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Integrating Blue Carbon Estimation into Mangrove-Based Coastal Protection Infrastructure Planning: A Case Study in Dompak Island, Tanjungpinang

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Abstract

Ecosystem-based coastal protection offers a strategic approach to mitigating the impacts of climate change, particularly in small island contexts. This study integrates remote sensing and geospatial analysis to estimate blue carbon stocks in the mangrove ecosystems of Dompak Island, Tanjungpinang, using Google Earth Engine (GEE) and Sentinel-2 satellite imagery. Through the application of the Normalized Difference Vegetation Index (NDVI) and an empirical model for Above Ground Biomass (AGB), spatial carbon stock distributions were generated and classified into three functional zones: conservation, restoration, and critical protection. Results reveal that areas with moderate vegetation exhibit the highest carbon stock (32.00 tons/ha), suggesting ongoing biomass accumulation. This spatial analysis informs a zoning framework that supports ecosystem-based infrastructure planning. The integration of carbon mapping with adaptive civil engineering strategies demonstrates a scalable model for climate-resilient coastal development in vulnerable regions.

Keywords: Blue carbon, mangroves, Google Earth Engine, coastal protection, natural infrastructure

1. Introduction

Coastal ecosystems in Tanjungpinang are are increasingly threatened by anthropogenic pressures, including trade expansion, urban development, and infrastructure growth[1]. Among the most affected habitats are mangrove forests, which face degradation due to illegal logging and land conversion. These environmental changes exacerbate coastal erosion, increase flood risks, and compromise marine biodiversity, ultimately threatening the livelihoods of local communities—particularly indigenous groups such as the Suku Laut in the Riau Archipelago[2]. Environmental decline hampers access to food and other livelihood sources, heightens vulnerability to natural disasters, and worsens socio-economic conditions—ultimately hindering sustainable development in coastal areas[3].

Mangroves play a critical role in coastal resilience. Their complex root systems attenuate wave energy, reduce shoreline erosion, and support sediment stability. Their dense root systems trap sediments, strengthen soil structures, and provide habitats for various marine species. Moreover, mangrove forests are recognized for their substantial carbon sequestration potential, storing carbon both above ground in biomass and below ground in soils. This makes them pivotal in global climate change

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mitigation strategies[4]. Despite their ecological and socio-economic value, ecological parameters like blue carbon stocks are often excluded from infrastructure planning.[5]. They can store substantial amounts of carbon, both in their aboveground biomass and in the soil. This carbon sequestration capability makes mangroves a vital component in climate change mitigation and greenhouse gas emission reduction strategies[6].

One of the key challenges in coastal protection efforts is the lack of integration of ecological data such as information on mangroves and other coastal ecosystems into civil engineering planning and design. The disconnect between civil engineering and environmental data can lead to poorly adapted developments that fail to protect coastal ecosystems or mitigate climate-related hazards. Bridging this gap requires an integrated approach that combines ecological assessment, spatial analysis, and engineering design to foster resilient, nature-based coastal infrastructure. Collaboration among scientists, engineers, and policymakers can lead to more holistic and sustainable coastal management solutions. Integrating ecological data into infrastructure design enhances coastal resilience to climate change impacts[7].

Estimating blue carbon defined as the amount of carbon stored in coastal ecosystems such as mangroves is essential for recognizing the ecological and economic value of these habitats. Such data can inform coastal protection planning, conservation zoning, and the development of ecosystem-based climate change mitigation strategies[8]. Incorporating blue carbon estimations into coastal protection plans enables more informed and sustainable decision-making. This integration supports the development of policies that acknowledge the critical role of coastal ecosystems in climate mitigation and land protection. Consequently, mangrove conservation and restoration efforts not only protect the environment but also deliver economic and social benefits to coastal communities.

