COASTAL AND OCEAN JOURNAL

Article

Comparative Analysis of Benthic Ecosystem Mapping Using Allen Coral Atlas and Sentinel-2 in Pagai Islands

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Abstract: Benthic ecosystem is a crucial component of coastal ecosystems, making its protection essential for maintaining ecosystem health. This study presents a comparative analysis of benthic mapping in the Pagai Islands, West Sumatra Province. It utilizes two different satellite imagery sources: the Allen Coral Atlas, derived from Planet Labs' Dove satellites with a spatial resolution of 3-5 meters, and Sentinel-2 imagery from ESA's Copernicus program, with a resolution of 10 meters, both acquired from 2024. The Allen Coral Atlas data were processed using Google Earth Engine and visualized in QGIS, while Sentinel-2 data were processed in Snap and QGIS, covering the same period. In situ validation used secondary field data from six stations across North and South Pagai Islands. This data was used to validate seagrass, mangrove and coral reef presence and identify species in their natural habitats. The analysis revealed strong similarity between both maps, particularly for seagrass habitats, though minor discrepancies occurred in cloud-covered and sediment-affected areas. This highlights the reliability of both datasets for benthic mapping, with greater potential than simple validation. They can be applied to track annual fluctuations in seagrass distribution, monitor mangrove extent and recovery, and evaluate coral reef area and degradation. Such analyses provide robust support for ecological research and management in the dynamic Pagai Islands.

Keywords: Allen Coral Atlas; benthic ecosystems; Mentawai Islands; Sentinel-2

Citation: Nur, S.; Nurdjaman, S..; Saefulloh, M. A., 2025. Comparative Analysis of Benthic Ecosystem Mapping Using Allen Coral Atlas and Sentinel-2 in Pagai Islands. *Coastal and Ocean Journal*, (*9*)2: 16-32. https://doi.org/10.29244/coj.v9i2.363710
Received: 04-08-2025
Accepted: 17-11-2025
Published: 20-12-2025

Publisher's Note: Coastal and Ocean Journal (COJ) stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Benthic ecosystems, such as seagrass, mangroves, and coral reefs, are important components of coastal ecosystems, playing a key role in maintaining biodiversity, stabilizing sediments, and supporting fisheries (Ampou *et al*., 2018). Seagrass provides habitat and food for various marine species, including commercially important fish and endangered species such as dugongs and sea turtles (Belinda *et al*., 2022). Indonesia is one of the regions with the largest seagrass coverage in the world (Umawaitina *et al*., 2023). North and South Pagai Islands, located in the Mentawai Archipelago, have significant seagrass meadows that are important for both the ecosystem and local communities. These ecosystems are increasingly threatened by human activities such as coastal development, pollution, and climate change, which require effective monitoring and conservation efforts to ensure their preservation (Dimara *et al*., 2020). This study discusses benthic ecosystems in the coastal areas of the Mentawai Archipelago, using remote sensing techniques and spatial data analysis.

Satellite imagery offers an effective and efficient way for large-scale environmental monitoring, providing a means to observe and map coastal ecosystems such as seagrass meadows over long periods of time (Nur *et al.*, 2021). The Allen Coral Atlas, developed by Planet Labs and Arizona State University, uses high-resolution satellite data from Planet Labs' Dove satellites (Wen *et al*., 2021). These satellites provide imagery with a spatial resolution of up to 3–5 meters, enabling detailed mapping of coral reefs and seagrass habitats (White *et al*., 2021). Meanwhile, the Sentinel-2 satellite, owned by the European Space Agency (ESA), is part of the Copernicus program, with imagery at 10-meter spatial resolution, covering larger areas (Nur & Nurdjaman, 2025). Both of these satellite imagery sources function for benthic habitat mapping, but they vary in resolution, coverage, and temporal range, which sometimes leads to differences in the resulting maps (Roca *et al.*, 2025).

