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Blue Carbon Potential of Mangrove Ecosystems and Its Management to Promote Climate Change Mitigation in Indonesia

Potensi Karbon Biru Ekosistem Mangrove dan Pengelolaannya untuk Mendorong Mitigasi Perubahan Iklim di Indonesia

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ABSTRACT

This research aimed to analyze blue carbon potential and mangrove ecosystem management in promoting climate change mitigation in Indonesia. The collected data included mangrove area data obtained through the Indonesian National Ecosystem Monitoring System (SIMONTANA). This research calculated the carbon stock using the global average of mangrove carbon stock. The results showed that the total blue carbon stored in mangrove ecosystems reached 3,267.87 Megaton Carbon (MtC). Papua and Kalimantan regions contributed the most significant potential, with 1,707.22 MtC and 608.17 MtC, respectively. The absorption of carbon dioxide (CO_2) reached 11,982.21 $MtCO_2e$. The most significant CO_2 gas emissions absorption was observed in the Papua region, amounting to 6,259.80 $MtCO_2e$, followed by Sumatra with 2,118.59 $MtCO_2e$. This high potential value correlated with mangrove ecosystem management policies, such as conservation, restoration, and blue carbon monetization. Mangrove management for climate change mitigation was carried out through national and international cooperation to achieve the 26% to 40% emission reduction target. The existing management model of mangrove ecosystems focused on improving ecological sustainability with less orientation on improving community welfare. Implementing blue carbon monetization at the district level by involving the community as the owners or managers of the mangrove ecosystems is crucial.

INTISARI

Penelitian ini bertujuan untuk menganalisis potensi karbon biru dan pengelolaan ekosistem mangrove dalam mendorong mitigasi perubahan iklim di Indonesia. Data yang dikumpulkan dalam penelitian ini adalah data luas mangrove di setiap wilayah yang diperoleh melalui Sistem Monitoring Hutan Nasional (SIMONTANA) dari Kementerian Lingkungan Hidup dan Kehutanan (KLHK). Rumus perhitungan stok karbon mengacu pada rata-rata global stok karbon mangrove. Hasil kajian menunjukkan bahwa total potensi karbon biru mangrove di Indonesia mencapai 3.267,87 MtC. Wilayah Papua dan Kalimantan menyumbang potensi paling signifikan, dengan kontribusi masing-masing sebesar 1.707,22 MtC dan 608,17 MtC. Sementara itu, potensi penyerapan gas karbon dioksida (CO_2e) sebesar 11.982,21 Mt CO_2e. Penyerapan CO_2e yang paling signifikan berada di wilayah Papua, yaitu 6.259,80 $MtCO_2e$, dan Sumatra 2.118,59 $MtCO_2e$. Nilai potensi tinggi tersebut sejalan dengan kebijakan pengelolaan ekosistem mangrove seperti konservasi, restorasi, dan monetisasi karbon biru. Pengelolaan mangrove untuk mitigasi perubahan iklim juga dilakukan melalui kerja sama nasional dan internasional yang merupakan salah satu cara untuk mencapai target pengurangan emisi sebesar 26%-40%. Model pengelolaan ekosistem mangrove di Indonesia saat ini fokus pada meningkatkan kelestarian ekologi, tetapi belum berorientasi pada meningkatkan kesejahteraan masyarakat. Oleh karena itu, perlu peningkatan monetisasi karbon biru di tingkat kabupaten yang melibatkan masyarakat sebagai pemilik atau pengelola ekosistem mangrove.

Introduction

Mangrove ecosystems store carbon in three key components: soil sediments as soil organic carbon (SOC), roots as below-ground carbon, and tree stands as above-ground carbon (Alongi 2014). Specifically, carbon storage in sediments leads to the accumulation of mangrove litter, such as leaves, stems, or twigs, which fall and collect at the bottom of mangrove sediments (Adame et al. 2015). Meanwhile, carbon storage in mangrove roots and tree stands occurs through photosynthesis and the storage of mangrove biomass (Hairiah & Rahayu 2007; Rahman et al. 2020a).

The blue carbon potential of mangrove ecosystems is primarily determined by several ecosystem characteristics, such as density, species type, and mangrove diameter (Rahman et al. 2017). Several studies have shown that the potential for blue carbon in mangroves ranges from 956 MgC/ha (Alongi 2014) to 1,200 MgC/ha (Donato et al. 2012). This potential is four to five times greater than that of other blue carbon ecosystems, such as seagrass, salt marshes, tropical ecosystems, and peat swamps (Alongi 2014).

The coast of Indonesia has the most significant potential for mangrove ecosystems in the world. Giesen et al. (2007), Giri et al. (2011), and Leal and Spalding (2024) showed that Indonesia has a mangrove area reaching 3.48 million ha, equivalent to 23% of the world's mangroves or 59.8% of mangroves in the Southeast Asian region. Due to this extensive coverage, Indonesian mangrove areas store much blue carbon. Scientists can estimate blue carbon using an allometric approach to assess biomass above and below ground, measuring organic carbon in sediments like soil carbon, or examining global carbon in mangrove areas.