Google Earth Engine (GEE) has emerged as a powerful tool for monitoring coastal vegetation dynamics, particularly in mangrove ecosystems. Its ability to access and process satellite imagery efficiently enables robust spatiotemporal analyses of land cover changes. For example, a study in Probolinggo utilized Sentinel-2A imagery and NDVI in GEE to monitor mangrove extent from 2019 to 2023, revealing significant fluctuations linked to human activity and environmental factors[9]. The Normalized Difference Vegetation Index (NDVI) is a widely used indicator for evaluating vegetation health and canopy density. In the context of mangroves, NDVI helps identify areas experiencing significant degradation or growth. A study by Bagas [10] employed MODIS data in GEE to visualize NDVI changes across Indonesia between 2018 and 2022, offering insights into national vegetation dynamics. The integration of GEE and NDVI enables efficient detection of mangrove change. Research in Bekasi Regency used Landsat 8 imagery and GEE to map a decade of mangrove change, uncovering concerning deforestation trends. This approach provides accurate data for coastal ecosystem conservation and rehabilitation planning[11].

The use of machine learning algorithms in GEE further enhances mangrove vegetation mapping accuracy. Recent studies have shown that combining Sentinel-1 and Sentinel-2 imagery with the Random Forest algorithm in GEE produces highly accurate mangrove maps, supporting coastal resource management and conservation efforts[12]. Despite the many advantages of GEE and NDVI, challenges such as limited spatial resolution and the need for representative training data persist. Nevertheless, advancements in technology and improved satellite data access continue to expand the opportunities for enhanced coastal ecosystem monitoring and management.

2. Method

This study was conducted along the coastline of Dompak Island, Tanjungpinang, located in the Riau Archipelago Province, Indonesia. Dompak Island was selected as the study site due to its extensive mangrove forests, strategic position as the centre of government for the Riau Islands Province, and ongoing development pressures on coastal ecosystems. The research method employed a spatial analysis approach using the Google Earth Engine (GEE) platform. The primary data source was Sentinel-2 multispectral imagery, which offers 10-meter spatial resolution in visible and near-infrared bands suitable for vegetation analysis. The study used imagery from the year 2023, selected based on minimal cloud cover to ensure optimal vegetation visualization. The workflow consisted of several key stages:

1. *Preprocessing Satellite Imagery*

   Sentinel-2 Level-2A imagery was accessed via GEE. Cloud masking was applied using the QA60 band and the s2cloudless function to eliminate cloud-covered pixels.

2. *Mangrove Detection and NDVI Calculation*

   Mangrove distribution was identified through the Normalized Difference Vegetation Index (NDVI), calculated using the red (Band 4) and near-infrared (Band 8) wavelengths as follows:

   $NDVI = \frac{(NIR-RED)}{(NIR+RED}$……………….(1)

   Threshold values were determined based on visual interpretation and previous studies, with NDVI > 0.4 indicating healthy and dense mangrove vegetation.

3. *Blue Carbon Estimation*

   To estimate blue carbon stock, NDVI values were converted to Above Ground Biomass (AGB) using an empirical linear model adapted from literature on tropical mangroves.

   AGB=a·NDVI+b………………………….(2)

   The AGB values (in tons/ha) were then converted into carbon stock using a biomass-to-carbon conversion factor of 0.47. Finally, the carbon stock values were converted into CO_2 equivalent (CO_2e) using the IPCC standard factor:

   $CO_2e = C \times 3.67$………………… ..(3)

   This allowed for spatial visualization of blue carbon potential across Dompak's coastal zone.

4. *Zoning for Coastal Protection and Restoration*

   Based on NDVI and carbon distribution maps, the coastal area was categorized into three ecological zones:

   a. Conservation Priority Zones: High NDVI and carbon stock
   b. Restoration Zones: Moderate NDVI with potential for rehabilitation
   c. Critical Zones: Low NDVI and degraded vegetation requiring urgent intervention

The results of this zoning provide guidance for planning ecosystem-based coastal infrastructure and targeted mangrove conservation. The overall workflow of this research is illustrated in Figure 1, which outlines each step from literature review and data acquisition to spatial analysis and interpretation. This structured methodology ensures a comprehensive assessment of blue carbon estimation in mangrove ecosystems using remote sensing and geospatial techniques.

