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MACROALGAE AS BLUE CARBON VEGETATION: SEASONAL TRENDS IN BIOMASS AND CARBON STORAGE ON JAVA'S SOUTH COAST

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Abstract
Macroalgae in the rocky intertidal zones of West Java's southern coast provide essential ecosystem services, including carbon storage and marine stability. Using GIS and remote sensing, this study assesses seasonal spatial distribution and carbon sequestration potential of macroalgae across Karapyak, Sindangkerta, and Sayangheulang beaches. Biomass and carbon stocks varied seasonally, with Sargassum and Gracilaria identified as primary contributors. Average carbon stocks ranged from 0.6 to 1.14 tons.ha^{-1} significantly higher than typical Indonesian seagrass levels (0.21–0.23 tons.ha^{-1}). Peak biomass reached 1050 gm^{-2} at Sayangheulang during the dry season, emphasizing macroalgae's ecological roles in productivity and habitat provision. However, environmental degradation threatens these zones, highlighting the need for conservation. The study reinforces the role of macroalgae in blue carbon storage and coastal ecosystem health.

Keywords: Carbon stock, macroalgae, rocky intertidal, seasonal variation, spatial distribution,

Introduction
Blue carbon refers to the capacity of coastal ecosystems to regulate the carbon cycle by acting as high-carbon storage areas, particularly vegetated coastal ecosystems (Macreadie *et al*. 2019). This service specifically denotes the ability of marine ecosystems to absorb and store carbon. Vegetation in these ecosystems can sequester atmospheric CO_2 as biomass and organic matter stored in sediments (Le Quéré *et al*. 2016, McLeod *et al*. 2011). Each year, 20-35% of anthropogenic CO_2 emissions are absorbed by marine ecosystems, and one of the vegetation types supporting this ability is macroalgae.

Macroalgae, along with seagrass, coral reefs, and mangroves, are among the biota acting as blue carbon vegetation, by providing the ecosystem service of carbon storage, which plays a crucial role in mitigating climate change (Macreadie *et al*. 2019, Saravanan *et al*. 2023). Macroalgae contribute to the export of organic carbon to the open ocean, amounting to 2.4 billion tons per year. Of the total net primary production of macroalgae, approximately 11%—equivalent to around 173 million tons annually—is stored as carbon within macroalgal vegetation. This is comparable to the carbon stored by all other blue carbon sources combined (Barrón & Duarte 2015, Duarte *et al*. 2013, Krause-Jensen & Duarte 2016). Macroalgae not only support carbon storage but also serve as key components of biogeochemical cycles by the process of absorbing and releasing organic matters that indirectly enhance sediment stability and nutrient recycling in coastal ecosystems, as observed in mangroves and seagrasses (Cai *et al*. 2024a). Such mechanisms highlight their role in improving coastal resilience against erosion and eutrophication (Cai *et al*. 2024a,b).

Macroalgae occupy the intertidal zone, an area subjected to tidal fluctuations, where only 0.01% of photosynthetic light is available (Agarwal *et al*. 2020). They attach to various substrates, such as sand and mud, as well as hard substrates like rocks and coral fragments. Given their occurrence in areas subject to tidal currents, disruptions in rocky intertidal zones are likely to significantly impact macroalgae populations. Research related to the condition of macroalgae in rocky intertidal habitats on the south coast of West Java is still needed, particularly regarding macroalgae biodiversity and community structure (Handayani 2019, 2020; Soedjiarto & Albuntana 2010).

Macroalgae are an abundant resource in Indonesian waters, occurring over an area of 1.2 million hectares. The south coast of West Java, with a coastline length of 398 km directly connected to the Indian Ocean, the waters of West Sumatra, and the Sunda Strait, experiences dynamic conditions. In this region, rocky coastlines foster macroalgae adaptation to environmental factors such as wave strength, tides, nutrient fluctuations, and water quality (Pratama *et al*. 2015). The various aspects and potential benefits of macroalgae on the south coast of West Java provide the basis for the importance of conducting research on the extent of their carbon sequestration potential in different seasons.

This study aims to evaluate the seasonal variations in biomass and carbon storage of macroalgae in the rocky intertidal zones along the southern coast of West Java, providing critical insights into their role as blue carbon agents and the environmental factors influencing their ecological function.

