Celebes Agricultural 4(2): 140 - 154 February (2024)

Research Article

Development of Spatial Platform Based Earth Engine Apps for Mangrove Carbon Stock: Case Study in Serang Coastal Zone, Banten Province

Pengembangan Platform Spasial Berbasis Earth Engine Apps untuk Mengetahui Stok Karbon Mangrove: Studi Kasus di Wilayah Pesisir Serang, Provinsi Banten

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Abstract: Mangroves exhibited considerable potential in mitigating global climate change, as these ecosystems can sequester and store substantial amounts of carbon in the form of live and decayed plant biomass across coastal areas. This research aimed to estimate carbon stocks and assess the dynamics of carbon reserves in the silvofishery area of Serang City, Banten, utilizing geospatial technology and cloud computing. Additionally, the study sought to develop the Indo InaC Data platform to monitor CO2 uptake on silvofishery land. The methodology employed included mangrove detection through unguided classification, and carbon stock estimation was performed using regression models derived from vegetation indices, specifically the Integrated Remote Sensing and Ecological Index (IRECI) and the Transformed Vegetation Index (TRVI). The results revealed fluctuations in mangrove vegetation cover between 2016 and 2023, with a notable decrease occurring from 2016 to 2017, as the cover declined from approximately 61.91 hectares to 50.53 hectares. This decrease was followed by an increase from 2017 to 2022, during which the area rose to 78.1 hectares; however, a subsequent decrease was observed in 2023, with the area reducing to 66.82 hectares. The estimated carbon reserves in the study area for 2023 amounted to 315 tons, reflecting similar dynamics to those observed in mangrove vegetation cover. The development of the Indo InaC Data platform is anticipated to facilitate ongoing monitoring of CO2 emissions uptake, and it is expected to inform future strategies for managing silvofishery land on an annual basis.

Keywords: CO_2 emission, climate change, mangrove

Abstrak. Mangrove memiliki potensi yang signifikan dalam mengurangi perubahan iklim global, karena ekosistem ini dapat menyerap dan menyimpan sejumlah besar karbon dalam bentuk biomassa tanaman hidup dan yang telah membusuk di daerah pesisir. Penelitian ini bertujuan untuk memperkirakan stok karbon dan menilai dinamika cadangan karbon di area silvofishery di Kota Serang, Banten menggunakan teknologi geospasial and komputasi awan. Selain itu, studi ini juga bertujuan untuk mengembangkan platform Data Indo InaC untuk memantau penyerapan CO_2 di lahan silvofishery. Metodologi yang digunakan mencakup deteksi mangrove melalui klasifikasi tanpa panduan, dan estimasi stok karbon dilakukan menggunakan model regresi yang berasal dari indeks vegetasi, yaitu Integrated Remote Sensing and Ecological Index/IRECI dan Transformed Vegetation Index/TRVI. Hasil penelitian ini mengungkapkan fluktuasi dalam tutupan vegetasi mangrove antara tahun 2016 dan 2023, dengan penurunan yang signifikan terjadi dari tahun 2016 hingga 2017, di mana tutupan menurun dari sekitar 61,91 hektar menjadi 50,53 hektar. Penurunan ini diikuti oleh peningkatan dari tahun 2017 hingga 2022, di mana area meningkat menjadi 78,1 hektar; namun, penurunan selanjutnya diamati pada tahun 2023, dengan area berkurang menjadi 66,82 hektar. Estimasi cadangan karbon di area penelitian untuk tahun 2023 mencapai 315 ton, mencerminkan dinamika yang serupa dengan yang diamati pada tutupan vegetasi mangrove. Pengembangan

Citation:
Puspitasari RF, Aisyah, Khotimah U, Nugraha MR, Dzulfigar A, Marfi KP, Septianingrum D, Asy'ari R, Pramulya R, Zamani NP, Setyawan Y. 2024. Development of spatial platform based earth engine apps for mangrove carbon stock: Case study in serang coastal zone, Banten Province. Celebes Agricultural. 4(2): 140-154. doi: 10.52045/jca.v4i2.746

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Recived: October 2024
Accepted: December 2024
Published: December 2024

p-ISSN: 2723-7974
e-ISSN: 2723-7966
doi: 10.52045/jca.v4i2.746

Website: https://ojs.untika.ac.id/index.php/faperta

platform Data Indo InaC diharapkan dapat memfasilitasi pemantauan berkelanjutan terhadap serapan CO_2, dan diharapkan dapat memberikan informasi untuk strategi pengelolaan lahan silvofishery di masa mendatang secara tahunan.

