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Carbon Stock Assessment as an Indicator of Ecosystem Resilience in Talaga Warna, West Java

Penilaian Cadangan Karbon sebagai Indikator Ketahanan Ekosistem di Talaga Warna, Jawa Barat

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ABSTRACT

Global climate change underscores the need for nature-based mitigation to reinforce ecosystem resilience. Therefore, this research aimed to examine carbon stocks in Talaga Warna, West Java, and evaluate their potential as an indicator of ecosystem resilience. Data were obtained from three transects and six permanent plots using allometric equations to estimate tree biomass and carbon stocks. Vegetation was classified into functional groups, while species diversity and evenness were assessed using the Shannon-Wiener diversity index (*H′*) and Pielou's evenness index (J). The results showed that carbon stocks varied across transects and plots, with an average of 192.77 tC/ha. Canopy trees accounted for the largest share of total carbon, while other vegetation groups played smaller but significant roles. Plots with higher *H′* and J values showed more balanced carbon distribution. Based on observations, plots dominated by large species stored more carbon despite lower diversity. Correlation analysis presented a weak positive relationship (R^2=0.024) between species diversity and total carbon. This suggested that stand structure and the dominance of high-biomass species had a stronger influence than diversity alone. In conclusion, carbon stock had potential as a practical indicator of ecosystem resilience, reflecting the balance among stand structure, vegetation diversity, and ecological function in the montane forest.

INTISARI

Perubahan iklim global menegaskan perlunya mitigasi berbasis alam untuk memperkuat ketahanan ekosistem. Studi ini mengkaji cadangan karbon di Talaga Warna, Jawa Barat, serta mengevaluasi potensinya sebagai indikator ketahanan ekosistem. Data diperoleh dari tiga transek dan enam plot permanen menggunakan persamaan alometrik untuk mengestimasi biomassa pohon dan cadangan karbon. Vegetasi dikelompokkan ke dalam functional group, *sementara keanekaragaman dan keseragaman spesies dinilai menggunakan indeks keberagaman Shannon-Wiener (H′) dan indeks keseragaman Pielou (J). Cadangan karbon bervariasi antartransek dan antarplot, dengan nilai rata-rata 192,77 tC/ha. Pohon kanopi memberikan kontribusi terbesar terhadap total karbon, sedangkan kelompok vegetasi lain berkontribusi lebih kecil namun tetap signifikan. Plot dengan nilai H′ dan J lebih tinggi menunjukkan distribusi karbon yang lebih seimbang, sementara plot yang didominasi spesies berukuran besar menyimpan karbon tinggi meskipun keanekaragaman rendah. Analisis korelasi menunjukkan hubungan positif yang lemah* (R^2=0.024) *antara keanekaragaman spesies dan total karbon, yang mengindikasikan bahwa struktur tegakan serta dominansi spesies berbiomassa besar memiliki pengaruh lebih kuat dibandingkan keanekaragaman saja. Studi ini menyimpulkan bahwa cadangan karbon berpotensi sebagai indikator praktis ketahanan ekosistem, karena mencerminkan keseimbangan antara struktur tegakan, keanekaragaman vegetasi, dan fungsi ekologis pada hutan pegunungan, meskipun perannya perlu diinterpretasikan secara hati-hati.*

Introduction

The sustainability of ecosystems worldwide is under increasing pressure from global climate change. Rising concentrations of greenhouse gases, particularly carbon dioxide (CO_2), have accelerated global warming. This leads to disruptions in ecological functions, increased frequency of natural disasters, and a decline in biodiversity. Therefore, nature-based mitigation strategies are gaining increasing importance as effective measures to reduce these impacts. This is particularly through carbon sequestration in forest ecosystems, which serve as long-term carbon sinks and reservoirs (Turner et al. 2022).

Forest ecosystems play a crucial role in absorbing atmospheric greenhouse gas emissions and contribute to maintaining overall ecological stability (He et al. 2024). Carbon stock capacity reflects key aspects of ecosystem condition. It is closely associated with vegetation structure, species composition, and productivity, which together influence ecosystem stability and responses to disturbance (Turner et al. 2022; Li et al. 2023; Pretzsch & Hilmers 2024). Therefore, carbon-stock assessment provides valuable insights into forests' contributions to climate change mitigation and the long-term resilience of ecological systems (Dakos & Kéfi 2022).

