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Multi-Intervention Scenarios in the Mangrove Blue Carbon Project Can Enhance Emission Reductions and Increase the Economic Value of Carbon

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ABSTRACT

Mangrove ecosystems provide globally important climate regulation services through long-term carbon sequestration, yet restoration programs frequently rely on single management interventions that may underestimate their mitigation potential. This study evaluated the climate mitigation performance of integrated blue carbon interventions across the northern coast of Java, Indonesia, by comparing conservation of intact wetlands with avoided deforestation, restoration of wetland ecosystems with active planting, and restoration with assisted natural regeneration. A spatially explicit Tier 3 carbon accounting framework was developed by integrating multi-temporal Landsat observations (1972–2025), Random Forest land-cover classification, mangrove carbon-stock data, field-derived growth measurements, and scenario-based greenhouse gas accounting over a 30-year project horizon. The results indicate an average potential emission reduction of 8.67 Mt CO_2e/year across the study area. Among the evaluated interventions, coastal erosion control through restoration with assisted natural regeneration achieved the highest mitigation performance (120 tCO_2e/ha/year), nearly four times that of planting-based rehabilitation (32 tCO_2e/ha/year). Over a 30-year simulation period, these scenarios are projected to generate 210 Mt CO_2e of tradable carbon units, equivalent to an average of 7 Mt CO_2e/year. At a carbon price of USD 5/t CO_2e, this volume could have an economic value exceeding USD 35 million per year. These findings demonstrate that integrated mangrove protection and restoration strategies can deliver substantial climate mitigation outcomes while creating significant economic incentives through carbon finance mechanisms.

1. Introduction

Mangrove ecosystems are increasingly recognized as among the most effective natural climate solutions due to their exceptional capacity to sequester and store carbon (Griscom et al. 2017; Novita et al. 2022). Collectively, as blue carbon ecosystems, mangroves, seagrasses, and salt marshes can accumulate organic carbon at rates several times higher than those of terrestrial forests (Ali et al. 2025). However, among these, mangroves have the highest carbon density, largely due to their deep, anoxic soils, which inhibit decomposition (Li et al. 2022). The strategic restoration and conservation of mangroves have therefore emerged as critical pathways for climate change mitigation, biodiversity conservation, and coastal protection (Arifanti et al. 2022).

Despite their importance, mangroves worldwide continue to experience severe degradation driven by land-use conversion, coastal development, aquaculture expansion, pollution, and hydrological disruption (Goldberg et al. 2020; Ilman et al. 2016; Maina et al. 2021; Richards and Friess 2016). Indonesia, which hosts the largest mangrove extent globally, has suffered substantial losses over the past decades, particularly in densely populated and economically dynamic regions (Hagger et al. 2022; Murray et al. 2022). The northern coast of Java, one of the most anthropogenically altered coastal zones in Southeast Asia, is a hotspot of mangrove degradation caused by long-term shoreline modification, subsidence, and industrial and settlement expansion (Hudalah et al. 2024).

The degradation of mangroves along the northern coast of Java has resulted in significant ecological and socio-economic consequences, including reduced coastal protection, biodiversity loss, and increased greenhouse gas (GHG) emissions from disturbed soils, representing a historical loss of 75% of their original extent (Andreas et al. 2019; Heriati et al. 2021). Restoring and conserving these ecosystems offers dual benefits: enhancing coastal resilience and generating measurable climate-mitigation outcomes through carbon-crediting mechanisms (Raw et al. 2023). The rising interest in blue carbon markets presents an opportunity to mobilize financial resources for mangrove rehabilitation and long-term stewardship (Choudhary et al. 2024).

An increasing number of studies argue that mitigation potential must be viewed through a multi-pathway lens, incorporating protection measures (avoided deforestation and degradation), active ecological restoration, hydrological reconnection, and regeneration processes driven by natural recovery dynamics. Each intervention presents varying degrees of carbon benefits, cost-efficiency, and implementation feasibility (Abelson et al. 2020; Arifanti et al. 2022; Lovelock et al. 2022). Moreover, as attention to high-quality carbon credits increases, quantifying potential emission reductions in a transparent, scientifically rigorous manner becomes vital to attract investment and design effective coastal restoration policies (Soto-Navarro et al. 2020).

Existing studies on blue carbon in Indonesia have generally focused on estimating carbon stocks (Ahalya and Park 2019; Hilmi et al. 2021; Murdiyarso et al. 2023), mapping mangrove extent (Bunting et al. 2022), or evaluating restoration outcomes at local scales (Brown et al. 2014). Few have assessed the comparative mitigation potential of different intervention scenarios within a unified analytical framework.

Understanding the emission-reduction potential of multi-intervention scenarios is crucial for guiding decision-makers, project developers, and coastal planners in prioritizing areas with the highest climate-mitigation returns (Ellison et al. 2020; Kadaverugu et al. 2022). This information can underpin the development of blue carbon projects at jurisdictional or project scales, support national and sub-national climate policies, and contribute to Indonesia's Nationally Determined Contributions (NDCs) (Griscom et al. 2020). However, mangrove restoration initiatives on Java Island have largely been implemented through single-intervention approaches, most commonly tree planting, without integrating multiple management interventions such as hydrological restoration, protection of existing stands, and assisted natural regeneration. This lack of integration creates a gap between restoration policies and their practical implementation, potentially limiting the effectiveness and long-term climate-mitigation potential of mangrove ecosystems. Consequently, a spatially explicit assessment of multi-intervention scenarios is needed to evaluate how integrated restoration strategies could enhance the potential for emission reductions.

Additionally, such analyses can help ensure environmental integrity and reduce the risk of over-crediting in carbon markets (Vanderklift et al. 2019).

In this context, the present study aims to quantify the potential emission reductions from a suite of intervention pathways implemented across the northern coast of Java. By integrating spatial analysis, biophysical assessment, carbon stock data, and scenario modeling to produce Tier 3 quantification results, this study evaluates how different strategies, ranging from conservation and natural regeneration to active restoration, contribute to the generation of blue carbon credits. The focus on scenario comparison allows for a nuanced understanding of trade-offs, opportunities, and spatial variability in mitigation outcomes.

Rapid climate change provides opportunities for the voluntary carbon market to gain momentum and must be used to improve and expand sustainable mangrove ecosystem management plans, limit carbon emissions and increase carbon sequestration (Bomfim et al. 2022). Rapid climate change has increased the momentum of the voluntary carbon market, creating opportunities to improve and expand sustainable mangrove ecosystem management, reduce carbon emissions, and enhance carbon sequestration (Bomfim et al. 2022). This study provides an evidence-based framework to support the development of high-integrity blue carbon projects. By elucidating the emission-reduction potential of multiple intervention scenarios, the findings offer valuable insights for policy formulation, project design, and participation in carbon markets. Ultimately, this work advances the role of mangrove-based blue carbon initiatives in achieving climate mitigation and coastal resilience.

2. Materials and Methods

2.1. Study Area

The study area encompasses the coastal landscape along Java's northern shoreline, extending from Serang Regency in Banten Province to Situbondo Regency in East Java Province at coordinates 5°47'7.98"–7°57'47.85" S and 106°1'59.22"–114°33'28.71" E (**Fig. 1**). This region forms one of the longest continuous coastal systems in Indonesia, characterized by low-lying alluvial plains shaped by centuries of riverine sedimentation and tidal influence. The coastline supports a mosaic of land uses, including agriculture, aquaculture, settlements, and remaining mangrove patches, all of which are shaped by both natural processes and intensive human activities.

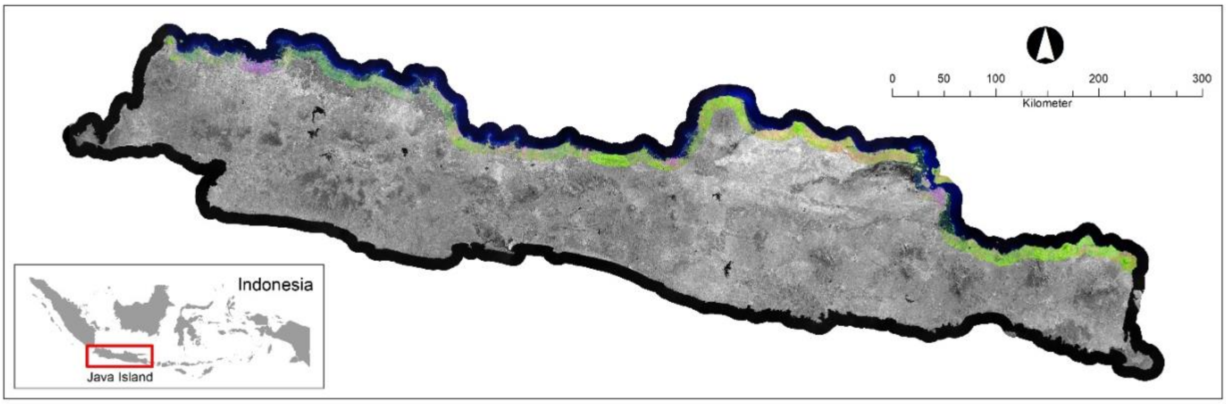

Fig. 1. Study location map and intertidal distribution along the northern coast of Java (colored area).

Biophysically, the northern coast of Java is strongly influenced by the dynamics of its major river basins, which supply substantial sediment loads that sustain deltaic formations and intertidal mudflats. These environments historically supported extensive mangrove ecosystems. However, rapid land subsidence, sediment imbalance, and hydrological alterations have disrupted many parts of the coastal system. In several regions, erosion has progressively consumed intertidal zones, while in others, sediment deposition continues to form new coastal landforms, illustrating the highly dynamic nature of this coastline.

2.2. Data Collection

2.2.1. Spatial Data

We used Landsat time-series data, a long-term sequence of continuous observations (Davies et al. 2016), including the Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper (ETM), ETM+, and Operational Land Imager (OLI) sensors. The United States Geological Survey (USGS) maintains the Landsat archive, which is reorganized into a tiered collection structure, to ensure that Landsat Level-1 products offer consistent, accessible data quality suitable for longitudinal analysis. This study used Landsat data with a 30-m spatial resolution as the primary dataset, which was accessed and processed in Google Earth Engine (Gorelick et al. 2017) to extract median reflectance values for 1972, 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2025. The 1972 dataset was selected as a historical baseline because it corresponds to the earliest available Landsat imagery (Landsat-1) and serves as a reference for relatively intact mangrove conditions. Five-year intervals were then applied from 1990 onward to consistently monitor long-term changes.

2.2.2. Emission Factors

We summarized emission factor data from Murdiyarso et al. (2023) for carbon stock pools and flux pathways across several land-use types, e.g., aquaculture, degraded mangrove, regenerated mangrove and undisturbed mangrove, to quantify potential emissions resulting from land-use changes (**Table 1**). To quantify carbon sequestration, we conducted field measurements of plant growth parameters for *Rhizophora* spp. (planting) and *Avicennia marina* (natural regeneration) over a 5-year observation period. To complete the carbon absorption estimates up to year 30, we extrapolated the values using allometric equations (Boer et al. 2025; Hu et al. 2025). A summary of CO_2 removal by mangrove stands per individual plant is presented in **Table 2**. In addition, we incorporated other parameters, such as surface elevation increment (Sidik et al. 2019), sedimentation rates (Kusumaningtyas et al. 2019; Sasmito et al. 2020), allochthonous carbon accumulation (Xiong et al. 2018), and coastal soil loss depth (Dong et al. 2024). From these references, we used the median value for each referenced parameter.

2.3. Data Analysis

2.3.1. Image classification

We classified the Landsat satellite imagery into 14 land-use/cover classes (i.e., dryland forest, mixed garden, shrubs, mixed agriculture, agriculture, aquaculture, built-up area, sea/water body, other islands, open land, mangrove herbaceous, mangrove forest 1, mangrove forest 2, mangrove forest 3). We performed supervised machine learning classification using the Random Forest algorithm (Latifah et al. 2025; Schonlau and Zou 2020) with 1,000 trees and nine features on the Google Earth Engine (GEE) platform to identify mangrove vegetation for the years 1970, 1990, 1995, 2000, 2005, 2010, 2015, and 2020. We used nine variables derived from Landsat imagery (i.e., reflectance bands and spectral indices). Additionally, this study utilized 1,000 data points, divided into a 75% training set (approx. 54 samples per class) and a 25% validation set (approximately 18 samples per class).

