

Carbon storage potential of Bluejack oak (*Quercus incana* Roxb.) forests under the influence of structural and functional ecological traits

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Abstract

Carbon storage in vegetation sustains climate regulation by facilitating carbon sequestration (CS). Varying abilities of plant species to sequester, retain, and emit carbon make their collective functional traits pivotal in deriving carbon storage in terrestrial ecosystems. However, combined impacts of stand structures and functional traits on multi-layered above-ground carbon storage across forest strata, and their shifts along the altitudinal gradients in single-species forests, remain understudied. Using data from 195 quadrates ($20 \times 20\text{m}^2$) across five monodominant *Quercus incana* forests in Hindu Himalayas, we analyzed relationship between stand structures, functional traits, and yearly CS. SEM used to assess direct and indirect influences of elevation, stand structural attributes DBH, H, CA, FB, and functional traits on carbon storage. The results showed that stand structures strongly influenced carbon storage, with significant correlations in Zone2 (1524 m; $\beta = 0.144$, $p = 0.04$), Zone3 (2000–2300 m; $\beta = 0.272$, $p = 0.001$), and Zone5 (2400–2700m; $\beta = 0.306$, $p = 0.001$). Functional traits exhibited elevation specific effects, BT and WD correlated positively with carbon in Zone3,5 ($p = 0.001$) but weakened in Zone1,2 ($p > 0.05$). Leaf traits LDMC, LT showed significant positive correlation in Zone5 ($p = 0.001$), while SLA had inconsistent effect, including slightly negative in Zone4 ($p \sim 0.05$). Our study illustrates that the effect of stand structures and functional traits on carbon storage are forest strata and elevation mediated, serving as key predictors of CS across elevations. Prioritizing these factors bid a robust framework for modeling how traits derive under climate change, particularly monodominant forests. This approach augments predictive accuracy in assessing climate carbon feedback and informs targeted ecosystem management.

Introduction

Forests play an important role in the formation of biodiversity and carbon sequestration in terrestrial ecosystems (Fichtner & Härdtle, 2021). Temperate forests store about 21% of the total carbon in the context of terrestrial carbon storage and contain a large amount of organic carbon due to abundant flora (Frelich & Montgomery; Zhang et al., 2025). Plants absorb carbon dioxide from the atmosphere and sequester a substantial amount of carbon in their above-ground biomass, thus reducing the impact of climate change (Jing et al., 2022). However, studies on the stand structures and functional traits of one species within the framework of carbon storage along the elevation gradients are limited and unprecedented in the current literature (Z. Wang et al., 2024; G. Yu, Lv, & Liu, 2024; Zhou et al., 2021). It limit our understanding how stand structure and functional traits influence above-ground carbon storage along elevation gradient within the monodominant forests (Wondimu, Nigussie, & Yusuf, 2021). A key area of ongoing research on how structural attributes and species traits individually or collectively contribute to carbon dioxide storage and subsequent carbon sequestration in forest ecosystems (Ma, Zhang, Jiang, Jiang, & Ju, 2025; Z. Wang et al., 2024). Stand structural attributes are commonly assessed through stand-level indicators such as variations in tree height, diameter at the breast height (DBH), and crown area (Alder, 2023), which deliberate size distinctiveness and help to understand structural functioning within the forest (Gonçalves, 2022b). Horizontal and vertical arrangements of

plant individuals are considered plant structures (Coverdale & Davies, 2023). Plants compete for resources such as nutrients and light through physical growth and the association of elements that impound carbon, for above-ground carbon is considered a key mechanism (Raven, 2022). Additionally, a bulk of evidence suggests that in forest ecosystems the stand structure is associated with carbon storage, enhancing stand age, stand productivity, and stand density (Gonçalves, 2022a; Q. Li, Liu, & Jin, 2022). In contrast, it remains unclear how stand structure alone or in combination with functional traits explains the variations in carbon storage in temperate forests (Lian, Wang, Fan, & von Gadow, 2022). Functional traits refers to morphological, phenological, and physiological features that play an important role in the plant's survival, growth, and reproduction (Armstrong, Miller, McAlvay, Ritchie, & Lepofsky, 2021). These traits are categorized as response traits how plants adapt to the environment, and affect traits that influence ecosystem processes (Cheng et al., 2022). However, the intricate relationship between stand structures, functional traits, and carbon sequestration along the elevation gradients in monodominant forest strata is limited.

The carbon storage process can be affected by various factors including elevation gradients, environmental influences, physical characteristics, and human disturbances (Dieleman, Venter, Ramachandra, Krockenberger, & Bird, 2013). Therefore, environmental factors are widely recognized as the main regulators of carbon storage in forest ecosystems (Mayer et al., 2023). Factors such as altitude, slope, and aspect significantly shape tree species distribution and affect forest carbon storage across different vegetation communities (Souza et al., 2023). However, according to (Moser et al., 2011) in the forest ecosystems, the biomass composition and carbon storage are mostly affected by elevation gradients. Thus, investigation of the carbon storage potential of forests with elevation gradient is necessary (Cuni-Sanchez et al., 2021).

The Hindu-Himalaya is the new folded mountain system, ranging from temperate to sub-alpine and alpine areas (Sati, 2023). The Himalayas region has remarkable natural and cultural diversity and a rich variety of nature in all aspects (Dimri et al., 2017). However, much of its uniqueness remains undiscovered because of its remoteness (Gautam, Timilsina, & Acharya, 2013). The temperate forests of the Hindu-Himalayas region play a vital role in carbon (C) storage, contributing significantly to climate mitigation (Ahmad, Liu, Nizami, Mannan, & Saeed, 2018). Several *Quercus* spp. have been recognized as a major contributor to C storage across altitudinal gradients (Qamer et al., 2016). On the global scale, temperate forest ecosystems store approximately 0.2-0.4PgC annually, measuring about 37% of the total carbon uptake, underscoring the vital role in the global carbon cycle (Canadell et al., 2007). Therefore, the sustainable management and conservation of *Quercus* forests with successional and pure-growing forest ecosystems are essential at both national and global scales to enhance, ecosystem services, and biodiversity protection (Torti, Coley, & Kursar, 2001). Forests with monodominant species exhibit low species diversity but may persist over long periods due to specific ecological mechanisms such as shade tolerance, allelopathic potential, and resistance to herbivory (Peh, Lewis, & Lloyd, 2011). Monodominance forests are commonly observed in certain tropical and temperate forest ecosystems, often influenced by soil conditions, disturbances regimes, and environmental factors (Hoshizaki & Miguchi, 2005). Carbon storage assessment is essential for understanding their role in mitigating

climate change (Keith, Mackey, & Lindenmayer, 2009). Based on the species composition the live carbon sequestered per unit leaf area varies and is also influenced by factors such as tree age, site position, and stand structure growth dynamics (Pretzsch, 2019). Both the young, and aged forests exhibit greater annual carbon sequestration levels compared to older forests and are generally more vulnerable to disturbances which can lead to a reduction in the overall carbon-storing process (Fraser et al., 2023). The effective integration of forest management and biodiversity function is challenging without implementing strategies for climate change adaptation (Hanewinkel, Cullmann, Schelhaas, Nabuurs, & Zimmermann, 2013; Kobler, Hochbichler, Pröll, & Dirnböck, 2024; Liang et al., 2025).

Hypothesized model

The biodiversity-ecosystem functioning theory suggests that greater species diversity enhances the temporal stability of the ecosystems, and larger species pools increase the similarity of including species becoming resilient to various disturbances by promoting redundancy and functional overlap in carbon sequestration (Hooper et al., 2012). However, the hypothesis states that species-rich forests provide more stability, and therefore more reliable in carbon sequestration but the monodominant forests have yet to be analytically tested (Hulvey et al., 2013; Kareiva & Levin, 2003). In this study, we hypothesized that monodominant *Quercus incana* forests exhibit predictable elevational shifts in stand structure and functional traits reflecting adaptive responses to elevation-driven abiotic constraints. Secondly, higher elevation zones of monodominant forests in the Hindu Himalayas demonstrate disproportionately greater carbon storage. To address these hypotheses this study aims to; 1) quantify the annual carbon sequestration of *Quercus incana* using allometric equations to estimate biomass growth. 2) assess the response of stand structure and functional traits to carbon storage along the elevation gradients, and 3) elevation-driven carbon storage in monodominant stand structure and associated functional traits.