Indonesian mangrove ecosystems have been under pressure since the 1800s, leading to significant degradation (Ilman et al. 2016). Anthropogenic activities have primarily driven this degradation by converting land into aquaculture (80,696 ha), settlement areas or infrastructure (8,295 ha), agriculture (50,834 ha), and timber extraction (167.5 ha) (Arifanti et al. 2021; FAO 2020; Rahman et al. 2020b; 2024a). Consequently, mangrove degradation has led to a decrease in the area of mangrove ecosystems and a corresponding reduction in blue carbon potential (Arifanti et al. 2019; Humber et al. 2024) and biodiversity of flora and fauna (Yudha et al. 2021). Specifically, Rahman et al. (2020b) explained that the degradation of mangrove ecosystems has triggered a decrease in blue carbon potential, particularly in *Sonneratia* and *Rhizophora* species.

Despite these challenges, significant information still needs to be provided regarding blue carbon potential in Indonesian mangroves, specifically after the various impacts of degradation. The latest information, reported by Arifanti et al. (2021) and Eddy et al. (2021), addressed the impact of deforestation on CO_2 emissions at both the national and regional scales. Researchers need to disclose information about the potential value of blue carbon and its role in climate change mitigation based on the latest area data. This information is a preliminary step in developing a blue carbon inventory. Furthermore, it is essential to correspond with nationally determined contribution (NDC) targets in the framework of climate change mitigation, as mandated by Presidential Regulation (Perpres) No. 98/2021 on Carbon Economic Values.

Research on blue carbon in mangrove ecosystems in Indonesia has progressed rapidly, yet gaps still need to be addressed. One of the main gaps is the incomplete mapping of blue carbon potential across different regions. Many previous studies had been limited to specific locations and had yet to cover the entire territory of Indonesia, which has a long and diverse coastline. Indonesia should effectively manage its existing blue carbon potential in mangroves to promote climate change mitigation. Various stakeholders, including the government, local communities, non-governmental organizations, academics, and experts, actively manage blue carbon in mangroves through diverse strategies. The research aims to address these gaps by expanding geographical coverage and collecting data from various locations throughout Indonesia. Therefore, this research provided a more comprehensive overview of the spatial distribution of blue carbon potential in mangrove ecosystems to serve as the basis for developing effective mangrove management policies that promote climate change mitigation.

Methods

Data Collection

This research collected mangrove area data from each region using the Indonesian National Ecosystem Monitoring System (SIMONTANA) from the Ministry of Environment and Foresty (MoEF), available at https://nfms.menlhk.go.id/. The SIMONTANA divided Indonesia into seven regions: Sumatra, Java, Kalimantan, Bali-Nusa Tenggara, Maluku Island, Sulawesi, and Papua (Figure 1). This research extracted data on mangrove areas and deforestation across all provinces between 2009 and 2020 from https://nfms.menlhk.go.id/statistic and https://nfms.menlhk.go.id/peta. The data were categorized by province and structured into seven key regions, as illustrated in Figure 1. This research evaluated the management of mangroves and their role in climate change mitigation by reviewing pertinent regulations issued by the Indonesian government, along with relevant working papers and literature.

Data Analysis

Data analysis included calculating carbon stock (MgC/ha) and carbon absorption ($MgCO_2e/ha$) values. Carbon absorption value showed mangroves' ability to mitigate climate change by sequestering carbon from the atmosphere. The carbon stock calculation with the Tier 1 model approach was based on global average value of mangrove carbon storage, as outlined by Donato (2011) and Alongi (2014). Their findings showed that one hectare of mangrove stores approximately 956 MgC/ha, consisting of 613 MgC/ha in soils below a depth of 30 cm, 209 MgC/ha in soils from 0 to 30 cm depth and roots, and 134 MgC/ha in above-ground biomass. Based on this perspective, the formula used to calculate carbon stock and carbon absorption in each region was as follows.

$$TCS = \text{Mangrove Area (ha)} \times GCS\ (MgC/ha) \quad (1)$$

$$TCO_2e = TCS \times (Mr\ CO_2/Ar\ C) \quad (2)$$

Where: TCS referred to the total carbon stock (MgC or MtC), Mangrove Area was the area of mangrove in the region (ha), GCS was the global carbon stock per hectare (MgC/ha) as outlined by Donato (2011) and Alongi (2014), TCO_2e was the total CO_2 uptake (tons or $MtCO_2e$), Mr CO_2 was the molecular weight of CO_2 (44 gr/mol), and Ar C was the atomic weight of C (12 gr/mol).