Table 1. Carbon stocks, greenhouse gas fluxes and soil carbon burial in various pools across Indonesian mangrove ecosystems under different management regimes (Murdiyarso et al. 2023)

Land-Use	Pool	Unit	Mean	n	SE	95%CI
Aquaculture	AGBC	tC/ha	11.01	10	3.86	2.29–19.73
	BGBC	tC/ha	2.64	7	1.3	-0.54–5.81
	Necromass	tC/ha	3.39	2	2.27	-31.15–37.93
	Soil (0–100 cm)	tC/ha	259.08	6	90.53	26.37–491.8
	Soil (0–300 cm)	tC/ha	562.36	10	50.2	448.81–675.91
	Soil CO_2 Fluxes	tCO_2/ha/year	23.81	30	1.4	-0.40–48.02
	Soil CH_4 Effluxes	tCO_2/ha/year	2.02	20	0.68	-1.11–5.16
	Soil N_2O Effluxes	$kgCO_2$/ha/year	n/a	9	0.16	n/a
	Soil carbon burial	tC/ha/year	n/a	7	2.25	n/a
Degraded Mangrove	AGBC	tC/ha	20.98	8	6.05	6.68–35.28
	BGBC	tC/ha	6.01	6	1.43	2.34–9.67
	Necromass	tC/ha	24.34	7	6.67	8.03–40.65
	Soil (0–100 cm)	tC/ha	215.66	13	38.07	132.7–298.62
	Soil (0–300 cm)	tC/ha	665.59	6	132.49	325.02–1006.15
	Soil CO_2 Effluxes	tCO_2/ha/year	n/a	4	7.61	-
	Soil CH_4 Effluxes	tCO_2/ha/year	4.18	3	0.73	-0.63–8.99
	Soil N_2O Effluxes	$kgCO_2$/ha/year	n/a	9	0.16	-
	Soil carbon burial	tC/ha/year	1.22	n/a	n/a	0.39–2.05
Regenerated Mangrove	AGBC	tC/ha	58.06	31	8.17	132.7–298.62
	BGBC	tC/ha	15.8	26	3.77	8.04–23.55
	Necromass	tC/ha	13.49	18	2.52	8.18–18.81
	Soil (0–100 cm)	tC/ha	296.41	27	20.11	255.07–337.75
	Soil (0–300 cm)	tC/ha	803.03	15	48.76	698.45–907.61
	Soil CO_2 Effluxes	tCO_2/ha/year	13.49	n/a	n/a	2.39–24.6
	Soil CH_4 Effluxes	tCO_2/ha/year	n/a	4	1.51	-
	Soil N_2O Effluxes	$kgCO_2$/ha/year	n/a	n/a	n/a	-
	Soil carbon burial	tC/ha/year	1.67	8	0.35	0.87–2.46
Undisturbed Mangrove	AGBC	tC/ha	101.67	114	4.79	92.18–111.16
	BGBC	tC/ha	28.7	98	1.65	25.42–31.98
	Necromass	tC/ha	14.47	63	1.22	12.03–16.9
	Soil (0–100 cm)	tC/ha	258.44	34	32.4	192.53–324.36
	Soil (0–300 cm)	tC/ha	916.42	75	47.6	821.57–1011.28
	Soil CO_2 Effluxes	tCO_2/ha/year	7.87	7	4.54	5.00–10.74
	Soil CH_4 Effluxes	tCO_2/ha/year	0.98	n/a	n/a	-0.44–2.4
	Soil N_2O Effluxes	$kgCO_2$/ha/year	-0.12	n/a	n/a	-0.48–0.25
	Soil carbon burial	tC/ha/year	3.2	5	0.29	-2.28–8.69

Notes: AGBC is above-ground biomass carbon, and BGBC is below-ground biomass carbon.

Table 2. Summary of CO_2 removal and carbon accumulation (autochthonous and allochthonous) in mangrove ecosystems

Age (year)	MAI planting (tCO2e/individual)	MAI natreg (tCO2e/individual)	Rate Autochthonous (tC/ha/year)	Rate Allochthonous (tC/ha/year)
0	0	0	0	0.00
1	0.00052	0.00003	0.11	0.22
2	0.00066	0.00013	0.21	0.44
3	0.00076	0.00030	0.32	0.66
4	0.00086	0.00054	0.43	0.88
5	0.00097	0.00085	0.53	1.10
6	0.00103	0.00124	0.64	1.32
7	0.00110	0.00171	0.75	1.54
8	0.00114	0.00225	0.85	1.75
9	0.00117	0.00287	0.96	1.97
10	0.00121	0.00356	1.07	2.19
11	0.00121	0.00434	1.17	2.41
12	0.00121	0.00519	1.28	2.63
13	0.00121	0.00612	1.39	2.85
14	0.00121	0.00714	1.49	3.07
15	0.00117	0.00823	1.60	3.29
16	0.00117	0.00940	1.71	3.51
17	0.00114	0.01066	1.81	3.73
18	0.00114	0.01199	1.92	3.95
19	0.00110	0.01341	2.03	4.17
20	0.00107	0.01490	2.13	4.39
21	0.00103	0.01648	2.24	4.61
22	0.00100	0.01815	2.35	4.83
23	0.00097	0.01989	2.45	5.04
24	0.00093	0.02172	2.56	5.26
25	0.00090	0.02363	2.67	5.48
26	0.00086	0.02562	2.77	5.70
27	0.00083	0.02770	2.88	5.92
28	0.00079	0.02986	2.99	6.14
29	0.00076	0.03210	3.09	6.36
30	0.00072	0.03443	3.20	6.58

Notes: MAI is the mean annual increment, and natreg is natural regeneration.

We also combined tidal flat data (Murray et al. 2019), impervious surface data (Huang et al. 2021), an aquaculture map by Clark Labs (Eastman et al. 2015), a land-cover map (Vancutsem et al. 2021), and a land-use map (Potapov et al. 2022), as additional information to improve the classification results produced by GEE. Furthermore, quality assurance was conducted to ensure the resulting maps were free of pixel noise.

Accuracy assessment was conducted using approximately 1,000 equalized, stratified random points for validation. Classification results were evaluated using an error matrix that compared classification or delineation outcomes with survey reference points. The accuracy measures applied included producer's, user's, overall, and Kappa accuracy (Foody 2020). We captured ecosystem dynamics using three categories based on the main ecosystem classes: intertidal, terrestrial, and marine. From these categories, a transition matrix was generated to assess accretion and erosion rates.

2.3.2. Mangrove changes and intertidal dynamic proxies

From the multitemporal land cover data, the derived proxies for mangrove ecosystem changes were divided into two categories: (1) Proxies of mangrove-cover changes, representing the floristic diversity of mangroves within intertidal ecosystems. Mangrove cover was derived from land-use/cover maps, and the analysis of mangrove cover transitions revealed three major categories of change: mangrove deforestation, degradation and reforestation. However, the main class used in further analysis was the mangrove deforestation rate. (2) Proxies of intertidal changes, referring to multitemporal changes in landscapes with substrates that support the growth of mangrove vegetation (intertidal accretion and erosion).

The study area was pre-defined prior to the analysis; therefore, the selection of intervention locations was not based on spatial prioritization using land-change indicators such as deforestation rates, erosion, or accretion patterns. Instead, these indicators were used to characterize the ecological dynamics in the study area and to support parameterization of the scenario analysis. The historical deforestation rate was specifically used as a proxy to estimate baseline emissions under the Reducing Emissions from Deforestation and Degradation (REDD) intervention scenario. In addition, coastal erosion and accretion were assessed to understand shoreline dynamics and sediment processes influencing mangrove extent and stability. Erosion indicates the potential loss of mangrove area and associated carbon stocks, while accretion reflects opportunities for natural expansion and carbon sequestration.

2.3.3. Baseline emissions and intervention scenarios

The baseline is defined as the condition expected to occur in the absence of project intervention. In contrast, intervention scenarios are activities currently underway or planned to mitigate climate change, as well as projections of future GHG emissions used to assess future vulnerability to climate change (Michaelowa et al. 2022). A critical component of these scenarios is additionality, which refers to project benefits that would not occur without project intervention (Zeng et al. 2021).

In this study, the potential climate change mitigation category in the mangrove ecosystem consists of all possible categories of GHG reduction activities, including REDD, afforestation, reforestation and revegetation (ARR), conservation of intact wetlands (CIW), and restoration of wetland ecosystems (RWE) as a part of Wetland Restoration and Conservation (WRC).

The REDD concept was originally a proposal to provide financial incentives to help developing countries voluntarily reduce national deforestation rates and associated carbon emissions below a baseline based on historical reference cases or future projections (Ehara et al. 2021). In the context of the mangrove ecosystem, REDD is one way to prevent and stop deforestation and degradation and will involve participation from the forestry, agriculture and aquaculture sectors.

Afforestation, reforestation, and revegetation (ARR) refers to activities aimed at increasing carbon stocks in woody biomass by building, improving and/or restoring forest cover through planting and/or natural regeneration of vegetation. Afforestation is an effort to improve land with non-forest cover caused by humans directly returning it to forested land through activities such as planting, nurseries, and promoting natural seed sources to form a new forest ecosystem (Cho et al. 2025). Reforestation generally refers to the process of replanting trees in areas where forests were previously lost, largely due to deforestation (Mohan et al. 2021). Revegetation is the replanting and rebuilding of disturbed land by natural processes, through plant colonization and succession, or through human intervention, an accelerated process designed to repair damage to the landscape from forest fires, mining, flooding, or other causes (Yuwati et al. 2021).

WRC is a category of activities covering various wetland areas, including mangrove forests, tidal wetlands, freshwater marshes, saltwater marshes, seagrass beds, floodplains, peatlands and other potential areas (Needelman et al. 2018). These activities are expected to result in reductions and elimination of GHG emissions through increasing biomass (Ledheng et al. 2022), increasing native soil organic carbon, reducing methane and/or nitrous oxide emissions due to increased salinity or land-use change, and reducing carbon dioxide emissions due to soil carbon loss (Adame et al. 2024; Arai et al. 2021).

RWE encompasses activities that reduce GHG emissions or enhance carbon sequestration in degraded wetlands through restoration activities. These activities include improving, creating, and/or managing hydrological conditions, sediment supply, salinity characteristics, water quality, and/or native plant communities (Messer et al. 2019). CIW includes activities that reduce GHG emissions by avoiding degradation and/or conversion of intact or partially modified wetlands while maintaining their natural functions, including hydrological conditions, sediment supply, salinity characteristics, water quality and/or native plant communities (Ma et al. 2025). The combination of mangrove blue carbon interventions and categories is summarized in **Fig. 2**.

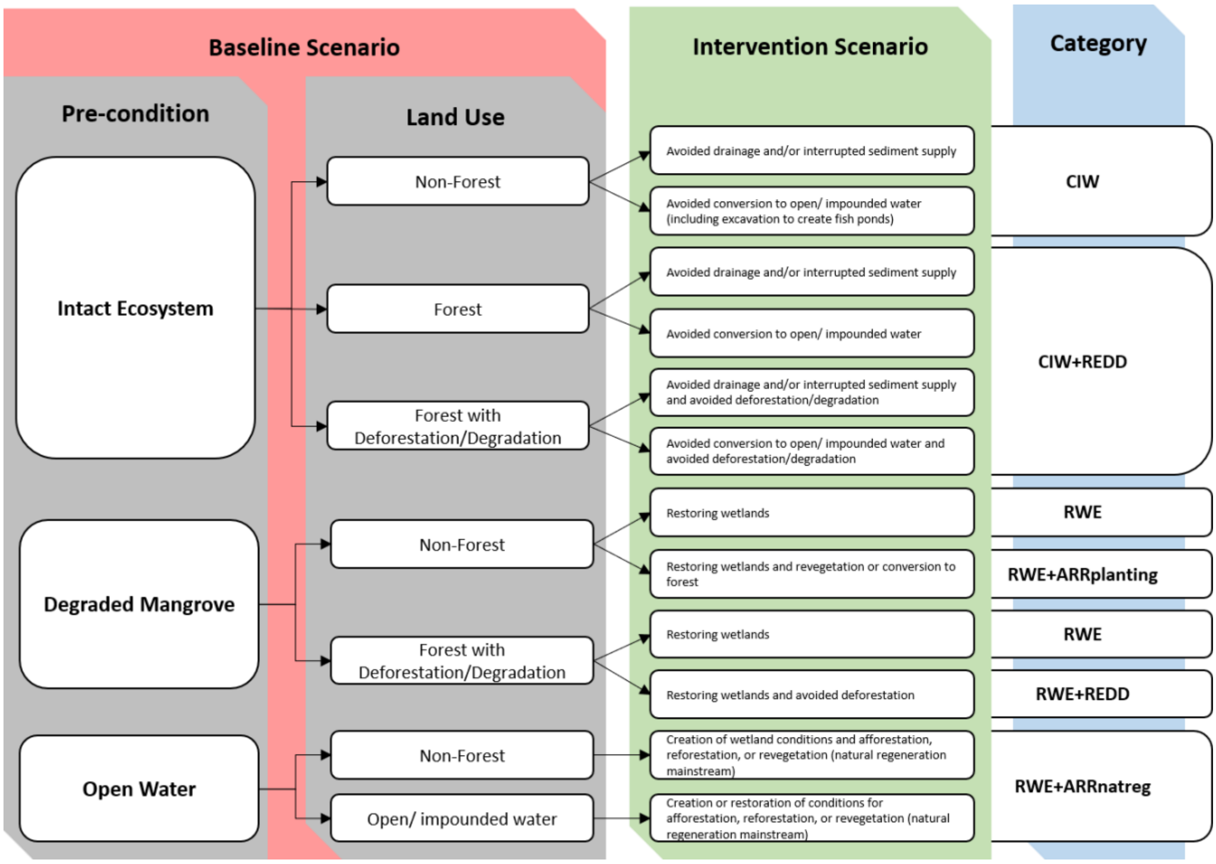

Fig. 2. Flowchart of the mangrove blue carbon interventions and categories. Notes: Degraded mangrove refers to areas that are drained, impounded, or experiencing interrupted sediment supply; non-forest includes aquaculture, shrublands, and grasslands. Abbreviations: ARR (afforestation, reforestation, and revegetation); CIW (conservation of intact wetlands); REDD (reducing emissions from deforestation and forest degradation); RWE (restoration of wetland ecosystems).

