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Species richness and carbon stock assessment in Southeast Asian wildlife sanctuary forests

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Abstract

Southeast Asian wildlife sanctuaries harbour exceptionally diverse tropical forests that function as important carbon reservoirs, yet systematic assessments linking species richness to carbon stocks within these protected landscapes remain limited. This research assessed tree species richness and estimated carbon stocks across five sampling sites within a wildlife sanctuary forest in West Java, Indonesia. A total of sixteen plots of 20 m × 20 m were established between March and November 2023 across lowland dipterocarp, hill dipterocarp, and montane forest formations. All trees with diameter at breast height of 10 cm or greater were inventoried and measured. Above-ground biomass was estimated using regional allometric equations validated for Indonesian dipterocarp forests. The inventory documented 1,285 trees belonging to 72 species across 32 families. Dipterocarpaceae dominated with eleven species representing 28% of total basal area. Shannon-Wiener diversity ranged from 2.85 in montane forest to 3.72 in lowland dipterocarp formations. Total carbon stocks including above-ground, below-ground, and litter components averaged 142.8 Mg C per hectare across all sites, with lowland dipterocarp forest showing the highest values at 195.2 Mg C per hectare. A significant positive relationship was observed between tree height and above-ground biomass across species. Carbon pool analysis revealed that above-ground biomass contributed 72% of total carbon stocks, followed by below-ground biomass at 18% and litter at 10%. These results demonstrate that wildlife sanctuary forests in Southeast Asia maintain carbon stocks comparable to or exceeding those of primary production forests, reinforcing the critical role of protected area networks in regional carbon management strategies.

Keywords: Species richness, carbon stock, wildlife sanctuary, dipterocarp forest, above-ground biomass, allometric equations, Southeast Asia, Indonesia, protected areas

Introduction

The forests of Southeast Asia have experienced some of the highest rates of deforestation and degradation globally over the past four decades, yet they continue to harbour exceptional biodiversity and substantial carbon reserves within remaining intact formations ^[1, 2]. Historically, the recognition of Southeast Asian forests as critical carbon sinks predates the modern era of climate change research, with early forestry inventories from the colonial period documenting the extraordinary timber volumes characteristic of dipterocarp-dominated stands ^[3]. These historical observations anticipated contemporary findings that position tropical Asian forests among the highest-biomass ecosystems on Earth.

Wildlife sanctuaries within the Southeast Asian landscape serve as refugia for threatened flora and fauna while simultaneously maintaining forest carbon stocks that would otherwise be released through conversion to agriculture or plantations ^[4]. The relationship between species richness and ecosystem carbon storage in these sanctuaries represents a convergence of conservation and climate interests, yet empirical data remain insufficient to fully characterize this relationship across the diversity of forest formations present within protected landscapes ^[5].

Indonesian forests in particular represent a globally

significant carbon pool, with above-ground biomass estimates for dipterocarp forests ranging from 150 to 350 Mg dry biomass per hectare depending on forest type and disturbance history ^[6, 7]. The dipterocarp family, which dominates the canopy of lowland and hill forests throughout the Sundaic region, includes species with exceptionally high wood densities and growth potential, making these forests among the most carbon-dense in the tropics ^[2].

Allometric biomass estimation in Southeast Asian forests has progressed substantially with the development of region-specific equations that account for the distinctive architectural properties of dipterocarp and non-dipterocarp species ^[8]. However, the application of these equations within wildlife sanctuaries, where forest structure may differ from production forests due to historical management practices and wildlife impacts, requires validation ^[9].

This research aimed to assess tree species richness and estimate multi-pool carbon stocks within a wildlife sanctuary forest in West Java, Indonesia, and to evaluate the influence of forest formation type on species composition and carbon storage capacity.

Material and Methods

Material

The research was conducted within a wildlife sanctuary

forest located in the highlands of West Java Province, Indonesia (6°45'S, 106°55'E), and encompassing approximately 4,200 hectares across an elevational gradient from 350 to 1,450 m above sea level. The climate is classified as Af (tropical rainforest) under the Köppen system, with mean annual rainfall of 3,200 mm and mean annual temperature ranging from 18°C at higher elevations to 27°C at lower elevations. The sanctuary was designated in 1992 and encompasses three principal forest formations: lowland dipterocarp forest (350-750 m), hill dipterocarp forest (750-1,100 m), and lower montane forest (1,100-1,450 m). Soils are predominantly volcanic andosols and latosols. Research authorization was obtained from the Indonesian Ministry of Environment and Forestry (SIMAKSI Permit No. SI.234/BTNGHS/PPA/2023) and the ethical clearance committee of the Jakarta Academy of Forestry Sciences.