Kata kunci: Emisi CO_2, Mangrove, Perubahan Iklim

INTRODUCTION

Climate change refers to long-term alterations in global weather patterns, reportedly accelerated by environmentally harmful human activities. The conversion of forests into plantations, industrial sites, or settlements significantly contributes to this phenomenon. In particular, the excessive transformation of mangrove forests in coastal areas into aquaculture ponds exacerbates climate change by diminishing carbon absorption and storage while increasing greenhouse gas emissions. Mangrove ecosystems play a crucial role in mitigating climate change, as they effectively sequester CO_2 and can store up to 296 tons of carbon per hectare. This carbon sequestration and storage processess continues over decades, as the mangrove and their understory plants remain healthy and alive, and organic matter decomposition within their root systems is minimized. These factors underscore the vital importance of preserving mangrove ecosystems across coastal and saline-affected riverine areas (Chatting et al. 2022; Choundary et al. 2022; Suratman 2008).

Mangrove ecosystems possess diverse potentials, including physical, economic, and ecological benefits (Fikri et al. 2023). As wetland forests, mangroves have a remarkable ability to absorb and store more carbon than many other plant types, making them vital for mitigating carbon emissions (Purnobasuki 2012). However, land use changes have diminished their role as effective CO_2 reservoirs. Efforts to improve land use on the north coast of Java Island have introduced silvofishery systems, where mangroves are planted in aquaculture pond areas (*e.g.,* Fitzgerald 2002; Musa et al. 2020; Sumarga et al. 2022). While promising, the success of mangrove growth in these systems often faces challenges due to habitat incompatibilities with aquaculture practices. This highlights the need for comprehensive monitoring to ensure mangrove habitats are appropriately managed and developed.

Monitoring the temporally changing and tide-prone mangrove habitats rendered direct survey methods ineffective due to time and cost constraints, leading to the development of remote sensing-based mangrove monitoring (Maurya et al. 2021). Advances in remote sensing facilitated rapid mangrove mapping with diverse observational data coverage, complex classifiers, and cost-effective, efficient methods suitable for physically inaccessible areas (Baloloy et al. 2020). Geographic Information System (GIS) emerged as a commonly used tool for vegetation monitoring, capable of visualizing and analyzing spatial data through satellite imageries. Various vegetation indices and multispectral image analyses were employed to assess changes in mangrove cover, proving effective for monitoring mangroves and their relation to CO2 emission uptake.

This research focused on the mangroves in the silvofishery area of Sawah Luhur Village, Kasemen District, Serang Regency, Banten Province. Therefore, the study aims to (1) analyze the spatiotemporal changes in mangrove area and carbon stocks from 2016 to 2023 in the Sawah Luhur Village silvofishery area and (2) to visualize carbon stock maps in silvofishery land using the Earth Engine Apps platform, specifically Data Indo InaC. The research provided spatiotemporal assessments of the changes in mangrove area and carbon stocks, highlighting the importance of mangroves in carbon sequestration. The findings may support the development of mangrove conservation strategies and promote sustainable community development based on silvofisheries in the northern Java coastal areas.

MATERIALS AND METHODS

Study Area

The study site is located on the coast of Serang City, Banten Province, precisely in Sawah Luhur Village. The study site is a silvofisheries area which is a mangrove rehabilitation area. Geographically, Sawah Luhur Village is located on the north coast of Java Island. The study area is a farming landscape dominated by silvofisheries. A map of the study area is shown in Figure 1.

