Aboveground Biomass and Carbon Stock of Trees and Poles in Tropical Peatland Forest Ecosystems: A Case Study from Riau, Indonesia

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Abstract. Tropical peatland forests play a vital role in carbon storage and global climate regulation but are increasingly threatened by degradation and land-use change. This study aims to analyze aboveground biomass (AGB), carbon stock, CO_2 sequestration potential, and tree volume across two forest management zones rehabilitation and conservation within PT Diamond Raya Timber, Riau, Indonesia. Data were collected from 30 - 50 plots representing two growth stages (poles and trees) using allometric models. The results showed that the conservation zone presented higher values across all parameters. At the pole stage, AGB, carbon, and CO_2 were 393.59, 184.99, and 678.95 t ha^{-1}, respectively, compared to 185.77, 87.31, and 320.43 t ha^{-1} in the rehabilitation zone. Similarly, at the tree stage, the conservation zone recorded 5,746.07 t ha^{-1} AGB, 2,700.65 t ha^{-1} carbon, and 9,991.40 t ha^{-1} CO_2, which were significantly higher than 2,900.03, 1,363.02 , and 5,002.27 t ha^{-1} in the rehabilitation zone. Tree volume estimation followed the same pattern. The total stand volume in the conservation zone reached 2,183.53 m^3 ha^{-1} (poles) and 8,775.36 m^3 ha^{-1} (trees), whereas in the rehabilitation zone it was only 960.12 m^3 ha^{-1} (poles) and 4,049.64 m^3 ha^{-1} (trees). These findings highlight that stand structure and management history strongly influence biomass accumulation and carbon dynamics. Conserving intact peat forests and restoring degraded zones through hydrological recovery and enrichment planting are essential strategies for enhancing carbon sink capacity and achieving Indonesia's FOLU Net Sink 2030 targets.

1 Introduction

Tropical peatland forests play a vital role in biomass accumulation and long-term carbon sequestration, making them essential components of climate change mitigation strategies. Indonesia harbors one of the world's largest peatland areas, with approximately 13.4 million hectares storing over 57 gigatons of carbon, primarily in Sumatra and Kalimantan [1]. However, these ecosystems face increasing threats from land-use changes, including agricultural conversion, infrastructure development, and logging activities, all of which

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contribute significantly to greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2) [2].

Among Indonesia's peatland distribution areas, Riau Province is a key region with peatlands exceeding 4 million hectares. Nevertheless, Riau's peat swamps experience high ecological pressure from land clearing, fires, and conversion, significantly reducing habitat quality and biodiversity [3, 4]. Peatland degradation and drainage result in a significant reduction of forest biomass and, consequently, carbon stock. Degraded lands tend to shift from functioning as carbon sinks to becoming major carbon sources. In contrast, well-managed and protected peatland forests retain their ecological role in sequestering carbon [5].

Assessing and comparing carbon stocks across different land-use zones, such as rehabilitation and conservation zones can help quantify the impact of land management on ecosystem carbon balance and provide a science-based foundation for sustainable planning. Previous research has shown that changes in plant community structure and species composition can serve as indicators of ecological pressure and management success [4, 6]. Conservation zones with high species diversity demonstrate relatively stable ecological conditions with minimal anthropogenic disturbance, while degraded zones tend to have weaker vegetation structure and limited regeneration capacity [7].

Biomass and carbon stock assessments traditionally relied on destructive methods, but these have been replaced by non-destructive techniques using allometric equations. These equations relate measurable tree parameters (e.g., diameter, height) to biomass estimates, offering a reliable, efficient, and environmentally friendly alternative [8]. Such field-based assessments are increasingly important in supporting REDD+ (Reducing Emissions from Deforestation and Forest Degradation) initiatives and national greenhouse gas reporting, as well as informing low-carbon development policies [9].

