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Carbon Footprint Assessment in *Acacia crassicarpa* Plantation Forests on Peatlands by Quantifying Emission Sources and Mitigation Potential

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ABSTRACT

Peatland forestry plantations significantly contribute to carbon dynamics, yet long-term carbon emissions from industrial timber plantations remain understudied. This study quantifies CO_2 emissions from peat subsidence, soil respiration following fertilization, logging residue decomposition, and fossil fuel combustion in an *Acacia crassicarpa* plantation in Siak Regency, Riau, Indonesia. Carbon emissions were measured through field observations and empirical models. The total peat carbon stock in the 43,538 ha study area was 137.733 megatons, equivalent to 505.023 megatons CO_2e. Peat subsidence rates from 2021 to 2023 averaged 0.29 cm/year, resulting in 3.058 tons CO_2e/ha annually. Fertilization-induced soil respiration contributed 2.552×10^{-4} tons CO_2e/ha/year, leading to 42.139 tons CO_2e over 20 years. Logging residue decomposition released 2.002 tons CO_2e/ha, with a 20-year cumulative emission of 280,984.70 tons CO_2e. Fossil fuel use required 4.02 liters per ton of wood, contributing 5,192.319 tons CO_2e per harvest cycle. Over 20 years, total emissions from all sources were substantial, highlighting peat subsidence as the dominant contributor. Optimizing fertilization practices, managing logging residues, and improving fuel efficiency could mitigate emissions. Future research should explore carbon sequestration strategies such as alternative fertilization, residue utilization, and water table management for sustainable peatland forestry.

Keywords: carbon footprint; *Acacia crassicarpa*; peatland; carbon emissions; sustainable forestry

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INTRODUCTION

Peatlands are among the most significant terrestrial carbon sinks, storing approximately 550 gigatons of carbon,

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which accounts for nearly 30% of the world's soil carbon (Harris et al., 2022; Girkin et al., 2023). However, land-use changes, including industrial plantation forestry, have substantially altered peatland ecosystems, contributing to significant greenhouse gas (GHG) emissions (Deshmukh et al., 2018). Drainage, biomass removal, fertilization, and decomposition processes in managed peatlands have been identified as key factors in carbon flux alterations, making peatlands a major global source of carbon dioxide (CO_2) emissions (Mander et al., 2024). Indonesia, home to one of the largest tropical peatland ecosystems, has recognized this challenge and committed to reducing 140 million tons of CO_2e emissions by 2030 through the Forestry and Other Land Use Net Sink 2030 (FOLU Net Sink 2030) strategy (Ministry of Environment and Forestry, 2022). Given this policy framework, a deeper understanding of carbon emissions from managed peatland forests is essential to ensure that plantation forestry aligns with national and global climate commitments.

Among various plantation species, *Acacia crassicarpa* has gained widespread adoption in Indonesia's industrial plantation forests, particularly in Riau Province, which serves as a hub for the country's pulpwood industry. This species is preferred due to its rapid growth, adaptability to acidic and waterlogged soils, and high biomass productivity (Hardiyanto et al., 2024). However, the environmental trade-offs associated with A. crassicarpa plantations on peatlands remain poorly understood. While oil palm plantations have been extensively studied for their impacts on peatland carbon emissions (Jaafar et al., 2020) industrial tree plantations have received significantly less attention, despite their growing footprint. The extent to which these plantations contribute to peat subsidence, soil carbon loss, and overall CO_2 emissions remains unclear, necessitating a more detailed investigation.

Previous studies on carbon fluxes in peatlands have largely focused on natural forests, degraded peatlands, and agricultural land-use changes (Houghton & Castanho, 2020; Girkin et al., 2023). While some research has examined carbon dynamics in plantation forests, such studies often generalize carbon emissions from large-scale forestry without differentiating specific emission sources (Suharto et al., 2017; Firyadi et al., 2018). In particular, studies have emphasized peat oxidation and subsidence as primary sources of emissions, but fewer have integrated multiple emission pathways, including soil respiration due to fertilization, logging residue decomposition, and fossil fuel use in harvesting operations. Furthermore, there is a significant lack of long-term projections on carbon fluxes in plantation forests, which limits the ability to align forest management practices with global climate mitigation goals.

Another major gap in the literature is the absence of empirical data quantifying emissions from industrial tree plantations on peatlands. Unlike natural forests, where carbon sequestration often offsets emissions, plantation forests undergo regular harvesting cycles that alter their carbon balance over time. While previous studies have attempted to quantify carbon stock fluctuations in plantation forests (Ratnaningsih et al., 2024), they have not comprehensively addressed the net carbon emissions from different plantation management activities. Additionally, while logging residue decomposition has been recognized as a potential carbon source in tropical forests (Yuniwati & Suhartana, 2014), its contribution to the carbon footprint of plantation forestry remains largely unquantified. This research aims to address these gaps by providing a comprehensive assessment of CO_2 emissions across multiple processes in A. crassicarpa plantations on peatlands.

This study aims to comprehensively assess the carbon footprint of A. crassicarpa plantation forests on peatlands by quantifying emissions from multiple sources, including peat subsidence, fertilization-induced soil respiration, logging residue decomposition, and fossil fuel combustion during harvesting operations. By integrating these emission sources into a single, comprehensive analysis, this study provides a more detailed and accurate account of carbon emissions in industrial plantation forests, an area that has been underexplored in previous research. Additionally, this research seeks to identify the most significant emission sources in A. crassicarpa plantations and evaluate their relative contributions to the overall carbon balance. Beyond short-term emissions, this study also examines long-term carbon flux projections over a 20-year plantation cycle, an aspect that has been largely overlooked in previous studies. Repeated plantation cycles alter peatland carbon dynamics, with cumulative emissions from peat subsidence, fertilization, and residue decomposition gradually accumulating over time. The long-term perspective adopted in this research provides a more realistic estimation of the total carbon footprint of industrial plantation forests, offering valuable insights for future land-use planning and emission reduction strategies.

