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Estimation of Above-Ground Biomass and Sequestered Carbon at Two Elevations in A Tropical Forest in Tingo María, Peru

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ABSTRACT

Climate change is a major ecological issue worldwide, and understanding its impacts requires analyzing above-ground biomass and sequestered carbon in tropical forests, as well as their role in climate change mitigation. The study aimed to quantify above-ground biomass and sequestered carbon in two developmental categories (stem trees and mature trees) and at two elevations (lower hill and upper hill) in a tropical forest in the central Peruvian Amazon, using species diversity, tree density, wood density, and forest structure. The study was conducted in two permanent measurement plots at different elevations. Data were collected using the Field Map Data Collector program on a laptop computer. Diameter at breast height (DBH) and total tree height were measured for individuals classified into two developmental categories: "stem trees" and "mature trees." Higher values of species diversity (3.9), uniform angle index (0.88), and dominance index (0.43) were recorded at the lowest elevation (low hill). In contrast, the highest elevation (high hill) had higher values for crown diameter (9.7), crown volume (518.2), species mixture index (0.93), average above-ground biomass (3.21), and total above-ground biomass (234.02), as well as average carbon sequestration (1.6) and total carbon sequestration (117.01). In conclusion, the study found that altitude, developmental category, species diversity, and tree density significantly influence the amount of carbon sequestered.

INTRODUCTION

Climate change is one of the main environmental challenges worldwide. Carbon dioxide is considered the primary greenhouse gas among the four that most significantly contribute to global warming. These include carbon dioxide (CO_2) (81%), methane (CH_4) (10%), nitrous oxide (N_2O) (7%), and halogenated gases such as chlorofluorocarbons (CFCs) (3%) (Houghton 2007). Atmospheric CO_2 levels have increased from pre-industrial concentrations of roughly 280 parts per million (ppm) to about 419 ppm globally(Bruhwiler et al. 2021). To understand its impacts, it is essential to analyze the above-ground biomass of forests (Winsemius et al. 2024), particularly that of old and intact tropical rainforests, whose carbon sequestration potential is progressively declining, mainly as a consequence of climate change (Heinrich et al. 2023). In this context, carbon dioxide capture and carbon sequestration play a crucial role in mitigating climate change (Raihan et al. 2021, Tadese et al. 2023). In fact, a 40 to 50% reduction in carbon sequestration and storage capacity has been reported in these ecosystems (Cuni-Sanchez et al.

2021), highlighting significant dynamic variations in carbon sequestration that directly affect atmospheric carbon dioxide concentrations (Ma et al. 2025).

A deeper understanding of how forest biomass and tree growth vary in relation to soil nutrient availability is essential for producing more accurate estimates of carbon stocks and carbon sequestration in tropical forests than those currently available (Paoli et al. 2008). Forest biomass refers to the total weight of organic material, either fresh or dry, found within a specific forest area over a given time period. Because it stores carbon, biomass serves as a key indicator for assessing forest productivity, stability, and sustainability (Cazzolla Gatti et al. 2015). Tropical forests, being the most diverse and productive ecosystems on Earth, play a critical role in global carbon and water cycles, as well as in preserving biodiversity (Gonzalez et al. 2021). Also, temperature and precipitation are key climatic factors that influence environmental conditions affecting surface forest carbon stocks. Forest structure shaped by species distribution, composition, and density is sensitive to climate-driven changes, which in turn affect forest productivity and ecological function (Rawat et al. 2020). Tropical forests serve as a major carbon sink (Lal 2005, Pan et al. 2011). Although they provide the essential ecosystem service of carbon sequestration, these forests are increasingly degraded by activities such as selective logging (Eguiguren et al. 2020) or completely cleared due to land-use changes for agriculture and livestock. In South America, deforestation accounts for a significant share of greenhouse gas emissions (Erb et al. 2018).

In Peru, a country with extensive forest cover, tropical forests play a fundamental role in carbon capture and storage (Cuellar & Salazar 2016). In this context, numerous studies have been conducted to estimate forest biomass using methodologies based on permanent plots and temporary plots (Corral-Rivas et al. 2009). These have become a key strategy for the periodic monitoring of forest structural dynamics, enabling a comprehensive assessment of forest ecosystem functioning and its carbon sources (Gutiérrez et al. 2015). They serve as an essential baseline for the development of conservation, management, and research plans, while also allowing for the analysis of the significant influence of tree diversity on above-ground biomass carbon - particularly within a context of high uncertainty regarding the complex interactions among species diversity, forest structure, and sequestered carbon (Li et al. 2022).