Data Source and Research Flow

The data utilized for monitoring the area and carbon uptake of mangroves consist of Sentinel-2 MSI images. Launched by the European Space Agency (ESA), Sentinel-2 images are designed to monitor Earth's surfaces and feature 13 multispectral bands with spatial resolutions ranging from 10 to 60 meters, acquired within an eight-day cycle (ESA 2024; Martimort et al. 2007). The specific bands included in the Sentinel-2 MSI images are detailed in Table 1. These images were obtained from Google Earth Engine (GEE) cloud computing storage. Additionally, administrative boundary data for Serang City were sourced from the Geospatial Information Agency (BIG). This research primarily estimates carbon storage using geospatial modelling to derive spatiotemporal mangrove carbon storage data, which is visualized on a platform called DataIndo InaC. The research flowchart is presented in Figure 2.

Figure 1. Study location map

Table 1. Spectral bands on Sentinel-2 MSI

Band Number	Band Description	Wavelength Range	Resolution
B1	Ultra Blue (Coastal aerosol)	433 nm – 453 nm	60 m
B2	Blue (B)	458 nm – 523 nm	10 m
B3	Green (G)	543 nm – 578 nm	10 m
B4	Red (R)	650 nm – 680 nm	10 m
B5	Red-Edge 1 (Re1)	698 nm – 713 nm	20 m
B6	Red-Edge 2 (Re2)	733 nm – 748 nm	20 m
B7	Red-Edge	773 nm – 793 nm	20 m
B8	Near Infrared (NIR)	785 nm – 900 nm	10 m
B8a	Near Infrared narrow (NIRn)	855 nm – 875 nm	20 m
B9	Water vapor	935 nm – 955 nm	60 m
B10	Shortwave Infrared/Cirrus	1360 nm – 1390 nm	60 m
B11	Shortwave Infrared 1 (SWIR1)	1565 nm – 1655 nm	20 m
B12	Shortwave Infrared 2 (SWIR2)	2100 nm – 2280 nm	20 m