The findings are expected to provide crucial insights into potential mitigation strategies, including optimized fertilization practices, efficient residue management, and improved logging operations, contributing to the development of sustainable peatland forestry practices. Furthermore, this study contributes to the broader scientific and policy discussions on climate change mitigation in peatland forestry by offering empirical data that aligns with Indonesia's FOLU Net Sink 2030 strategy. The results will serve as a reference for policymakers, plantation managers, and researchers in formulating data-driven strategies to reduce emissions from industrial plantation forests while ensuring economic viability. Given the increasing global pressure to balance economic productivity with environmental sustainability, this research provides a critical foundation for developing evidence-based land-use policies that support climate resilience in peatland ecosystems.

MATERIALS AND METHODS

Study Area and Site Description

This study was conducted in an industrial plantation forest located in Siak Regency, Riau Province, Indonesia, a region characterized by extensive peatland ecosystems managed for large-scale forestry. The study area covers 43,538 ha, with plantations dominated by *A.*

crassicarpa, a fast-growing tree species widely cultivated for pulp and paper production. The study site experiences a tropical humid climate, with an annual average temperature of 26–28°C and mean annual precipitation of 2,500–3,000 mm, with a distinct dry season occurring from June to September. The soil is classified as ombrotrophic peat with depths ranging from 0.5 to 11 m, exhibiting an average pH of 4.0–4.5.

The plantation operates under a rotational harvesting system, with trees being harvested at approximately 4–5 years of age. Standard silvicultural practices include controlled drainage, mechanized harvesting, and periodic fertilization. To quantify the carbon footprint of these plantations, emissions from peat subsidence, fertilization-induced soil respiration, logging residue decomposition, and fossil fuel combustion from harvesting operations were assessed using field measurements, laboratory analysis, and secondary data sources.

Peat Characteristics Analysis

To characterize the physical and chemical properties of the peat, samples were collected from the study site at 50 cm depth intervals using an Eijkelkamp peat auger. Peat characteristics were analyzed for bulk density, fiber content, moisture content, ash content, and organic carbon content, following Indonesian National Standard (Badan Standardisasi Nasional [BSN], 2011).

Bulk Density (BD)

Bulk density (g/cm3) was determined using the oven-drying method (BSN, 2011). Peat samples were weighed before and after drying at 105°C for 48 h, and bulk density was calculated as:

$$BD = \frac{M_d}{V} \qquad [1]$$

where:
BD = Bulk density (g/cm^3)
M_d = Dry mass of the sample (g)
V = Sample volume (cm^3)

Moisture Content (%)

Peat moisture content was determined using the gravimetric method, by calculating the difference between fresh and oven-dried weight:

$$MC = \frac{M_f - M_d}{M_d} \times 100 \qquad [2]$$

where:
MC = Moisture content (%)
M_f = Fresh weight of the sample (g)
M_d = Dry weight of the sample (g)

Ash Content (%)

Ash content was measured by combusting 2 g of dried peat in a muffle furnace at 550°C for 6 h, and calculating the remaining mineral content:

$$AC = \frac{M_{ash}}{M_d} \times 100 \qquad [3]$$

where:
AC = Ash content (%)
M_{ash} = Weight of residual ash after combustion (g)

Organic Carbon Content (%)

The organic carbon content (C_{org}) in peat was determined using the Walkley-Black method. The percentage of organic carbon was calculated based on the mass of oxidized carbon in the sample using the following equation:

$$C_{org} = \frac{(M_f - M_d) \times OC_{conc}}{M_f} \times 100 \qquad [4]$$

where:
C_{org} = Organic carbon content in peat (%)
OC_{org} = Organic carbon concentration from titration (mg/g)

Fiber Content (%)

Fiber content was determined using the sieving method, classifying peat as fibric (>67% fibers), hemic (33–67% fibers), or sapric (<33% fibers) following USDA classification (Chmielewska, 2023).

Peat Subsidence and Carbon Emission Estimation

Carbon emissions due to peat subsidence were estimated using secondary data from 2021–2023, with an average subsidence rate of 0.29 cm/year, following the correlation between peat depth, subsidence rate, and carbon release as proposed by Aswandi et al.

(2016). The decomposition rate due to subsidence was calculated using the model adapted from Triadi et al. (2014):

$$T_s = \frac{D}{S} \quad [5]$$

$$E_{\text{subsidence}} = \frac{C_{\text{peat}}}{T_s} \quad [6]$$

where:
T_s = Peat subsidence period (years)
D = Peat depth (cm)
S = Average subsidence rate (cm/year)
$E_{subsidence}$ = Annual carbon emission from peat subsidence (Mt CO_2 /year)
C_{peat} = Total carbon stored in peat (Mt CO_2)

Soil Respiration from Fertilization

CO_2 emissions from fertilized peat soils were measured in A. crassicarpa plantations one week after NPK fertilizer application. Gas flux measurements were conducted at three different times (morning, noon, and afternoon) using a modified Verstraete method (Lestari et al., 2024; Suhesti et al., 2024). In each observation plot, film canisters filled with 10 ml of 0.1N KOH solution were placed inside open chambers made of transparent plastic jars with known dimensions. The chambers were left for 1 h, during which CO_2 released from soil respiration was absorbed by the KOH solution. The absorbed CO_2 was then analyzed through acid-base titration, following the method of Andelia et al. (2020).

