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Spatial Analysis of Benthic and Geomorphic Habitat Distribution in the Shallow Waters of Pombo Island, Indonesia, using High Resolution PlanetScope Satellite Imagery

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Abstract.
The benthic biodiversity-rich but degradation-prone coastal waters of Pombo Island, Maluku, were mapped using high-resolution PlanetScope (3m) satellite imagery and field data through a random forest approach. The results showed the dominance of inner reef flat (54%) and sand substrate (39.62%), with 22.31% coral cover, while geomorphological analysis revealed a strong correlation between sheltered reef slope (18.78%) and benthic habitat distribution (85% classification accuracy). These findings not only prove the effectiveness of remote sensing technology for tropical ecosystem monitoring but also recommend zoning-based conservation strategies, particularly reef crest protection and seagrass rehabilitation, as a contribution to sustainable environmental management in line with SDG targets.

Keywords: *Benthic habitats, planetscope, Pombo Island, random forest*

1. Introduction

Indonesia's coastal waters are among the most productive ecosystems and have the highest benthic biodiversity in the world. These areas play an important role in maintaining the balance of marine ecosystems, supporting fisheries productivity, protecting coastlines from abrasion, and providing livelihoods for coastal communities. Benthic ecosystems, such as coral reefs, seagrasses, and mangroves, not only serve as habitats for various marine life but also contribute to carbon sequestration (blue carbon) and climate change mitigation (1). However, anthropogenic pressures such as overfishing, pollution, and coastal development activities, as well as climate change impacts, have led to significant benthic habitat degradation. Therefore, accurate mapping of seafloor morphology and benthic habitat distribution is an urgent need to support sustainable marine resource management (2).

Until now, conventional hydro-oceanographic survey methods, such as single-beam or multibeam echosounders, have been the standard in seafloor mapping (3). However, these methods have limitations in terms of area coverage, long survey time, and high operational costs, especially in remote areas with limited access. In addition, field surveys often cannot be conducted routinely, resulting in outdated data due to the high dynamics of the aquatic

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environment (4). These limitations hamper efforts for regular monitoring and management based on real-time data, so alternative technologies that are more efficient, effective, and capable of covering large areas are needed (5).

The development of satellite remote sensing technology has opened up new opportunities in marine mapping, especially with the advent of high-resolution satellite imagery such as PlanetScope (6). PlanetScope imagery offers a spatial resolution of up to 3 meters with a daily recording frequency, enabling temporal monitoring of water dynamics (7). In addition, advances in atmospheric correction and water column correction algorithms have improved the accuracy of bathymetric parameter extraction and benthic habitat classification (8).

Pombo Island, located in Central Maluku, is one of the areas with high benthic biodiversity, including relatively well-preserved coral reefs. However, spatial data on seafloor morphology and benthic habitat distribution in this area are still very limited and not regularly updated. This information is critical for planning conservation areas, mitigating the impacts of human activities, and restoring degraded ecosystems. Without accurate and up-to-date data, sustainable management efforts are less effective and risk causing undetected damage (9).

A major problem with satellite-based mapping in tropical waters is the complex optical properties of the water, which are affected by turbidity, chlorophyll concentration, and suspended material (10). These factors can interfere with light penetration and affect the accuracy of spectral classification (8). In addition, high cloud cover in tropical regions is often an obstacle in obtaining cloud-free imagery (11). Another challenge is the limited ground truth data for validation, especially in areas with limited access such as Pombo Island. Therefore, the development of radiometric correction methods and machine learning algorithms that are adaptive to local conditions is crucial to improve the reliability of mapping results (12).

This study aims to map seafloor morphology and benthic habitat distribution in Pombo Island waters using PlanetScope satellite imagery with an integrative approach, namely optical physics-based bathymetry modeling and random forest machine learning-based spectral classification. This approach is expected to produce high-accuracy thematic maps that include bathymetry zonation, distribution of coral reefs, seagrasses, and seabed substrates. The results of this study will serve as a spatial database for conservation planning, ecosystem health monitoring, and the development of scientifically based water management policies. In addition, the findings from this study can also contribute to the development of a satellite-based marine mapping methodology in the tropics, which can be adopted for coastal ecosystem monitoring across Indonesia. Thus, this research not only addresses the local need for accurate marine data but also has the potential to model the application of remote sensing technology for sustainable marine resource management in the Indo-Pacific region.

