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Forest-Type Variation in Vegetation Structure and Tree Carbon Stocks in the Mid-Hill Forests of Central Nepal Himalaya

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Abstract

Forest ecosystems are major contributors to climate change mitigation and the provision of ecosystem services. In this study, we assessed plant diversity and carbon stocks across different forest types in a middle mountain region of Lalitpur district of Nepal. Stratified purposive vegetation sampling was used for data collection. The results revealed that different vascular plant species diversity varies with forest type and structure. Herbaceous plant diversity was highest followed by tree and shrubs. The *Quercus* forest exhibited a higher carbon stock of 118.06 t/ha, suggesting strong carbon storage potential, whereas the *Alnus* forest had the lowest carbon stock (30.25 t/ha), indicating limited carbon storage capacity. It is concluded that *Quercus* forests are the most effective for carbon storage and climate change mitigation, whereas broadleaf mixed forests have high ecological significance by supporting rich biodiversity and providing considerable carbon storage potential. Based on these findings, forest management and conservation strategies are essential for the restoration and conservation of ecologically sensitive forest ecosystems in the middle mountains of the Nepal Himalaya.

Keywords: *Biodiversity conservation, climate change, community forest, forest restoration, plant invasion*

Introduction

Forests are globally important terrestrial ecosystems for biodiversity conservation and carbon storage but their proper study and measurements are still lacking (Dixon et al., 1994; Schimel et al., 2001). Measurements of forest components, including species composition, diversity, basal area, tree density, stem height, stem diameter, and age-class and geographic distribution patterns, can all be used to describe the "structure" of a forest (Smith, 1992; Sharma et al., 2020b). Forest vegetation has been a significant focus of ecological studies aimed at exploring the relationships and interactions between different vegetation types and their natural environments. Such understanding aids informed decision-making for the conservation and management of natural resources (Lynam et al., 2007; Paudel et al., 2011).

Several studies (Paudyal et al., 2015; Sharma et al., 2020a; Pandey, 2021) have documented forest carbon stocks and species diversity in Nepal, particularly in mid-hill forests and Himalayan regions. These studies consistently show that both carbon storage and species diversity vary across forest types and along elevational gradients, driven by changes in species composition, forest structure, and environmental conditions. In Nepal, such patterns are further influenced by forest management regimes, especially community forests, which play an important role in conserving biodiversity, enhancing forest regeneration, and maintaining ecosystem services through local stewardship.

Community forests provide a wide range of ecosystem services, including the supply of firewood and fresh water, water regulation, soil protection, landscape beauty, biodiversity conservation and carbon sequestration (Paudyal et al., 2015). Carbon absorbed by plants is primarily converted and stored as biomass through natural physiological processes (Jindal et al., 2008). Unlike many agricultural crops, woody vegetation has a much greater capacity to store carbon over long periods, ranging from decades to centuries.

Consequently, forest ecosystems act as major carbon sinks, storing approximately 20 to 100 times more carbon per unit area than agricultural lands (Dixon et al., 1994; Paudyal et al., 2015; Singh et al., 2025).

In the context of Nepal, relatively little is known about carbon stocks in *Alnus* forests. Moreover, no comparative multi-forest-type study integrating importance value index (IVI), carbon stock, and biodiversity has been conducted in Mahankal Rural Municipality of Lalitpur District. This research gap is addressed through a comparison of forest structure, species composition (tree, shrub, and herb layers), and carbon stock across three forest types (*Alnus* forest, broadleaf mixed forest, and *Quercus* forest) occurring at different elevations in Mahankal Rural Municipality, Lalitpur District of Central Nepal. Therefore, this study aimed to compare and assess the ecosystem characteristics of different forest types across an elevational gradient in central Nepal.