This method was most effective for large-scale, national, or continental mangrove areas. Large-scale

Figure 1. Map of Indonesia by seven major regions of mangrove ecosystems

mangrove areas were better able to represent diverse ecosystem conditions, including mangrove species composition, density, and ecosystem type. Studies by Murdiyarso et al. (2015) and Kusumaningtyas et al. (2019) showed that the total sediment carbon (soil C-stock) of mangrove varied by ecosystem type, with 1059±189 MgC/ha in bay-type, 485±197 MgC/ha in estuary type, 288±175 MgC/ha in lagoon type, and 37±3 MgC/ha in open coast areas. Therefore, this research used the global average carbon stock values from Alongi (2014) to estimate the potential of blue carbon in large-scale mangrove areas greater than 10,000 ha, including those in Indonesia.

Results and Discussions

Mangrove Ecosystems Condition

Data analysis on mangrove ecosystem conditions showed that Papua had the largest mangrove area in Indonesia, with 1,634,003.454 ha in 2009 and 1,627,720.102 ha in 2020 (Table 1). In contrast, Java and Bali–Nusa Tenggara Island had the smallest mangrove area, with 34,481.626 ha and 34,524,675 ha in 2009, as well as 31,866.735 ha and 27,727.247 ha in 2020, respectively. Changes in mangrove areas showed deforestation due to various anthropogenic activities (Ilman et al. 2016; Rahman et al. 2020b). Kalimantan and Sulawesi experienced significant deforestation from 2011 to 2021. During this period, deforestation in these areas reached 58,379.22 ha in Kalimantan and 27,093.06 ha in Sulawesi, with annual deforestation rates of 5,837.92 ha/year and 2,709.31 ha/year, respectively (Table 2). The highest deforestation rate occurred between 2018 and 2019, with 38,655.78 ha lost, while the lowest was between 2009 and 2011, with 62.94 ha lost. The increase in deforestation from 2018 to 2019 was primarily due to the Kalimantan and Sulawesi regions, which contributed 12,694.36 ha and 11,877.82 ha, respectively.

Land conversion into shrimp ponds, agricultural fields, settlements, and infrastructure development, including roads and wharves, triggers mangrove deforestation (Maryantika & Lin 2017; Rahman et al. 2020b; Richards & Friess 2016). Similarly, Arifanti et al. (2021) highlighted that cultivation, agriculture, infrastructure, and mining activities drove mangrove deforestation in Indonesia. In general, land conversion into cultivation areas, such as aquaculture and infrastructure development, including settlements, were the primary triggers for mangrove ecosystem degradation in Indonesia. However, this was only the case in some regions. Between 2009 and

Table 1. Comparison of mangrove area from 2009 and 2020 by region in Indonesia

Regions	Mangrove area in 2009 (ha)	Deforestation in 2009 – 2020 (ha)	Deforestation rate (ha/year)	Mangrove area in 2020 (ha)
Papua	1,634,003.454	6,283.35	628.34	1,627,720.102
Maluku	178,750.649	943.57	94.36	177,807.083
Bali – NTI	34,524.675	6,797.43	679.74	27,727.247
Sulawesi	147,018.307	27,093.06	2,709.31	119,925.245
Kalimantan	638,283.693	58,379.22	5,837.92	579,904.468
Jawa	34,481.626	2,614.89	261.49	31,866.735
Sumatra	576,956.056	26,064.18	2,606.42	550,891.876
Total	3,244,018.460	12,8175.70	628.34	3,115,842.756

Notes: NTI (Nusa Tenggara Island)

Table 2. Mangrove deforestation from 2009 – 2020 by region in Indonesia.

Period	Papua	Maluku Island	Bali-NTI	Sulawesi	Kalimantan	Jawa	Sumatra	Total
2009-2011	403.13	22.94	122.81	638.46	3,008.00	-45.88	-4086.53	62.94
2012-2013	410.56	-831.07	-1,920.03	194.24	9,110.26	-32.28	6,235.11	13,166.80
2013-2014	127.99	410.54	30.97	987.74	6,851.06	1,208.36	1,895.10	11,511.75
2014-2015	629.67	103.94	29.55	1,022.86	3,158.93	9.28	1,727.55	6,681.79
2015-2016	1,473.02	208.98	-66.54	2,339.99	5,864.85	-0.33	3,691.52	13,511.48
2016-2017	-0.32	-623.23	2,441.03	5,015.26	10,226.80	16.05	2,583.55	19,659.13
2017-2018	393.64	703.61	23.77	4,567.83	5,404.99	-110.47	1,647.28	12,630.66
2018-2019	2,559.30	916.97	5,931.25	11,877.82	12,694.36	1,534.81	3,141.28	38,655.78
2019-2020	286.37	30.89	204.62	448.85	2,059.97	35.36	9,229.31	12,295.37
Total	6,283.35	943.57	6,797.43	27,093.06	58,379.22	2,614.89	26,064.18	128,175.70

Notes: NTI (Nusa Tenggara Island)

2020, mangrove deforestation due to these various uses totaled 80,696 ha from aquaculture at a rate of 5.76% per year, 8,295 ha from infrastructure development such as mining, settlement area, and port harbor at a rate of 0.59% per year. Furthermore, 50,834 ha were from agriculture at a rate of 3.63% per year, and 167.5 ha from timber at 0.01% per year (Arifanti et al. 2021; Rahman et al. 2020b; 2024a).