In Indonesia, natural forest management especially in peatlands is regulated under forest concession licenses (IUPHHK-HA), which apply a zonation system dividing areas into conservation, production, and rehabilitation zones to ensure sustainable forest and to maintain wildlife migration routes and habitats. Rehabilitation zone are typically degraded due to historical exploitation, while conservation zones are relatively intact and better protected. These contrasting conditions present an opportunity to assess the effectiveness of conservation versus utilization by analyzing differences in biomass and carbon storage across zones. Such comparison offers insights into which practices maintain or restore the forest's role as a carbon sink. These are also highly relevant to Indonesia's FOLU Net Sink 2030, as forest rehabilitation to increasing carbon stocks and support ecosystem services and biodiversity conservation [10].

Classifying vegetation by growth stage such as poles (10–20 cm DBH) and trees (>20 cm DBH) adds depth to carbon assessments. Mature trees typically contain larger carbon stocks, whereas pole-sized trees represent regeneration and recovery potential. This classification supports an understanding of forest structure and successional dynamics, especially when analyzed across different land-use types [5, 8]

This study aims to quantify and compare above-ground biomass, carbon stock, and CO_2 sequestration potential across two peat forest zones with different management statuses, using growth stage classification. The results are expected to contribute to sustainable forest management strategies by identifying the ecological and climatic benefits of conserving peatland forests. Ultimately, the study will provide a scientific basis to inform policy, monitoring, and climate change mitigation efforts in tropical peatland landscapes.

2 Methodology

Vegetation sampling was conducted at two different locations in PT Diamond Raya Timber: conservation zone at coordinates approximately 2°03'53.04" N, 101°00'28.15" E, and rehabilitation zone at 2°03'53.04" N and 101°00'28.15" E. Data collection was conducted from May to July 2024, representing peak vegetation growth conditions in the early dry season.

Sampling was conducted using plot-based transects as the basis for biomass and carbon stock calculations. In the rehabilitation zone, three transects were established, and in the conservation zone, five transects, each consisting of 10 plots measuring 20 m × 20 m for recording trees with DBH ≥20 cm. Within the main plot, a 10 m × 10 m subplot was created for pole-level trees (DBH 5–19.9 cm). Plots were arranged systematically; in each plot, species, number of individuals, DBH, tree height, and GPS coordinates were recorded. This design follows tropical forest inventory principles to obtain representative biomass and carbon estimates and enable inter-zone comparisons [11].

Vegetation measurements included recording the diameter at breast height (DBH, measured at 1.3 m above ground), total tree height. The parameters analyzed comprised aboveground biomass (AGB), carbon stock (C), carbon dioxide equivalent emissions (CO_2-eq), and tree volume.

2.1 AGB Formula for Tropical Peat Swamp Forest

Derived from the allometric equations proposed by [12], specifically developed for various forest ecosystem types in Indonesia.

$$AGB\ (kg) = 0.153103 \times D^{2.40} \tag{1}$$

where D is the tree diameter at breast height (DBH, cm). This equation was selected because it has been validated for various forest ecosystem types in Indonesia and provides reliable estimates of AGB for both mature trees and pole-sized trees. Carbon content (C) and CO_2 emissions were subsequently calculated using standard conversion factors (C = 0.47 × AGB, CO_2 = 3.67 × C).

2.2 Carbon and CO_2 Calculations

Carbon content was estimated using a conversion factor from AGB (typically 47%), while CO_2-equivalent emissions were calculated using the molecular weight ratio of CO_2 to carbon (44/12).

2.2.1 Carbon

$$C = 0.47 \times AGBC \tag{2}$$

2.2.2 Carbon Dioxide (CO_2)

$$CO_{2\ (tonnes)} = 3.67 \times \frac{C}{1000} \tag{3}$$

2.3 Tree Volume

Tree volume was computed using volume estimation formulas based on field measurements of diameter and height. Trees volume is calculated using the silvicultural approach formula [12]:

2.3.1 Volume

$$V = Form\ Factor \times (\pi \times D^2)/4 \times H \quad (4)$$

where:
D = tree diameter (m),
H = tree height (m)
Form Factor = 0.6 (the general average for natural stands).