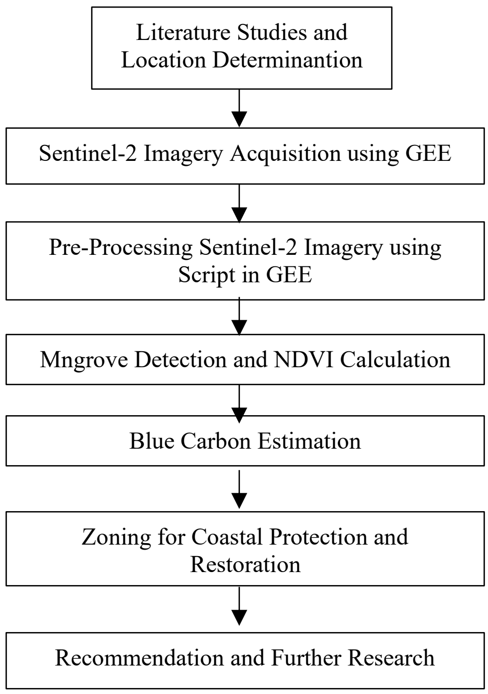

Figure 1. Flowchart of the research methodology.

3. Results and Analysis

3.1 Mangrove Distribution Map and Estimated Carbon Stock per Hectare

The spatial distribution of mangrove vegetation across Dompak Island was effectively mapped using Sentinel-2 imagery combined with Normalized Difference Vegetation Index (NDVI) thresholding techniques. This remote sensing approach enabled a clear classification of mangrove density into distinct categories: non-mangrove, sparse, moderate, and dense vegetation cover. Figure 2 illustrates the NDVI-based mangrove density map, where various shades of green correspond to different levels of vegetation health and density. The darker green areas represent dense mangrove coverage, while lighter shades indicate moderate to sparse vegetation. Grey areas denote regions identified as non-mangrove. This classification provides valuable insight into the spatial variability of mangrove ecosystems and their extent across the island. The map also reveals key areas with degraded or less vegetated zones, offering essential baseline information for future conservation planning, restoration initiatives, and blue carbon stock estimation efforts.