CO_2 emission rates were calculated using the following equation:

$$C_{CO_2} = \frac{(a - b) \times t \times 12}{T \times \pi \times r^2} \quad [7]$$

where:
C_{CO2} = Soil CO_2 respiration rate (mg CO_2 /m^2/ h^1)
a = Volume of HCl used for the sample titration (mL)
b = Volume of HCl used for the blank titration (mL)
t = Normality of HCl (N)
T = Incubation time (h)
r = Radius of the chamber (m)
12 = Atomic mass of carbon

Fossil Fuel Emissions from Logging Operations

CO_2 emissions from fossil fuel consumption were calculated by measuring fuel usage during logging activities, including harvesting, skidding, and transportation. The amount of fuel consumed was recorded and converted into CO_2 emissions using the method proposed by Suharto et al. (2017). The following equation was applied:

$$E_{fuel} = FUEL_a \times EF_a \quad [8]$$

where:
E_{fuel} = CO_2 emissions from fossil fuel consumption (tons CO_2)
$FUEL_a$ = Energy generated from fuel type aa (TJ)
EF_a = Emission factor for fuel type a (t CO_2/TJ)

The energy content of the fuel was determined using:

$$FUEL_a = \text{Liters of fuel}_a \times \text{Density of fuel}_a \times NCV_a \times 10^{-3} \quad [9]$$

where:
Liters of fuel_a = Amount of fuel consumed (liters)
Density of fuel_a = Fuel density (kg/liter)
NCV_a = Net calorific value of fuel (TJ/Gg)

Default emission factors were based on IPCC Guidelines (Buendia et al., 2019), as shown in Table 1.

Table 1
Default IPCC emission factors for fossil fuels

Fuel Type	Density (kg/liter)	NCV (TJ/Gg)	Emission Factor (t CO_2/TJ)
Gasoline	0.7407	44.3	69.3
Diesel	0.8439	43.0	74.1

Total CO_2 emissions from fossil fuel use were estimated using:

$$E_{transport} = FUEL_a \times EF_a \quad [10]$$

where $E_{transport}$ represents CO_2 emissions from transportation activities.

Carbon Estimation from Logging Residues

To assess CO_2 emissions from logging residues, circular sampling plots (0.04 ha each) were established across three different harvested stands, representing variations in tree density and biomass distribution. Within each plot, tree diameter at breast height (DBH) and total tree height were recorded to estimate the total biomass left as logging residues. Logging residues were categorized into four components: stumps, branches, sorting residues, and upper trunk sections, following the classification by Yuniwati & Suhartana (2014). The carbon content of each residue category was estimated using allometric models as follows:

$$C_{stump} = 0.000141D^{3.084} \quad [11]$$

$$C_{branch} = 1.26979 \times 10^{-10}D^{6.908} \quad [12]$$

$$C_{sorting} = 1.13411 \times 10^{-10}D^{6.645} \quad [13]$$

$$C_{upper\ trunk} = 2.01512 \times 10^{-8}D^{4.767} \quad [14]$$

where:
C_{stump},C_{branch},$C_{sorting}$,$C_{upper\ trunk}$ = Carbon stock in different tree components (tons C)
D = Diameter at breast height (m)

The CO_2 emissions from decomposing residues were estimated using an exponential decay model:

$$E_{residue} = C_{residue} \times (1 - e^{-kt}) \times \frac{44}{12} \quad [15]$$

where:
$E_{residue}$ = CO_2 emissions from residue decomposition (tons CO_2 /ha/year)
$C_{residue}$ = Carbon stock in logging residues (tons C/ha)
k = Decomposition rate constant ($year^{-1}$)
t = Time (years)
44/12 = Carbon-to-CO_2 conversion factor

Decomposition rates were determined through periodic residue sampling over 12 months, with litterbag collections at 1, 3, 6, and 12 months. The cumulative carbon emissions from logging residues were then projected over a 20-year plantation cycle, assuming a four-year rotation period for harvested stands.

Data Analysis

Carbon emissions were expressed as tons CO_2e per hectare per year. Peat subsidence emissions were analyzed using linear regression models, while soil respiration was evaluated through two-way ANOVA. Logging residue decomposition was modeled using an exponential decay function, and fossil fuel emissions were analyzed using IPCC default conversion factors. All statistical analyses were performed using R software (v4.2.1), with significance levels set at $p < 0.05$.

RESULTS AND DISCUSSION

Peat Characteristics and Carbon Content

Peat characteristics at the study site were analyzed to understand their role in carbon storage and emission dynamics. The peat characteristics observed in the study site are summarized in Table 2, which presents variations in bulk density, moisture content, ash content, organic carbon content, and fiber content across different peat depths. Bulk density values ranged from 0.06 to 0.14 g/cm^3, with an average of 0.082 g/cm^3. This indicates that the peat has a highly porous structure, which influences its ability to retain water and store carbon. Bulk density is a critical parameter in determining peat subsidence rates, as lower bulk density values correspond to higher compressibility and greater susceptibility to decomposition when exposed to air. Lower bulk density also implies that carbon loss per unit volume of peat may be significant upon drainage and oxidation (Hooijer et al., 2011).

Moisture content ranged from 550.51 to 1260.26 percent, showing high water retention capacity, which is a typical characteristic of tropical peatlands. High moisture content plays a crucial role in limiting oxygen diffusion, thereby slowing microbial decomposition and reducing carbon release. However, when the water table drops, aeration increases, leading to accelerated oxidation of organic matter and greater CO_2 emissions. The variability in moisture content across different depths suggests that water retention decreases in deeper layers due to compaction and structural changes in peat composition (McCarter et al., 2020).

