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Elevation Effects on Carbon Stock and Tree Species Diversity in Central Himalayan Community Forests, Nepal

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Abstract

Forest biomass and carbon management are central to climate change mitigation, particularly in countries where community forestry plays a major role. In Nepal, community forests cover more than 2.4 million ha and are increasingly linked to REDD+ initiatives, making it important to understand how carbon stocks and biodiversity vary across environmental gradients. This study assesses patterns of aboveground biomass, carbon stock, and tree species diversity along an elevational gradient (245–3,549 m a.s.l.) in the Charnawati and Kayarkhola watersheds of Nepal's central Himalayas. Data from permanent sample plots established in community forests were used to estimate tree biomass, carbon stocks, and species importance value index (IVI). The results indicate strong altitudinal variation in forest structure and composition. Aboveground biomass was highest at lower elevations (500–1,000 m a.s.l.), reaching 344.97 t ha^{-1}, whereas tree density peaked at mid-elevations (2,000–3,000 m a.s.l.) with up to 1,600 individuals ha^{-1}. Species dominance shifted from Shorea robusta at lower elevations to mixed Quercus–Rhododendron forests at mid-elevations and conifer-dominated stands at higher elevations. Regression analyses revealed elevation-specific relationships, with altitude positively influencing carbon stocks at low (<500 m a.s.l.) and high (2,000–3,000 m a.s.l.) elevations, while tree height showed a positive association with carbon stocks only at 1,000–2,000 m a.s.l. However, all models exhibited low explanatory power ($R^2 < 0.11$), indicating the influence of multiple interacting factors. Overall, the findings suggest that carbon–biodiversity relationships in community forests are not uniform but are mediated by elevation-specific ecological conditions. These insights highlight the need for elevation-sensitive REDD+ and forest management strategies to enhance both climate mitigation and biodiversity co-benefits.

Key Words:
Community forestry · Aboveground biomass · Carbon stock · Elevational gradient · REDD+

Introduction

Climate change is one of the most pressing global challenges, driven primarily by anthropogenic greenhouse gas (GHG) emissions. Forests play a critical role in climate change mitigation, as deforestation and forest degradation account for approximately 20% of global GHG emissions. Consequently, forest carbon finance has emerged as a central component of international mitigation strategies. Beyond carbon sequestration, forests also provide a range of ecological and social co-benefits, including biodiversity conservation, ecosystem services, and livelihood support. Recognizing these multiple functions, global initiatives such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation, and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks) emphasize an integrated approach in which forests are valued not only as carbon sinks but also as providers of broader environmental and social benefits.

Nepal is a forest-rich country, with forests and other wooded lands covering 44.74% of its total land area, of which 40.36% is classified as forest cover (DFRS 2015). Forest distribution varies markedly across physiographic regions: the Hill region contains the largest share of forest area, followed by the Mountain and Terai regions. Historical assessments indicate that Nepal experienced significant deforestation during the late twentieth century, particularly in the Terai and Siwaliks, driven mainly by resettlement programs, agricultural expansion, and illegal timber extraction (NFI 1999). In contrast, lower rates of deforestation in the Hills are widely attributed to the success of the community forestry (CF) programme, which has become the dominant forest management regime in the country. Although precise national estimates of CO_2 emissions from deforestation and forest degradation remain uncertain, earlier assessments suggest that the land-use sector has been a substantial source of emissions, underscoring the potential importance of forest-based mitigation initiatives such as REDD+ in Nepal.

Forests are deeply embedded in the livelihoods of Nepal's rural population, particularly in the Hill region, where community forestry provides timber, fuelwood, fodder, and other ecosystem services. Ecologically, Nepal is exceptional due to its pronounced altitudinal gradient, extending from lowland tropical forests to alpine ecosystems within a short latitudinal span. This gradient, among the steepest in the world (Grytnes and Vetaas 2002), combined with strong east–west climatic variation, supports high biodiversity, including 118 ecosystems, 75 vegetation types, and 35 forest types (Olson and Dinerstein 1998). Such environmental heterogeneity makes Nepal an important natural laboratory for examining how forest structure, biomass, carbon stocks, and species composition vary across elevation. Climate change is expected to further alter forest ecosystems through shifts in species distributions, changes in community composition, and modified ecosystem processes, with implications for both carbon dynamics and rural livelihoods.

Nepal has been an active participant in REDD+ since its early engagement with global initiatives such as the Forest Carbon Partnership Facility (FCPF) and the UN-REDD Programme. Progress has included the submission of a Forest Reference Level (FRL), the development of a National REDD+ Strategy (2025–2034), and access to results-based payments for verified emission reductions. A major milestone was the endorsement of Nepal's first bilateral Emission Reductions Purchase Agreement (ERPA) in 2023, which establishes a benefit-sharing mechanism to channel REDD+ payments directly to local communities managing forests. Parallel to these policy advances, Nepal has strengthened its national forest monitoring system through successive National Forest Inventories (NFI 2015; ongoing NFI-3), providing improved estimates of forest carbon stocks at the national scale.