In the Papua and Maluku Island regions, mangrove deforestation was caused solely by infrastructure development and timber extraction. Aquaculture, infrastructure development, and timber extraction also caused deforestation in the Bali, Sulawesi, and Java regions. However, in the Kalimantan and Sulawesi regions, all these factors, including mining activities, contributed to significant mangrove ecosystem degradation (Figure 2). Many deforestation activities led to severe degradation of mangrove ecosystems in Kalimantan and Sulawesi.

At the end of 2020, the Indonesian government initiated efforts to restore mangrove forests on critical lands through the MoEF and the Peatland and Mangrove Restoration Agency (BRGM). These restoration activities will continue until 2024. According to the MoEF report from 2021, the area of mangrove ecosystems in Indonesia increased from 3,115,842 ha in 2020 to 3,360,080 ha in 2021. This increase showed the success of the restoration and management efforts for mangrove ecosystems in Indonesia. Therefore, the government should continue to expand mangrove ecosystem restoration and conservation activities.

Blue Carbon Potential for Climate Change Mitigation

The total potential of blue carbon stored in Indonesian mangroves was estimated to be 3,267.87 mangrove blue carbon stock (MtC). The regions of Papua, Kalimantan, and Sumatra contributed the most significant amounts, with contribution values of 1,707.22 MtC (52.24%), 608.17 MtC (18.61%), and 577.79 MtC (17.68%), respectively. In contrast, the lowest carbon stocks were found in Bali-Nusa Tenggara, with 29.07 MtC (0.89%), and Java, with 33.41 MtC (1.02%) (Figure 3). These results correlated with Murdiyarso et al. (2015), which reported that carbon stocks in Bintuni Bay, Papua, represented Indonesia's most significant carbon stores, approximately 1,397 ± 191 MgC/ha. Meanwhile, the lowest carbon storage was in the Cilacap region of Java, with 572 ± 200 MgC/ha.

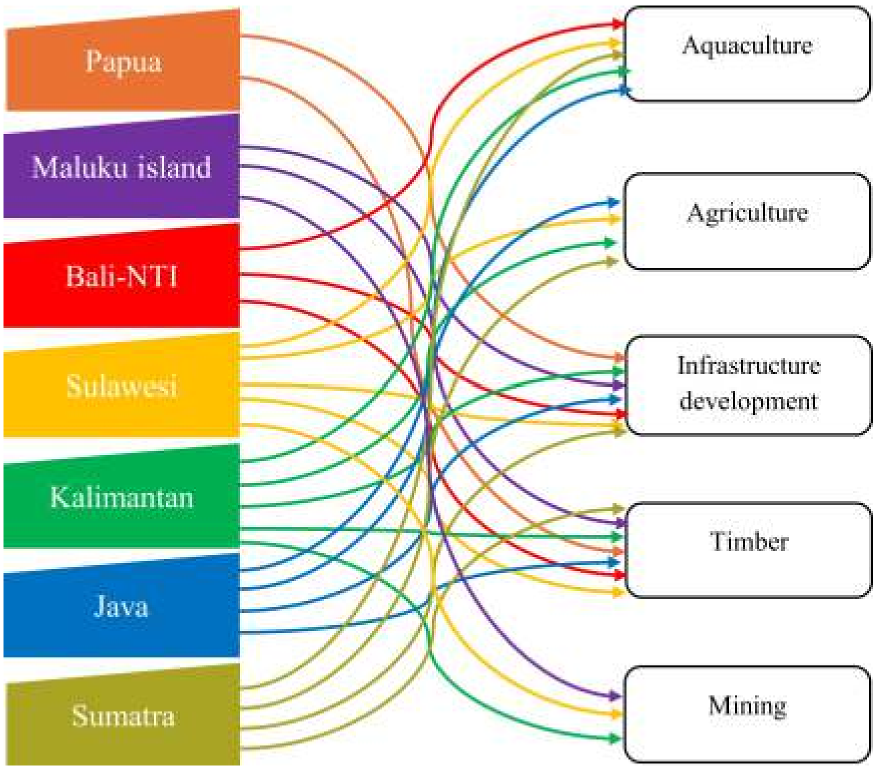

Figure 2. Drivers of mangrove deforestation from 2010 – 2020 by region in Indonesia

