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Divergent Effects of Topography on Soil Properties and Above-Ground Biomass in Nepal's Mid-Hill Forests

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Abstract: Various factors, including topography, climate, soil attributes, and vegetation composition, influence above-ground biomass productivity in forest ecosystems. Despite the success of community forestry in restoring degraded hill forests in Nepal, existing research offers limited insights into how topographic factors and plant species affect soil chemical properties and, in turn, influence above-ground biomass. This study investigates the interrelations between altitude, aspect, soil depth, and vegetation type on soil organic carbon (SOC), total nitrogen (TN), available phosphorus (P), available potassium (K), and soil pH. These soil metrics are further correlated with forestry indices, such as diameter at breast height (DBH), tree height (Ht), above-ground tree biomass (AGTB), basal area (BA), and above-ground total carbon (AGTC), in the mid-hill region of central Nepal. Our findings indicate that aspect had a significant influence on SOC ($p < 0.001$), TN ($p < 0.001$), P ($p < 0.05$), and pH ($p < 0.001$) levels. Soils in the northwest (NW) aspect exhibited higher levels of SOC and TN but lower levels of P and pH than those in the southeast (SE) aspect. Altitude did not significantly affect soil properties. Variations in SOC, TN, K, and pH were observed across different soil depths. Key forestry metrics like DBH, Ht, AGTB, and AGTC were notably higher at elevated altitudes and under the NW aspect. We also found that vegetation composition adds a layer of complexity to the relationship between aspect, soil properties, and above-ground biomass. The higher altitudes in the SE aspect are more conducive to above-ground biomass productivity, while the NW aspect is favorable for higher levels of SOC and TN in the soil. These variations could be due to differences in carbon deposition rates, plant compositions, soil microbial activities, and microclimatic conditions between the aspects. These findings highlight the need for holistic forest management approaches that consider topographic factors, soil depth, and plant species, offering practical implications for the region's sustainable forest management and restoration efforts.

Keywords: above-ground biomass; aspect; elevation; soil carbon; soil nitrogen

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1. Introduction

Forests are pillars of global ecosystems, performing pivotal roles in carbon sequestration, biodiversity maintenance, and the delivery of various ecosystem services [1–3]. The productivity of these ecosystems, notably above-ground biomass, is a function of a myriad of factors, including topographic features, climatic variables, soil properties, and biological characteristics [1]. Topics focusing on the interrelations between topography, vegetation, and soil have consistently gained attention in ecological science [4–6]. Regional climatic and topographic variations significantly shape vegetation and soil spatial patterns [7]. Locally, topographic elements like elevation, aspect, and slope greatly affect vegetation by modulating radiation, temperature, precipitation, and soil nutrient availability [4,8].

In central Himalaya's mid-hills, rapid alterations in climate and plant composition along elevation gradients have been well documented [9]. This region is notably vulnerable due to high human and animal population densities coupled with intense seasonal rainfall [10]. The forest ecosystems here are subject to stress from both environmental and anthropogenic factors, such as land use and management practices [2,11,12]. These practices influence long-term vegetation patterns and soil organic matter cycling, which are further modulated by topographic features like slope and aspect [13,14]. Key soil nutrients like soil organic carbon (SOC), total nitrogen (TN), available phosphorus (P), and available potassium (K) play essential roles in biological processes and plant nutrition [9,15]. These nutrients are regulated by microclimate, forest type, soil microbiology, and topography [16].

In the context of central Nepal's mid-hills, where maintaining a sensitive equilibrium between human livelihoods and ecological preservation is essential [10,12], understanding the interaction of topography, soil, and vegetation is of utmost significance [13]. The region's rich biodiversity and the well-being of its communities are closely tied to the health of its forests [3,12]. Effective forest management practices must consider not only the natural factors influencing soil and vegetation but also the socio-economic dynamics of the communities reliant on these ecosystems [3]. Conflicting studies exist regarding how topography influences above-ground biomass production, especially regarding aspect and altitude [17–19]. In hilly terrains, vegetation is crucial for soil properties and as a safeguard against soil erosion and water depletion [20,21]. Soil and vegetation systems are highly interdependent [22–24], with soil offering the essential physical environment and nutrients for plant growth [25–27]. Topographic factors further mediate such interactions [4,28]. Moreover, anthropogenic activities like tree harvesting, land management, and land use changes are vital but often overlooked influences on these natural relationships [29,30].

In Nepal, community forestry has been instrumental in forest restoration and management [3,31,32]. Despite these efforts, there is a significant knowledge gap concerning the nuanced impacts of topographic features on soil properties and their subsequent effects on above-ground biomass production in the region. Therefore, this study aims to bridge this gap by examining how aspect, altitude, and soil depth influence soil chemical properties. We also evaluate these factors' relationships with above-ground biomass in the community-managed forests of central Nepal's mid-hill region.

2. Materials and Methods

2.1. Study Area

The study was carried out in two community-managed forests: Sworgiya Humendada and Chhyaldevi community forests, located in the Kavrepalanchowk district of central Nepal (Figure 1a). The study area lies between 27°37′34.06″ and 27°37′41.57″ north and 85°34′51.25″ and 85°34′38.39″ east and is 1100 m to 1500 m above mean sea level. The site has a subtropical climate with a mean annual temperature of 17.5 °C, an annual minimum temperature of 11.9 (range: 4.4–18.1 °C), and an annual maximum temperature of 23.1 (range: 17.4–26.3 °C) [33]. Annual rainfall is about 1311.3 mm, with a seasonal range of 39.2–1046.7 mm [33]. Sworgiya Humendada forest has moderate to steep slopes, while the Chhyaldevi forest has moderate to precipitous slopes. The site is characterized by coarse- to medium-textured, shallow, and acidic soils with underlain granite and gneiss rock types [34]. *Pinus wallichiana* (A.B. Jacks) and *Schima wallichii* (DC. Korth.) were the dominant tree species in both forests. Other tree species were *Alnus nepalensis* (D. Don) and *Grevillea robusta* (A. Cunn. ex R. Br.). Over the last two decades, both forests covering 33.25 hectares have been managed and conserved by 937 local villagers from 245 households [34]. Before their management by these communities, overexploitation highly degraded the forests [34]. *Pinus wallichiana* trees in the forests were planted four decades ago, while other species were established naturally (Figure 1b).

