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Potential carbon content by mangrove forest along the coastline of trenggalek regency

Muhammad Yunan Fahmi[1], Andik Dwi Muttaqin[1*], Rizqi Eka Ardiansyah[1], Retno Anggreini[1], Syafira Salma Luna Widyawati[1]

[1] Department of Marine Science, Faculty of Science and Technology, UIN Sunan Ampel Surabaya, Gunung Anyar, Surabaya 60294, Indonesia

* Corresponding author's e-mail: andik.muttaqin@uinsa.ac.id

ABSTRACT

This study focuses on estimating carbon stocks in Trenggalek's forest and coastal areas, assessing their contributions to carbon sequestration and climate change mitigation. The study was conducted in two phases. First, a field-based estimation of carbon stocks was carried out for both mangrove and plantation forests, with 72 sample plots (10 × 10 m) laid out systematically. Above-ground biomass was calculated using an allometric model, while below-ground biomass was based on ratios of above-to-below ground biomass. Results showed that mangrove forests had an average carbon stock of 12.80, 23.45, and 76.15 tons/ha in above-ground biomass, below-ground biomass, and soil organic carbon, respectively, while plantation forests had higher values of 77.05, 114.2, and 75.76 tons/ha. The potential CO_2 absorption also varied, with mangrove forests showing lower values due to their smaller biomass compared to plantation forests, though the mangroves had higher soil organic carbon storage. In parallel, the study evaluated the carbon uptake potential of coastal waters in Trenggalek Regency, based on primary productivity from phytoplankton. Sampling was done purposively, and carbon sequestration potential was calculated using the dark-light bottle method. The waters exhibited a mesotrophic state with primary productivity values ranging from 150–950 mgC/m³/day. The carbon uptake potential varied across stations from 3.69 to 23.35 tonsC/m²/year, indicating that coastal waters in Trenggalek Regency acts as a carbon sink, driven by a positive net primary productivity (NPP). Additionally, remote sensing techniques were used to analyze changes in land cover and carbon stock in Trenggalek's coastal areas over time, using temporal Landsat data and Google Earth Engine. From 2001 to 2023, the carbon stock declined from 4,126,833.64 tons to 3,769,725.32 tons, but a slight increase is predicted by 2034 to 3,778,537.21 tons. These findings highlight the importance of field data in accurately predicting future carbon stock estimates, enhancing the understanding of forest and marine ecosystems roles in climate change mitigation and the importance of sustainable land use management to preserve carbon stock potential in Trenggalek's ecosystems. The current research provides new insights into carbon stock estimation in the mangrove and plantation forests of Trenggalek, Indonesia. One of the key findings revealed for the first time is that, while mangrove forests have lower aboveground and belowground biomass compared to plantation forests, they possess significantly higher soil organic carbon content. This is primarily due to mangroves' ability to trap carbon for longer periods in the soil due to anaerobic conditions. Moreover, the study highlights the carbon uptake potential of Trenggalek's coastal waters, which act as a carbon sink, with primary productivity driven by phytoplankton. This is among the first studies to quantify the combined carbon sequestration from both forest ecosystems and coastal waters in Trenggalek, showing how these ecosystems contribute collectively to climate change mitigation.

Keywords: biomass, carbon sequestration, carbon stock, land use change, mangrove, phytoplankton, soil.

INTRODUCTION

Carbon dioxide is a major greenhouse gas, contributing approximately three-quarters of global emissions and playing a significant role in climate change. Since the onset of the industrial revolution, carbon emissions have surged due to human activities, including the combustion of fossil fuels for energy and manufacturing, intentional wildfires, and inefficient transportation services. Carbon emissions have increased by 40% annually from 1750 to 2011 (Zhang et al., 2008). This study aims to fill the gap in understanding how specific ecosystems contribute to carbon sequestration, particularly in the context of Trenggalek Forest and coastal ecosystems. By investigating the carbon stock potential of these ecosystems, this research seeks to provide valuable insights into their role in mitigating climate change and informing conservation strategies.

As carbon emissions continue to grow each year, scientists predict that cumulative carbon dioxide levels could reach 467–555 ppm, potentially causing the Earth's average surface temperature to rise between 2 and 4.2 °C (Rahman et al., 2015). Data collected from 13 climate stations in Indonesia provide evidence of climate change occurring on both the east and west coasts. The west side of Indonesia has experienced temperature increases ranging from 0.5 to 1.1 °C and 0.6 to 2.3 °C, while the east side has seen rises between 0.2 and 0.4 °C and 0.2 and 0.7 °C (Aldrian, 2007). The Earth faces a significant threat if temperature increases and climate change continue annually.

This issue can lead to numerous disasters, beginning with extreme climate change that impacts polar ice sheets, resulting in excessive melting and contributing to sea level rise. In 2014, Mengpin Ge reported that cumulative greenhouse gas emissions in Indonesia from 1990 to 2011 accounted for 4% of global emissions, making Indonesia the world's sixth-largest emitter. However, by 2018, the country had dropped to the eighth position among the top ten global emitters, with cumulative emissions of 2.03% of the world total (Friedrich et al., 2020).

Intensive and unsustainable land use accounts for the second-largest share of humanity's carbon emissions, following the burning of fossil fuels. Alterations in land use have significant consequences for carbon emissions production levels. The Dewan Nasional Perubahan Iklim (DNPI), Indonesia's national council established to coordinate climate change mitigation efforts, reported that approximately 85% of Indonesia's emissions in 2005 were caused by land-use-related activities. Changes in land use, such as converting forests into residential areas, industrial complexes, and agricultural land, lead to increased carbon emissions released into the atmosphere. This transformation reduces the forest's ability to act as a carbon sink due to deforestation (IPCC, 2014). Land use transitions have a dominant influence, particularly on marine environments, which serve as the largest long-term carbon sinks. Approximately 93% of carbon emissions are stored in marine environments, and research by Hansell et al. (2013) estimated that inorganic carbon burial in coastal sediment environments is around 150 PgC per year. In addition to the important role of the water column as a carbon sink and coastal sediments as sites for inorganic carbon burial, marine ecosystems contribute significantly to the cycling and storage of carbon over short, medium, and long periods.

Notably, Hong et al. (2016) reported that mangrove forests are among the most productive in terms of carbon storage, being 3 to 5 times more effective than other types of forests in tropical regions. The global carbon stock stored by mangrove forests is estimated at 954 MgC per hectare, surpassing the carbon stocks found in tropical rainforests, peat swamps, salt marshes, and seagrass meadows (Hong et al., 2016). Mangrove trees capture carbon dioxide from the atmosphere and convert it into organic carbon, which is stored as biomass throughout the tree (Hong et al., 2016). Furthermore, the soil in mangrove ecosystems acts as a significant carbon reservoir, which can be critical for assessing the long-term impacts of climate change, potentially accounting for 50% to 90% of the total carbon stored (Hong et al., 2016).