In line with this perspective, the concept of ecosystem resilience has become an important indicator for evaluating the sustainability of conservation-area management. It describes the extent to which an ecosystem can tolerate stress, reorganize in response to disturbance, and re-establish stable functioning (Anamaghi et al. 2026). Regarding forest conservation, assessing the relationship between carbon stocks and ecosystem resilience can inform management strategies that emphasize carbon sequestration and the long-term sustainability of ecological functions (Turner et al. 2022).

Numerous studies on ecosystem resilience have examined ecological responses to various disturbances, including drought, forest fragmentation, and land degradation. However, most studies focus on recovery dynamics, disturbance intensity, and environmental drivers of resilience (Yi & Jackson 2021; Yao et al. 2022; Han et al. 2025). Research explicitly linking carbon stocks to indicators of ecosystem resilience remains limited, particularly in forest conservation areas in Indonesia. This knowledge gap is significant, as analyzing the correlation between carbon stocks and resilience is essential for evaluating ecosystem functioning and providing a scientific foundation for more comprehensive conservation and climate-mitigation strategies.

The Talaga Warna Nature Reserve (*Cagar Alam* – CA) and Nature Recreation Park (*Taman Wisata Alam* – TWA) are important conservation areas that play a crucial role in maintaining ecological and hydrological functions and preserving biodiversity. The area serves not only as a habitat for diverse flora and fauna but also as a provider of ecosystem services that support environmental stability in surrounding landscapes. Located within a montane forest ecosystem in West Java, it is characterized by relatively intact forest structure, diverse vegetation strata, and minimal disturbance in core zones. Hence, it is suitable for assessing the relationships between carbon stock and ecosystem resilience. Assessing carbon stocks in this area provides an opportunity to evaluate their role as a proxy for ecosystem resilience, particularly in conservation landscapes with dual management functions (protection and tourism), underscoring the relevance of selecting Talaga Warna as a research site.

This research aimed to quantify carbon stocks in the Talaga Warna Nature Reserve and Nature Recreation Park and evaluate the relationship with ecosystem resilience indicators, including vegetation structure and species diversity. By explicitly linking carbon stocks to ecological attributes, the potential of carbon stocks as a practical indicator of ecosystem resilience in montane forest conservation areas is established.

Methods

Research Location

This research was conducted at Talaga Warna Nature Reserve and Nature Recreation Park in Bogor Regency, West Java, in 2025. The area covered a total of 497.65 ha, consisting of 493.05 ha of nature reserve and 4.6 ha of nature recreation park. Furthermore, the landscape featured hilly topography, a montane forest ecosystem, and a natural lake that played an essential role in maintaining local hydrological functions. The area had dual management status, with the Nature

Figure 1. Map of Talaga Warna Nature Recreation Park and Nature Reserve

Reserve designated primarily for biodiversity protection and the nature recreation park for nature-based tourism activities. The combination of conservation and tourism functions made Talaga Warna a strategic site for assessing carbon-stock potential and evaluating ecosystem resilience. Spatial location, administrative boundaries, and landscape context of the research area are shown in Figure 1.

Data Collection

Sampling adopted transect-based and permanent-plot methods following the forest biomass and carbon measurement protocols introduced by Kauffman et al. (2016), with adaptations to suit the site's characteristics. Three transects were established to representatively span both management zones of the nature reserve and the nature recreation park, accounting for variations in land cover and vegetation characteristics. Each transect consisted of six observation plots, for a total of 18 sampling units. The plots served as the primary sampling units for carbon-stock estimation. This design was intended to capture the overall ecological conditions of the area and to support research replicability and reproducibility in future assessments.

Vegetation data were collected by measuring tree parameters within each plot, including diameter at breast height (DBH) and species identification, to facilitate biomass estimation. All vegetation with a DBH larger than 5 cm was recorded within a circular plot with a 10 m radius. Smaller vegetation (DBH < 5 cm) was measured within a nested subplot with a 2 m radius to capture understory components. In addition to tree biomass, other carbon pools were assessed to provide a more comprehensive estimation. Understory vegetation and litter were sampled at designated subplots, while dead wood was measured using line transect methods at each plot. Soil samples were collected at specified depths to estimate belowground carbon content. Additionally, vegetation measurements were used to calculate carbon stock, which served as the basis for evaluating ecosystem resilience indicators. The overall sampling plot design is illustrated in Figure 2, while the transect and soil sampling points within the study area are shown in Figure 3.