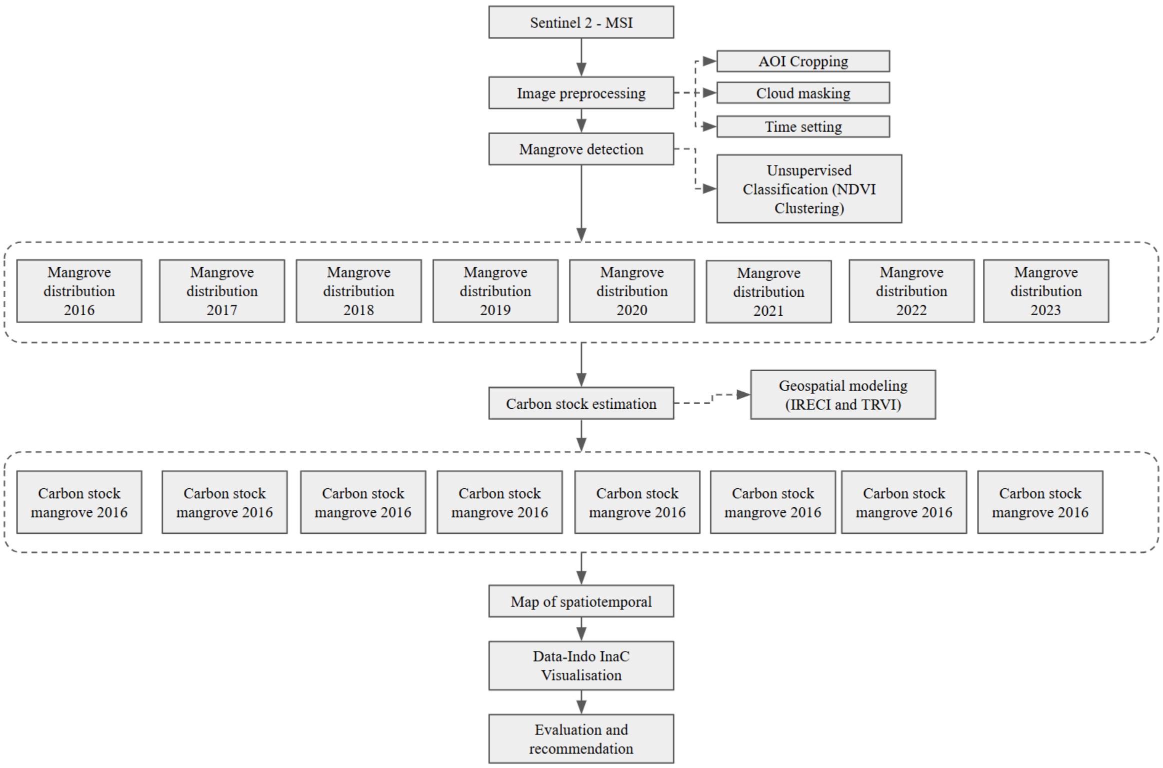

Figure 2. Research flow chart

Mangrove Detection

Mangrove detection using unsupervised classification method NDVI clustering. The area used is a pond landscape that has only two types of land cover, namely water bodies and mangrove vegetation so that by using NDVI clustering mangroves can be detected properly. clustering used as many as 2 clusters of vegetated and non-vegetated land with reference to Marwoto and Ginting (2009). Vegetated areas have NDVI values above 0.3 so that mangrove detection is done by selecting pixels that have NDVI values greater than 0.3.

Mangrove Carbon Estimation

Carbon stock estimation in the study area was conducted using a geospatial approach with reference to Suardana et al. (2023). Suardana et al. (2023) have developed a regression equation from Sentinel - 2 MSI satellite imagery using vegetation indices, namely Inverted Red Edge Chlorophyll Index (IRECI) and Total Ratio Vegetation Index (TRVI), to estimate carbon stocks in the ecosystem. The equation has a high R-square value of 95%. The equation for estimating carbon stocks is presented in equation (1). Meanwhile, IRECI and TRVI were calculated following equations 2 and 3.

$$AGC = 13{,}99 + 104{,}741\,(IRECI) + 3{,}025\,(TRVI) \quad (1)$$

$$IRECI = \frac{(NIR - Red)}{\sqrt{\frac{Red\ Edge\ 1}{Red\ Edge\ 2}}} \quad (2)$$

$$TRVI = \sqrt{\frac{NIR}{Red}} \quad (3)$$

RESULTS

The spatiotemporal monitoring results of coastal mangrove areas are presented in Figure 3. This figure illustrated the distribution of mangroves, predominantly located in the pond regions. Notably, the southern pond areas exhibited a significant increase in estimated carbon levels. The southwest and southeast sections of the ponds transitioned from low, scattered carbon concentrations in 2016, with fluctuating patterns from 2018 to 2021, to a more uniform and compact distribution with relatively high carbon content. These findings indicated that mangrove development in the ponds was stable from 2022 until the end of the observation period.