The calculation of carbon sequestration in living trees is based on the estimation of above-ground biomass, which is obtained using allometric equations that incorporate individual vegetation characteristics (Fernández-Guisuraga et al. 2024). Consequently, the accurate estimation of biomass is essential both for assessing carbon emissions and for understanding the potential release of carbon into the atmosphere (Brown 1997).

The study of forest area structure is crucial for sustainable forest management, as this structure is expressed through spatial attributes (such as tree distribution and interspecific competition) and non-spatial attributes (such as dominance or degree of mixing) (Hui et al. 2019, Ma et al. 2023). These attributes, together with tree species richness and forest area density, significantly influence carbon sequestration in forest ecosystems (Strassburg et al. 2010, Mensah et al. 2016, Zhang et al. 2017, Lan et al. 2019).

This influence is explained by the interactions that species establish with key ecological factors, such as soil nutrients, water availability, and access to sunlight, which directly regulate the carbon capture capacity in forests (Shirima et al. 2015). However, it is important to note that these processes can vary substantially depending on the type of ecosystem and its specific environmental conditions (Lan et al. 2019, Yuan et al. 2021). In this regard, some studies suggest that there may be a negative correlation between carbon storage and forest area density (Wang et al. 2022), which is attributed to increased intraspecific competition in denser areas, thereby limiting individual tree growth and, consequently, their potential for biomass and carbon accumulation.

Under this approach, a comprehensive study that systematically examines the mechanisms influencing sequestered carbon in forest ecosystems has yet to be developed. In particular, there is a lack of research that jointly analyzes the relationship between species diversity, tree density, wood density, forest structure, above-ground biomass, and sequestered carbon.

This study examined the following: (1) determination of species diversity, tree density, wood density, and forest structure at two elevations (lower hill and upper hill) of a Peruvian tropical forest, (2) determination of above-ground biomass with commercial value in two development categories (stem tree and mature tree) and at two elevations (lower hill and upper hill) of a Peruvian tropical forest, (3) determination of carbon stored in two development categories (stem tree and mature tree) and at two elevations (lower hill and upper hill) of a Peruvian tropical forest, (4) analysis of the relationships between species diversity, tree density, wood density, and forest structure with sequestered carbon in two development categories (stem tree and mature tree) and at two elevations (lower hill and upper hill) of a Peruvian tropical forest.

MATERIALS AND METHODS

Study Area

The sampled stem and mature trees were randomly chosen from permanent measurement plots established at two different elevations within a tropical forest in Tingo María, Huánuco region, Peru. The first plot was situated at 735 meters above sea level (9˚18′30.84″W-75˚59′40.84″N), while the second was at 875 meters (9˚18′49.14″ W-75˚59′14.67″N). Elevation data were determined using GIS software, which generated slope, altitude, and physiographic maps. The study area features a humid tropical climate characterized by two main seasons: dry and rainy. Meteorological records indicate an average annual temperature of 24˚C, total annual precipitation of 2,300 mm, and relative humidity exceeding 80%. The locations of the permanent plots at both elevations are illustrated in Fig. 1.

Experimental Data

Individual trees with a diameter over bark at breast height (DBH) equal to or greater than 10 cm were analyzed, distributed in 10,000 m² plots, each composed of 50 subplots of 400 m² (Phillips et al. 2016). The DBH measurement was conducted using a specialized diameter tape, model 283D.5m^{-1} from Forestry Suppliers Inc®. For this purpose, the radiation method was used, which consisted of recording the relative reference coordinates X, Y, and Z from a fixed point known as the "radiation post" (Salazar Espinoza 2018). Likewise, the Field Map Data Collector software, installed on a laptop, was used in conjunction with specialized equipment, including the TruPulse 360R laser rangefinder, the ARMOR, a tripod, an electronic compass, an electronic inclinometer, and a reflector. The latter was placed at the base of the evaluated individuals, as illustrated in Fig. 2.

For trees with buttress roots reaching up to 1.30 meters in height, the diameter was measured at a point 0.5 meters above the base of these roots. In cases where trees had deformities at the standard 1.30-meter measurement height, the diameter was recorded 2 cm below the deformity. For trees on sloped terrain, the diameter was measured at 1.30 meters along the direction of the steepest slope. For leaning trees, measurements were taken at 1.30 meters from the point of inflection in the trunk. Tree height was determined using the Field Map system (TruPulse 360R) by aiming a laser at the tree's base and the top of the crown. Data were automatically stored in the Field Map Data Collector software. Additionally, a laser rangefinder recorded horizontal distances to each tree, and an electronic inclinometer measured the inclination angles at both the base and the top of the trees. The collected data were then exported from the Field Map Project Manager to a spreadsheet in dBase format, compatible with Microsoft Excel, for further analysis, as illustrated in Fig. 3. The tree species in the studied plots were identified and certified by the Missouri Botanical Garden – HOXA Herbarium.