Methods

Field measurements were conducted between March and November 2023. A stratified random sampling design was employed with sixteen plots of 20 m × 20 m distributed across five sampling sites spanning the three forest formations: six plots in lowland dipterocarp, six in hill dipterocarp, and four in lower montane forest. Within each plot, all trees with DBH of 10 cm or greater were identified using taxonomic keys specific to Javanese flora. DBH was measured at 1.3 m height, total tree height was estimated

using a Suunto clinometer, and crown dimensions were recorded.

Above-ground biomass was estimated using the regional allometric equation developed by Basuki *et al.* (2009) for Indonesian tropical forests: $AGB = \exp(-1.201 + 2.196 \ln(D) + 0.445 \ln(H) - 0.207 \ln(D)^2)$, where D is DBH and H is total height. Below-ground biomass was calculated as 25% of AGB following the root-to-shoot ratio established for Southeast Asian tropical forests. Litter biomass was measured by collecting all litter material within four 1 m × 1 m subplots per plot, oven-drying at 70°C for 72 hours, and weighing. Carbon content was assumed at 47% of dry biomass for all pools. Species diversity was calculated using Shannon-Wiener and Simpson indices. Carbon pool contributions were analysed by site and formation type. Statistical comparisons employed Kruskal-Wallis tests and Dunn's post-hoc procedure, with significance set at $p < 0.05$. All analyses were performed using R version 4.3.1.

Results

The inventory across sixteen plots documented 1,285 trees belonging to 72 species and 32 families. Dipterocarpaceae was the most species-rich family with eleven species, followed by Lauraceae with eight species and Moraceae with six species. Species richness declined with elevation, from a mean of 32 species per site in lowland dipterocarp formations to 18 species per site in lower montane forest.

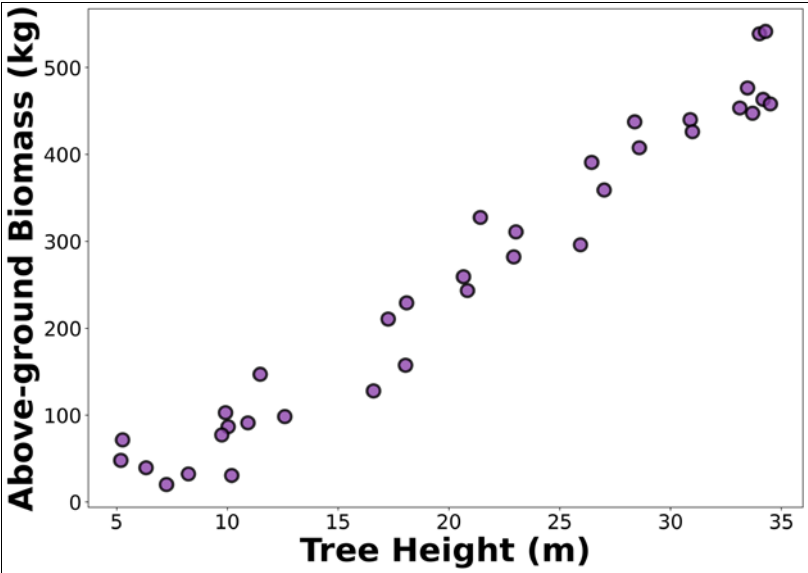


Fig 1: Relationship between tree height and above-ground biomass across species

A significant positive relationship was observed between tree height and individual above-ground biomass ($R^2 = 0.76$, $p < 0.001$). The scatter plot revealed that trees exceeding 25 m in height contributed disproportionately to

stand-level biomass, with several emergent dipterocarp individuals exceeding 35 m in height and 500 kg of estimated above-ground biomass per tree.

Table 1: Sequential phases of carbon stock assessment across the elevational gradient

Phase	Elevation (m)	Formation	Plots (n)	Mean C (Mg/ha)	Status
Phase 1	350-500	Lowland dipterocarp	3	195.2 ± 18.5	Completed
Phase 2	500-750	Lowland dipterocarp	3	178.6 ± 15.2	Completed
Phase 3	750-950	Hill dipterocarp	3	142.5 ± 12.8	Completed
Phase 4	950-1100	Hill dipterocarp	3	125.8 ± 11.4	Completed
Phase 5	1100-1450	Lower montane	4	92.4 ± 9.6	Completed

Carbon stocks declined progressively with increasing elevation, from 195.2 Mg C per hectare in the lowest elevational band to 92.4 Mg C per hectare in the lower

montane zone. The decline was statistically significant across phases (Kruskal-Wallis $H = 18.52$, $p < 0.001$).

