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Research Article

Estimation of mangrove requirements for the absorption and storage of anthropogenic carbon emissions in the coastal area of Gresik Regency, East Java Province, Indonesia

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Abstract

Because they are able to absorb and store atmospheric carbon, mangrove ecosystems help combat climate change. Nevertheless, few studies combining spatial analysis of mangrove carbon stock estimation with estimation of the mangrove area required to offset anthropogenic emissions at the subdistrict level have been conducted in rapidly developing coastal regions. This research aimed to estimate the mangrove area needed to offset anthropogenic carbon emissions in the coastal areas of Gresik Regency, East Java Province, Indonesia. Transects and 10 × 10 m plots were used for field surveys conducted in seven coastal subdistricts. DBH measurements of mangroves were fitted to species-specific allometric equations to determine biomass and carbon stocks. A 2023 Landsat image was used to map mangrove distribution with the help of geographic information system (GIS)-based spatial analyses. Anthropogenic emissions were estimated based on available data for transport, livestock and poultry, liquefied petroleum gas (LPG) consumption, and electricity. The results showed that Gresik Subdistrict had the highest total emissions, at 6,795.91 t CO_2-eq yr^{-1}, and Ujungpangkah Subdistrict had the highest carbon stock value, at 264,803.16 t C. Spatial analysis showed that Kebomas, Panceng, and Gresik subdistricts needed additional mangrove areas of 52.07 ha, 50.21 ha, and 57.10 ha, respectively, to neutralize emissions under their current emission conditions. These results highlight the need for mangrove restoration as a crucial element of effective regional climate change mitigation and, thus, sustainable coastal management.

Key words: Carbon absorption, carbon emissions, climate change mitigation, Gresik Regency, mangrove

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Introduction

Climate change, one of the most serious global environmental challenges of the 21st century, could have major negative impacts on ecosystem stability and affect human health, food security, and the sustainability of human economic activities. The most recent Intergovernmental Panel on Climate Change report demonstrated that human activities, through the emission and buildup of greenhouse gases, essentially CO_2, have caused increases in global tem-

peratures (IPCC 2023). These increases in carbon emissions are mainly driven by fossil fuel burning, urbanization, industrialization, transportation activities, land-use change, and the degradation of natural ecosystems (Friedlingstein et al. 2019; Tong et al. 2019). This has led to the exacerbation of global warming at an unprecedented rate, stimulating a series of environmental issues, including sea-level rise, coastal erosion, extreme weather events, deterioration of the coastal environment, and biological extinctions (Bindoff et al. 2019; Menéndez et al. 2020). In Indonesia, the expansion of industrial areas and growing population density in coastal regions have resulted in increased anthropogenic carbon emissions and have also placed pressure on the physical conditions of coastal ecosystems (Riyanto et al. 2020). Over the past few years, nature-based mitigation strategies (NBS) have gained traction as a potentially critical tool for removing atmospheric carbon or decreasing its impacts alongside human-powered strategies (Griscom et al. 2017; Seddon et al. 2020). The mangrove forest ecosystem is one that plays a vital role in climate change mitigation. Mangroves occur in coastal wetlands along creeks and estuaries and form woodlands of trees in littoral areas influenced by tides. Hence, these ecosystems are commonly known as tidal forests, bay forests, brackish-water forests, or simply mangrove forests (Sodikin et al. 2018). Mangroves are blue carbon ecosystems, meaning that they can sequester large amounts of carbon from the atmosphere in both vegetation biomass and organic sediments over timescales ranging from decades to centuries (Murdiyarso et al. 2015; Macreadie et al. 2021). Specifically, it has been estimated that the carbon storage capacity of mangroves is higher than that of most terrestrial tropical forests because of the large amounts of soil organic carbon found within coastal sediments (Hamilton and Friess 2018; Sasmito et al. 2019). In addition to serving as carbon sinks, mangrove ecosystems provide multiple ecological services, such as natural coastal protection from abrasion and wave damping, habitat for coastal biota, pollutant filtration through their root systems, and buffers against climate change impacts, such as sea-level rise and coastal flooding (Friess et al. 2019; Goldberg et al. 2020). Globally, mangrove ecosystems have faced extensive changes that have created serious imbalances in associated coastal ecosystems (Sodikin et al. 2025). Indonesia has the largest mangrove area in the world; however, changes in mangrove ecosystem conditions still occur in some coastal areas of Indonesia because of anthropogenic pressure and environmental changes. Various studies have found that the causes of mangrove degradation in Indonesia differ; however, land conversion to fishponds, plantation expansion, coastal infrastructure development, and illegal logging are among the causes (Goldberg et al. 2020; Sasmito et al. 2023). In addition, increased urbanization and industrial activities in coastal zones accelerate changes in mangrove land cover, which reduce their carbon storage function (Kurniawansyah et al. 2023). Recent observations demonstrate that Indonesia experienced the loss of approximately 430,000 ha of mangroves through land conversion for aquaculture, agriculture, plantations, and coastal development between 1985 and 2019 (Ilman et al. 2023; Sudjana et al. 2024). The loss of mangrove area leads directly to increased carbon emissions, loss of habitat for coastal biota, reduced coastal protection, and increased vulnerability of coastal communities to abrasion, tidal flooding, and sea-level rise (Menéndez et al. 2020; Sasmito et al. 2023). Mangrove degradation can addi-

tionally reduce the global carbon sink capacity of coastal ecosystems, aggravating the effects of climate change (Macreadie et al. 2021). Although much research has been conducted on mangrove biomass and carbon stocks, the majority of previous studies mainly provided estimates of carbon storage, vegetation characteristics, or partial assessments of changes in mangrove areas. Studies that integrate inventories of anthropogenic carbon emissions with spatially based estimates of mangrove area requirements at regional and national scales remain limited (Zeng et al. 2021), especially in coastal areas with increasing urbanization and industrial activities.