Materials and methods

The field data collection was carried out over 1 year to observe the change of macroalgal condition across the seasons. Data collection took place in July-September for the dry season and in November-January for the wet season. The data collection locations were in the upper intertidal zone on three rocky substrate beaches: Sayangheulang Beach, Garut Regency (7°38'36.84"S, 107°40'57.94"E), Sindangkerta Beach, Tasikmalaya Regency (7°45'54.60"S, 108°3'35.88"E), and Karapyak Beach, Pangandaran Regency (7°41'43.16"S, 108°45'29.51"E). (Fig. 1). Rocky substrate beaches have a high probability of abundant macroalgae, which helps with effective integration of field data with remote sensing methods.

Macroalgae sampling. A geographic information system (GIS) was used to design the field sampling strategy, with a total of 158 sample sites distributed across the three beaches. Sample sites were purposively selected to represent the full range of NDVI values observed in the intertidal zone, using PlanetScope imagery, in order to capture spatial variation in macroalgal cover.. Field data was collected using the quadrant transect method with 1x1 m square plots. Subsequently, the collected macroalgae samples underwent analysis to quantify species composition, biomass, and carbon storage potential. Environmental parameters (temperature, pH, salinity, and dissolved oxygen) were measured *in situ* at each designated observation plot, and a Kruskal-Wallis test was conducted to test the significance of differences between the two seasons. Rainfall data was extracted to measure the extent of the seasonal differences.

Biomass and carbon stock of macroalgae. The calculation of macroalgae biomass was carried out using the following equation (Sidik *et al*. 2001):

$$\text{Biomass} = \frac{\text{Dry Weight (g)}}{Area\ (m^2)}$$

Explanation: Dry weight: weight after oven-drying for 48 hours at 80°C; Area: Cross-sectional area of the transect.

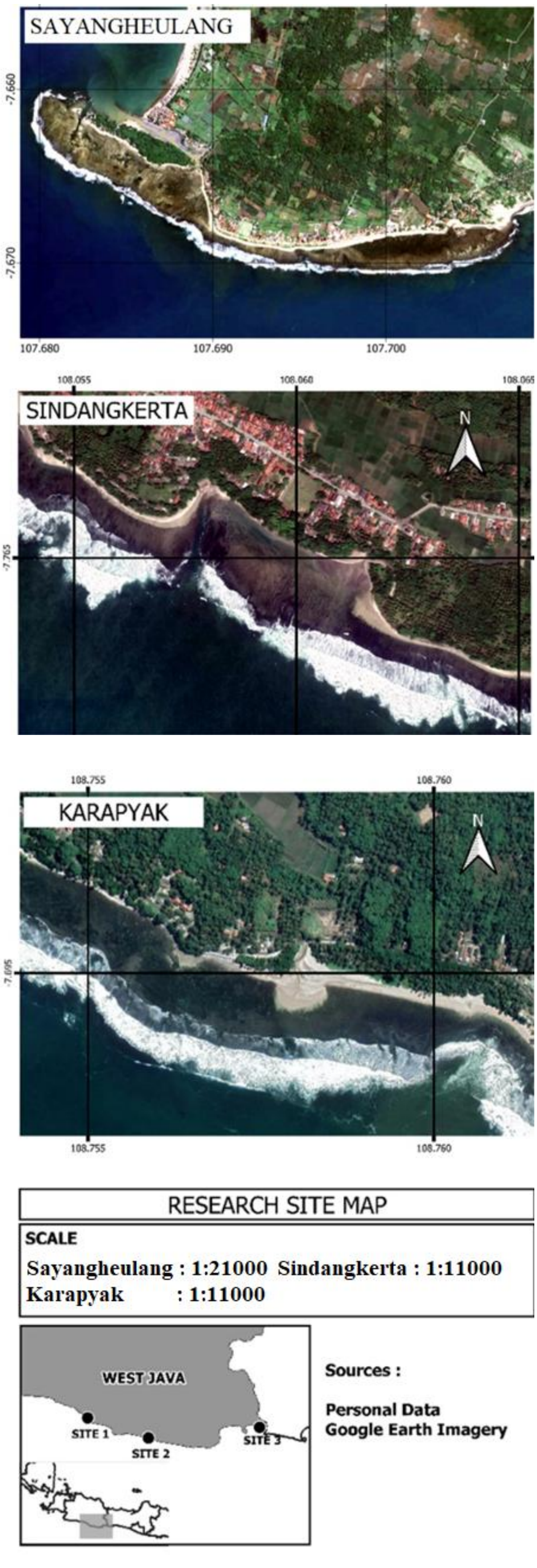

Figure 1. Rocky intertidal zone at three study sites: Sayangheulang Beach, Sindangkerta Beach, and Karapyak Beach on Java, Indonesia.