All data on AGB, carbon stock, CO_2 emissions, and tree volume were compiled and standardized to a per-hectare basis using area-based conversion factors. The calculations only include aboveground biomass (AGB) at tree and pole levels, and thus do not include belowground carbon components such as roots, litter, or peat soil carbon. Therefore, reported values represent partial estimates of total ecosystem carbon stock.

3 Results and discussion

3.1 Results

The analysis of above-ground biomass (AGB), carbon stock, CO_2 sequestration potential, and tree volume reveals distinct differences between the conservation zone and the rehabilitation zone across both pole and tree growth stages. These differences reflect the influence of forest condition and management on biomass accumulation and carbon storage in tropical peatland ecosystems. Mean values are accompanied by standard deviations (SD) to illustrate inter-plot variation. Detailed results are presented in **Table 1**.

Table 1. Summary of biomass, carbon, and CO_2 per hectare in two forest management zones.

Zone	Growth Stage	AGB (t ha^{-1} ± SD)	Carbon (t ha^{-1} ± SD)	CO_2 (t ha^{-1} ± SD)
Rehabilitation	Pole	185.77±1.10	87.31±0.51	320.43±1.89
Rehabilitation	Tree	2,900.03±13.78	1,363.02±6.48	5,002.27±23.77
Conservation	Pole	393.59±2.36	184.99±1.11	678.95±4.08
Conservation	Tree	5,746.07±12.90	2,700.65±6.06	9,991.40±22.25

Above-ground biomass (AGB) reveals substantial variation between the two management zones and growth stages. In rehabilitation zone, the AGB at the pole stage was 185.77 ±1.10 t ha^{-1}, while in the tree stage, it was significantly higher at 2,900.03±13.78 t ha^{-1}. Conversely, in conservation zone, AGB reached 393.59±2.36 t ha^{-1} at the pole stage and 5,746.07±12.90 t ha^{-1} at the tree stage.

Carbon stock values follow a similar pattern to AGB, given the direct correlation. In rehabilitation zone, the carbon stock was 87.31±0.51 t ha^{-1} at the pole stage and 1,363.02±6.48 t ha^{-1} at the tree stage. Meanwhile, in the conservation zone, carbon stock reached 184.99±1.11 t ha^{-1} at the pole stage and 2,700.65±6.06 t ha^{-1} at the tree stage.

When converted to carbon dioxide equivalents (CO_2), rehabilitation zone showed a sequestration potential of only 320.43±1.89 t ha^{-1} at the pole stage and 5,002.27±23.77 t ha^{-1} at the tree stage. In stark contrast, the conservation zone exhibited a CO_2 storage potential of 678.95±4.08 t ha^{-1} at the pole stage and 9.991.40±22.61 t ha^{-1} at the tree stage.

Table 2. Tree volume estimation by growth stage in different forest management zones

Zone	Growth Stage	Number of trees/ha (ind)	Average volume per tree (m³)	Total volume (m³ ha^{-1} ± SD)
Rehabilitation	Pole	8,100	0.1185	960.12±0.06
Rehabilitation	Tree	4,150	0.9758	4,049.64±0.76
Conservation	Pole	15,100	0.1446	2,183.53±0.16
Conservation	Tree	8,925	0.9832	8,775.36±0.77

Table 2 shows that the rehabilitation zone had lower total volume at both growth stages compared to the conservation zone. In the rehabilitation zone, the pole stage had a total volume of 960.12 ± 0.06 m³ ha^{-1} and the tree stage of 4,049.64 ± 0.76 m³ ha^{-1}. Meanwhile, the conservation zone showed higher total volume at both growth stages, namely 2,183.53 ± 0.16 m³ ha^{-1} at the pole stage and 8,775.36 ± 0.77 m³ ha^{-1} at the tree stage. This difference indicates that stand volume in the conservation zone is greater than in the rehabilitation zone.