Mangroves contribute 3–4% of global carbon capture within the world's tropical forest area, despite comprising only 1% of the total global forest cover (Aye et al., 2022). This highlights the important role mangrove forests play in managing the world's climate. The loss of mangrove forests has been reported to contribute to 10% of global carbon emissions due to the destruction of marine ecosystems (Murdiyarso et al., 2015). In addition to their function as carbon sinks through photosynthesis, phytoplankton also play a crucial role in carbon capture. Similar to mangrove ecosystems, phytoplankton can simultaneously take up and store carbon through photosynthesis. Studies have shown that phytoplankton are key players in the global carbon cycle, contributing approximately half of global primary productivity.

The organic sequestration of CO_2 in oceans occurs through phytoplankton, which convert atmospheric carbon into organic matter via photosynthesis. This organic matter is then transferred along the food chain to consumer fish and zooplankton. Primary productivity refers to the rate at which energy is transformed into organic materials within a specific region or ecosystem. This transformation is carried out by autotrophic organisms that convert solar or chemical energy into biomass. In ecology, productivity indicates the rate of biomass generation, energy addition, carbon fixation, or organic matter accumulation in an ecosystem. Therefore, it can be concluded that higher rates of primary productivity lead to increased carbon uptake.

The rapid development of marine environments, particularly through land conversion for tourism activities, can diminish the capacity of these environments to absorb carbon emissions from the atmosphere. One clear example of this impact is the accelerated land-use change in the coastal areas of Trenggalek Regency, driven by tourism sector development. A study conducted by Ningsih and Wahyuhana (2022) found that the tourism sector significantly influences physical land use, leading to the establishment of hotels, business spaces for local residents, and various supporting facilities. Therefore, there is a pressing need to model carbon stocks resulting from land cover changes in the coastal areas of Trenggalek Regency. Additionally, research on carbon absorption by mangrove forests and the primary productivity of phytoplankton is essential for understanding their effectiveness in reducing atmospheric CO_2 levels.

The current study aims to fill a critical gap in understanding how both forest ecosystems and coastal waters contribute to carbon sequestration in an integrated manner. While previous research has only focused on mangrove carbon sinks, this study uniquely examines the combined effects of mangrove and plantation forests alongside the role of coastal waters in carbon absorption. Additionally, the study seek to provide a novel quantification of how Trenggalek's coastal waters, through phytoplankton-driven productivity, act as a carbon sink, complementing the forests' role in mitigating climate change. It is expected that this integrated approach will provide a more comprehensive understanding of carbon dynamics across different ecosystems, which had not been achieved in previous studies.

METHODS

Study area

The study was conducted from March to May 2024 along the coast of Trenggalek Regency (Figure 1). Analysis of carbon storage and absorption was performed using data collected from mangrove forest stands and sediment samples. Research stations were determined using a purposive sampling method, selecting locations based on mangrove density and the suitability for collecting the required data. The sampling sites were

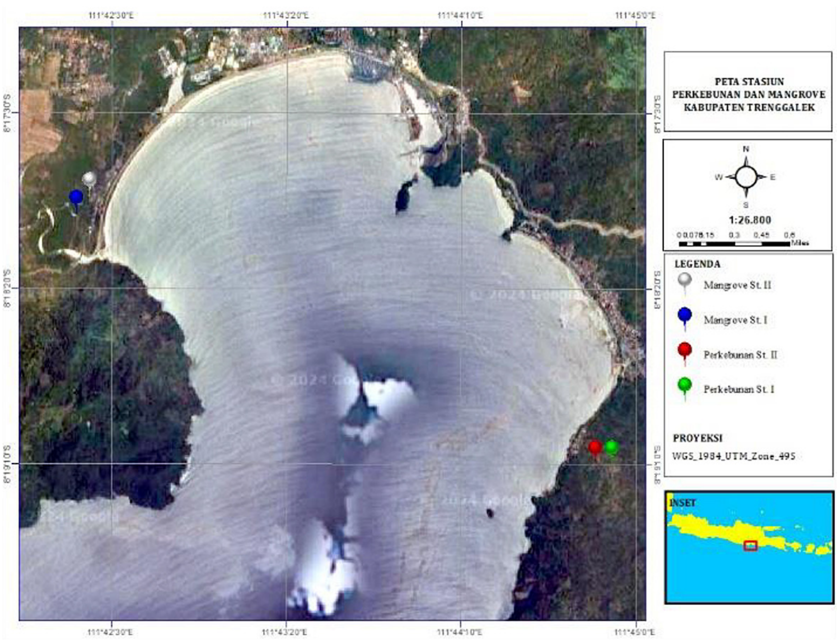

Figure 1. Studied area location

Table 1. Coordinates of the sampling station

Forest	Station	Coordinate	
		Latitude	Longitude
Mangrove forest	I	111.705372	-8.298477
	II	111.706718	-8.29691
Plantation forest	I	111.746259	-8.319038
	II	111.745757	-8.318974

identified based on observations made during a preliminary field survey (Table 1).

Data collection

Mangrove and plantation forest carbon sequestration and stock

To measure carbon sequestration and stock, this is done using a measurement station. This measurement station is divided into four stations, including 2 stations for mangrove forests and 2 stations for forest plantations. A total of 30 sampling plots (10 plots in each zone) of size of 10 × 10 m was established for non-destructive determination of biomass and soil carbon stock as well as species composition.

Transect for mangrove and plantation forest

Sampling and data collection were conducted using quadrant transects at each predetermined station. Transects were established at 3 stations, with each station consisting of 6 sampling plots. Observation plots were made with a size of 10 × 10 meters. Biomass measurement in mangrove stands was performed using a non-destructive method. Sampling was conducted on tree vegetation by measuring tree diameter using a measuring tape. Tree diameter, also known as diameter at breast height (DBH), was obtained from measuring girth at breast height (GBH).

Sediment

- Sediment sampling – the sampling procedure was conducted in several work stages (Howard et al., 2014), including: Ensuring the ground surface is free from organic debris, then pipe is inserted vertically into the ground until it reaches the base of the pipe. After reaching full depth, the pipe is rotated to cut fine roots present in the soil. The obtained samples are placed in zip-lock bags and labeled accordingly.
- LOI method – soil organic carbon content was determined using the LOI (loss on ignition) method by measuring the weight loss of the sample after being heated at high temperatures (Azzahra et al., 2020). The use of LOI in the analysis of soil organic carbon content was conducted at the Laboratory of the Industrial Research and Consultation Center. The following are the work stages performed (Howard et al., 2014): The sample is dried in an oven at 60 °C (48 hours) or using a temperature above 100 °C to expedite the drying process, then the sample is ground with a mortar to ensure each sample is homogenized. Approximately ± 2 grams of the ground sediment is weighed and placed in a porcelain crucible to be inserted into a muffle furnace. The sediment sample is burned at 450 °C for 4 hours. After that, the sample is weighed again.