Tree biomass was estimated using standard allometric equations appropriate for montane forest vegetation in the research area. Carbon stock was estimated from biomass using a conversion factor of

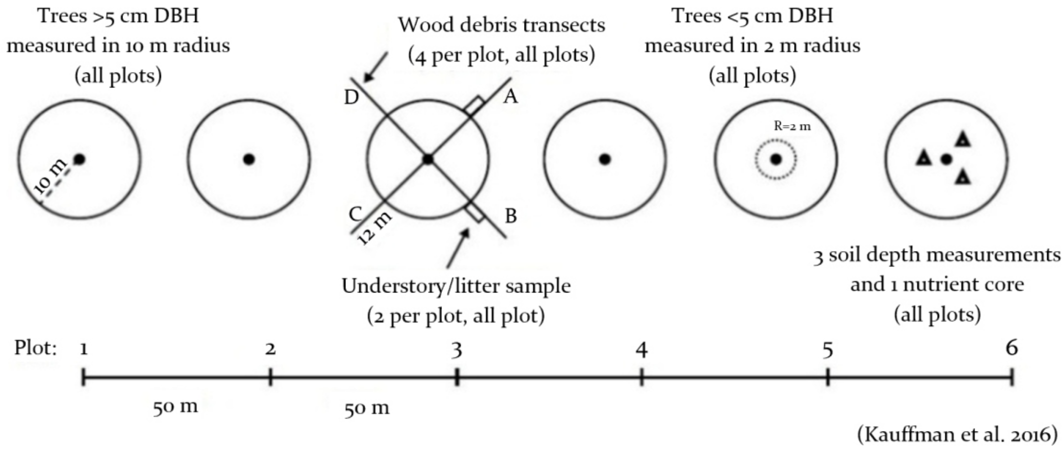

Figure 2. Schematic diagram of the sampling plot design

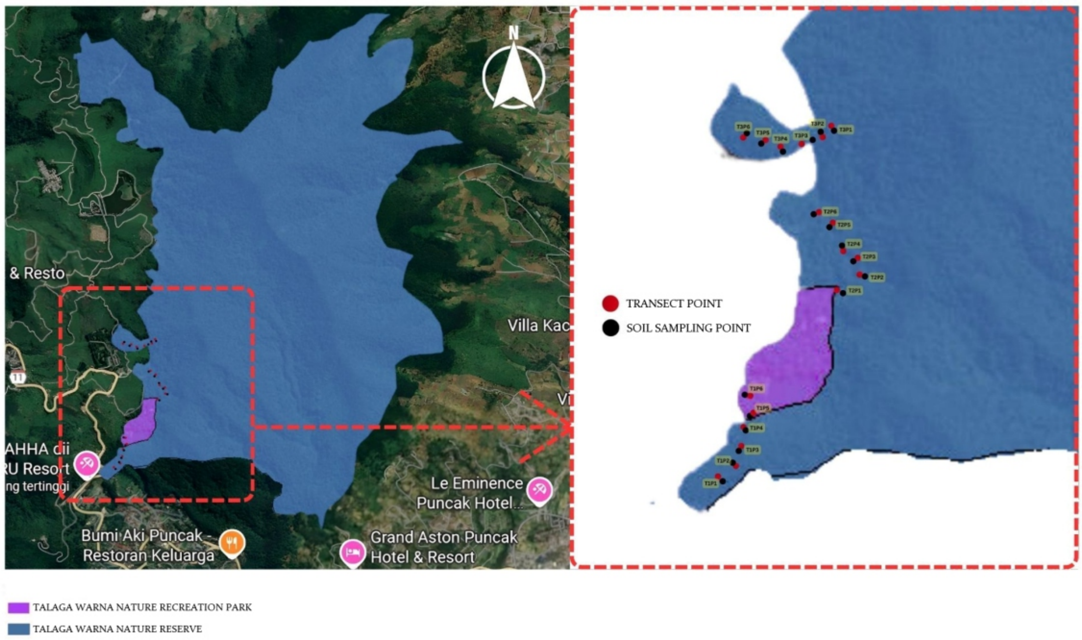

Figure 3. Spatial distribution of transects and soil sampling points in the study area

0.47. This represented the average proportion of carbon contained in dry biomass (Intergovernmental Panel on Climate Change 2006). The calculations for biomass produced values for both belowground carbon (BGC) and aboveground carbon (AGC) (Kurtz et al. 2024). Total carbon stock per plot was calculated as the sum of aboveground biomass (AGB), below-ground biomass (BGB), dead organic matter, and soil carbon pools, expressed in tons of carbon per hectare (tC/ha).