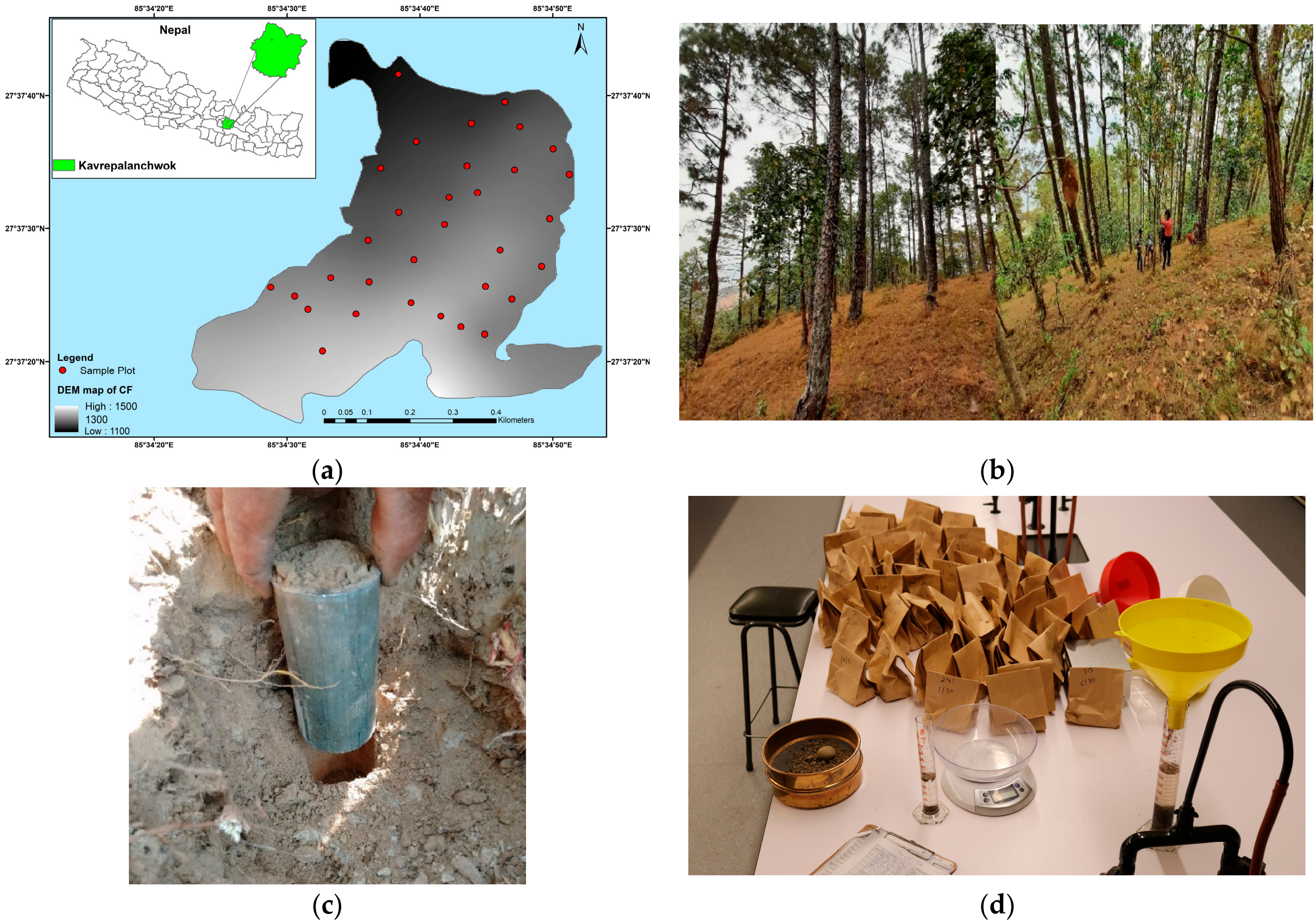

Figure 1. Map of study area and sample plot distributions (**a**), dominant forest types (**b**), soil sampling in the field (**c**), and laboratory analysis of soil samples (**d**).

2.2. Design of the Experiment

The experimental design involved the stratification of the study area into two distinct geographic altitudinal zones, namely 1100 to 1300 m and 1300 to 1500 m, and two aspects, southeast (SE) and northwest (NW). We established a total of 32 sample plots by randomly selecting eight plots of 10 × 10 m^2 within each altitudinal zone and aspect combination (2 altitudes × 2 aspects × eight replicates). In each of these plots, we meticulously recorded the diameter and height of individual tree species. Soil samples were systematically collected at three different depths, specifically 0–10 cm, 10–20 cm, and 20–30 cm, from the central point of each plot. The collection process was carried out using a soil auger (as shown in Figure 1c), resulting in a total of 96 soil samples representing the various combinations of altitudes, aspects, and depths (2 altitudes × 2 aspects × eight replicates × 3 soil depths). These soil samples were carefully placed in zip-locked plastic bags, securely sealed, and transported to the laboratory for subsequent analysis, as depicted in Figure 1d.