Surface water sampling

Samples of surface water were collected at ten monitoring locations along the coast of Trenggalek. The collected water samples were analyzed for 6 physicochemical parameters including pH, temperature, water brightness, dissolved oxygen (DO), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}). Four indicators including pH, temperature, water brightness, and DO were measured directly in the field. Specifically, nitrate (NO_3^-) and orthophosphate (PO_4^{3-}) were analyzed according to (SNI 06-2480-1991) and (SNI 06-6989.31-2005), respectively. An additional 300 mililiters sample in 2 bright sample bottle and 1 dark sample bottle for every 10 location for calculating phytoplankton primary productivity.

Phytoplankton samples

Phytoplankton samples were collected from the euphotic zone (approximately 0.3–0.5 m beneath the surface) at each site by filtering 100 liters of lake water with a plankton net. The samples were then transferred to vials, with each vial containing 2–3 drops of Lugol's solution, and securely sealed to prevent any leakage.

Land use change data

Data collected from encompassed aerial images and real data from the field observed data, which comprised reference points collected using the Global Positioning System (GPS). Landsat satellite imagery were acquired for three years, namely 2001, 2012 and 2023 to map land cover of Trenggalek coast and assess changes in these 6 categorized classes are built-up land, forest, rice fields, plantations, water bodies and mangroves. These images were procured without incurring any costs through the Earth Explorer USGS (United States Geological Survey) web site (https://earthexplorer.usgs.gov/) (Izadi and Sohrabi, 2021; Seenipandi et al., 2021). The selection of Level-1 products, including, Landsat 7 ETM+ (2001), and Landsat 8 OLI/TIRS (2012 and 2023), ensured the availability of data that had undergone geometric and radiometric correction (Table 2).

Carbon pool data

The carbon stock data collection used in this study refers to the *Carbon* Pool. This carbon pool will refer to each differentiated land characteristic. The carbon pool data in this study was collected from various previous studies presented in Table 3.

Data processing

Land cover

This research utilizes Google Earth Engine (GEE) for land cover processing, consisting of two main stages. The first stage involves image mosaic and cloud masking, where missing image data is replaced, and cloud cover is removed using the median reducer method. This method calculates the median pixel values over a specified period, producing images free from cloud cover, high reflection values, and shadows.

The second stage focuses on land cover classification, dividing the area into six categories: built-up land, forest, rice fields, plantations, water bodies, and mangroves. This classification follows Technical Guidelines 1/PSDH/PLA/1/7/2020 and SNI 7645:2010, employing a supervised classification approach with training samples for each category. The algorithms used for this process include random forest (RF) and classification and regression trees (CART).

Land cover change modeling

The processing of driving factors for land cover prediction is divided into two main stages. The first stage involves the processing of elevation and slope data obtained from NASA's Aster GDEM, which requires projection and masking during pre-processing. The second stage focuses

Table 2. Properties of Landsat images used

Type	Data	Acquisition date	RGB band composition	Sources
Satellite images	Landsat 7 ETM+	1/1/2001	3,2,1	Earth Explorer USGS (United States Geological Survey) web site (https://earthexplorer.usgs.gov/)
	Landsat 8 OLI/TIRS	1/1/2012	4,3,2	
	Landsat 8 OLI/TIRS	1/1/2023	4,3,2	
Ancillary data	Google Earth Engine	-	-	Google Inc
	Field data	-	-	Study area

Table 3. Carbon pool values

Land cover	Above(tons/ha)	Below(tons/ha)	Soil (tons/ha)	Dead (tons/ha)
Built-up land	0.4[a]	0[a]	7.73[a]	0[a]
Forest	20.41[a]	10.45[a]	42.75[a]	2.62[a]
Plantation	19[b]	7.5[b]	66[b]	12[b]
Water body	0[a]	0[a]	0[a]	0[a]
Rice field	1.31[a]	0.73[a]	11.65[a]	0[a]
Mangroves	400.45[c]	417.93[d]	341.33[e]	3.9[e]

Note: [a] [Ke & Tang, 2019; Yan et al., 2015]; [b] [Ladawan, 2011]; [c] [Ashuri dan Patria, 2018]; [d] [Ahmed et al.,2023]; [e] [Jia et al., 2022].

on calculating distances from roads, rivers, and buildings using ArcGIS software with the Euclidean distance feature, which determines the spatial relationships between these elements.

For land cover change modeling, QGIS version 2 is used alongside the MOLUSCE plugin. The modeling process begins with inputting land use maps and driving factors, followed by a Pearson correlation analysis to assess relationships among the driving factors. The results include a table detailing changes in area and percentage for each land use type, as well as a rate of change matrix. Additionally, an artificial neural network (ANN) model is employed to predict potential land expansion, utilizing samples for training to optimize results. Cellular automata (CA) simulations are also performed to model spatial distribution processes, calculating predictions based on previous years and vulnerability duration.

Carbon stock processing based on land cover change

Carbon stock data processing is conducted using InVEST software to analyze carbon stocks in three sub-districts of Trenggalek Regency. The researchers aim to predict the spatial distribution of carbon based on land cover changes from 2001 to 2034, ultimately estimating the gain or loss of carbon storage during that period. The calculations are based on specific equations within the InVEST model.

Data analysis

Mangrove forest density along the coast of trenggalek regency

Mangrove forest density refers to the extent to which trees are distributed and the proximity of one tree to another within a mangrove forest area. The closer the spacing between trees, the better the mangrove forest's ability to maintain coastal stability, provide habitat, and store and absorb carbon. Mangrove forest density varies greatly depending on several factors, including the dominant species and environmental conditions.

$$Di = \frac{ni}{A} \tag{1}$$

where: Di – density of species i (tree/m^2); ni – number of counts per species i; A – Total area of data collection (m^2).

Above and below ground biomass calculation

Several factors need to be considered when estimating carbon in vegetation. First, it is essential to identify the species of vegetation to be sampled. Then, measure the diameter at breast height (DBH) and record the location or ID. The calculation of aboveground carbon is conducted using allometric equations. The use of allometric equations relies solely on diameter and density (Howard et al., 2014) Table 4–7). The obtained diameter data is entered into the allometric equation to calculate the biomass value for each tree.

