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Loss of carbon stock as an impact of anthropogenic activities in a protected mangrove forest

SYAIFUL EDDY[1,♥], ANDI ARIF SETIAWAN[1], MIRNA TAUFIK[2], MAHARANI OKTAVIA[2], BUDI UTOMO[2], NORIL MILANTARA[3]

[1]Departement of Environmental Science, Faculty of Natural Sciences and Technology, Universitas PGRI Palembang. Jl. Jend. A. Yani, 9/10 Ulu, Palembang 30251, South Sumatra, Indonesia. Tel.: +62-711-510043, ♥email: syaifuleddy@gmail.com

[2]Departement of Geography Education, Faculty of Teacher Training and Education, Universitas PGRI Palembang. Jl. Jend. A. Yani No. 9/10 Ulu, Palembang 30251, South Sumatra, Indonesia

[3]Faculty of Forestry, Universitas Muhammadiyah Sumatera Barat. Jl. Pasir Kandang No. 4, Koto Tangah, Padang 25172, West Sumatra, Indonesia

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Abstract. *Eddy S, Setiawan AA, Taufik M, Oktavia M, Utomo B, Milantara N. 2023. Loss of carbon stock as an impact of anthropogenic activities in a protected mangrove forest. Biodiversitas 24: 6493-6501.* The significant anthropogenic activities within the mangrove forest, known as the Air Telang Protected Forest (ATPF) in the Banyuasin District, South Sumatra, Indonesia, have led to an alarming degradation, leaving only its primary mangrove forests, currently constituting approximately 26% of the total forest area. This study aims to analyze changes in land cover, quantify carbon reserve loss due to CO_2 emissions, and assess carbon sequestration in the ATPF over two periods: 1999-2010 and 2010-2023. Remote sensing data for 1999, 2010, and 2023 were utilized from Landsat imagery, employing ENVI and ArcGIS for land cover classification. Carbon density, CO_2 emissions, and carbon sequestration were analysed using the Land Use Planning for Multiple Environmental Services (LUMENS) software. The research findings reveal an increase in the primary forest area in the first period (by almost a quarter); however, more than half of this area was lost in the second period. The secondary forest area consistently decreased over the two periods, while the open area experienced significant growth. Carbon stocks in 2010 exceeded those in 1999 due to an increase in the primary forest area, but by 2023, carbon stocks decreased significantly due to extensive land clearing. The second period witnessed the largest emissions, exceeding those of the previous period by five times. Carbon sequestration in the first period surpassed that in the second period by more than three times, with the most significant sequestration resulting from the growth of secondary mangrove forests into primary mangrove forests. The study highlights the necessity of restoration and conservation of mangrove forest areas in ATPF for sustenance of its natural function as a protected forest.

Keywords: Air Telang Protected Forest, anthropogenic activities, carbon loss, Landsat, mangrove forest

Abbreviations: ATPF: Air Telang Protected Forest, LUMENS: Land Use Planning for Multiple Environmental Services

INTRODUCTION

Mangrove forests play a crucial role in environmental preservation, particularly in mitigating climate change the remarkable capacity to store carbon stocks (Eddy et al. 2016; Atwood et al. 2017; Hochard et al. 2019; Kusmana et al. 2019; Ouyang and Lee 2020; Basyuni et al. 2021, 2023). Multiple studies have highlighted their significance, indicating that mangroves can store more carbon than terrestrial tropical forests (three times more) and upland forests (five times more) (Donato et al. 2011; Murdiyarso et al. 2015). However, anthropogenic activities have triggered degradation in these forests, leading to a decline in species diversity and subsequent emissions of greenhouse gases into the atmosphere (Mai et al. 2019; Eddy et al. 2021a,b).

Air Telang Protected Forest (ATPF) in South Sumatra Province, Indonesia, spans approximately 12,660.87 ha of mangrove forests. Unfortunately, degradation caused by anthropogenic activities such as development of coconut and oil palm plantations, pond constructions, agricultural practices, and infrastructure constructions has significantly reduced the forest's species diversity and coverage (Eddy et al. 2017, 2019, 2021a,c, 2022). Presently, only 26% of the ATPF consists of primary mangrove forests. A previous study by Eddy et al. (2021b) revealed that the ATPF experienced net carbon emissions of 1,928,076.56 tonnes of CO_2-eq between 2000 and 2020, with an annual emission rate of 96,403.83 tonnes of CO_2-eq/year. The conversion of primary forests, coconut plantations, and secondary forests into open areas were found to be the primary source of emissions.