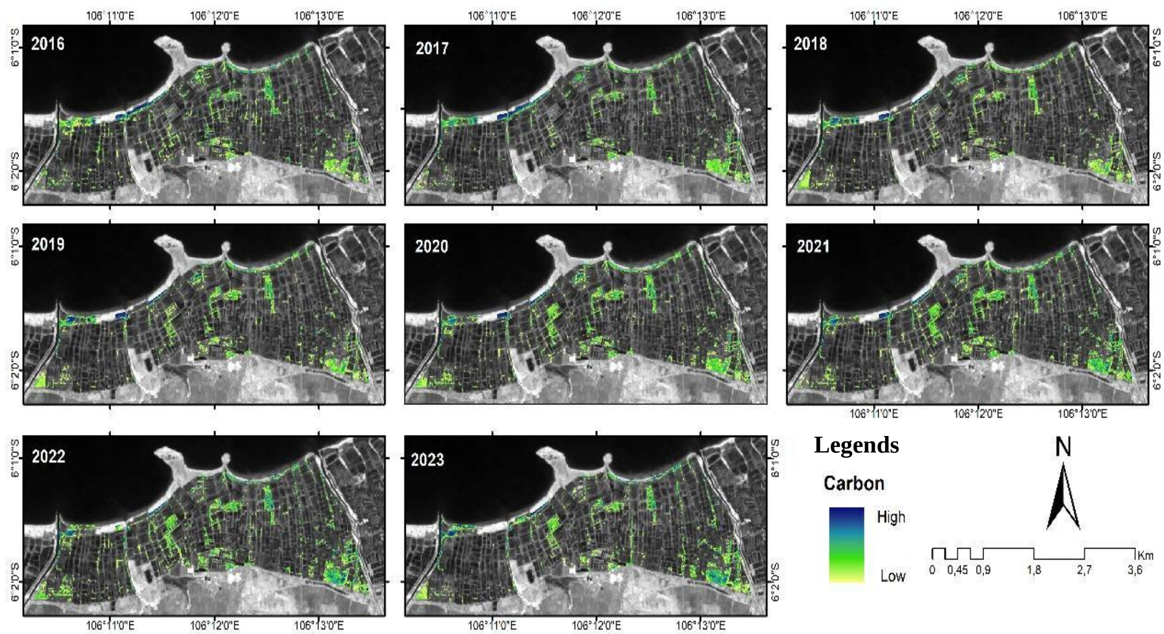

Figure 3. Map of mangrove distribution spatiotemporally

The analysis of mangrove area (Figure 4) and carbon stocks (Figure 5) revealed fluctuations in both metrics from 2016 to 2023. In 2023, the mangrove area within the study site was recorded at 66.82 hectares, reflecting a decrease from 2022. Notably, the mangrove area exhibited a steady increase from 2016 to 2021. Conversely, while mangrove carbon stocks also increased over the study period, which were peaked in 2021 at 456.51 tons, with 2023's total carbon stock amounting to 315.32 tons.

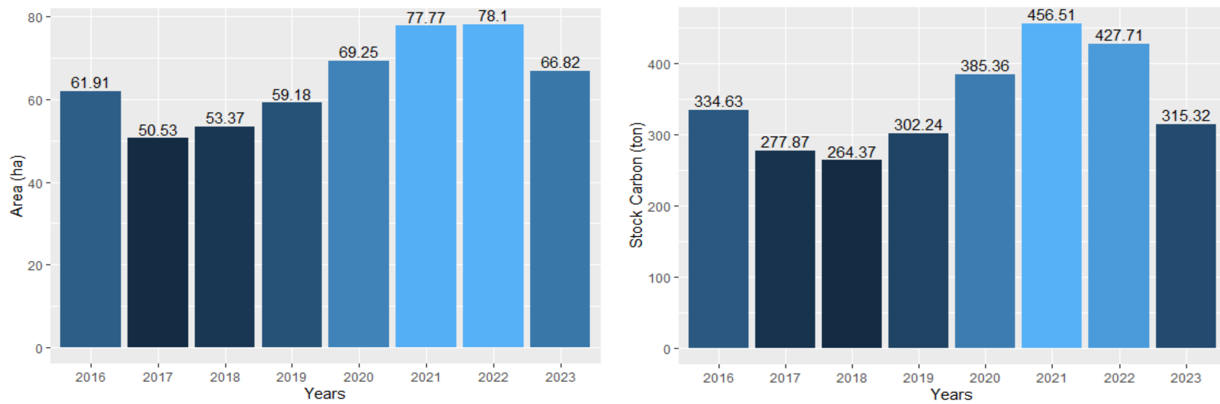

Figure 4. Spatial dynamics of (left) mangrove area and (right) mangrove carbon stocks from 2016 to 2023

The results of the carbon stock analysis in the silvofishery area of Sawah Luhur Village were subsequently input into the carbon monitoring platform and successfully displayed on the platform, Data Indo InaC (Figure 5). Data Indo InaC is a geospatial-based platform that utilizes cloud computing storage available in Earth Engine Apps (EE Apps). This platform enables users who may be unfamiliar with GIS technology to access spatial data that provides information on carbon stocks within an ecosystem.