Table 4. Allometric equation of mangrove forest aboveground biomass

Type	Allometric equation	Research source
Avicennia marina	$Y = 0.1848(D)^{2,3524}$ D_{max} = 35.2 cm	Dharmawan & Siregar (2008)
Sonneratia alba	$Y = 0.258\ (D)^{2,287}$	Kusmana et.al. (2018)
Rhizophora apiculata	$Y = 0.235\ (D)^{2,42}$ D_{max} = 28 cm	Ong et.al. (2004)
Ceripos decandra	$Y = 0.251\ \rho\ (D)^{2,42}$ ρ = 0.87 g/cm^3, D_{max} = 47.7 cm	Komiyama et.al. (2005)

Table 5. Allometric equation of mangrove forest subsoil biomass

Type	Allometric equation	Research source
Avicennia marina	$Y = 0.1682(D)^{1,7939}$ D_{max} = 35.2 cm	Dharmawan & Siregar, (2008)
Sonneratia alba	$Y = 0.230\ \rho(D^2H)^{0.740}$ ρ = 0.47 g/cm^3, H = 370 cm	Kusmana et al. (2018)
Rhizophora apiculata	$Y = 0.00698\ (D)^{2,61}$ D_{max} = 28 cm	Ong et.al. (2004)
Ceripos decandra	$Y = 0.199\ \rho^{0,899}\ (D)^{2,22}$ ρ = 0.87 g/cm^3, D_{max} = 47.7 cm	Komiyama et.al. (2005)

Note: Y – biomass (tons/ha); D – diameter data at breast height (cm); ρ – wood density (g/cm^3); D_{max} – maximum tree diameter (cm).

Table 6. Allometric equation for plantation biomass

Allometric equation	Research resource
Above-ground biomass	
$Y = 0.11\ \rho\ D^{2.62}$	Ketterings et.al. (2001)
Below-ground biomass	
Y = AGB X 0.26	Cairns et.al. (1997)

Note: Y –biomass (tons/ha); D – diameter data at breast height (cm); ρ – wood density (g/cm^3); 0.26 – convertion factor (26% from AGB).

Table 7. Wood density of trees on plantations

Type	Wood density (g/cm^3)
Clove	0.79
Jackfruit	0.56
Rambutan	0.83
Durian	0.49
Coconut	0.83

$$W_{average} = \frac{number\ of\ values}{total\ data} \tag{2}$$

Carbon is the most important component of biomass because 46–50% of biomass is carbon (Kauffman & Donato, 2012 in Farahisah et al., 2021). Therefore, the estimation of carbon content can be done by converting biomass into carbon by multiplying by 0.47, as calculated using Equation 3 (Brown 1997 in Prakoso et al., 2018).

$$C = W \times 0.47 \tag{3}$$

where: *C* – carbon content (g); *W* – average stand biomass (g). (National Standardization Agency of Indonesia, 2011).

After obtaining the average biomass values for aboveground and belowground biomass, the carbon content is calculated to determine the carbon content per hectare using Equation 4.

$$\mathrm{Cn} = \frac{C}{1000} \times \frac{10.000}{Lplot} \tag{4}$$

where: *Cn* – carbon content (tons/ha); *C* – carbon content of each transect plot(g); *Lplot* – total transect area (m^2).

Soil organic carbon calculation

The calculation of soil organic carbon is performed by analyzing the soil carbon content obtained from ashing using the Loss on Ignition (LOI) method. The calculation of organic matter can be done using Equations 5 and 6 (Howard et al., 2014).

$$Bk = \frac{Wo - Wt}{Wo} \times 100 \tag{5}$$

where: *Bk* – dry weight; *Wo* – the weight of the sample before the open furnace (g); *Wt* – the weight of the sample after the open furnace (g).

$$Bd = \frac{m}{v} \tag{6}$$

where: *Bd* – bulk density (g/cm^3); *m* – average sample dry weight (g); *v* – sample wet weight (cm^3).

After obtaining the sediment density value, it then continues with the calculation of soil carbon using Equation 7 (National Standardization Agency of Indonesia, 2011).

$$Ct = Kd \times Bd \times \%C\text{-}organic \tag{7}$$

where: *Ct* – sediment carbon content (tons/ha); *Kd* – depth of sample sediment (cm); *%C-organic* – value of carbon presentation (0.47).

Once the average value of organic matter in each depth layer is obtained, the soil organic carbon content is calculated to determine the carbon content in each hectare, through Equation 8 (National Standardisation Agency, 2011).

$$Cn = C \times 100 \tag{8}$$

where: *Cn* – carbon content (tons/ha); *C* – average organic carbon content; 100 – conversion factor from g/cm^2 to tons/ha.

Carbon uptake calculation

Then, after obtaining the carbon value of each biomass, carbon dioxide content was calculated to determine carbon uptake using Equation 9 (Dharmawan and Siregar, 2008).

$$CO_2 = \frac{\mathrm{Mr\ CO2}}{Ar\ C} \times \mathrm{C} \tag{9}$$

where: CO_2 – carbon sequestration (tons/ha); Mr CO_2 – relative molecular mass of CO_2 compounds (44); *Ar* CO_2 – relative atomic mass C (12); C – carbon content (tons/ha).

Phytoplakton cell density

Cell density was measured using the method described by APHA (1989) with a Sedgewick Rafter counting chamber. The collected samples were allowed to settle for 48 hours, after which the clear water was removed and the remaining sediment was transferred to a cylinder for volume measurement. Before analysis, the sample in the cylinder was mixed thoroughly, aspirated, and placed into the

Sedgewick Rafter counting chamber. The formula for calculating phytoplankton density is as follows:

$$N = \frac{T}{L} \times \frac{P}{p} \times \frac{V}{v} \times \frac{1}{w} \quad (10)$$

where: N – Number of plankton per litre; T – Area of cover glass (mm2); L – Visual field area (mm^2); P – Number of plankton counted; p – Number of field of view observed; V – Volume of filtered plankton sample (ml); v – Volume of plankton sample under the cover glass (ml); w – Volume of filtered plankton sample (litre).

Phytoplakton biology index

Phytoplankton diversity and uniformity were calculated by using Shannon-Wiener formula and the dominance index were analyzed according to the Simpson's dominance index formula (Table 8).

Phytolankton primary productivity

The dissolved oxygen value were calculated using Equation 10 (Vollenweider, 1969).

$$GP = \frac{ppm\ O^2 in\ BB - ppm\ O^2\ in\ DB}{(PQ)(t)} \times 0.375 \quad (11)$$

where: GP – Gross Photosynthesis; BB – Bright Bottle; DB – Dark Bottle; PQ – Photosynthesis Quotiens (1, 2); t – time.

Carbon uptake by phytoplankton

The calculation of phytoplankton potential carbon uptake uses the calculation of Hasibuan, et.al (2018):

$$TC = Area \times (Mr\ CO_2 / Mr\ C \times NP) \quad (12)$$

where: TC – Total Carbon; Mr CO_2 – relative molecular mass of CO_2 compounds (44); Ar CO_2 – relative atomic mass C (12); NP – Nett Photosynthesis.

Calculating carbon stock based on land cover change and modelling analysis accuracy assessment

Then, after obtaining the carbon value of each biomass, carbon dioxide content was calculated to determine carbon uptake using Equation 9 (Dharmawan & Siregar, 2008).