Materials and Methods

Study area

The study was carried out in Mahankal rural municipality, the southern part of Lalitpur district. It extends from 85.3333^0 to 85.4333^0 East and 27.4167^0 to 27.5833^0 North (Figure 1). Elevation range of study area is 1433m to 2353m. The climatic condition of the study site is warm temperate to cool temperate climate. The average annual temperature range of study site is 10^0C to 20^0C and annual rainfall is about 1400 mm (https://www.dhm.gov.np/). The study site encompasses the community forest of Mahankal Rural Municipality, covering approximately 500 ha of forest land distributed across the three major forest types: *Alnus* forest (approximately 80 ha), broadleaf mixed forest (approximately 270 ha) and *Quercus* forest (approximately 150 ha).

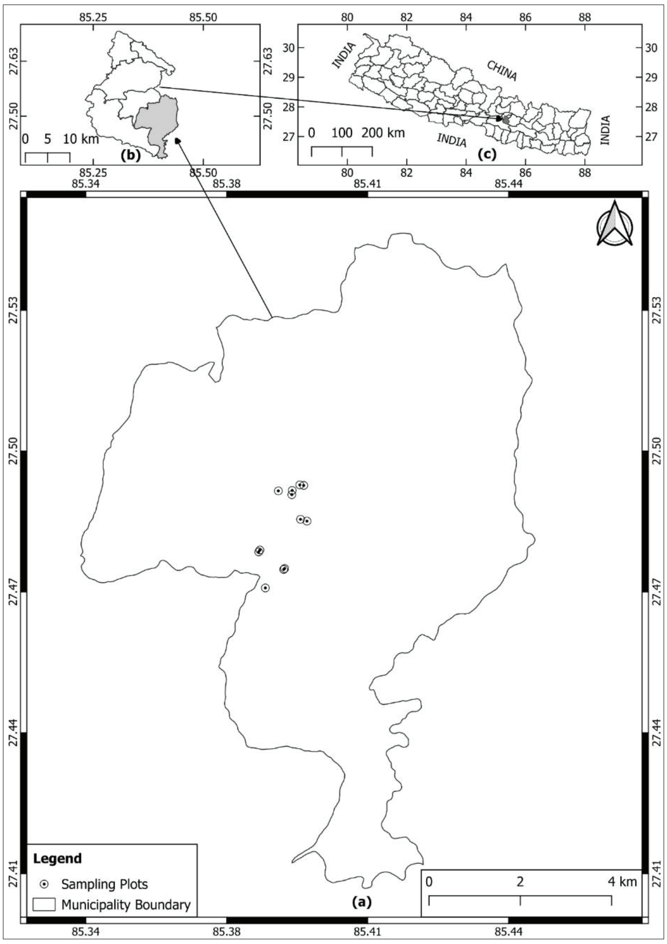

Figure 1: Study area map showing the sample plots in Mahakal rural municipality Lalitpur Nepal (a), Lalitpur district with local bodies (b), District map of Nepal (c).

Table 1: Characteristics of the study sites, forests and vegetation sample plots

SN	Forest type	Plot no.	Latitude (˚N)	Longitude (˚E)	Slope (˚)	Altitude (m)	Aspect (˚)	Litter Depth (cm)	Canopy (%)
1	*Alnus* forest	1	27.49249	85.39119	29	1433	266	6.0	84
		2	27.49237	85.39207	5.0	1506	73	1.2	93
		3	27.49033	85.38943	39	1474	296	0.8	63
2	Broadleaf mixed forest	4	27.47395	85.38784	40	1529	142	4.0	90
		5	27.48486	85.39136	34	1779	94	4.5	90
		6	27.49126	85.38951	38	1463	150	8.0	86
		7	27.47373	85.38763	49	1930	78	4.1	93
3	*Quercus* forest	8	27.47763	85.38209	43	2206	58	5.0	84
		9	27.46963	85.38356	45	2301	254	6.0	91
		10	27.47804	85.38235	37	2062	321	2.5	94
		11	27.49116	85.38644	54	2353	61	1.2	93
		12	27.48445	85.39279	54	2052	181	3.9	95