Species Diversity, Tree Density, Wood Density and Forest Structure

The quantification of tree species diversity at the two

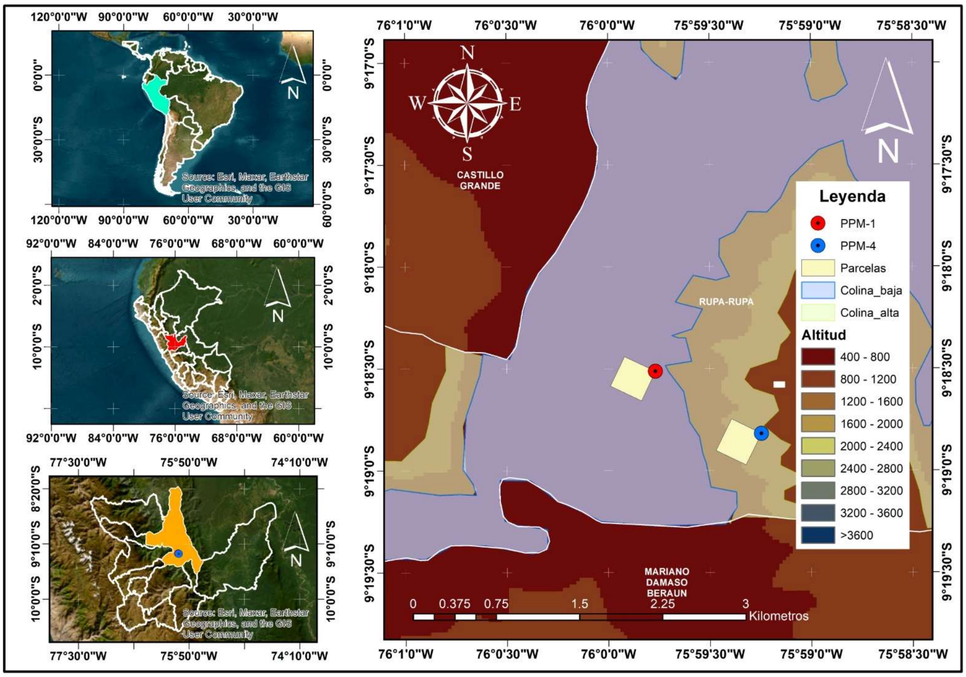


Fig. 1: Distribution of permanent measurement plots at the two elevations.

elevations was carried out using the Shannon-Wiener index (Shannon and Weaver, 1949), whose Equation 1 is as follows:

$$H' = -\sum(\mathrm{pi}\ln \mathrm{pi}) \qquad \ldots(1)$$

The variable H' represents the species diversity index for each plot, where pi denotes the relative abundance of species i within the overall population.

Tree density refers to the degree of occupancy of individuals within the evaluated plots at a specific point in time (Hernández Ramos et al. 2013).

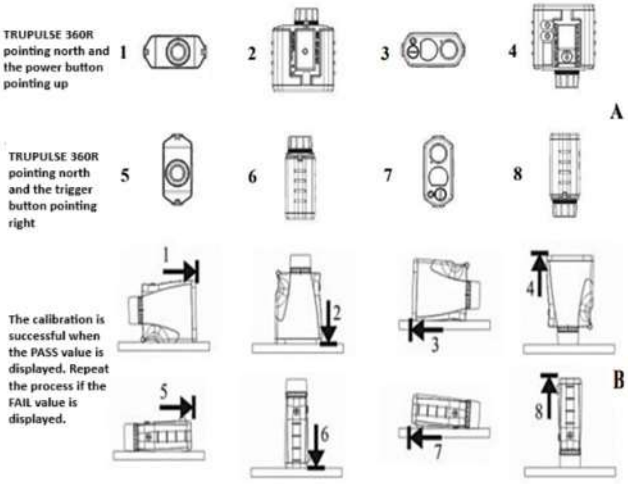
The structural conditions of the forest area at both elevations include spatial structure and crown structure. Crown volume is an essential metric for describing tree crowns, as it has a direct impact on biomass generation and significantly contributes to ecosystem services like sequestered carbon (Zhu et al. 2021). To describe these conditions, commonly used metrics such as crown diameter and crown volume were applied, using Equations 2 and 3.