Despite these advances, a key gap remains: locally detailed baseline information on forest carbon stocks and their relationships with biodiversity and forest structure across spatial gradients, particularly elevation. Such information is essential for refining national benchmarks, validating remote sensing products, and designing effective and equitable REDD+ interventions at sub-national and community levels. In particular, the interaction between tree species composition, biomass accumulation, and elevation in community-managed forests remains poorly understood in Nepal.

Community forests cover approximately 20% of Nepal’s total forest area and have demonstrated notable recovery and restoration, suggesting strong potential for long-term carbon sequestration. However, empirical data on aboveground biomass and its relationship with species diversity along elevational gradients in community forests are limited and often outdated. Management practices, species composition, and local microclimatic conditions strongly influence forest growth and carbon storage capacity, yet these factors have rarely been examined together in a spatially explicit framework.

Against this backdrop, the objectives of this study are to: (1) quantify the spatial distribution of aboveground biomass along an elevational gradient in community forests; (2) examine the relationship between biomass, tree species diversity, and species composition across elevation; and (3) assess the implications of these relationships for the design and implementation of REDD+ initiatives in Nepal. To our knowledge, this is the first study to explicitly investigate the combined effects of elevational gradients on forest structure, species composition, and aboveground biomass in Nepal’s community forests. By quantifying the three-dimensional structure of these forests across elevation, this study provides critical baseline information to support climate mitigation, biodiversity conservation, and evidence-based forest policy in Nepal.

Material and method

1 Study area

The present study was carried out in community forests (CFs) within the Charnawati (Dolakha district) and Kayarkhola (Chitwan district) watersheds, both located in Bagmati Province, Nepal (Figure 1). Physiographically, Kayarkhola spans the Siwalik and Hill regions, while Charnawati extends across the Hill and Mid-mountain regions. Basic information on the two watersheds is summarized in Table 1.

Table 1

Basic information of the watersheds (Source: REDD$^+$ Pilot Project 2013)

Watershed (district)	Altitudinal range (masl*)	Average temperature [0^o centigrade]	Latitude(N) and longitude(E)	Average annual rainfall [mm]	Total Watershed area [ha]	No of CFs** within watershed	Total area in CFs** [ha]	Total number of psp***
Kayarkhola (Chitwan)	245-1,944	16-19 (min), 29-32 (max)	27^0 40’07.79’’ 27^0 46’ 37.15’’ and 84^{0}33’25.88’’ 84^{0}41’ 48.85’'	1,436	8,002	15	2,381.96	180
Charnawati (Dolakha)	835-3,549	19.9 (max), 8.3(min)	27^0 35’16.12’’ 27^0 44’ 47.92’’ and 85^{0}56’18.41’’ 86^{0}03’ 56.92’’	1,972-2,000	14,037	58	5,996.17	183

Note: *meters above sea level, **Community Forests, ***permanent sample plots

Nepal Biodiversity Strategy (2002) identified five principal physiographic zones in Nepal, primarily based broad climatic variation. These principal physiographic zones have further been classified into six regions based on elevational ranges and further local level climatic variations. Summary of physiographic zone and their general spatial and bio-climatic information is provided in Table 2.

Table 2

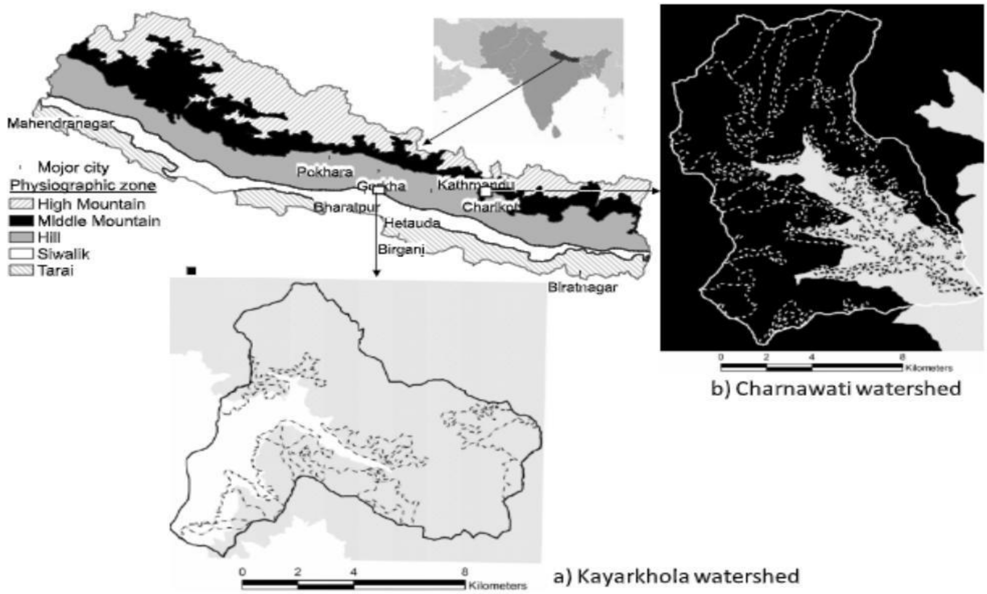
General spatial and bio-climatic information of physiographic regions of Nepal (italicized texts indicate information on the physiographic regions covered in this study)