Sampling Methods

A stratified purposive sampling design was used, with plots placed in representative, structurally intact (dense) patches of each forest type to capture characteristic species assemblages across the elevational gradient (Tylor et al., 1993; Sharma et al., 2020a). A total of 60 plots were established, 36 plots for herbs and seedlings, 12 plots for shrubs and samplings and 12 plots for trees. Sub-plots were created for shrub and sapling as well as herbs and seedlings inside the main tree plot. The number of plots were maintained at a minimum of three per forest stand but differed among forest types because sampling intensity was adjusted according to within-stand heterogeneity and patch size. Relatively homogeneous and spatially limited *Alnus* forest patches required fewer plots, as their structural and compositional variability was low. In contrast, *Quercus* forest and broadleaf mixed forest exhibited higher structural and compositional heterogeneity, requiring a greater number of plots to adequately capture their variability and ensure representative sampling. Therefore, three main plots in *Alnus* forest, four main plots in *Quercus* forest and five main plots in broadleaf mixed forest were established. Plots were selected to represent the range of elevations, slopes, and aspects present within each forest type (Table 1). For tree species, a main plot measuring 20 m × 20 m was established using a rectangular quadrat and marked with ribbons, measuring tape and rope. The vegetation data, including diameter at breast height (DBH) and height of each tree within this area, were measured and recorded.

For shrubs and saplings, a sub-quadrat measuring 5m×5m was used. Saplings were recorded based on a DBH of less than 5 cm and greater than 1 cm, while shrubs were defined as individuals with several main stems arising at or near the ground, with stem diameter measured at height 10 cm above the soil surface. Additionally, three subplots measuring 1m×1m were designated for sampling seedlings, herbs, including pteridophytes. Seedlings were counted and recorded if they had a DBH of less than 1 cm. Herb cover was estimated visually as a percentage. Tree canopy measurements were taken using a densitometer at the four corners and the center of each plot. Mean canopy cover was calculated based on these observations. Shrub and tree cover were also measured in terms of basal area. All relevant information on trees, shrubs, saplings, herbs, and seedlings, including species names, diameter, heights, slopes and cover, was recorded from each sampling plot.

Vegetation data analysis

The recorded data were used to calculate frequency, density, basal area, and importance value index (IVI) of plant species using the following formulae (Curtis & McIntosh, 1951; Zobel et al., 1987; Singh et al., 2014):

$$\text{Frequency (F)} = \frac{\text{No. of plot in which species occurred}}{\text{Total number of plot examined}} \times 100\%$$

$$\text{Relative Frequency (RF)} = \frac{\text{Frequency of individual species}}{\text{Total frequency of all species}} \times 100\%$$

$$\text{Density (stem/ha)} = \frac{\text{Total number of individual of species in all plot}}{\text{Total number of sample plot x size of plot}} \times 10000$$

$$\text{Relative Density (RD)} = \frac{\text{Density of the individual species}}{\text{Total density of all species}} \times 100\%$$

$$\text{Herb Coverage (\%)} = \frac{\text{Area covered by a species within the quadrat} \times 100}{\text{Total area of the quadrat}}$$

$$\text{Relative Coverage (\%)} = \frac{\text{Coverage of individual species}}{\text{Total coverage of all species}} \times 100\%$$

$$\text{Basal Area (BA)} = \frac{\pi D^2}{4}$$

Where,

d = DBH (diameter at breast height)

$$\text{Basal area of a species (per ha)} = \frac{\text{Total basal area of a species in all plots}}{\text{Size of the plot (m}^2\text{)} \times \text{no. of plots}} \times 10000$$

$$\text{Relative Basal Area (RBA)} = \frac{\text{Basal area of individual species}}{\text{Total basal area of all species}} \times 100\%$$

Importance Value Index (IVI) = RF +RD + RBA

Note: Range of IVI is 0 to 300.

Biomass and Carbon Stock Estimation

The biomass and carbon stock estimation were done using the allometric models developed by Chave et al. (2005) for moist forest with rainfall 1500 mm to 4000 mm, and the wood density of trees were taken from ICRAF database (http://db.worldagroforestry.org/).