In REDD interventions, the stock-difference method is predominantly applied. This approach is appropriate because the primary objective of REDD interventions is to prevent the loss of forest carbon stocks from deforestation and forest degradation. Within this framework, emissions are estimated as the difference in carbon stocks between the initial and projected conditions following land-cover change under both the baseline and project scenarios. Accordingly, the stock-difference approach enables the estimation of avoided emissions by comparing the carbon stock that would be lost under a non-intervention scenario with the carbon stock maintained under the REDD intervention scenario.

In contrast, ARR interventions are more appropriately assessed using the gain-loss method, as the dominant process involved is the accumulation of carbon through vegetation biomass growth. In this approach, changes in carbon stocks are estimated by quantifying biomass gains over time, reflecting tree and vegetation growth, while accounting for potential carbon losses from mortality, harvesting, or ecosystem disturbances. The gain-loss method, therefore, enables the estimation of carbon sequestration rates associated with planting activities or vegetation recovery in areas that were previously non-forested or have been degraded.

For WRC interventions, which include CIW and RWE, carbon accounting generally requires an integrated application of both the stock-difference and gain-loss approaches. In CIW activities, the primary objective is to prevent the loss of carbon stocks stored within intact wetland ecosystems. Consequently, the stock-difference method is used to estimate avoided emissions resulting from preventing wetland degradation or land-use conversion. Conversely, in RWE activities focused on the recovery of previously degraded wetland ecosystems, the gain-loss approach is used to estimate the increase in carbon stocks associated with vegetation regeneration and the restoration of ecosystem functions. This integrated approach enables a more comprehensive assessment of both avoided emissions and carbon sequestration in wetland restoration and conservation interventions.

2.3.4. Multi-intervention scenarios on carbon credits simulation

We combined several possible intervention scenarios that can be simulated in the study area to maximize emission reduction performance, including CIW+REDD, RWE+ARRplanting, and RWE+ARRnatreg. In the CIW+REDD intervention category, emissions were calculated based on several main components: above-ground biomass (AGB) losses, below-ground biomass (BGB) losses, and the flux of soil organic carbon (SOC) released in the form of CO_2, CH_4, and N_2O as a result of mangrove deforestation (change of mangrove to ponds). In the CIW+REDD intervention scenario, we assumed a gradual 10% reduction in the deforestation rate per year, achieving 95% performance by the 10th year.

The RWE+ARRplanting intervention category represents a strategic approach in climate change mitigation, degraded land rehabilitation, and restoration of critical ecosystems, including coastal ecosystems such as mangroves. RWE is technically a hydrological improvement in pond areas with an ecological mangrove rehabilitation approach (Ellison et al. 2020; van Bijsterveldt et al. 2022). The ARRplanting intervention in this context is a mangrove-planting intervention. The main objective of this intervention is to restore ecological functions and environmental services lost due to the conversion of mangroves into ponds, while optimizing socio-economic benefits. In the ARRplanting scenario, we simulated planting carried out until the 10th year by dividing the remaining intertidal aquaculture area into ten blocks. We assumed that survival rates were not explicitly accounted for during the initial planting phase. This assumption was adopted because the project is designed as a long-term intervention, allowing replanting (gap filling) to replace seedlings that fail to establish or die during the early stages of planting. Consequently, potential early-stage mortality was considered manageable through adaptive management and subsequent replanting activities over the course of the project implementation period.

In the RWE+ARRnatreg category, the baseline represents a condition in which the project area continues to experience coastal erosion, serving as a proxy for the historical erosion rate. In contrast, the intervention scenario targets adjacent water areas with the potential to become new land through accretion. Once formed, these newly accreted areas are protected and allowed to undergo natural mangrove regeneration (ARRnatreg).

The Ecological Engineering (EE) approach in mangrove ecosystems is an ecological design strategy that applies ecological principles to design, rehabilitate, or engineer mangrove ecosystems, aiming to sustain ecological functions and ecosystem services (Gijsman et al. 2021). This approach integrates the disciplines of ecology, civil engineering, and coastal governance to restore the natural structure and functions of mangrove ecosystems, including biodiversity, productivity, and climate change mitigation capacity. It aims to reduce disaster risks such as coastal erosion, shoreline retreat, and tidal flooding through the use of nature-based solutions, while enhancing socio-ecological resilience, for example, by incorporating local community needs into restoration or conservation design (van Zetten et al. 2023).

2.3.5. Potential net emission reduction

Potential Emission Reduction (ER) is calculated using Equation 1, Net Emission Reduction (NER) using Equation 2, and Tradable Units using Equation 3 (Verra 2024). The estimation of ER utilizes a Tier 3 approach based on site-specific biomass data; leakage and risk buffers must also be accounted for. Leakage occurs when an action that reduces emissions in one place increases emissions elsewhere (Filewod and McCarney 2023). Ideally, leakage should be quantified using activity-shifting or market-leakage models. However, due to the absence of detailed activity-displacement information in the study area, site-specific leakage could not be directly modeled. Instead, to maintain a conservative approach, a standard default leakage rate of 10% was applied to the ER, and a subsequent 10% risk buffer was deducted from the NER.

$$ER = \Delta GHG_{baseline} - \Delta GHG_{intervention} \quad (1)$$

$$NER = ER - Leakage \quad (2)$$

$$Tradable\ Units = NER - Risk\ Buffer \quad (3)$$

where *ER* is Emission Reductions (tCO_2e), *NER* is Net Emission Reductions (tCO_2e), *Leakage* is the deduction applied to account for emissions displaced outside the project boundary (tCO_2e), *Risk Buffer* is the deduction applied to account for non-permanence risk (tCO_2e), *ΔGHGbaseline* is the GHG emissions of baseline scenarios (tCO_2e), and *ΔGHGintervention* is the GHG emissions of intervention scenarios (tCO_2e).

3. Results and Discussion

3.1. Accuracy Assessment

The classification of land-use/cover types has proven reliable and stable over five decades, with most classes exhibiting high accuracy (**Table 3**). This sustained reliability reflects the method's effectiveness in distinguishing a wide range of land cover types, including more complex categories such as mixed agricultural systems and mangrove vegetation with varying densities.

Table 3. Summary of accuracy assessment for land-use/cover classification

Class	1970				1990				1995				2000			
	PA	UA	OA	KA	PA	UA	OA	KA	PA	UA	OA	KA	PA	UA	OA	KA
1	100	93.0			100	90.1			100	94.4			100	90.1		
2	80.8	88.7			90.7	95.8			94.6	98.6			92.2	100		
3	93.1	94.4			94.5	97.2			97.1	93.0			97.1	95.8		
4	98.5	94.4			100	100			98.6	100			100	100		
5	97.2	97.2			100	100			100	100			97.3	100		
6	94.7	100			100	97.2			97.3	100			100	98.6		
7	95.9	98.6	96.7	96.4	97.3	100	98.1	97.9	100	98.6	98.7	98.6	100	100	97.2	97.0
8	100	100			100	100			100	100			83.5	100		
9	100	100			100	100			100	100			100	100		
10	100	100			100	98.6			100	98.6			98.3	80.3		
11	100	91.5			94.7	100			94.7	100			95.9	98.6		
12	98.6	97.2			97.2	98.6			100	100			100	98.6		
13	98.6	100			100	98.6			100	98.6			100	100		
14	98.6	98.6			100	97.2			100	100			100	98.6		

Class	2005				2010				2015				2020			
	PA	UA	OA	KA	PA	UA	OA	KA	PA	UA	OA	KA	PA	UA	OA	KA
1	100	91.5			98.6	95.8			100	94.4			100	95.8		
2	92.1	98.6			95.9	98.6			94.6	98.6			94.6	98.6		
3	98.5	91.5			98.5	93.0			97.2	97.2			95.8	95.8		
4	98.6	98.6			98.6	98.6			93.2	95.8			92.2	100		
5	100	100			98.6	98.6			97.1	93.0			100	97.2		
6	100	98.6			100	100			100	100			100	100		
7	100	100	96.4	96.1	100	100	98.5	98.4	100	100	98.5	98.4	100	100	98.4	98.3
8	100	100			100	100			100	100			100	100		
9	100	100			100	100			100	100			100	100		
10	100	76.1			100	100			100	100			100	100		
11	80.5	98.6			93.3	98.6			97.3	100			98.6	98.6		
12	87.5	98.6			97.2	98.6			100	100			98.5	94.4		
13	98.6	98.6			98.6	98.6			100	100			98.6	98.6		
14	100	98.6			100	98.6			100	100			100	98.6		

Notes: 1: Forest, 2: Mixed garden, 3: Shrubs, 4: Mixed agriculture, 5: Agriculture, 6: Aquaculture, 7: Built-up area, 8: Sea/water body, 9: Other islands, 10: Open land, 11: Mangrove herbaceous, 12: Mangrove forest 1, 13: Mangrove forest 2, 14: Mangrove forest 3. PA: producer accuracy, UA: user accuracy, OA: overall accuracy, KA: kappa accuracy

3.2. Mangrove Changes and Intertidal Dynamic Proxies

Regions characterized by severe mangrove deforestation and intense coastal erosion are critical priorities for climate-mitigation interventions, including protection and restoration efforts. These priorities are reflected in the spatial dynamics observed along the northern coast of Java, where total gross mangrove deforestation reached 46,034 ha between 1970 and 2020. During this period, the estimated annual rates of mangrove deforestation, intertidal erosion, and accretion were 514 ha/year, 705 ha/year, and 916 ha/year, respectively (**Table 4**). Notably, deforestation accelerated between 2005 and 2020, driven primarily by extensive losses in the fringe and interior zones.

Table 4. Rates of mangrove changes

Changes	1970 –1990	1990 –1995	1995 –2000	2000 –2005	2005 –2010	2010 –2015	2015 –2020	Mean ± SD (ha/year)
Deforestation	1,870	171	465	279	159	181	472	514 ± 613
Accretion	691	658	977	587	944	1,331	1,226	916 ± 288
Erosion	555	167	823	560	887	917	1,026	705 ± 297

The average deforestation rate is used as a proxy for the deforestation rate to quantify the potential for emission reductions. The deforestation rate proxy used in this study aggregates both planned and unplanned deforestation. Unplanned deforestation can result from socio-economic forces driving alternative forest land uses, as well as from the failure of institutions to regulate these activities (Dwiprabowo et al. 2014). Poor law enforcement and a lack of property rights can lead to piecemeal conversion of forest land. Unplanned deforestation activities can include subsistence farming or illegal logging that occurs either on public lands legally designated for timber production or on poorly managed or degraded public or communal lands (Angi and Wiati 2017). Deforestation patterns can result from the expansion of roads and other infrastructure into forest areas, which can increase forest access and lead to increased encroachment by human populations, such as through subsistence farming and firewood collection on previously inaccessible forest lands (Tun et al. 2021).

Planned deforestation can include a variety of conversion activities to non-forest land. These include national transmigration programs from non-forested areas to forested areas (Santika et al. 2017), a national plan to reduce forest areas and convert them to industrial-scale commodity production, where the converted land will not qualify as forest land (Tsujino et al. 2016), and forest conversion plans for urban and infrastructure development (Teo et al. 2020).