Upon obtaining the output data and results from the InVEST software, the processed data of carbon will be analyzed using the equations

Table 8. Formula for calculating indices

Indices	Equation	Description
Diversity index	$H' = -\sum(\frac{Ni}{N})\ln(\frac{Ni}{N})$	H' = Diversity Index N = Total number of plankton Ni = Type of individual plankton
Uniformity index	$E = \frac{H'}{H'max}$	E = Uniformity index H' = Shannon-Wiener diversity index H' max = Maximum species diversity
Dominance index	$D = (\frac{Ni}{N})$	D = Dominance Index Ni = Number of Individuals of the Species N = Total number of individuals

Table 9. Formula for calculating indices

Indices	Equation	Description
Calculating carbon stock	$C_i = C_{i\_above} + C_{i\_below} + C_{i\_soil} + C_{i\_dead}$ $Ctotal = \sum_{i=1}^{n} Ci \times Si$	C_i – Total density C_{i_above} – Average carbon above surface C_{i_below} – Average carbon below the surface C_{i_soil} – Average carbon in soil C_{i_dead} – Average carbon in litter C_{total} – Total carbon stock SI – Area of the land use type
Producer's accuracy	$\frac{Xii}{Xi+}\ 100\%$	Xii – Diagonal values of the contingency matrix of row i of column X+i – Number of pixels in the i-th column Xi+ – Number of pixels in the i-th row N – Number of pixels in the sample
User's accuracy	$\frac{Xii}{X+i}\ 100\%$	
Over all accuracy	$\frac{\sum_{i=1}^{r} Xii}{N}\ 100\%$	
Kappa accuracy	$\frac{N\sum_{i=1}^{r} Xii - \sum_{i=1}^{r} Xi + X_{+i}}{N^{2-}\sum X_i + X_{+i}}$	

presented in the Table 9. Beside of that, all the data that has been modeled will undergo an analysis stage that includes an accuracy assessment to evaluate the classification errors in the research area. This assessment measures accuracy through various calculations, including producer accuracy, user accuracy, overall accuracy, and Kappa accuracy, to determine the reliability of the research findings.

RESULTS AND DISCUSSION

Species composition and structure of the forest

Four species of mangroves were identified sucha as *Rhizophora apiculata, Ceriops decandra, Sonneratia alba, and Avicennia marina*, with a total of 740 individuals. At the research site of plantation forest, the vegetation is characterized by heterogeneity, where the area is not dominated by a single species. The plantation forest is located in the hilly areas of Trenggalek Regency, and most of its vegetation falls into the tree category. Based on the analysis of the plantation forest's vegetation structure, five tree species were identified there are clove trees, rambutan trees, jackfruit trees, durian trees, and coconut trees, with a total of 230 stands found within the research site. *Ceriops decandra* demonstrates the highest species density among mangroves, with 344 individuals, while Sonneratia alba has the lowest density at 0.10 individuals per hectare (Figure 2). This species displays a more uniform distribution, likely due to its high adaptive capacity, thriving in deeper areas with muddy substrates that flood only during the highest tides. As noted by Jamili et al. (2009), the *Ceriops decandra* zone is the least frequently flooded, with a maximum depth of 20.4 cm. Significant differences exist between mangrove stands at Station I and Station II: Station I primarily consists of seedlings and poles, while Station II features mostly trees, poles, and saplings (Figure 3). These variations are attributed to nutrient availability and the age of the mangrove planting, as Station I is closer to settlements and experiences less flooding, whereas Station II benefits from consistent flooding and nutrient runoff from the adjacent river (Table 10).

The vegetation in the heterogeneous plantation forest was predominantly clove (*Syzygium aromaticum*), with Station II exhibiting the highest density of 1.42 individuals per square meter and an average stem diameter of 12.77 cm. In contrast, the lowest density was recorded for the rambutan tree (*Nephelium lappaceum*) at Station I, with only one individual and a stem diameter of 25.62 cm. Vegetation density can be influenced by several factors, including soil conditions, climate, and planting techniques. Soil fertility and organic

Figure 2. Species composition of mangrove forest; a) Rhizopora apiculata, Ceriops decandra, Sonneratia alba, and Avecennia marina

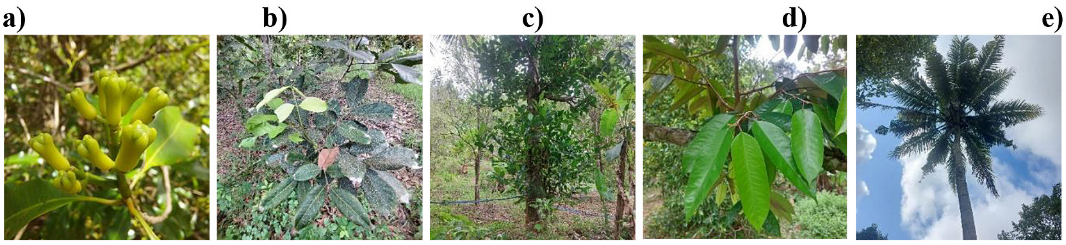

Figure 3. Species composition of plantation forest: (a) cloves, (b) rambutan, (c) jackfruit, (d) durian, (e) coconut

Table 10. Forest community structure at station I and II

Forest	Station	Species	Total (ind)	Density (ind/m^2)
Mangrove forest	I	*Rhizophora apiculata*	90	0.9
		Ceriops decandra	279	2.79
	II	*Sonneratia alba*	10	0.1
		Avicennia marina	17	0.17
		Ceriops decandra	344	3.44
Plantation forest	I	Clove	71	0.71
		Rambutan	1	0.01
		Jackfruit	2	0.02
	II	Clove	142	1.42
		Rambutan	6	0.06
		Durian	6	0.06
		Coconut	2	0.02

matter content are key determinants of vegetation density. The high density of clove trees at the research site may be attributed to the favorable climatic conditions, which are conducive to clove cultivation. The study area, located on hillsides, experiences a cool and humid climate, which is ideal for clove growth. Additionally, the elevation of the clove plantation affects temperature, humidity, and wind, all of which can influence pest populations and, in turn, the growth of clove plants. Elevation plays a significant role in regulating air temperature, which directly impacts the metabolic processes and life cycles of pests, affecting their feeding and reproduction rates (Rahayu, 2011).

Carbon content

Above-ground biomass

In the mangrove forests of Trenggalek, *Sonneratia alba* at Station II demonstrated the highest carbon content, with a biomass value of 149.61 grams, contributing to a carbon content of 7.03 tons/ha and a carbon absorption capacity of 25.78 tons/ha. In contrast, *Ceriops decandra* exhibited the lowest biomass at both Station I and Station II, with corresponding carbon contents of 0.12 tons/ha and 0.19 tons/ha, respectively. Carbon storage in mangrove forests is strongly influenced by biomass and stem diameter, with larger diameters resulting in greater biomass and carbon sequestration, as noted by Bachmid et al. (2018) and Suryono et al. (2018). Factors such as tree height and wood type further influence biomass (Ati et al., 2014), and the higher carbon content at Station II is likely due to older mangrove stands with larger diameters, which accumulate more organic material over time (Suryono et al., 2018).