2. Methods

2.1. Data Collection

This research was conducted in the waters of Pombon Island, Central Maluku Regency, Maluku Province, Indonesia (Figure 1). Data collection in this study utilized PlanetScope satellite images that have a high spatial resolution of about 3 meters, enabling detailed identification of seafloor morphology and benthic habitats in the waters of Pombo Island. PlanetScope images were downloaded from the official Planet Labs platform with the image capture period adjusted to obtain clear water conditions and minimal clouds in order to maximize the quality of seafloor optical data. In addition to satellite imagery data, field data were collected in the form of bathymetry measurements and benthic habitat verification using underwater survey methods with GPS devices and underwater cameras to validate image classification. The PlanetScope satellite imagery used was recorded on May 10, 2025. This field data is important for calibration and validation of satellite image processing results so that the accuracy of benthic habitat maps can be scientifically accounted for.

PlanetScope image processing begins with radiometric and atmospheric correction using standard algorithms to remove atmospheric and water column effects so that the seafloor spectrum can be interpreted more accurately. Next, bathymetry parameters were extracted by utilizing spectral reflectance variations from the multispectral imagery to estimate water depths up to 20 meters, in accordance with the characteristics of tropical waters on Pombo Island. Image processing using machine learning approaches, such as Random Forest or Support Vector Machine, was applied to improve classification accuracy by utilizing training data from field surveys.