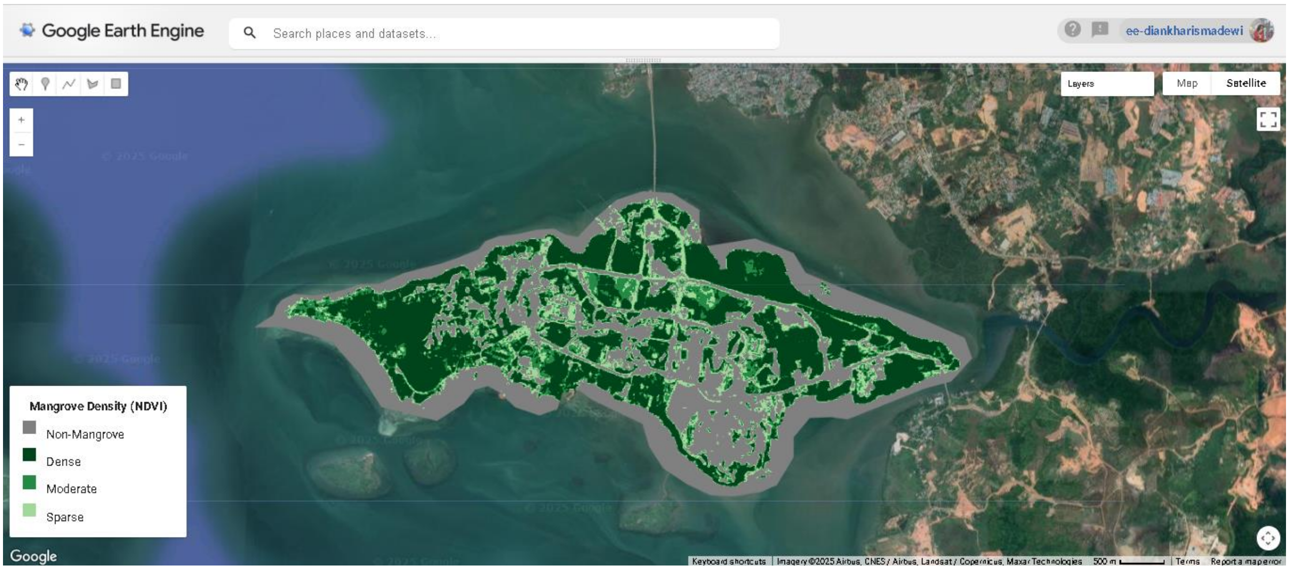

Figure 2. NDVI Mapping of Dompak Island

Based on processed data, the total area covered by mangrove in the study location was estimated at 1078.45 hectares, primarily concentrated along the coastal fringes of Dompak Island. Using established NDVI-to-AGB and AGB-to-carbon stock conversion models, the average carbon stock per hectare was estimated to be 35.965 tons/ha, with values ranging from 0 to 45 tons/ha. This corresponds to an average CO_2 equivalent (CO_2e) of 530.81 tons/ha. Compared to previous mangrove studies in Benoa Bay, Bali, which reported carbon stocks ranging from 55–90 tons/ha[13], Dompak's average reflects moderate sequestration potential, possibly influenced by anthropogenic pressures and fragmented canopy cover. Table 1 summarizes the spatial statistics of mangrove zones categorized by vegetation density and carbon stock level. These results highlight key areas of carbon sequestration and can guide conservation and zoning efforts.

Table 1. Summary of Carbon Estimation Results in Dompak Island

NDVI Class	Average Carbon Stock (tons/ha)	Average CO_2e (tons/ha)
> 0.6 (Dense)	16.13	27.82
0.3–0.6 (Moderate)	32.00	58.40
< 0.3 (Sparse)	12.50	21.60

Notably, the moderate NDVI class (0.3–0.6) exhibits the highest average carbon stock (32.00 tons/ha) and CO_2e equivalent (58.40 tons/ha), indicating that these zones play a particularly significant role in carbon storage despite not having the densest vegetation cover. This may reflect optimal growing conditions or restoration zones with active biomass accumulation. In contrast, areas with dense vegetation (NDVI > 0.6), though ecologically mature, show slightly lower average carbon values (16.13 tons/ha), which could be attributed to saturation in biomass accumulation or variation in species structure. Meanwhile, sparse vegetation zones (NDVI < 0.3) contribute the least to carbon stock (12.50 tons/ha), underlining their vulnerability and the need for targeted restoration efforts. These distinctions emphasize the dynamic relationship between vegetation health, as indicated by NDVI, and ecosystem service provisioning, especially in terms of blue carbon potential.

3.2 Spatial Interpretation: Priority Areas for Protection/Restoration

To determine priority areas for mangrove protection and restoration, spatial analysis was conducted using the carbon stock estimation layer derived from Sentinel-2 imagery. The entire workflow was performed using Google Earth Engine (GEE), enabling efficient processing of high-resolution satellite data. The resulting carbon stock map revealed that high-density mangrove zones, typi cally with stock values exceeding 40 tons/ha, were concentrated in the Notheast coastal segments of Dompak Island. These areas are high-priority for conservation. Conversely, fragmented or cleared areas with carbon stock below 30 tons/ha were identified as restoration zones.

This classification aligns with studies by Alongi [14], which demonstrate that dense mangrove forests not only store carbon but also attenuate wave energy, stabilize shorelines, and enhance coastal protection. Integrating these insights with zoning enhances both ecological and engineering planning. The resulting carbon stock map was visualized in GEE, revealing distinct spatial patterns across the study area. High-density mangrove zones, typically characterized by carbon stock values exceeding 45 tons/ha, were observed in the Northeast coastal sections of Dompak Island. These zones are considered high-priority for conservation, given their ecological integrity and contribution to carbon sequestration. Conversely, fragmented mangrove patches or cleared areas with significantly lower carbon stock values below 20 tons/ha were identified as potential sites for ecological restoration.

Figure 3 displays the spatial distribution of mangrove carbon stock across Dompak Island, visualized using a color gradient ranging from light yellow (low carbon stock) to dark red (high carbon stock), with values ranging from 0 to 70 tons per hectare.