2.3. Soil Laboratory Analysis

The soil samples were air-dried at room temperature prior to laboratory analysis. A 2 mm soil sieve was used to filter soil samples for the analyses. The TN was measured using the Kjeldahl method [35], while SOC was determined using the standard Walkley and Black method [36]. Total phosphorus was measured by modifying Oslen's bicarbonate method using Shimadzu UV-1800 spectrophotometer (Shimadzu Corporation, Kyoto, Japan) [37]. Employing the neutral normal ammonium acetate method, a flame photometer (Sherwood Scientific Ltd., Cambridge, United Kingdom) was used to extract potassium from the soil samples [38]. For the soil pH, soil:water ratio (1:10) was taken, then it was mixed, suspended in a rotatory shaker for 20 min, and measured using a digital pH meter. All the lab analyses were carried out at the soil and fertilizer testing laboratory in Hetauda, Nepal.

2.4. Above-Ground Vegetation Analysis

Within a 0.01 hectare square plot, trees with a diameter at breast height (DBH) of greater than 5 cm were measured. The trees were all identified at the species level. All trees in 32 plots were measured for their DBH and total tree height (Ht). The Ht was measured with a sunto-clinometer (Suunto, Vantaa, Finland) and DBH was measured with a graduated diameter tape. The basal area (BA) in terms of m^2 ha^{-1} was calculated using DBH data and plot size. The sum of stem, branch, and foliage biomass was used to compute the total above-ground tree biomass (DBH $\geq$ 5 cm). Stem biomass was estimated by multiplying stem volume by wood density species [39]. The stem volume equation developed for Nepalese tree species was used to compute stem volume [39]. Species wood density values of Nepalese tree species were taken from Jackson (1994) [40]. Using species-specific branch-to-stem biomass and foliage-to-stem biomass ratios, branch and foliage biomasses were calculated from stem biomass [39]. Using a species-specific carbon factor, the above-ground biomass of tree species was converted to carbon [41]. A default carbon fraction of 0.47 was applied to the species for which a carbon factor was unavailable [42]. The biomass and carbon contents of the trees were estimated at plot level. Although below-ground biomass plays a significant role in the overall carbon budget, it was not assessed in this study as the focus was solely on above-ground biomass components.

2.5. Statistical Analysis

The R statistical computing system was used to conduct all statistical analyses [43]. Using the "nlme" package in R statistical software (R Package Version 3.1-137, R Foundation for Statistical Computing: Vienna, Austria) [44], the effects of altitude, aspect, and soil depth on soil and vegetation parameters were investigated using linear mixed-effects random intercept models. For the soil parameters, altitude, aspects, and soil depth were considered as fixed effects, and their interactions were tested. The altitude, aspects, species type, and interactions were fixed parts of the model of each response variable for vegetation parameters. The plot in our dataset is the replicated variable, which is a blocking factor. In linear mixed-effects models, the non-independence and replicated within-plot variation were accounted for by plot as the random effect structure [45]. The selected random effect structure of the random intercept model for both soil and vegetation model analyses was ~1 | plot (i.e., the random effect of the plot, which was associated with the intercept), as the plot was a blocking factor. Our data's linear mixed-effects random intercept model is represented mathematically in Equation (1) [45].

$$Y_i = \beta_0 + \beta_1 X_i + u_i + \varepsilon_i \tag{1}$$

where Y_i is the response variable (SOC, TN, P, K, pH, DBH, Ht, BA, above-ground tree biomass (AGTB), and above-ground total carbon (AGTC)) for different factor levels i (i.e., two levels of altitude, two levels of aspect, three levels of soil depth); X_i is the fixed term (i.e., altitude, aspects, soil depth, and species type); u_i is the plot-specific random term; and ε_i is the standard error term. Unless otherwise stated, Tukey's LSD test was used for post hoc multiple comparisons of treatment means at a significance level of <0.05.

3. Results

3.1. Effects of Aspect, Altitude, and Soil Depth on Soil Parameters

Detailed statistics of the soil chemical parameters and above-ground vegetation parameters, including minima, maxima, means, and standard errors, are given in Table 1. Our analysis indicates that soil properties are significantly influenced by aspect, although altitude showed no such effect (Table 2). Specifically, the SOC and TN levels were significantly higher in the NW aspect compared to the SE aspect. On the other hand, the levels of available P and soil pH were lower in the NW aspect (Table 4; Figure 2a–c,e). No significant impact of aspect was found on available K. Our results confirm the soil depth's significant influence on SOC, TN, K, and pH levels (Table 2). For example, higher levels of SOC and TN were observed at a soil depth of 0–10 cm (D1) compared to those at deeper soil layers (Table 4; Figure 2a,b). The K and pH levels also followed this trend (Table 4; Figure 2d,e). No significant differences in soil chemical properties were observed between soil depths of 10–20 cm (D2) and 20–30 cm (D3). Furthermore, no interaction effects were observed between aspect, altitude, and soil depth on any of the soil nutrient variables analyzed (Table 2).

Table 1. Descriptive statistics of the soil chemical parameters (n = 96) and above-ground vegetation parameters (n = 32).

Variables	Min	Max	Mean	SE
Soil organic carbon (%)	0.30	2.40	1.16	0.05
Total nitrogen (%)	0.02	0.21	0.10	0.00
Total phosphorus (kg ha^{-1})	24.10	3330.30	727.00	100.34
Potassium (kg ha^{-1})	51.60	325.20	178.46	8.04
Soil pH	3.00	4.60	3.83	0.03
Diameter at breast height (cm)	5.25	29.83	21.45	0.60
Tree height (m)	4.50	17.67	12.38	0.35
Tree basal area (m^2 ha^{-1})	0.43	41.68	18.63	1.19
Above-ground total tree biomass (ton ha^{-1})	0.99	288.52	116.27	8.28
Above-ground total tree carbon (ton ha^{-1})	0.45	133.29	53.54	3.83

Table 2. Soil chemical properties characteristics across varying topographic aspects, altitudes, soil depths, and species types. The relationships were assessed based on a linear mixed-effects model with random intercept. For the soil-related outcomes, response variables included soil organic carbon (SOC), total nitrogen (TN), total phosphorus (P), total potassium (K), and soil pH (pH), and the predictors were aspect, altitude, soil depth, and their interactions. Degrees of freedom (df) are separated with commas as numerator and denominator. Only significant test statistics (F-values) and p-values were reported.