Sedimentation processes, particularly in tidal areas, enhance carbon storage by depositing organic matter that becomes trapped in mangrove root systems, fostering fertile conditions for growth (Yaqin et al., 2022). Despite this, the overall biomass and carbon content in Trenggalek's mangroves were relatively low, with a biomass value of 241.63 grams and a carbon content of 12.80 tons/ha. These values are lower than those reported in other regions, such as Sungai Kupah Village in Kubu Raya Regency, which had a biomass value of 273.98 grams and a carbon content of 136.99 tons/ha (Kristianto et al., 2023). This difference highlights the critical role that stem diameter plays in determining biomass and carbon storage capacity in mangrove forests.

The highest carbon content in the plantation forest of Trenggalek was found in durian (*Durio zibethinus*) trees, with a carbon content of 26.25 tons per hectare and a carbon sequestration capacity of 96.26 tons per hectare (Table 11). In contrast, the lowest carbon content and sequestration values were observed in clove (*Syzygium aromaticum*) trees. At Station I, clove trees exhibited a carbon content of approximately 1.91 tons per hectare and a carbon sequestration capacity of 7.01 tons per hectare, while at Station II, the carbon content increased to 4.49 tons per hectare with a sequestration capacity of 16.48 tons per hectare.

The variation in biomass among species reflects differences in individual growth rates. Clove trees, which had the smallest biomass at both stations, typically have a smaller average diameter compared to other species. This is attributed to

Table 11. Mangrove and plantation forest above-ground biomass and carbon stocks values

Forest	Station	Species	DBH (cm)	Biomass (g)	Carbon content (tons/ha)	Carbon sequestration (tons/ha)
Mangrove forest	I	*Rhizophora apiculata*	2.59	3.31	0.16	0.57
		Ceriops decandra	2.44	2.6	0.12	0.45
	II	*Sonneratia alba*	13.18	149.61	7.03	25.78
		Avicennia marina	14.5	81.97	5.3	19.43
		Ceriops decandra	2.99	4.13	0.19	0.71
	Total			241.63	12.8	46.95
Plantation forest	I	Clove	9.46	42.73	1.91	7.01
		Rambutan	25.62	447.84	3.78	13.87
		Jackfruit	22.68	370.49	11.75	43.08
	II	Clove	12.77	98.97	4.49	16.48
		Rambutan	11.94	63.69	2.99	10.98
		Durian	33.32	558.58	26.25	96.26
		Coconut	27.69	384.52	18.07	66.72
	Total			2230.04	81.63	299.3

their genetic characteristics and plant structure, as clove trees are classified as shrubs with long, brittle branches (Al Muhdhar et al., 2018). In contrast, durian trees have significantly larger trunk diameters, averaging 33.32 cm, and a biomass of 558.58 grams. The larger trunk diameter of *Durio* species allows for greater biomass storage compared to smaller tree species. Additionally, durian trees are long-lived and capable of thriving for several decades, enabling them to accumulate substantial carbon content in their above-ground biomass over time.

Below-ground biomass

Below-ground biomass estimation using allometric equations revealed that *Avicennia marina* had the highest biomass at 477.46 grams, with corresponding carbon content and sequestration values of 22.44 tons/ha and 82.28 tons/ha, respectively. In contrast, *Rhizophora apiculata* at Station I exhibited the lowest carbon content (0.01 tons/ha) and sequestration (0.02 tons/ha). The higher carbon content in *Avicennia marina* is attributed to its larger size and more complex root system, which enhances its ability to trap particles and store carbon, as noted by Muhsoni (2021). This extensive root network enables greater carbon absorption compared to smaller species. In contrast, *Rhizophora apiculata* allocates more nutrients to trunk and leaf growth, with less emphasis on root development, especially in areas like Station I, where limited tidal flooding reduces the need for complex root structures for carbon storage (Table 12).

The biomass of plantation forests in Trenggalek ranged from 7.14 to 145.23 grams, with the highest carbon content observed in clove trees, which had a carbon content of 41.69 tons per hectare and a carbon sequestration capacity of 152.88 tons per hectare. Plants growing at different elevations develop specific survival strategies to adapt to their environments (Uemura & Hausman, 2013). The research findings show a notable increase in below-ground biomass productivity (BGBP) with increasing elevation. High-elevation areas are typically characterized by more challenging environmental conditions, which exert greater survival pressures on plants. As a result, plants in these regions tend to adopt conservative resource utilization strategies, allocating more biomass to their below-ground structures to enhance survival (Yang et al., 2009). Furthermore, species composition varies across elevations (Guo et al., 2018). In higher elevations, species that adapt effectively to the local soil and climatic conditions often develop more robust root systems, contributing to greater below-ground biomass.

Soil organic carbon

The soil organic carbon content in the mangrove forest varies significantly between stations, with Station I, located closer to the mainland, exhibiting higher levels at a depth of 0–30 cm compared to Station II, which is in the river flow area (Table 13). At Station I, total carbon sequestration reaches 3,766.14 tons/ha, with a soil organic

Table 12. Mangrove and plantation forest below-ground biomass and carbon stocks values

Forest	Station	Species	DBH (cm)	Biomass (g)	Carbon content (tons/ha)	Carbon sequestration (tons/ha)
Mangrove Forest	I	Rhizophora apiculata	2.59	0.13	0.01	0.02
		Ceriops decandra	2.44	1.58	0.07	0.27
	II	Sonneratia alba	13.18	17.41	0.82	3
		Avicennia marina	14.5	477.46	22.44	82.28
		Ceriops decandra	2.99	2.41	0.11	0.42
	Total			498.99	23.45	85.99
Plantation forest	I	Clove	9.46	7.14	5.91	21.67
		Jackfruit	22.68	64.99	6.11	22.4
		Rambutan	25.62	116.44	5.47	20.07
	II	Clove	12.73	24.86	41.69	152.88
		Durian	33.32	145.23	40.95	150.17
		Rambutan	11.94	16.56	4.67	17.12
		Coconut	27.69	99.98	9.4	34.46
	Total			475.2	114.2	418.77

carbon content of 37.66 tons/ha, while Station II records a soil organic carbon content of approximately 37.62 tons/ha and a carbon sequestration of 3,761.96 tons/ha. This discrepancy in carbon content at Station I can be attributed to environmental conditions, the availability of organic matter, and microbial activity.

Station I benefits from more stable environmental conditions due to its infrequent flooding by daily tides, leading to higher organic material inputs. The organic matter tends to accumulate on the surface and undergo slow decomposition, aided by the anaerobic conditions created by solid or clayey mud soils. As noted by Sari and Prayudyaningsih (2017), low oxygen levels encourage anaerobic microbial activity, facilitating the accumulation of organic matter and delaying the release of carbon dioxide into the atmosphere.