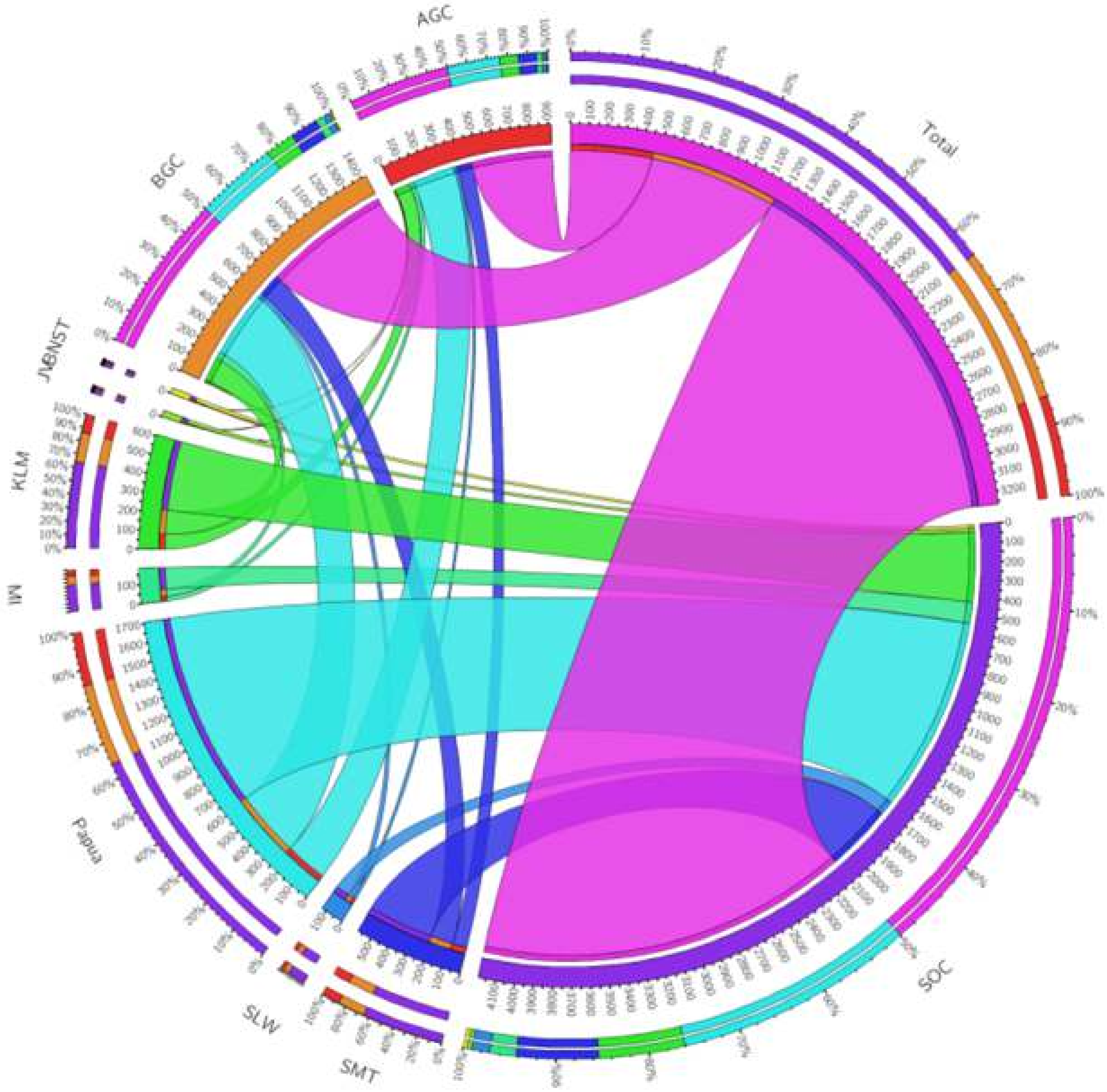

Figure 3. MtC by region in Indonesia: MI = Maluku Island, SLW = Sulawesi, SMT = Sumatra, KLM = Kalimantan, JV = Java, BNST = Bali-Nusa Tenggara, SOC = Soil Organic Carbon (soils below 30 cm), BGC = Below-ground Carbon (soil 0-30 cm + roots), AGC = Above-ground Carbon, (http://mkweb.bcgsc.ca/tableviewer/visualize/)