To calculate aboveground biomass (AGB) = ($0.0509 \times \rho D^2 H$) kg was used. Where, ρ = specific wood density, d = diameter (cm) and H = height of plant (m).

Similarly, Below Ground Tree biomass (BGTB) was calculated considering 25% of the above ground tree biomass. Aboveground carbon (AGC) and belowground carbon (BGC) were determined by multiplying the biomass by 0.47 and total carbon stock was calculated as (Mac Dicken, 1997):

Total Carbon Stock (Kg) = AGC + BGC

Collected and calculated data were organized and managed using spreadsheets. Descriptive statistical methods were applied to summarize and compare key forest vegetation parameters. The results were presented through bar graphs, scatter plots, tables, and pie charts to interpret and visual comparison of vegetation characteristics among forests.

Results and Discussion

Forest Structure and Composition

A total of 80 herb and seedling species, 23 tree species as well as 27 shrub and sapling species were recorded in the study forests (Figure 2). The tree layer included ecologically important taxa such as *Quercus, Castanopsis, Schima, Rhododendron*, and *Symplocos*. In the shrub layer, dominant taxa were *Rubus, Symplocos*, and *Rhododendron*. Similarly, in the herb layer, taxa such as *Bidens*, *Strobilanthes* and *Ageratina* were dominant (Figure 3, 4 &5). These results are comparable with the findings (Pandey, 2007; Baral & Katzensteiner, 2009; Joshi et al., 2023).

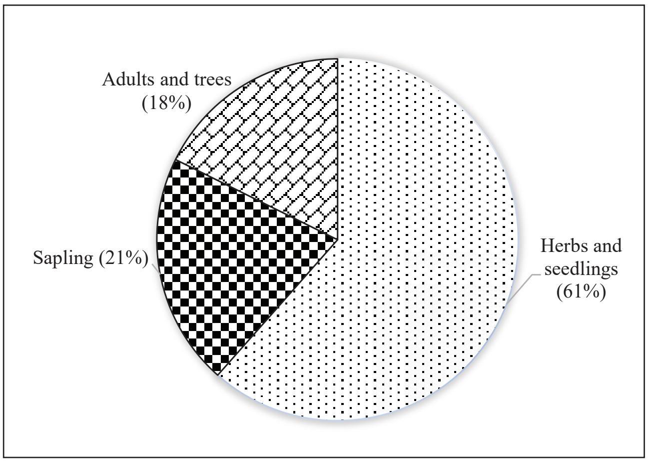

Figure 2. Number and percentage contribution of species in each life form in the study forests

Herb and Seedling Layer

The herb and seedling layer was highly diverse, comprising 80 species in total (Figure 2), indicating rich understory diversity and favorable microhabitats. In *Alnus* forest, 27 herbaceous species were recorded, with *Persicaria capitata* (IVI 54.60) and *Bidens pilosa* (IVI 53.23) as the most dominant species (Figure 3a). Their dominance highlights their importance in understory structure and ecological functioning. This pattern is consistent with previous studies showing that *B. pilosa* is common in disturbed habitats and acts as a pioneer species contributing to soil stabilization (Yu & Sun, 2013). In broadleaf mixed forest, 54 herb species were recorded, with *Strobilanthes* sp. (IVI 31.50) as the most dominant species, followed by *Onychium* sp. (IVI 29.57) and *Impatiens* sp. (IVI 25.50), whereas *Ageratina adenophora* and *Oplismenus* sp. showed moderate dominance and *Achyranthes aspera* and *Fagopyrum* sp. were least dominant (Figure 3b). Two unidentified species also contributed 20 and 36 individuals, indicating gaps in species identification. In *Quercus* forest, *Strobilanthes* sp. remained dominant (IVI 27.32), followed by *Impatiens* sp. (IVI 19.76), *Pilea* sp. (IVI 18.56), and *A. adenophora* (IVI 11.28), while *Hedera nepalensis* (IVI 2.08) and *Phyllanthus* sp. (IVI 1.32) had low ecological importance (Figure 3c). Overall, the dominance of pioneer and shade-tolerant species suggests that the understory communities are influenced by canopy conditions and disturbance history and the findings are comparable with the findings (Sharma et al., 2020a; Joshi et al., 2023).