The predominant open area, a result of deforestation and fires, now covers half of the ATPF's total area (Eddy et al. 2021a, 2022), causing a decline in mangrove root mass and facilitating the invasion of species such as nipah (*Nypa fruticans* Wurmb) across various zones within the forest (Eddy and Basyuni 2020; Eddy et al. 2023). The disruption in mangrove forest succession, coupled with biological invasions, inhibits growth of mangrove and affects aquatic biota, reducing fisheries productivity and exacerbating broader ecological issues (Biswas et al. 2012; Numbere 2019). Additionally, the reduction in forest biomass amplifies greenhouse gas production due to decreased carbon sequestration capacity (Chen et al. 2023).

This study examines land cover changes and associated carbon stock losses and sequestration in ATPF over two periods: 1999-2010 and 2010-2023, utilizing Landsat imagery data and using the Land Use Planning for Multiple Environmental Services (LUMENS) software. The outcomes aim to guide policy formulation and mitigation efforts by providing stakeholders with valuable insights into carbon emissions and sequestration dynamics, offering a blueprint for climate change intervention.

MATERIALS AND METHODS

Study area

This research was conducted in the Air Telang Protected Forest (ATPF) in Banyuasin District, South Sumatra, Indonesia (Figure 1), encompassing the administrative area of Banyuasin II, Tanjung Lago, and Sumber Marga Telang Districts of Banyuasin Regency, South Sumatra Province, covering an area of around 12,660.87 ha. The protected forest's original area was designated as 14,460.00 ha the Minister of Forestry of the Republic of Indonesia's decree No. SK.76/Menhut-II/2001 of 2001. However, this area was reduced to 12,660.87 ha following the issuance of the Minister of Forestry of the Republic of Indonesia's decree No. SK.822/Menhut-II/2013 in 2013, resulting in a reduction of around 1,799.13 ha.

Situated adjacent to the flowing waters of the Banyuasin River and the Bangka Strait, ATPF is a vital area in need of conservation. Unfortunately, it has been experiencing considerable degradation and consistent decline in its mangrove forest area over the years. Most of the ATPF has been converted into coconut plantations, oil palm plantations, ponds, and ports (Eddy et al. 2017, 2021a, 2022). Despite this, the vegetation in this area is still predominantly composed of true mangrove plants, specifically *N. fruticans*, *Rhizophora apiculata* Blume, and *Acrostichum aureum* L. (Eddy et al. 2019, 2022).

Data collection

This study utilized Landsat imagery data for ATPF from the years 1999, 2010, and 2023, which were downloaded from https://earthexplorer.usgs.gov. The downloaded images were sourced from Landsat 7 ETM and Landsat 8 OLI, selected based on minimal cloud coverage (<10%) in the respective years (Table 1). The study used the UTM (Universal Transverse Mercator) coordinate system of Zone 48. The selection of research locations were carried out through purposive sampling, aligning with the research objectives. The verification of information on land cover types and the boundaries of each land cover type was carried out through field surveys. Subsequently, the study utilized the survey results to classify Landsat images, in order to create land cover maps.

Table 1. Specific Landsat imagery data used in this study

Year	Data	Date of acquisition	Bands	Resolution (m)	Source
1999	Landsat 7 ETM + C2 L1	15 December 1999	Multi-spectral	30	https://earthexplorer.usgs.gov
2010	Landsat 7 ETM + C2 L1	16 March 2010	Multi-spectral	30	https://earthexplorer.usgs.gov
2023	Landsat 8 Oli C2 L1	21 April 2023	Multi-spectral	30	https://earthexplorer.usgs.gov