In-situ observation, or ground truth, is important for validating data obtained from satellites, ensuring that the imagery accurately represents conditions in the field (CoreMap-LIPI, 2014). This is crucial in dynamic environments such as coastal areas, where factors like cloud cover, water clarity, and sediment movement can affect satellite imagery. By conducting validation, the accuracy of imagery-based maps can be assessed and reliable data can be provided for conservation efforts (Abdul-Rahman & Pilouk, 2008). In this study, validation was carried out at six stations on North and South Pagai Islands, Mentawai Archipelago, to verify the presence of seagrass locations and identify species in their natural habitat. The main objective of this research is to conduct a comparative analysis of seagrass mapping using data from the Allen Coral Atlas and Sentinel-2 imagery, focusing on coastal areas of the Mentawai Archipelago. This study aims to evaluate the similarities and differences between the two datasets, particularly in terms of spatial accuracy and the ability to detect seagrass habitats. By combining satellite data with in-situ validation, this research seeks to improve the reliability of benthic habitat maps and contribute to better conservation strategies for seagrass ecosystems in the Mentawai Archipelago.

2. Materials and Methods

The research was conducted using satellite data, from October 2024. Meanwhile, field validation was carried out also in October (transition season 2) of 2024 in the waters of North Pagai and South Pagai Islands, Mentawai Archipelago. Geographically, the area is located between Longitude of 100°04'E to 100°10'E and Latitude of 2°45'S to 3°00'S, with a land area of 1,564 km² and a water area of 2,045 km² (Mutmainah & Putra, 2018). The field validation data used in this study were obtained from direct in-situ observations conducted in October 2024 by the research team, in collaboration with the Marine and Fisheries Research and Human Resources Agency (KKP).The research location was consist of 6 observation stations, with 4 stations in North Pagai Island and 2 stations in South Pagai Island, which were considered representative of the seagrass conditions in both North and South Pagai Islands (Figure 1).