The amount of carbon stored by macroalgae was determined by subjecting 0.1 grams of dried macroalgae to the Walkley and Black method of carbon measurement (Michael 1995). Both of these equations were applied to all field samples, and extrapolation was performed to determine the macroalgae biomass. Extrapolation employed the inverse distance weighted (IDW) algorithm in GIS software.

Spatial Distribution and Estimation of Macroalgae Carbon Stock Spatial distribution and estimation of macroalgae carbon stock. The spatial distribution of biomass was visualized by plotting geo-referenced scatter points representing measured macroalgae biomass values obtained from field data sampling. These data points were then interpolated using the Inverse Distance Weighting (IDW) method within a GIS platform to generate continuous surface maps illustrating the local distribution of macroalgal *biomass* (Faizal *et al*. 2012). The estimation of macroalgae carbon stock was integrated with data on carbon storage values and pixel values from the NDVI classification and PCA transformation. Principal Component Analysis (PCA) is a descriptive statistical method used to maximize the information in a dataset. PCA values are generated through linear combinations of the original variables, resulting in synthetic indices that effectively summarize the data (Legendre & Legendre 2012).

Ecological Status Group (ESG) and Importance Value Index (IVI). The ESG is part of the Ecological Evaluation Index (EEI) used to estimate the ecological condition of areas undergoing transition from natural to degraded states, using macrophytes—specifically macroalgae—as biological indicators (Sup. Table 1). This ecological gradient begins with the dominance of late-successional macroalgae, characteristic of natural and stable environments, and shifts toward degraded conditions characterized by the dominance of the opportunistic category of macroalgae, which are fast-growing, short-lived species that tend to thrive under nutrient enrichment and other anthropogenic pressures(Orfanidis *et al*. 2011).

The IVI can show how dominant a species is in an ecosystem and the significance of the role of that species in the vegetation of a community (Asigbaase *et al*. 2019). The collected data were analyzed to determine relative density (RD), relative cover (RC), and relative frequency (RF), and these three data were summed to calculate the Importance Index (Pratiwi *et al*. 2018).

Results

Environmental Conditions. The Kruskal-Wallis test revealed significant seasonal differences in pH, salinity, dissolved oxygen (DO), and light intensity ($p<0.05$). The pH value in the dry season was more acidic than in the wet season, while salinity in the wet season decreased compared to the dry season. The oxygen content in the wet season showed a notable increase compared to the dry season, and the same trend was observed for light intensity. Conversely, temperature showed no significant seasonal variation, although a slight increase was observed during the wet season (Sup. Table 2).

ESG and INP. In the Karapyak location during the dry season, the genus *Gracilaria* was dominant, followed by the genus *Padina*. Transitioning to the wet season, the genus *Sargassum* replaced *Gracilaria* as the dominant genus. At the other two locations, Sindangkerta and Sayangheulang, the genus *Sargassum* consistently played a key role in the macroalgae community with an IVI value above 100. From the grouping of ESG, across all three locations, degraded habitats dominated, as opportunistic species outnumbered late-successional species. However, at Sayangheulang, a balanced ratio of opportunistic and late-successional species made it challenging to classify the location as entirely degraded (Fig. 2).

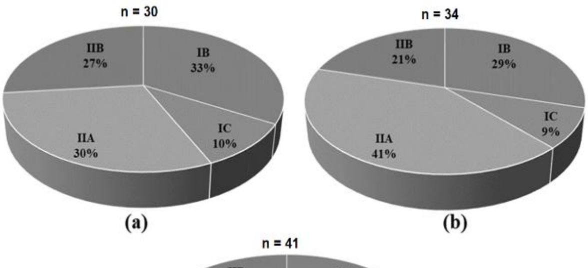

Figure 2. Grouping of Macroalgae in ESG in the rocky intertidal zone of the south coast of West Java, **(a)** Dry Season, **(b)** Wet Season, and **(c)** throughout the year

The genus *Gracilaria*, which has the highest IVI in the dry season, is known for its resilience to drought during low tide conditions. During the wet season, the genus *Sargassum* takes on a significant role compared to *Gracilaria*, as indicated by its high IVI. The differences in IVI among species in this study can illustrate the competition between each species in utilizing nutrients, light input, and substrate types.