Data Analysis

Vegetation Structure

Vegetation structure for each plot was characterized using formulas derived from established forest ecology literature. The calculations included basal area (the cross-sectional area of trees at breast height), density (number of individuals/unit area), canopy cover percentage (proportion of ground area shaded by tree crowns), and species dominance (total basal area contributed by each species), which collectively described the primary characteristics of stand structure (Ahmad et al. 2025). Basal area was calculated from DBH measurements, where DBH refers to diameter at breast height (typically 1.3 m above the ground). Density was calculated as the number of individuals per unit area, and canopy cover was estimated from crown projection area. Species dominance was determined by the total basal area contributed by each species within a plot. Carbon

Table 1. Equations and descriptions of vegetation structure characteristics

No.	Vegetation Characteristics	Equation	Description	Source
1	Carbon Stock (Cb)	Cb = B x %C organic	Cb=Carbon content of biomass (kg) B=Totalbiomass (kg) %C Organic= percentage value of carbon content, 0.47 or using the carbon percentage value obtained from laboratory measurements.	(Arifanti et al. 2014)
2	*Basal Area* (BA)	$BA = \pi \times \left(\frac{DBH}{2}\right)^2$	BA = basal area of the tree stem (m^2); DBH = diameter at breast height (m); π = 3.1416 (constant).	(Tiwari et al. 2022)
3	Density	$D = \left(\frac{N}{A}\right)$	D = individual density per unit area (ind/ha or ind /m^2); N = number of trees within the plot; A = plot area (ha or m^2).	(Pretzsch & Hilmers 2024)
4	Percentage Canopy (% *Canopy Cover*)	$\% \text{ Canopy} = \left(\frac{\sum \text{Crown Area}}{\textit{Plot Area}}\right) \times 100$	Σ Crown Area = total projected crown area of all trees (m^2); Plot area = total sampled area (m^2); 100 = conversion to percent (%).	(Jennings et al. 1999)
5	Crown Area (Sub-formula)	$\text{Acrown} = \pi \times \left(\frac{d}{2}\right)^2$	$A_{(crown)}$ = individual crown area (m^2); d = crown diameter (m); π = 3.1416 (constant).	(Jennings et al. 1999)
6	*Species Dominance* (m^2/ha)	$Dom = \left(\frac{\sum \text{BA species}}{\textit{Plot Area}}\right)$	Σ BA Species = total basal area of a species (m^2); Plot area = total sampled area (m^2);	(Nursanti et al. 2021)

stock data were first analyzed using descriptive statistics, including mean, minimum, maximum, and standard deviation, to characterize variability across plots and transects. These followed methodologies applied in tropical forest carbon research in Ethiopia by Obonyo et al. (2023). The formulas and notation descriptions are presented in Table 1.

Ecosystem Resilience Indicators

Ecosystem resilience assessment in this research was based on an indicator-driven method. An integrative ecological indicator framework that incorporated ecosystem function, structure, and responses to environmental stressors, and all equations in this section were adopted from Flensborg et al. (2023). This method enabled a holistic evaluation of ecosystem resilience in the Talaga Warna landscape. Resilience indicators included functional group richness, redundancy, Shannon-Wiener diversity index (*H′*), and Pielou's evenness index (*J*). Functional group richness represented the number of functional groups within each plot, while redundancy reflects the average number of species within each functional group. *H′* and J were calculated to quantify species diversity and distribution uniformity at plots. These metrics were selected to represent ecological stability and the distribution of functional roles in the ecosystem. All equations and detailed formulations for the indicators are presented in Table 2.