Physiographic zone	Surface area (%)	Elevational range (m)	Climate	Floral and faunal diversity
High Himal	23	above 5,000	tundra-type & arctic	Harsh environmental conditions, a large number of endemic species
High Mountains	20	4,000-5,000 3,000-4,000	Alpine sub-alpine	
Mid-hills	30	2,000-3,000	cool temperate monsoon	Subtropical to temperate climatic zones comprising a rich flora and fauna, greatest diversity of ecosystems and species in Nepal
		1,000-2,000	warm temperate monsoon	
Lowlands (Terai & Siwalik Hills)	27	500-1,000	hot monsoon & subtropical	tropical deciduous riverine to tropical evergreen forest, mostly dominated by Sal (Shorea robusta) trees, internationally important both in terms of the number of globally threatened species and their diversity
		below 500	Hot monsoon & tropical	

Source: Nepal Biodiversity Strategy (2002)

Figure 1

Location of the study watersheds representing three different physiographic regions of Nepal. The dotted polygons within the watershed boundaries represent community forest (CF) areas, where the measurements were carried out in randomly distributed permanent sample plots.



b) Charnawati watershed

a) Kayarkhola watershed

2. Tree Vegetational analysis

This study was carried-out in series of randomly distributed permanent plots in community forests (CFs) of two watersheds in central and western development regions, representing Siwalik, Hill and Middle Mountain physiographic zones. To capture variation in tree biomass, circular permanent sample plots (each 250 m² with a radius of 8.92 m) were established across the study watersheds. These plots (30 in Charnawati and 50 in Kayerkhola) were distributed randomly on maps and established in the field. Within each plot, dbh and height were measured using diameter tape for diameter measurement and clinometers and linear tape or vertex –IV/transponder for height measurement and of trees with diameters at breast height (dbh) ≥ 5 cm and species were identified. All fieldwork was conducted between March and June 2020.

2.1 Tree biomass and carbon

Tree allometric equations developed by (Chave, 2005) were applied to mean dbh, height and wood specific gravity of each tree species to calculate the biomass stock of individual tree components. After taking the sum of the individual biomass weight (in Kg) of a sampling plot and dividing it by the area of a sampling plot (250 m^2), the biomass stock was attained in kg m^{-2}. This value was then converted to t ha^{-1} by multiplying it by 10. Since the project area are part of the tropical region, tree biomass stock was then converted into tree carbon stock after multiplying it with the default carbon fraction of 0.47 (IPCC , 2006).

2.2. Tree species diversity

We focused only on trees (≥5 cm dbh) to compare tree species diversity and tree carbon stock along the physiographic gradients. We quantified importance value indices (IVI) as suggested by Newton (2007). The importance value index, that combines frequency, density and dominance values, has been widely used to measure species composition (Mclaren et. al 2005, Pelissier 1996, Greig-Smith, 1957). The importance value index (I_j) was calculated using the following equation provided by Husch et al. (2003).

$$I_j = 100\left(\frac{n_j}{N} + \frac{d_j}{D} + \frac{x_j}{X}\right)$$

where n_j is the number of sampling units where j^{th} species is present (occurrence), N is the total number of sampling units, d_j is the number of individuals of the j^{th} species present in sample population (density), D is the total number of individual in sample population ($D = \sum d_j$), x_j is the sum of basal area for the j^{th} species (dominance), and X is the total basal area across all species ($X = \sum x_j$).

To compare tree species diversity, data were analysed with freely available R statistical software (R Development Core Team 2009) and its associated packages, particularly Biodiversity R (Kidt and Coe 2005).

Altitudinal variations in diversity of tree species are compared by species area accumulation curve and Renyi diversity profile. The Renyi diversity profile uses profiles to characterise richness (vertically) and evenness (horizontally) (Kindt 2006).