Fig. 3a shows a notable escalation in mangrove deforestation between 2005 and 2020, marking the most critical phase of degradation during the observed timeframe. During this period, deforestation expanded more aggressively into both fringe and interior mangrove zones, suggesting an intensifying trend driven by expanding aquaculture, coastal development, and altered hydrological conditions. This acceleration underscores the urgent need for targeted conservation and restoration actions to curb further losses and stabilize the remaining mangrove ecosystems along the northern coast of Java. Furthermore, **Fig. 3b** indicates that while certain areas experienced natural land gain, the overall trajectory of mangrove loss remains significant, highlighting the combined pressures of human land-use change and coastal geomorphic processes.

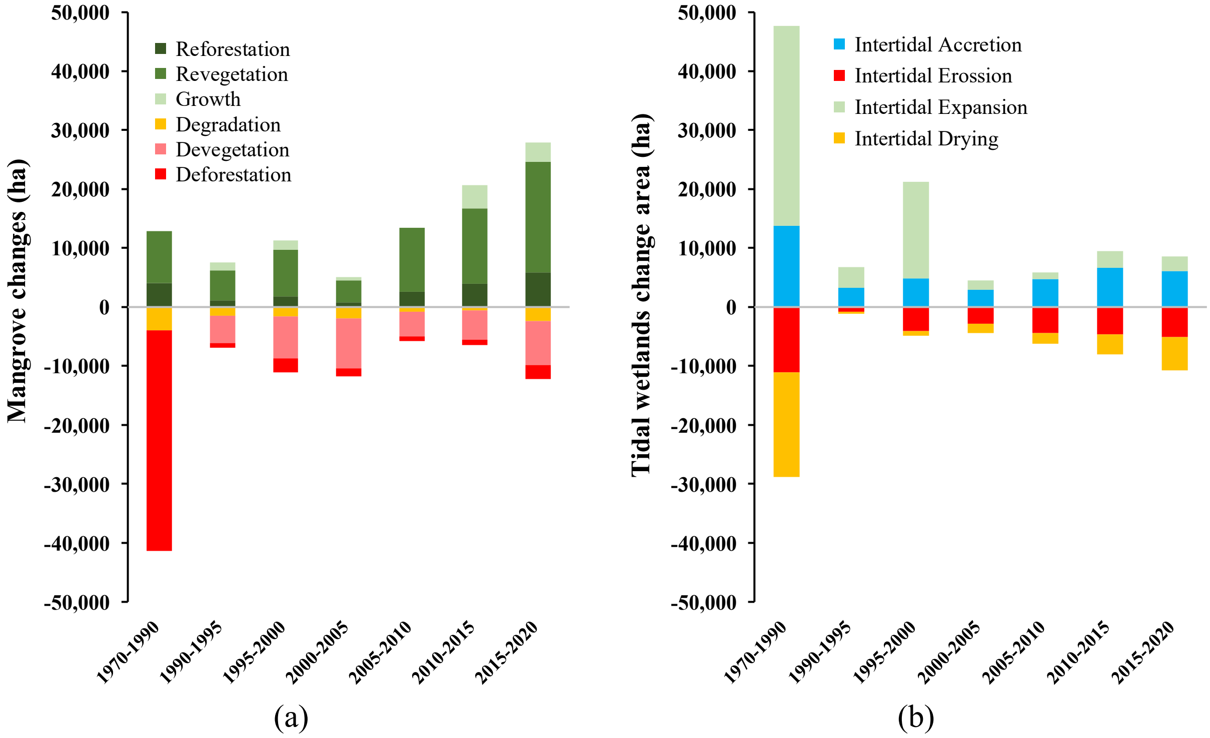

Fig. 3. Graph of mangrove changes (a) and intertidal changes (b).

3.3. Mangrove Extent and Intervention Design

By 2025, the remaining mangrove forests along the northern coast of Java covered an estimated 20,035 ha (**Fig. 4**), representing the fragments of natural habitats that have persisted amid decades of land conversion and intensive coastal development. In contrast, tidal wetland areas that have been transformed into aquaculture ponds occupied a substantially larger extent, totaling 153,951 ha. This stark difference illustrates the magnitude of mangrove loss in the region and highlights the dominance of pond-based land use within the coastal landscape. The spatial imbalance between intact mangroves and converted ponds underscores the coastal vulnerability (Sagala et al. 2024).

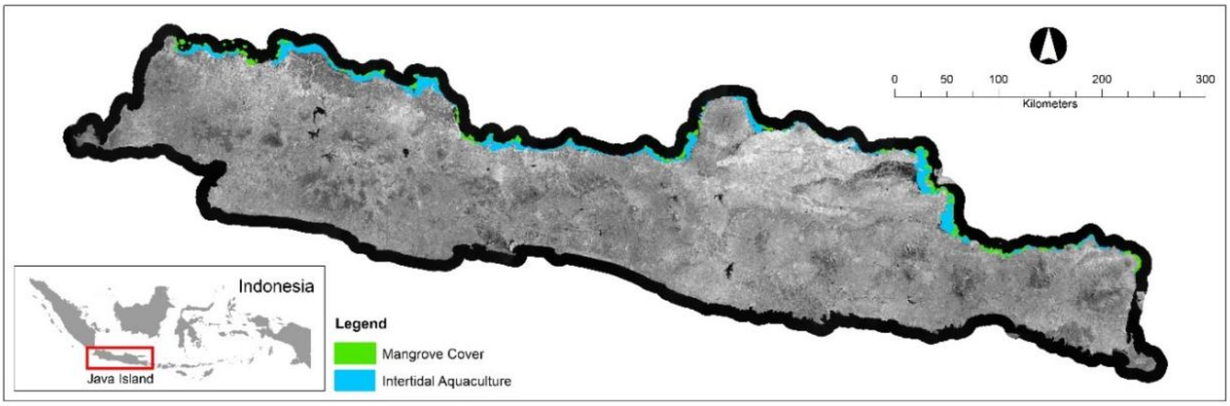

Fig. 4. Distribution of mangrove cover and intertidal aquaculture in 2025.

For the scenario analysis, we categorized these spatial units according to their suitability for different intervention pathways. The remaining mangrove forest patches were allocated to the CIW+REDD scenario, reflecting their role as priority areas for conservation, improved management, and avoided deforestation measures. The extensive aquaculture ponds were designated for the RWE+ARRplanting scenario, acknowledging their biophysical potential for active restoration and replanting to recover above-ground biomass and carbon stocks. Meanwhile, areas exhibiting natural land accretion, typically formed through sediment deposition processes, were assigned to the RWE+ARRnatreg scenario, where passive or assisted natural regeneration is considered the most ecologically and economically feasible approach. Together, these allocations form the basis for assessing the region's blue carbon mitigation potential under differentiated intervention strategies.

The extensive footprint of aquaculture ponds presents both challenges and opportunities for intervention. Many abandoned or low-productivity ponds have altered hydrological regimes, reduced sediment connectivity, and elevated soil salinity, which can impede natural regeneration if left unmanaged. However, these areas also represent the largest potential zones for large-scale mangrove rehabilitation, particularly through strategies such as ecological mangrove restoration (EMR), hydrological reconnection, and managed realignment. Prioritizing intervention areas within these pond-dominated landscapes can significantly enhance the carbon sequestration potential while simultaneously strengthening coastal resilience. Understanding the spatial distribution of mangrove remnants and degraded pond systems is therefore essential for designing effective blue carbon interventions across the northern Java coastline.

3.4. Potential Emission Reduction

We applied the REDD+CIW scenario intervention category to mangrove forests. In the REDD+CIW category, we simulated average baseline emissions from unplanned deforestation schemes over 30 years, resulting in 412,069 tCO_2e/year from AGB and BGB losses and aquaculture SOC fluxes (i.e., CO_2, CH_4, and N_2O). *Ex-ante* deforestation-reduction interventions result in an average emission reduction of 27,579 tCO_2e/year. In addition, the reduction in the deforestation rate leads to increases in autochthonous and allochthonous carbon, which store an average of 75,437 tCO_2e/year. The average potential net emission reduction in the REDD+CIW category is 459,927 tCO_2e/year. By the 30th year of this scenario, the total potential ER performance reaches 14,257,740 tCO_2e (**Fig. 5a**).

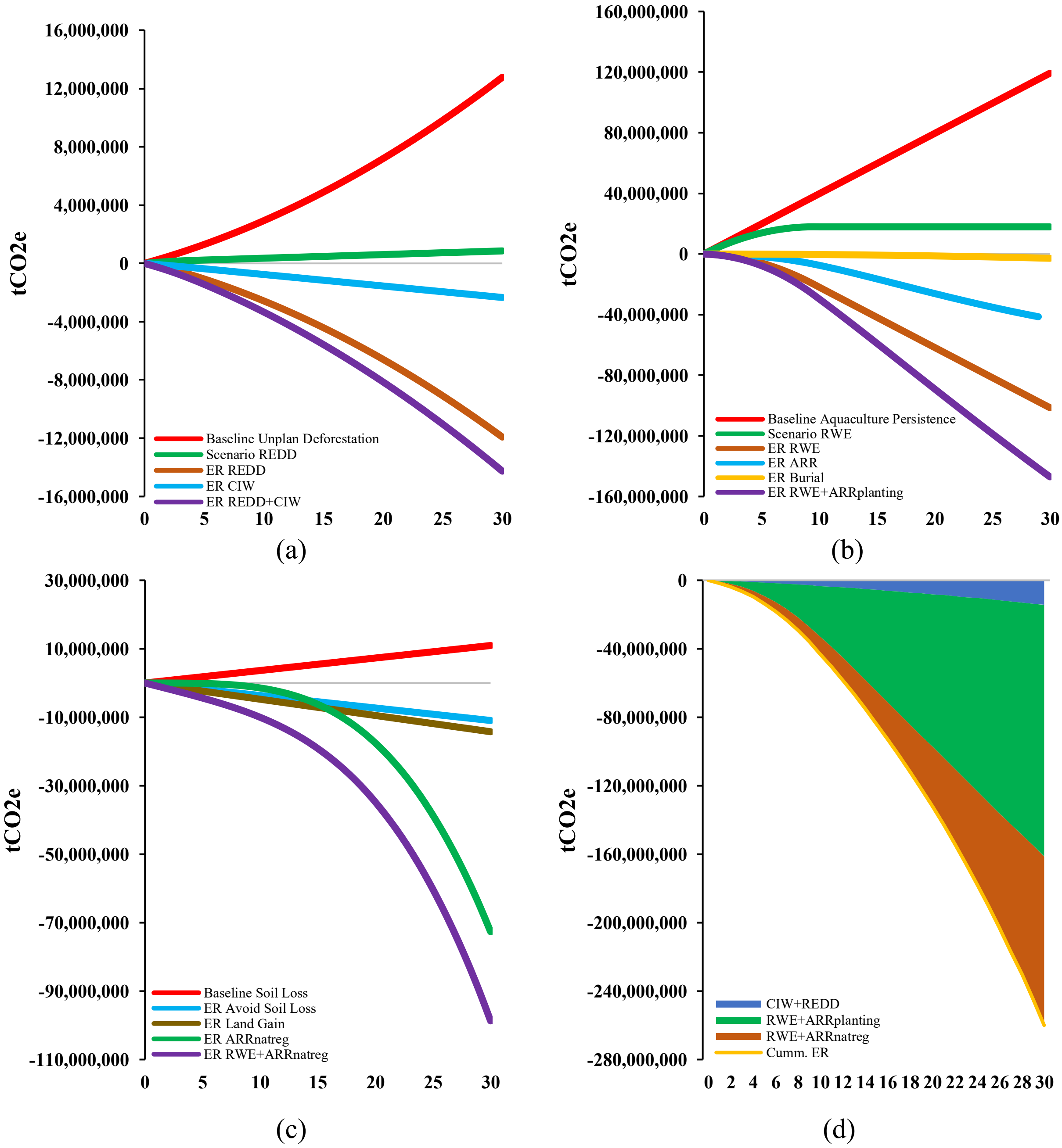

Fig. 5. Graph of cumulative value of net emission reduction from the CIW+REDD (a), RWE+ARRplanting (b), and RWE+ARRnatreg (c) scenarios, and cumulative potential multi-intervention ER (d).