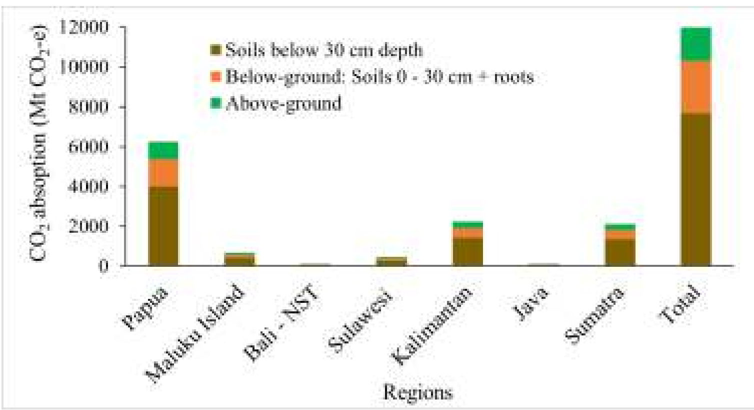

Figure 4. CO_2e absorption of mangrove ecosystems by region in Indonesia

Based on the blue carbon potential value, Indonesia could reduce carbon dioxide gas emissions (CO_2e) by 11,982.21 MtCO_2e. The most considerable CO_2e absorption was in the Papua region, with 6,259.80 MtCO_2e, followed by Kalimantan with 2,229.94 MtCO_2e, and Sumatra with 2,118.59 MtCO_2e (Figure 4). These values showed that Indonesia's potential for carbon storage and absorption was the largest in the Southeast Asian region. According to a meta-analysis, Indonesian mangrove ecosystems contributed 59.8% of the region's climate change mitigation efforts through CO_2e storage and absorption. Meanwhile, mangrove ecosystems in other areas stored between 0.55 to 649.75 MtC and absorbed CO_2e ranging from 2 to 2,382.43 MtCO_2e (Thorhaug et al. 2020).

Mangrove Ecosystems Management to Blue Carbon Conservations

Indonesia's commitment to climate change mitigation began with implementing the Kyoto Protocol. The Indonesian government ratified the Kyoto Protocol as an official regulation through the Law of Indonesia Number 17 of 2004. Law No. 17 of 2004 created several derivative regulations that aim to mitigate climate change and reduce greenhouse gas emissions.

(1) Presidential Regulation (Perpres) No. 61 of 2011 concerning the National Action Plan for Reducing Greenhouse Gas Emissions (RAN-GRK). This regulation aimed to fulfill the Indonesian government's commitment to reducing greenhouse gas emissions by 26% or reaching 41% with international assistance by 2020.

(2) Presidential Regulation (Perpres) No. 71 of 2011 concerning implementing the National Greenhouse Gas Inventory.

Efforts to reduce greenhouse gas emissions were further outlined in the National Long-Term Development Plan (RPJPN) 2005-2025 (Qodriyatun 2016). Among the strategic steps in implementing the 2020-2025 RPJMN related to climate change mitigation was the management of mangrove ecosystems. This commitment was reinforced by issuing several regulations focusing on conserving, restoring, and monetizing blue carbon (Table 3).

The entire management process involved various stakeholders, from ministries to local communities. Ministries comprised the Ministry of Marine and Fisheries (KKP), MoEF, and BRGM. In its implementation, ministries could cooperate internationally to enhance the management of blue carbon mangroves to mitigate global warming. For example, KKP collaborated with the Japan International Cooperation Agency (JICA) to study the potential for blue carbon in various mangrove ecosystems across Indonesia. This collaboration aimed to achieve the NDC target, which focused on reducing emissions by up to 40%.

The government conducted various outreach activities to share information on blue carbon management with all provincial and district/city leaders in Indonesia. These efforts included seminars held offline but broadcast online, ensuring they could reach various parties anytime and anywhere. KLHK, along with KKP, strengthened the governance of the blue carbon ecosystem in Indonesia (https://www.youtube.com/watch?v=WY1HnPxAlCk) by providing resources and support to stakeholders to facilitate effective blue carbon mangrove management in their respective districts and cities. Similarly, KKP and JICA (https://www.youtube.com/watch?v=YwOmDXgtXXU) carried out the same activity to promote the implementation of blue carbon strategies, advancing towards a blue economy through a carbon trading mechanism. These activities had significant implications for managing mangrove ecosystems in Indonesia, as evidenced by the increase in mangrove ecosystems area reported by BRGM in 2021.

These management policies on mangrove conservation and rehabilitation efforts successfully maintained ecological sustainability and increased the area of the mangrove ecosystem in 2021. Moreover, the collaboration between government entities and community groups showed the institutional strength that actively contributed to preserving mangrove ecosystems. A significant example of successful mangrove conservation and rehabilitation occurred in Mekarpohaci Village. Rahman et al. (2024b) highlighted a successful initiative in 2020, where PT Pertamina Hulu Energy Offshore North West Java (PT PHE ONWJ), in collaboration with the Environmental Research Center – IPB University (PPLH IPB

Table 3. Several models of blue carbon management of mangrove ecosystems for climate change mitigation in Indonesia