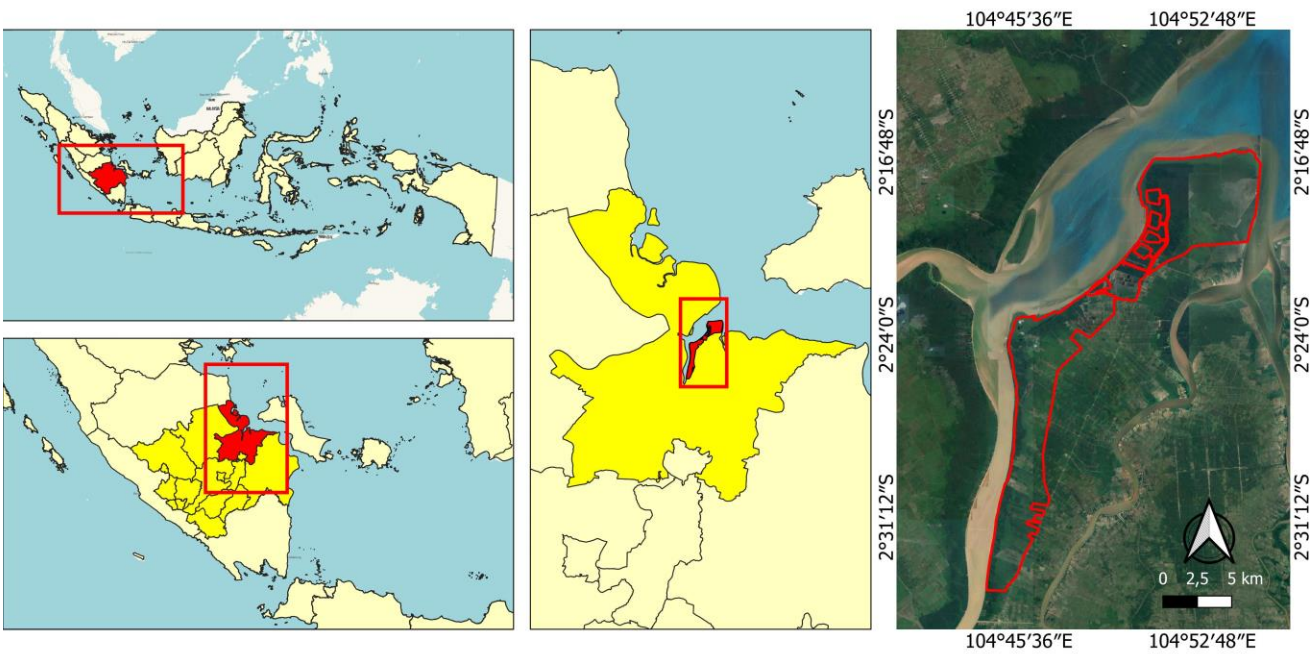

Figure 1. Research locations in the Air Telang Protected Forest (ATPF), Banyuasin District, South Sumatra, Indonesia