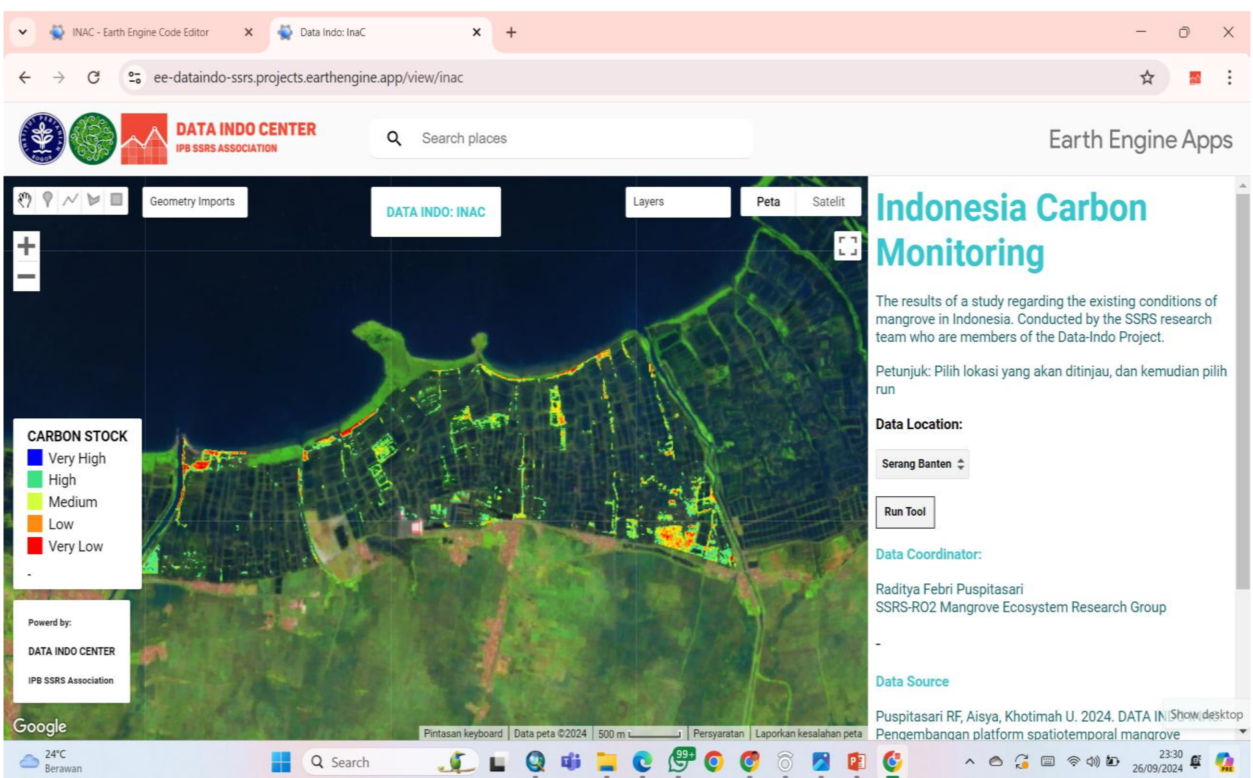

Figure 5. View of Data Indo InaC platform

DISCUSSION

Regional and Ecosystem Conditions of Sawah Luhur Silvofishery

Sawah Luhur is an area located on the coast of Banten Bay, characterized primarily by fish ponds (Figure 1). Other ecosystems present in Sawah Luhur include rice fields, settlements, and mangrove forests (Santoso et al. 2021). The mangrove forest in this region functions as a protective barrier for the ponds owned by coastal communities on the mainland. According to Santoso et al. (2021), the area of ponds in Sawah Luhur Village extends to 507.8 hectares, significantly larger than the mangrove area, which measures only 39.03 hectares. Furthermore, Ilman et al. (2011) reported that the conversion of 511 hectares of mangrove land into ponds in Sawah Luhur Village has led to seawater intrusion extending as far as 4 kilometers inland.

Coastal land use in the form of silvofishery represents a sustainable solution for aquaculture. Silvofishery is a farming system that integrates fisheries with mangrove planting to minimize inputs, reduce environmental impacts, and protect the coastal areas. Development of mangrove ecosystems within pond areas can served as windbreak, attenuated large-waves, and harbored cultivated species like mangrove crabs (Muthoh et al. 2022; Rahmawati et al. 2024; van Hespen et al. 2023). Ecologically, silvofishery presents various advantages, including high carbon stock storage, which contributes to its viability as a sustainable land use scheme (Nesperos et al. 2021). Furthermore, the silvofishery system supplies natural food for cultivated species, thereby enhancing its economic value (Matsui et al. 2024). Research conducted by Parni et al (2020) indicated that aquaculture utilizing the silvofishery method yielded significant economic benefits and improved the survival rate of mangrove crabs. Adni et al (2024) reported that the silvofishery area in Sawah Luhur Village, Serang City, substantially benefited to the surrounding communities, primarily serving as a source of income from pond cultivation.