Moreover, few existing studies have addressed the question of the extent to which preexisting mangrove ecosystems can mitigate carbon emissions resulting from human activities in coastal areas. As a result, scientific evidence that can be used to justify increasing mangrove areas as a carbon-offset strategy based on coastal ecosystems remains limited. Gresik Regency in East Java Province is also one of the strategic coastal areas in Indonesia where industrialization, urbanization, and transportation processes continue to develop rapidly. These developments can increase carbon emissions and add pressure to the sustainability of coastal ecosystems, such as mangroves. This study indicates that the economic valuation of mangrove ecosystem services in the eastern coastal area of Gresik Regency remains strong in supporting climate change mitigation and that the resource potential of mangroves can provide sufficient long-term benefits to meet the need for sustainable intergenerational carbon management, which can potentially be developed using adaptive approaches based on local wisdom. Nevertheless, few spatial studies have connected mangrove carbon sequestration capacity and total anthropogenic carbon emissions at the subdistrict scale in the coastal region of Gresik Regency. This study differs from previous studies using geographically distributed, field-based mangrove biomass estimates, spatial neighborhood analysis based on Landsat spectral data, and a comprehensive inventory of anthropogenic emissions to assess suitable additional mangrove areas (AMAs) needed to reach carbon neutrality (zero net greenhouse gas emissions relative to the average level of carbon offsets achieved within each LGA coastal subdistrict) across northern Australia. Therefore, this study delivers a novel scientific innovation through a spatial analysis framework to assess the potential of mangrove-based carbon offsets at the coastal administrative scale. The research findings are expected to provide a scientific basis for blue carbon management planning, create opportunities for mangrove rehabilitation and coastal climate change adaptation, and help Indonesia meet its Paris Agreement commitment to reducing greenhouse gas emissions.

Materials and methods

The study was conducted in the coastal area of Gresik Regency, East Java Province, Indonesia. The study area comprised seven coastal subdistricts: Panceng, Ujungpangkah, Bungah, Sidayu, Manyar, Gresik, and Kebomas. These subdistricts were selected because they represent the major mangrove ecosystems along the coast of Gresik Regency and exhibit varying levels of anthropogenic pressure and land-use change. The geographical location of the study area is presented in Fig. 1.

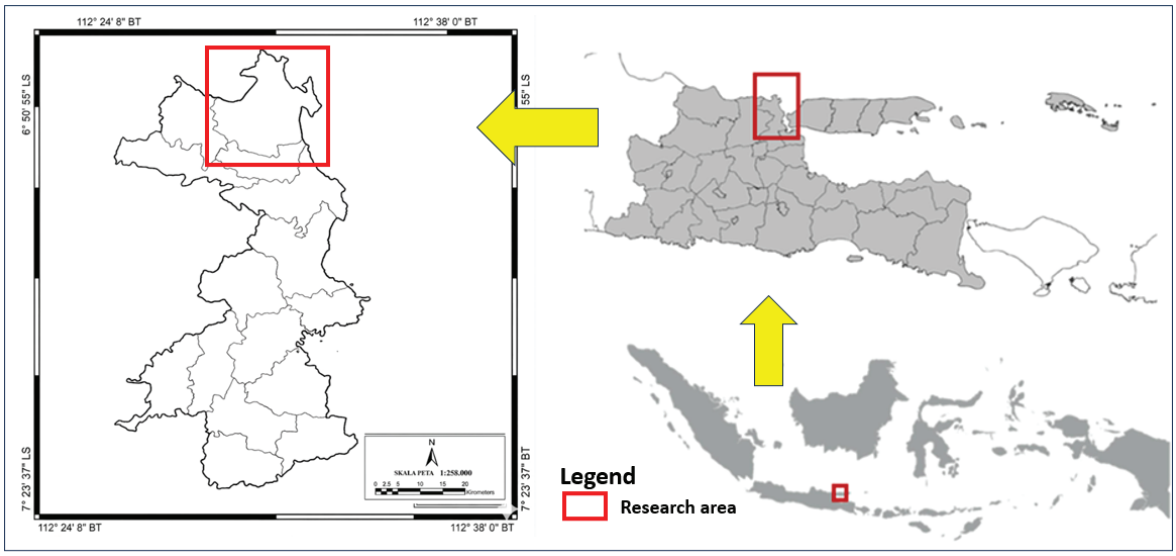

Figure 1. Research location.