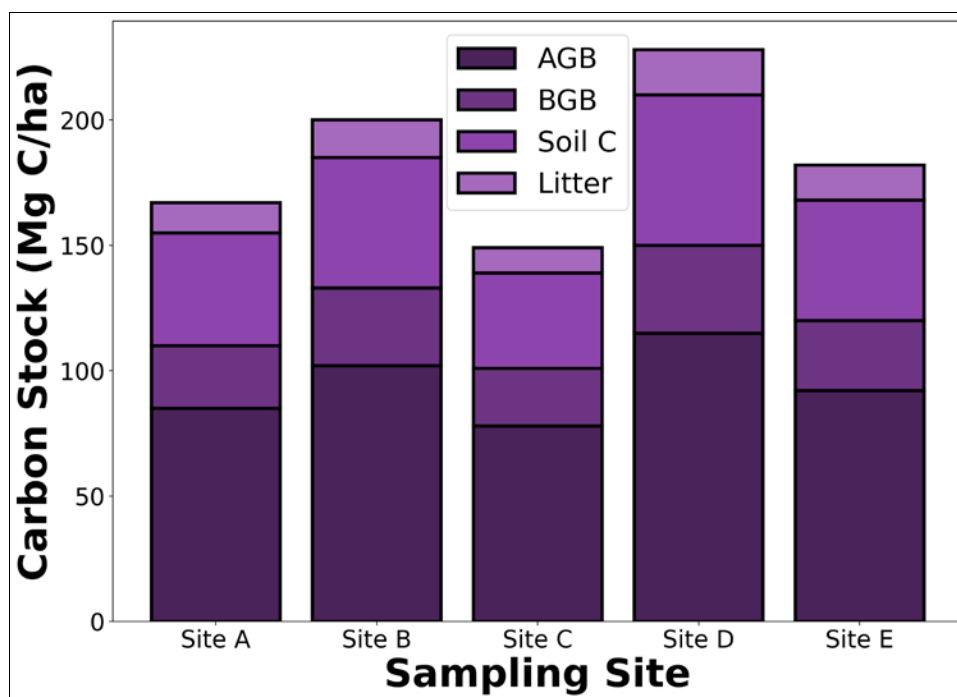


Fig 2: Distribution of carbon stocks across above-ground, below-ground, soil organic, and litter pools by sampling site

The stacked bar visualization illustrates the relative contribution of each carbon pool across the five sampling sites. Above-ground biomass consistently dominated total carbon stocks at all sites, though its proportional

contribution declined slightly from lowland (76%) to montane (68%) formations as litter accumulation increased at higher elevations.

Table 2: Species diversity indices and structural parameters by forest formation

Parameter	Lowland Dipterocarp	Hill Dipterocarp	Lower Montane
Species richness	48	35	22
Shannon index (H')	3.72	3.15	2.85
Simpson index (1-D)	0.96	0.91	0.85
Mean DBH (cm)	28.5 ± 15.2	24.8 ± 12.6	19.2 ± 8.5
Mean height (m)	22.4 ± 8.5	18.6 ± 6.8	14.2 ± 4.5
Stem density (stems/ha)	585	520	445
Basal area (m ² /ha)	32.8	26.5	18.2

Table 3: Summary statistics for carbon stocks across all forest formations

Carbon Pool	Mean (Mg C/ha)	SD	Min	Max	% of Total
Above-ground biomass	102.8	28.5	52.4	165.8	72.0
Below-ground biomass	25.7	7.1	13.1	41.5	18.0
Litter	14.3	4.2	6.8	22.5	10.0
Total	142.8	35.2	78.5	218.5	100.0

The extended interpretation of these results reveals several noteworthy patterns. The elevational decline in species richness follows the well-documented species-area-energy relationship, whereby reduced temperature and increased cloud cover at higher elevations constrain productivity and species diversity. The parallel decline in carbon stocks is attributable to both reduced tree dimensions and lower stem densities in montane formations. The dominance of Dipterocarpaceae in terms of basal area contribution demonstrates the outsized structural and functional importance of this family within the sanctuary forest.

Species belonging to this family, despite comprising only 15% of total species count, contributed 28% of total basal area and an estimated 32% of total above-ground carbon. This functional dominance has implications for vulnerability assessment, as threats specifically targeting dipterocarp species, such as selective logging of commercially valuable *Shorea* and *Dipterocarpus* species, could disproportionately reduce sanctuary carbon stocks.