Distribution of Mangrove Areas and Carbon Sequestration

The results of the spatiotemporal-based mangrove classification analysis indicated notable differences in the distribution and extent of mangrove vegetation cover between 2016 and 2023. Figure 2 illustrated that the distribution of mangroves was predominantly located within the pond area. In 2016, the mangrove distribution was highly fragmented, confined to a few small patches, followed by a decrease in area in 2017. However, after this decline, there was a gradual expansion of mangroves in the pond area until 2020. During the years 2021-2022, mangroves began to spread more widely and uniformly throughout the pond area, suggesting that most regions had undergone effective restoration. In 2023, there was no increase in the distribution of mangrove area compared to previous years; instead, a decrease in mangrove distribution within the pond area was observed. The dynamics of mangrove land cover were influenced by various factors, both ecological and social. Environmental change factors (ecological), such as alterations in salinity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen (DO), significantly impacted the condition of mangrove ecosystems over the long term (Hastuti et al. 2012).

Figure 3 illustrated that mangrove cover in the Sawah Luhur area fluctuated over the years. From 2016 to 2017, mangrove vegetation cover decreased from 61.91 hectares to 50.53 hectares. This was followed by an increase from 2017 to 2022, rising to 78.1 hectares, which was attributed to effective collaboration between the community and Wetlands International Indonesia in conservation efforts (Hikmawan & Iqbal 2023). However, in 2023, the area decreased again to 66.82 hectares. The reduction in mangrove area on silvofishery land indicated a failure in planting efforts, while the increase suggested successful restoration. This finding aligned with the research conducted by Anurogo et al. (2018), which reported 44.70% damage and 23.76% severe damage to the mangrove ecosystem in Banten Bay. Additionally, the conversion of 511 hectares of mangrove land into ponds in Sawah Luhur Village resulted in seawater intrusion extending 4 kilometers inland (Ilman et al. 2011).

Figure 4 shows that the total carbon content of mangrove areas has different values every year. There was a decrease in carbon content from 2016 - 2018 then an increase from 2019 - 2021, and a decrease again in 2022 - 2023. The calculation results show that the carbon stock with the highest value occurs in 2021 with a carbon content value of 460 ca, while for the lowest amount of carbon content occurs in 2018 with a carbon content value of 260 ca. The increase and decrease in mangrove cover area is proportional to the amount of carbon stock in the study area.

Mangroves constituted vital ecosystems that fulfilled essential roles in the maintenance of coastal stability, with their functions delineated into three primary dimensions: ecological, economic, and social (Kustanti 2011). These ecosystems were extensively distributed across coastal and aquaculture regions, frequently integrated with fisheries through practices such as silvofishery. Furthermore, mangroves were often situated adjacent to agricultural lands in coastal areas (Rahmawati et al. 2024) and were predominantly found in river estuaries characterized by abundant sediment, which provided critical nutrients for the growth of mangrove vegetation. The mangrove ecosystems within these estuaries underwent natural succession, thereby enhancing their resilience and biodiversity (Dzulfigar et al. 2024).

Nevertheless, mangrove ecosystems, particularly on the island of Java, encountered significant challenges, primarily attributable to degradation. This degradation was frequently driven by land clearing for aquaculture and alterations in land use (Asy'ari et al. 2023). The loss of mangrove forests engendered profound implications for greenhouse gas emissions and climate change. Research conducted by Arifianti et al (2022) revealed that the deforestation of mangrove forests in Indonesia resulted in higher greenhouse gas emissions compared to the deforestation of tropical forests, with the rate of mangrove deforestation in the country remaining alarmingly elevated. Consequently, it became imperative to undertake restoration efforts for mangrove ecosystems, which possessed the potential to sequester substantial quantities of carbon. Such restoration initiatives could have conferred benefits upon approximately 74 million coastal residents and contributed to a reduction in national land sector emissions by as much as 16% (Sasmito et al. 2023).