Meanwhile, Johnson et al. (2025) served as the primary reference for developing the ecosystem resilience index, which incorporated characteristics related to vegetation function (total carbon stock), structure, and composition (species diversity). Through this method, the indicators used were expected to provide a comprehensive depiction of forest ecosystem resilience and offer an integrated understanding of the system's ability to maintain ecological stability within the Talaga Warna Nature Reserve and Nature Recreation Park.

Linking Carbon Stock and Ecosystem Resilience Indicators

To examine the relationship between carbon stock and ecosystem resilience indicators, a simple linear regression analysis was applied using the model: Y = a + βX, where Y represents total carbon stock (tC/ha), X represents the Shannon-Wiener diversity index (H′), a represents the intercept, and β represents the regression coefficient. This regression analysis was adopted to evaluate the extent to which variation in species diversity explained variation in carbon stock. Prior to regression analysis, data were visually inspected using scatter plots to assess linearity. The strength of the relationship was evaluated through the coefficient of determination (R^2). Given the exploratory

Table 2. Description of ecosystem resilience indicators and the metrics used for the quantification (Flensborg et al. 2023)

Resilience category	Metric notation	Equation	Symbols used in equation	Output	Range	Referense
Functional group richness	Richness	$Richness = \sum_i x$	x = number of functional groups (FG)	Mean number of FG per ICES rectangle	>1	(Symstad 2000)
Functional group redundancy	Redundancy	$Redudancy = \frac{N}{\sum_i x}$	x = number of functional groups (FG); N = number of species	Mean number of species per FG per ICES rectangle	>1	(Legendre & Anderson 1999)
Functional group evenness	EvennessSh	$H' = -\sum_{i=1}^{S} P_i \, InP_i$	Pi = ni /N; ni = abundance of species i; N = total individuals	Mean Shannon–Wiener diversity index per FG	0–1	(Roswell et al. 2021)
Functional group evenness	EvennessPE	$J = \frac{H'}{\ln(S)}$	H' is the Shannon–Wiener diversity index. ln (S) = maximum equitability diversity	Mean Pielou's evenness index per FG	0–1	(Pielou 1966)
Functional group response diversity	Response diversitysyn	$Syn = \frac{\sigma(n_T)^2}{(\sum_i \sigma(n_i))^2}$ With: $n_T(t) = \sum_{i=1}^{N} n_i(t)$	$\sigma(n_T)^2$= variance of aggregated species abundances $\sigma(n_i)$ = variance of individual species abundances	Synchrony-mean variance per FG	0–1	(Ross et al. 2023)
Functional group response diversity	Response diversitypoe	$log(\sigma_i^2) = \beta_o + z \, . \, log(\mu_i) + \varepsilon_i$	z = slope; μ_i = mean abundance; ε_i = residual error	Portfolio effect–mean variance per FG	>0	(Ross et al. 2023)

"For most metrics, larger values reflect greater potential ecosystem resilience, while lower values show the opposite. An exception is the Syn metric, where values approaching 1 signify reduced response diversity and hence lower resilience. Values presented in the figures represent averages across functional groups for each grid cell, derived from 100 bootstrap resampling iterations"

nature of the research, a regression analysis was used to identify general patterns rather than to establish strong predictive relationships. All statistical analyses were conducted using standard spreadsheet-based calculations.

Result and Discussion

Vegetation Structure Characteristics

Vegetation-structure analysis was conducted to determine the species composition and dominance within each observation plot (Li & Wei 2024). Table 3 showed variations in vegetation structure across all observation plots within the three transects, including individual density, basal area, canopy cover percentage, and the species with the highest dominance values. Both density and basal area varied among plots, reflecting differences in tree size and abundance at each location. Canopy-cover percentages exceeded 100% in several plots, which suggested overlapping crowns among trees, particularly in areas dominated by broad-canopied species such as *Castanopsis javanica*. The species also appeared to be the most dominant in most plots, underscoring its substantial role in shaping stand structure and in contributing to carbon stocks. The variation observed across parameters showed ecological heterogeneity within the Talaga Warna forest ecosystem, characte-rized by differences in vegetation density, tree size, and dominant species composition. This heteroge-neity suggests that carbon stocks were primarily influenced by stand structural attributes rather than by uniform species distribution, underscoring the importance of tree size and dominance in carbon accumulation.