Macroalgae found in the rocky intertidal zone of the southern coast of West Java are dominated by species classified under ESG II, which are macroalgae species with R-selection characteristics, exhibiting high growth rates but having short lifespans. Species in ESG I experienced a decline during the wet season, likely due to high nutrient inputs from increasing rainfall, which favors opportunistic macroalgae species. Looking at ESG analysis based on locations, Sayangheulang shows a balanced proportion of opportunistic and non-opportunistic species, indicating that this location is still in relatively good condition.

Biomass and Carbon Stock of Macroalgae. The average biomass in the rocky intertidal zone of the southern coast of West Java was 278 gm^{-2} dry weight, with an increase during the wet season to 288 gm^{-2} dry weight. The Sayangheulang location recorded the highest average biomass in both seasons, reaching 354 gm^{-2} dry weight. At Sindangkerta, biomass decreased during the wet season, likely due to a reduction in Chlorophyceae coverage. Across all locations and seasons, the Phaeophyceae class—represented by genera such as *Sargassum* and *Padina*—dominated the macroalgae community. Florideophyceae, which includes *Gracilaria*, and Chlorophyceae, which includes genera such as *Ulva*, exhibited higher biomass during the dry season but declined in the wet season (Fig. 3).

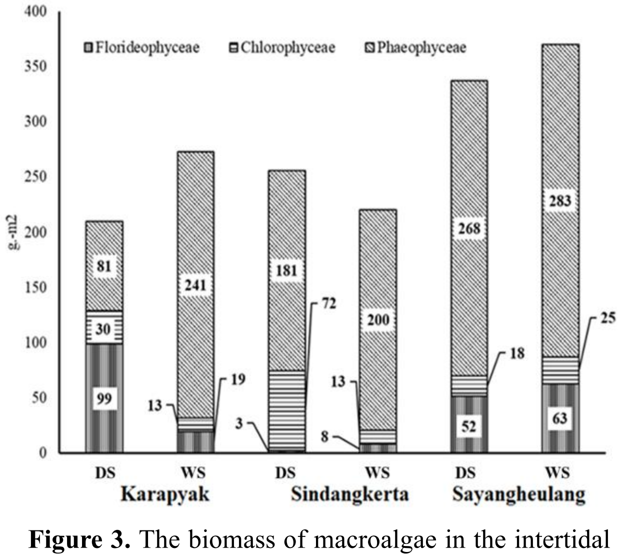

Figure 3. The biomass of macroalgae in the intertidal zone of the southern coast of West Java (DS: Dry Season, WS: Wet Season) shows significant differences between locations.

Fluctuations in carbon storage mirrored the biomass trends. The average carbon storage of macroalgae was 68.49 gcm^{-2}, increasing from 59.25 gcm^{-2} in the dry season to 77.74 gcm^{-2} in the wet season. Again, Sindangkerta was the exception, experiencing a decline in carbon storage during the wet season. At the Karapyak location in the dry season, no single macroalgae class dominated carbon storage, as Phaeophyceae and Florideophyceae contributed relatively equally. Both Florideophyceae and Chlorophyceae showed decreases during the wet season, except at Sayangheulang. *Sargassum* and *Gracilaria* genera were identified as the primary contributors to carbon storage, highlighting their ecological importance (Fig. 4).

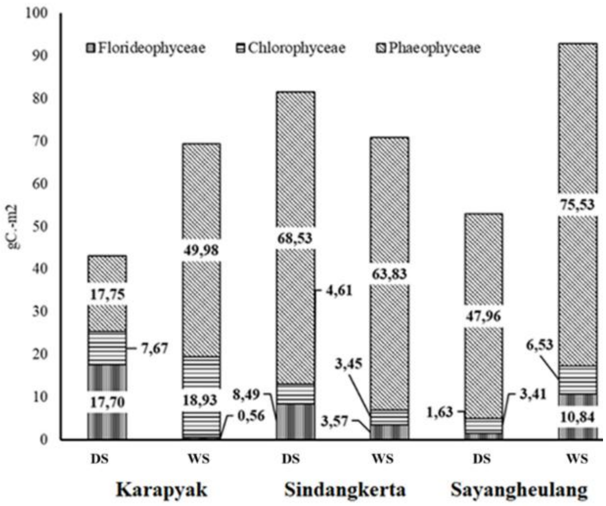

Figure 4. The carbon storage of macroalgae in the intertidal zone of the southern coastal area of West Java; DS = dry season, WS = wet season. There are significant differences between locations