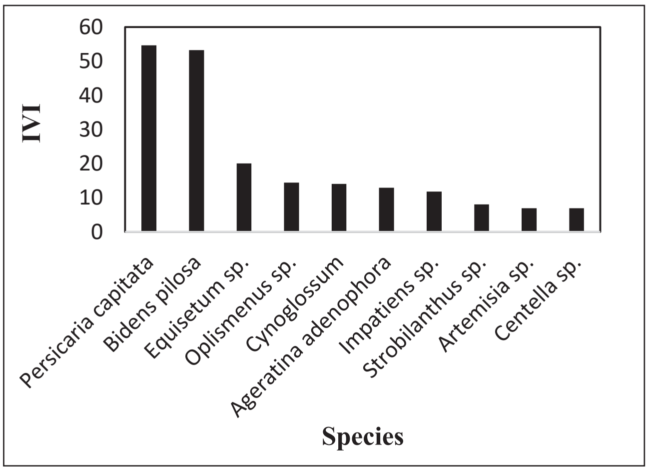

Figure 3a: IVI value of top 10 herbs and seedling species of *Alnus* forest

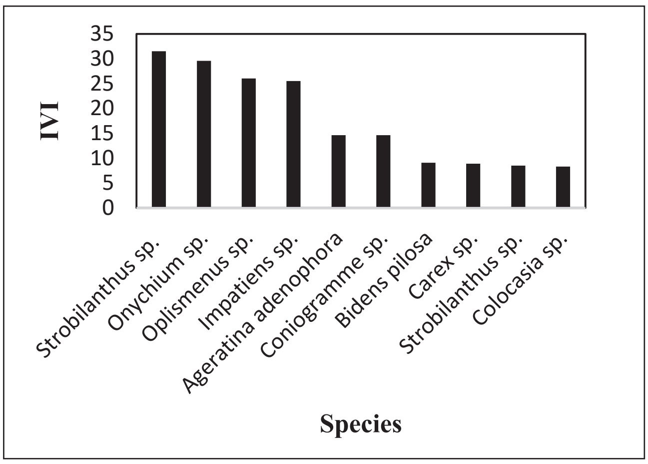

Figure 3b: IVI value of top 10 herbs and seedling species of broadleaf mixed forest

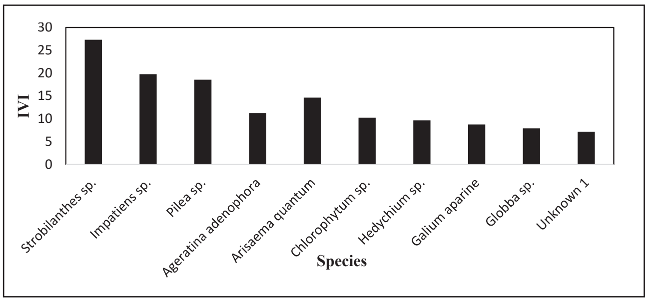

Figure 3c: IVI of herbs to 10 herbs and seedling of *Quercus* dominated forest

Shrub and Sapling Layer

The shrub and sapling layer comprised 27 species, reflecting active regeneration and structural complexity within the forests. In broadleaf mixed forest, *Pyrus pashia* (IVI 26.52) and *Schima wallichii* (IVI 24.76) were the dominant species, followed by *Syzygium cumini* (IVI 22.13) and *Alnus nepalensis* (IVI 10.57) (Figure 4a). In *Quercus* forest, *Litsea* sp. showed the highest dominance (IVI 71.10), followed by *Callicarpa arborea* (IVI 67.17) and *Eurya acuminata* (IVI 33.98), whereas *Rhododendron arboreum* and *Wikstroemia* sp. exhibited moderate importance (IVI 13.80 and 9.62) (Figure 4b). In *Alnus* forest, only five shrub species were recorded, with *Rubus ellipticus* (IVI 80.47) being consistently dominant, followed by *Koenigia mollis* (IVI 57.89) and *E. acuminata* (IVI 57.45) (Figure 4c). The dominance of *R. ellipticus*