3.2 Discussion

In the rehabilitation zone, AGB at the tree level reached 2,900.03 t/ha, higher than the pole level of 185.77 t/ha. A similar pattern occurred in carbon content, with the tree level storing 1,363.02 t/ha carbon and the pole level storing 87.31 t/ha. CO_2 sequestration potential increased to 320.43 t/ha for poles and 5,002.27 t/ha for trees. However, compared to the conservation zone, all these parameters remain lower with volume of 960.12 m³/ha for poles and 4,049.64 m³/ha for trees, indicating sparse stand structure and open canopy, while the conservation zone exhibits denser stands, closed canopy, and much higher biomass accumulation [8].

In the conservation zone, values were much higher across all parameters. AGB at the pole level reached 393.59 t/ha, while at the tree level 5,746.07 t/ha. Carbon stocks of 184.99 t/ha (pole) and 2,700.65 t/ha (tree) respectively reflect dense biomass accumulation and active regeneration. CO_2 storage potential also showed increases of 678.95 t/ha for poles and 9,991.40 t/ha for trees, indicating strong carbon storage function even at early growth stages [5]. Tree volume in the conservation zone was also higher, 2,183.53 m³/ha for poles and 8,775.36 m³/ha for trees, indicating strong regeneration, high tree density, and faster canopy closure [1].

AGB and carbon stock increased significantly from pole to tree stage. This indicates active biomass growth among younger vegetation, possibly due to recent disturbance or regeneration phases. However, the magnitude of difference in the conservation zone is much greater. The absolute difference in the conservation zone is much larger, indicating that management with minimal disturbance supports sustained succession and optimal biomass accumulation, while the rehabilitation zone is still in recovery stages. The observed result undicates several important ecological implications. First, management history is a key determinant: the rehabilitation zone, which previously experienced logging and drainage, shows slow recovery and poor biomass accumulation [2].

Conversely, protection and minimal disturbance in the conservation zone support sustained succession and natural forest regeneration, thus enabling higher biomass accumulation even at early growth stages [8]. One of the main factors explaining the high carbon stocks in the conservation zone is the presence of large-diameter trees, as biomass

increases exponentially with stem diameter, allowing big trees to store far more biomass than many small trees. These trees also play key roles in hydrological balance, supporting regeneration of younger trees, enhancing species diversity, and strengthening ecosystem resilience. Additionally, higher species diversity and structural complexity in the conservation zone likely contribute to increased productivity and ecological resilience [13].

Structural and ecological recovery in the rehabilitation zone is still constrained by legacy impacts of past land use, including logging, drainage, and fire exposure. These disturbances often result in hydrological changes and poor seedling recruitment, thus hindering succession. Therefore, restoration efforts must be accompanied by hydrological restoration and enrichment planting to restore biomass accumulation and carbon function [14, 15].

When compared with research results in other regions and contexts, AGB and carbon stock values in the conservation zone of this study are relatively consistent with the range of primary peat forest ecosystem carbon stocks reported by Novita [16] in Tanjung Puting, Central Kalimantan, reaching 1,770 ± 123 Mg C/ha. Meanwhile, carbon stocks in secondary forests decreased to 533 ± 49 Mg C/ha, and in oil palm plantations only 759 ± 87 Mg C/ha, showing more than 50% carbon reserve loss due to conversion. Values in the rehabilitation zone still in recovery stages (approximately 87–1,363 t C/ha) reflect conditions similar to secondary forests or recently restored lands.

Globally, Kauffman et al. [17] found that total carbon stocks in tropical peat forest ecosystems range from 172–9,379 Mg C/ha (mean 2,137 Mg C/ha), with 86% of carbon stored in peat soil. This indicates that increases in aboveground biomass (AGB) as occurring in the conservation zone are an important component in strengthening carbon absorption function, but full recovery of carbon storage capacity will only occur after hydrological stability and peat soil layers recover.