No	Management Models	Aims	Regulation	Stakeholders	Impact
1	Mangrove conservation based on ecotourism	(1) Protect ecosystem biodiversity. (2) Enhance community livelihoods to promote blue economy.	International regulations: (1) UNCED (Rio de Janeiro 3-14 Juni 1992) (2) World Heritage Convention, (3) The International Convention on Wetlands (Ramsar) (4) The Convention on Biological Diversity. National regulations: (1) UU no. 5 of 1994 (2) Presidential Decree No. 48 of 1991 (3) Presidential Decree No. 121 of 2012, (4) Presidential Decree No. 73 of 2012 (5) Regulation of Marine and Fisheries Ministry No. 24 of 2013 (6) Coordinating Minister for Economic Affairs No. 4 of 2017.	(1) Government of Indonesia (2) Ministry of Marine and Fisheries (KKP) (3) Ministry of Environment and Forestry (KLHK) (4) Non-governmental Organizations (5) Local community	(1) Protected ecosystem biodiversity includes diverse mangrove species, marine fauna, and terrestrial fauna. (2) People's welfare increased because they benefited from tourist activities around mangrove ecosystem area through several ecotourism services. (3) Protected blue carbon mangrove and promoted climate change mitigation.
2	Mangrove rehabilitation	(1) Mangrove restoration to increase the coverage area and density. (2) Increase mangrove carbon storage.	(1) Law 27 of 2007, in conjunction with Law 1 of 2014, concerning the Management of Coastal Areas and Small Islands (2) Presidential Regulation No. 121 of 2012 concerning the Rehabilitation of Coastal Areas and Small Islands	(1) Government of Indonesia (2) Ministry of Marine and Fisheries (KKP) (3) Ministry of Environment and Forestry (KLHK) (4) Peatland and Mangrove Restoration Agency (BRGM) (5) Non-governmental Organizations (NGO) (6) Local community	(1) Increase in mangrove area from 3,115,842,756 ha in 2020 to 3,360,080 ha in 2021. (2) Increased the capability of mangrove ecosystem for carbon storage and climate change mitigation.
3	Monetization of blue carbon ecosystem through the carbon trading market.	(1) Reduce greenhouse gases based on Nationally Determined Contribution (NDC). (2) Promote blue economy. (3) Promote Clean Development Programs.	(1) Presidential Regulation No. 98 of 2021 concerning carbon economic value for target achievement nationally defined contributions and controls greenhouse gas emissions in national development.	(1) Government of Indonesia (2) Ministry of Marine and Fisheries (KKP) (3) Ministry of Environment and Forestry (KLHK)	(1) Protecting blue carbon mangrove. (2) Reducing greenhouse gas emissions by 30% according to NDC target. (3) Increasing provincial and district/city revenues through carbon trading

University), the Ministry of Environment and Forestry (KLHK), and the local community of Mekarpohaci Village, planted between 1,200 and 2,000 mangrove seedlings. This effort significantly enhanced both the area and density of mangrove ecosystems. The success of this project is further evidenced by an increase in canopy cover, as illustrated in Figure 5.

However, the conservation and rehabilitation management model was less oriented toward economic value for people's welfare because the policy focused primarily on ecological conservation rather than economic improvement (Fauziyah et al. 2023). Although the government expected the communities to benefit economically from utilizing mangrove ecosystems for ecotourism and fishing, the management model through blue carbon monetization had yet to reach coastal communities, who were the primary managers of these ecosystems.

The implemented carbon market tended to be monopolized by the government or specific institutions without involving the community. Many mangrove ecosystems in Indonesia continued to be managed destructively, converting mangroves into ponds, harvesting them for timber, or using them for residential areas (Rahman et al. 2020b).

To simultaneously enhance the potential of blue carbon and improve the welfare of coastal communities, it was crucial to include these communities in blue carbon mangrove monetization. Under this approach, the community, guided by the government, would be recognized as key stakeholders, providing mangrove nursery services to offset development-related emissions. All stakeholders who produced CO_2e emissions in a particular area, such as a province or regency, would be required to plant mangroves equivalent to the value of CO_2e emitted. In this model, the communities would be tasked with supplying mangrove seeds, thereby directly benefiting economically. The government's role would be limited to supervision and the provision of regulations governing the blue carbon mangrove monetization mechanism at the district level. On implementation, the Indonesian mangrove ecosystem could achieve ecological sustainability while simultaneously improving the economy and people's welfare.