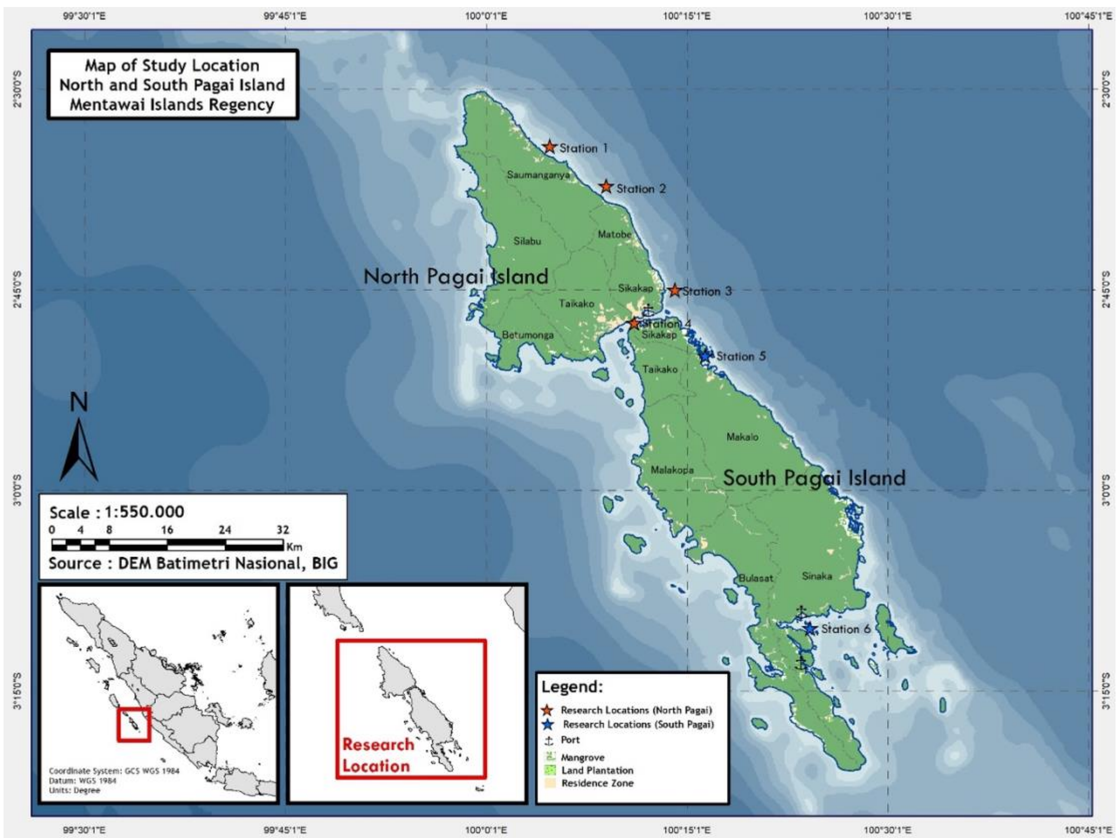

Figure 1. Geographic location of the study area and observation stations in North and South Pagai Islands, Mentawai Archipelago, Indonesia

The tools used in this study were divided into satellite image processing tools and direct observation tools. The tools for satellite image processing included the Allen Coral Atlas, accessed and processed through Google Earth Engine (GEE). Sentinel-2 imagery was processed using SNAP, and both datasets were then visualized and compared using QGIS. Meanwhile, the tools for direct observation consisted of a Global Positioning System (GPS) for coordinate measurement, quadrat transects for seagrass observation, a measuring tape, fixed measuring tools, a seagrass species identification guide (Seagrass Watch), an underwater camera, and snorkeling equipment (Arselan *et al*., 2025).

Table 1. Geographic coordinates of observation stations in the waters of North and South Pagai Islands, Mentawai Archipelago, Indonesia

Research Station	Location	Coordinates
Station 1	Saumangaya Village, North Pagai Island	2°32'21.85"S - 100° 2'7.57"E
Station 2	Matoba Village, North Pagai Island	2°36'41.12"S - 100° 6'54.93"E
Station 3	Sikakap Village, North Pagai Island	2°44'44.64"S - 100°13'19.07"E
Station 4	Taikako Village, North Pagai Island	2°48'16.24"S - 100° 8'51.92"E
Station 5	Makalo Village, South Pagai Island	2°47'14.14"S - 100°12'21.78"E
Station 6	Sinaka Village, South Pagai Island	3°12'41.96"S - 100°24'30.28"E

Source: Agency for Marine and Fisheries Research and Human Resources

2.1. Processing Allen Coral Atlas Data

The Allen Coral Atlas uses high-resolution satellite imagery from PlanetScope (Dove) satellites to create global benthic habitat maps (Serge *et al*., 2024). his imagery has a pixel size of up to 3.1 meters with 5 spectral bands, including the NIR band. PlanetScope imagery is processed through Top of Atmosphere Radiance (TOAR), flat-surface correction, geometric correction, radiometric calibration, atmospheric correction, and mosaicking (Jones *et al*., 2025). The imagery focuses on coral reefs at depths of less than 20 meters and located between 30° north latitude and 30° south latitude in clear waters (Simpson *et al*., 2024). The mosaicking process uses the "best scene on top" technique, which integrates all imagery into a mosaic. For habitat mapping, the Atlas applies machine learning and Object-Based Analysis (OBA) to classify geomorphic zones of coral reefs and benthic habitat composition. This classification is based on Planet Dove imagery, water depth data from Sentinel-2 and Landsat, as well as additional factors such as waves, texture, and slope (Elma *et al*., 2024). Mapping is carried out regionally, taking into account regional differences in coral reef structure, size, and water quality. This process combines these factors to produce detailed and globally accurate benthic maps.