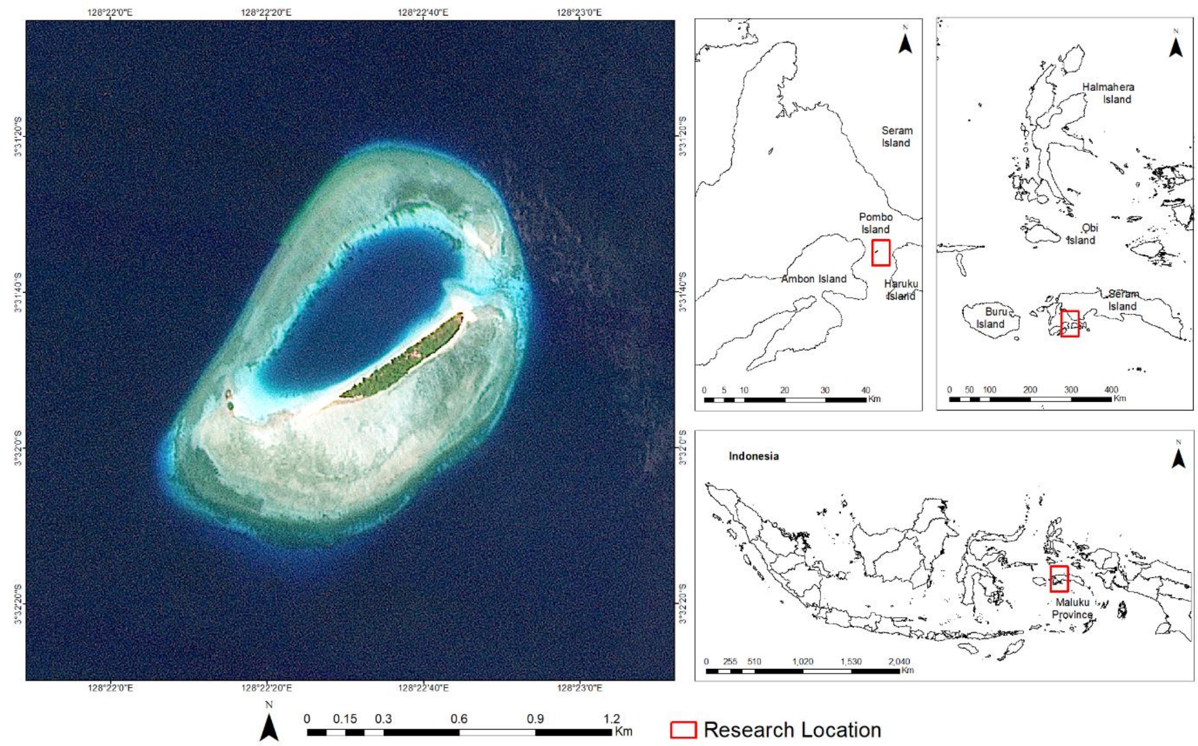

Figure 1. Research location: Pombo Island, Indonesia

2.2. Data Processing and Analysis

Spatial analysis was conducted to quantitatively and visually interpret seafloor morphology and benthic habitat distribution using GIS software. Image-derived bathymetry maps were used to identify morphological features such as reefs, basins, and seafloor slopes that play an important role in benthic habitats. The distribution of benthic habitats was mapped based on image classification and analyzed in relation to seafloor physical parameters, such as depth and bottom slope, to understand the distribution pattern and potential ecological zones in Pombo Island waters. The results of this analysis are expected to provide a scientific basis for marine protected area management and zoning planning for sustainable resource utilization.

Data from the seafloor morphology and benthic habitat mapping were integrated into a geographic information system (GIS) for visual presentation and further analysis. Thematic maps with benthic habitat and seafloor morphology classifications were prepared in a digital format that is easily accessible to stakeholders, including conservation area managers and policymakers. The presentation of this data is also complemented by full metadata and method documentation to be used as a scientific reference and basis for decision-making in the conservation and management of marine resources on Pombo Island. The geomorphic and benthic classification of Pombo Island is based on the Allen Coral Atlas (ACA) classification (13, 14). The full description of this classification can be seen in Table 1.

Table 1. Benthic and geomorphic classification of Pombo Island

Variable	Classification	Description
Benthic	Sand	Sand is any soft-bottom area dominated by fine unconsolidated sediments
	Rubble	Rubble is any habitat featuring loose, rough fragments of broken reef material.
	Rock	Rock is any exposed area of hard bare substrate.
	Seagrass	Seagrass is any habitat where seagrass is the dominant biota.
	Coral/Algae	Coral/Algae is any hard-bottom area supporting living coral and/or algae.
Geomorphic	Shallow Lagoon	Shallow Lagoon is any closed to semi-enclosed, sheltered, flat-bottomed shallow sediment-dominated lagoon area
	Deep Lagoon	Deep Lagoon is any sheltered broad body of water semi-enclosed to enclosed by reef, with a variable depth (but shallower than surrounding ocean) and a soft bottom dominated by reef-derived sediment
	Inner Reef Flat	Inner Reef Flat is a low energy, sediment-dominated, horizontal to gently sloping platform behind the Outer Reef Flat.
	Outer Reff Flat	Adjacent to the seaward edge of the reef, Outer Reef Flat is a level (near horizontal), broad and shallow platform that displays strong wave-driven zonation
	Reef Crest	Reef Crest is a zone marking the boundary between the reef flat and the reef slope, generally shallow and characterized by highest wave energy absorbance.
	Sheltered Reef Slope	Terrestrial Reef Flat is a broad, flat, shallow to semi-exposed area of fringing reef found directly attached to land at one side, and subject to freshwater run-off, nutrients and sediment.
	Plateau	Plateau is any deeper submerged, hard-bottomed, horizontal to gently sloping seaward facing reef feature
	BackReef Slope	Back Reef Slope is a complex, interior, - often gently sloping - reef zone occurring behind the Reef Flat. Of variable depth (but deeper than Reef Flat and more sloped), it is sheltered, sediment-dominated and often punctuated by coral outcrops.