Results and Discussion

1. Stand characteristics

The tree density and basal area according to the altitudinal range in the study sites varied significantly and we found maximum tree density and basal area 4720 ind ha^{-1} at an altitudinal rage of 2000-3000 m a.s.l, and 121.97 m^{2} ha^{-1} at an altitude of 1000-2000 m.a.s.l respectively, while the minimum tree density and basal area was 120 ind ha^{-1} at an altitudional rage of 500-1000 m a.s.l, and 0.71 m^{2} ha^{-1} at the same altitudional gradient respectively (Table3). The elevation less then 500 shows the significant relation with tree density and basal area. The Importance value index value shows the decreasing pattern with increasing elevation, *Shorea robusta* (Sal) was the major dominant tree species up to the 1000 m elevation in terms of basal area and importance value index, where as *Rhododendron arboreum* (Guras) and *Schima wallichi* (chilaunae) were dominant species for the elevation above 1000 and upto 3000 m.a.s.l. (Figure 6).

Table 3

Summary statistics of key characteristics based on measurements of trees (≥5 cm dbh)

Elevation range (m a.s.l.*)	Tree density (No. ha^{-1})			Basal area (m^2 ha^{-1})			Biomass (t DM ha^{-1})		
	Min	Mean ± SE	Max	Min	Mean ± SE	Max	Min	Mean ± SE	Max
<500	240	1400.95 ± 92.05^{ab}	4160	2.12	28.08 ± 2.09^{a}	90.95	4.40	272.94 ± 27.42^{a}	1084.71
500-1000	120	829.40 ± 58.32^{c}	3000	0.71	31.16 ± 1.86^{ab}	79.53	1.20	344.97 ± 29.94^{a}	1056.53
1000-2000	80	1153.06 ± 87.64^{a}	4200	0.00	24.30 ± 1.81^{c}	121.97	0.00	138.54 ± 13.08^{b}	714.19
2000-3000	160	1600.40 ± 101.64^{b}	4720	3.04	36.04 ± 1.80^{b}	88.60	4.83	158.60 ± 11.66^{b}	508.39

*m a.s.l. = meter above sea level,

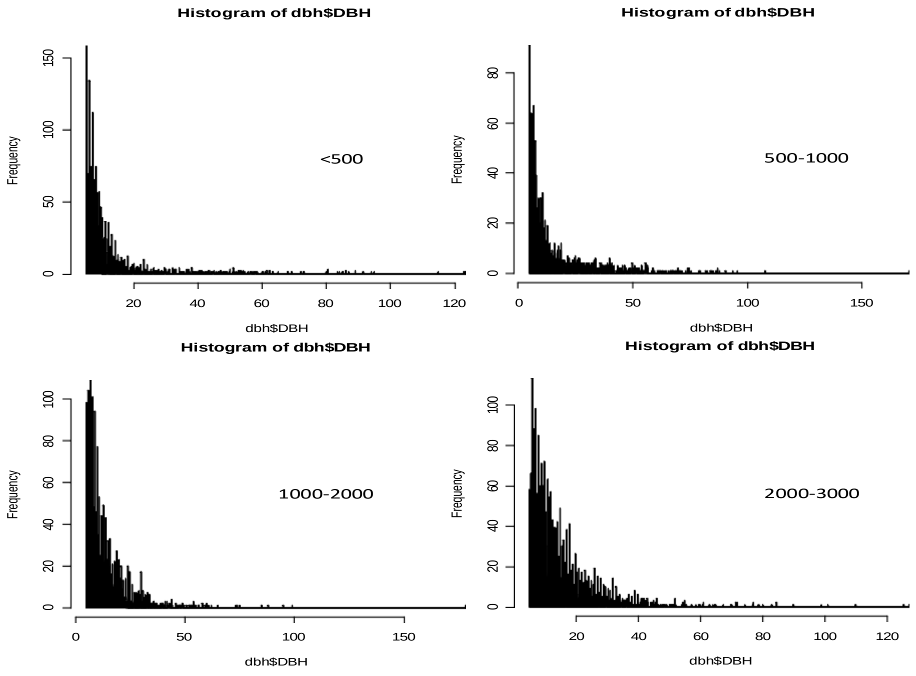
Different superscript letters in mean value indicate significant differences in parameters between the altitudinal gradient computed by Welch Two Sample t-test ($p = <0.05$).

2. Size class distribution of trees

The size class distribution figures are different for different altitudinal gradient i.e the frequency of the occurrence of younger size class trees increased with increasing the elevation and there was a reverse trend with decreasing the elevational gradient. The typical reversed J-shaped curve was observed which is good for the regeneration pint of view in the study sites (Figure 2).