The materials and equipment used in this study included a Global Positioning System (GPS), a field meter, an Indonesian mangrove identification guidebook, and 2023 Landsat satellite imagery. Mangrove distribution analysis was conducted using the Landsat 8 Level 2 image collection available on the Google Earth Engine (GEE) platform. The initial data-processing stage included image preprocessing through the application of a cloud-masking algorithm to remove cloud-contaminated pixels and cloud shadows, resulting in a 2023 annual composite image with optimal visual and radiometric quality. Next, the Normalized Difference Vegetation Index (NDVI) was automatically calculated for the entire study area using mathematical functions available on the GEE platform. The resulting NDVI values were then used as input variables in a machine learning-based mangrove cover classification process employing the Random Forest and Classification and Regression Trees (CART) algorithms. Training data were obtained from the coordinates of 10 × 10 m field observation plots determined using the transect method. The next stage was the image classification process to produce a mangrove distribution map for 2023. Validation of the classification results was carried out through accuracy testing using a confusion matrix calculated directly on the GEE platform.

The identification of mangrove vegetation and density, as well as the measurement of tree diameter, particularly diameter at breast height (DBH), was conducted using a combination of plot and transect methods. At each sampling station, a 100 m line was drawn perpendicular to the coast, and 10 × 10 m observation plots were intentionally placed along the line at 0, 50, and 100 m. The design of the observation plots is shown in Fig. 2.

Carbon emissions from population-related activities were measured by calculating liquefied petroleum gas (LPG) consumption, vehicle use, electricity consumption, and household waste production generated by residents of Gresik Regency. The formulas used to calculate the emissions are shown in Table 1.

Calculation of mangrove biomass

Mangrove biomass was calculated using allometric equations, as presented in Table 2.

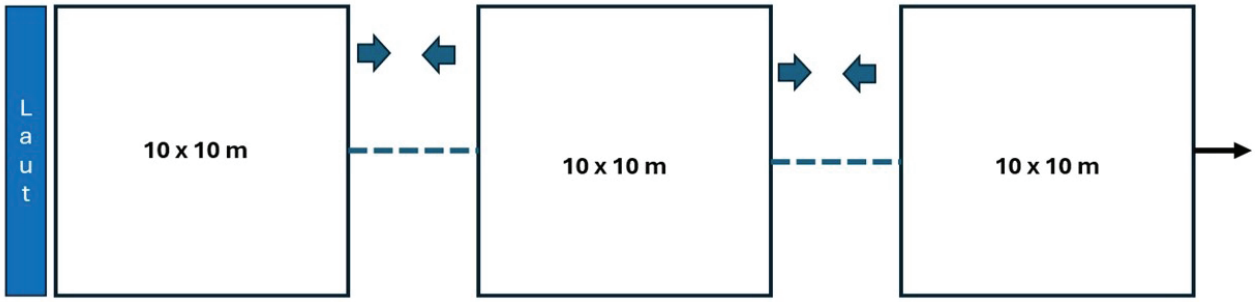

Figure 2. Design of the observation plots using a combination of path and checkered-line methods.

Table 1. Formulas for calculating carbon emissions from population activities.

Emission category	Formulation	Emission factor
Carbon emissions from population	Population × average per capita emission	2.5 tons CO_2 per year
Emissions from livestock	Number of livestock × average emission per livestock (in kg CH_4 per year)	20 kg CH_2 per year
Carbon emissions from LPG consumption	Amount of gas consumed × emission factor (kg CO_2/unit of gas)	3 kg CO_2 per kg LPG
Emissions from vehicle use	Fuel consumption (liters) × gasoline emission factor (kg CO_2/liter)	Gasoline = 2.31 kg CO_2 Diesel = 2.68 kg CO_2
Emissions from electricity use	Energy consumption (kWh) × electricity emission factor (kg CO_2/kWh)	kg CO_2 per kWh

Table 2. Allometric equations for several mangrove species and genera.

Mangrove species/genus	Allometric equation	Reference
Avicennia sp.	$B = 0.251\rho (D)^{2.46}$	Komiyama et al. 2005
Avicennia marina	$B = 0.1848 (D)^{2.3624}$	Dharmawan and Siregar 2008
Avicennia alba	$B = 0.079211 (D)^{2.470895}$	Tue et al. 2014
Ceriops tagal	$B = 0.251\rho (D)^{2.46}$	Komiyama et al. 2005
Lumnitzera littorea	$B = 0.251\rho (D)^{2.46}$	Komiyama et al. 2005
Rhizophora apiculata	$B = 0.043 (D)^{2.63}$	Amira 2008
Rhizophora mucronata	$B = 0.1466 (D)^{2.3136}$	Dharmawan and Siregar 2008
Sonneratia alba	$B = 0.3841 (D)^{2.101*}\rho$	Kauffman et al. 2014
Xylocarpus granatum	$B = 0.1832 (D)^{2.21}$	Tarlan 2008

Description:
B = biomass (kg/m^2)
ρ = plant density (g/cm^3)
D = diameter at breast height (cm)

Calculation of carbon availability

Carbon availability was calculated using the following formula:

$$C = 0.5 \times W,$$

where
C: carbon content (Kg/m^2)
W: biomass (Kg)

Carbon dioxide absorption rate in mangroves

To calculate mangrove carbon absorption, carbon stocks were converted into total CO_2 using the relative atomic mass ratio of CO_2 to C, which was formulated as follows:

$$CO_2 = Cn \times 3.67,$$

where

Cn: carbon stock

3.67: conversion factor based on the atomic weights of C and O, where C = 12 and O = 16; $CO_2 = (1 \times 12) + (2 \times 16) = 44$, and the conversion factor is 44/12 = 3.67.