$$\mathrm{CD} = \frac{1}{2}(\mathrm{CD1} + \mathrm{CD2}) \qquad \ldots(2)$$

$$\mathrm{CV} = \mathrm{CS} \times \mathrm{CH} \times \mathrm{CDmáx}^2 \qquad \ldots(3)$$

Where CD1 represents the crown measurement in the east-west direction, and CD2 represents the crown measurement in the north-south direction. CS indicates the crown shape, CH refers to the crown height, and CDmax denotes the maximum crown diameter value for each tree individual (Zhu et al. 2021).

The spatial structural parameters were also analyzed using the Wi (Aguirre et al. 2003), the Mi, and the neighborhood Ui (Hui et al. 2019), applying Equations 4, 5, and 6, respectively.



TRUPULSE 360R pointing north and the power button pointing up

TRUPULSE 360R pointing north and the trigger button pointing right

The calibration is successful when the PASS value is displayed. Repeat the process if the FAIL value is displayed.

Fig. 2: Methodology for locating the evaluated individuals.

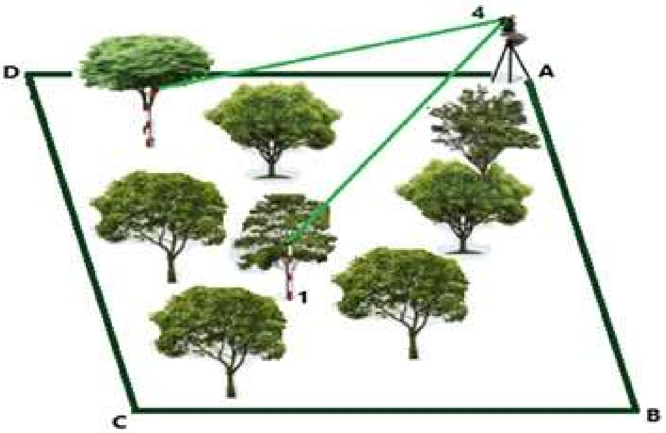


Fig. 3: Calibration procedure: A: Horizontal angle, B: Inclinometer sensor. Source: Adapted from Lasertech (2005).

These indicators allow for the characterization of the spatial distribution pattern of individual trees, the assessment of the degree of isolation among species, and the determination of size differentiation, taking into account different structural classes and conditions of the forest (Hui et al. 2019).

$$\mathrm{Wi} = \frac{1}{n}\sum_{j=1}^{n} v_{ij} \quad \text{...(4)}$$

Where vij equals 1 when the angle α between two neighboring tree individuals is less than or equal to the standard angle α=72∘, otherwise, it takes the value of 0. This parameter indicates the regularity or irregularity in the spatial distribution of tree individuals (Pommerening 2002, Aguirre et al. 2003).

$$\mathrm{Mi} = \frac{1}{n}\sum_{j=1}^{n} v_{ij} \quad \text{...(5)}$$

Where, $0 \leq \mathrm{Mi} \leq 1$, vij equals 0 when tree individual j is of the same species as the reference tree individual i, and will be 1 otherwise. This parameter indicates the diversity in spatial distribution (Graciano-ávila et al. 2020).

$$\mathrm{Ui} = \frac{1}{n}\sum_{j=1}^{n} v_{ij} \quad \text{...(6)}$$

Where, $0 \leq \mathrm{Ui} \leq 1$, vij will be equal to 1 if tree individual j is smaller than tree individual i (the reference tree), and 0 otherwise. This parameter indicates the relative dominance of a species in its immediate environment, through variables such as height or diameter (Graciano-ávila et al. 2020).

Above-Ground Biomass Values

Above-ground biomass was calculated using an allometric equation that considers three variables: total height, diameter at breast height, and basic wood density. This equation applies to tropical forest areas with an annual precipitation exceeding 3500 mm (Chave et al. 2014). The above-ground biomass was initially obtained in kilograms and then converted to tons. For this calculation, Equation 7 was used:

$$\mathrm{AGB} = 0.0673 \times (\mathrm{pD^2H})^{0.976} \quad \text{...(7)}$$

Where AGB is the above-ground biomass (kg), ρ is the basic wood density ($\mathrm{g\ cm^{-3}}$), D is the diameter at breast height (cm), and H is the total height (m).