Figure 2

Diameter class distribution of all measured trees (≥5 cm dbh)

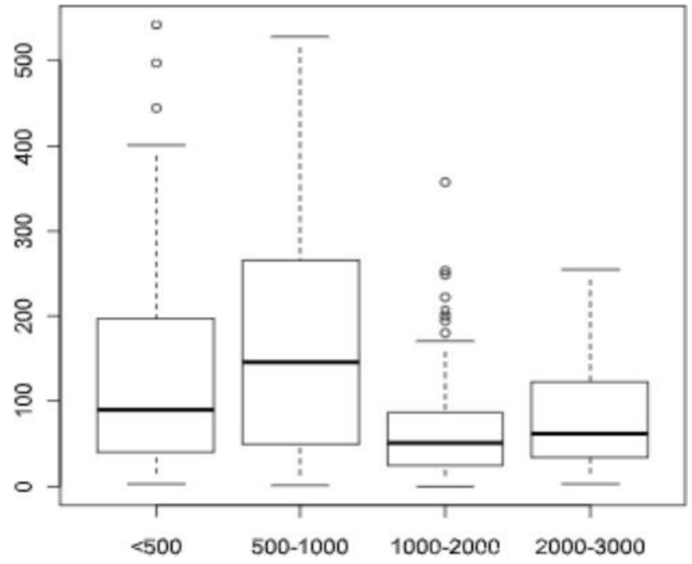


3. Tree biomass and tree carbon stock

The total tree biomass among the study sites varied significantly with varying elevational gradient, the total tree biomass ranged between 508.39 and 1084.71 t ha^{-1} the tree biomass values were found significant with in the altitudinal range less then 500 and 500-1000 m.a.s.l also it was significant among the elevational gradient of 1000-2000 and 2000-3000 m.a.s.l (Table 3). On the other hand the carbon stock varied between 238.94 and 509.81 t c ha^{-1} among all elevational gradient (Figure 3).

Figure 3

Summary of above ground carbon stock of trees (≥5 cm dbh) in the physiographic regions



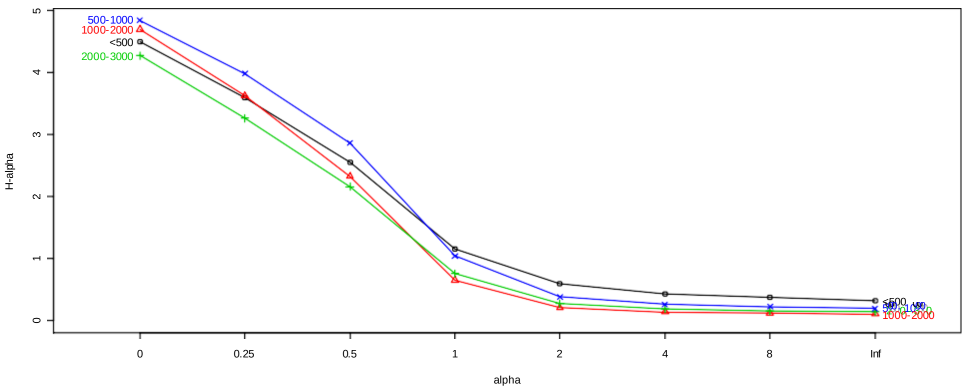
4. Tree species diversity

Species diversity varies along elevation gradients, but not necessarily in the same way. There is a significant monotonically decreasing trend in total species richness from 1000-200 m to 2000-3000 m a.s.l. at <500 m a.s.l., there was a clear and gentle increase in tree species diversity (Figure 4). We got only one significant value for the elevation and tree species diversity (P=0.8699) for the elevation < 500 m.a.s.l. as presented in (Table4).

In this study we found that the tree species diversity decreased or changed according to the elevational gradient**,** the tree species diversity decreased with increasing elevational range **.**

Figure 4

Comparison of diversity profiles of trees (≥5 cm dbh) in the three physiographic regions based on the Rényi series H_α

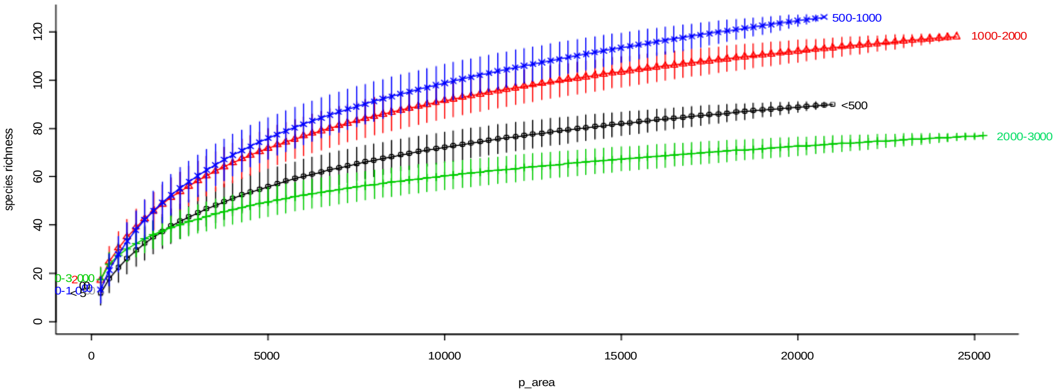


5. Species area curve

We estimated species–area curves based on species richness calculated from all possible combinations of quadrats (Figure 5). The species-area curve has been used to link the biological with the geographical. Larger areas of land would seem to contain more species as a result of both the effect of sampling (i.e. more samples are taken to represent larger areas) and ecological processes (i.e. island biogeography theory and hypotheses relating to habitat diversity, successional development, species-energy, target-area, incidence function, small island habitat and disturbance).