Carbon balance data analysis

The comparison was based on net carbon storage, annualized gross carbon uptake, and total CO_2 emissions. This method attempts to assess the ability of the ecosystem to counterbalance greenhouse gas emissions released into the atmosphere during the same period. Thus, this analysis can represent the equilibrium of a region in which its annual carbon absorption capacity equals the total amount of carbon emissions produced. The calculation was performed using the following formula:

$$NYA_i = TE_i - TCU_i$$

Description:

NYA_i = not yet absorbed (remaining emissions that have not been absorbed) in subdistrict i.

TE_i = total emissions (total carbon emissions) in subdistrict i.

TCU_i = total carbon uptake (total carbon absorption) in subdistrict i.

Interpretation:

If $NYA_i < 0$ (negative), the region is experiencing an absorption surplus (the absorption capacity is greater than the emissions; sufficient).

If $NYA_i > 0$ (positive), the region is experiencing an absorption deficit (the emissions are greater than the absorption capacity; insufficient).

Results

Carbon emissions generated by the activities of residents in the coastal areas of Gresik Regency

Based on the calculation results for population size, livestock numbers, LPG consumption, motor vehicle use, and electricity consumption, the emission values for the coastal areas of Gresik Regency are presented in Table 3.

The distribution of carbon emissions among the coastal subdistricts of Gresik Regency varies considerably because of differences in the levels of urbanization, economic activities, land-use patterns, and transportation intensity (Table 3). The results indicate that Gresik Subdistrict generated the highest total carbon emissions, reaching 6,795.91 t CO_2-eq yr^{-1}. This was primarily driven by emissions from the transportation sector, which contributed 5,712.52 t CO_2-eq yr^{-1}, accounting for

Table 3. Carbon emissions in the coastal areas of Gresik Regency.

Subdistrict	Population (t CO_2-eq yr^{-1})	Livestock (t CO_2-eq yr^{-1})	LPG consumption (t CO_2-eq yr^{-1})	Transportation (t CO_2-eq yr^{-1})	Electricity (t CO_2-eq yr^{-1})	Total emissions (t CO_2-eq yr^{-1})
Ujungpangkah	165.50	1,382.22	0.24	1,163.87	38.50	2,750.33
Bungah	217.55	1,150.49	0.31	1,483.80	49.09	2,901.24
Manyar	375.92	1,081.16	0.53	2,541.82	84.09	4,083.52
Sidayu	139.50	1,254.82	0.20	949.38	31.41	2,375.30
Kebomas	356.90	2,326.26	0.51	2,455.42	81.23	5,220.32
Panceng	167.49	1,568.09	0.78	3,731.07	123.43	5,590.86
Gresik	256.44	636.79	1.20	5,712.52	188.98	6,795.91

approximately 84% of the total emissions in the subdistrict. The dominance of transportation emissions reflects the high level of urban mobility, logistics activities, and motorized vehicle density within the subdistrict. According to the East Java Central Statistics Agency (2023), the number of registered motor vehicles in Gresik Regency reached 801,969 units, indicating that rapid growth in vehicle ownership is a major contributor to increasing carbon emissions in the coastal region. These findings are consistent with Kim et al. (2021), who reported that coastal urbanization accelerates energy consumption and carbon emissions through intensified human activities. Likewise, Ribeiro et al. (2019) demonstrated that increasing urban population density is closely associated with higher carbon emissions because of greater energy demand and economic activities.

Among all coastal subdistricts, Manyar recorded the highest emissions from the population sector, amounting to 375.92 t CO_2-eq yr^{-1}. In addition, Manyar also exhibited relatively high emissions from transportation (2,541.82 t CO_2-eq yr^{-1}), electricity consumption (84.09 t CO_2-eq yr^{-1}), and livestock (1,081.16 t CO_2-eq yr^{-1}), resulting in total emissions of 4,083.52 t CO_2-eq yr^{-1}. These findings suggest that carbon emissions in Manyar are influenced not only by population size but also by rapid suburban development, industrial expansion, warehousing activities, and increasing household energy consumption. As a rapidly developing peri-urban area, Manyar has experienced substantial growth in residential, industrial, and commercial infrastructure, leading to increased electricity demand, domestic fuel consumption, and transportation activities. Such characteristics are commonly associated with higher household and transportation-related emissions in suburban regions.