Materials and methods

Study Area

The Hindu-Himalayas mountain range is located in upper Swat, Khyber Pakhtunkhwa is characterized by rugged terrain formations as a result of tectonics, and topographical extremes include sharply cut river valleys, glacially sculpted slopes and steep, and microclimates shaped by elevation-gradients (Nasir, Ahmad, Jun, Iqbal, & Bateni, 2023). The geographic latitude and longitude of the study area is 34°30'00" to 35°50'00" N and 72°05'00" to 72°50'00" E (S. F. Ali & Khan; Qasim, Hubacek, Termansen, & Khan, 2011). The study area selection was based on stand structures and functional traits, especially the young monodominance species of *Quercus incana* within the Hindu-Himalayas Mountains. The total area of the study area is approximately 537 km² (Habib Ullah, Rashid, Liu, & Hussain, 2018). The average annual rainfall received by the Swat Valley is about approximately 800 mm, with around 431 mm occurring between June and September (J. Khan, Ghaffar, & Khan, 2018). The Swat region is endowed with abundant water resources within the Swat River. The northern parts of Swat exhibit diverse

physiognomic features, including glaciers, temperate forests, and plains, and are rich in ecological resources such as diverse flora, fauna, and medicinal plants (Ahmad & Nizami, 2015). The Valleys are classified into irrigated land and rainfed areas, with the latter supporting a single crop per season. The main crops cultivated in the region are wheat, maize, rice, potatoes, and fodder (Fig. 1) (J. Khan et al., 2018). We divided the study area into 5 zones based on elevation gradients ranging from 4000 ft to 8000 ft at sea level.

Forest Inventory

We established a total of 195 quadrats, each measuring ($20 \times 20\text{m}^2$) across five elevation zones in the Hindu-Himalaya mountains. All the quadrats were systematically placed to assess forest stand structure and functional attributes and their impacts on carbon storage variations across varying altitudes.

Stand structural and Functional traits data acquisition

Stand structure attributes such as diameter at breast height (DBH) were measured at 1.3 m above the ground using measuring tape. The tree height were measured by Trigonometric methods using angles and distances to calculate the height (West & West, 2004). Similarly, the area of an ellipse (Ae) formula was used for calculating tree crown area (CA) (Eq. 6). While the first branch (FB) of the tree were recorded from the ground to the first branch (FB) on the trunk, for estimation of crown length (Honda, 1971). The functional traits attribute, including bark thickness (BT), leaf thickness (LT), specific leaf area (SLA), leaf dry matter content (LDMC), and wood density (WD), were measured following the standardized protocols. We assessed fresh and dry weight of leaves and wood to find out SLA, and similarly, wood volume and bark thickness were measured with a digital vernier caliper and graduated cylinder (Bandow, 2022; Islam, Hamid, Nawchoo, & Khuroo, 2024).

Assessment of annual carbon sequestration

The annual carbon sequestration in each forest was estimated based on measurements of the sum of diameter at the breast height (DBH) and tree height (H) for all individuals within each quadrat (S. Ali et al., 2023; Garnier, Navas, & Grigulis, 2016).

The total green biomass of the tree was measured using the following equation.

$$W_{ag} = 0.15 \times D^2H \quad (1)$$

Where W_{ag} shows the above-ground biomass of a tree, measured in pounds (lbs), D represents the diameter of the tree stem in inches, and H denotes the tree height in feet. The green weight of the tree resembles the live tree weight. Before, the above-ground green weight of the tree was measured using the following equation (Clark, Saucier, & McNab, 1986). The below-ground biomass is 20% greater than the above-ground biomass, so the total green weight of a tree can be calculated by multiplying the above-ground biomass by 1.2 (Næsset & Gobakken, 2008).

$$W_{\text{tgw}} = 1.2 \times W_{\text{ag}} \quad (2)$$

The dry weight of a tree is determined by multiplying its total green mass by 0.725. Trees have an average dry matter weight of around 72.5% and a moisture content of 27.5% (DeWald, 2005).

$$W_{\text{dry weight}} = 0.725 \times W_{\text{total green weight}} \quad (3)$$

The average carbon content in the tree is generally 50% of the total tree volume (DeWald, 2005; Tooichi, 2018). So, we calculated the weight of carbon in the trees by multiplying their dry weight by 0.5.

$$W_{\text{carbon}} = 0.5 \times W_{\text{dry weight}} \quad (4)$$

Two molecules of oxygen and one molecule of carbon make up carbon dioxide (CO_2). Since the atomic weights of carbon and oxygen are respectively 12.001115 and 15.9994, the weight of CO_2 in trees can be calculated using the formula $\text{C} + 2 \times \text{O} = 43.999915$. $\text{C} = 43.999915 / 12.001115 = 3.6663$. As a result, after rounding to the nearest whole number, we calculated the weight of the CO_2 stock in the tree, multiplied by the carbon weight in the tree by 3.67 (Afzal & Akhtar, 2013; Tooichi, 2018).

$$W_{\text{CO}_2} = 3.67 \times W_{\text{c}} \quad (5)$$

The area of an ellipse (A_e) formula was used for calculating the tree crown area (CA)

$$A_e = \pi (0.5x) \times (0.5y) \quad (6)$$

Where (x) is the crown length and (y) is the width of the tree crown towards perpendicular (W. Li et al., 2021; Van de Perre et al., 2018).

Statistical Analysis

First, all permanent numerical variables were normalized and standardized to assess normality and linearity, which helped in comparing multiple variables in complex structural equation models using library writes in R Studio version (4.4.2).

Second, we applied multiple regression analysis to assess how the relationship between stand structure, functional traits, and carbon storage varies across the elevation variation. This technique evaluates the structural and functional trait correlations with carbon storage within five distinct altitudinal zones, treated as linear intervals (Lu et al., 2023). To investigate the direct, indirect, and interactive effects of overstory stand structure and functional traits on carbon storage in five different zones, we employed the structural equation model (SEM). This technique approach allows us to evaluate complex ecological relationships by integrating multiple predictor variables such as (DBH, H, FB, CA) and Functional traits (BT, LT, LDMC, SLA, LDMC) and carbon sequestration within a unified model using R Studio version (4.4.2). Lastly, to identify the most influential overstory stand structure and functional traits in each zone contributing to carbon storage, and to reduce the dimensionality of these interrelated variables, we

conducted Ellipse Principal Component Analysis (PCA), separately for stand structure and functional traits. This helped to summarize the variation of complex datasets by transforming correlated variables into a smaller set of uncorrelated principal component that clasps most of the variance. The Ellipse PCA further visualizes the cluster and spreads predictable variables across different zones.

Results

Relationship between monodominant stand structure and carbon sequestration

This study investigates how the forest stand structure significantly influences carbon storage across all elevation zones. The result showed that the functional trait diversity significantly influenced across all elevation zones. Zones 2 (1524 to 1924 m) above the sea level (asl) ft, Zone 3 (2000 to 2300 m), and Zone 5 (2400 to 2700 m) contribute significantly to carbon stock influenced by monodominant Forest Stand Structure and tree functional traits (Fig. 4). The forest stand structures (DBH, H, CA, and FB) are positively correlated with CS in all the five zones (Table 1, $p < 0.001$).

