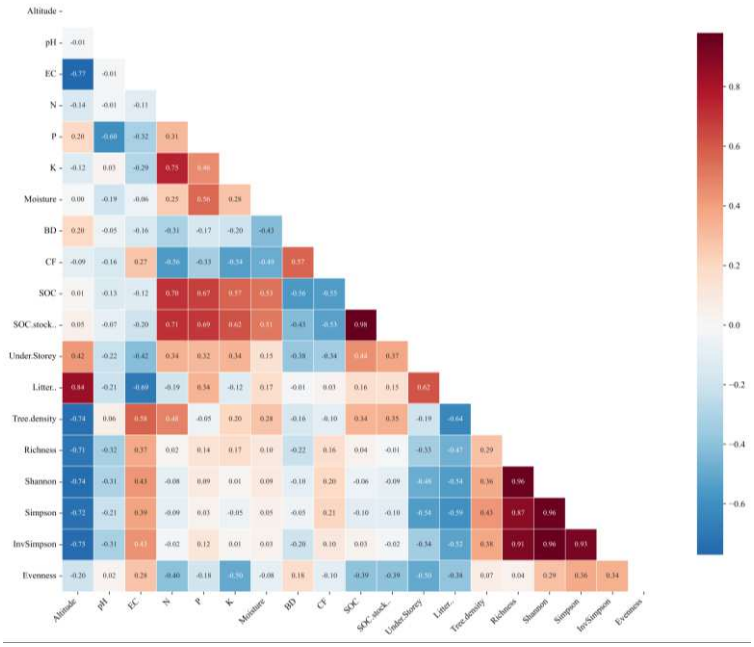


Fig. 6 Pearson correlation matrix showing relationships among environmental, soil physicochemical, vegetation, and diversity variables

3.7 Species allocation by the pace of altitude

Species richness showed a positive relationship with Shannon diversity. The result showed that as elevation increased, tree density was negatively decreased. Similarly, species richness and Shannon diversity declined significantly along the elevational gradient in the Talra Wildlife Sanctuary.

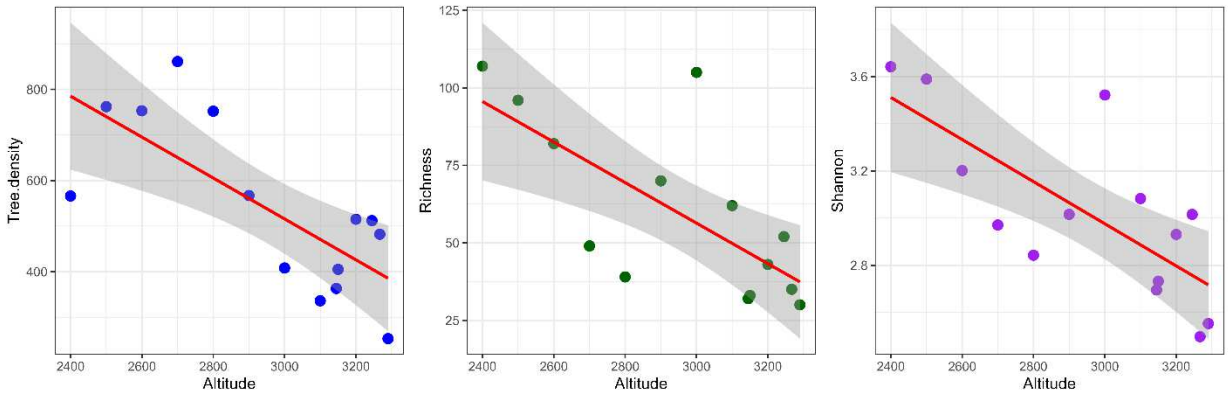


Fig. 4 Relationships among: (a) species richness and Shannon diversity, (b) elevation and tree density, (c) elevation and species richness, and (d) elevation and Shannon diversity

4. Discussion

Varying environmental characteristics and orographic factors provide the specialized habitats and ecological features, which are major determinants of plant diversity, community structure, and patterns across the western Himalaya [56; 57]. Mixed conifer forest stands, particularly with *Abies pindrow* and *Picea smithiana*, have higher species richness than *Quercus semecarpifolia*, which are less structurally complex. The higher diversity and species richness recorded in conifer-mixed stands are likely due to habitat heterogeneity, different soil conditions. The higher range of ecological niches at altitudinal gradients create favorable conditions for the coexistence of different species [58;59]. Similar results have been reported in temperate Himalayan forests, where mixed conifer ecosystems consistently maintain the greater biodiversity than monospecific stands due to increased habitat complexity and reduced competitive exclusion [60;61].

The same patterns were found in the literature synthesis by Zhang et al. [62]. Their meta-analysis found that species mixing increases biomass accumulation potential, thereby increasing soil

nutrient availability and nutrient balance compared with monocultures, as observed in the current study. Species richness in the mountain region varied with the pace of altitude change [63]. However, in the short ecological zones, regional factors such as habitat type, aspect, community composition, and human interference also play a key role, which is also observed in the present study. Regional environmental factors such as ambient temperature, soil moisture, nutrients, and other limiting factors are fundamental drivers that balance ecological forces [64]. In the *Abies pindrow* and *Picea smithiana* forests in lower-altitude stands, seedling and sapling densities were lower than in the *Quercus semecarpifolia* forest at higher-altitude stands. This may be due to the higher altitude, less anthropogenic interference, and lower competition from mature trees than the conifer forests.