Factors	df	Soil Parameters									
		SOC		TN		P		K		pH	
		F	p	F	p	F	p	F	p	F	p
Aspect	1,28	22.79	0.0001	16.93	0.0003	4.20	0.0499			16.43	0.0004
Altitude	1,28										
Depth	2,56	18.66	<0.0001	16.61	<0.0001			17.01	<0.0001	12.13	<0.0001
Species	3,28										

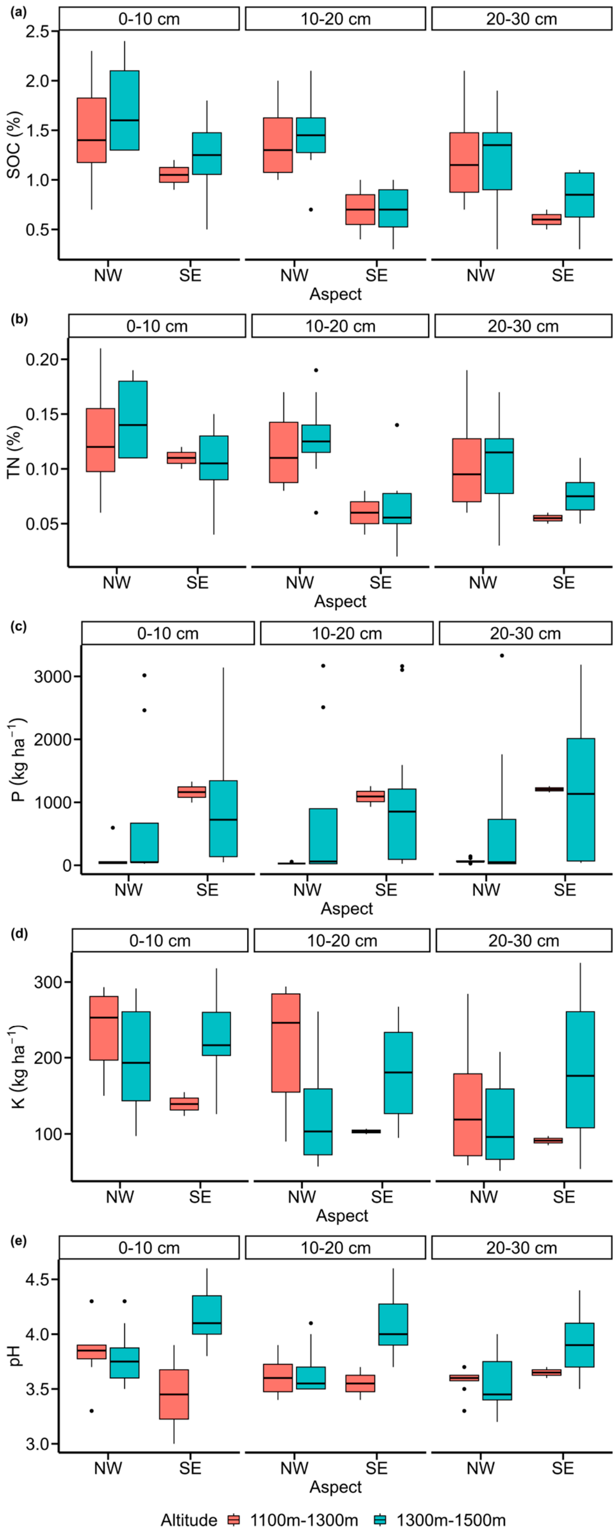

Figure 2. Values of soil organic carbon (SOC) (**a**), total nitrogen (TN) (**b**), total phosphorus (P) (**c**), total potassium (K) (**d**), and soil pH (pH) (**e**) varied by aspect (northwest: NW and southeast: SE), altitude, and soil depth. The black dots on the figure represent outliers for each variable.

3.2. Effects of Aspect, Altitude, and Species Type on Vegetation Parameters

Our analysis revealed significant differences in vegetation parameters such as DBH, Ht, BA, AGTB, and AGTC based on aspect, altitude, and species type (Table 3). Aspect substantially impacted all parameters except BA (Table 3). Specifically, the SE aspect exhibited higher values for DBH, Ht, AGTB, and AGTC when compared to those of the NW aspect (Tables 4 and 5; Figure 3a–c). Similarly, altitude significantly influenced all vegetation parameters, with higher altitudes generally showing increased values for the examined metrics (Table 5; Figure 3a–c). However, no interaction effects between aspect and altitude were detected in our study. Species type significantly influenced all vegetation parameters, as confirmed by our statistical analysis ($p < 0.001$) (Table 3). Specifically, *Pinus wallichiana* outperformed the other three species—*Schima wallichii*, *Alnus nepalensis*, and *Graviella robusta*—in all measured metrics (Table 5; Figure 4a–e). For instance, the DBH in *P. wallichiana* was significantly greater than that of the other species, with increases ranging from approximately 57% to 165% (Table 5; Figure 4a). Similar trends were observed for other parameters, such as Ht, BA, AGTB, and AGTC (Table 5; Figure 4b–e). Only Ht varied significantly among the other three species, while the other metrics did not (Table 5).