The extent of the remaining mangrove forest and the rate of deforestation are key in this scenario, as both directly determine the magnitude of potential emission reductions achievable (Ekawati et al. 2019). The larger the area of intact mangroves and the higher the deforestation pressure, the greater the potential emission reductions. Therefore, protecting the remaining mangroves is critical to maintaining high carbon stocks, preventing large emissions, and maximizing the climate-mitigation benefits of this ecosystem.

The second scenario is the RWE+ARRplanting scenario for intertidal and aquaculture ponds. In the RWE+ARRplanting category, the average baseline emission is 3,848,351 tCO_2e/year due to maintaining existing ponds; this value also represents emissions that can be avoided if RWE interventions are carried out in the form of hydrological improvements in pond areas with the ecological mangrove rehabilitation approach (Ellison et al. 2020; Lewis 2005; Lewis and Brown 2014). ARRplanting contributes to carbon absorption of 1,427,209 tCO_2e/year over 10 years of gradual planting, in addition to producing autochthonous carbon of 93,328 tCO_2e/year; the average potential total emission reduction is 4,900,673 tCO_2e/year. In the 30th year, the RWE+ARRplanting scenario cumulatively produced a total potential ER of 147,020,181 tCO_2e (**Fig. 5b**).

Restoring natural tidal flows reestablishes the biophysical conditions necessary for successful mangrove planting (van Bijsterveldt et al. 2020). Without hydrological improvement, rehabilitation efforts often fail because mangrove seedlings lack the water, sediment, and nutrient supplies their habitat requires (Twomey et al. 2024). Therefore, appropriate hydrological engineering is fundamental to ensuring optimal planting interventions.

Hydrological restoration not only increases the success rate of planting but also accelerates the recovery of the overall functioning of the mangrove ecosystem. Once hydrological connectivity is restored, critical ecological processes such as sedimentation, substrate formation, and the influx of natural propagules resume (Li et al. 2025). These processes create suitable environmental conditions that facilitate natural mangrove recruitment and allow species to establish according to their ecological niches along tidal gradients. As a result, natural regeneration often leads to higher survival rates and more structurally diverse mangrove stands compared with planting-based rehabilitation, which frequently relies on a limited number of species and may not fully match local environmental conditions. This naturally driven recovery enables former pond areas to resume functioning as productive mangrove ecosystems with high carbon storage potential. Previous studies have shown that mangrove restoration strategies based on hydrological restoration tend to produce more stable ecosystem recovery (Ellison et al. 2020; Lewis 2005; Lewis and Brown 2014). Therefore, hydrological improvement is a strategic element for achieving the maximum climate-mitigation outcomes in the RWE+ARRplanting scenario.

The third scenario, RWE+ARRnatreg, was designed to avoid soil loss and increase accretion areas. Under this scenario, the estimated carbon dynamics consisted of avoided soil-loss emissions of 353,223 tCO_2e/year, SOC sequestration of 474,345 tCO_2e/year, allochthonous carbon from SOC of 12,095 tCO_2e/year, CO_2 removal through natural regeneration of 2,421,690 tCO_2e/year, autochthonous carbon from mangrove forests of 5,555 tCO_2e/year, and allochthonous carbon from mangrove forests of 2,830,747 tCO_2e/year. The average total potential emission reduction reached 3,290,103 tCO_2e/year. By year 30, the RWE+ARRnatreg scenario cumulatively generated a total potential ER of 98,703,079 tCO_2e (**Fig. 5c**).

The potential for emission reductions from natural regeneration strategies is higher than that from planting, as noted by Li et al. (2025). These results underscore the importance of natural regeneration strategies in regional, national, and global restoration agendas. Soil carbon sequestration consistently contributes significantly, underscoring the critical role of mangrove soils in long-term organic carbon storage (Sasmito et al. 2020).

Furthermore, the contribution of allochthonous SOC, which is carbon transported from outside the system and accumulated in the soil, indicates the presence of external organic inputs, such as carbon-rich sediments from rivers or tides (Xiong et al. 2018). Meanwhile, naturally growing mangrove vegetation contributes gradually over time (Fickert 2020; Teutli-Hernández et al. 2019). Autochthonous carbon, derived from local mangrove biomass growth, increases linearly following the accumulation of above-ground biomass growth (Hu et al. 2022). The contribution of allochthonous carbon, which represents the input of organic matter from outside the area through natural processes, will also continue to increase until the end of the period.

The multi-intervention scenario simulation resulted in an average annual emission reduction of 8,666,033 tCO_2e/year, with a total ER of 259,981,000 tCO_2e in year 30 (**Fig. 5d**). These estimates suggest that a multi-intervention approach could yield higher mitigation outcomes than restoration initiatives relying on a single intervention strategy. However, these results should be interpreted as modeled projections under the assumptions of the scenario analysis rather than demonstrated project performance.

Compared to other ecosystems (e.g., drylands and peatlands), mangrove ecosystems exhibit a more complex balance of carbon dynamics. (Ali et al. 2025). The carbon dynamics of mangrove ecosystems are influenced by interconnected water, sediment, and biomass balances (Zhu and Yan 2022). Consequently, mangrove protection and restoration will significantly contribute to climate change mitigation (Arifanti et al. 2022; Novita et al. 2022). Over 30 years, the contribution of the mangrove ecosystem to greenhouse gas emission reductions in design simulations comes from three main sources: soil carbon sequestration, carbon sequestration from planted vegetation, and carbon sequestration from natural regeneration. A summary of annual projections of total emission reductions (ER), net emission reductions (NER), and tradable carbon units over 30 years is presented in **Table 5**.

REDD+CIW, in practice, is an effort to protect remaining mangrove forests, accounting for only 5% of the total potential net emission reductions. Although this percentage may seem lower than in other intervention scenarios, it is a direct result of lower deforestation rates in Java compared to in other regions (Arifanti et al. 2021). Due to the vast pond area on the northern coast of Java, the hydrological improvement and planting scenarios under the RWE+ARRplanting interventions account for 57% of the total potential reductions. The availability of land for this intervention may decrease as urban areas in the Java region continue to grow (Fajary et al. 2024).

Meanwhile, RWE+ARRnatreg, with its coastal erosion-prevention approach and habitat creation (land gain) through the mainstreaming of natural regeneration, accounts for 38% of the total potential net emission reductions. This intervention holds significant potential when linked to mangrove protection in the estuarine delta region on the northern coast of Java. The coastal typology of the estuarine delta offers significant potential for carbon storage (Kusumaningrum and Haryono 2020; Sidik et al. 2016; Soebowo et al. 2023) and continues to expand due to high sedimentation rates (Murdiyarso et al. 2022).

Achieving the emission-reduction targets in mangrove ecosystems certainly requires commitment and discipline at each phase, along with a combination of prohibition policies on conversions, strengthened area monitoring, community empowerment, and incentives (Sasmito et al. 2023). Technically, the scenario consists of three phases: The Initiation Phase (Years 0–10) focuses on strengthening area governance, administrative protection, and awareness campaigns, alongside a targeted reduction in deforestation rates compared to the baseline. The Consolidation Phase (Years 11–20) involves implementing participatory monitoring, improving tenure certainty, and integrating carbon incentives to achieve increased emission-reduction targets relative to the baseline. Finally, the Stabilization Phase (Years 21–30) is expected to reduce deforestation to near-zero (zero net deforestation) while achieving social and ecosystem co-benefits.

Table 5. Annual projections of total emission reductions (ER), net emission reductions (NER), and tradable carbon units over 30 years

Year	CIW+REDD (tCO_2e)	RWE+ARRplanting (tCO_2e)	RWE+ARRnatreg (tCO_2e)	Total ER (tCO_2e)	Total NER (tCO_2e)	Tradable Unit (tCO_2e)
0	0	0	0	0	0	0
1	238,903	488,357	853,677	1,580,937	1,422,843	1,280,559
2	260,128	999,294	859,564	2,118,986	1,907,087	1,716,378
3	287,800	1,527,165	871,729	2,686,693	2,418,024	2,176,222
4	315,396	2,071,970	892,875	3,280,241	2,952,217	2,656,995
5	336,393	2,633,711	925,758	3,895,862	3,506,276	3,155,648
6	353,269	3,206,741	968,542	4,528,551	4,075,696	3,668,126
7	366,773	3,791,060	1,026,950	5,184,784	4,666,305	4,199,675
8	380,058	4,381,025	1,103,556	5,864,639	5,278,175	4,750,358
9	393,330	4,976,634	1,200,955	6,570,919	5,913,827	5,322,444
10	406,601	5,577,889	1,321,759	7,306,249	6,575,624	5,918,062
11	419,873	5,696,807	1,452,409	7,569,089	6,812,180	6,130,962
12	433,145	5,793,146	1,608,559	7,834,850	7,051,365	6,346,229
13	446,417	5,872,550	1,792,578	8,111,545	7,300,390	6,570,351
14	459,688	5,935,020	2,006,845	8,401,554	7,561,399	6,805,259
15	472,960	5,974,911	2,253,754	8,701,624	7,831,462	7,048,316
16	486,232	6,003,511	2,500,598	8,990,341	8,091,307	7,282,176
17	499,503	6,015,177	2,780,217	9,294,897	8,365,408	7,528,867
18	512,775	6,021,198	3,094,728	9,628,702	8,665,832	7,799,249
19	526,047	6,015,930	3,446,261	9,988,238	8,989,414	8,090,473
20	539,319	5,999,372	3,836,950	10,375,640	9,338,076	8,404,268
21	552,590	5,977,169	4,207,380	10,737,139	9,663,425	8,697,082
22	565,862	5,949,321	4,615,050	11,130,232	10,017,209	9,015,488
23	579,134	5,915,828	5,061,807	11,556,769	10,401,092	9,360,983
24	592,405	5,876,690	5,549,504	12,018,600	10,816,740	9,735,066
25	605,677	5,837,552	6,079,999	12,523,229	11,270,906	10,143,815
26	618,949	5,792,770	6,559,478	12,971,197	11,674,077	10,506,669
27	632,221	5,747,987	7,077,730	13,457,938	12,112,144	10,900,930
28	645,492	5,697,560	7,636,317	13,979,369	12,581,432	11,323,289
29	658,764	5,647,132	8,236,800	14,542,696	13,088,427	11,779,584
30	672,036	5,596,705	8,880,748	15,149,489	13,634,540	12,271,086
Total	**14,257,740**	**147,020,181**	**98,703,079**	**259,981,000**	**233,982,900**	**210,584,610**
Mean/ year	**475,258**	**4,900,673**	**3,290,103**	**8,666,033**	**7,799,430**	**7,019,487**
%	**5**	**57**	**38**	**100**		

Notes: CIW (conservation of intact wetlands), REDD (reducing emissions from deforestation and forest degradation), RWE (restoration of wetland ecosystems), ARR (afforestation, reforestation, and revegetation), ER (emission reductions), NER (net emission reductions). Planting and natreg indicate planting-based rehabilitation and natural regeneration, respectively.

3.5. Comparison of Intervention Scenarios

The REDD+CIW intervention, implemented across 20,035 ha, yields an average ER of 475,258 tCO_2e/year, equivalent to approximately 24 tCO_2e/ha/year. This relatively low per-hectare value is expected for avoided-deforestation interventions, which primarily prevent further carbon losses rather than generating substantial new carbon sequestration. Consequently, although the overall ER is meaningful, its mitigation intensity is the lowest among the three pathways.

In contrast, the RWE+ARRplanting scenario, covering a much larger area of 153,951 ha, produces a mean ER of 4,900,673 tCO_2e/year, or 32 tCO_2e/ha/year. This substantially higher per-hectare reduction reflects the strong carbon accumulation associated with active mangrove restoration on former pond systems, where degraded substrates enable rapid biomass recovery when hydrological conditions are restored.

The RWE+ARRnatreg pathway, despite covering a comparatively smaller area of 27,488 ha, provides 3,290,103 tCO_2e/year, with the highest per-hectare mitigation rate of 120 tCO_2e/ha/year. This exceptionally high value is characteristic of natural regeneration on newly accreted lands, where carbon gains are driven by rapid sediment deposition and natural mangrove colonization, resulting in accelerated below-ground and soil carbon accumulation. The average potential ERs by intervention category are shown in **Table 6**.

Table 6. Comparison of average potential ERs by multi-intervention categories

Potential ERs	REDD+CIW	RWE+ARRplanting	RWE+ARRnatreg
Mean ER (tCO_2e/year)	475,258	4,900,673	3,290,103
Intervention area* (ha)	20,035	153,951	27,488
Mean ER (tCO_2e/ha/year)	24	32	120
Performance Ratio	1	1	5

Note: * Predicted land gain over 30 years.