Relationship between functional traits and carbon sequestration

The correlation between functional traits (SLA, LDMC, BT, LT, and WD), reveals a diverse relationship with CS across all the altitudinal zones, as indicated by constantly high loading factors (standardized estimates > 0.7) and highly significant p-values ($p < 0.001$) (Fig. 4) respectively. Functional trait BT exhibited a strong positive correlation with CS in zone 3, 4 and 5 (Table 2, $p < 0.001$) while showing weekend correlation with CS and becoming non-significant in zone 2, and highly negative in zone 1 (Table 2, $p > 0.05$). Similarly, WD positively correlated with CS in zone 5 (Table 2, $p < 0.001$), with the weakening relationship in other zones (Table 2, $p > 0.05$). In contrast, LDMC shows significant positive relationship in zone 5 (Table 2, $p < 0.001$), and negligible correlations with CS in all the other respective zones (Table 2, $p > 0.05$), and LT correlated positively with CS in zone 3 (Table 2, $p < 0.001$), showing no significant correlation with CS in other zones zone (Table 2, $p > 0.05$). Additionally, SLA signifies positive and consistent correlations in zones 1, 2, 3 and 5 to weak overall (Table 2, $p < 0.001$), rather than a marginal negative change in zone 4 (Table 2. $p \sim 0.05$).

Relationship between elevation and carbon sequestration

Each zone had a latent construct representing a standing structure and functional traits derived from observed variables (DBH, H, CA, FB, SLA, LDMC, BT, LT, and WD,), all occurring across altitudinal zones and are strongly correlated (Table 1, $p < 0.001$) with carbon sequestration in Zone 2, (Table 1, $p < 0.046$) zone 3, (Table 1, $p < 0.000$) and zone 5, (Table 1, $p < 0.000$). Meanwhile, all the elevational zones exhibit a significant relationship with CS (Fig. 6).

Direct and indirect effects of stand structures and elevational zones on carbon sequestration

The direct and indirect effects of stand structures consisting of (DBH, H, CA, FB) and elevational zones comprising (Zone 1–5) exhibit a range with all factors from 0.994 to 0.998 and z-values between 18.24

and 19.78, all are highly significant at $p < 0.001$ (Table 1). The SEM for stand structure attributes and CS demonstrates a strong internal consistency between them for CS. In zone 3 (Table 1, $\beta = 0.272$, $z = 3.720$, $p = 0.001$) and zone 5 (Table 1, $\beta = 0.306$, $z = 4.169$, $p = 0.001$) showed a highly significant positive relationship with CS. Zone 2 displayed a significant positive effect on CS (Table 1, $\beta = 0.144$, $z = 1.999$, $p = 0.04$), suggesting a less structural influence on CS. Conversely, zones 1 and 4 did not exhibit significant effects on CS (Table 1, $\beta = 0.026$, $p = 0.178$; $\beta = 0.020$, $p = 0.779$). Overall, the zones significantly influence stand structure variables (Table 1, $p < 0.05$), representing an indirect effect on CS.

Direct and indirect effects of functional traits and elevational zones on carbon sequestration

The principal components analysis was conducted to reduce the dimensionality of stand structure and functional traits variables across all the zones with elevation gradients, identifying the key determinants influencing carbon sequestration. In the results zone two, zone three, and five emerged as the most effective zones for carbon sequestration, with structural (DBH, H, FB, CA), and functional traits attributes linking strongly with the principal components driving carbon storage. Zones with their stand structures were reduced with PCA, which shows that zones two, three, and five are the most highly performed zones in carbon sequestration, while elevation zone five significantly enhances carbon sequestration (Fig. 5.).

Discussion

This study is one of the first to evaluate the influence of plant stand structures and functional traits on carbon sequestration within natural *Quercus incana* dominated ecosystems, analyzing sites spanning altitudinal gradients. The Hindu-Himalaya Mountain range, characterized by ecological and topographical diversity, hosts a variety of forest ecosystems vital for biodiversity conservation and ecosystem functioning (Singh, 2020). This mountain range encompasses an incredible diverse array of forest types due to its significant topographical and ecological zones extending from the foothills of the Himalaya to alpine and glacial zones (Hameed Ullah et al., 2022). Among these, the monodominant *Quercus incana* forests, commonly known as dark bluejack oak, play a pivotal role in ecological balance, particularly in the moist temperate zones of the Hindu-Himalaya Mountain range (S. A. Khan et al., 2020). However, the functional ecology of these single-species (monodominant), despite the well-documented influence of topographical changes on species composition, physiological traits (Happonen, Virkkala, Kemppinen, Niittynen, & Luoto, 2022), and ecosystem processes (M. Rawat, Arunachalam, Arunachalam, Alatalo, & Pandey, 2019).

The current study evaluates the influence of stand structures, DBH, H, CA, FB and functional traits including BT, LT, SLA, LDMC, and WD, on carbon storage within the monodominant *Quercus incana* Roxb. in the Hindu-Himalaya Mountain range across elevational zones, emphasizing their functional ecology and role in climate change mitigation. Similarly, *Quercus leucotrichophora*, a key species in the temperate Himalayas, is renowned for its broad altitude, contribution to climate change, and ecosystem services, including soil and water conservation. These forests support subsistence livelihoods and play a

substantial role in CO₂ sequestration (S. Rawat et al., 2022). *4.1 Stand Structures Pillars of the carbon sequestration*

Among the stand structures analyzed in this study, factors like DBH, H, CA, and FB of the tree emerge as primary determinants of carbon sequestration across all the five zones, with trees exhibiting larger structures showing higher carbon sequestration potential. The trees in the forests serve as carbon sinks by capturing CO₂ through photosynthesis and storing surplus carbon in their biomass, with their net CO₂ source or sink dynamics fluctuating as they grow, die, and decompose. Our study shows the complex relationship between carbon sequestration and tree dimension and biomass accumulation across different elevations. The study of (Jana, Biswas, Majumder, Roy, & Mazumdar, 2009) also find out the relationship among carbon storage, trees dimension and biomass accumulation across various elevation ranges. In tree stand structures, we found that Diameter at the breast height DBH and Height H are primary determinants of carbon sequestration, trees with larger DBH and H have a great potential for carbon storage. Several studies emphasize the importance of tree dimensions particularly diameter at the breast height (DBH > 30 cm) and height H, as key biotic factors in carbon sequestration (K. Wang et al., 2024). Specifically, DBH shows a strong correlation with above-ground biomass, serving as a dependable indicator of carbon storage potential in forests (Shimamoto, Botosso, & Marques, 2014). This study is also supported by other research findings on carbon sequestration by trees above-ground biomass with altitudinal gradients (Terakunpisut, Gajaseni, & Ruankawe, 2007). (S. Ali et al., 2022) reported from Margalla Hills National Parks (MHNP) that tree DBH has more potential for carbon sequestration than tree H and crown area (CA). In the current study DBH, H, and CA indicate high potential for carbon sequestration because our study was for monodominant species phytogeographically located in the temperate region of Hindu Himalaya of Pakistan with a slow growth rate (Rahman, Khan, Bräuning, Ullah, & Rahman, 2022), while the Margalla Hills National Parks (MHNP) study shows mixed species with different stand structure diversity and crown area. The fourth stand structure biotic factor first branch of the tree (FB) was measured from the ground up to the first branch as we considered the crown length (Zhu, Kleinn, & Nölke, 2021). Forest managers and modelers place significant importance on tree crown size (Porté & Bartelink, 2002). Managers aim to identify the most productive and essential trees, while modelers link crown attributes to other tree variables, such as (DBH) and height (Drake, Dubayah, Knox, Clark, & Blair, 2002). Previous research indicates that tree crown size or length increases carbon sequestration, as observed in *Platanus hybrida* Brot. in Rome, where crown traits were closely associated with the carbon sequestration potential of trees (Gratani & Varone, 2007). Recent literature (Board on Population, Public Health, Committee on the Effect of Climate Change on Indoor Air, & Public, 2011; Jucker, Bouriaud, & Coomes, 2015) highlights that crown area is a key functional trait of plants, enabling them to capture a higher level of carbon dioxide (CO₂) and enhance above-ground biomass. Crown traits (CA, FB) association with CS, though novel, may constrain plasticity, slow growth rate of the *Quercus incana*, limiting its explanatory power compared to faster growing species. In this study, the first branch (FB), measured as the distance from the ground to the lowest branch, was used to assess the crown length, further supporting the critical role of crown traits in carbon sequestration. This approach underscores the relationship between crown structure and the