Sequestered Carbon Calculation

Studies on sequestered carbon in tropical forests commonly use a conversion factor of 0.5 to estimate carbon content from above-ground biomass. This value is based on the assumption that approximately 50% of the total biomass of living trees corresponds to carbon (Yepes et al. 2011). Based on this, Equation 8 was applied to calculate the sequestered carbon.

$$\mathrm{SC} = \mathrm{AGB} \times 0.5 \quad \text{...(8)}$$

Where SC is the sequestered carbon (kg), AGB is the above-ground biomass (kg), and 0.5 is the conversion factor.

Statistical Analysis

To study the complex relationships between species diversity, tree density, wood density, and forest structure with above-ground biomass and sequestered carbon, correlation analysis and multiple regression analysis were statistically applied. The statistical software Past version 4.5.1 was used.

RESULTS AND DISCUSSION

Assessment of Species Diversity, Tree Density, Wood Density, and Forest Structure at Two Elevations (Lower Hill and Upper Hill)

The t-test showed statistically significant differences ($p < 0.05$) between the two elevations in species diversity, crown diameter (CD), and crown volume (CV). Conversely, no significant differences were observed in the uniform angle index (Wi), mixture degree (Mi), or dominance degree (Ui) ($p > 0.05$). The lower hill elevation exhibited the highest species diversity, while the upper hill had the greatest values for CD and CV (Table 1). Additionally, the lower hill recorded a higher number of individuals (680), whereas the upper hill demonstrated greater species richness (114).

Determination of Above-Ground Biomass With Commercial Value in Two Development Categories (Stem Tree And Mature Tree) AND At Two Elevations (Lower Hill and Upper Hill)

The t-test indicated statistically significant differences ($p < 0.05$) in both average above-ground biomass (AGB) and total above-ground biomass across the two elevations and developmental categories. The highest values in both metrics were observed in the "upper hill" elevation and the "mature

Table 1: Student t-test ($p < 0.05$) for SD: species diversity, CD: crown diameter, CV: crown volume, Wi: uniform angle index, Mi: mixture degree, Ui: dominance index.

Elevation	SD	CD	CV	Wi	Mi	Ui
Lower Hill	3.9 ± 0.0a	9.3 ± 3.0a	460.4 ± 272.2a	0.88 ± 0.2a	0.92 ± 0.2a	0.43 ± 0.4a
Upper Hill	3.6 ± 0.0b	9.7 ± 3.2b	518.2 ± 348.9b	0.76 ± 0.2b	0.93 ± 0.2a	0.42 ± 0.3a

Values on each horizontal line followed by the same letter do not differ significantly ($p = 0.05$)

Table 2: Student t-test ($p < 0.05$) for above-ground biomass in two development categories (stem tree and mature tree) and at two elevations (lower hill and upper hill).

Elevation	Developmental category	Average above-ground biomass [t]		Total above-ground biomass [t]	
Lower hill	Stem tree	0.22 ± 0.42a	0.32 ± 0.42a	141.89a	214.38a
	Mature tree	1.51 ± 0.44b		72.49b	
Upper hill	Stem tree	0.32 ± 1.46a	0.70 ± 1.72b	153.61a	387.64b
	Mature tree	3.21 ± 1.75b		234.02b	

Values on each horizontal line followed by the same letter do not differ significantly ($p = 0.05$)

Table 3: Student t-test ($p < 0.05$) for sequestered carbon in two development categories (stem tree and mature tree) and at two elevations (lower hill and upper hill).

Elevation	Developmental category	Average sequestered carbon [t]		Total sequestered carbon [t]	
Lower hill	Stem tree	0.11 ± 0.21a	0.16 ± 0.21a	70.94a	107.19^{a}
	Mature tree	0.76 ± 0.22b		36.25b	
Upper hill	Stem tree	0.16 ± 0.73a	0.35 ± 0.86b	76.81a	193.82b
	Mature tree	1.60 ± 0.87b		117.01b	

Values on each horizontal line followed by the same letter do not differ significantly ($p = 0.05$)

trees” category. Conversely, in the “lower hill” elevation, the stem tree category exhibited higher total above-ground biomass values (see Table 2).

Determination of Sequestered Carbon in Two Development Categories (Stem Tree and Mature Tree) and at Two Elevations (Lower Hill and Upper Hill)

The Student t-test indicated statistically significant differences ($p < 0.05$) in both sequestered carbon (SC) and total sequestered carbon across elevations and developmental categories. The “upper hill” elevation and the “mature trees” category exhibited the highest values in both average and total sequestered carbon. Conversely, in the “lower hill” elevation, the stem tree category displayed higher total sequestered carbon values (Table 3).