Distribution of biomass and carbon stock estimation of macroalgae. The biomass varied at each beach from east to west. At Karapyak, the eastern side had the highest biomass, recorded at 625 gm^{-2} in the dry season and 790 gm^{-2} in the wet season. Biomass gradually decreased moving toward the western side of the beach, a pattern likely influenced by the presence of wave-breaking walls.

At Sindangkerta, biomass appeared higher in the dry season, although it was less evenly distributed compared to the wet season. During the wet season, the biomass was more evenly distributed across the beach, even though the peak biomass (470 gm^{-2}) was lower than that in the dry season (1050 gm^{-2}).

At Sayangheulang, the highest biomass was observed in the dry season, reaching 1050 gm^{-2}, compared to 750 gm^{-2} in the wet season. Interestingly, the eastern side of the Sayangheulang coast, which consistently had lower biomass, exhibited an increase during the wet season, reflecting a localized improvement (Fig. 5). Across all locations, *Sargassum* dominated in both seasons, except at Karapyak during the dry season, where *Gracilaria* was the dominant genus.

The estimation of macroalgae carbon stock was conducted using two models: NDVI-based prediction and Principal Component Analysis (PCA). PCA was employed to reduce data redundancy, generating new uncorrelated image bands with significant data variance (Raharja et al., 2019). The transformed images were processed using equations derived from regression analysis, and the transformation results are illustrated in Fig. 6. Regression analysis was conducted for all locations and seasons concerning NDVI and PCA values, but only wet season data yielded sufficient R-squared values for reliable regression (Fig. 7). In the dry season, an interpolation model was used due to low regression values (below 0.5).

The estimated carbon stock values are presented in Sup. Table 3. In the wet season, Sayangheulang exhibited the highest carbon storage per hectare across all models 1.05 tons.ha^{-1} (NDVI), 1.07 tons.ha^{-1} (PCA) and 1.08 tons.ha^{-1} (Interpolation). Comparatively, Sindangkerta and Sayangheulang experienced decreases in carbon storage per hectare in the interpolation model, while Karapyak showed an increase.

Discussion

This study provides insights into the ecological dynamics of macroalgae in the rocky intertidal zones of the southern coast of West Java by examining seasonal variation in environmental conditions, species composition, ecological status, biomass, and carbon stock. The results reveal complex interactions between abiotic factors and macroalgae community structure, which are further explored in this discussion.

Environmental drivers such as pH, salinity, dissolved oxygen, and light intensity exhibited significant seasonal variations, influencing macroalgae distribution and productivity. As noted by Marianingsih *et al*. (2013), macroalgae generally thrive within a pH range of 7–8, while values below 6.5 can suppress growth. In this study, the lower pH during the dry season is suspected to have limited species richness,