Ash content varied from 0.61 to 5.04 percent, indicating that the peat is primarily organic with minimal mineral content. The lower ash content suggests limited mineral input from external sources, which is characteristic of ombrotrophic peatlands. The presence of higher ash content in the upper layers may be attributed to external sediment deposition or organic matter decomposition over time. Peat with low ash content tends to have higher carbon storage potential but is also more vulnerable to rapid degradation when drained (Pardede et al., 2021).

Organic carbon content ranged between 51.09 and 57.65 percent, confirming the high carbon storage capacity of the study site. Deeper peat layers exhibited slightly higher organic carbon concentrations, which aligns with previous studies indicating that decomposition is less intense in deeper layers due to reduced microbial activity and oxygen availability. Organic carbon levels are a key factor in determining the carbon sequestration potential of peatlands, with variations in carbon content affecting total carbon stock estimates. The strong correlation between peat depth and organic carbon content reinforces the importance of maintaining natural peat hydrology to prevent excessive carbon loss (Nurzakiah, 2014).

Table 2
Peat characteristics at the study site

Peat Depth (cm)	Bulk Density (g/cm³)	Moisture Content (%)	Ash Content (%)	Organic Carbon (%)	Fiber Content (%)
0-50	0.14	550.51	5.04	55.08	50.56
50-100	0.10	879.32	3.09	56.21	51.33
100-150	0.06	1095.59	2.98	56.28	51.44
150-200	0.07	1141.40	1.61	57.05	52.14
200-250	0.08	1108.44	1.56	57.10	53.43
250-300	0.08	1174.18	1.98	56.61	55.43
300-350	0.07	1260.26	1.86	56.93	56.00
350-400	0.07	1103.76	1.71	54.21	56.17
400-450	0.07	1108.35	1.52	54.80	56.50
450-500	0.08	1132.51	0.61	57.65	57.33
500-550	0.08	1134.45	0.84	57.52	58.00
550-600	0.09	1030.16	0.83	57.52	58.33
600-650	0.07	988.39	0.93	51.09	59.67
650-700	0.10	1035.72	0.89	54.74	60.00

The relationship between organic carbon content and peat depth demonstrates that deeper layers tend to retain higher carbon concentrations, likely due to lower decomposition rates and minimal exposure to aerobic conditions, as shown in Figure 1. Regression analysis indicated a significant correlation between peat depth and total carbon content, represented by the equation $Y = 192.8127 + 4.460X$, where X is peat depth (m) and Y is total carbon content (tons). The model yielded a high coefficient of determination ($R^2 = 0.99$) and a statistically significant P-value < 0.05, confirming that peat depth has a significant effect on carbon storage at a 5% significance level. The study area, covering 43,538 hectares, was estimated to contain a total peat carbon stock of 137.733 megatons, which is equivalent to 505.023 megatons of CO_2e. The distribution of carbon content across different peat depths is illustrated in Figure 1, further highlighting the role of deep peat layers in long-term carbon sequestration. The inverse correlation between bulk density and organic carbon stock emphasizes the importance of maintaining natural peatland conditions to prevent excessive carbon loss and minimize greenhouse gas emissions.

Fiber content ranged from 50.56 to 60 percent, indicating that the peat in the study area is predominantly hemic. Hemic peat is characterized by a moderate level of decomposition, where plant structures are still recognizable but have undergone partial breakdown. Peat with higher fiber content tends to have greater water retention capacity, reducing decomposition rates under natural conditions. However, once drained, hemic peat can become highly susceptible to degradation, contributing to long-term CO_2 emissions. The fiber content values observed in this study align with previous findings on tropical peat characteristics and their role in carbon cycling (Ahmad et al., 2021).

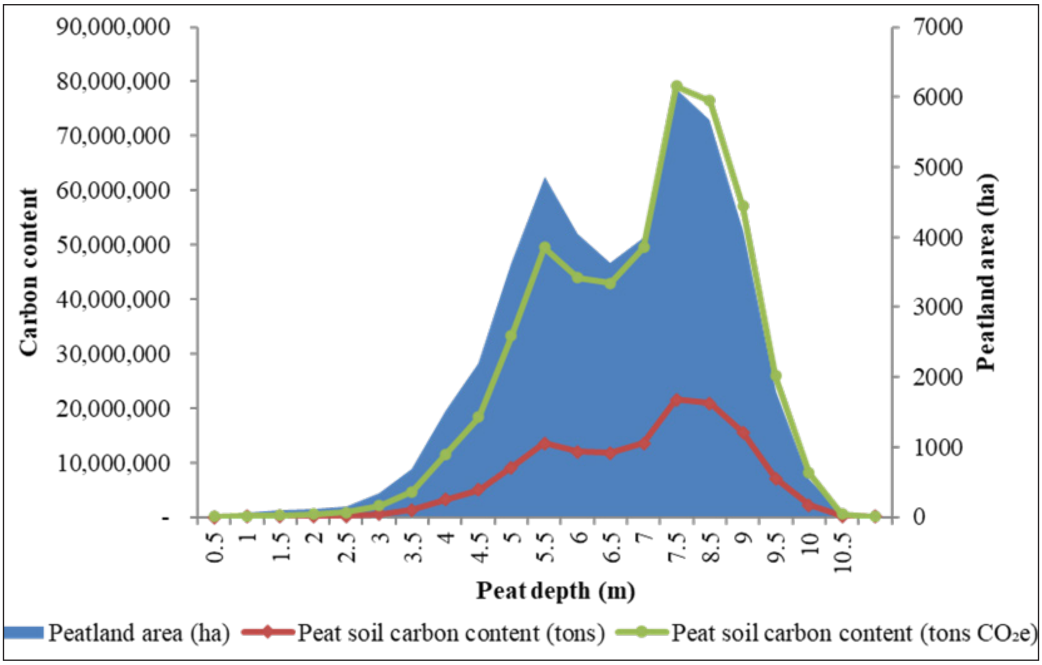

Figure 1. Organic carbon content distribution across peat depths

These findings emphasize the critical role of peat depth and composition in maintaining ecosystem carbon balance. Given the high carbon stock observed in the study area, it is essential to implement sustainable peatland management practices to minimize carbon loss. Future studies should investigate the influence of hydrological management on peat decomposition rates and explore potential carbon sequestration strategies such as controlled water table regulation and alternative peatland restoration methods.