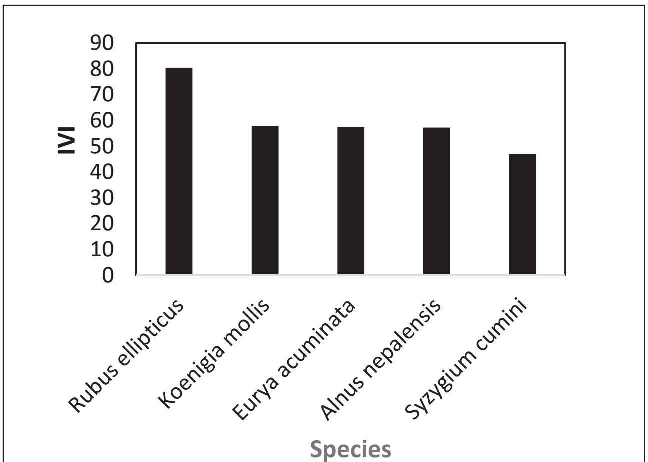

Figure 4a: IVI value of top five shrubs and sapling species of *Alnus* forest

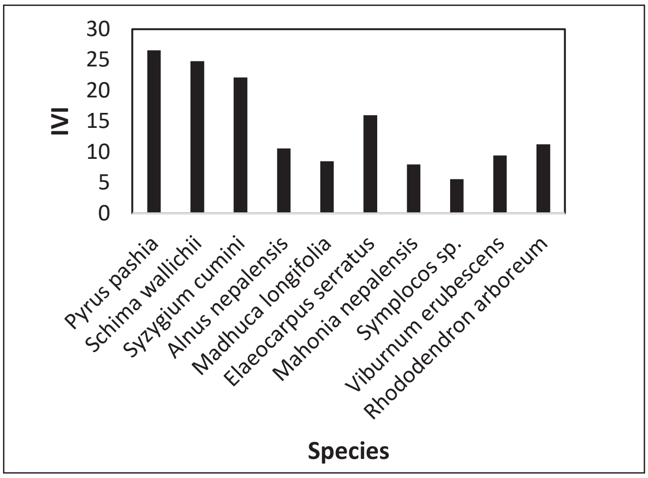

Figure 4b: IVI value of top 10 shrubs and sapling species of broadleaf mixed forest

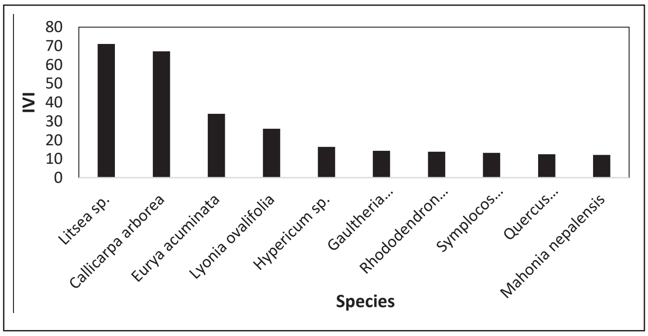

Figure 4c: IVI of top 10 shrub and sapling of *Quercus* forest

in disturbed and regenerating stands comply with previous reports highlighting its importance in maintaining forest biodiversity (Yu & Sun, 2013; Sharma et al., 2020a). Moreover, the occurrence of *E. acuminata* in both tree and shrub layers indicates high successional dynamics and shade tolerance for natural regeneration.