In contrast, Sidayu Subdistrict produced the lowest total emissions, amounting to 2,375.30 t CO_2-eq yr^{-1}. The relatively low emissions can be attributed to its dominant traditional economic activities, including small-scale fisheries and agriculture, combined with low-density settlements and limited industrial development. Transportation emissions in Sidayu were also comparatively low (949.38 t CO_2-eq yr^{-1}), while electricity-related emissions reached only 31.41 t CO_2-eq yr^{-1}, reflecting lower energy consumption than in the more urbanized subdistricts. These conditions indicate that coastal rural areas with limited industrialization and lower fossil fuel consumption retain significant potential for implementing low-carbon development strategies through sustainable spatial planning and climate change mitigation initiatives. In general, the spatial variation in carbon emissions in the coastal areas of Gresik Regency shows a strong relationship between urbanization, regional economic structure, land-use pat-

terns, and local carbon emissions. Subdistricts that are built around industry, trade, and transportation have higher emissions than those that still maintain their traditional agricultural and fishing functions. Thus, emission-reduction mechanisms in coastal areas should include low-emission transportation systems, energy savings in the domestic sector, compact city form, and the conservation of coastal ecosystems as natural carbon pools, such as mangroves.

Mangrove carbon sequestration and carbon storage in the coastal area of Gresik Regency

Coastal mangroves in Gresik Regency are scattered across almost every subdistrict that directly adjoins the coastline, based on the results of the 2023 Landsat imagery data analysis. Fig. 3 shows the spatial distribution of mangroves in the coastal area of Gresik Regency.

Based on Fig. 3, Ujungpangkah Subdistrict has a large mangrove area of 1,615.54 ha, whereas Kebomas Subdistrict has only a small mangrove area of approximately 0.75 ha. Kebomas itself is one of the most developed areas, where much of the mangrove land has been repurposed. Thirteen mangrove species were identified based on field observations in the coastal areas of Gresik, including *Rhizophora mucronata*, *Rhizophora apiculata*, *Avicennia lanata*, *Avicennia marina*, *Bruguiera cylindrica*, *Sonneratia alba*, *Sonneratia caseolaris*, *Xylocarpus moluccensis*, *Xylocarpus mekongensis*, *Ceriops tagal*, *Acanthus ilicifolius*, *Acanthus ebracteatus*, and *Excoecaria agallocha*. *Avicennia* and *Rhizophora* are the dominant mangrove genera in the coastal area of Gresik Regency. Ujungpangkah Subdistrict has a relatively extensive mangrove area because it is positioned at the estuary of the Bengawan Solo River, which has high sedimentation and continuous formation of new land through the accretion process (Sodikin et al. 2024). It is also responsible for an annual suspended load of 1,703.014 t in this area. Fig. 4 shows the biomass of each type of mangrove vegetation.

The spatial distribution of mangrove biomass varied considerably among the coastal subdistricts of Gresik Regency. Bungah Subdistrict had the highest biomass accumulation, at 378.77 t ha^{-1}, whereas Ujungpangkah Subdistrict had 327.82 t ha^{-1}, as shown in Fig. 4; several other subdistricts had biomass accumulation below 200 t ha^{-1}. Biomass was substantially lower in several suburban and industrial subdistricts, ranging from 64.86 t ha^{-1} in Gresik Subdistrict to 60.68 t ha^{-1} in Panceng Subdistrict. The lowest biomass value was recorded in Kebomas Subdistrict, at only 54.64 t ha^{-1}, following a similar pattern to the carbon stock and sequestration values and reflecting the estimated variability among areas. Based on the data obtained from the analysis, the average carbon stock in the coastal areas of Gresik Regency ranged from a minimum of 27.32 t C ha^{-1} to a maximum of 189.35 t C ha^{-1}. The spatial distribution and parameters of this potential carbon sequestration are shown in Table 4.

According to Table 4, substantial spatial variation was observed in mangrove area, carbon stock, and carbon sequestration among the coastal subdistricts of Gresik Regency. Although Bungah Subdistrict recorded the highest carbon stock density (189.35 t C ha^{-1}) and carbon sequestration capacity (694.91 t CO_2 ha^{-1}), Ujungpangkah Subdistrict had the largest total carbon stock (264,803.16 t C) and total carbon sequestration (971,827.60 t CO_2 yr^{-1}). This was primarily attributable to its extensive mangrove area (1,615.54 ha), which is considerably