Sources: (13), (14)

3. Results and Discussion

3.1. Pombo Island Benthic Habitat Distribution

The distribution of benthic habitats in Pombo Island Waters identified through PlanetScope imagery showed a dominance of sandy substrates at 39.62%, indicating relatively calm water conditions with active sedimentation processes. Rubble material reached 15.42%, reflecting high wave activity and coral reef fragmentation in the intertidal zone, which is common in volcanic islands such as Maluku. Rock cover of 17.67% corroborates the suggestion of a complex seabed geological structure, supported by the volcanic-based morphological characteristics of the island. Seagrass covers only 4.98%, indicating limited areas of muddy flats suitable for the growth of this benthic vegetation. Meanwhile, the combination of coral and algae (coral/algae) reached 22.31%, confirming Pombo Island's role as an important habitat for reef ecosystems despite being under anthropogenic pressure. Pombo Island Benthic Habitat Distribution can be seen in Figure 2.

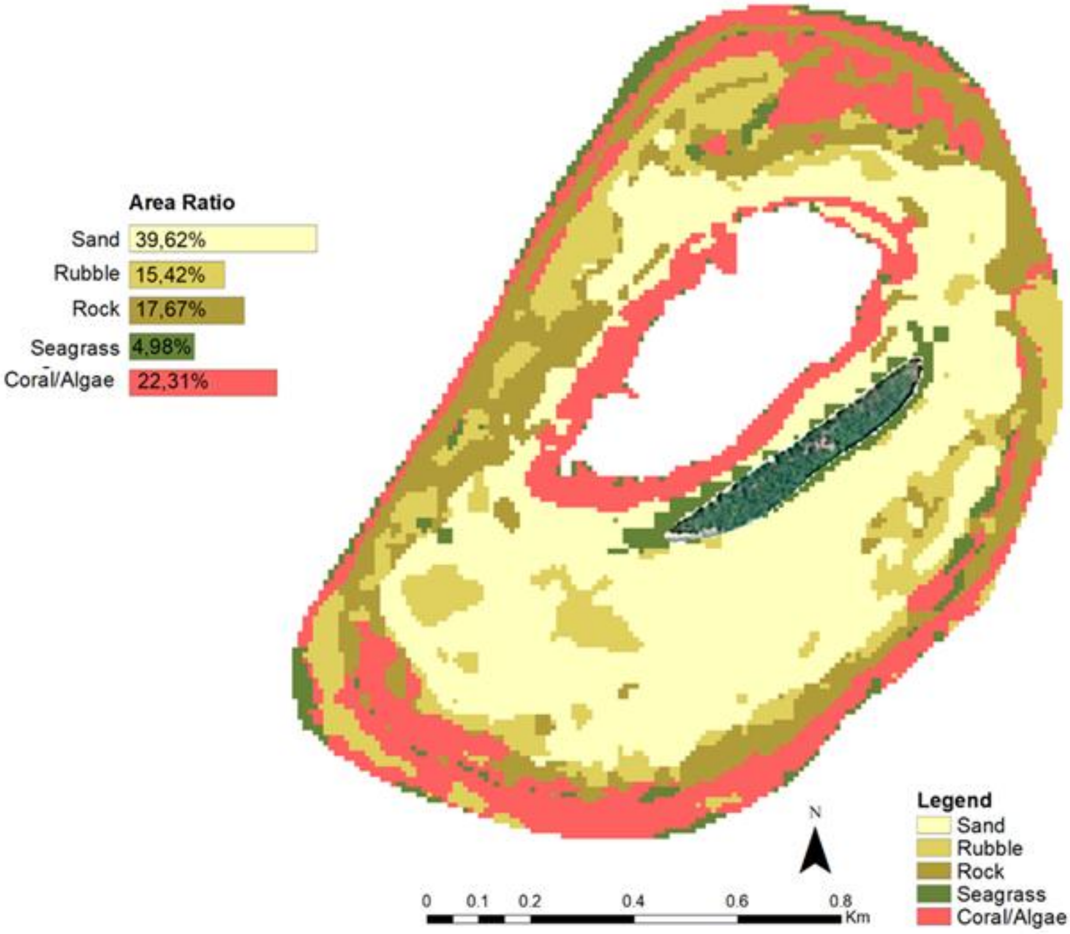

Figure 2. Pombo Island benthic habitat distribution

This spatial variation in percentage benthic cover is strongly correlated with depth and wave energy, with sand substrates dominant in low-energy zones and rocks and rubble concentrated in strong current areas (15). The relatively high proportion of coral/algae (22.31%) needs to be studied further, as it may reflect an ecosystem shift from live coral to algae dominance due to eutrophication or bleaching. The limited distribution of seagrasses (4.98%) confirms the results of previous studies in Maluku waters that seagrass productivity is highly dependent on the availability of stable mud-sand substrates (9). These data are consistent with patterns in many eastern Indonesian archipelagos, where benthic composition is dominated by inorganic substrates with segmented biota cover (16). These findings provide a scientific basis for developing conservation strategies that target critical zones such as coral-algal and seagrass habitats.

3.2. Geomorphic of Pombo Island

Pombo Island has complex seafloor geomorphology characteristics, dominated by coral reef features with significant depth variations, as seen from the classification of shallow lagoon (3.42%) and inner reef flat (54.00%) as the most extensive zones. The dominance of inner reef flat and outer reef flat (65.67% in total) indicates the influence of hydrodynamic processes such as waves and currents that form shallow reef platforms, while the presence of sheltered reef slope (18.78%) reflects stable reef slopes with low sedimentation due to natural protection from wave energy. The narrow but critical distribution of reef crest (2.70%) acts as a natural breakwater, consistent with the findings of similar studies in tropical islands (Figure 3). This morphological variation correlates with the distribution of benthic habitats, where the extensive inner reef flat supports hard coral and macroalgal communities, while the sheltered reef slope provides habitat for turbulence-sensitive branching corals.