Figure 5

Species area curve (±2 SD) comparing accumulation of species in the physiographic regions (rarefaction was used as accumulation method)



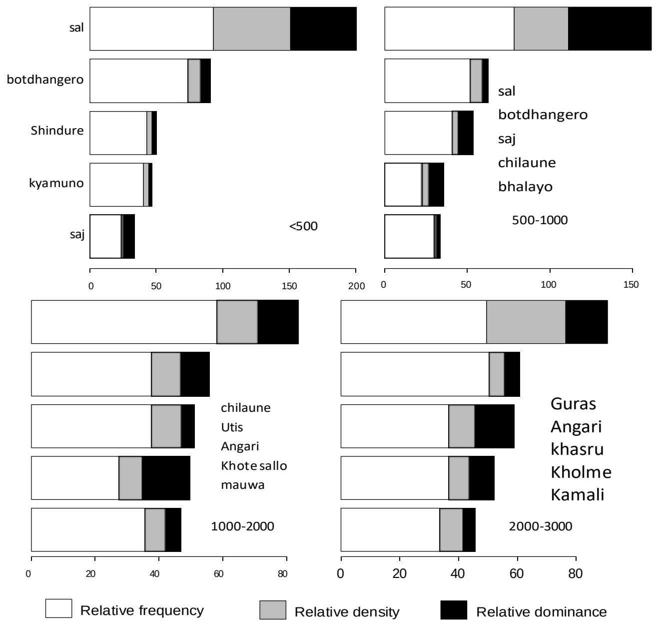
6. Species importance value index

We calculated the tree Importance Value Index (IVI) across elevational ranges in two watersheds in the central Himalayas and it reveals a distinct ecological stratification shaped by temperature, moisture, and biotic interactions. At lower elevations (below 1,000 m), warm and humid conditions favors broadleaf species such as Sal (*Shorea robusta*), which exhibit high IVI scores due to their dominance in density, frequency, and basal area. As elevation increases to the mid-zones (1,000–2,000 m), a transitional mixed forest emerges where species like oaks and pines peak in IVI, reflecting optimal growing conditions and niche partitioning that support high biodiversity. Beyond 2,000 m, conifers such as Fir and spruce dominate, though overall IVI may decline due to harsher climates, yet certain temperate species like *Rhododendron* maintain strong ecological importance in structuring alpine scrub and timberline communities (Figure 6).

This gradient is not merely a botanical pattern but a functional response to environmental filters species with high IVI in each zone play keystone roles in maintaining ecosystem stability, nutrient cycling, and habitat provision. Comparing zones, lower elevations show greater species dominance by a few robust taxa, mid-elevations display balanced species packing with overlapping IVIs, and higher elevations demonstrate ecological filtering where only stress-tolerant species persist. Such IVI profiles are vital for conservation planning, as they identify priority species that define forest integrity at each altitude. Furthermore, under climate change, this elevational IVI distribution serves as a baseline to predict upward shifts in species dominance, potential invasions, and biome transitions. In essence, the IVI-elevation relationship encapsulates the Himalayan forests' adaptive architecture, offering insights for sustainable management, climate resilience, and biodiversity preservation across one of the world's most critical and vulnerable montane ecosystems.

Figure 6

Species area curve comparing accumulation of trees (≥5 cm dbh) species in the physiographic regions



7. Relationship between tree species diversity, carbon stock and elevation

The relationships between species diversity, biomass and carbon stocks at varied altitudes can have crucial implications for the management and conservation of C sinks. This table reveals distinct and elevation-dependent relationships between altitude, forest height, and carbon stock across the Himalayan gradient. At the lowest elevations (<500 m), altitude has a significant positive relationship with carbon stock (p=0.002), though it explains only 11% of the variation, indicating a subtle increase in carbon with altitude in these tropical-to-subtropical forests, while forest height shows no meaningful link to carbon. In the mid-elevation belt (500–1000 m), the relationship flips, with altitude showing a significant negative correlation with forest height (p=0.016), suggesting a gradual structural change, but no link to carbon stock remains. The most ecologically telling zone is 1000–2000 m, where forest height and carbon stock show a marginally significant positive relationship (p=0.054) the strongest in the gradient implying that tree height becomes a better predictor of carbon in these temperate forests, whereas the altitude-carbon link turns weakly negative. Finally, in the high mountains (2000–3000 m), a significant but very weak positive altitude-carbon relationship re-emerges (p=0.030), possibly reflecting alpine conifer dominance, while the height-carbon slope turns negative, indicating a structural decoupling likely due to environmental stress and different tree allometry. Critically, all models exhibit very low explanatory power ($R^2 < 0.11$), underscoring that single-factor linear relationships are inadequate; carbon stock is governed by complex interactions of species composition, climate, and disturbance across elevations. This layered analysis confirms that ecological drivers of forest carbon are not constant but shift fundamentally across the elevational spectrum, with mid-elevations showing the strongest structural control and both low and high zones being more influenced by altitude-related environmental filters.