Based on the performance ratios presented in **Table 6**, the net emission reduction ratios for the REDD+CIW, RWE+ARRplanting, and RWE+ARRnatreg interventions were 1:1:5, respectively. Comparing emission-reduction values across intervention scenarios can help indicate priority levels for encouraging climate change mitigation efforts, particularly in mangrove ecosystems. Natural restoration and protection interventions that allow the passive regeneration of mangrove vegetation can be a key driver of increased long-term carbon sequestration, especially when combined with stabilizing mangrove soil carbon stores over time (Fickert 2020; Li et al. 2025; Teutli-Hernández et al. 2019). Thus, the synergy between soil carbon stabilization and natural vegetation restoration is a key pillar in achieving GHG mitigation targets.

3.6. Economic Valuation of Potential Carbon Credit

The potential emission reductions from multi-intervention scenarios provide the basis for carbon credit valuations. **Table 7** shows the economic value of carbon resulting from potential tradable carbon units from mangrove ecosystems over 30 years under various international carbon market price scenarios. In this study, we assumed several market value scenarios ranging from USD 5 to USD 30, as in Zeng et al. (2021). This threshold is the value that has actually been transacted in voluntary market-based offsets, especially in business-to-business mechanisms.

Potential tradable carbon units are calculated by subtracting the risk buffer from the NER. The risk buffer represents a proportion of emissions set aside to account for uncertainties, including activity-shifting leakage, market leakage, internal and external risks, natural risks, and potential project failure over time (Fickert 2020; Nielsen et al. 2021). At the end of the 30th year, the total potential tradable carbon units reached 210,584,610 tCO_2e, corresponding to an average annual volume of 7,019,487 tCO_2e/year. Based on this volume, the potential economic value in the carbon market was estimated at USD 35,097,435/year at a carbon price of USD 5/tCO_2e. This financial estimate represents the verified net carbon value available for nature-based offsets or carbon credits.

Table 7. Economic valuation of potential tradable carbon units under various carbon market pricing scenarios

Year	Tradable Unit (tCO_2e)	Carbon market pricing options (USD)					
		5	10	15	20	25	30
0	0	-	-	-	-	-	-
1	1,280,559	6,402,796	12,805,591	19,208,387	25,611,183	32,013,978	38,416,774
2	1,716,378	8,581,892	17,163,784	25,745,677	34,327,569	42,909,461	51,491,353
3	2,176,222	10,881,108	21,762,217	32,643,325	43,524,434	54,405,542	65,286,650
4	2,656,995	13,284,977	26,569,955	39,854,932	53,139,909	66,424,887	79,709,864
5	3,155,648	15,778,242	31,556,484	47,334,727	63,112,969	78,891,211	94,669,453
6	3,668,126	18,340,632	36,681,263	55,021,895	73,362,527	91,703,159	110,043,790
7	4,199,675	20,998,374	41,996,748	62,995,121	83,993,495	104,991,869	125,990,243
8	4,750,358	23,751,788	47,503,576	71,255,365	95,007,153	118,758,941	142,510,729
9	5,322,444	26,612,220	53,224,441	79,836,661	106,448,881	133,061,101	159,673,322
10	5,918,062	29,590,310	59,180,620	88,770,930	118,361,241	147,951,551	177,541,861
11	6,130,962	30,654,811	61,309,623	91,964,434	122,619,245	153,274,056	183,928,868
12	6,346,229	31,731,143	63,462,286	95,193,428	126,924,571	158,655,714	190,386,857
13	6,570,351	32,851,757	65,703,513	98,555,270	131,407,027	164,258,783	197,110,540
14	6,805,259	34,026,293	68,052,587	102,078,880	136,105,173	170,131,467	204,157,760
15	7,048,316	35,241,578	70,483,156	105,724,734	140,966,312	176,207,890	211,449,468
16	7,282,176	36,410,881	72,821,762	109,232,643	145,643,524	182,054,405	218,465,286
17	7,528,867	37,644,334	75,288,668	112,933,001	150,577,335	188,221,669	225,866,003
18	7,799,249	38,996,243	77,992,487	116,988,730	155,984,974	194,981,217	233,977,460
19	8,090,473	40,452,364	80,904,728	121,357,092	161,809,456	202,261,820	242,714,184
20	8,404,268	42,021,342	84,042,683	126,064,025	168,085,366	210,106,708	252,128,049
21	8,697,082	43,485,412	86,970,824	130,456,235	173,941,647	217,427,059	260,912,471
22	9,015,488	45,077,442	90,154,883	135,232,325	180,309,766	225,387,208	270,464,649
23	9,360,983	46,804,913	93,609,825	140,414,738	187,219,651	234,024,564	280,829,476
24	9,735,066	48,675,329	97,350,658	146,025,987	194,701,316	243,376,645	292,051,974
25	10,143,815	50,719,076	101,438,153	152,157,229	202,876,306	253,595,382	304,314,459
26	10,506,669	52,533,347	105,066,694	157,600,041	210,133,388	262,666,735	315,200,082
27	10,900,930	54,504,650	109,009,300	163,513,951	218,018,601	272,523,251	327,027,901
28	11,323,289	56,616,443	113,232,886	169,849,329	226,465,772	283,082,215	339,698,658
29	11,779,584	58,897,921	117,795,841	176,693,762	235,591,682	294,489,603	353,387,523
30	12,271,086	61,355,431	122,710,862	184,066,292	245,421,723	306,777,154	368,132,585
Total	**210,584,610**	**1,052,923,049**	**2,105,846,098**	**3,158,769,147**	**4,211,692,196**	**5,264,615,245**	**6,317,538,294**
Mean/year	**7,019,487**	**35,097,435**	**70,194,870**	**105,292,305**	**140,389,740**	**175,487,175**	**210,584,610**
USD/ha		**202**	**403**	**605**	**807**	**1,009**	**1,210**

The economic value of carbon can increase alongside biodiversity management through standards such as the Climate, Community, and Biodiversity (CCB) Standards (Farahmand et al. 2025). The CCB standards ensure that projects not only reduce carbon emissions but also provide social and environmental benefits, such as restoring biodiversity (Wang et al. 2025). Furthermore, the maximum potential economic value of the carbon market averaged USD 210,584,610/year at USD 30/tCO_2e. Overall, the findings confirm that mangrove protection and restoration provide not only ecological benefits but also substantial financial benefits.

4. Conclusions

Mangrove ecosystems along the northern coast of Java have substantial potential for climate change mitigation through protection, improved management, and restoration strategies. This study demonstrates that while REDD+CIW contributes to ecosystem protection, the RWE+ARRplanting and particularly the RWE+ARRnatreg scenarios provide substantially greater emission-reduction potential. Specifically, ecological engineering approaches based on natural regeneration (120 tCO_2e/ha/year) outperformed planting-based rehabilitation (32 tCO_2e/ha/year) by approximately 4-fold and REDD+CIW (24 tCO_2e/ha/year) by approximately 5-fold. In addition, the projected generation of more than 7 million tradable carbon units annually, corresponding to potential annual revenues of USD 35.1–210.6 million, highlights the considerable economic potential of mangrove-based carbon finance. However, these estimates remain subject to uncertainties related to baseline assumptions, restoration success, permanence risks, and unquantified leakage. They should therefore be interpreted as scenario-based projections rather than definitive outcomes. Policy implications emphasize integrating mangrove restoration into carbon market mechanisms such as Verra, strengthening coastal governance, and incentivizing the conversion of abandoned aquaculture ponds into mangrove restoration areas, thereby supporting climate mitigation, coastal resilience, and sustainable financing.

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Author Contributions

A.R.: Conceptualization, Data Curation, Methodology, Formal Analysis, Spatial Analysis, Resources, Project Administration, Writing – Original Draft Preparation, Writing – Review and Editing; L.B.P.: Conceptualization, Supervision, Methodology, Resources, Project Administration, Writing – Review and Editing; Y.S.: Conceptualization, Supervision, Data Curation, Methodology, Writing – Review and Editing; C.K.: Supervision, Writing – Review and Editing.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation

Generative AI tools were used solely to assist with grammar refinement and sentence restructuring. All conceptual development, data analysis, results, and conclusions were undertaken entirely by the authors. The authors accept full responsibility for all aspects of the manuscript.

References

Abelson, A., Reed, D. C., Edgar, G. J., Smith, C. S., Kendrick, G. A., Orth, R. J., Airoldi, L., Silliman, B., Beck, M. W., Krause, G., et al. 2020. Challenges for Restoration of Coastal Marine Ecosystems in the Anthropocene. *Frontiers in Marine Science* 7: 1–14. DOI: 10.3389/fmars.2020.544105

Adame, M. F., Cormier, N., Taillardat, P., Iram, N., Rovai, A., Sloey, T. M., Yando, E. S., Blanco-Libreros, J. F., Arnaud, M., Jennerjahn, T., et al. 2024. Deconstructing the Mangrove Carbon Cycle: Gains, Transformation, and Losses. *Ecosphere* 15(3): e4806. DOI: 10.1002/ecs2.4806

Ahalya, A., and Park, J. S. 2019. Blue Carbon Stock of Mangrove Ecosystems. *International Journal of Science and Research* 8(12): 1371–1375. DOI: 10.21275/ART20203497

Ali, S., Dey, G., Nuong, N. H. K., Rahman, A., Wang, L.-C., Sukul, U., Das, K., Sharma, R. K., Wang, S.-L., and Chen, C. Y. 2025. Carbon Sequestration in Mangrove Ecosystems: Sources, Transportation Pathways, Influencing Factors, and Its Role in the Carbon Budget. *Earth-Science Reviews* 269: 105184. DOI: 10.1016/j.earscirev.2025.105184

Andreas, H., Abidin, H. Z., Sarsito, D. A., Meilano, I., and Susilo. 2019. Investigating the Tectonic Influence to the Anthropogenic Subsidence Along Northern Coast of Java Island Indonesia

Using GNSS Data Sets. *International Symposium on Global Navigation Satellite System 2018* 94: 9. DOI: 10.1051/e3sconf/20199404005

Angi, E. M., and Wiati, C. B. 2017. Kajian Ekonomi Politik Deforestasi dan Degradasi Hutan dan Lahan di Kabupaten Paser, Kalimantan Timur (The Political Economic of Deforestation and Forest Degradation in Paser Regency, East Kalimantan). *Jurnal Penelitian Ekosistem Dipterokarpa* 3(2): 63–80. DOI: 10.20886/jped.2017.3.2.63-80

Arai, H., Inubushi, K., and Chiu, C. Y. 2021. Dynamics of Methane in Mangrove Forest: Will It Worsen with Decreasing Mangrove Forests? *Forests* 12(9): 1204. DOI: 10.3390/f12091204

Arifanti, V. B., Kauffman, J. B., Subarno, Ilman, M., Tosiani, A., and Novita, N. 2022. Contributions of Mangrove Conservation and Restoration to Climate Change Mitigation in Indonesia. *Global Change Biology* 28: 1–16. DOI: 10.1111/gcb.16216

Arifanti, V. B., Novita, N., Subarno, and Tosiani, A. 2021. Mangrove Deforestation and CO_2 Emissions in Indonesia. *IOP Conference Series: Earth and Environmental Science* 874(1): 012006. DOI: 10.1088/1755-1315/874/1/012006

Boer, M., Kurniawan, F., Kurnia, R., Zairion, Z., Priyambodo, B., and Yunus, M. 2025. Bibliographic Analysis and Refinement of General Allometric Models for Biomass and Carbon Stock Estimation in Tropical Mangroves of Indonesia. *Next Research* 2(2): 100342. DOI: 10.1016/j.nexres.2025.100342

Bomfim, B., Pinagé, E. R., Emmert, F., and Kueppers, L. M. 2022. Improving Sustainable Tropical Forest Management with Voluntary Carbon Markets. *Plant and Soil* 479: 53–60. DOI: 10.1007/s11104-021-05249-5

Brown, B., Fadillah, R., Nurdin, Y., Soulsby, I., and Ahmad, R. 2014. Community Based Ecological Mangrove Rehabilitation (CBEMR) in Indonesia. *S.A.P.I.EN.S* 7(2): 1–13. URL: http://journals.openedition.org/sapiens/1589

Bunting, P., Rosenqvist, A., Hilarides, L., Lucas, R. M., Thomas, N., Tadono, T., Worthington, T. A., Spalding, M., and Murray, N. J. 2022. Global Mangrove Extent Change 1996 – 2020: Global Mangrove Watch Version 3.0. *Remote Sensing* 14: 3657. DOI: 10.3390/rs14153657

Cho, S., Baral, S., and Burlakoti, D. 2025. Afforestation/Reforestation and Avoided Conversion Carbon Projects in the United States. *Forests* 16(1): 115. DOI: 10.3390/f16010115

Choudhary, B., Dhar, V., and Pawase, A. S. 2024. Blue Carbon and the Role of Mangroves in Carbon Sequestration: Its Mechanisms, Estimation, Human Impacts and Conservation Strategies for Economic Incentives. *Journal of Sea Research* 199: 102504. DOI: 10.1016/j.seares.2024.102504

Davies, K. P., Murphy, R. J., and Bruce, E. 2016. Detecting Historical Changes to Vegetation in a Cambodian Protected Area Using the Landsat TM and ETM+ Sensors. *Remote Sensing of Environment* 187: 332–344. DOI: 10.1016/j.rse.2016.10.027

Dong, W. S., Ismailluddin, A., Yun, L. S., Ariffin, E. H., Saengsupavanich, C., Abdul Maulud, K. N., Ramli, M. Z., Miskon, M. F., Jeofry, M. H., Mohamed, J., Mohd, F. A., Hamzah, S. B., and Yunus, K. 2024. The Impact of Climate Change on Coastal Erosion in Southeast Asia and the Compelling Need to Establish Robust Adaptation Strategies. *Heliyon* 10(4): e25609. DOI: 10.1016/j.heliyon.2024.e25609

Dwiprabowo, H., Djaenudin, D., Alviya, I., and Wicaksono, D. 2014. *Dinamika Tutupan Lahan: Pengaruh Faktor Sosial Ekonomi*. PT Kanisius.