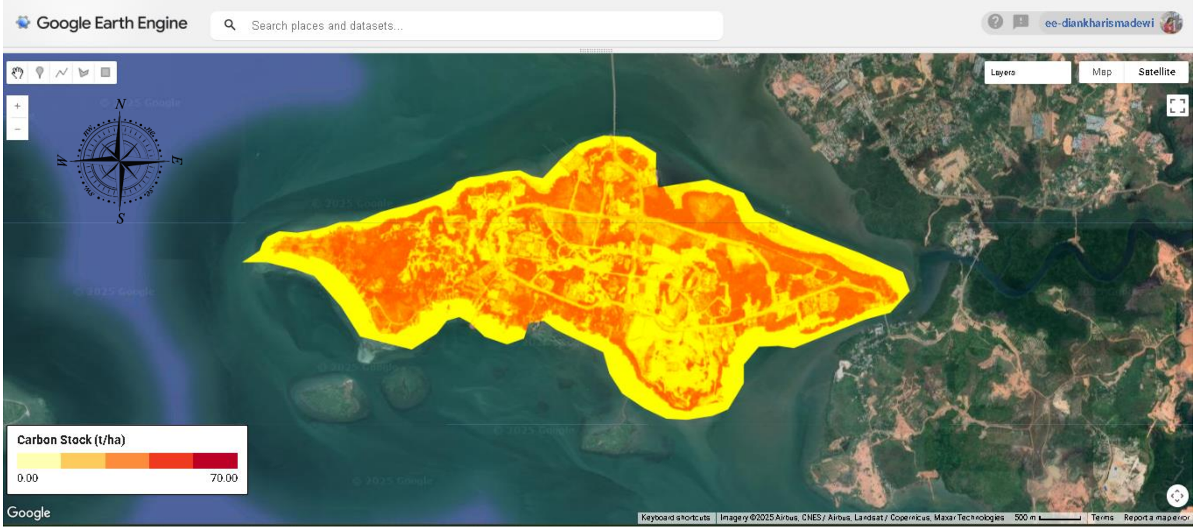

Figure 3. The Carbon Stock Mapping in Dompak Island

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This visualization allows for a nuanced understanding of spatial variability in ecosystem service provisioning. Based on these carbon stock levels; the island can be zoned into three key management categories:

a. High-Priority Protection Zones – Represented by darker orange to red hues, these areas exhibit the highest levels of carbon stock (typically above 50 t/ha) and are likely composed of well-preserved, mature mangrove stands. These zones should be prioritized for strict conservation measures to maintain their carbon sequestration function and ecological integrity.
b. Restoration Potential Zones – Indicated by intermediate orange shades, these areas have moderate carbon stock values (around 20–50 t/ha) and may include degraded or recovering mangroves. Targeted restoration or enrichment planting efforts in these zones could substantially enhance their carbon storage capacity and biodiversity value.
c. Low-Intervention or Monitoring Zones – Highlighted in yellow tones (below 20 t/ha), these regions have minimal carbon stock and likely represent non-mangrove areas, sparsely vegetated land, or regions unsuitable for mangrove establishment. While they may not require intensive intervention, ongoing monitoring is recommended to detect any potential land-use change or degradation.

This classification framework supports informed decision-making for coastal zone management by aligning ecological data with policy action. It offers a practical tool for local authorities and stakeholders to allocate resources efficiently, protect high-value ecosystems, and plan sustainable mangrove rehabilitation programs tailored to spatial priorities.

3.3 Strengths and Limitations of Satellite-Based Approaches

The use of satellite imagery such as Sentinel-2 offers significant advantages in mapping mangrove distribution and estimating carbon stock over large and remote areas with high temporal resolution. The integration with cloud computing platforms like Google Earth Engine enables efficient data processing and repeatability for multi-temporal monitoring. However, limitations still exist. The medium spatial resolution (10 m) may not detect narrow or sparse mangrove belts, especially in fragmented coastlines. Moreover, the biomass estimation relies on empirical models that may not fully account for local species composition or age structure of mangroves. Ground-truthing and integration with LiDAR or UAV data could enhance the accuracy of these estimates in future studies.