Ecosystem Resilience Indicators

Vegetation carbon stocks were derived from biomass calculations using allometric equations, producing both BGC and AGC components. The field measurement revealed that carbon stock in the montane forest of the Talaga Warna Nature Reserve (CA) and Nature Recreation Park (TWA) varied considerably across transects and plots (Table 4). This high variability was closely related to differences in stand structure and species composition. Plots dominated by large canopy trees store significantly higher carbon stocks than those dominated by understory vegetation or shrubs. Based on observat-ion, large trees contributed disproportionately to tropical forest carbon stocks (Li et al. 2026). This pattern showed that biomass accumulation was strongly controlled by tree size distribution and stand

Table 3. Vegetation structure characteristics across transects and plots

Transect	Plot	Density (ind/m2)	Basal Area (m2)	Canopy Cover (%)	Dominant Species	Dominance (m2/ha)
T1	P1	0.13	3.43	275.20	Castanopsis javanica	94.50
	P2	0.12	1.17	58.41	Castanopsis javanica	14.84
	P3	0.08	0.97	30.72	Turpinia sphaerocarpa	8.50
	P4	0.22	1.42	124.02	Castanopsis javanica	23.58
	P5	0.11	1.73	20.12	Villebrun erubescens	32.54
	P6	0.06	3.47	189.59	Lithocarpus elegans	35.14
T2	P1	0.14	1.11	9.39	Musa acuminata	10.30
	P2	0.10	0.58	0.00	Litsea diversifolia	7.61
	P3	0.21	2.60	124.45	Lithocarpus pseudomoluccus	32.88
	P4	0.21	0.56	0.00	Saurauia bracteosa	6.31
	P5	0.19	1.41	50.45	Magnolia sumatrana	22.20
	P6	0.22	2.00	19.24	Trema orientalis	26.30
T3	P1	0.32	2.36	74.41	Turpinia sphaerocarpa	17.76
	P2	0.30	4.31	226.32	Castanopsis argentea	57.63
	P3	0.20	1.95	11.45	Neolitsea cassiaefolia	20.80
	P4	0.23	0.98	47.54	Magnolia sumatrana	7.13
	P5	0.25	1.28	87.02	Castanopsis javanica	16.72
	P6	0.21	2.58	235.59	Castanopsis javanica	57.96

Table 4. Carbon stock/transects and plot in the Talaga Warna area (tC/ha)

Transect	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Average
1	370.27	108.19	92.44	132.80	483.34	87.30	212.39
2	97.86	50.23	289.30	51.00	139.54	196.01	137.33
3	234.76	502.17	187.80	82.80	107.45	256.60	228.60
			Total Average				192.77

Table 5. Species richness, redundancy, Shannon-Wiener diversity index (*H*)', and Pielou's evenness index (J) per transect and plot in the Talaga Warna area

Transect	Plot	Total Individuals (N)	Number of Species (S)	FG Richness Amount	Redundancy (N/S)	Shannon-Wiener diversity Index (*H'*)	Pielou's Evenness index (J)
T1	P1	41	19	4	4.75	1.17	0.84
T1	P2	37	14	5	2.80	1.61	1.00
T1	P3	24	17	3	5.67	1.05	0.96
T1	P4	69	21	5	4.20	1.18	0.73
T1	P5	36	18	4	4.50	1.18	0.85
T1	P6	18	10	4	2.50	1.35	0.98
T2	P1	45	14	4	3.50	1.22	0.88
T2	P2	30	5	2	2.50	0.24	0.35
T2	P3	66	15	4	3.75	0.70	0.51
T2	P4	66	12	3	4.00	0.60	0.55
T2	P5	60	15	4	3.75	0.86	0.62
T2	P6	68	10	5	2.00	0.93	0.58
T3	P1	99	25	5	5.00	1.21	0.75
T3	P2	94	31	5	6.20	1.29	0.80
T3	P3	64	15	5	3.00	1.27	0.79
T3	P4	73	30	5	6.00	1.43	0.89
T3	P5	80	14	5	2.80	1.34	0.83
T3	P6	65	13	4	3.25	0.99	0.72
Average		57.50	16.56	4.22	3.90	1.09	0.76

Remarks: T1-3=Transect 1–3; P1-6=Plot 1-6

maturity, rather than solely by species richness.