Table 3. Above-ground vegetation characteristics across varying topographic aspects, altitudes, soil depths, and species types. The relationships were assessed based on a linear mixed-effects model with random intercept. For the vegetation characteristics, response variables included diameter at breast height (DBH), tree height (Ht), basal area (BA), above-ground total tree biomass (AGTB), and above-ground total tree carbon (AGTC), and the predictors were aspect, altitude, and their interactions, and the main effects of species type. Degrees of freedom (df) are separated with commas as numerator and denominator. Only significant test statistics (F-values) and *p*-values were reported.

Factors	df	Vegetation Parameters									
		DBH		Ht		BA		AGTB		AGTC	
		F	*p*	F	*p*	F	*p*	F	*p*	F	*p*
Aspect	1,28	13.2962	0.0011	16.6391	0.0003			4.51651	0.0425	4.49901	0.0429
Altitude	1,28	8.8149	0.0061	13.4725	0.0010	5.94251	0.0214	8.84873	0.0060	8.78523	0.0061
Depth	2,56										
Species	3,28	16.0605	<0.0001	18.5343	<0.0001	21.89512	<0.0001	21.44612	<0.0001	21.58518	<0.0001

Table 4. Mean (±1 se) values of soil (SOC = soil organic carbon, TN = total nitrogen, P = total phosphorus, K = total potassium, pH = soil pH) for each aspect (SE = southeast, NW = northwest), altitude (A1 = 1100 m–1300 m, A2 = 1300 m–1500 m), and soil depth (D1 = 0–10 cm, D2 = 10–20 cm, D3 = 20–30 cm). Treatment means within a category followed by the same letter do not differ significantly at α = 0.05 level using Tukey's HSD test.

Category	Levels	Soil Parameters				
		SOC	TN	P	K	pH
Aspect	SE	0.85 ± 0.11 a	0.08 ± 0.01 a	1095 ± 338 a	154 ± 21.7 a	3.80 ± 0.08 a
	NW	1.42 ± 0.08 b	0.12 ± 0.01 b	403 ± 223 b	171 ± 14.3 a	3.67 ± 0.05 a
Altitude	A1	1.08 ± 0.12 a	0.09 ± 0.01 a	612 ± 353 a	154 ± 22.6 a	3.61 ± 0.09 a
	A2	1.20 ± 0.07 a	0.10 ± 0.01 a	886 ± 198 a	171 ± 12.7 a	3.86 ± 0.05 b
Soil depth (cm)	D1	1.38 ± 0.09 b	0.12 ± 0.01 b	732 ± 215 a	201 ± 15.9 b	3.81 ± 0.06 a
	D2	1.06 ± 0.09 a	0.09 ± 0.01 a	716 ± 215 a	157 ± 15.9 a	3.73 ± 0.06 a
	D3	0.97 ± 0.09 a	0.08 ± 0.01 a	800 ± 215 a	130 ± 15.9 a	3.68 ± 0.06 a

Table 5. Mean (±1 se) values of above-ground vegetation metrics (DBH = diameter at breast height, Ht = tree height, BA = basal area, AGTB = above-ground total tree biomass, AGTC = above-ground total tree carbon) for each aspect (SE = southeast, NW = northwest), altitude (A1 = 1100 m–1300 m, A2 = 1300 m–1500 m), soil depth (D1 = 0–10 cm, D2 = 10–20 cm, D3 = 20–30 cm), and tree species type (four species). Treatment means within a category followed by the same letter do not differ significantly at α = 0.05 level using Tukey's HSD test.

Category	Levels	Vegetation Parameters				
		DBH	Ht	BA	AGTB	AGTC
Aspect	SE	23.60 ± 1.73 b	13.10 ± 0.94 b	21.00 ± 3.98 a	124.90 ± 26.60 a	57.50 ± 12.30 a
	NW	18.50 ± 1.17 a	10.60 ± 0.63 a	15.30 ± 2.63 a	89.80 ± 17.60 a	41.30 ± 8.14 a
Altitude	A1	18.70 ± 1.81 a	10.10 ± 0.99 a	14.00 ± 4.17 a	69.30 ± 27.80 a	31.80 ± 12.86 a
	A2	23.40 ± 1.02 b	13.60 ± 0.55 b	22.40 ± 2.33 a	145.00 ± 15.60 b	67.00 ± 7.21 b
Species	*Pinus wallichiana*	27.00 ± 1.41 b	15.21 ± 0.71 c	19.86 ± 1.62 b	129.87 ± 11.10 b	59.97 ± 5.13 b
	Schima Wallichii	16.30 ± 1.35 a	9.67 ± 0.68 b	3.91 ± 1.55 a	22.19 ± 10.70 a	9.99 ± 4.92 a
	Alnus nepalensis	17.20 ± 2.38 a	10.52 ± 1.20 b	4.13 ± 2.75 a	17.58 ± 18.90 a	8.26 ± 8.70 a
	Gravellia robusta	10.20 ± 2.55 a	5.64 ± 1.29 a	1.24 ± 2.93 a	5.47 ± 20.20 a	2.57 ± 9.30 a