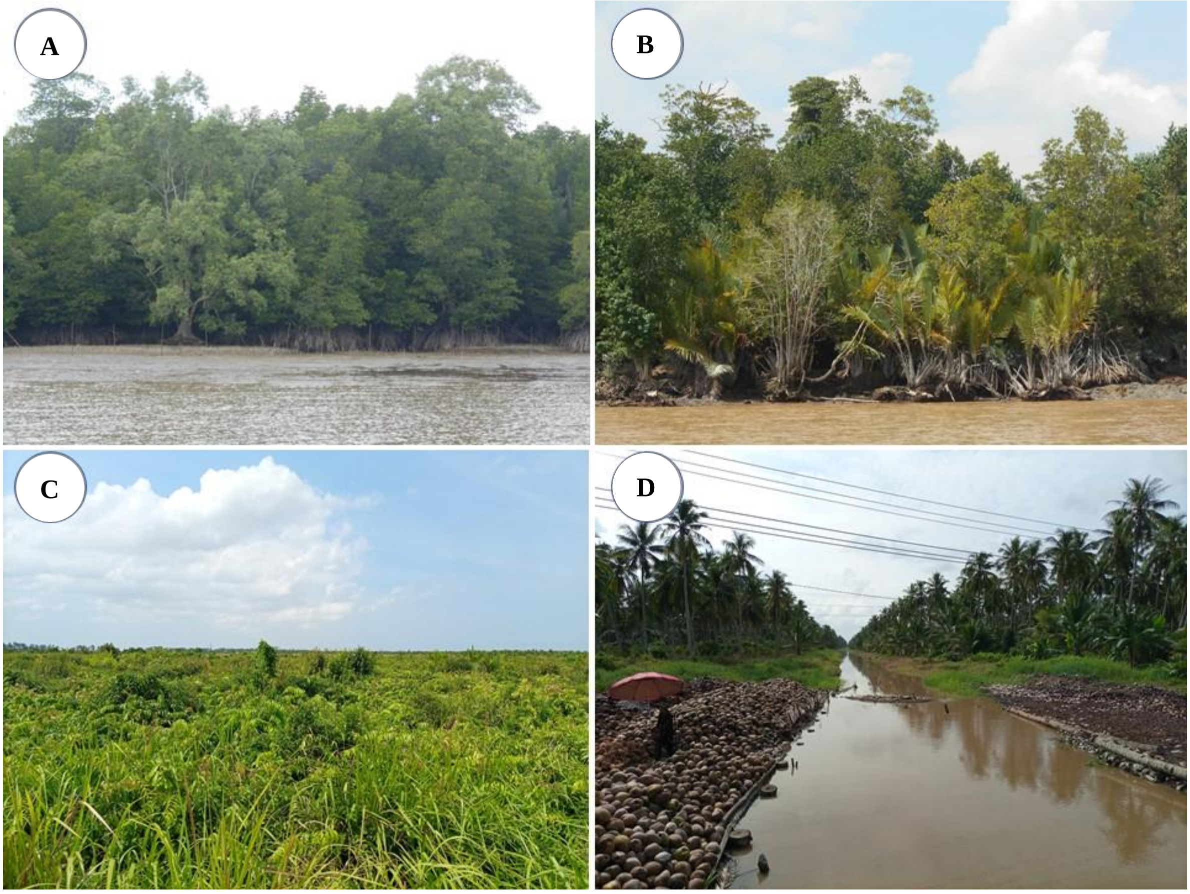

Figure 2. Existing conditions of the research area based on land cover type, consisting of the following: A. Primary mangrove forest, B. Secondary mangrove forest, C. Open area with shrub plants, and D. Coconut plantation

Data analysis

The categories and definitions of land cover in this study were obtained from the national thematic maps of the Ministry of Environment and Forestry, Republic of Indonesia. The characteristics of each land cover type classification followed the definitions provided by Eddy et al. (2021a); The study area was classified into primary mangrove forest, secondary mangrove forest, plantation, open area, and waterbody area (Figure 2).

Thereafter, supervised classification of image for visual interpretation was performed for documenting various land covers and their alterations (Butt et al. 2015; MoEF 2015). Geometric correction of Landsat images were conducted to ensure they shared the same coordinate specifications as the coordinates as the base map and the Global Positioning System (GPS). The Landsat 8 image served as a reference for geometric correction, with a Root Mean Square Error (RMSE) threshold value set at 0.5.

Furthermore, object recognition in the images was facilitated by generating Red Green Blue (RGB) colour composite channels. The interpretation of coastal land cover, especially mangroves, utilized a combination of bands 543 and 654 in Landsat 7 and Landsat 8 imageries, respectively. The determination of land cover density was carried out using the Normalised Differenced Vegetation Index (NDVI) method, with the help ENVI and ArcGIS.

The carbon stock, carbon sequestration, and carbon emission values in the ATPF were determined through analysis using the open source LUMENS version 0.1 (Nguyen et al. 2016; Untari et al. 2018; Do et al. 2020). Notably, the LUMENS software employed a stock difference approach, comparing the differences in carbon stock across the years under study (Eddy et al. 2021b). It is important to clarify that emissions signify a scenario where the land cover carbon stock in the final period is lower than that in the initial period, while sequestration denotes a condition where the land cover carbon stock in the final period is higher than that in the initial period.

As per the established protocol, this study utilized the LUMENS instrument with the Quantification of Environmental Services (QUES). Specifically, the QUES sub-menu employed in this research was Pre-QUES, designed for measuring changes in land cover over a specified period. QUES-C was then applied to calculate carbon emissions and sequestration based on land use changes within the designated timeframe. The data utilized by LUMENS consisted of spatial data in the form of raster image files derived from the results of image interpretation. Moreover, the carbon stock constants were obtained from tabular data representing all land cover types in the ATPF. The calculation of carbon reserves involved multiplying the area of each land cover type by the carbon density reference data for the South Sumatra Province. The rates of change in carbon emissions and sequestration for each land cover type were assumed to align with the changes in the area of each land cover type within the same region over the specified period, measured in area units (pixels).

RESULTS AND DISCUSSION

Land cover changes for the period 1999-2023 in ATPF

In this study, the classification of land cover types in 1999, 2010, and 2023 in the ATPF organized these types into five groups: primary mangrove forest, secondary mangrove forest, plantations, open area, and water bodies (Figure 3). Other land cover types were not defined because they were static, relatively smaller and harder to detect, such as ponds and settlements. Primary and secondary mangrove forests were dominated by true mangrove plants, while open areas were dominated by shrubs (Eddy et al. 2017, 2022). The dominant plantations consisted of coconut plantations and oil palm plantations. This study combined the two into one category-plantations-because the LUMENS software had only one constant category for plantations.

In 2004, one of the development-related priorities in the ATPF mandated the construction of a passenger and cargo port at Tanjung Api-Api, which became operational in 2018. Unlike our previous papers, the map presented in this paper excluded this port area. In fact, the port area of Tanjung Api-Api (depicted in white on the maps in Figure 3) was excluded from the total ATPF area of 621.17 ha based on the decree of the Minister of Forestry of the Republic of Indonesia No. SK.866/Menhut-II/2014 and the decree of the Governor of South Sumatra No. 72/KPTS/BPKAD/2022. Moreover, the ATPF spatial data for 1999, 2010, and 2023 processed in this study referred to the decree of the Minister of Forestry of the Republic of Indonesia No. SK.822/Menhut-II/2013 of 2013, covering an area of 12,660.87 ha.