The upper layer of soil (0-15 cm) contained greater SOC, available nitrogen, phosphorus, potassium, and moisture than the 15-30 cm depth in the current study. This phenomenon may be due to higher moisture in the upper layer, greater accumulation of litter inputs from humus, greater microbial activity, and less compaction, which leads to the transfer of organic material and subsequently enhances soil quality. In contrast, at deeper layers the soil becomes more compacted, slowing the above processes and declining nutrient availability. Soil moisture plays a crucial role in regulating the nutrient cycle and also regulates microbial carbon and phosphorus metabolism in the soil [65]. Cui et al. [66] reported in their study on the Loess Plateau, China, that soil moisture is interrelated with phosphorus in both microbes and plants, and found maximum carbon limitation in Early Forest, while greater Phosphorus limitation in climax Forest.

4.1 Mixed conifer forests maintain higher plant diversity

The present study demonstrates that mixed forest community composition with greater floristic diversity is a major factor across the northwestern Himalaya. Mixed conifer communities, particularly those dominated by *Abies pindrow* and *Picea smithiana*, hold high species richness than *Quercus semecarpifolia* forest communities. The greater species richness (108 species) is found in the *Abies pindrow–Picea smithiana* mixed forest, however the *Prunus cornuta–Quercus semecarpifolia* communities has the lowest richness (33 species). These results imply that species composition and structure are responsible for the formation of underground diversity

patterns within Himalayan temperate forests. Similarly, Rahman et al. [67] observed that the mixed conifer forests exhibit significant plant diversity due to the coexistence of various species across different elevations in the forest stand. The results showed that 218 plant species were recorded in mixed coniferous forests. The *Pinus–Cedrus–Viburnum* (PCV) community had greater species richness (156 species), followed by the *Viburnum-Pinus-Abies* (VPA) community (128 species), *Abies-Juniperus-Picea* (AJP) community (58 species and *Picea-Abies-Juniperus* (PAJ) community (52 species). This is because conifer forests form the favorable environmental conditions at different altitudes, and topographic, climatic, and edaphic factors support greater species richness and high species evenness.

The heterogeneous canopy structure in the forest ecosystem creates different environmental conditions with high light intensity on the ground floor, thereby permitting different understory species to coexist and collectively maximize forest productivity [68]. Earlier studies have highlighted that the interaction between plant structure and forest floor microbial decomposition is significant for understanding biogeochemical pathways, nutrient availability, and health [69; 70]. However, the relationship between forest canopy structure and understory vegetation growth has yet to be studied extensively in the Himalayas, and it needs long-term studies. The present study showed that the *Abies pindrow–Picea smithiana* mixed forest has a high species diversity. It may be due to a heterogeneous forest structure that generally maintains regional microclimatic conditions, retains soil moisture, supports higher microbial activity, and reduces evaporative losses from the forest stands, ultimately providing favorable conditions for different plant species. Similar associations have been widely reported for temperate mixed forests worldwide, where ecological structure and function are directly linked to forest productivity via niche complementarity and species facilitative interactions [71;72;73).

This forest pattern aligns with previous studies of the Himalayan region. These studies reveal that diverse plant communities exist within Himalayan Forest ecosystems, as varying habitats, topography, climate, and soil conditions collectively determine their structure and composition [74;75;76). The key elements of the forest stand, including SOC %, soil nutrient availability, physiological properties, and moisture, form a complex network that creates a favorable habitat for the species, fostering distinct species communities and coexistence [77]. Interestingly, community structure changes across different altitudes in the Himalayas [78]. Significant

ecological components in the forest ecosystem, such as habitat type, climate conditions, slope aspect, and vegetation structure, shape the ecological characteristics of species and their habitats [64].

Earlier studies also discussed the role and significance of these complex factors including traits, composition in forests [79]. They highlighted that species diversity, vegetation composition, and soil conditions often depend on regional environmental factors, with elevation playing a role at a regional scale [80;81]. The seedling and sampling density were found to be lower in the conifer forest stand, including *Abies pindrow* and *Picea smithiana*, than the *Quercus semecarpifolia* forest stand. However, both stands faced these challenges due to the recruitment of tree seedlings to sampling, which has limited the natural succession patterns that need to be addressed. At higher elevations, *Quercus semecarpifolia* sampling was slightly higher, possibly due to less disturbances for the underground vegetation, including low grazing pressure, which subsequently provide microsites for seed germination and their early establishment; in this context, soil moisture plays an important role.