capacity of a tree to store carbon, aligning with findings that link crown characteristics to biomass accumulation (Hasenauer, 2006). However, the dominance of DBH over H, and CA contrasts with findings from mixed-species forests (S. Ali et al., 2022), suggesting that monodominant forests ecosystems may favor lateral expansion over vertical growth to optimize light adaptability in dense canopy stands. This finding underscores the role of competition in shaping structural exchange, where *Quercus incana* suffuse in trunk girth to outcompete neighbours for limited resources. The reliance on static structural matrices overlooks temporal dynamics such as growth rate and mortality, which are essential for long-term carbon sequestration (Levine, HilleRisLambers, Petry, Usinowicz, & Crowther, 2024). Moreover, excluding below-ground biomass risks underestimating total ecosystem carbon, as root system contribute substantially to soil organic carbon pools (Grime, Hodgson, & Hunt, 2014).

4.2 Functional Traits and Carbon Sequestration

Functional traits such as LT, BT, WD, SLA, and LDMC played a diverse role in carbon sequestration. Our findings show that the elevation-specific relationship between all the functional traits and CS remains different across elevation. The bark thickness (BT) exhibits a robust positive association between bark thickness BT and carbon sequestration, indicating that thicker bark BT significantly enhances carbon sequestration (Rosell, Gleason, Méndez-Alonzo, Chang, & Westoby, 2014). With the support of (Trugman, Medvigy, Hoffmann, & Pellegrini, 2018) studies, our research is consistent with the study that bark constitutes around 20% of a tree's total above-ground biomass (AGB). Additionally, it is often inadequately represented in carbon sequestration estimates. Since the bark density of hardwood species is 40–50% lower than that of softwood, while being nearly comparable in conifers, this approach tends to overestimate bark carbon for many plant species (Neumann & Lawes, 2021). The research work of (Wijas et al., 2024) also investigated that bark thickness BT are crucial biotic variable in carbon estimation, as it significantly impacts the carbon storage capacity of forest ecosystems. The findings of these studies highlight the need to integrate bark-specific characteristics into allometric models to achieve more precise evaluations of carbon sequestration across various forest types. The leaf traits are often utilized to illustrate how plants are adapted to their environment (H. Yu et al., 2022). Our results illustrate that the relationship between leaf thickness and carbon sequestration appears to be minimal. Our findings differ from previous studies (Lin, Lee, Lin, & Chang, 2001) reported that an increase in leaf thickness of 4–35% across various species, including oak, pine, poplar, soybean, and sweet gum, under elevated CO₂ levels, indicating a direct correlation between leaf thickness LT and carbon sequestration. Similarly, (Shah et al., 2022) reported that leaf thickness is a key factor influencing the individual above-ground biomass (AGB) of *Leptochloa chinensis* on the drought-prone Mongolian plateau and throughout the broader study area which experiences significant climate variability. This trait is directly associated with the carbon sequestration potential of the species. In oak, the increase in leaf thickness under CO₂ is primarily driven by cell expansion in the palisade tissue. A limitation of our research is the minimal observed relationship between leaf thickness and carbon sequestration across all the five zones, which contrasts with other findings also from (Gratani, Catoni, & Varone, 2011), who reported a significant positive effect of leaf thickness on carbon storage in *Quercus ilex* L. This discrepancy suggests that our

results may overlook other important variables that influence carbon dynamics in *Quercus incana* from moist temperate forests of the Hindu Kush Mountain range. Furthermore, the less decrease in carbon sequestration with increasing leaf thickness (LT) could reflect an oversimplification of the role of leaf traits in carbon storage, potentially missing the other physiological and environmental factors. Future study is needed to explore the leaf thickness of different plant species and provide a more comprehensive understanding of leaf morphology in carbon sequestration.

Specific leaf area (SLA) and carbon sequestration (CS) validate a distinct positive correlation between specific leaf area SLA and carbon sequestration in zone four of the forest region, highlighting that increased SLA supports more carbon sequestration. The specific leaf area SLA supports previous research on the understory palms *Socratea exorrhiza*, where the specific leaf area accounts for 52% of the vegetation in carbon storage (Avalos, 2023). The study conducted by (Wright et al., 2019) in subtropical forests highlighted the importance of SLA as a key trait affecting carbon storage efficiency, especially in fast-growing species thriving in nutrient-rich environments, further emphasizing its role in the carbon sequestration model. Therefore, the study on the Specific leaf area-based traits underscores the significance of specific leaf area SLA as a key functional trait influencing carbon storage capacity among various plant species and ecological settings, contributing to the sequestration of carbon. This study concludes with functional traits of *Quercus incana* forests in the Hindu Kush Mountain range that there is a strong positive relationship between leaf dry matter content (LDMC) and carbon sequestration, particularly plant traits in soil organic carbon storage in the nondominant species in zone five forests of Hindu Kush Mountain range. The results from the study area highlight that higher LDMC enhances carbon sequestration by extending the durability and nutrient efficiency of litter inputs (Austin & Vivanco, 2006). The plant-specific functional traits and environmental variables, including soil fertility and microclimate factors, may influence this relationship, requiring further exploration. Our findings confirm the pivotal role of LDMC in increasing the carbon sequestration capacity of temperate monodominant broadleaved forests of the Himalaya region, Pakistan. For further estimation of carbon sequestration should integrate leaf dry matter content LDMC with other plants' functional traits to deepen understanding of its importance across diverse ecosystems and inform sustainable forest management practices.

The findings suggest that wood density (WD) and carbon sequestration appear positive significant association in zone 5. For instance (Profft, Mund, Weber, Weller, & Schulze, 2009) investigated wood densities in various species, including *Picea abies*, *Pinus sylvestris*, *Fagus sylvatica*, and oak (*Quercus* spp.), and found that the majority of carbon was allocated to products derived from spruce (49%), followed by beech (35%), pine (13%), and oak (3%). This distribution emphasizes the varying carbon storage contributions across species, dedicated to their wood density WD. In contrast (Ray, Majumder, Chowdhury, & Jana, 2012) highlighted a positive relationship between wood density WD and carbon sequestration in mangroves, where species with higher wood densities sequester carbon more rapidly ($0.156\text{--}0.171\mu\text{g C kg}^{-1}\text{ ABG s}^{-1}$) compared to those with lower wood densities (0.088 and $0.092\text{ }171\mu\text{g C kg}^{-1}\text{ ABG s}^{-1}$). This significant correlation underscores the role of wood dens as a determining factor in carbon storage efficiency. The disparity between our findings and these studies could stem from

ecological, methodological, or species-specific differences. While mangroves may show a clear density-carbon relationship, monodominant forest species might exhibit more complex dynamics influenced by growth rate, biomass allocation, or other environmental factors. Functional traits-based research is required for the estimation of carbon sequestration in different zones of monodominant Oak forests in the Hindu Himalayan Mountains. The study concluded that there are great changes in responses of stand structures and functional traits towards carbon sequestration across different elevational zones, therefore we conducted the regression analysis for elevation gradients with carbon sequestration, suggesting that elevation had very little effect on the CS of monodominant species. Furthermore, this study suggests that forest policymakers need to expand and grow as a key monodominant forest in such suitable elevations, for protection and conservation.