Conclusions

In conclusion, mangrove ecosystems in Indonesia significantly contributed to carbon sequestration and climate change mitigation. This contribution corresponded with mangrove ecosystem management policies such as conservation, restoration, and the monetization of blue carbon. The government involved various stakeholders in formulating regulations to manage these ecosystems, including NGOs and local communities. Furthermore, climate

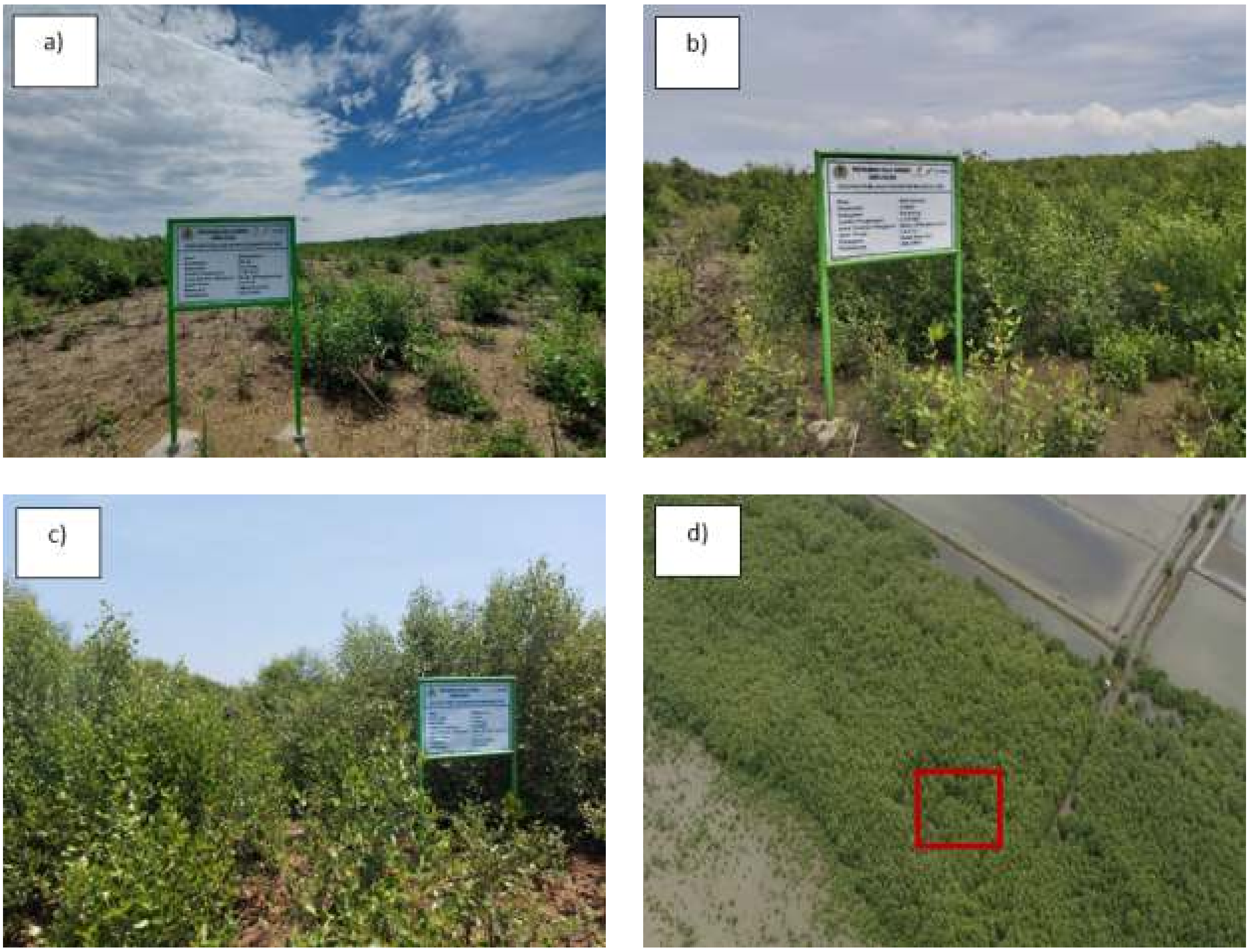

Figure 5. Conditions of mangrove planted in 2020–2023: a) initial conditions in 2020; b) mangrove conditions in 2021; c) mangrove conditions in 2022; and d) mangrove conditions in 2023 - The red box is the same location as Figure 5a, 5b. and 5c.

change mitigation efforts were enhanced through international cooperation, aiming to achieve emission reduction targets of 26% as part of NDC and 40% through international cooperation. However, while Indonesia's current mangrove ecosystem management model has effectively improved ecological sustainability, it has not yet significantly improved community welfare. Therefore, it is necessary to implement blue carbon monetization at the district level by involving the communities as active owners or managers of mangrove ecosystems.

The central and local governments actively strengthen policies and regulations for mangrove conservation, including providing legal protection for mangrove areas and offering incentives for communities to participate in mangrove rehabilitation activities. Moreover, the government needs to monitor policy implementation to ensure its effectiveness, allocate adequate budgets for mangrove conservation and rehabilitation programs, and facilitate access to funding from various sources, such as the private sector, through Corporate Social Responsibility (CSR) initiatives and international funds for climate change mitigation.

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