Analysis of the Relationships Between Species Diversity, Tree Density, Wood Density, and Forest Structure With Sequestered Carbon in Two Development Categories (Stem Tree and Mature Tree) and at Two Elevations (Lower Hill And Upper Hill)

The Pearson correlation analysis indicated a significant positive relationship between elevation and sequestered carbon ($p < 0.05$). It also showed highly significant positive correlations between developmental category, tree density, and species diversity with sequestered carbon ($p < 0.01$). Conversely, there was a highly significant negative correlation between mixture degree (Mi) and uniform angle index (Wi) with sequestered carbon ($p < 0.01$). Additionally, a strong positive association was found between tree density and species diversity (R2=0.82, $p < 0.01$), with a correlation coefficient exceeding 0.8 between CV and CD (Fig. 4). Elevation, developmental category, species diversity, and tree density all had a significant direct impact on sequestered carbon (Fig. 5).

The biplot derived from Principal Component Analysis (PCA) illustrates the relationships among sequestered carbon and other variables at different elevations—lower hill and upper hill. The PCA accounts for 99.90% of the total variability within the first two principal components, with PC1 explaining 99.86% and PC2 only 0.04%. A strong positive correlation is evident between sequestered carbon, the upper hill, and mature trees. Conversely, variables such as species diversity, wood density, mixture degree (Mi), uniform angle index (Wi), dominance index (Ui), crown diameter (CD), and tree density cluster near the origin of the plot, indicating no significant variation between elevations (Fig. 6).

The results indicated that variables such as elevation, developmental category, tree species, and mixture degree (Mi) significantly influenced sequestered carbon ($R^2 = 0.479$, $p < 0.05$, $p < 0.01$, and $p < 0.001$, Fig. 7). Among these, tree density showed the greatest influence on the response variable.

Discussion

Sustainable forest management is guided by predicting the potential and rate of carbon storage resulting from the relationships between the structural characteristics of forest areas, tree density, and carbon storage at a regional scale, as well as the influence, together with crown diameter and clustering degree, on the association between species diversity and the stability of forest *áreas* (Ma et al. 2025). Regarding the structural characteristics of the two elevations,

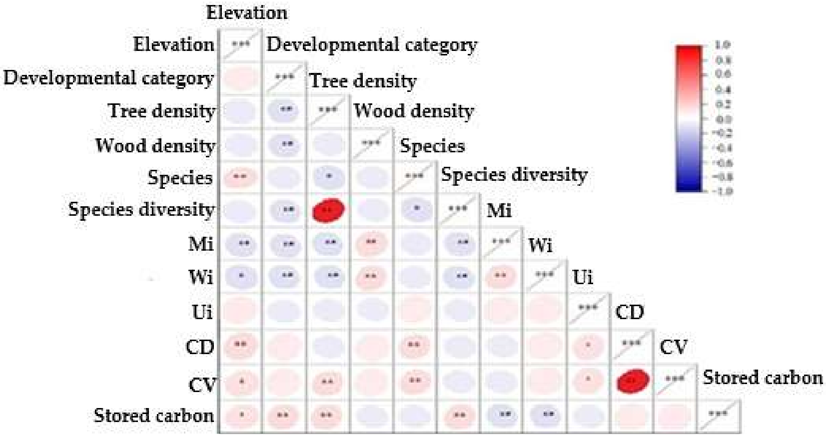


Fig. 4: Correlation analysis of structural factors, tree density, wood density, diversity, and sequestered carbon across the two elevations and two developmental categories. * indicates a significance level of 0.05, ** indicates a significance level of 0.01. Mi: mixture degree, Wi: uniform angle index, Ui: dominance index, CD: crown diameter, CV: crown volume.