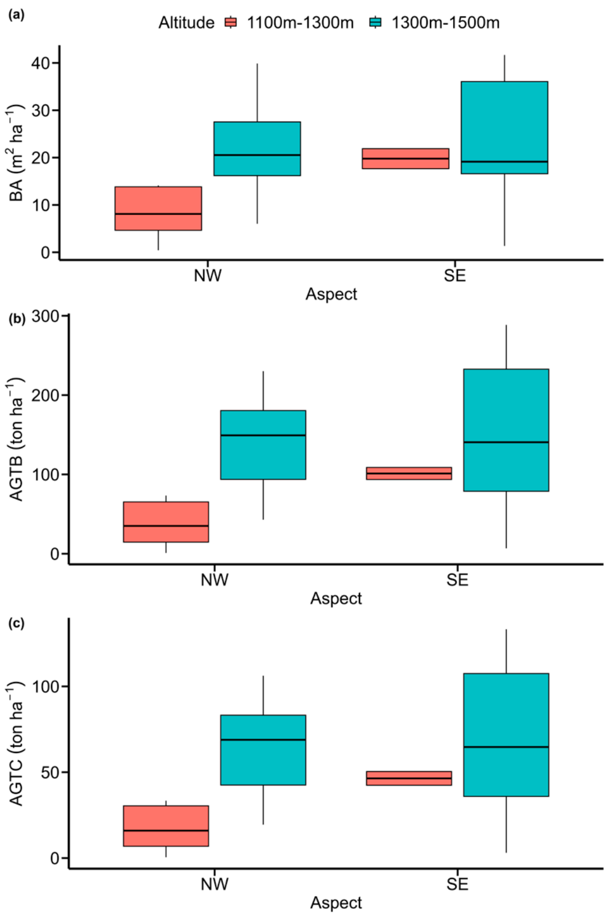

Figure 3. Values of basal area (BA) (**a**), above-ground total tree biomass (AGTB) (**b**), and above-ground total tree carbon (AGTC) (**c**), varied by aspect (northwest: NW and southeast: SE) and altitude.

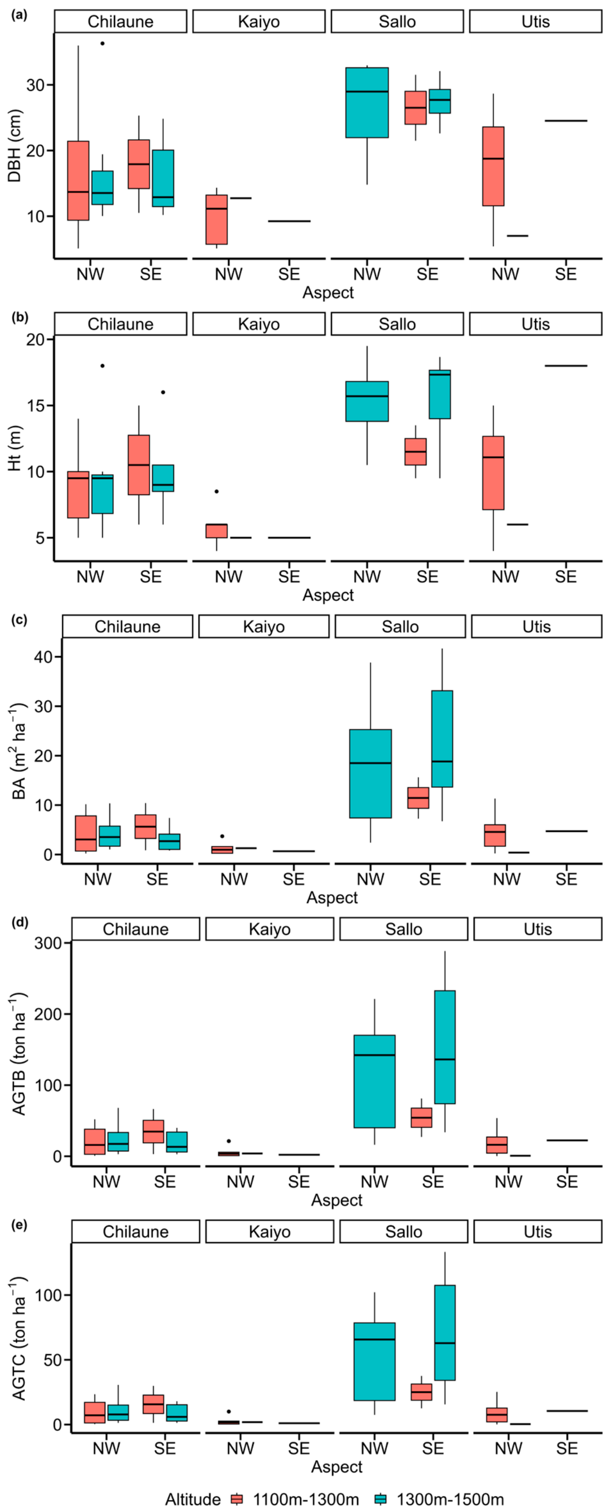

Figure 4. Values of diameter at breast height (DBH) (**a**), tree height (Ht) (**b**), basal area (BA) (**c**), above-ground total tree biomass (AGTB) (**d**), and above-ground total tree carbon (AGTC) (**e**) varied by tree species (Chilaune = *Schima Wallichii*, Kaiyo = *Grevillea robusta*, Sallo = *Pinus Wallichiana*, and Utis = *Alnus nepalensis*) via linear mixed-effects random intercept models. The black dots on the figure represent outliers for each variable.

3.3. Relationships between Above-Ground Variables and Soil Nutrients

Our investigation into the links between the above-ground vegetation variables and soil nutrient content yielded significant correlations (Table 6). DBH exhibited a negative correlation with SOC and N ($p < 0.01$) but was positively correlated with P ($p < 0.001$) and soil pH ($p < 0.05$). Similarly, Ht had a negative relationship with SOC and N ($p < 0.001$) but showed a positive correlation with P ($p < 0.01$) and pH ($p < 0.05$). BA was positively associated with both phosphorus (P) ($p < 0.001$) and K ($p < 0.05$). Notably, both AGTB and AGTC shared a positive correlation with phosphorus (P) ($p < 0.001$). No significant correlations were detected between DBH or Ht and K. Among the soil nutrients, K was positively correlated with organic carbon, N, and soil pH ($p < 0.05$). In terms of the above-ground vegetation metrics, DBH showed a robust positive relationship with other variables such as Ht, BA, AGTB, and AGTC ($p < 0.001$).