3.4 Implications for Civil Engineering: Toward Green Infrastructure Design

The findings of this study underscore the potential of integrating mangrove ecosystems into green infrastructure planning for coastal protection. In civil engineering, this translates into hybrid solutions where mangrove conservation is combined with traditional structures like seawalls or breakwaters to reduce wave impact and erosion. Spatial estimation of carbon stock in mangrove ecosystems serves a dual purpose: informing ecological management and guiding the integration of ecosystem-based approaches into sustainable coastal engineering design.

Based on the mapped results of NDVI and carbon stock, we propose a zoning strategy that aligns ecological conditions with appropriate civil engineering interventions. This study proposes a zoning-based approach to integrate mangrove ecosystem data into coastal engineering. Narayan[15] found that mangrove belts can reduce annual flood damage by over $65 billion globally, emphasizing the economic value of natural infrastructure.

Therefore, hybrid designs that combine mangroves with engineered structures such as bamboo wave breakers or adaptive seawalls are increasingly relevant. These zones—A (Conservation), B (Restoration/Hybrid), and C (Critical Protection)—are aligned with NDVI and carbon stock data. Recommended Zoning and Ecosystem-Based Civil Engineering Strategies:

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a. Zone A – Intensive Conservation
Characteristics: NDVI > 0.6; carbon stock > 60 tons/ha; dense and healthy mangrove cover.
Recommendations:
Designated as a full conservation zone with strict protection measures. No structural interventions are recommended to avoid disturbing the ecosystem balance. Monitoring should be conducted regularly using remote sensing technology to track ecological stability.
Civil Engineering Approach:
Development is not recommended in this zone. Efforts should focus on mapping, delineating protective buffer zones, and reinforcing policy-based conservation.

b. Zone B – Restoration and Hybrid Engineering
Characteristics: NDVI between 0.3–0.6; carbon stock between 30–60 tons/ha; fragmented or sparsely growing mangroves.
Recommendations:
Restoration efforts are recommended, ideally through participatory, community-based reforestation programs. Nature-based solutions such as brushwood dams, bamboo wave breakers, or floating barriers can be introduced to reduce wave energy and promote sediment accumulation.
Civil Engineering Approach:
Apply eco-hydraulic design principles that work with natural processes to support mangrove regrowth. This includes assessing local hydrodynamics and geotechnical conditions to optimize intervention layout and material selection.

c. Zone C – Critical Protection
Characteristics: NDVI < 0.3; carbon stock < 30 tons/ha; exposed to severe erosion or heavy anthropogenic pressure (e.g., settlements, port areas).
Recommendations:
Where necessary, introduce hard coastal protection structures such as lightweight revetments or seawalls. However, these structures should be designed to integrate controlled mangrove planting, thereby establishing a functional green buffer zone.
Civil Engineering Approach:
Employ adaptive engineering designs that can respond to long-term sea-level rise. Favor the use of locally sourced and environmentally friendly materials, and include provisions for ecological enhancement within the structure.

By aligning engineering practices with ecological data, this zonation framework encourages a shift from purely structural approaches to nature-inclusive coastal infrastructure, ultimately supporting both climate resilience and sustainable development goals.

3.5 Zonation Mapping Based on the Case Study in Dompak Island

Based on the spatial mapping results conducted in this study using satellite imagery and processing through Google Earth Engine (GEE), the coastal area of Dompak Island was classified into three main zones according to mangrove health indicators (NDVI) and estimated carbon stock per hectare.

a. Zone A – Intensive Conservation:
Coastal segment located in Northeast of Dompak Coastline shows NDVI values above 0.6 and carbon stock exceeding 60 tons/ha. This area is characterized by dense and healthy mangrove cover, making it a priority for full conservation without structural interventions.

b. Zone B – Restoration and Hybrid Engineering:
The North and Southeast Dompak Coastline] falls into the intermediate category with NDVI between 0.3–0.6 and moderate carbon stock (30–60 tons/ha). Mangrove stands are patchy and fragmented, indicating the need for ecological restoration combined with soft-engineering techniques.

c. Zone C – Critical Protection:
At South-Southwest-West of Dompak Coastline the mapping shows NDVI values below 0.3 and carbon stock less than 30 tons/ha. These areas are under high anthropogenic pressure or are actively eroding, requiring more robust civil

engineering protection such as lightweight revetments or adaptive seawalls.