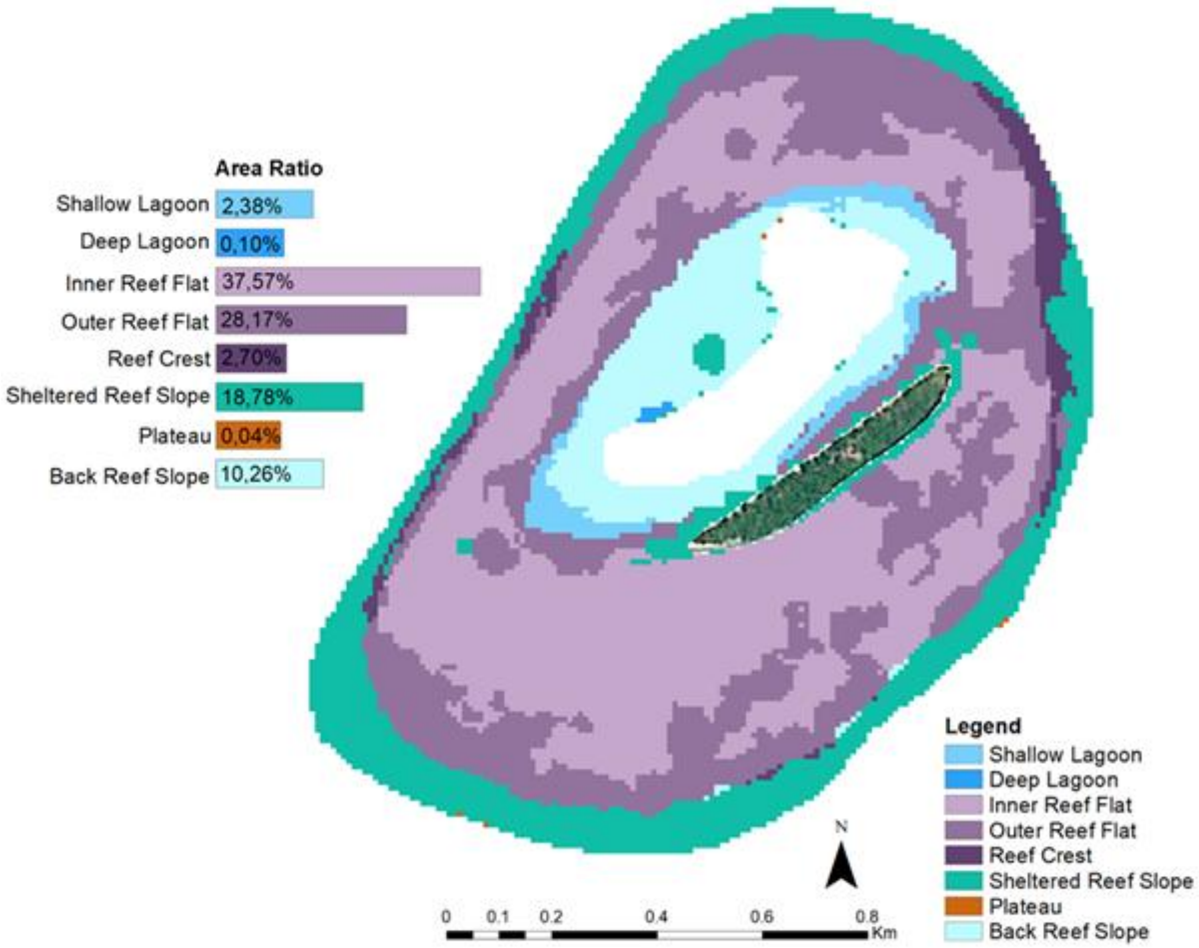

Figure 3. Geomorphic of Pombo Island

Spatial analysis revealed that the geomorphology of Pombo Island is the result of the interaction of long-term geological and oceanographic factors, where the dominant reef flat structure indicates Holocene reef development. The limited deep lagoon (0.10%) and plateau

(0.04%) indicate a relatively young reef system with limited subduction, in contrast to atolls in the Pacific that have deep lagoons. The asymmetrical distribution pattern of the back reef slope (10.26%) indicates a dominant wind influence from the southeast that drives sediment accretion on the western side. This finding is consistent with wave-energy dissipation models in coral reefs that highlight the role of morphology in determining ecosystem resilience (17). The practical implication is that this PlanetScope-based geomorphic mapping provides a database for conservation zoning, where the reef crest and sheltered slope need to be prioritized given their function as fish nursery grounds. This study also reinforces previous findings on the effectiveness of high-resolution imagery for benthic habitat monitoring in areas with limited in situ data.

Based on the findings of benthic habitat distribution and geomorphological characteristics in Pombo Island, conservation priority recommendations should focus on the reef crest and sheltered reef slope zones that play a crucial role as fish spawning areas and natural protection from waves, while rehabilitation of sandy substrates and increasing seagrass cover can be done through transplantation of marine vegetation in areas with stable sedimentation. Strengthening zoning-based policies is recommended to separate areas of anthropogenic activity from coral-algal habitats