The changes in land cover examined in this study consisted of two periods: the first from 1999-2010 (about 11 years) and the second 2010-2023 (about 13 years) (Table 2). This study observed an increase in the primary forest area in the first period, specifically an addition of almost a quarter of the initial primary forest area (1999). However, more than half of the primary forest area was lost in the second period. Meanwhile, the secondary forest area consistently decreased over the two periods, with the most significant loss occurring in the second period (a loss of more than half of its extant area).

On the other hand, the open area increased significantly significantly in both periodsm with the largest increase occurring in the second period, exceeding its initial area by almost three times (2010). The open area became the dominant land type in the ATPF as of 2023, comprising more than half of the total forest area. Meanwhile, the plantation area decreased significantly in the first period but increased significantly in the second period.

Conditions of carbon stocks, emissions, and sequestration at the ATPF in the 1999-2023 period

The largest carbon stocks in the ATPF were observed in 1999 and 2010, but the forest's carbon stock was projected to decrease drastically in 2023 (Figure 4). Carbon density in the range of 100-200 tonnes of CO_2-eq was predominantly found in the northern and western regions in the 1999-2010 period. However, the carbon density decreased in 2023, with carbon density ranging of 0-50 tonnes of CO_2-eq. Moreover, the carbon stocks in 2010 were greater than those in 1999, mainly due to an increase in the amount of primary forest area, especially in the northern part of the ATPF. Meanwhile, in 2023, the carbon stocks were projected to decrease significantly due to massive land clearing activities, converting more than half of the forest area into open areas.

The largest amount of carbon emissions was observed in the second period; the total emissions in this period exceeded the total emissions in the previous period by more than five times (Table 3). The emissions in the first period were mostly in the range of 0-200 tonnes of CO_2-eq, while the emissions in the second period were mostly in the range of 200-600 tonnes of CO_2-eq (Figure 5). The most significant emissions in the first period occurred due to the conversion of plantations into open area, while the most significant emissions in the second period occurred due to the conversion of primary mangrove forests into open areas.

Table 2. Types of land cover, their respective areas (ha), and trends (increase/decrease) for each type of land cover in the 1999–2023 period

Land cover type	1999		2010		2023		Gap 1999-2010			Gap 2010-2023		
	ha	%	ha	%	ha	%	ha	%	Trend	ha	%	Trend
Primary mangrove forest	6,131.46	48.43	7,596.19	60.00	3,370.50	26.62	1,464.72	23.89	inc	4,225.69	55.63	dec
Secondary mangrove forest	3,044.63	24.05	2,550.57	20.15	1,244.91	9.83	494.06	16.23	dec	1,305.65	51.19	dec
Open area	637.22	5.03	1,680.28	13.27	6,588.34	52.04	1,043.06	163.69	inc	4,908.06	292.10	inc
Plantation	2,473.38	19.54	459.67	3.63	1,197.37	9.46	2,013.71	81.42	dec	737.71	160.49	inc
Waterbody	374.17	2.96	374.17	2.96	259.74	2.05	0.00	0.00	no	114.43	30.58	dec
Total	12,660.87	100.00	12,660.87	100.00	12,660.87	100.00						