Table 6. The correlations between the soil chemical properties: soil organic carbon (SOC), total nitrogen (TN), total phosphorus (P), total potassium (K), and soil pH (pH); and the above-ground vegetation variables: diameter at breast height (DBH), tree height (Ht), basal area (BA), above-ground total tree biomass (AGTB), and above-ground total tree carbon (AGTC). Significant *p*-values are indicated as: *, significant at $p < 0.05$; **, significant at $p < 0.01$; and ***, significant at $p < 0.001$.

Variables	SOC	TN	P	K	pH	DBH	Ht	BA	AGTB	AGTC
SOC	1	0.95 ***	−0.07	0.25 *	0.03	−0.29 **	−0.39 ***	−0.11	−0.15	−0.16
TN		1	−0.08	0.21 *	0.00	−0.27 **	−0.37 ***	−0.03	−0.09	−0.09
P			1	0.17	0.18	0.38 ***	0.28 **	0.40 ***	0.37 ***	0.36 ***
K				1	0.26 *	0.13	0.06	0.21 *	0.19	0.19
pH					1	0.21 *	0.23 *	0.02	0.05	0.05
DBH						1	0.82 ***	0.73 ***	0.71 ***	0.71 ***
Ht							1	0.66 ***	0.75 ***	0.75 ***
BA								1	0.97 ***	0.97 ***
AGTB									1	1.00 ***
AGTC										1

4. Discussion

4.1. Effects of Aspect, Altitude, and Soil Depth on Soil Chemical Properties

The SOC values recorded in our research (ranging between 0.30% and 2.40%) are consistent with the results of a study by [29]. The latter study observed SOC values between 0.10% in severely degraded forests and 5.55% in well-managed, dense community forests in the mid-hills of central Nepal. This concurs with the findings of [12], who emphasized that SOC levels are largely contingent upon the condition of the forest, suggesting that soil chemistry varies according to forest management practices. Our study further substantiates the influential role of aspect on SOC and TN levels. Specifically, the NW aspect displayed elevated SOC and TN levels compared to the SE aspect, corroborating similar observations in prior studies [29,46]. The increased SOC and TN values in the NW aspect are typically associated with cooler, more humid soil conditions that favor slower rates of both plant growth and organic matter decomposition, thereby leading to the greater accumulation of organic carbon. Conversely, the SE aspect, characterized by warmer, drier conditions, demonstrates decreased SOC and TN levels, likely due to accelerated mineralization processes [47]. These variations in soil properties can also be connected to topography's influence on factors like solar radiation and soil moisture, which in turn impact vegetation growth [48].

In regions with a northern aspect, the amount of sunlight reaching the soil is lessened, which consequently modifies the microclimate by increasing soil moisture and lowering soil temperatures [49]. These conditions have been found to slow down the rate of litter decomposition [50,51]. While one might initially expect this delay in decomposition to decrease SOC and TN values, studies such as [52] suggest that litter has an extended duration in these areas. This longer duration could interact with other mechanisms, like increased microbial activity or root exudates, thereby facilitating a net increase in SOC and TN despite the slower decomposition rates. The dynamics between delayed decomposition and increased SOC and TN values are complex and likely involve multiple contributing factors that merit further investigation. Our research area, characterized by hilly and steep slopes, shows that northwest aspects, which are cooler and moister, result in greater SOC and TN accumulation. Our correlation analysis confirmed significant associations between SOC and TN ($p < 0.001$) and SOC and K ($p < 0.05$) (Table 6). According to [53], SOC values increased in north-, northeast-, and northwest-facing sites but decreased in southern and southeastern aspects. Ref. [50] further indicates that northern slopes display lower nitrogen mineralization and nitrification rates due to cooler conditions. These slopes conserve moisture due to fewer hours of sunshine, leading to lower temperatures and diminished microbial activity and subsequently resulting in elevated soil organic matter levels [53]. Ref [47] corroborates these findings, reporting higher carbon and nitrogen levels as well as a higher cation exchange capacity in north-facing slopes, which contributes to increased soil fertility. Given its impact on soil fertility and agricultural productivity as well as its potential to cause topsoil erosion, rainfall is also posited to affect SOC levels [47]. In this study, variations in soil pH were notably influenced by aspect, but not P levels. Furthermore, there is no correlation between P and pH levels (Table 6). It is possible that the influence of aspect on both P and pH levels may be mediated by additional unaccounted factors or interactions not explicitly reflected in the correlation analysis. For example, the effect of aspect on soil properties and vegetation characteristics could be indirect, influenced by variables not included in the correlation analysis. These ecological relationships often encompass a range of interactions that may not be entirely captured by simple pairwise correlations. Specifically, the P and pH values were significantly higher in the SE aspect. This is consistent with the literature indicating that the soil phosphorus concentration is linked to parent material and rock weathering [54] and that much of this phosphorus may not be available for plant uptake [55]. Our data showed that the soil pH was slightly more acidic at lower altitudes under the NW aspect compared to the SE aspect ($p < 0.001$). This acidity could be attributed to the greater moisture content, more abundant organic matter, and different vegetation communities found in north-facing slopes [30,56]. For instance, our NW plots predominantly featured vegetation types such as *Alnus nepalensis*, which have been known to influence soil pH and nutrient cycling. These biotic and abiotic factors collectively shape the microclimate and, in turn, significantly impact soil properties including SOC, TN, P, and pH. These microclimatic differences between aspects are believed to have significant consequences for plant development and, subsequently, for soil chemical attributes.