Figure 4 presents the zonation mapping of Dompak Island, which divides the island into four primary zones—Zone A, Zone B, and Zone C, based on the spatial variation in carbon stock as derived from Sentinel-2 imagery and Carbon Stock-based classification. This zonation approach is designed to facilitate targeted management strategies by aligning ecological characteristics with specific intervention needs.

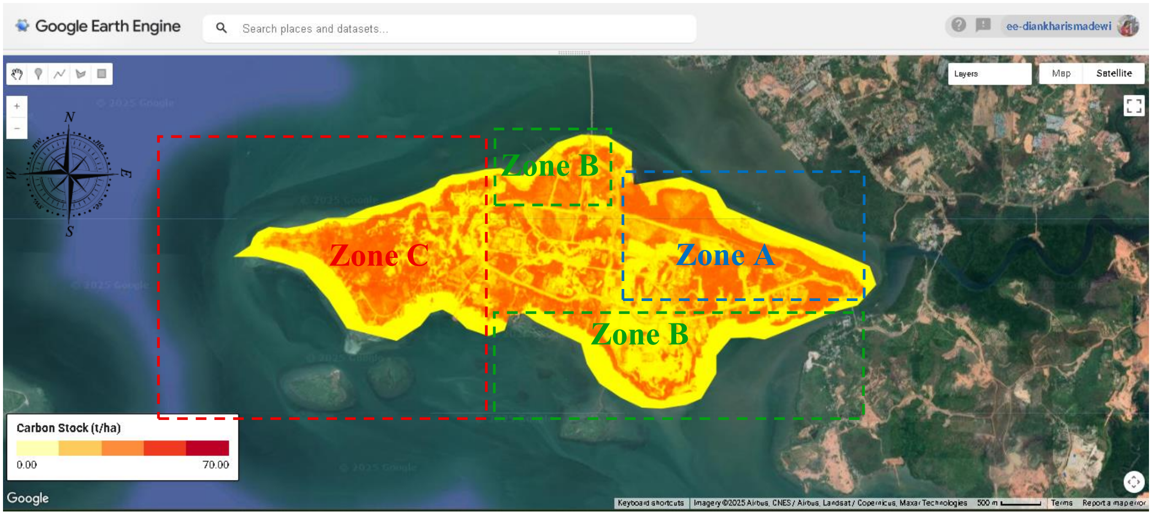

Figure 4. The Zone Mapping in Dompak Island

This zonation provides a spatially explicit recommendation for ecosystem-based coastal protection planning and highlights how remote sensing data can guide targeted engineering strategies. The integration of ecological and engineering parameters supports a sustainable and site-specific approach to coastal infrastructure development. Although this study provides valuable insights through satellite-based estimation, it acknowledges the limitation of not incorporating field-based validation data.

The biomass and carbon stock models rely on generalized NDVI–AGB correlations derived from literature, which may not fully capture local variability in species composition, soil characteristics, or mangrove age structure. Future studies are recommended to incorporate ground-truth measurements and local calibration to improve the accuracy and contextual relevance estimations.

4. Conclusion

This study demonstrates the effectiveness of combining remote sensing and geospatial analysis in estimating blue carbon stock and informing coastal protection planning. By utilizing Sentinel-2 imagery and NDVI in the Google Earth Engine (GEE) platform, we successfully mapped mangrove distribution and quantified carbon stock in Dompak Island's coastal zone. The resulting data enabled the classification of coastal segments into three functional zones conservation, restoration, and critical protection each accompanied by tailored engineering strategies. The integration of ecological indicators with civil engineering recommendations provides a replicable model for sustainable coastal infrastructure planning. This approach bridges environmental conservation with climate-resilient development, especially in areas vulnerable to erosion, sea-level rise, and habitat degradation. Moving forward, incorporating field validation, higher-resolution imagery, and hydrodynamic modelling is recommended to enhance accuracy and inform more robust engineering designs. The findings of this study support the adoption of nature-based solutions and hybrid infrastructure as essential components of coastal resilience strategies.

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