Conclusion

This study reveals that *Quercus incana* species growth occurs in dominated form, exhibit low species diversity but may persist over long periods due to specific ecological mechanisms such as shade tolerance, allelopathic potential, and resistance to herbivory. Evergreen physiological nature, which sustains photosynthetic activity, and biomass accumulation of *Quercus incana* positions contribution against climate change, engaging in undisturbed carbon storage throughout the year. The slow growing rate, dense wood, and deep rhizosphere enhances above and below ground carbon storage by stabilizing litters, organic matter, and facilitating water-nutrient synergies that promote root-driven carbon allocation and sequestering. The broad leaves, and seeds shedding of this plant in larger amount further contribute to Soil Organic Carbon (SOC) pools through continuous organic input, fostering humus formations and long-term soil carbon stabilization. Moreover, this study underscores that *Quercus incana* contribution in Above-below ground carbon sequestration mediated by its growth traits including stand structures, functional, and ecological adaptations. The seeds and species-specific growing manner of *Quercus incana* is necessary for further research. Our findings emphasize the need for further studies on functional traits and stand structures at different elevation gradients, conservation strategies, and reforestation of the monodominant forests at elevations we identified to maximize carbon sequestration and ecosystem resilience. By integrating functional traits into carbon models, we can improve sequestration estimates, and guide reforestation efforts. The conservation of these monodominant, broad-leaf oak forests is essential at global and national levels for sustaining global carbon cycles and strengthening climate change mitigation.

Declarations

Declaration of Interest

The authors declare no conflict of interest, financial or otherwise, that could influence the outcomes or interpretation of this work. All authors have read, understood, and complied as applicable with the journal's ethical responsibilities.

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Author Contribution

Nazir Mohammad: Fieldwork, Methodology, Software work, Validation, Visualization, Investigation, formal analysis, Writing an original draft. Shujaul Mulk Khan: Supervision, Investigation, Methodology, Conceptualization, Shahab Ali: Investigation, Conceptualization, Formal analysis, Resources, Software, Validation, Visualization. Jawad Hussain: Revision, writing. Muhammad Shakeel Khan, Zeeshan Ahmad: Formal analysis, validation, revision.

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This research work is original and brings novelty, especially in the field of forest ecology and environmental management. I hope our work will align with the aims and objectives of the journal. We expect from the editor that our work will be considered for possible publication.

Data availability

Data will be available upon request

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Tables

Table 1. SEM for stand structures DBH= Diameter at Breast Height, H= Height, FB= First Branch of the Tree, CA= Crown Area, CS= Carbon Sequestration.

Response	OP	Predictor	Estimates	Std.Err	z-value	P(> z)
Zone 1	~	DBH	0.997	0.05	19.748	0.001
Zone 1	~	H	0.991	0.051	19.518	0.001
Zone 1	~	FB	0.983	0.051	19.206	0.001
Zone 1	~	CA	0.976	0.052	18.94	0.001
Zone 2	~	DBH	0.988	0.05	19.759	0.001
Zone 2	~	H	0.985	0.05	19.669	0.001
Zone 2	~	FB	0.978	0.05	19.38	0.001
Zone 2	~	CA	0.97	0.051	19.094	0.001
Zone 3	~	DBH	0.964	0.049	19.784	0.001
Zone 3	~	H	0.958	0.049	19.557	0.001
Zone 3	~	FB	0.946	0.05	19.069	0.001
Zone 3	~	CA	0.924	0.051	18.248	0.001
Zone 4	~	DBH	0.998	0.05	19.783	0.001
Zone 4	~	H	0.994	0.051	19.614	0.001
Zone 4	~	FB	0.986	0.051	19.307	0.001
Zone 4	~	CA	0.975	0.052	18.895	0.001
Zone 5	~	DBH	0.953	0.048	19.706	0.001
Zone 5	~	H	0.951	0.048	19.627	0.001
Zone 5	~	FB	0.941	0.049	19.217	0.001
Zone 5	~	CA	0.938	0.049	19.118	0.001
Zone 1	~	CS	0.026	0.072	0.361	0.718
Zone 2	~	CS	0.144	0.072	1.999	0.046
Zone 3	~	CS	0.272	0.073	3.72	0.001
Zone 4	~	CS	0.02	0.072	0.28	0.779
Zone 5	~	CS	0.306	0.074	4.169	0.001

Table 2. SEM for functional traits BT= Brak Thickness, LT= Leaf Thickness, SLA= Specific Leaf Area, LDMC= Leaf Dry Matter Content, WD= Wood Density, CS= Carbon Sequestration.

Response	OP	Predictor	Estimate	Std.Err	z-value	P(> z)
Zone 1	~	BT	0.968	0.051	0.28	0.78
Zone 1	~	LT	0.744	0.06	1.2	0.345
Zone 1	~	SLA	0.85	0.056	4.9	0.001
Zone 1	~	LDMC	0.964	0.051	0.75	0.456
Zone 1	~	WD	0.93	0.053	1.55	0.132
Zone 2	~	BT	0.985	0.051	0.5	0.62
Zone 2	~	LT	0.891	0.055	0.19	0.62
Zone 2	~	SLA	0.969	0.052	4.2	0.001
Zone 2	~	LDMC	0.839	0.057	1.25	0.21
Zone 2	~	WD	0.973	0.052	1.44	0.15
Zone 3	~	BT	0.952	0.052	4	0.001
Zone 3	~	LT	0.966	0.052	4.5	0.001
Zone 3	~	SLA	0.96	0.052	3.8	0.001
Zone 3	~	LDMC	0.309	0.07	2.2	0.03
Zone 3	~	WD	0.962	0.052	0.58	0.567
Zone 4	~	BT	0.974	0.051	3.9	0.001
Zone 4	~	LT	0.965	0.052	0.75	0.45
Zone 4	~	SLA	0.821	0.058	1.96	0.05
Zone 4	~	LDMC	0.964	0.052	0.99	0.32
Zone 4	~	WD	0.949	0.053	1.25	0.21
Zone 5	~	BT	0.949	0.051	3.5	0.001
Zone 5	~	LT	0.898	0.053	0.78	0.432
Zone 5	~	SLA	0.946	0.051	4.1	0.001
Zone 5	~	LDMC	0.882	0.054	3.1	0.001
Zone 5	~	WD	0.936	0.052	3.8	0.001
Zone 1	~	CS	-0.148	0.073	-2.034	0.042
Zone 2	~	CS	-0.053	0.072	-0.74	0.46
Zone 3	~	CS	0.098	0.073	1.357	0.175

Zone 4	~	CS	-0.077	0.072	-1.057	0.29
Zone 5	~	CS	0.198	0.073	2.697	0.007

Appendix

The supplementary table file is not available with this version.