Carbon Emissions from *A. crassicarpa* Plantation Management

CO_2 Emissions from Peat Subsidence

Peat subsidence is the process of surface lowering due to compaction, oxidation, or decomposition, which is primarily driven by drainage construction that facilitates water loss from peat soils. As water drains, oxygen infiltrates the peat matrix, accelerating microbial decomposition of organic matter into inorganic compounds, thereby releasing CO_2 emissions (McCarter et al., 2020). This process reduces peat biomass and bulk density, ultimately leading to subsidence. Peatland drainage for plantation forestry has been widely recognized as a significant contributor to soil carbon loss and increased emissions (Mander et al., 2024; McCalmont et al., 2021; Hooijer et al., 2011).

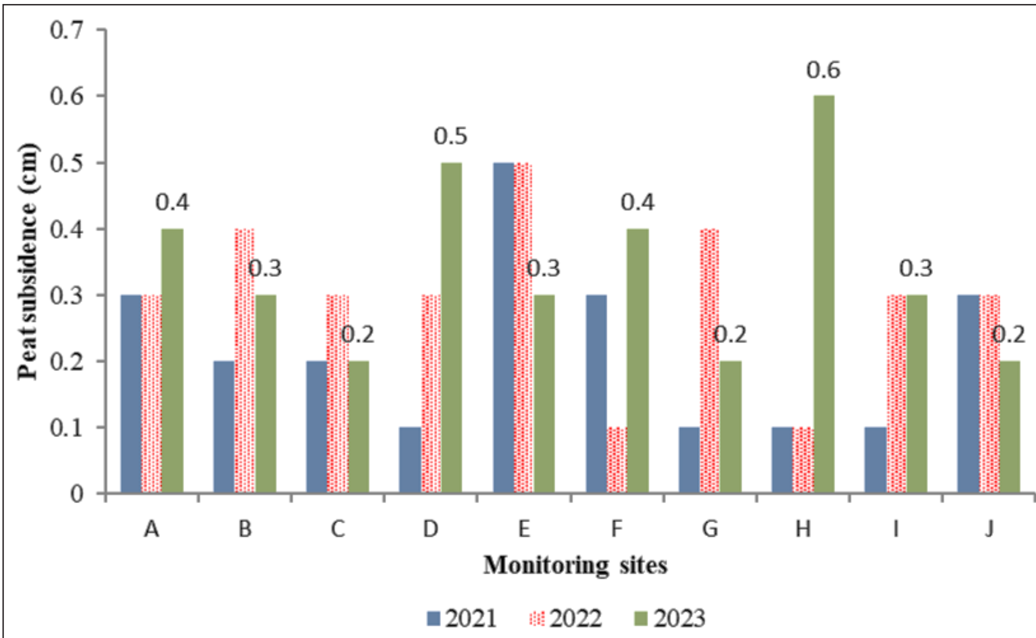

Figure 2. Peat subsidence at 10 monitoring sites in the study area

To quantify peat subsidence in this study, secondary data were collected from 10 monitoring sites distributed across the research site. The observed fluctuations in peat subsidence over three years are presented in Figure 2. The average subsidence rates were 0.34 cm in 2023, 0.3 cm in 2022, and 0.22 cm in 2021, yielding a three-year mean subsidence rate of 0.29 cm/year. This rate is significantly lower than the 5.5 cm/year reported by Lisnawati et al. (2015) in Rasau Kuning, Riau Province, where subsidence was strongly correlated with groundwater table fluctuations.

Hooijer et al. (2011) established a link between peat subsidence and carbon loss, as subsidence directly corresponds with organic matter degradation and peat compaction, leading to increased CO_2 emissions. The estimated total carbon stock in the study area, with a peat depth of 11 meters, was 505,022,898.29 tons CO_2e.. Annual carbon emissions from peat subsidence were estimated at 133,142.40 tons CO_2e, equivalent to 3.058 tons CO_2e/ha/year. Over a 20-year projection, total emissions from peat subsidence alone were estimated at 2,662,848 tons CO_2e, as illustrated in Figure 3.