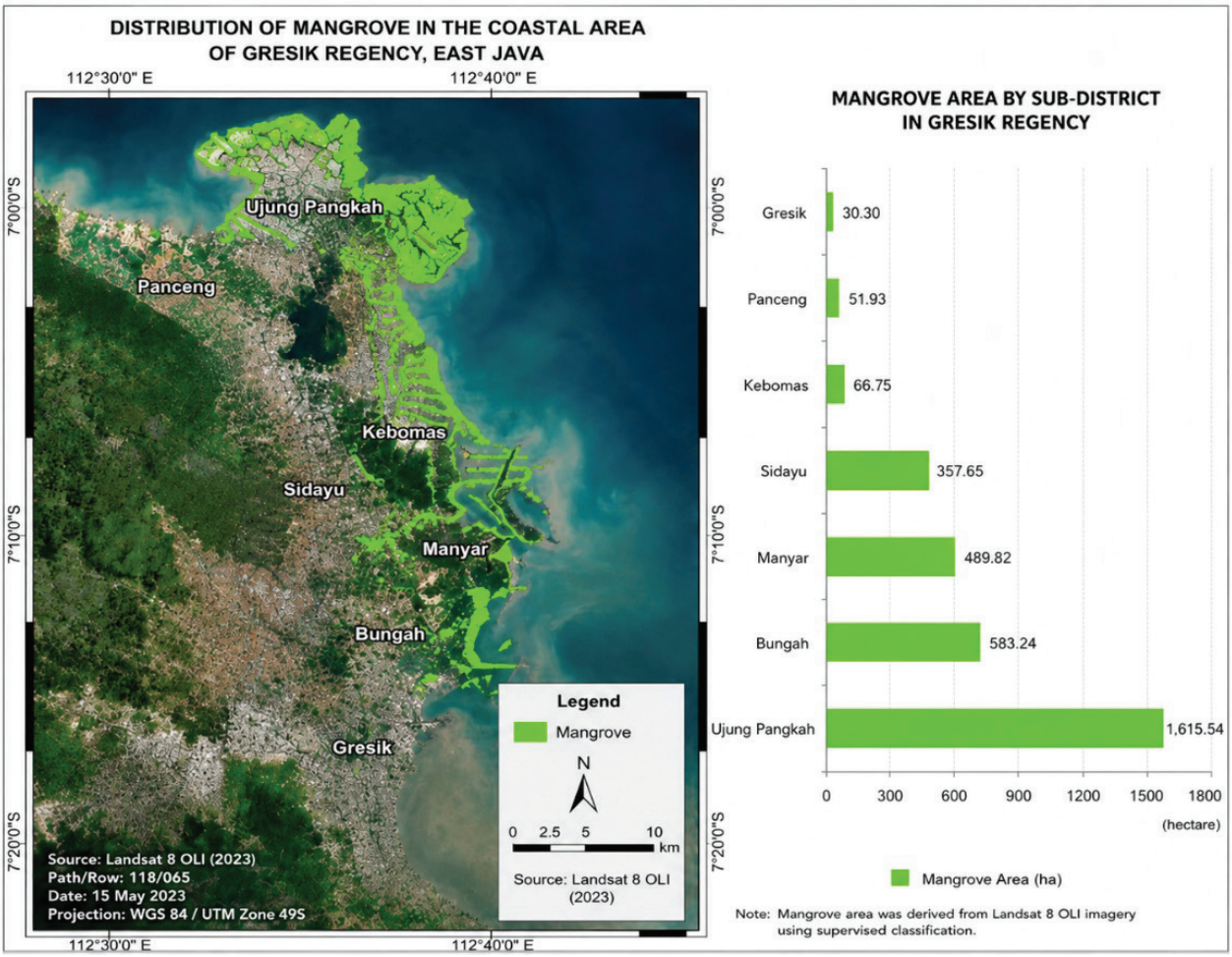

Figure 3. Distribution of mangroves in the coastal areas of Gresik Regency in 2023.

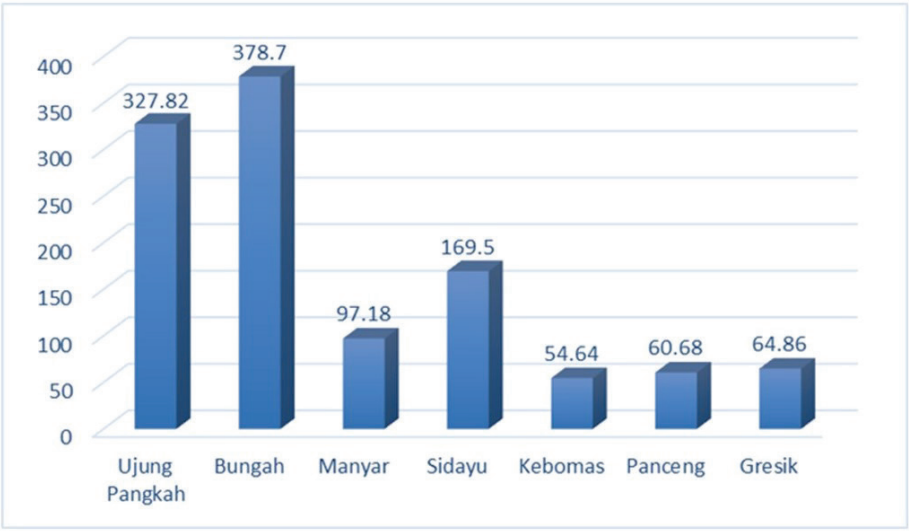

Figure 4. Diagram of the amount of biomass in the coastal area of Gresik Regency.

larger than those of the other coastal subdistricts. These findings indicate that while carbon stock density reflects the carbon storage capacity per unit area, the total amount of carbon stored and sequestered is strongly influenced by

the overall extent of mangrove forests. Similar findings have been reported by Alongi (2018), who demonstrated that tropical mangrove ecosystems represent some of the most efficient coastal carbon sinks because of their high biomass accumulation and long-term carbon storage capacity. Rovai et al. (2018) reported that mangrove extent is one of the primary predictors of total ecosystem carbon stocks at regional and global scales. An interesting pattern was observed between Manyar and Sidayu subdistricts. Although Manyar had a larger mangrove area (407.52 ha) than Sidayu (277.05 ha), its total carbon stock (19,801.40 t C) and total carbon sequestration (72,671.13 t CO_2 yr^{-1}) were lower than those of Sidayu, which stored 23,479.99 t C and sequestered 86,171.55 t CO_2 yr^{-1}. This result suggests that mangrove area alone does not determine total carbon storage capacity. Instead, stand structure, vegetation density, species composition, and biomass productivity also play important roles in determining ecosystem carbon storage and sequestration potential.