Note: inc: increase, dec: decrease

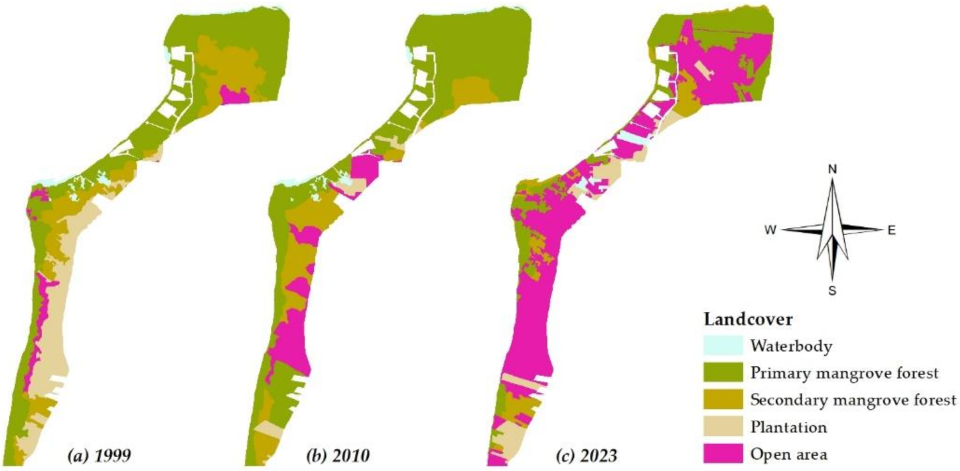

Figure 3. Land cover changes in the ATPF in the 1999-2023 period

Figure 4. Carbon density in ATPF in 1999, 2010, and 2023

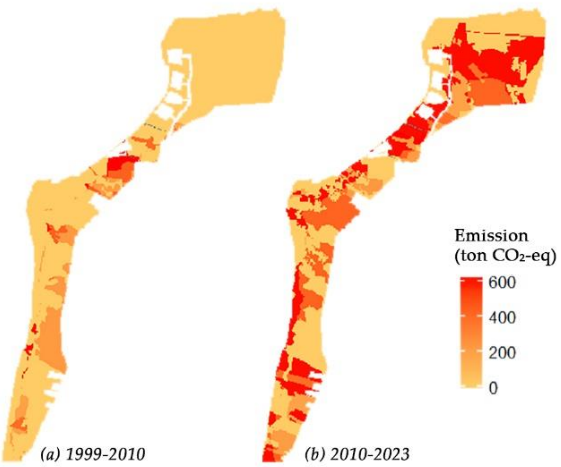

Figure 5. Carbon emissions in ATPF in the 1999-2010 and 2010-2023 periods

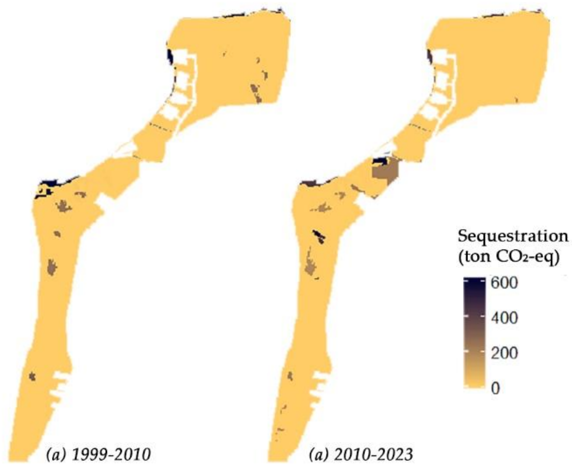

Figure 6. Carbon sequestration in the ATPF in the 1999-2010 and 2010-2023 periods

Table 3. Main emission sources (tonnes of CO_2-eq) in the 1999-2010 and 2010-2023 periods

Main Emission Sources	Emission in 1999-2010 Period		Emission in 2010-2023 Period	
	Tonnes CO_2-eq	%	Tonnes CO_2-eq	%
Plantation to open area	220,150.00	36.01	0.00	0.00
Primary mangrove forest to open area	145,357.80	23.78	2,078,145.50	64.21
Secondary mangrove forest to open area	119,436.40	19.54	735,954.40	22.74
Primary mangrove forest to plantation	63,529.40	10.39	129,426.70	4.00
Primary mangrove forest to secondary mangrove forest	38,296.40	6.26	117,739.10	3.64
Secondary mangrove forest to plantation	24,602.90	4.02	70,589.10	2.18
Primary mangrove forest to waterbody	0.00	0.00	50,224.00	1.55
Plantation to waterbody	0.00	0.00	27,419.20	0.85
Plantation to open area	0.00	0.00	26,848.50	0.83
Total	611,372.90	100.00	3,236,346.50	100.00

Table 4. Sequestration values (tonnes of CO_2-eq) in the 1999–2010 and 2010–2023 periods

Main Sequestration Sources	Sequestration in 1999-2010 Period		Sequestration in 2010-2023 Period	
	Tonnes of CO_2-eq	%	Tonnes of CO_2-eq	%
Secondary mangrove forest to primary mangrove forest	268,477.00	31.54	27,315.80	11.12
Plantation to primary mangrove forest	180,268.30	21.18	0.00	0.00
Plantation to secondary mangrove forest	175,577.40	20.63	0.00	0.00
Open area to secondary mangrove forest	136,413.70	16.03	10,064.80	4.10
Open area to primary mangrove forest	90,389.10	10.62	39,987.90	16.28
Waterbody to secondary mangrove forest	0.00	0.00	98,794.90	40.21
Open area to plantation	0.00	0.00	68,619.90	27.94
Waterbody to open area	0.00	0.00	853.50	0.35
Total	851,125.50	100.00	245,636.80	100.00

Table 5. Statistical data on CO_2 emissions and sequestration in the 1999-2010 and 2010-2023 periods