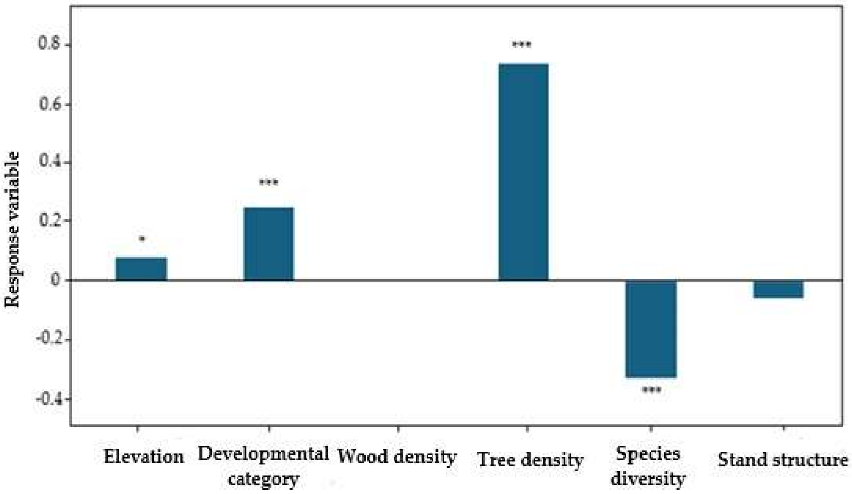


Fig. 5: Direct and indirect effects of the explanatory variables (elevation, developmental category, species diversity, and tree density) on the response variable (sequestered carbon) in the best-fitting statistical model. * and *** indicate significance levels of 0.05 and 0.001, respectively.

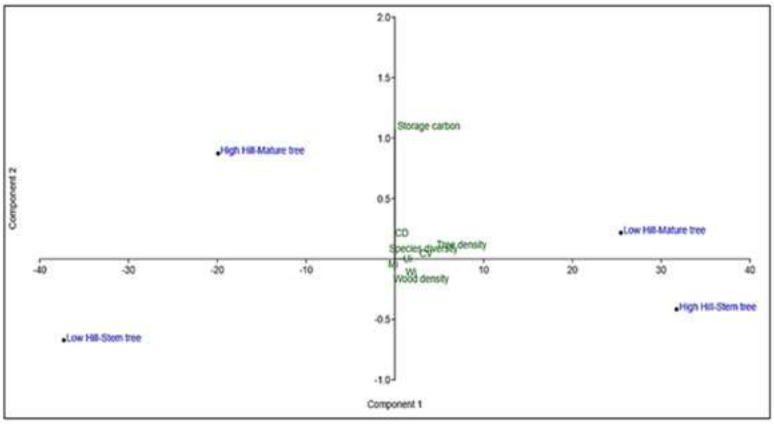
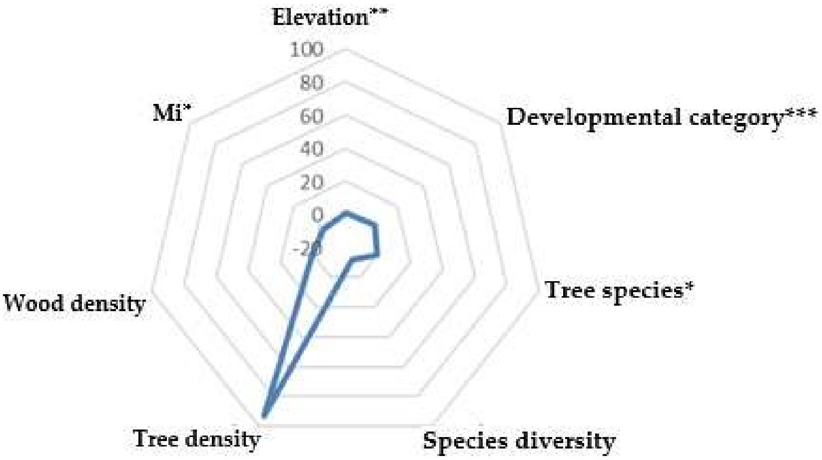


Fig. 6: Biplot of Principal Component Analysis (PCA) by elevation of storage carbon, wood density, tree density, and species diversity.



* indicates a significance level of 0.05, ** indicates a significance level of 0.01, *** indicates a significance level of 0.001. Mi: mixture degree, Wi: uniform angle index, Ui: dominance degree, CD: crown diameter, CV: crown volume.

Fig. 7: Multiple regression analysis of the developmental category, species diversity, tree species, wood density, elevation, mixture degree (Mi), and tree density.

the relationships of mixture degree (Mi), uniform angle index (Wi), and dominance index (Ui) are notable for their relevance in regulating competition status, crown formation, as well as seedling growth and survival. (Dong et al. 2020). The results for the mixture degree (Mi) indicate a higher species mixture in the upper hill; however, both elevations exhibit a very high degree of mixture. This finding is consistent with the studies of Rubio-Camacho et al. (2017), who reported high mixture values in protected natural areas. On the other hand, the uniform angle index (Wi) indicates a highly clustered distribution of individuals in the lower hill and a clustered distribution in the upper hill, with values close to 1 and 0.75, respectively. This classification contrasts with findings from several studies, which state that in natural forests or those with minimal disturbance, the spatial distribution of trees tends to be random (Aguirre et al. 2003).