Table 4

Regression analysis between tree species diversity, carbon stock and elevation.

		H~CStock	**Alti~CStock**	**Alti~H**
<500		y = 0.016x + 0.844	y = 0.017x - 3.614	y = -0.000x + 0.949
	R^2	0.01728	0.1092	0.0003293
	R^2Adj.	0.005292	0.09829	-0.01186
	P	0.2333	**0.002145**	0.8699
500-1000		y = 0.011x + 0.789	y = 0.000x + 3.899	y = -0.000x + 1.459
	R^2	0.007607	0.0005733	0.06947
	R^2Adj.	-0.004645	-0.01177	0.05798
	P	0.433	0.8299	0.01606
1000-2000		y = 0.046x + 0.417	y = -0.001x + 3.382	y = -0.000x + 0.785
	R^2	0.03859	0.03288	0.01807
	R^2Adj.	0.02847	0.0227	0.007737
	P	0.05379	0.0755	0.1892
3000		y = -0.017x + 0.550	y = 0.001x - 0.732	y = 0.000x + 0.198
	R	0.0114	0.04015	0.01969
	R^2Adj.	0.001417	0.03046	0.009787
	P	0.2879	0.03046	0.1616

r^2 and adjusted r^2 refer to linear -linear regression models. Relationship with $p < 0.05$ is printed in bold.

Discussions

Carbon management in forest is, one of the most important agenda of the 21st century in context of greenhouse gases effects and mitigation of global climate changes. Site specific carbon estimates depends on stand composition, age, site quality, elevation gradient and the management practices. Forest species composition have been received considerable attention as a forest restoration strategy.

The findings of this study elucidate the complex and non-linear relationships between elevation, forest structure, carbon stocks, and biodiversity in Nepal’s community forests, offering critical insights for forest management and climate policy. The observed peak in aboveground carbon stocks at lower elevations (<1000 masl) aligns with the high productivity of tropical and subtropical forests dominated by Shorea robusta, a species with substantial wood density and basal area (Chave et al., 2014). This dominance is reflected in the high IVI values for S. robusta in this zone, confirming its role as a keystone carbon steward. Conversely, the highest tree density in the 2000–3000 masl range, coupled with lower biomass, indicates a stand structure characterized by smaller, stress-adapted species a typical pattern in high-elevation temperate and subalpine forests where environmental harshness limits individual tree size but not necessarily stem count (Singh et al., 1994). This analysis of community forests across Nepal's central Himalayan elevation gradient reveals a fundamental ecological trade-off shaped by climate, species traits, and management history. While tree density significantly increases with elevation—peaking at 1,600 stems ha^{-1} in the 2,000–3,000 m zone due to stress-adapted, smaller trees—aboveground biomass shows an inverse and dramatic decline, falling by over 50% from the productive lowlands (<1,000 m; 273–345 t ha^{-1}) to the higher zones.

The shift in species composition along the gradient, from S. robusta dominance to mixed broadleaf-conifer stands and finally to Rhododendron and conifer dominance, mirrors well-documented biome transitions driven by decreasing temperature and changing moisture regimes (Grytnes & Vetaas, 2002). The IVI profiles provide a quantitative fingerprint of these transitions, showing how ecological dominance shifts from a few competitive species at lower elevations to a more filtered suite of stress-tolerant specialists at higher altitudes. This sharp gradient underscores that carbon storage is overwhelmingly concentrated in lower-elevation forests, particularly those dominated by high wood-density Shorea robusta. A distinctive and critical finding is the significant mid-elevation (1,000–2,000 m) biomass dip, which contrasts with the unimodal patterns often reported in less-disturbed regions. This pattern is best explained by a legacy of higher anthropogenic pressure in these accessible zones, potentially keeping forests in a lower-biomass, successional state. The results validate that drivers of forest carbon are not uniform but are mediated by elevation-specific ecological filters and human influence. Consequently, effective REDD+ and forest management policies must adopt a stratified approach: prioritizing conservation of high-carbon Sal forests in the lowlands, enhancing restoration and structural complexity in the utilized mid-hills, and preserving the high-density, high-elevation forests for their biodiversity and watershed services.