The emission rate reported in this study is lower than previous findings in other land-use types. Aswandi et al. (2016) documented 5.96 tons CO_2e/ha/year in secondary forests and 7.45 tons CO_2e/ha/year in oil palm plantations, while degraded tropical forests were found to emit up to 65 tons CO_2e/ha/year (Hooijer et al., 2010). The lower emissions observed in the managed A. crassicarpa plantation suggest that while drainage-induced subsidence

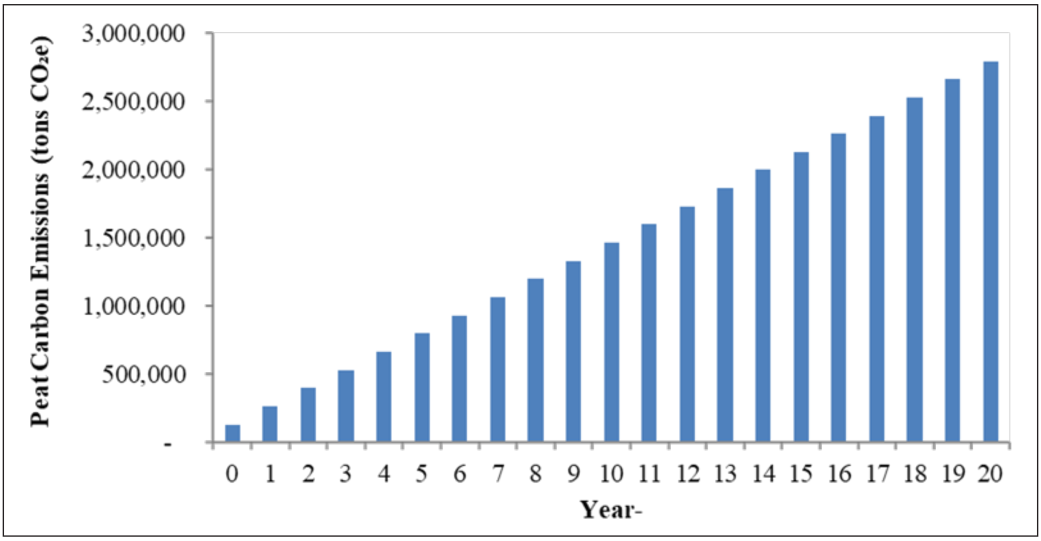

Figure 3. CO_2 emissions from peat subsidence over 20 years

occurs, it is not as severe as in other more intensively disturbed land-use systems. The rate of subsidence is influenced by multiple factors, including drainage depth and peat thickness. Deeper drainage channels and thicker peat layers typically result in higher subsidence rates, leading to greater carbon emissions. This finding underscores the need for improved water table management in plantation forestry to minimize peat oxidation and CO_2 release.

CO_2 Emissions from Fertilized Peat Soil Respiration

To enhance soil fertility and improve the productivity of A. crassicarpa plantations, fertilization is commonly applied. The main purpose of fertilization is to increase soil nutrient availability, thereby supporting optimal tree growth (Purnama et al., 2023). Zincobor fertilizer has been reported to enhance tree height, stem straightness, and prevent shrubby growth in A. crassicarpa plantations (Hidayat et al., 2022). However, fertilization on peatlands may also influence microbial activity, potentially leading to increased CO_2 emissions (Shi et al., 2025). Serrano-Silva et al., (2011) found that urea application enhances soil microbial activity, consequently increasing soil respiration and CO_2 release into the atmosphere.

At the study site, fertilization was applied twice during the plantation cycle. The first application, or basal fertilization, consisted of BTA 12 (1 kg per tree) and NPK (80 g per tree), while the second application, or topdressing, involved NPK (80 g per tree). CO_2 emissions were measured one week after fertilization at 1-, 3-, 5-, and 7-days post-application, with the results presented in Figure 4. The average soil CO_2 emissions from

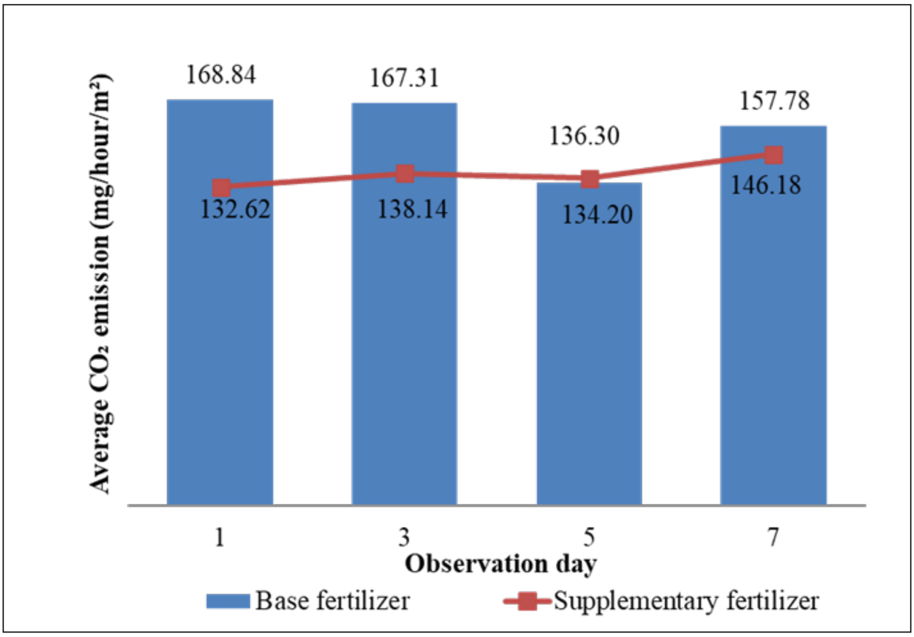

Figure 4. CO_2 emissions following fertilization

basal fertilization were 157.036 mg/m²/h, whereas topdressing resulted in slightly lower emissions of 138.308 mg/m²/h. The total estimated annual CO_2 emissions from fertilization were 2.552×10^{-4} tons/ha/year. The temporal pattern of emissions showed an initial increase immediately after fertilization, followed by a gradual decline over time.