Mangroves exhibited a remarkable capacity to store substantial carbon stocks. In addition to sequestering carbon in the form of tree biomass, mangrove ecosystems also retained carbon reserves within soil sediments. According to Kusumaningtyas et al (2019), mangrove ecosystems in Indonesia demonstrated carbon reserves ranging from 167 to 1,722 tons of carbon per hectare. Furthermore, the restoration of mangrove ecosystems played a critical role in mitigating climate change by enhancing carbon dioxide absorption. This restoration process facilitated carbon uptake through the carbon flux mechanism, wherein the carbon flux in restored areas derived from the Net Primary Production (NPP) of the ecosystem, which represented the accumulation of organic matter resulting from tree growth and litter production. Restored mangrove areas exhibited a heightened capacity for carbon absorption due to their relatively low ecosystem respiration rates, which corresponded to reduced carbon dioxide efflux (Sidik et al. 2019).

The results of this study indicated that the application of geospatial technology and remote sensing approaches effectively demonstrated that mangrove restoration efforts in Sawah Luhur, Serang Regency, Banten, enhanced carbon reserves and absorption. Remote sensing technology proved capable of accurately detecting and estimating mangrove carbon reserves. The investigation conducted by Patill et al (2015) reported an accuracy level of 96.4% when comparing the remote sensing method with traditional land inventory techniques. Furthermore, the utilization of geospatial technology facilitated the detection of mangrove distribution with commendable accuracy exceeding 80% (Dzulfigar et al. 2024; Rahmawati et al. 2024; Asy'ari et al. 2022).

Data Indo InaC Platform

The results of the carbon stock analysis conducted in the silvofishery area of Sawah Luhur Village were successfully presented on the Indo InaC Data platform, which can be easily accessed using GEE cloud computing https://ee-dataindo-ssrs.projects.earthengine.app/view/inac. This platform effectively displayed the carbon stock reserves within the study area, employing a color spectrum on the map to differentiate carbon stocks: blue indicated very high carbon stocks, yellow signified medium levels, and red denoted areas with very low carbon stocks. As an Earth Engine Apps-based platform, it provided a user-friendly interface for data utilization, featuring several tools such as a legend and location selection.

This platform demonstrated significant potential for the development of a comprehensive monitoring system for carbon uptake in Indonesia, thereby serving as a database for carbon stocks across various ecosystems. In comparison to other platforms, it uniquely offered data on mangrove carbon reserves. This platform served as an alternative platform besides other current global and regional mangrove monitoring information systems, like Global Mangrove Watch (Bunting et al. 2022; https://www.globalmangrovewatch.org/), NASA-based mangrove monitoring systems (Lagomasino et al. 2019; Simard et al. 2019; Simard et al. 2024), UN biodiversity land use map (https://map.unbiodiversitylab.org/earth) and MapBiomass Indonesia (https://platform-map.nusantara.earth/). However, despite its numerous advantages, the platform exhibited certain limitations, particularly in its provision of temporal data, as it currently supplied only spatial distribution information. Furthermore, the carbon estimation relied on models derived from existing literature, underscoring the necessity for the development of a more robust carbon estimation methodology that integrated field methods with spatial technology.

CONCLUSIONS

The spatiotemporal analyses revealed that the total area of mangroves experienced fluctuations between 2016 and 2023. The largest recorded area of mangroves occurred in 2022, measuring 78.1 hectares, while the smallest area was noted in 2017, at 50.53 hectares. The estimated carbon reserves in 2023 amounted to 315.32 tons of carbon. The observed increases and decreases in mangrove area were found to be proportional to the availability of carbon reserves within the mangrove ecosystem. The results of the analyses were presented on the Indo InaC Data platform in the form of a time series, facilitating the monitoring of both the area and carbon storage of the mangrove ecosystem. The final outcomes of this monitoring process are anticipated to serve as a valuable resource for ongoing efforts to oversee mangrove areas, thereby contributing to strategies aimed at mitigating and preventing damage to mangrove ecosystems in silvofishery lands. Additionally, these efforts support the maintenance of climate stability and align with Sustainable Development Goal 13 (SDG 13) on Climate Action, which seeks to protect the Earth from environmental degradation.

ACKNOWLEDGMENT

The authors would like to thank the IPB SSRS Association for facilitating this research.

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