Our data show that these mid-elevation forests, while having moderate carbon stocks, host the most balanced species packing and the strongest positive relationship between forest height and carbon. This suggests that structural complexity, rather than mere tree density, is a key carbon driver here, supporting theories that niche partitioning in diverse stands enhances total ecosystem carbon capture (Liang et al., 2016).

The regression analysis reveals the context-dependency of carbon drivers. The significant but weak positive relationship between altitude and carbon at the highest and lowest elevations suggests that broad-scale environmental gradients (temperature, precipitation) set the potential carbon ceiling, but within-zone variation is governed by other factors. The lack of a strong, consistent relationship between forest height (a proxy for structure) and carbon across all zones, except the mid-elevation belt, is particularly telling. It implies that allometric relationships and wood density vary significantly among the functional types that dominate different elevations (e.g., light-wooded pioneers at high elevations vs. dense-wooded climax species at low elevations). This decoupling challenges the use of simple, universal predictive models for carbon estimation in topographically complex regions like the Himalayas.

The low R^2 values across all regression models are a crucial result. They strongly indicate that single-factor explanations are insufficient. Carbon stock at any given point is likely the product of a complex interaction between historical disturbance (e.g., community forestry practices), edaphic factors, microclimate, species functional traits, and current stand age. This complexity is both a challenge and an opportunity for REDD+. It is a challenge because simplistic, plot-scale carbon measurement may not capture the true drivers of long-term carbon stability. It is an opportunity because it argues for a holistic, landscape-scale approach to REDD+ planning that secures co-benefits like biodiversity and watershed protection, which may themselves enhance resilience and long-term carbon storage (Pandey et al., 2014).

Our study has limitations. The snapshot data from permanent plots cannot capture temporal dynamics or successional changes. Soil carbon, a major component of forest carbon sinks, was not included. Furthermore, the study watersheds, while representative, do not capture the full east-west biogeographic variation within Nepal. Future research should prioritize long-term monitoring of these plots to track changes under climate change, integrate soil carbon assessments, and employ multivariate modeling (e.g., structural equation modeling) to disentangle the relative weights of different drivers—climate, soil, diversity, and management—on carbon stocks across elevations.

In conclusion, this discussion affirms that the carbon-biodiversity nexus in the Himalayas is elevation-contextual. Effective REDD+ implementation in Nepal must therefore move beyond a one-size-fits-all approach. Policy should incentivize management that protects high-carbon, low-diversity Sal forests in the Terai, promotes structurally complex mixed forests in the mid-hills, and conserves the high-altitude forests for their unique biodiversity and role in securing alpine water towers. By embedding this elevational stratification into its forest carbon strategy, Nepal can pioneer a model for REDD+ that genuinely balances climate mitigation with the conservation of its unparalleled biodiversity.

Conclusions

This study provides a comprehensive, elevation-stratified analysis of aboveground carbon stocks and tree species diversity in the community forests of Nepal’s central Himalayas, offering critical baseline data for climate change mitigation and forest policy. The key findings demonstrate that both carbon storage and biodiversity patterns are fundamentally shaped by the elevational gradient. Carbon stocks are highest in the lowland forests (<1000 masl) dominated by Shorea robusta, while tree density peaks in the high-elevation (2000-3000 masl) stands of smaller, stress-tolerant species. The Importance Value Index (IVI) analysis clearly tracks the transition in ecological dominance from moisture-loving broadleaf species in the lowlands to mixed assemblages in the mid-hills and finally to cold-adapted conifers and Rhododendron at higher altitudes.

Critically, the relationships between key variables—altitude, forest height, and carbon stock are not constant but shift across elevation zones. Statistical models reveal significant yet weak elevation-carbon links at the extremes of the gradient, and a significant structure-carbon relationship only in the mid-elevation temperate forests. The consistently low explanatory power ($R^2 < 0.11$) of these linear models underscores a central conclusion: forest carbon dynamics in this complex landscape cannot be predicted by altitude or structure alone. They are the emergent property of intricate interactions involving species composition, historical management, microclimate, and edaphic factors.

The implications for Nepal’s REDD+ and forest management agenda are profound. A uniform national strategy would be ineffective. Instead, policies must be differentiated by physiographic zone: promoting conservation and sustainable management of high-carbon Sal forests in the lowlands, enhancing structural complexity and diversity in the bio-culturally rich mid-hills, and preserving the integrity of high-mountain forests for their biodiversity and watershed services. This stratified approach ensures that the pursuit of carbon finance through REDD+ synergistically strengthens biodiversity conservation, ecosystem resilience, and local livelihoods. Ultimately, this research affirms that protecting the Himalayan forest continuum, with all its elevational complexity, is indispensable for securing Nepal’s climate future and preserving its unique natural biodiversity hotspots.

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