Plate 11

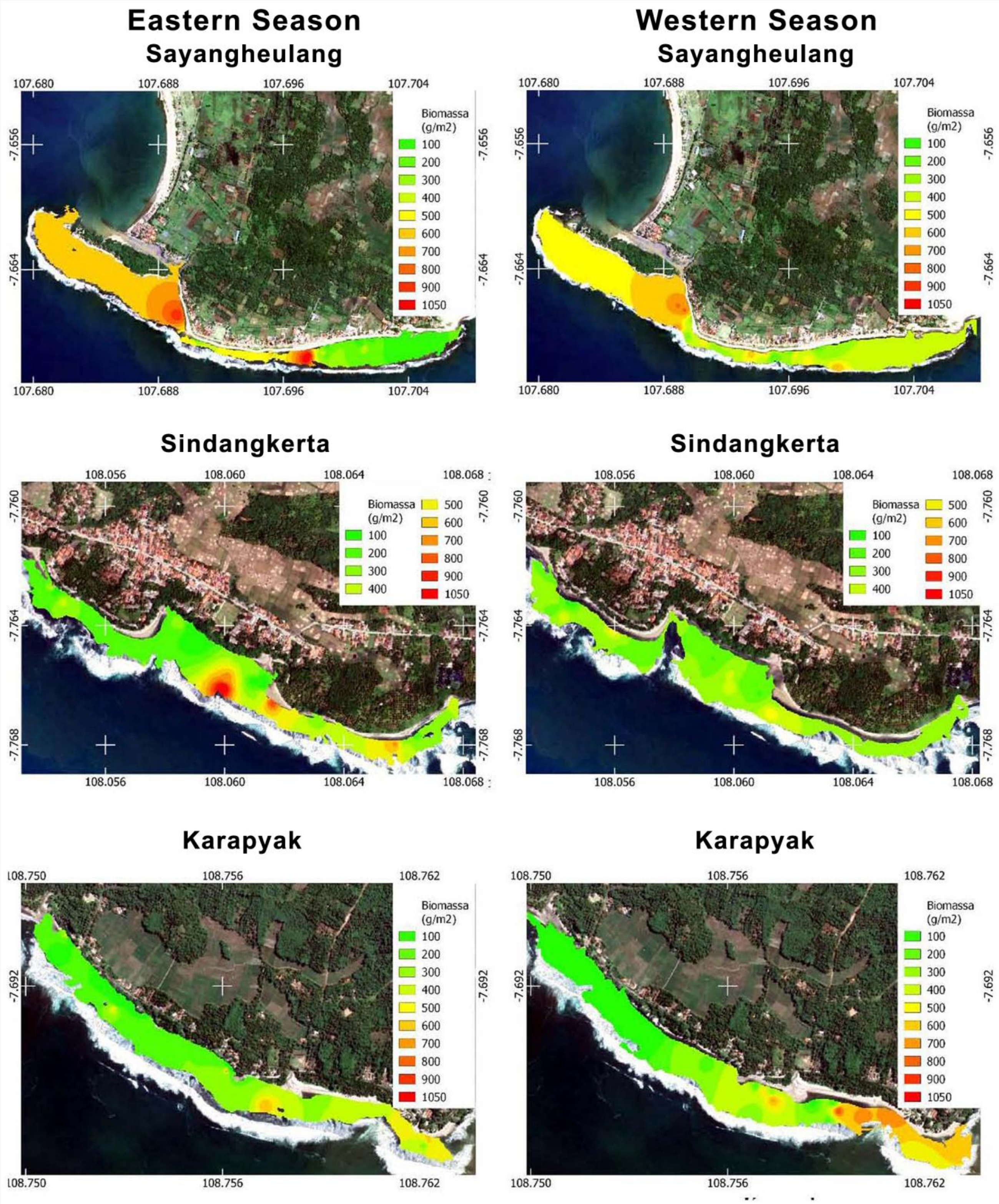

Figure 5. Interpolation of macroalgae biomass at the three stations: Sayangheulang, Sindangkerta, and Karapyak during eastern and western seasons