The emissions observed in this study are significantly higher than those reported by Andelia et al. (2020), who found soil CO_2 emissions of 29.56 mg/m²/h in green bean cultivation fertilized with manure and NPK. In contrast, NPK application in oil palm plantations has been reported to generate CO_2 emissions ranging from 1.090 to 230 mg/m²/h (Riyani et al., 2021). The higher emissions in A. crassicarpa plantations may be attributed to peat soil conditions, fertilizer type, and microbial activity associated with decomposition processes. In this study, fertilization was assumed to follow a four-year harvesting cycle, where fertilizer application occurred at 14 and 90 days after planting. Annual CO_2 emissions from fertilization were estimated at 2.107 tons in the first year, with emissions remaining consistent from year 2 to year 20. Over a 20-year plantation cycle, the total CO_2 emissions from fertilization were calculated at 42.139 tons. The cumulative emissions over this period are illustrated in Figure 5.

The results highlight the necessity of refining fertilization strategies in peatland forestry to reduce carbon emissions while sustaining soil fertility and enhancing productivity. Future studies should investigate the effectiveness of alternative fertilization approaches,

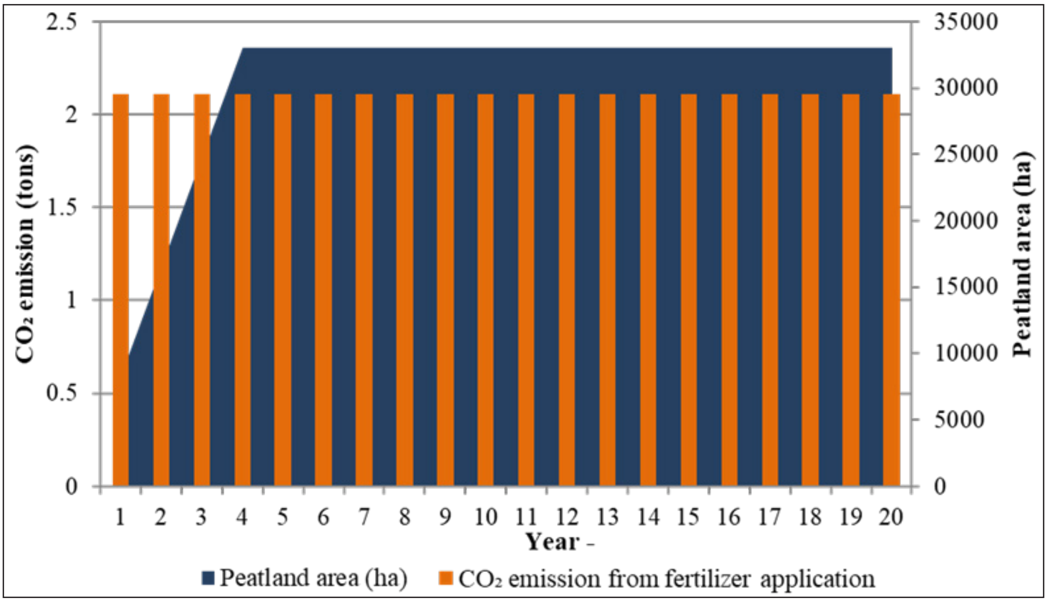

Figure 5. Cumulative CO_2 emissions from fertilization over a 20-year cycle.

such as slow-release fertilizers or biochar amendments, in mitigating CO_2 emissions from fertilized peat soils.

CO_2 Emissions from Logging Residue Decomposition

One of the major sources of carbon emissions in A. crassicarpa plantation management is logging operations. According to Yuniwati & Suhartana (2014), timber harvesting in tropical forests across Asia can reduce carbon stocks by 22–67% due to the decomposition of residual biomass left after harvesting. Logging residues typically consist of stumps, branches, short wood pieces, and upper trunk sections (Surasana et al., 2020). These residues decompose over time, releasing carbon into the atmosphere (Yuniwati & Suhartana, 2014).

Table 3
Emissions from logging residues

No plot	Number of Trees (trees/ha)	Stump Carbon Mass (ton/ha)	Branch Carbon Mass (ton/ha)	Sorting Carbon Mass (ton/ha)	Upper Trunk Carbon Mass (ton/ha)	Total Carbon Mass (ton/ha)	Carbon Mass (ton CO_2e)
1	1266	0.507	0.017	0.007	0.007	0.538	1.972
2	1385	0.460	0.013	0.006	0.006	0.484	1.776
3	1464	0.571	0.025	0.011	0.009	0.616	2.258
Average		**0.513**	**0.018**	**0.008**	**0.007**	**0.546**	**2.002**

The estimation of carbon emissions from A. crassicarpa logging residue decomposition was conducted using an allometric equation from Yuniwati & Suhartana (2014). The estimated carbon storage and emission potential from logging residues are presented in Table 3. The total estimated carbon emissions from logging residues were 0.546 tons/ha, equivalent to 2.002 tons CO_2e/ha. Assuming a four-year harvesting cycle, the total emissions from logging residues in the fourth year would reach 4,507.78 tons CO_2e. From year 4 to year 20, emissions remain relatively stable as plantation management follows a continuous cycle. Over a 20-year period, the cumulative emissions from logging residue decomposition were estimated at 76,632.19 tons of carbon, equivalent to 280,984.70 tons CO_2e. The long-term emission trend from logging residue decomposition is illustrated in Figure 6.