In contrast, Station II has lower soil organic carbon levels due to frequent high water flow, which disrupts the sediment layers formed from previously accumulated organic material. The transport of leaf litter and branches by water flow during high tides further reduces the amount of organic material available for decomposition. At depths of 30–50 cm, soil organic carbon content is generally higher than at 0–30 cm, likely due to slower decomposition processes (Yaqin et al., 2022). Research by Aldiano et al. (2022) indicates that the highest soil organic carbon content in the Mangrove Forest of Gunung Anyar, Surabaya, was found at depths of 60–100 cm, while Indraiswari and Putra (2018) observed similar results in the Mangrove Forest of Perancak, Bali, where the highest carbon content was at depths of 50–100 cm, contrasting with lower levels at surface depths.

The study reveals that Station II, located at a higher elevation than Station I, has a greater carbon content and sequestration at both depths of 0–30 cm and 30–50 cm. Specifically, Station II shows carbon content values of 38.41 tons/ha and 38.44 tons/ha at respective depths, while Station I has slightly lower values. These differences may be attributed to the terrain, with Station II having a flatter landscape that retains more moisture, allowing for better microbial activity, organic matter decomposition, and carbon accumulation.

Soil conditions and rainfall significantly influence the carbon content in these regions. Station I's steeper slopes, which promote faster drainage and drier soils, limit microbial activity and slow organic matter breakdown. Higher rainfall at Station II's elevation enhances vegetation growth and litter accumulation, contributing to the higher organic carbon content. Additionally, the deeper soil layers (30–50 cm) in both stations tend to have greater carbon accumulation due to slower decomposition rates, higher bulk density, and the contribution of decomposing roots, as noted by Siringoringo (2014), who emphasized the role of root carbon transport and organic matter decomposition at greater depths.

Mangrove forests, however, exhibit even greater soil organic carbon content than plantation forests, highlighting their superior carbon storage capacity. According to Alongi et al. (2012), most

Table 13. Organic carbon soils

Forest	Location	Sample	Depth	Carbon content (ton/ha)	Carbon sequestration (ton/ha)
Mangrove forest	I	1	0–30 cm	37.02	3702.03
		2		28.98	2897.55
		3		29.47	2946.61
		AVERAGE		37.66	3766.14
		1	30–50 cm	38.32	3832.07
		2		38.27	3826.58
		3		38.54	3854.39
		AVERAGE		38.38	3837.68
	II	1	0–30 cm	37.68	3768.23
		2		28.63	2862.89
		3		29.22	2922.23
		AVERAGE		37.62	3761.96
		1	30–50 cm	38.84	3884.16
		2		38.66	3866.14
		3		38.52	3852.04
		AVERAGE		38.67	3867.45
Plantation forest	I	1	0–30 cm	36.77	3676.58
		2		37.71	3770.58
		3		36.99	3698.9
		AVERAGE		37.28	3727.75
		1	30–50 cm	38.55	3855.18
		2		38.43	3843.43
		3		38.26	3825.8
		AVERAGE		38.41	3841.47
	II	1	0–30 cm	37.61	3761.18
		2		37.4	3739.63
		3		37.4	3740.42
		AVERAGE		37.47	3747.08
		1	30–50 cm	37.84	3784.28
		2		38.81	3880.63
		3		38.45	3844.6
		AVERAGE		38.44	3843.87

of the carbon in mangrove forests is stored below ground in the form of soil organic carbon. The study shows that mangrove forests hold 76.17 tons/ha of organic carbon with sequestration levels of 7616.61 tons/ha, surpassing the 75.76 tons/ha of carbon content and 7576.40 tons/ha of sequestration found in plantation forests. This underscores the significant role mangroves play as carbon sinks compared to other forest types.

Ocean's carbon sequestration

Phytoplankton convert inorganic carbon into organic carbon through the process of photosynthesis, which is then used as an energy source. Based on the calculations, the potential for carbon sequestration in the waters of Trenggalek is presented in the following Table 14.

Carbon absorption in Trenggalek's waters ranges from 3.69 to 23.35 tons C/m²/year, with the highest levels occurring at Station 1, near the bay's mouth facing the open sea, and the lowest at Station 9, close to the PPN Prigi harbor. This variation suggests that carbon absorption is affected by different pollution levels across the region. Additional factors influencing absorption include nutrient availability, water temperature, clarity, and phosphorus levels (NP), which vary between stations.

Table 14. Carbon sequestration in Trenggalek bodywaters

Station	Carbon sequestration (tonC/m² /thn)
1	23.35
2	11.68
3	9.83
4	15.36
5	5.53
6	5.53
7	6.14
8	6.14
9	3.69
10	7.99
Total	95.25

These findings align with the study by Fitra et al. (2013), which highlights that CO_2 absorption in marine waters is largely dependent on the primary productivity of phytoplankton. Phytoplankton are crucial in controlling the regional and seasonal movement of CO_2. Stations with more nutrients and optimal conditions, like Station 1, tend to have higher carbon absorption due to enhanced phytoplankton growth. Conversely, areas with higher pollution, such as Station 9, likely experience lower phytoplankton productivity, resulting in reduced carbon absorption.

Overall, the study emphasizes the critical role phytoplankton play in reducing CO_2 emissions in coastal areas. The ability of phytoplankton to absorb CO_2 highlights the need to maintain their health and productivity in Trenggalek's waters for effective carbon sequestration. Proper nutrient management and pollution control are essential for preserving and enhancing the capacity of these waters to absorb and store carbon.

Land cover change on carbon stock

Changes in carbon stocks are highly dependent on existing land cover conditions. In 2023, the total carbon stock in the coastal area of Trenggalek Regency reached 3,769,735.32 tons, which is divided into six land cover categories. Plantation forests have the highest carbon stock, followed by forests, rice fields, mangroves and built-up land. In 2034, the total predicted carbon stock increased to 3,778,537.21 tons, with an increase of 8,801.89 tons from 2023. However, some lands such as forests, built-up land, and mangroves are predicted to experience a decrease in carbon stocks, by 87.517 tons, 1.327 tons, and 2.562 tons, respectively (Figure 4).

On the other hand, plantation forest land cover is predicted to experience an increase in carbon stock of 94.179 tons, bringing the total to 3,309,799.37 tons. Forest land also experienced an increase of 5.992 tons, with the total carbon stock reaching 319,569.99 tons. Although some lands experienced a decrease in carbon stocks, the increase in plantation forests and forests contributed to the increase in total carbon stocks in the region.