Figures

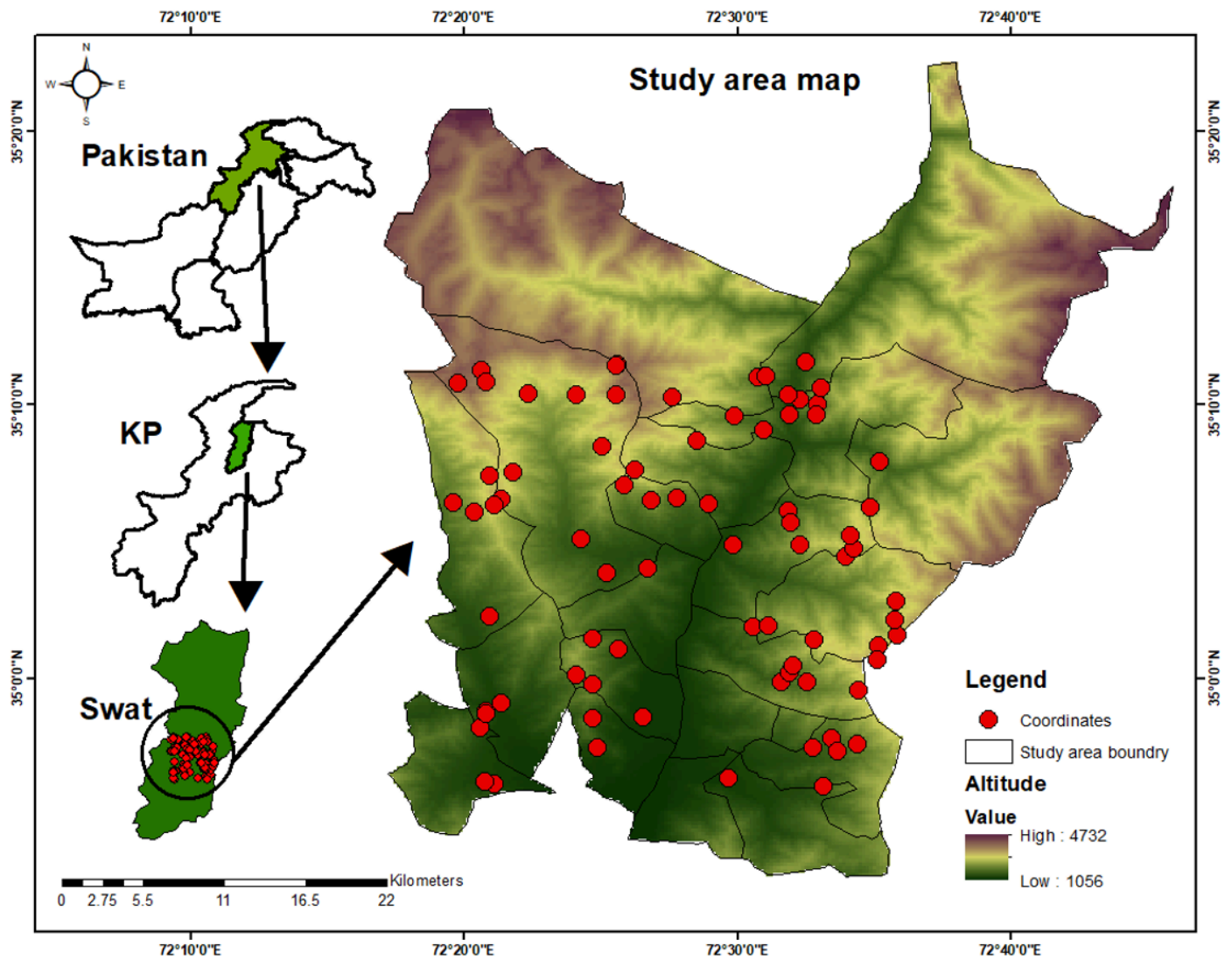


Figure 1

Map of the study area

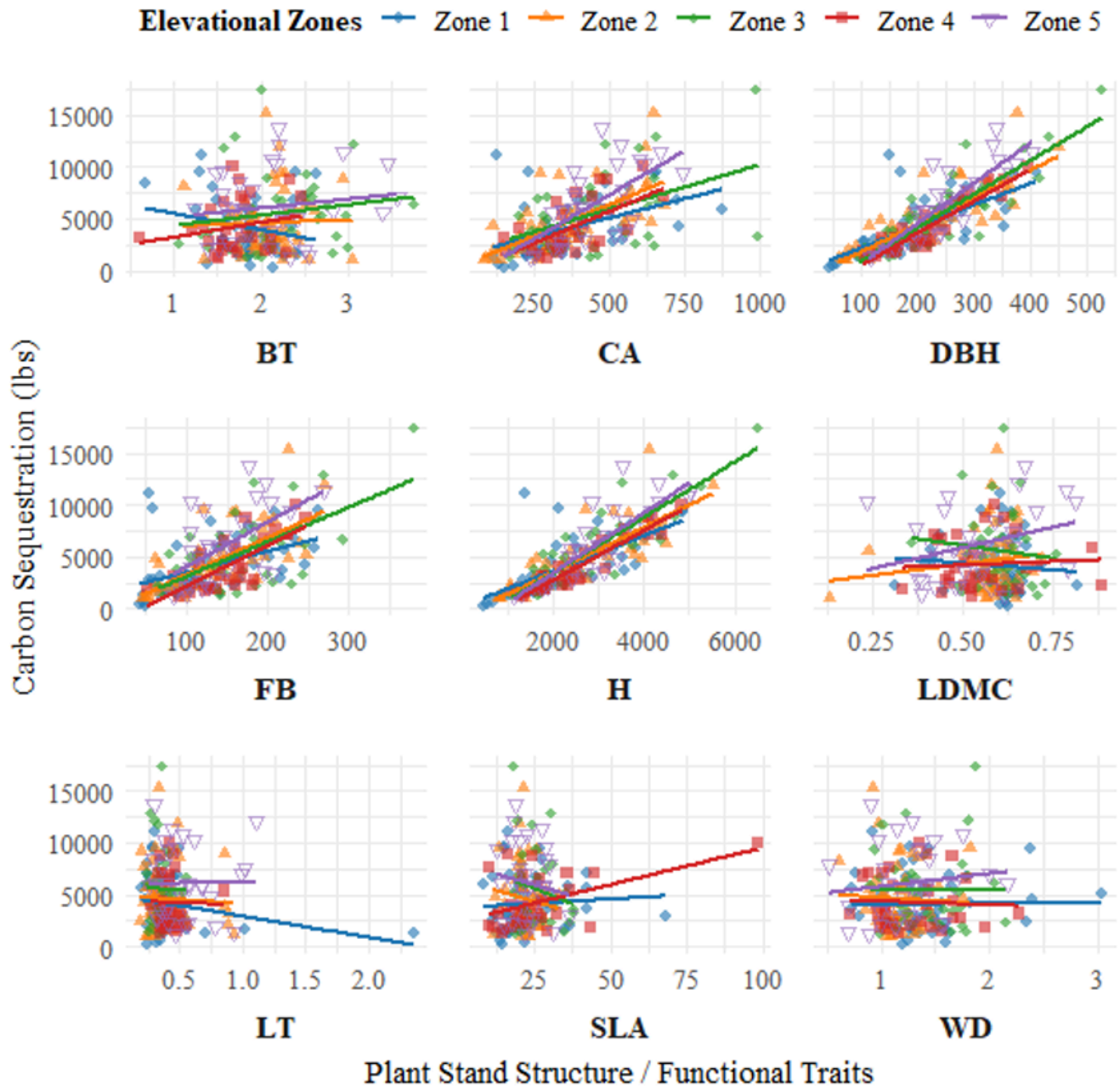


Figure 2

Correlation between plant stand structures and functional traits with carbon sequestration across elevation gradients in all the five zones, DBH= Diameter at the Breast Height and Carbon sequestration, H= Tree Height and Carbon sequestration, FB= First Branch of the Tree and Carbon sequestration, CA= Crown Area and Carbon sequestration, BT= Bark Thickness and Carbon sequestration, LT= Leaf Thickness and Carbon sequestration, SLA= Specific Leaf Area and Carbon sequestration, LDMC= Leaf Dry Matter Content and Carbon sequestration, WD= Wood Density and Carbon sequestration.