4.3 Depth wise physicochemical variation of Soil

Soil physiological properties showed notable depth trends in the current study. The concentrations of the key components at a depth of 0–15 cm, SOC, available nitrogen (N), phosphorus (P), potassium (K), electrical conductivity (EC), and soil moisture, were higher in the subsurface layer (15–30 cm). In contrast, at high depth, the concentrations of these components were lower, while bulk density (BD) and coarse fragment (CF) content were higher in the 15–30 cm depth. The top layer of soil contains a thick layer of litter, which maintains soil moisture [82]. The detrital pathway drives the decomposition of litter and other detritus through microbial activity, promoting humus formation, nutrient mineralization, and soil organic matter accumulation [83;84]. Hence, the upper soil layer exhibits higher decomposition rates, greater nutrient availability, and enhanced soil fertility than deeper layers, owing to continuous litter inputs and more active microbial communities [85].

The Litter-derived carbon is converted into microbial biomass and residues before being stabilized through interactions with the mineral soil matrix, leading to long-term soil organic

matter accumulation [86]. Gruneberg et al. [87] in their study had also reported bulk density increased and soil organic carbon percentage decreased at deeper soil horizons due to compaction and reduced nutrient flow. Similarly, the increase in coarse fragment content with depth marked closer proximity of subsoil horizons to the weathered parent material and the lower accumulation of fine organic-rich particles compared with the surface layer [88].

4.4 Soil vegetation interactions and ecosystem multifunctionality

The dynamics of the forest ecosystem have been regulated by a complex biogeochemical network instead of a single environmental factor [64]. The current study showed that soil moisture primarily regulates soil health as indicated by the positive relationships between SOC%, available nitrogen (N), and phosphorus (P); suggesting that soil moisture is a key driver in maintaining soil nutrient stoichiometry. Therefore, soil moisture content controls carbon fluxes, while arid conditions may cause photosynthetic depression in high-altitude mountain regions [89]. However, root and rhizosphere characteristics play a significant role in regulating nutrient content, including carbon partitioning, and water uptake through their collective functioning [90].

Van der Heijden et al. [91] also revealed that soil biodiversity is the key component and plays a significant role in balancing ecological forces. They showed that declines in soil biodiversity significantly impaired ecosystem multifunctionality, including plant diversity, decomposition, nutrient retention, and biogeochemical cycles. The functional traits play a vital role in maintaining ecosystem functioning and understanding the climate change impacts on plants. These traits and the complex network between them need to be studied holistically in the Himalayan Forest ecosystem. However, the complex phenomenon of forest ecosystems, how these cycles vegetation, soil physicochemical properties, root–rhizosphere processes, microbial communities, and climate- jointly regulate soil carbon dynamics and ecosystem multifunctionality through complex biogeochemical interaction networks, is important for understanding forest dynamics.

5. Conclusion

This study concludes that Himalayan Forest ecosystem and their different forest community composition are primary drivers of different species diversity, soil physicochemical properties, and soil organic carbon percentage. In Talra Wildlife Sanctuary, the results also found that mixed conifer forests dominated by *Abies pindrow* and *Picea smithiana* occur at lower altitudes. In comparison, pure *Quercus seicarpifolia* forests occur at higher altitudes. The study concludes that high moisture and favorable soil conditions lead to high soil organic carbon percentages and carbon stocks, and that these forest ecosystems are carbon sinks and play a key role in climate mitigation strategies. The study also concludes that the upper soil layer (0–15 cm) is more nutrient-rich than the 15- 30 cm layer.

In contrast, bulk density and coarse fragment percentage were higher in the 15- 30 cm layer. Ecological regional factors, including habitat type, aspect, slope, and associated edaphic factors, play a key role in community structure and species composition. The findings of the current study conclude that conserving the forest ecosystem is important for maintaining ecological forces and the biogeochemical cycle of the IHR. The study also finds a key gap in Himalayan research: difficult terrain, limited research infrastructure, and resource constraints mean that the study is limited to a single component. Long-term studies are needed that include environmental components of the ecosystem and use established approaches and long-term monitoring. By doing long-term experiments, we can determine the forest's actual condition and its stage processes, such as whether it is a carbon sink or an old forest that has reached the stage of a carbon source. This type of study needs to be done in the Indian Himalayan region, focusing on ecosystem multifunctionality.

Author Contributions

AK: Conceptualization, field data collection, writing, data curation, and synthesis; KSK: Writing and editing; Reviewing; SP: Writing and editing; PK: Writing and editing; RKV: Writing and editing.

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Ethics Declaration

Plant identification and ethical compliance

The vegetation survey and associated ecological investigations were conducted in accordance with applicable local and national guidelines governing research on wild plant species. Plant species were identified with the assistance of Dr. R. K. Verma, Scientist-G and Head, ICFRE–Himalayan Forest Research Institute (HFRI), Shimla, Himachal Pradesh, India.

Permission for field investigations

Prior permission was obtained from the competent Forest Department authority for conducting field study within the area. All field activities were conducted in accordance with the applicable regulations and conditions governing scientific research in protected areas.

Conflicts of Interest

The authors declare no competing interests

Data Availability Statement

The datasets collected and analyzed during the present study are available from the corresponding author upon reasonable request.

Reference

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