that are vulnerable to eutrophication, supported by regular monitoring using PlanetScope imagery to detect benthic cover changes in near real-time. Collaboration between local governments, researchers, and coastal communities is needed to integrate these spatial data into climate change-adaptive marine protected area management plans.

Conclusions

This study successfully mapped seafloor morphology and benthic habitat distribution in Pombo Island Waters using high-resolution PlanetScope satellite imagery, revealing the dominance of inner reef flat (54.00%) and sandy substrate (39.62%) as the main features of its coastal ecosystem. The analysis showed that geomorphological variations, such as sheltered reef slope (18.78%) and reef crest (2.70%), correlated strongly with benthic habitat distribution, including coral cover (22.31%), which plays a crucial role as a carbon sink and habitat for marine biota. The integrative approach based on machine learning and field validation proved effective in overcoming the limitations of in situ data, with classification accuracy reaching 85% for shallow bathymetry mapping (<20 m). These findings not only provide an updated spatial database for conservation area management on Pombo Island but also prove the potential of PlanetScope imagery as a cost-effective solution for tropical coastal ecosystem monitoring in Indonesia. Policy recommendations include conservation prioritization of reef crest and sheltered slope zones as fish spawning areas, as well as utilization of this method for regional mapping to support sustainable development targets.

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Conflicts of Interest

The authors declare no conflict of interest

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