Eastman, J. R., Crema, S. C., Sangermano, F., Cunningham, S., Xiao, X., Zhou, Z., Hu, P., Johnson, C., Arakwiye, B., and Crone, N. 2015. A Baseline Mapping of Aquaculture and

Coastal Habitats in Thailand, Cambodia and Vietnam. In: *Aquaculture and Coastal Habitats Report*.

Ehara, M., Saito, H., Michinaka, T., Hirata, Y., Leng, C., Matsumoto, M., and Riano, C. 2021. Allocating the REDD+ National Baseline to Local Projects: A Case Study of Cambodia. *Forest Policy and Economics* 129: 102474. DOI: 10.1016/j.forpol.2021.102474

Ekawati, S., Subarudi, Budiningsih, K., Sari, G. K., and Muttaqin, M. Z. 2019. Policies Affecting the Implementation of REDD+ in Indonesia (Cases in Papua, Riau and Central Kalimantan). *Forest Policy and Economics* 108: 101939. DOI: 10.1016/j.forpol.2019.05.025

Ellison, A. M., Felson, A. J., and Friess, D. A. 2020. Mangrove Rehabilitation and Restoration as Experimental Adaptive Management. *Frontiers in Marine Science* 7: 327. DOI: 10.3389/fmars.2020.00327

Fajary, F. R., Lee, H. S., Kubota, T., Bhanage, V., Pradana, R. P., Nimiya, H., and Putra, I. D. G. A. 2024. Comprehensive Spatiotemporal Evaluation of Urban Growth, Surface Urban Heat Island, and Urban Thermal Conditions on Java Island of Indonesia and Implications for Urban Planning. *Heliyon* 10(13): e33708. DOI: 10.1016/j.heliyon.2024.e33708

Farahmand, S., Hilmi, N., and Duarte, C. M. 2025. The Rise and Flows of Blue Carbon Credits Advance Global Climate and Biodiversity Goals. *NPJ Ocean Sustainability* 4(1): 1–11. DOI: 10.1038/s44183-025-00141-6

Fickert, T. 2020. To Plant or Not to Plant, That Is the Question: Reforestation vs. Natural Regeneration of Hurricane-Disturbed Mangrove Forests in Guanaja (Honduras). *Forests* 11(10): 1068. DOI: 10.3390/f11101068

Filewod, B., and McCarney, G. 2023. Avoiding Carbon Leakage from Nature-Based Offsets by Design. *One Earth* 6(7): 790–802. DOI: 10.1016/j.oneear.2023.05.024

Foody, G. M. 2020. Explaining the Unsuitability of the Kappa Coefficient in the Assessment and Comparison of the Accuracy of Thematic Maps Obtained by Image Classification. *Remote Sensing of Environment* 239: 111630. DOI: 10.1016/j.rse.2019.111630

Gijsman, R., Horstman, E. M., van der Wal, D., Friess, D. A., Swales, A., and Wijnberg, K. M. 2021. Nature-Based Engineering: A Review on Reducing Coastal Flood Risk with Mangroves. *Frontiers in Marine Science* 8: 702412. DOI: 10.3389/fmars.2021.702412

Goldberg, L., Lagomasino, D., Thomas, N., and Fatoyinbo, T. 2020. Global Declines in Human-Driven Mangrove Loss. *Global Change Biology* 26(10): 5844–5855. DOI: 10.1111/gcb.15275

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., and Moore, R. 2017. Google Earth Engine: Planetary-Scale Geospatial Analysis for Everyone. *Remote Sensing of Environment* 202: 18–27. DOI: 10.1016/j.rse.2017.06.031

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., et al. 2017. Natural Climate Solutions. *Proceedings of the National Academy of Sciences of the United States of America* 114(44): 11645–11650. DOI: 10.1073/pnas.1710465114

Hagger, V., Worthington, T. A., Lovelock, C. E., Adame, M. F., Amano, T., Brown, B. M., Friess, D. A., Landis, E., Mumby, P. J., Morrison, T. H., O'Brien, K. R., Wilson, K. A., Zganjar, C., and Saunders, M. I. 2022. Drivers of Global Mangrove Loss and Gain in Social-Ecological Systems. *Nature Communications* 13(1): 6373. DOI: 10.1038/s41467-022-33962-x

Heriati, A., Solihuddin, T., Husrin, S., Salim, H. L., Mustikasari, E., Kepel, T. L., and Ati, R. N. A. 2021. Mangrove Ecosystem Development on North Coast of Java. *IOP Conference Series: Earth and Environmental Science* 925(1): 012020. DOI: 10.1088/1755-1315/925/1/012020

Hilmi, N., Chami, R., Sutherland, M. D., Hall-Spencer, J. M., Lebleu, L., Benitez, M. B., and Levin, L. A. 2021. The Role of Blue Carbon in Climate Change Mitigation and Carbon Stock Conservation. *Frontiers in Climate* 3: 710546. DOI: 10.3389/fclim.2021.710546

Hu, J., Loh, P. S., Pradit, S., Le, T. P. Q., Oeurng, C., Mohamed, C. A. R., Lee, C. W., Lu, X., Anshari, G. Z., Kandasamy, S., Wang, J., Li, Z., Qin, H., Ji, L., and Guo, J. 2022. Assessing the Effect of Age and Geomorphic Setting on Organic Carbon Accumulation in High-Latitude Human-Planted Mangroves. *Forests* 13(1): 105. DOI: 10.3390/f13010105

Hu, K., Wang, W., Qian, W., Sheng, N., Cheng, J., and Xiong, Y. 2025. Responses of Biomass and Allometric Growth Equations of Juvenile Mangrove Plants to Salinity, Flooding, and Above-Ground Competition. *Horticulturae* 11(7): 712. DOI: 10.3390/horticulturae11070712

Huang, X., Li, J., Yang, J., Zhang, Z., Li, D., and Liu, X. 2021. 30 m Global Impervious Surface Area Dynamics and Urban Expansion Pattern Observed by Landsat Satellites: From 1972 to 2019. *Science China Earth Sciences* 64: 1922–1933. DOI: 10.1007/s11430-020-9797-9

Hudalah, D., Octifanny, Y., Talitha, T., Firman, T., and Phelps, N. A. 2024. From Metropolitanization to Megaregionalization: Intentionality in the Urban Restructuring of Java's North Coast, Indonesia. *Journal of Planning Education and Research* 4(1): 292–306. DOI: 10.1177/0739456X20967405

Ilman, M., Dargusch, P., Dart, P., and Onrizal. 2016. A Historical Analysis of the Drivers of Loss and Degradation of Indonesia's Mangroves. *Land Use Policy* 54: 448–459. DOI: 10.1016/j.landusepol.2016.03.010

Kadaverugu, R., Dhyani, S., Purohit, V., Dasgupta, R., Kumar, P., Hashimoto, S., Pujari, P., and Biniwale, R. 2022. Scenario-Based Quantification of Land-Use Changes and Its Impacts on Ecosystem Services: A Case of Bhitarkanika Mangrove Area, Odisha, India. *Journal of Coastal Conservation* 26(30): 1–19. DOI: 10.1007/s11852-022-00877-0

Kusumaningrum, P. B., and Haryono, E. 2020. The Potential of Delta Ecosystem in North Coast of Java in Reducing CO_2 Emissions. *IOP Conference Series: Earth and Environmental Science* 451(1): 012071. DOI: 10.1088/1755-1315/451/1/012071

Kusumaningtyas, M. A., Hutahaean, A. A., Fischer, H. W., Pérez-Mayo, M., Ransby, D., and Jennerjahn, T. C. 2019. Variability in the Organic Carbon Stocks, Sources, and Accumulation Rates of Indonesian Mangrove Ecosystems. *Estuarine, Coastal and Shelf Science* 218: 310–323. DOI: 10.1016/j.ecss.2018.12.007

Latifah, S., Gandaseca, S., Afifi, M., Prasetyo, A. R., Purnama, M. I., Kertalam, L. R. A., and Pratama, R. P. 2025. Three Decades of Forest Biomass Estimation in Southeast Asia: A Systematic Review of Field, Remote Sensing, and Machine Learning Approaches (1995–2025). *Jurnal Sylva Lestari* 13(3): 728–746. DOI: 10.23960/jsl.v13i3.1162

Ledheng, L., Naisumu, Y. G., and Binsasi, R. 2022. The Estimation of Biomass in *Rhizophora apiculata* and *Rhizophora mucronata* in Tuamese Village, North Central Timor Regency, East Nusa Tenggara Province. *Jurnal Sylva Lestari* 10(1): 39–48. DOI: 10.23960/jsl.v10i1.555

Lewis, R. R. 2005. Ecological Engineering for Successful Management and Restoration of Mangrove Forests. *Ecological Engineering* 24(4): 403–418. DOI: 10.1016/j.ecoleng.2004.10.003

Lewis, R. R., and Brown, B. 2014. *Ecological Mangrove Rehabilitation: A Field Manual for Practitioners*. Education.

Li, G., Zhuo, T., Ma, Y., Qi, X., and You, X. 2025. Global Mangrove Natural Regeneration Potential Assessment for Identifying Carbon Potentials of Natural Regeneration and Plantation. *Forest Ecology and Management* 598: 123195. DOI: 10.1016/j.foreco.2025.123195

Li, Z., Ma, L., Gou, D., Hong, Q., Fai, L., and Xiong, B. 2022. The Impact of Urban Development on Wetland Conservation. *Sustainability* 14(21): 13747. DOI: 10.3390/su142113747

Lovelock, C. E., Barbier, E., and Duarte, C. M. 2022. Tackling the Mangrove Restoration Challenge. *PLoS Biology* 10: e3001836. DOI: 10.1371/journal.pbio.3001836

Ma, S., Mistry, P., Badiou, P., Bansal, S., and Creed, I. F. 2025. Factors Regulating the Potential for Freshwater Mineral Soil Wetlands to Function as Natural Climate Solutions. *Wetlands* 45(11): 1–26. DOI: 10.1007/s13157-024-01893-6

Maina, J. M., Bosire, J. O., Kairo, J. G., Bandeira, S. O., Mangora, M. M., Macamo, C., Ralison, H., and Majambo, G. 2021. Identifying Global and Local Drivers of Change in Mangrove Cover and the Implications for Management. *Global Ecology and Biogeography* 30(10): 2057–2069. DOI: 10.1111/geb.13368

Messer, T. L., Douglas-Mankin, K. R., Nelson, N. G., and Etheridge, J. R. 2019. Wetland Ecosystem Resilience: Protecting and Restoring Valuable Ecosystems. *Transactions of the ASABE* 62(6): 1541–1543. DOI: 10.13031/trans.13578

Michaelowa, A., Michaelowa, K., Hermwille, L., and Espelage, A. 2022. Towards Net Zero: Making Baselines for International Carbon Markets Dynamic by Applying 'Ambition Coefficients'. *Climate Policy* 22(9–10): 1343–1355. DOI: 10.1080/14693062.2022.2108366