Category	Summary	
	1999-2010	2010-2023
Total area (ha)	12,660.87	12,660.87
Total emission (tonnes CO_2-eq)	611,372.90	3,236,346.50
Total sequestration (tonnes CO_2-eq)	851,125.50	245,636.80
Net emission (tonnes CO_2-eq)	-239,752.60	2,990,709.70
Emission rate (tonnes CO_2-eq/year)	-21,795.69	230,054.59
Emission rate per-unit area (tonnes CO_2-eq/ha/year)	-1.72	18.17

The carbon sequestrations observed in the two periods indicate that carbon sequestration in the initial period exceeded that in the subsequent period by more than threefold (Table 4). However, sequestrations in both periods were predominantly in the range of 0–200 tonnes of CO_2-eq, with only a few instances surpassing 200 tonnes of CO_2-eq (Figure 6). The primary contributor of sequestration in the first period was the expansion of secondary mangrove forests into primary mangrove forests, while the later period, the conversion of waterbody areas into secondary mangrove forests resulted in the highest sequestration. The total sequestration in the first period surpassed the total emissions, leading to negative net emissions (Table 5). This indicates that during the first period, the amount of carbon sequestered by plants exceeded the carbon released into the environment.

Discussion

Driving factor of ATPF degradation

The conversion of forest functions in ATPF started since the 1970s when individuals entered the forest area to clear it and construct residential buildings. The community engaged in land clearing for agriculture and coconut plantations utilizing access to the forest through rivers and ditches/canals constructed by the community. Aquaculture activities commenced in 1987, and by 1997, the area dedicated to aquaculture saw rapid expansion due to intensive development by the surrounding community.

The introduction of highway access to the Tanjung Api-Api port, operational around the 2000s, further contributed to increased community activity in the ATPF and its surrounding areas. Notably, the development of oil palm plantations commenced in 2008. Conversions of forest areas into agricultural land and plantations in the ATPF took two forms: planted agricultural areas and open areas (not yet planted). According to Eddy et al. (2022), as of 2021, only 14.5% of the ATPF's plantation land was planted with coconut and oil palm, while nearly 50% of the total ATPF area was categorized as open areas.

Currently, open areas dominate the ATPF, comprising over half of its total area. The prevalence of open areas is primarily a result of anthropogenic activities, specifically the community's efforts to clear land for plantations and agriculture (Eddy et al. 2021b). Indeed, mangrove degradation worldwide is predominantly caused by anthropogenic activities (Eddy et al. 2019; Sannigrahi et al. 2020; Eddy et al. 2021a, 2022). Additionally, the construction of a passenger and cargo port at Tanjung Api-Api, initiated in 2004 and operational since 2018, enhances community access to the ATPF area.

Since 2014, the area surrounding the ATPF has been designated by the Central Government of the Republic of Indonesia as a Special Economic Zone (SEZ) in South Sumatra, through the Indonesian Government Regulation Number 51 of 2014 concerning the Tanjung Api-Api Special Economic Zone. However, the development of this area was not completed and did not meet the necessary requirements for operation status, leading to its cancellation in 2022 through Indonesian Government Regulation Number 2 of 2022. The revocation may result in land abandonment and potential land ownership disputes between the local community and the government.

Efforts to preserve the ATPF through forest restoration have been carried out several times, involving various stakeholders such as the government, local communities, the Indonesian National Army (TNI), academics, and international NGOs (CIFOR). Restoration programs included planting mangroves in Tanjung Carat (2006), Teluk Payo Village (2013), near Tanjung Api-Api Harbour (2015), and establishing a mangrove park at the Harbour Tanjung Api-Api (2019). Mangrove planting on emerging land near the ATPF occurred recently, in May 2023. However, these efforts faced challenges due to limited community participation. Some areas where mangroves were planted are now claimed as community property and converted into plantations. Despite efforts to encourage pond farmers to apply the silvofishery method in the ATPF's surrounding areas, the community has not experienced significant results and continues to employ conventional pond techniques in their ponds (Basyuni et al. 2022).

Land cover changes in the 1999-2023 period in the ATPF

In the ATPF, the primary mangrove forest area increased by approximately 1,464.72 ha during the first period under study (1999-2010). This increase was attributed to the reduced forest encroachment by the community, facilitating the succession of secondary forests into primary forests. However, in the second period (2010-2023), there was a drastic decrease in the primary forest area (around 4,225.69 ha). This decline resulted from extensive logging by the surrounding community to clear land for coconut and oil palm plantations. Additionally, the occurrence of a major fire in 2015 and subsequent fires contributed to this decline. When the area was designated as a protected forest in 2013, the total area covered by both primary and secondary forests was approximately 8,974.8 ha (Eddy et al. 2017). As per this study, deforestation of primary and secondary forests will persist until 2023, resulting in a remaining area of primary and secondary forests amounting to only 4,615.41 ha (36.45%).