To assess whether carbon stock possessed the ability to serve as an indicator of ecosystem resilience, functional–group metrics for each plot, namely richness, redundancy, Shannon-Wiener diversity index (*H'*), and Pielou's evenness index (J), were calculated, as detailed in Table 5. The Shannon diversity index (*H'*) and evenness index (J) provided additional insights into ecosystem resilience. Plots with high *H'* and J values (e.g., T1–P2 and T3–P4) showed a more even distribution of species, leading to more even carbon contributions across functional groups. This supports the view that functional diversity enhances ecosystem stability by reducing dependence on a single vegetation group (Pielou 1966). However, higher diversity rarely coincided with greater total carbon stocks, indicating that diverse communities promote ecosystem balance more than they increase total biomass.

The distribution of carbon stocks across functional groups reflected the contribution of each vegetation layer to the total ecosystem carbon pool. The groups assessed include canopy, mid-story, and understory trees, shrubs/herbs, as well as lianas/climbers. Canopy trees stored the highest carbon stock, followed by the mid-story and understory layers. Table 6 shows that differences in carbon contributions among functional groups were evident across transects and plots. These distribution patterns underscored the dominant role of canopy trees in determining total ecosystem carbon. Other groups, though contributing smaller amounts, remained ecologically significant in maintaining ecosystem balance. Lower vegetation strata contributed less to carbon stock, but played an important role in maintaining structural complexity and supporting regeneration processes, which were essential components of ecosystem resilience.

Relationship between Carbon Stock and Ecosystem Resilience Indicators

A simple linear regression analysis was conducted to examine the relationship between *H′* and total carbon stock (tC/ha). Prior to the analysis, data were visually assessed using a scatter plot (Figure 4) to evaluate linearity and the absence of extreme outliers. It is important to note that regression assumptions, such as linearity and homogeneity of variance, were

Table 6. Carbon-stock distribution by functional group (tC/ha)

Transect	Plot	Carbon Stock (tC/ha)					
		Total Carbon	Canopy	Mid-Story	Understory	Shrubs/Herbs	Liana/Climber
T1	P1	370.27	363.76	1.89	4.45	0.17	0.00
T1	P2	108.19	64.19	13.20	17.60	5.12	8.08
T1	P3	92.44	29.39	34.76	28.29	0.00	0.00
T1	P4	132.80	111.24	13.25	7.12	0.77	0.42
T1	P5	483.34	323.90	131.32	20.36	0.00	7.77
T1	P6	87.30	0.00	30.26	0.95	2.95	53.15
T2	P1	97.86	7.56	22.43	42.62	25.25	0.00
T2	P2	50.23	0.00	47.62	2.62	0.00	0.00
T2	P3	289.30	212.89	56.68	19.71	0.03	0.00
T2	P4	51.01	0.00	15.36	27.00	8.65	0.00
T2	P5	139.54	75.51	30.87	33.14	0.03	0.00
T2	P6	196.01	22.25	1.26	123.89	44.30	4.31
T3	P1	234.76	86.74	71.30	53.68	2.81	20.23
T3	P2	502.17	414.71	31.41	39.07	0.35	16.63
T3	P3	187.80	11.68	103.04	50.42	20.40	2.25
T3	P4	82.80	38.53	29.83	3.81	5.16	5.48
T3	P5	107.45	60.74	5.98	19.21	5.89	15.63
T3	P6	256.60	247.95	5.58	1.06	2.02	0.00
Average		192.77	115.06	35.89	27.50	6.88	7.44