Mohan, M., Rue, H. A., Bajaj, S., Galgamuwa, G. A. P., Adrah, E., Aghai, M. M., Broadbent, E. N., Khadamkar, O., Sasmito, S. D., Roise, J., Doaemo, W., and Cardil, A. 2021. Afforestation, Reforestation and New Challenges from COVID-19: Thirty-Three Recommendations to Support Civil Society Organizations (CSOs). *Journal of Environmental Management* 287: 112277. DOI: 10.1016/j.jenvman.2021.112277

Murdiyarso, D., Arifanti, V. B., Sidik, F., Sillanpää, M., and Sasmito, S. D. 2022. Optimizing Carbon Stocks and Sedimentation in Indonesian Mangroves Under Different Management Regimes. In: *Wetland Carbon and Environmental Management*. 159–172. DOI: 10.1002/9781119639305.ch8

Murdiyarso, D., Krisnawati, H., Adinugroho, W. C., and Sasmito, S. D. 2023. Deriving Emission Factors for Mangrove Blue Carbon Ecosystem in Indonesia. *Carbon Balance and Management* 18: 12. DOI: 10.1186/s13021-023-00233-1

Murray, N. J., Phinn, S. R., DeWitt, M., Ferrari, R., Johnston, R., Lyons, M. B., Clinton, N., Thau, D., and Fuller, R. A. 2019. The Global Distribution and Trajectory of Tidal Flats. *Nature* 565(7738): 222–225. DOI: 10.1038/s41586-018-0805-8

Murray, N. J., Worthington, T. A., Bunting, P., Duce, S., Hagger, V., Lovelock, C. E., Lucas, R., Saunders, M. I., Sheaves, M., Spalding, M., Waltham, N. J., and Lyons, M. B. 2022. High-Resolution Mapping of Losses and Gains of Earth's Tidal Wetlands. *Science* 376(6594): 744–749. DOI: 10.1126/science.abm9583

Needelman, B. A., Emmer, I. M., Emmett-Mattox, S., Crooks, S., Megonigal, J. P., Myers, D., Oreska, M. P. J., and McGlathery, K. 2018. The Science and Policy of the Verified Carbon Standard Methodology for Tidal Wetland and Seagrass Restoration. *Estuaries and Coasts* 41: 2159–2171. DOI: 10.1007/s12237-018-0429-0

Nielsen, T., Baumert, N., Kander, A., Jiborn, M., and Kulionis, V. 2021. The Risk of Carbon Leakage in Global Climate Agreements. *International Environmental Agreements: Politics, Law and Economics* 21: 147–163. DOI: 10.1007/s10784-020-09507-2

Novita, N., Subarno, Lestari, N. S., Anshari, G. Z., Lugina, M., Yeo, S., Malik, A., Asyhari, A., Putra, C. A. S., Gangga, A., Ritonga, R. P., Albar, I., Djaenudin, D., Arifanti, V. B., Poor, E., Jupesta, J., Tryanto, D. H., Basuki, I., and Ellis, P. 2022. Natural Climate Solutions in Indonesia: Wetlands Are the Key to Achieve Indonesia's National Climate Commitment. *Environmental Research Letters* 17(11): 114045. DOI: 10.1088/1748-9326/ac9e0a

Potapov, P., Turubanova, S., Hansen, M. C., Tyukavina, A., Zalles, V., Khan, A., Song, X. P., Pickens, A., Shen, Q., and Cortez, J. 2022. Global Maps of Cropland Extent and Change Show Accelerated Cropland Expansion in the Twenty-First Century. *Nature Food* 3: 19–28. DOI: 10.1038/s43016-021-00429-z

Raw, J. L., Van Niekerk, L., Chauke, O., Mbatha, H., Riddin, T., and Adams, J. B. 2023. Blue Carbon Sinks in South Africa and the Need for Restoration to Enhance Carbon Sequestration. *Science of the Total Environment* 859: 160142. DOI: 10.1016/j.scitotenv.2022.160142

Richards, D. R., and Friess, D. A. 2016. Rates and Drivers of Mangrove Deforestation in Southeast Asia, 2000-2012. *Proceedings of the National Academy of Sciences* 113(2): 344–349. DOI: 10.1073/pnas.1510272113

Sagala, P. M., Bhomia, R. K., and Murdiyarso, D. 2024. Assessment of Coastal Vulnerability to Support Mangrove Restoration in the Northern Coast of Java, Indonesia. *Regional Studies in Marine Science* 70: 103383. DOI: 10.1016/j.rsma.2024.103383

Santika, T., Meijaard, E., Budiharta, S., Law, E. A., Kusworo, A., Hutabarat, J. A., Indrawan, T. P., Struebig, M., Raharjo, S., Huda, I., et al. 2017. Community Forest Management in Indonesia: Avoided Deforestation in the Context of Anthropogenic and Climate Complexities. *Global Environmental Change* 46: 60–71. DOI: 10.1016/j.gloenvcha.2017.08.002

Sasmito, S. D., Basyuni, M., Kridalaksana, A., Saragi-Sasmito, M. F., Lovelock, C. E., and Murdiyarso, D. 2023. Challenges and Opportunities for Achieving Sustainable Development Goals Through Restoration of Indonesia's Mangroves. *Nature Ecology and Evolution* 7(1): 62–70. DOI: 10.1038/s41559-022-01926-5

Sasmito, S. D., Kuzyakov, Y., Lubis, A. A., Murdiyarso, D., Hutley, L. B., Bachri, S., Friess, D. A., Martius, C., and Borchard, N. 2020. Organic Carbon Burial and Sources in Soils of Coastal Mudflat and Mangrove Ecosystems. *Catena* 187: 104414. DOI: 10.1016/j.catena.2019.104414

Schonlau, M., and Zou, R. Y. 2020. The Random Forest Algorithm for Statistical Learning. *Stata Journal* 20(1): 3–29. DOI: 10.1177/1536867X20909688

Sidik, F., Fernanda Adame, M., and Lovelock, C. E. 2019. Carbon Sequestration and Fluxes of Restored Mangroves in Abandoned Aquaculture Ponds. *Journal of the Indian Ocean Region* 15: 177–192. DOI: 10.1080/19480881.2019.1605659

Sidik, F., Neil, D., and Lovelock, C. E. 2016. Effect of High Sedimentation Rates on Surface Sediment Dynamics and Mangrove Growth in the Porong River, Indonesia. *Marine Pollution Bulletin* 107(1): 355–363. DOI: 10.1016/j.marpolbul.2016.02.048

Soebowo, E., Sarah, D., and Wibawa, S. 2023. Sedimentary Facies of the Cimanuk River Delta on the North Java Coastal Area and Its Geotechnical Properties. *IOP Conference Series: Earth and Environmental Science* 1163(1): 012014. DOI: 10.1088/1755-1315/1163/1/012014

Soto-Navarro, C., Ravilious, C., Arnell, A., De Lamo, X., Harfoot, M., Hill, S. L. L., Wearn, O. R., Santoro, M., Bouvet, A., Mermoz, S., Le Toan, T., Xia, J., Liu, S., Yuan, W., Spawn, S. A., Gibbs, H. K., Ferrier, S., Harwood, T., Alkemade, R., Schipper, A. M., Schmidt-Traub, G., Strassburg, B., Miles, L., Burgess, N. D., and Kapos, V. 2020. Mapping Co-Benefits for Carbon Storage and Biodiversity to Inform Conservation Policy and Action. *Philosophical Transactions of the Royal Society B: Biological Sciences* 375(1794): 20190128. DOI: 10.1098/rstb.2019.0128

Teo, H. C., Lechner, A. M., Sagala, S., and Campos-Arceiz, A. 2020. Environmental Impacts of Planned Capitals and Lessons for Indonesia's New Capital. *Land* 9(11): 438. DOI: 10.3390/land9110438

Teutli-Hernández, C., Herrera-Silveira, J. A., Comín, F. A., and López, M. M. 2019. Nurse Species Could Facilitate the Recruitment of Mangrove Seedlings After Hydrological Rehabilitation. *Ecological Engineering* 130: 263–270. DOI: 10.1016/j.ecoleng.2017.07.030

Tsujino, R., Yumoto, T., Kitamura, S., Djamaluddin, I., and Darnaedi, D. 2016. History of Forest Loss and Degradation in Indonesia. *Land Use Policy* 57: 335–347. DOI: 10.1016/j.landusepol.2016.05.034

Tun, Z. N., Dargusch, P., McMoran, D. J., McAlpine, C., and Hill, G. 2021. Patterns and Drivers of Deforestation and Forest Degradation in Myanmar. *Sustainability* 13(14): 7539. DOI: 10.3390/su13147539

Twomey, A. J., Nunez, K., Carr, J. A., Crooks, S., Friess, D. A., Glamore, W., Orr, M., Reef, R., Rogers, K., Waltham, N. J., and Lovelock, C. E. 2024. Planning Hydrological Restoration of Coastal Wetlands: Key Model Considerations and Solutions. *Science of the Total Environment* 915: 169881. DOI: 10.1016/j.scitotenv.2024.169881

van Bijsterveldt, C. E. J., Debrot, A. O., Bouma, T. J., Maulana, M. B., Pribadi, R., Schop, J., Tonneijck, F. H., and van Wesenbeeck, B. K. 2022. To Plant or Not to Plant: When Can Planting Facilitate Mangrove Restoration? *Frontiers in Environmental Science* 9: 690011. DOI: 10.3389/fenvs.2021.690011

van Bijsterveldt, C. E. J., van Wesenbeeck, B. K., van der Wal, D., Afiati, N., Pribadi, R., Brown, B., and Bouma, T. J. 2020. How to Restore Mangroves for Greenbelt Creation Along Eroding Coasts with Abandoned Aquaculture Ponds. *Estuarine, Coastal and Shelf Science* 235: 106576. DOI: 10.1016/j.ecss.2019.106576

van Zetten, R., van der Meulen, F., and IJff, S. 2023. Building with Nature at the Coast. *Nordic Journal of Botany* 2023(1): e03663. DOI: 10.1111/njb.03663

Vancutsem, C., Achard, F., Pekel, J. F., Vieilledent, G., Carboni, S., Simonetti, D., Gallego, J., Aragão, L. E. O. C., and Nasi, R. 2021. Long-Term (1990–2019) Monitoring of Forest Cover Changes in the Humid Tropics. *Science Advances* 7(10): 1–21. DOI: 10.1126/sciadv.abe1603

Vanderklift, M. A., Marcos-Martinez, R., Butler, J. R. A., Coleman, M., Lawrence, A., Prislan, H., Steven, A. D. L., and Thomas, S. 2019. Constraints and Opportunities for Market-Based

Finance for the Restoration and Protection of Blue Carbon Ecosystems. *Marine Policy* 107: 103429. DOI: 10.1016/j.marpol.2019.02.001

Verra. 2024. *VM0007 REDD+ Methodology Framework (REDD+MF)*, v1.8. Verified Carbon Standard. URL: https://verra.org/methodologies/vm0007-redd-methodology-framework-redd-mf-v1-8/

Wang, Q., Hu, Y., Chen, R., Zeng, W., and Cheng, Y. 2025. Do Forest Carbon Offset Projects Bring Biodiversity Conservation Co-Benefits? An Examination Based on Ecosystem Service Value. *Forests* 16(8): 1–19. DOI: 10.3390/f16081274

Xiong, Y., Liao, B., and Wang, F. 2018. Mangrove Vegetation Enhances Soil Carbon Storage Primarily Through *In Situ* Inputs Rather Than Increasing Allochthonous Sediments. *Marine Pollution Bulletin* 131: 378–385. DOI: 10.1016/j.marpolbul.2018.04.043

Yuwati, T. W., Rachmanadi, D., Pratiwi, Turjaman, M., Indrajaya, Y., Nugroho, H. Y. S. H., Qirom, M. A., Narendra, B. H., Winarno, B., Lestari, S., Santosa, P. B., Adi, R. N., Savitri, E., Putra, P. B., Wahyuningtyas, R. S., Prayudyaningsih, R., Halwany, W., Nasrul, B., Bastoni, and Mendham, D. 2021. Restoration of Degraded Tropical Peatland in Indonesia: A Review. *Land* 10(11): 1170. DOI: 10.3390/land10111170

Zeng, Y., Friess, D. A., Sarira, T. V., Siman, K., and Koh, L. P. 2021. Global Potential and Limits of Mangrove Blue Carbon for Climate Change Mitigation. *Current Biology* 31(8): 1737–1743.e3. DOI: 10.1016/j.cub.2021.01.070

Zhu, J. J., and Yan, B. 2022. Blue Carbon Sink Function and Carbon Neutrality Potential of Mangroves. *Science of the Total Environment* 822: 153438. DOI: 10.1016/j.scitotenv.2022.153438