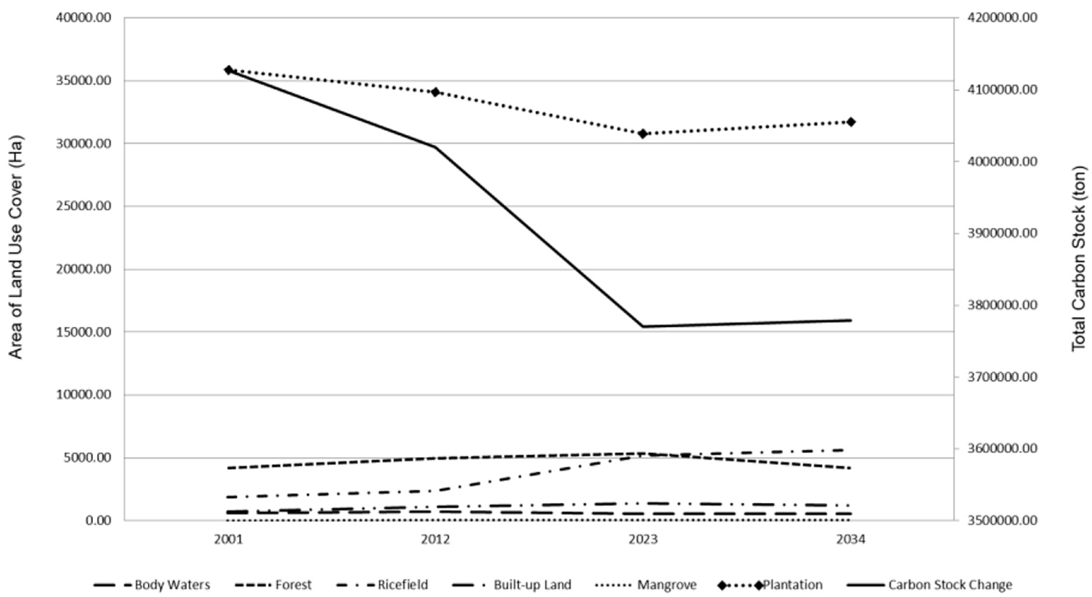

Figure 4. Graphic trend of land use land cover and carbon stock changes in Trenggalek regency

The role of forest cover and water bodies in mitigating global warming

This research demonstrates how carbon absorption in both forests and coastal waters functions as an integrated system for mitigating climate change. In forests, carbon is absorbed through the aboveground biomass (trees and vegetation), belowground biomass (roots), and particularly in the soil, where mangroves store substantial organic carbon due to anaerobic conditions. In coastal waters, phytoplankton play a crucial role in capturing carbon through photosynthesis, converting atmospheric CO_2 into organic carbon, which is then stored in marine ecosystems. What sets this research apart is not only the precise determination of carbon balance in soil and water but also the revelation of how these two systems work together as complementary carbon sinks. This study uniquely quantifies the combined carbon sequestration potential of both ecosystems, providing a more holistic understanding of carbon dynamics across Trenggalek's coastal forests and waters, which had not been achieved in previous studies.

The results revealed that different land cover types, including mangrove forests, plantation forests, and water body, contributed to varying levels of carbon stock reserves. The research highlighted a decline in overall carbon stock reserves from 2001 to 2023, but a slight increase is projected by 2034. This dynamic assessment of land use changes enabled the estimation of carbon stocks and helped identify key ecosystems, such as mangrove and plantation forests that play crucial roles in carbon sequestration along the Trenggalek coast. Beside that, we employed carbon accounting as a monitoring tool to assess the role of mangrove and plantation forests in Trenggalek in climate change mitigation. The findings demonstrated that these forests act as significant carbon sinks, capturing atmospheric carbon dioxide (CO_2) and storing it in their biomass and soils. Plantation forests were shown to store more carbon in both above-ground and below-ground biomass. However, mangrove forests, despite lower biomass, exhibited higher soil organic carbon content, making them critical for long-term carbon storage due to the anaerobic conditions of mangrove soils, which slow decomposition and trap carbon over extended periods. Additionally, the role of phytoplankton in Trenggalek waters was highlighted, with these organisms contributing significantly to carbon sequestration by absorbing CO_2 through photosynthesis and converting it into organic carbon. This study underscores the complementary roles of terrestrial and marine ecosystems in mitigating climate change, with both forests and coastal waters playing integral roles in regional carbon sequestration efforts.

Forests in Trenggalek, both mangrove and plantation, are highly useful for mitigating climate change due to their significant carbon absorption and storage capabilities. Mangrove forests, in particular, store large amounts of organic carbon in their soils, making them vital for long-term carbon sequestration. However, the findings also suggest that these ecosystems are sensitive to land-use changes and environmental pressures. While the forests are currently functioning as effective carbon sinks, continued deforestation or degradation could severely reduce their carbon storage capacity, potentially exacerbating climate change. Therefore, the results show that it is crucial to adopt sustainable land management practices to protect and conserve these ecosystems. Urgent action may be needed to halt activities that threaten forest and coastal ecosystems, ensuring they continue to play their role in reducing atmospheric CO_2 and mitigating global warming.

In accordance with Indonesia Presidential Regulation No. 98 of 2021, climate change mitigation strategies can be implemented through various approaches, including the establishment of a greenhouse gas emission inventory. This process involves activities such as data collection, monitoring, and calculation of emissions (Presidential Regulation No. 98 of 2021). Carbon stock monitoring serves as a critical mechanism to assess carbon emission levels and quantify the amount of carbon stored in specific regions. Such periodic assessments provide a scientific basis for the development of policies aimed at addressing climate change (Utami et al., 2024; Presidential Regulation No. 98 of 2021). Additionally, several studies have examined the driving factors behind changes in carbon stocks and have developed predictive models for future carbon reserves—an essential component of effective climate change mitigation (Hortay and Pálvölgyi, 2022; Huang, 2018). These drivers and carbon stock reserves can be analyzed through land use assessments, providing insights into the mechanisms that influence carbon dynamics (Anindita et al., 2022; Nave et al., 2022; Weindl et al., 2017).

CONCLUSIONS

The study successfully achieved its objective of estimating the carbon sequestration potential of mangrove and plantation forests, as well as coastal waters, along the coastline of Trenggalek Regency, and elucidated their roles in climate change mitigation. Detailed carbon stock assessments revealed that while plantation forests have higher aboveground biomass, mangrove forests are more efficient at storing carbon in their soils due to anaerobic conditions. Coastal waters, influenced by phytoplankton productivity, also significantly contribute to carbon absorption, acting as complementary carbon sinks. Remote sensing analysis showed a decline in total carbon stock from 4,126,833.64 tons in 2001 to 3,769,725.32 tons in 2023, with a slight increase projected by 2034.

These findings present critical opportunities for implementing sustainable land use management, particularly in protecting and expanding mangrove and plantation forests, both of which play key roles in carbon sequestration. The research underscores the importance of conserving these ecosystems to maximize their carbon storage potential. The Trenggalek government must prioritize efforts to preserve mangrove forest cover. If development in mangrove areas is unavoidable, it should be counterbalanced by increasing plantation tree coverage, as both types of vegetation serve similar roles in absorbing carbon dioxide. This approach can help maintain ecological balance while enhancing carbon capture.

In conclusion, this research provides valuable insights into the integrated carbon dynamics of terrestrial and marine ecosystems and their significant roles in reducing atmospheric CO_2 levels. It emphasizes the urgent need to protect these ecosystems from degradation, ensuring their continued contribution to climate change mitigation. The study also highlights the importance of remote sensing technologies for effective ecosystem monitoring and management, paving the way for targeted conservation strategies.

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