Remarks: T1-3=Transect 1–3; P1-6=Plot 1-6

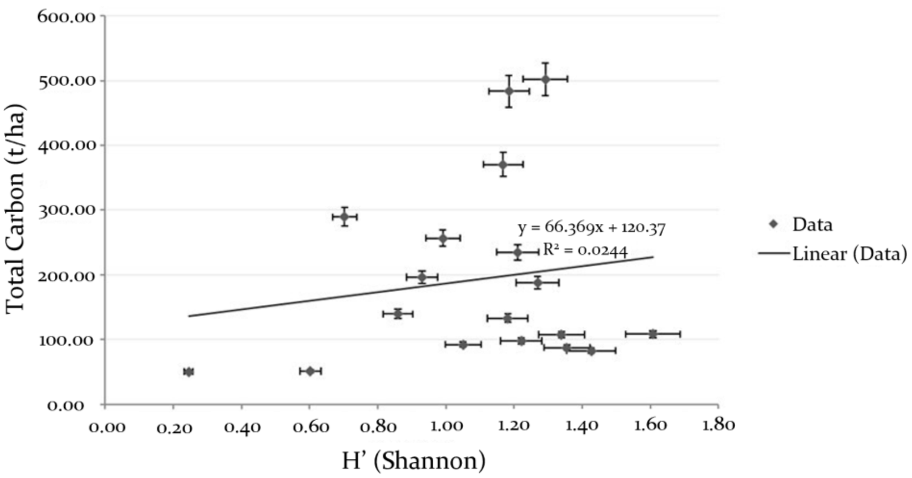

Figure 4. Scatter plot and the regression line between *H′* and total carbon of each plot (tC/ha)

assessed visually, and no formal statistical tests were conducted. Given the limited sample size (n=18), the analysis was treated as exploratory, and results were interpreted cautiously. The regression results should be interpreted as more indicative than conclusive. The regression model (Y = 66.37X + 120.37) produced a very low coefficient of determination (R^2=0.024), suggesting that species diversity explains only a small proportion of the variation in carbon stock. Although the regression coefficient was positive, the relationship was weak and insufficient to establish a strong predictive link between diversity and carbon stock. The result showed that carbon stock in the Talaga Warna ecosystem was more strongly influenced by stand structure, particularly the presence of large trees and dominant species, rather than species diversity alone. Therefore, diversity should be interpreted as contributing to ecosystem stability and functional balance rather than directly determining carbon magnitude.

Research in the sub-montane forest of Mount Halimun Salak National Park (Taman Nasional Gunung Halimun Salak - TNGHS) reported stand carbon stocks of 185.18 tC/ha (Arifanti et al. 2014). This reflects the characteristics of a primary montane forest with relatively intact stand structure. The value was lower than that in Bukit Tigapuluh National Park, which reached 269 tC/ha (range 247–291 tC/ha) in protected primary and secondary forests (Darmawan et al. 2022). However, it was considerably higher than coastal forests in Hatusua, Maluku, which stored only approximately 89.41 tC/ha (Irwanto et al. 2024). These differences showed that factors such as elevation, the size of dominant trees, stand density, and human disturbance strongly influenced the magnitude of carbon stock. Although carbon stock in TNGHS was lower than in Bukit Tigapuluh, the dense sub-montane canopy still made the forest a significant carbon reservoir compared with lowland or coastal ecosystems. This comparison reinforced those structural characteristics, rather than diversity, were key determinants across different forest types.

This research observed contrasting patterns between diversity and carbon stock, confirming that high carbon stock occurred in low-diversity stands dominated by large trees, while high diversity was associated with lower biomass in regenerating forests. Diversity shows a nonlinear relationship with carbon stock, and carbon accumulation was primarily driven by structural attributes rather than species richness (Nord-Larsen et al. 2019). The results suggest that carbon stock did not fully reflect ecosystem resilience but served as a partial indicator when combined with vegetation structure and diversity, underscoring the importance of using multiple ecological indicators when assessing ecosystem resilience in forest conservation areas.

Conclusion

Carbon stocks in the Talaga Warna Nature Reserve and Nature Recreation Park varied across transects and plots, primarily influenced by differences in stand structure and species composition. Plots dominated by large canopy trees stored significantly higher carbon, confirming the important role of tree size and structural characteristics. Although H′ and J contributed to a more balanced distribution of carbon among functional groups, the relationship between diversity and total carbon stock was weak. This showed that diversity played a greater role in maintaining ecosystem structure and balance. The results suggest that carbon stock did not fully reflect ecosystem resilience but served as a complementary indicator when combined with vegetation structure and diversity. Therefore, assessments of ecosystem resilience in montane forests should incorporate multiple ecological indicators to capture both structural and functional aspects of the ecosystem. From a management perspective, maintaining stand structure, particularly the presence of large trees alongside conserving species diversity, was essential for sustaining both carbon stock and ecological stability. Long-term monitoring using permanent plots was recommended to better understand temporal changes in carbon dynamics and ecosystem responses to disturbance.

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