Sufficiency of mangrove vegetation to store and absorb carbon emissions in the coastal areas of Gresik Regency

Based on the results of a comparative analysis between the carbon storage capacity and carbon emission absorption capacity of mangrove vegetation in the coastal area of Gresik Regency, the following findings were obtained. Table 5 displays the total carbon stored, total carbon uptake, and total emissions resulting from population activities in each subdistrict. In addition, this table also presents the amount of emissions that have not been absorbed or stored, as well as the status of the adequacy of mangrove vegetation in absorbing and storing carbon emissions.

A comparative analysis of anthropogenic carbon emissions and the carbon storage and sequestration capacity of mangrove ecosystems in Gresik Regency revealed considerable spatial variation in the ability of coastal subdistricts to offset carbon emissions (Table 5). The results indicate that Ujungpangkah, Bungah, Manyar, and Sidayu possess sufficient mangrove ecosystems to function as net carbon sinks. Among these, Ujungpangkah Subdistrict exhibited the greatest carbon storage and sequestration capacity, with a total carbon storage of 264,803.16 t C and annual carbon sequestration of 971,827.60 t CO_2 yr^{-1}. In comparison, the annual anthropogenic carbon emissions in this subdistrict were only 2,750.34 t CO_2-eq yr^{-1}, resulting in a net CO_2 balance of −969,077.26 t CO_2-eq yr^{-1}, which indicates that the annual carbon sequestration capacity of the mangrove ecosystems substantially exceeded local anthropogenic carbon emissions. These findings demonstrate that extensive and well-preserved mangrove forests can provide significant climate change mitigation services by effectively offsetting carbon emissions. Similar findings were reported by Rovai et al. (2018), who demonstrated that tropical mangrove ecosystems possess exceptional carbon storage and sequestration capacities because of high biomass productivity and long-term carbon accumulation within coastal sediments.

In contrast, the greatest carbon sequestration deficits were observed in the more urbanized and industrialized subdistricts of Kebomas, Panceng, and Gresik, all of which were classified as having insufficient mangrove capacity to offset anthropogenic carbon emissions (Table 5). Among these, Gresik Subdistrict recorded the highest annual anthropogenic carbon emissions, reaching 6,795.91 t CO_2-eq yr^{-1}, whereas its existing mangrove ecosystems stored

Table 4. Total carbon storage and uptake from mangroves in the coastal area of Gresik Regency.

Subdistrict	Area (ha)	Carbon stock (t C ha^{-1})	Carbon sequestration (t CO_2 ha^{-1})	Total carbon stock (t C)	Annual carbon sequestration (t CO_2 yr^{-1})
Ujungpangkah	1,615.54	163.91	601.55	264,803.16	971,827.60
Bungah	458.54	189.35	694.91	86,824.55	318,646.09
Manyar	407.52	48.59	178.33	19,801.40	72,671.13
Sidayu	277.05	84.75	311.03	23,479.99	86,171.55
Kebomas	0.75	27.32	100.26	20.49	75.20
Panceng	15.13	30.34	111.35	459.04	1,684.69
Gresik	10.67	32.43	119.02	346.03	1,269.92

Table 5. Sufficiency of mangrove vegetation to store and absorb carbon emissions in the coastal areas of Gresik Regency.

Subdistrict	Total carbon stored (t C)	Annual carbon sequestration (t CO_2 yr^{-1})	Annual carbon emissions (t CO_2-eq yr^{-1})	Net CO_2 balance (t CO_2-eq yr^{-1})	Carbon storage balance (t C)	Status
Ujungpangkah	264,803.16	971,827.60	2,750.34	−969,077.26	−262,052.82	Sufficient
Bungah	86,824.55	318,646.09	2,901.24	−315,744.86	−83,923.31	Sufficient
Manyar	19,801.40	72,671.13	4,083.52	−68,587.61	−15,717.88	Sufficient
Sidayu	23,479.99	86,171.55	2,375.30	−83,796.25	−21,104.68	Sufficient
Kebomas	20.49	75.20	5,220.32	5,145.12	5,199.83	Insufficient
Panceng	459.04	1,684.69	5,590.86	3,906.17	5,131.82	Insufficient
Gresik	346.03	1,269.92	6,795.91	5,525.99	6,449.88	Insufficient

only 346.03 t C and provided annual carbon sequestration of 1,269.92 t CO_2 yr^{-1}. Consequently, the subdistrict exhibited a net CO_2 balance of 5,525.99 t CO_2-eq yr^{-1}, indicating that this amount of annual carbon emissions could not be offset by the existing mangrove ecosystem. In addition, the carbon storage balance reached 6,449.88 t C, reflecting the substantial disparity between the existing mangrove carbon stock and the magnitude of anthropogenic carbon emissions. This ecological imbalance suggests that rapid urbanization, industrial expansion, and increasing energy consumption have reduced the capacity of mangrove ecosystems to mitigate greenhouse gas emissions effectively. Similar observations were reported by Goldberg et al. (2020), who demonstrated that mangrove degradation and fragmentation resulting from coastal urbanization significantly diminish ecosystem carbon storage and carbon sequestration capacity, thereby increasing the vulnerability of coastal regions to climate change.