This study found no significant impact of altitude on soil variables, as shown in Table 2. This lack of significance could be due to the relatively narrow range of altitudes covered in our study (i.e., 1100 m to 1500 m). These findings align with previous research that also reported no significant altitudinal effects on soil properties within similar ranges [57–59]. Though not statistically significant, our study observed a general increase in all considered soil chemical properties with increasing altitude (Table 4). This aligns with the existing literature suggesting that soil and air temperatures inversely correlate with SOC and TN, especially at high altitudes [15,60]. Ref. [53] reported a positive correlation between soil properties and altitude, particularly noting that the organic matter content increased at higher elevations in both agricultural and forest soils. This rise is attributed to reduced decomposition rates and increased litter accumulation. In our study site, which predominantly features *Pinus wallichiana* forest in its southeastern aspect, lower SOC and TN values were observed at higher altitudes due to reduced decomposition rates and increased litter production.

Regarding soil depth, our study found significant effects on SOC, TN, K, and pH values ($p < 0.001$), as outlined in Table 2. These properties generally decreased with increasing soil depth (Table 4). Refs. [13,61] suggest that this could be due to increased microbial activity fueled by a higher quantity of litter in the topsoil, accelerating decomposition in deeper soil layers. Ref. [14] also observed that higher SOC and TN values were more likely to occur in topsoil due to its higher litter fall input. In this study, SOC was significantly higher at a soil depth of 0–10 cm (D1) than at depths of 10–20 cm (D2) and 20–30 cm (D3) by 29.95% and 85.85%, respectively. Similar trends were noticed for other soil variables studied. We speculate that this pattern might be influenced by variations in factors such as the gravel content, soil bulk density, and organic matter, as suggested by [62]. According to the authors of [62], the decline in SOC content with soil depth is tied to the soil texture, affecting the stability of soil organic matter by limiting the formation of aggregates between mineral components and SOC in deeper layers.

4.2. Effects of Aspect, Altitude, and Species Type on Vegetation Parameters

In our study, the DBH, Ht, BA, AGTB, and AGTC were found to be significantly higher in the SE aspect and at higher altitudes. Contrasting this, ref. [63] found higher above-ground tree biomass and total carbon content in the northern aspect due to higher SOC availability. As [64] suggested, silvicultural practices can affect biomass parameters. In the community-managed forests of central Nepal, activities like thinning and pruning are common silvicultural practices due to local demand for timber and firewood [31]. These practices can also influence soil chemical properties, making it important to consider human interventions when analyzing biomass production dynamics. Specifically, in our SE aspect plots, we observed a mature stand of *P. wallichiana*, which has slower growth rates compared to those of species grown in the northern aspect. This might explain the higher values of above-ground vegetation variables compared to the northern aspect. These differences are also likely influenced by variations in temperature and precipitation. Additionally, human interventions such as changing the light intensity and timing of illumination can also affect tree growth rates, as noted by [65].

Similar to our findings, ref. [66] reported that trees in the southern aspect had a significantly larger DBH than those in the northern aspect. This is likely due to the southern aspect receiving more solar radiation [67]. In our study area, which predominantly features pine trees, we observed increased tree diameters at higher altitudes, a pattern corroborated by [68] in their study on oak forests. We also found that the DBH and Ht were higher at elevated altitudes and in the SE aspect. These observations can be attributed to the availability of rich soil resources, reduced environmental stress, and decreased competition for light [69]. Nonetheless, physiological processes like photosynthesis and respiration can be limited by lower temperatures at high altitudes [70]. Leaf water stress, which can limit photosynthesis, can also increase due to gravity even when soil moisture is abundant [71,72]. Consistent with [73], we found that the AGTB and AGTC increased with altitude. This was due to mature and larger trees at higher elevations and in the SE aspect. Previous research indicates that above-ground biomass is influenced by factors like forest type, species composition, tree diameter, topography, and climate [17,74]. Contrary to some studies suggesting a decrease in above-ground biomass with increasing altitude [75,76], we did not observe such a trend. Regarding species-specific observations, *P. wallichiana* exhibited significantly higher values in terms of DBH, Ht, BA, AGTB, and AGTC than other species like *Schima wallichiana*, *Alnus nepalensis*, and *Grevillea robusta*. We observed a strong positive correlation between all above-ground variables and P levels ($p < 0.001$). Additionally, the DBH and Ht were positively correlated with soil pH ($p < 0.05$) (Table 6). We also found that the SOC and TN were higher in plots where the soil K levels were elevated, displaying a significant positive correlation. High levels of TN were also related to elevated K levels. On the other hand, the SOC and TN values were lower in the SE aspect, which had higher above-ground variables due to drier and warmer conditions. This led to a negative relationship between the SOC and TN with above-ground tree variables (Table 6). In summary, the vegetation type influences above-ground carbon dynamics by affecting soil chemical properties and other processes like soil respiration, carbon flux, and carbon fixation in deeper soil layers [11].

This study has limitations to consider. It primarily focuses on a specific region in the mid-hills of central Nepal, potentially limiting its generalizability. The relatively narrow altitudinal range studied might have contributed to the absence of significant altitudinal effects on soil properties. Additionally, it does not address below-ground biomass, and the influence of human interventions on biomass patterns needs further investigation. While insightful, these findings should be interpreted within these limitations, and future research should address these aspects for a more comprehensive understanding of the matter.

5. Conclusions

In this study, we found that both topographic aspects and soil depth considerably impacted soil chemical properties. Specifically, the SOC and TN were significantly higher in the NW aspect than in the SE aspect. Conversely, the available P and pH levels were notably higher in the SE aspects. These differences can primarily be attributed to microclimate variations influenced by the aspect. As for above-ground biomass, all observed variables were higher at increased altitudes and in the NW aspect. Interestingly, these prominent variations in above-ground vegetation did not correspond to equally significant changes in soil properties. This discrepancy suggests that additional factors—such as local human interventions, species composition, or growth rates—could be influencing the above-ground variables. We recommend additional research to explore these complexities in more detail, especially in various mountainous systems.

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