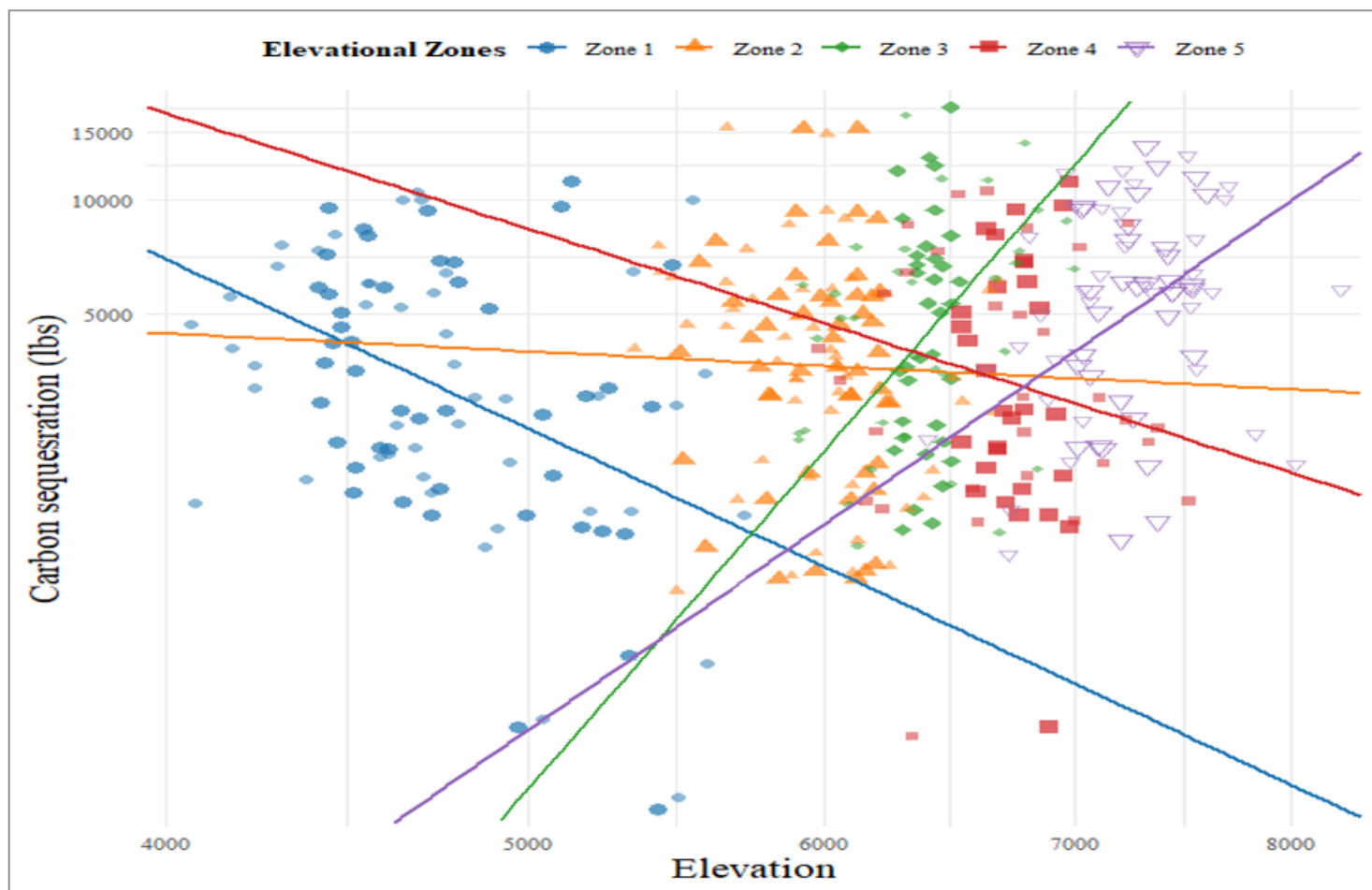


Figure 3

Correlations of carbon sequestration across elevation gradients in all the five zones.

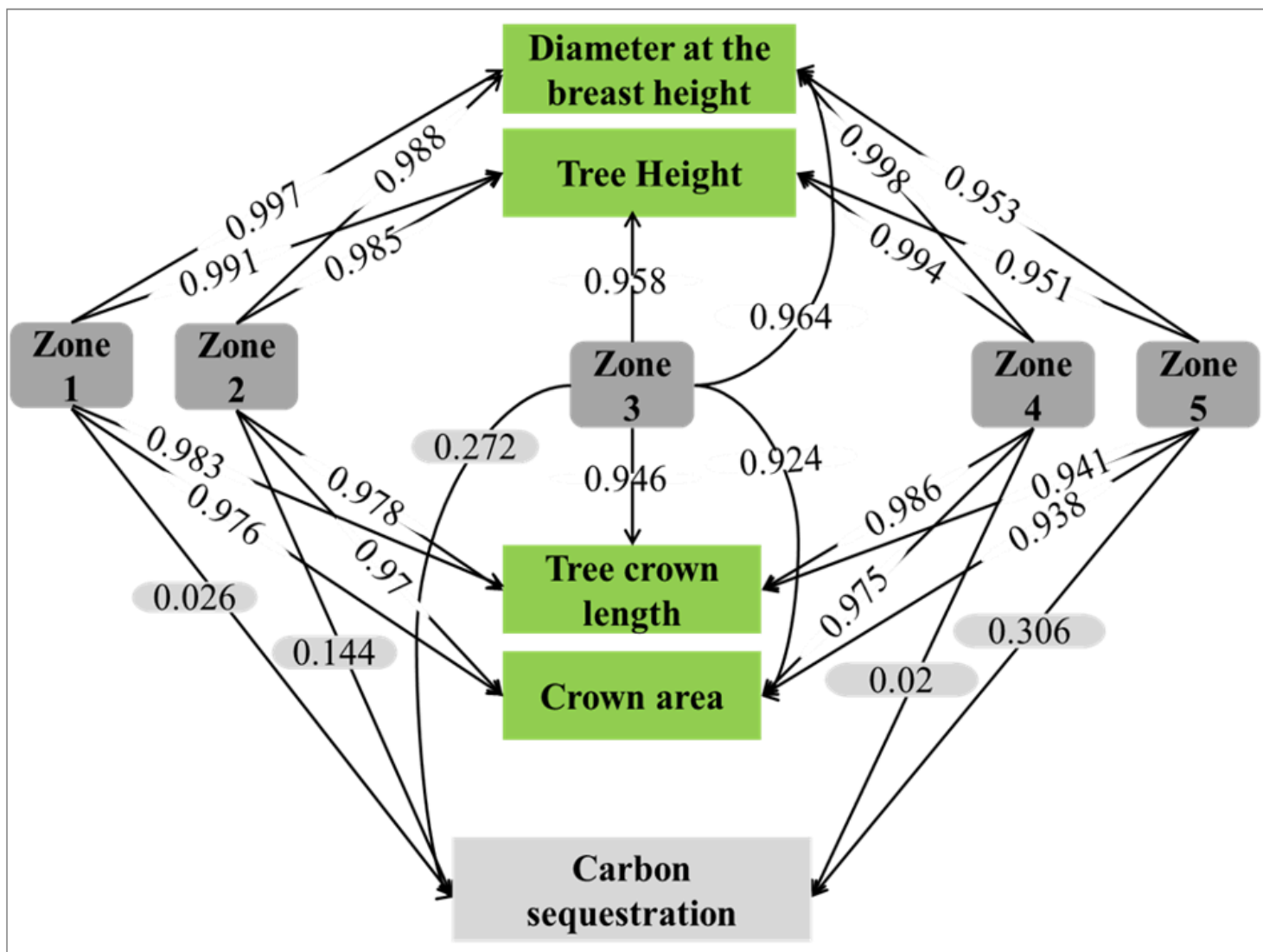


Figure 4

SEM for Stand structural attributes with carbon sequestration across different zones. The lines are the standardized path coefficients, and the β values represent the coefficient of determination. The bold green lines show the strength of the relationship with zones, followed by nonbold green lines, and red lines show no relationship with CS. (DBH= Diameter at the Breast Height, H= Height, FB= First Branch of the Tree, CA= Crown Area, CS= Carbon Sequestration).