The dominance index (Ui) reveals that both elevations exhibit height heterogeneity, being classified as codominant since the values obtained are close to 0.50. This suggests that two neighboring trees are taller than the reference tree, which can be attributed to competition among individual trees for resources such as light, water, and nutrients (Pommerening 2002, Li et al. 2012).

Regarding tree density, its influence on the efficiency of space utilization by individual trees, as well as on their morphology and growth, was confirmed. This is because the results show that higher tree density is associated with lower averages of sequestered carbon and total sequestered carbon, as a result of increased competition among trees and reduced crown volume, which limits their ability to capture essential resources such as light and heat (Liu et al. 2018).

In the upper hill, a higher percentage of large-sized individuals was recorded (88.5% with heights over 12.9 m), supporting the conclusions of (Thom & Keeton 2019), who indicated that tree density influences carbon storage, which is enhanced by the size of the trees. Likewise, in agreement with our results, the mature tree category showed the highest average amount of sequestered carbon, likely due to their ability to acquire and utilize greater amounts of nutrients through a well-developed root system and crown structure, key factors in carbon storage (Mensah et al. 2018). However, the effects of the stem tree category should not be underestimated, as in forest areas with a high number of individuals in this category, along with large and scattered trees, the forest's aboveground biomass remains stable (Boucher et al. 2021). On the other hand, the study results indicate that 29.2% of the individuals had wood densities below 0.50 kg cm^{-3}, yet they accounted for 49% of the total above-ground biomass and total sequestered carbon. These findings support the results of (Mensah et al. 2016), who demonstrated that species with low wood density tend to have higher above-ground biomass. The faster growth of species with lower density partly explains this (Wright et al. 2010). Our results also reveal a highly significant positive correlation between sequestered carbon and species diversity, which differs from the findings reported by(Ma et al. 2025), likely due to natural disturbances such as variations in tree density across elevations. Nonetheless, a significant and direct influence of species diversity on carbon sequestration was identified, in line with the findings of (Ma et al. 2025) and (Shirima et al. 2011) in various high-altitude forest communities. Furthermore, our results confirm the findings of (Zhao et al. 2020), showing that site conditions at each elevation directly influence productivity. This is because forest density and species diversity likely affect the stability of forest areas, which in turn impacts carbon storage (Ma et al. 2025). Variations in forest biomass may be linked to the interaction of abiotic factors such as temperature, precipitation, and nutrient availability (Rutishauser et al. 2015), to factors affecting vegetation regeneration, like landslides (Myster 2020), or to species-specific traits such as wood density (Keeling & Phillips 2007). On the other hand, the high carbon content stored in the montane forest may be attributed to its greater basal area compared to lower elevation forests. As noted by Cueva et al. (2019) and Jadán et al. (2020)Elevation tends to increase both forest density and basal area, which in turn leads to higher aboveground biomass. Additionally, differences in carbon stocks among forest species are influenced by factors such as tree diameter, age, wood density, and forest type (Brown 1997, Chave et al. 2006). Rojas-Vargas et al. (2019)also pointed out that carbon sequestration in ecosystems is closely linked to floristic composition, tree age, and wood density.

CONCLUSIONS

The effect of elevation has been recognized as an important factor in sustainable forest management. Regarding the structure of forest areas at each elevation, it is important to highlight the significant impacts of the mixing degree (Mi), the uniform angle index (Wi), and the crown diameter (CD) on forest dynamics. However, in this study, forest structure did not show a significant direct or indirect effect on sequestered carbon, suggesting that other factors, such as tree density, species diversity, and development stage, play a more substantial role in carbon storage. It is worth noting that tree density was the variable with the greatest direct influence on sequestered carbon, while elevation and species diversity also demonstrated significant positive associations with this process. Together, these results provide a solid scientific foundation for future research on carbon reservoirs in forest areas and offer valuable guidance for decision-making in sustainable forest management, thereby promoting the conservation and efficient use of forest resources across different elevations. For the Peruvian Amazon, integrating these factors into conservation and restoration strategies will optimize carbon sequestration and contribute to national climate commitments. Adaptive management that prioritizes forest density and maintenance will promote ecological sustainability and the well-being of local communities.

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