The spatial imbalance between carbon-surplus and ecological-deficit areas suggests that, although Gresik Regency still indicates an overall carbon surplus—largely attributable to the high contribution of the Ujungpangkah Subdistrict conservation area—the increasing accumulation of unabsorbed emissions in urban and suburban zones represents a loss of coastal ecosystem function driven by ongoing habitat fragmentation and land conversion. This condition strongly indicates the need for spatially based carbon management policies implemented through mangrove restoration, control of coastal industrial areas, and strengthened conservation of areas with high carbon absorption potential. An advantage of blue carbon-based mitigation is that it helps protect coastal environmental resilience while reducing regional carbon emissions sustainably.

Estimated mangrove area required to offset carbon emissions in the coastal area of Gresik Regency, East Java

The analysis indicated that three coastal subdistricts—Kebomas, Panceng, and Gresik—still require additional mangrove areas to offset their anthropogenic carbon emissions. The estimated additional mangrove area required in each subdistrict was determined by comparing total carbon emissions with the existing carbon sequestration capacity of mangrove ecosystems. Detailed estimates of the required mangrove area are presented in Table 6.

The approach used to calculate the ideal carbon credit mitigation requirements in the three subdistricts of Gresik Regency—Kebomas, Panceng, and Gresik, which are ecologically deficient—shows a substantial spatial gap between the existing mangrove coverage and the ideal target. Based on the data in Table 6, Kebomas Subdistrict shows the most urgent need for restoration. With an existing area of only 0.75 ha, this region requires an additional area of 190.33 ha to reach the ideal carbon storage area of 191.08 ha, as well as an additional 51.32 ha to optimize its annual absorption capacity. A similar pattern of substantial deficits was also observed in Panceng and Gresik subdistricts. Panceng Subdistrict requires an additional 169.14 ha beyond its current area of 15.13 ha to reach the ideal target of 184.27 ha, whereas Gresik Subdistrict requires the largest additional expansion, at 198.89 ha, to offset its high urban emission load. This projection confirms that, to create a carbon assimilation balance in the urban-industrial zone, environmental recovery policies should no longer focus solely on passive conservation but also on landscape reconstruction through reforestation based on minimum area targets to restore carbon-sink functions lost because of anthropogenic pressures (Alongi 2018; Friess et al. 2019). This need for area expansion is consistent with the findings of Taillardat et al. (2018), who suggested that the global mitigation potential of mangrove ecosystems largely relies on minimizing deforestation while restoring the spatial integrity of vegetation. In relation to this, Ketaren (2023) stressed the importance of mangrove density and spatial coverage in enabling mangrove ecosystems to serve as an effective tool for monitoring greenhouse gas (GHG) emissions at a regional scale. Either way, given these high emissions in urban areas, rehabilitation approaches should focus on planting species with higher rates of growth and sequestration.

Table 6. Estimated additional mangrove area required to offset anthropogenic carbon emissions in the coastal area of Gresik Regency.

Subdistrict	Existing mangrove area (ha)	Required area for carbon storage (ha)	Required area for CO_2 sequestration (ha)	Total required mangrove area for carbon storage (ha)	Total required mangrove area for CO_2 sequestration (ha)
Kebomas	0.75	190.33	51.32	191.08	52.07
Panceng	15.13	169.14	35.08	184.27	50.21
Gresik	10.67	198.89	46.43	209.56	57.1

Conclusion

This study demonstrates a clear spatial disparity between anthropogenic carbon emissions and the carbon storage and sequestration capacities of mangrove ecosystems in the coastal area of Gresik Regency. Coastal subdistricts

with extensive and relatively well-preserved mangrove forests, particularly Ujungpangkah and Bungah, exhibited the highest carbon stock and carbon sequestration capacities, indicating their important role as natural carbon sinks. In contrast, the more urbanized and industrialized subdistricts, namely Gresik, Kebomas, and Panceng, showed insufficient mangrove capacity to offset anthropogenic carbon emissions because of limited mangrove extent and high emission levels.

The analysis further indicates that conserving the remaining mangrove forests alone is insufficient to achieve regional carbon balance in these subdistricts. Additional mangrove restoration and expansion are required to increase carbon sequestration capacity and offset anthropogenic carbon emissions. Therefore, the estimated mangrove area identified in this study provides a practical basis for planning site-specific mangrove restoration and supporting evidence-based blue carbon management strategies.

Overall, these findings highlight the importance of integrating mangrove conservation and restoration into regional climate change mitigation policies and sustainable coastal management to strengthen ecosystem resilience and contribute to Indonesia's greenhouse gas emission reduction targets.

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Additional information

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The authors have declared that no competing interests exist.

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Data availability

All of the data that support the findings of this study are available in the main text.