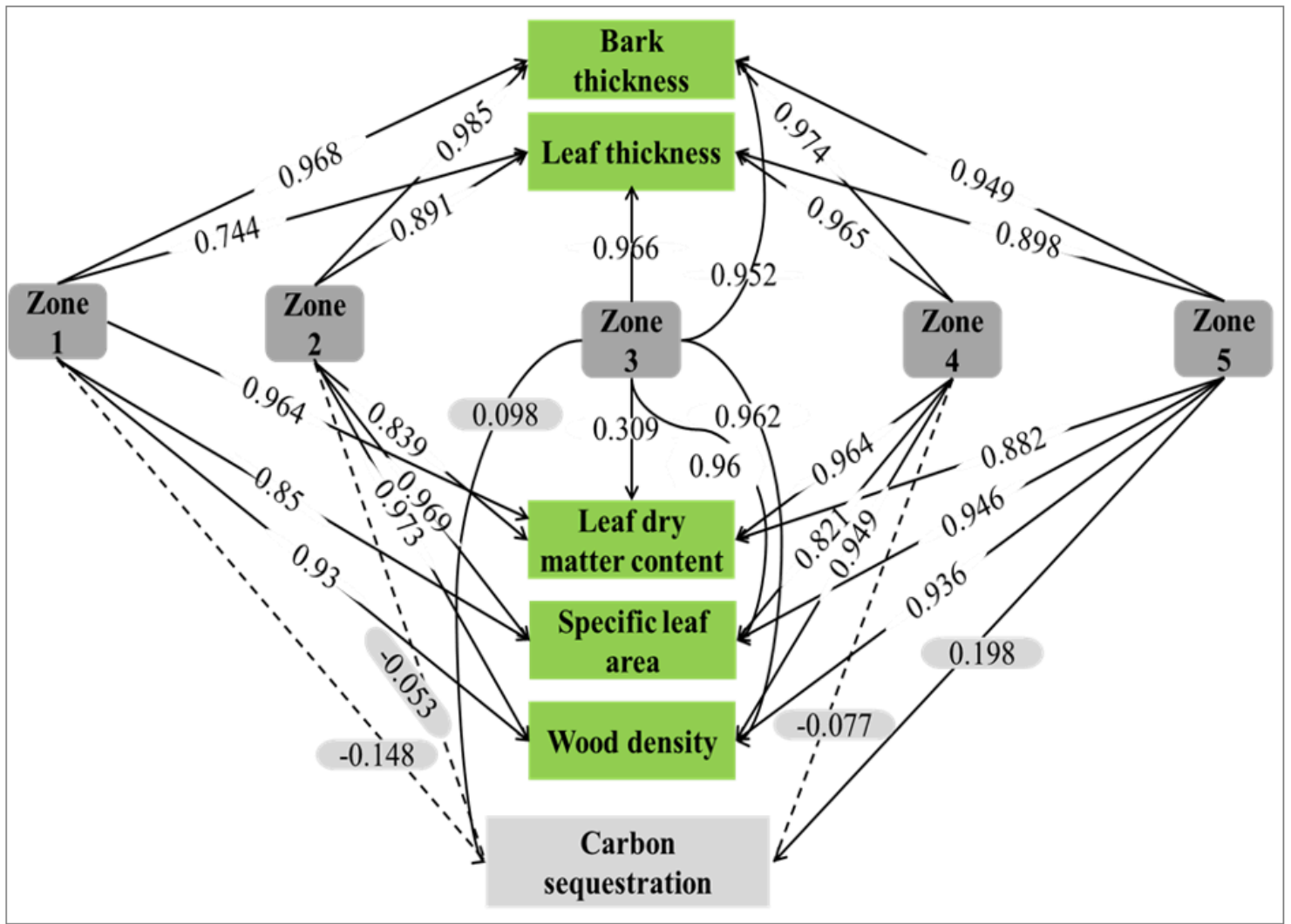


Figure 5

SEM for functional traits with carbon sequestration across different zones. The lines are the standardized path coefficients, and the β values represent the coefficient of determination. The bold green lines show the strength of the relationship with zones, followed by nonbold green lines, and red lines show no relationship with CS. (BT= Brak Thickness, LT= Leaf Thickness, SLA= Specific Leaf Area, LDMC= Leaf Dry Matter Content, WD= Wood Density, CS= Carbon Sequestration).

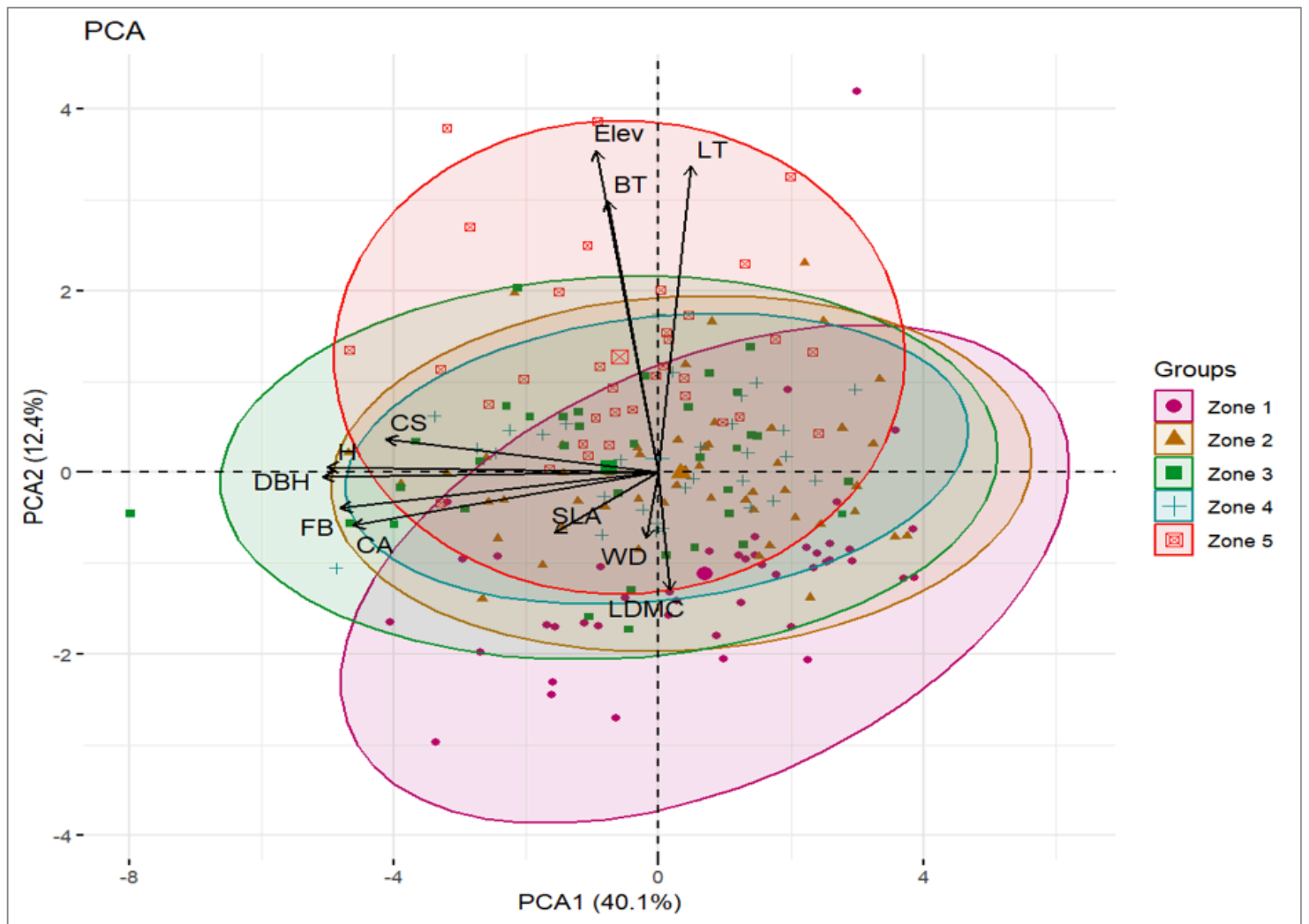


Figure 6

Principal Component Analysis of stand structures with Carbon Sequestration and elevation across the five zones. (DBH= Diameter at Breast Height, H= Height, FB= First Branch of the Tree, CA= Crown Area, BT= Brak Thickness, LT= Leaf Thickness, SLA= Specific Leaf Area, LDMC= Leaf Dry Matter Content, WD= Wood Density, CS= Carbon Sequestration, and Elevation.