Tree Layer

The tree layer exhibited distinct compositional patterns among forest types. In *Alnus* forest, *Alnus nepalensis* showed high density (128.75 stems ha{^{1}) and 100% frequency across plots, contributing more than 95% of the IVI and indicating a nearly monospecific stand, while species such as *Syzygium cumini* and *Eurya acuminata* contributed less than 5% IVI. The strong dominance of *A. nepalensis* reflects its role as a pioneer nitrogen-fixing species that enhances soil fertility and facilitates ecosystem recovery in the plant invaded disturbed sites (Sharma et al., 1998; Ranabhat et al., 2008). In broadleaf mixed forest, 18 tree species were identified, with *Rhododendron arboreum* (IVI 43.24) and *E. acuminata* (IVI 42.79) being the most dominant species, while *Prunus* sp., *Engelhardtia* sp., and *Ficus* sp. showed very low IVI values, indicating limited ecological contribution (Figure 5a). In contrast, *Quercus* forest was strongly dominated by *Quercus semecarpifolia* (IVI 108.01) (Figure 5b), highlighting its high ecological importance. These patterns suggest that each forest type is characterized by a distinct dominant species, reflecting differences in successional stage, environmental conditions, and species-specific ecological strategies.

Litter depth and canopy cover varied among forest types. Mixed forests showed higher litter accumulation (3.9–8.0 cm) with dense canopy cover (86–95%), while *Quercus* forests exhibited moderate to high canopy cover (84–94%) with variable litter

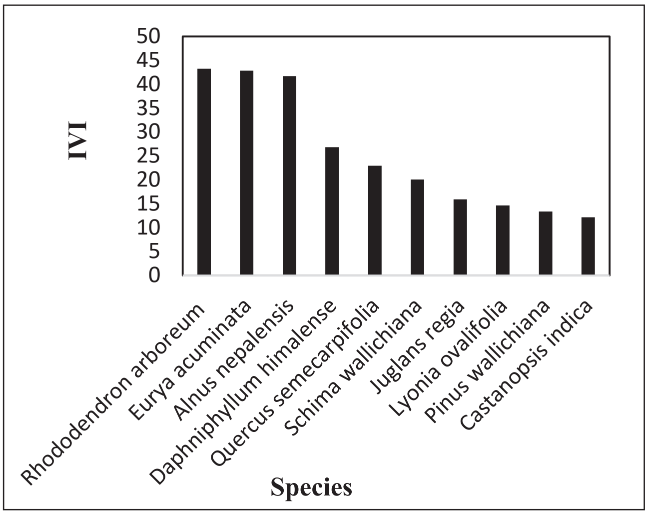

Figure 5a: IVI value of top 10 tree species of broadleaf mixed forest

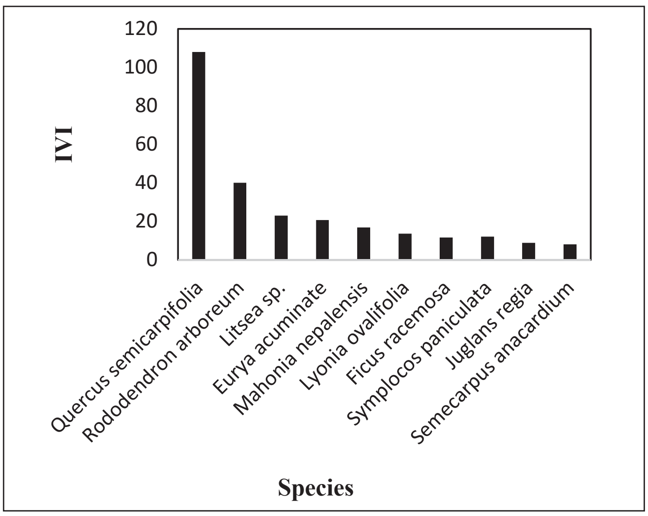

Figure 6: IVI value of top 10 tree species of Quercus forest

depth. *Alnus* forests showed comparatively lower litter depth despite high canopy closure in some plots (Table 1).