Research findings by Verwer & van der Meer [18] also support this pattern, with carbon stocks in undisturbed peat forests ranging from 182–306 t C/ha in biomass and up to 3,528 t C/ha in peat layers. Thus, the striking difference between the conservation zone and rehabilitation zone in this study illustrates two extreme conditions of the spectrum of peat ecosystem degradation and recovery.

Furthermore, findings by Sasmito et al. [19] in Southeast Asia confirm that conservation and restoration of peat swamp forests can reduce up to half of carbon emissions from land-use change in this region (±691.8 Tg CO_2e /year), and additional mitigation potential of 94 Tg CO_2e/year can be achieved through rewetting and revegetation of degraded lands. This strengthens the argument that conservation zones as in this study have a strategic role in national and regional climate mitigation contributions.

Methodologically, the approach to measuring AGB and carbon stocks in this study also aligns with recommendations by Hetzer [11], which emphasize the importance of adequate plot numbers and distribution to obtain representative carbon stock estimates in tropical forests. This shows that management based on good field data can be the basis for credible carbon accounting for carbon trading schemes or REDD+.

The conservation zone demonstrates superior ecological function and carbon sequestration capacity at all growth stages, while the rehabilitation zone still requires active intervention. High carbon stocks not only reflect climate change mitigation capacity, but also serve as direct indicators of ecosystem resilience. Forests with high biomass and carbon generally have layered canopy structure, stable nutrient cycling, and greater ability to recover from disturbances. In the context of national policy, these findings are relevant to the Forestry and Other Land Use (FOLU) Net Sink 2030 target, where the forestry sector is expected to become a net sink for carbon emissions [10]. Conservation zones with large carbon stocks function as "natural carbon assets" supporting FOLU Net Sink achievement through conservation, while rehabilitation zones become priorities for restorative intervention to accelerate net carbon uptake nationally.

The results of this study not only illustrate biophysical differences between zones, but also provide a scientific basis for landscape-based policies in achieving carbon balance, ecosystem resilience, and sustainability of Indonesian peatland management toward FOLU Net Sink 2030.

4 Conclusion

This study demonstrates that conservation zone consistently outperforms the rehabilitation zone in above-ground biomass, carbon stock, CO_2 sequestration potential, and tree volume across both pole and tree growth stages. The significantly higher values in the conservation zone reflect better forest structure, active regeneration, and minimal disturbance, underscoring the importance of maintaining intact peatland forests. In contrast, the rehabilitation zone shows limited recovery, likely due to past logging, drainage, and poor regeneration capacity. Higher carbon and biomass values were observed at the tree level compared to the pole level in both zones, indicating dynamic succession and the important role of younger vegetation layers in carbon accumulation. These findings emphasize that forest conditions and management history significantly affect ecosystem productivity and carbon function. To support long-term climate change mitigation and ecosystem resilience, protecting undisturbed peat forests and implementing hydrological restoration and assisted regeneration in degraded zones are essential. Integrating conservation with sustainable restoration strategies will enhance the carbon sink capacity and ecological stability of tropical peatland. The results support evidence-based restoration planning under Indonesia's FOLU Net Sink 2030.

Acknowledgments
The authors would like to thank all parties who have supported the implementation of this research, including conservation area management agencies and field teams for technical and logistical assistance. Institutional support and research facilities provided by universities and field work partners greatly contributed to the success of this study. Our gratitude goes to APBF Fakultas Kehutanan dan Sains, Universitas Lancang Kuning for the support and funding of this study.

Data Availability
Data supporting the findings of this research are available from the authors upon reasonable request.

Conflict of Interest
The authors declare no conflicts of interest affecting the results or interpretation of this research.

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