Plate 12

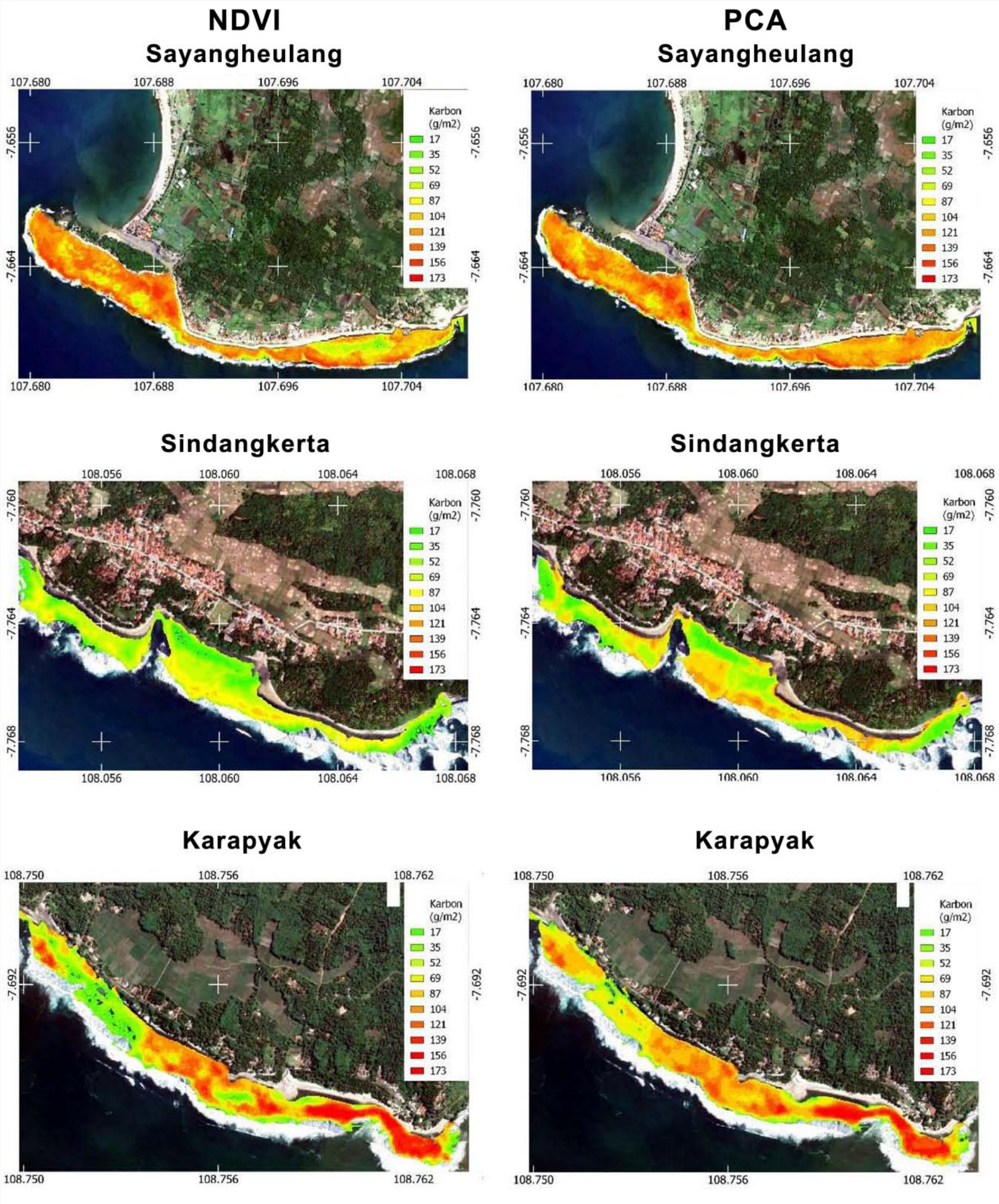

Figure 6. Map of macroalgae carbon estimation at each research location: Sayangheulang, Sindangkerta, and Karapyak; the estimated carbon stock values at each location are presented in Table 3

coverage, and biomass, which may explain the overall increase in macroalgal biomass and diversity observed during the wet season.

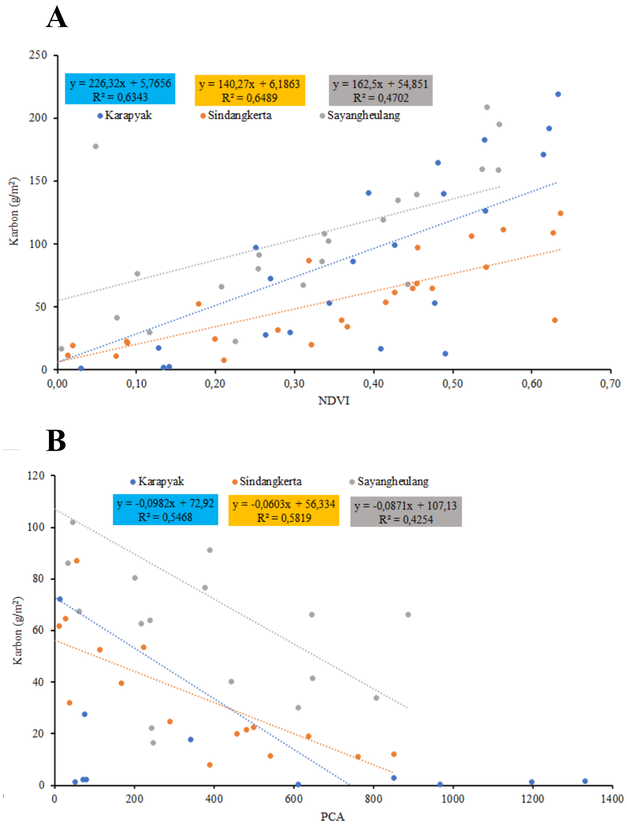

Figure 7. Regression of carbon values against NDVI **(a)** and PCA; **(b)** $p<0.05$