Carbon Stocks

Carbon stock analysis revealed clear differences among forest types. *Quercus* forest exhibited the highest mean carbon stock (118.06 t/ha), ranging from 73.97 to 202.16 t/ha, followed by mixed forest (88.86 t/ha; 24.57–180.87 t/ha), while *Alnus* forest had the lowest stock (30.25t/ha; 13.46–44.93 t/ha) (Figure 6). The higher carbon stock in *Quercus* forest reflects its mature stand structure and high biomass accumulation, consistent with earlier studies reporting strong carbon storage capacity in oak-dominated forests (Bruckman et al., 2011; Rawat et al., 2022).

The relatively moderate carbon stock in mixed forests suggests species-driven variability in biomass accumulation (Malhi et al., 1999; Sharma et al., 2020b; Joshi & Garkoti, 2021), while the low carbon stock in *Alnus* forests may be attributed to their young, regenerating nature and smaller diameter classes. *Alnus* forests primarily contribute to nutrient cycling rather than long-term carbon storage (Houghton et al., 2012). Similar patterns have been reported in Nepalese forest systems (Sharma et al., 2020a; Joshi et al., 2021).

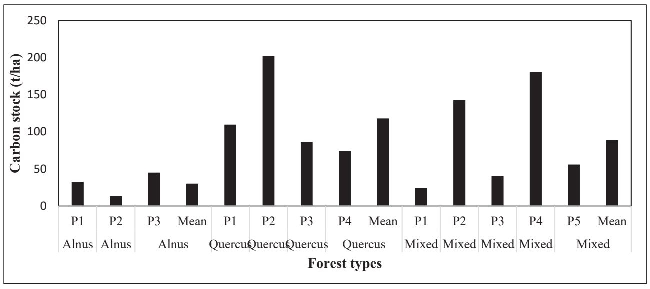

Figure 7: Plot wise and mean carbon stock of the different forest types

A positive but non-significant relationship between elevation and carbon stock was observed (Figure 7), possibly due to limited sample size and elevation range. Overall, these findings highlight that *Quercus* forests are the most effective carbon sinks, followed by mixed forests, while *Alnus* forests contribute less to carbon storage but play an important role in ecosystem succession and soil improvement (Joshi & Garkoti, 2021). These results emphasize the importance of forest type-specific management for optimizing carbon sequestration, biodiversity conservation and landscape management in mid-hill forests of Nepal (Gilani et al., 2025; Nag & Magar, 2023).

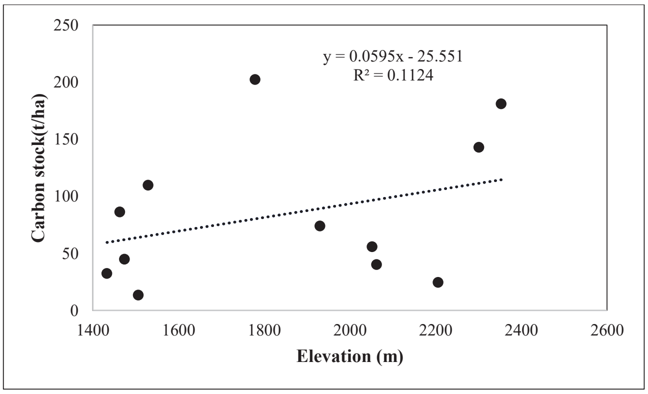

Figure 8: Relationship between carbon stock and elevation

Conclusion

Different forest types exhibit distinct structures and species compositions. We conclude that mixed forests are the most effective in sustaining ecosystem functions, particularly biodiversity conservation, plant invasion control and climate change mitigation through carbon sequestration. *Quercus* forests have high potential for carbon storage, whereas *Alnus* forests are relatively poor in species diversity and carbon stock; however, they play a crucial role in slope stabilization and forest development as pioneer communities in ecological succession. In the middle mountains of Nepal, these forest types are ecologically important and should be prioritized for conservation to ensure the proper functioning and long-term sustainability of these ecosystems.

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