Furthermore, the open area in the ATPF increased significantly in the two study periods. According to this study, by 2023, open areas will constitute more than half of the ATPF's total area. This expansion attributed to large-scale forest clearing for the development of coconut and oil palm plantations. The plantation development process involves initial forest land clearing through logging or burning, followed by leaving the cleared land for a few months before planting with coconut and oil palm. Additionally, plantation land that is no longer productive undergoes rejuvenation using new plants, categorizing areas in the process of rejuvenation as open land. Although aquaculture activities and oil palm plantation are primary causes of mangrove forest loss in Indonesia (Ilman et al. 2011; Richards and Friess 2016), this study identifies deforestation and coconut plantations as dominant causes of mangrove forest loss.

Moreover, plantation land witnessed significant decrease in the first period under study due to a massive rejuvenation process for establishing coconut plantations, designating open plantation land as open areas. Furthermore, oil palm plantations were only established only in the first period under study, classifying areas cleared for oil palm plantations as open areas. However, plantation land increased significantly in the second period, mainly because plantation crops matured and produced fruits, clearly identifying them as plantation land. Notably, the primary conversion carried out by the surrounding community was the conversion of mangrove forests into plantations. Consequently, significant anthropogenic disturbances impacted the ATPF, resulting in extensive degradation of the aforementioned conversion, with suboptimal levels of reclamation activities. This finding aligns with the existing literature, highlighting that various anthropogenic activities are the main contributors to global mangrove forest degradation (Giri et al. 2014; Jones et al. 2014; Komiyama 2014; Laulikitnont 2014; Sannigrahi et al. 2020).

Carbon loss in ATPF

The total carbon emissions during the second period under study significantly surpassed those of the first period, exceeding them by more than five times. Conversely, the total carbon sequestration in the first period exceeded that of the second period by more than three times. The lower emissions and higher sequestration in the first period were primarily due to the main driving factor, namely the expansion of primary forest area. In contrast, the higher emissions and lower sequestration in the second period resulted from another main driving factor, namely the substantial increase open areas. These findings align with argument that mangrove deforestation yields smaller carbon emissions compared to the emissions resulting from the conversion of mangrove forests into other land types (Eddy et al. 2021a). In other words, preventing further loss and conversion of mangroves can lead to significant emission reductions (Pendleton et al. 2012; Sasmito et al. 2019).

Undoubtedly, there has been extensive degradation in the ATPF's mangrove forest area due to anthropogenic activities, without corresponding restoration efforts. To restore the natural function of the ATPF as a protected forest, collaborative restoration efforts from both the government and the surrounding community are imperative. However, returning the ATPF to its original state as a protected forest is challenging, as degraded mangrove forests cannot be easily restored within a short timeframe. Development activities in various countries that contribute to mangrove forest degradation are the primary causes of damage; restoring such damaged forests require more than 20 years for optimal restoration (Mukherjee et al. 2014). Additionally, successful restoration necessitates government support and active community participation. The process may face disruptions due to the institutional dysfunctionality and inadequate community engagement (Mangora 2011).

In this study, the primary source of emissions in the first period was the conversion of land cover from plantations, primary mangrove forests, and secondary mangrove forests into open areas. In the second period, the most significant source of emissions was the conversion of land cover from primary and secondary mangrove forests into open areas. Moreover, the main source of carbon sequestration in the first period was the transformation of secondary mangrove forest areas into primary mangrove forest areas, while in the second period, the primary source was the conversion of waterbody areas into secondary mangrove forest areas.

Furthermore, the major anthropogenic activity, namely the extensive logging of mangrove forests, was identified as the primary source of the carbon stock loss in the ATPF. The conversion of both primary and secondary mangrove forests into plantations was deemed the dominant factor contributing to the high carbon emissions from the ATPF. Notably, reforestation and restoration efforts for mangrove forests were found to be inadequate in the ATPF over the study periods. Therefore, more impactful efforts are essential in the future to restore the ATPF area, ensuring the conservation of its mangrove forest areas and the restoration of its natural function as a protected forest.

In summary, this study comprehensively described all land cover types in the ATPF and simultaneously quantified CO_2 emissions and carbon sequestration over the two periods. The study also analysed the main factors driving the increase in CO_2 emissions from the area. This analysis is crucial for identifying issues causing mangrove forest degradation and optimising restoration efforts. Consequently, it facilitates in anticipating the impact of global warming by reducing carbon emissions and simultaneously enhancing carbon sequestration.

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