The ecological status of macroalgal communities, assessed through the ESG index, reflects environmental pressures and habitat conditions. ESG II species, which are opportunistic and exhibit high growth rates but short life cycles, dominated across most locations, indicating degraded habitat conditions. These species are well adapted to nutrient-enriched, fluctuating environments, a situation commonly found in polluted or anthropogenically disturbed areas (Orfanidis *et al*. 2011). The consistent dominance of opportunistic species suggests that nutrient enrichment—possibly from agricultural runoff or increased freshwater input—may be influencing these coastal ecosystems.

Despite this trend, Sayangheulang showed a relatively balanced composition of opportunistic and late-successional species, indicating that it may be in a transitional ecological state rather than fully degraded. The dominance of *Sargassum* (ESG I) and other brown macroalgae (Phaeophyceae), particularly during the wet season, may contribute to this stability, as Phaeophyceae are typically more resilient and associated with healthier marine habitats (De Paula *et al*. 2020).

Species dynamics across seasons were also evident. *Gracilaria*, dominant during the dry season, is known for its drought resistance under low tide exposure (Pratiwi *et al*. 2018), while *Sargassum* replaced it during the wet season. According to Low & Chou (2013) *Sargassum* is well-adapted to reef flats and can dominate in areas with increased nutrient and light availability. This interspecies shift reflects competition for resources such as nutrients, substrate, and light, consistent with findings by Parmadi *et al.* (2016).

Regarding functional traits and nutrient use, ESG I species such as *Cystoseira crinitophylla* require high light and nutrient reserves and are usually found in unpolluted environments (Orfanidis *et al*. 2011). In contrast, ESG II species like *Ulva rigida* can thrive in degraded environments with low nitrogen levels. The shift in dominance from ESG I to ESG II species during the wet season could be attributed to elevated nutrient input from runoff and rainfall, which favors fast-growing, opportunistic taxa.

Biomass and carbon storage patterns mirrored environmental and ecological dynamics. Sayangheulang consistently showed the highest macroalgal biomass and carbon stock, especially during the wet season. In contrast, Sindangkerta experienced a decline in both metrics, likely due to a decrease in Chlorophyceae, which are more prevalent during dry, stable conditions (Adsul *et al*. 2019). The observed decline in Florideophyceae and Chlorophyceae during the wet season, except at Sayangheulang, may also be due to lower salinity and reduced light penetration. Florideophyceae, in particular, benefit from optimal light conditions in the dry season (Asmida *et al*. 2017).

Carbon sequestration potential followed the spatial distribution of biomass, with macroalgal communities in Sayangheulang exhibiting the highest values. This reinforces the ecological importance of macroalgae such as Sargassum and Gracilaria, which play central roles in carbon capture in intertidal systems. Spatial patterns, such as higher biomass on the eastern side of Karapyak, are likely influenced by physical features like wave-breaking walls that affect nutrient flow and sediment stability. Similarly, in Sindangkerta, more even biomass distribution during the wet season may reflect improved environmental conditions due to enhanced water movement and nutrient availability (Melsasail *et al*. 2018, Supardi & Nugroho 2019).

The carbon stock estimation using NDVI and PCA models demonstrated spatial prediction potential, particularly during the wet season when regression models showed stronger correlations. However, during the dry season, low R^2 values required the use of interpolation models, suggesting that environmental variability and external influences may complicate remote-sensing predictions. Still, these models provide a useful baseline for mapping biomass and carbon storage on larger spatial scales (Raharja *et al*. 2019).

Estimation of macroalgae carbon stock is still rarely conducted, so the closest comparison for macroalgae vegetation is seagrass vegetation. When compared, the carbon stock values of macroalgae per hectare in this study are higher than the carbon storage in the previous study Ramadona *et al*. (2021) which estimated seagrass carbon stock on Pokemon Beach, Karimun Jawa Island, at 0.23 tonsC.ha-1, and in the study conducted by Ibnu Graha *et al*. (2016) conducted in the Sanur Beach area, Denpasar City, with a seagrass carbon storage of 0.21 ton.ha-1.This suggests that macroalgae could play a more substantial role in blue carbon strategies than previously acknowledged, although further research is needed to validate these findings under different coastal conditions.

Author contributions
All authors contributed equally

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