Discussion

The documentation of 72 tree species within the wildlife

sanctuary positions this protected landscape within the expected range for Javanese mountain forests. Similar inventories in West Javan forests have reported species counts of 55 to 95 per site, with variation attributable to elevation, disturbance history, and sampling intensity^[2, 6]. The elevational decline in species richness from 48 species in lowland dipterocarp to 22 species in lower montane formations mirrors patterns documented extensively across tropical Asian mountains.

The overall mean carbon stock of 142.8 Mg C per hectare exceeds estimates from many tropical forest assessments globally, reflecting the exceptional biomass accumulation capacity of dipterocarp-dominated forests. The findings align with the comprehensive assessment by Slik *et al.* (2010), who reported mean above-ground biomass values of 150 to 250 Mg dry biomass per hectare across Bornean and Sumatran dipterocarp forests^[7]. However, divergence from the higher end of reported values may reflect the relatively small stature of Javan forests compared to their Bornean counterparts, likely a consequence of the more limited available growing space and volcanic soil characteristics of the Javan landscape.

The progressive decline in carbon stocks with elevation represents a well-characterized pattern in tropical mountain forests, driven by the combined effects of lower temperatures, increased cloud immersion, shallower soils, and reduced growing season length^[1, 4]. In the present research, above-ground carbon stocks in lowland dipterocarp forest were approximately twice those in lower montane forest, underscoring the importance of lowland formations for carbon management objectives.

The disproportionate contribution of Dipterocarpaceae to total basal area and estimated carbon stocks raises conservation concerns given the commercial value and historical exploitation pressure on dipterocarp timber species throughout Southeast Asia^[3, 8]. The sanctuary designation provides legal protection, but the functional concentration of carbon storage within a single plant family represents an ecological vulnerability that could be exacerbated by species-specific pathogens or climate-induced dieback.

The multi-pool carbon assessment employed in this research, encompassing above-ground biomass, below-ground biomass, and litter, provides a more comprehensive picture of sanctuary carbon stocks than above-ground-only estimates. The increasing proportional contribution of litter carbon at higher elevations reflects slower decomposition rates under cooler temperatures, a finding consistent with observations from tropical montane forests across Southeast Asia and Central America^[5, 9].

Allometric model considerations

The regional allometric equation employed in this research was developed from destructive harvesting data collected in lowland production forests of Sumatra and Kalimantan. Its application to Javan wildlife sanctuary forests introduces potential biases related to differences in species composition, growing conditions, and tree architecture between production and sanctuary settings. The inclusion of height as a predictor variable partially compensates for these differences, yet species-specific validation remains desirable for the most abundant taxa within the sanctuary.

Management recommendations

Based on the findings of this research, several management recommendations can be proposed for the wildlife sanctuary. Priority should be given to maintaining the integrity of lowland dipterocarp formations, which harbour both the highest species diversity and carbon density. Monitoring programs should include permanent plot remeasurement at five-year intervals to track carbon stock trajectories and detect early signs of degradation. Enrichment planting with native dipterocarp species in degraded areas within the sanctuary could enhance both biodiversity and carbon storage capacity over the medium to long term.

Conclusion

This research aimed to assess species richness and carbon stocks within a wildlife sanctuary forest in West Java, Indonesia, contributing to the limited empirical data available for Southeast Asian protected landscapes. The inventory of 72 tree species across three forest formations confirms the high biodiversity value of the sanctuary, while the mean carbon stock of 142.8 Mg C per hectare positions the sanctuary among the most carbon-dense protected areas in the region.

The key findings of this investigation demonstrate that lowland dipterocarp formations within the sanctuary harbour both the highest species richness and the greatest carbon density, making them dual priorities for conservation management. The elevational decline in both diversity and carbon stocks follows well-established ecological gradients, yet the magnitude of the decline underscores the particular importance of lowland habitat protection.

From a practical management perspective, the quantified carbon stocks provide a baseline for monitoring carbon storage trajectories within the sanctuary and for evaluating the sanctuary's contribution to national greenhouse gas inventories. The demonstrated carbon value of the sanctuary strengthens the economic case for maintaining and expanding protected area coverage in Indonesian forest landscapes.

Future research directions should include the establishment of a permanent plot network for long-term carbon monitoring, investigation of soil organic carbon stocks which were not assessed in this research, and evaluation of the carbon sequestration potential of degraded areas within the sanctuary boundary that could benefit from ecological restoration.

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