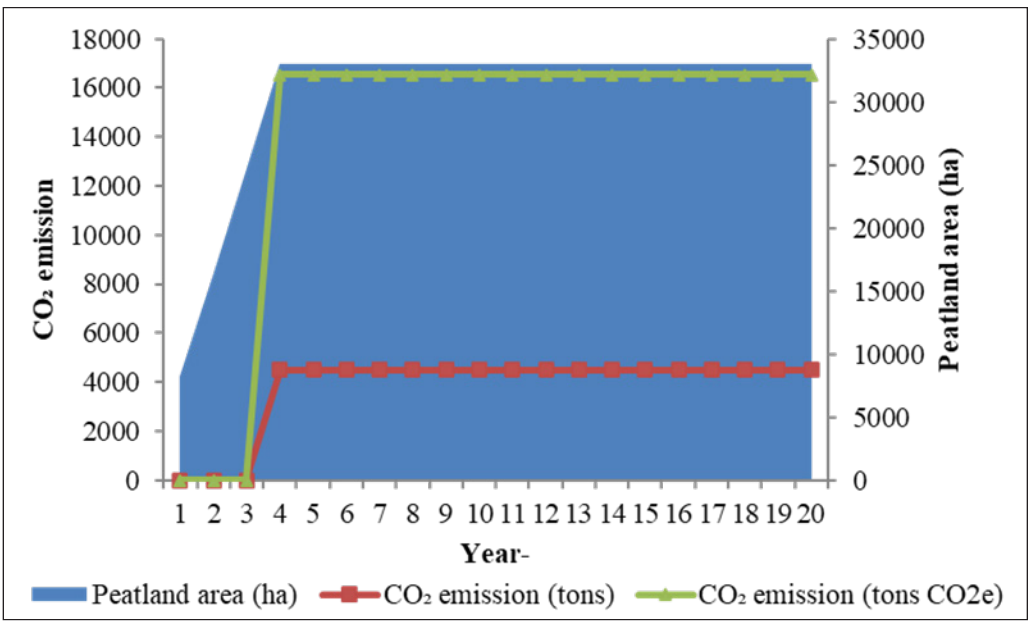

Figure 6. Carbon emissions from logging residue decomposition

These findings underscore the importance of optimizing logging residue management to minimize emissions from decomposing biomass. Future studies should explore alternative methods such as biochar conversion or residue repurposing to enhance carbon sequestration while maintaining sustainable forest productivity.

CO_2 Emissions from Fossil Fuel Use in Logging Operations

Timber harvesting in A. crassicarpa plantation management involves multiple stages, including felling, delimbing, skidding, loading, and transportation (Mohamad-Amini, 2024). In large-scale operations, mechanized harvesting is the standard approach, requiring significant fossil fuel consumption for operating heavy machinery and transport vehicles (McEwan et al., 2020). Fossil fuel combustion from these activities contributes to CO_2, NO_x, and SO_2 emissions (Mohammed et al., 2024). The carbon footprint of fossil fuel use in industrial timber harvesting has been estimated at 1,100 tons CO_2e (Suharto et al., 2017). The fossil fuel consumption required for logging A. crassicarpa plantations is summarized in Table 4.

Table 4
Fossil fuel consumption in logging operations of A. crassicarpa

Activity	Equipment	Fuel Type	Trials	Fuel Consumption (L)	Wood Transported (tons)	Average Fuel Consumption per Ton (L)	CO_2 Emissions (tons)
Felling	Excavator with feller buncher	Diesel	1	65	78	0.8266	0.0022
			2	61	67		
			3	53	72		
Pre-Bunching	Excavator with fixed grapple	Diesel	1	55	70	0.7620	0.0020
			2	57	77		
			3	57	75		
Delimbing & Cut-to-Length	Chainsaw	Gasoline	1	20	35	0.5516	0.0012
			2	30	40		
			3	16	48		
Skidding	Excavator with fixed grapple	Diesel	1	57	57	0.9872	0.0027
			2	50	52		
			3	55	55		
Log Transport	Tug boat	Diesel	1	51	210	0.243	0.0022
			2	50	202		
			3	55	230		
	Truck	Diesel	1	30	50	0.572	
			2	31	60		
			3	33	55		
Loading	Excavator with rotary grapple	Diesel	1	33	384	0.0799	0.0002
			2	38	480		
			3	43	576		
Total						**4.0227**	**0.0106**

Based on Table 4, the total fuel consumption for harvesting 1 ton of A. crassicarpa timber was 4.02 liters, resulting in CO_2 emissions of 0.0106 tons per ton of harvested wood. The amount of fuel required for logging operations is influenced by annual production targets, with emissions estimated at 5,192.319 tons CO_2e, consistent with findings by Suharto et al. (2017). Among all activities, skidding required the highest fuel consumption, as it involves transporting logs from the felling site to temporary storage areas (Surasana et al., 2020). Conversely, log loading required the least fuel consumption.

Fuel consumption in heavy machinery is influenced by engine power, machine type, and workload intensity (Purwanto et al., 2021). Additionally, the type of machinery used and the operational workload directly affect fuel efficiency (Banggur et al., 2023). These findings suggest that improving fuel efficiency and optimizing transport logistics could reduce CO_2 emissions in large-scale forestry operations.

CONCLUSION

This study quantified CO_2 emissions from *A. crassicarpa* plantations on peatlands, identifying peat subsidence as the dominant emission source, contributing 3.058 tons CO_2e/ha annually, followed by logging residue decomposition (2.002 tons CO_2e/ha), fertilization-induced soil respiration (2.552×10^{-4} tons CO_2e/ha/year) and fossil fuel used contributing 5,192.319 tons CO_2e per harvest cycle. Over a 20-year projection, cumulative emissions from all sources were substantial, highlighting the long-term impact of plantation forestry on peat carbon stocks. To mitigate emissions, optimizing fertilization practices, improving residue management, and enhancing fuel efficiency are essential. Maintaining higher water table levels and integrating carbon sequestration strategies such as alternative fertilization and biochar application could further reduce emissions while ensuring sustainability. Future research should refine long-term carbon flux models, explore adaptive land-use strategies, and develop science-based policies to align plantation forestry with global climate commitments.

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