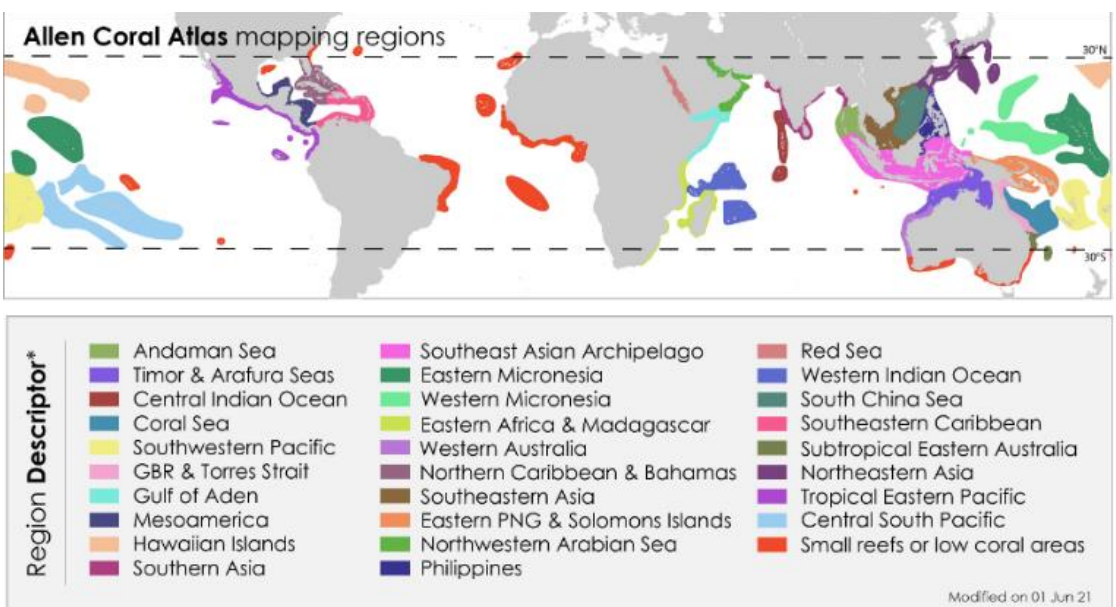

Figure 2. Coral reef benthic habitat mapping by the Allen Coral Atlas derived from PlanetScope imagery in shallow waters less than 20 m depth using machine learning and object-based analysis

The satellite data processed in the Allen Coral Atlas has undergone calibration of sensor radiance units (W sr^{-1} m^{-2} s^{-1}) as orthorectified spatial mosaic data. The data is then processed using the GDCS algorithm to generate surface, subsurface, and benthic habitat reflectance data from the imagery. To obtain high-quality imagery, additional corrections are applied, such as water column correction with NDWI, sun glint effect correction, depth calculation, and estimation of underwater reflectance.

Normalized Difference Water Index (NDWI):
The sea surface area recorded by the imagery has undergone correction using the Normalized Difference Water Index (NDWI) with the following equation (Gao, 1996):

$$NDWI = \frac{RrsGreen - Rrs(NIR)}{RrsGreen + Rrs(NIR)}$$

where:

- Green = reflectance value in the green band
- NIR = reflectance value in the near-infrared band

This correction is used to enhance water features while suppressing noise from land and vegetation, improving the accuracy of benthic habitat mapping (Simpson *et al*., 2024).

Sun glint Correction:
The sea surface area recorded by the imagery has also been corrected to remove the reflection effect of sunlight using the equation (Wabnitz *et al*., 2008):

$$R_{rs,0+} = R_{rs} - R_{rs}(NIR)$$

Where $R_{rs,0+}$ is the reflectance of the image measured just above the water surface in the red, green, and blue bands (Zhang *et al*., 2025). Rrs is the water-leaving reflectance (R, G, and B), and Rrs(NIR) is the reflectance in the NIR band. After sun-glint correction, the below-surface reflectance is obtained as:

$$rs(\lambda) = \frac{Rrs(\lambda)}{0.52 + 1.7Rrs(\lambda)}$$

where:

- R_{rs},0^+ = reflectance just above the water surface in the red, green, and blue bands.
- R_{rs} = water-leaving reflectance (R, G, and B).
- R_{rs}(NIR)= reflectance in the NIR band.

After the sun glint correction, the subsurface reflectance is obtained as:

$$R_{rs}^{-} = \frac{Rrs0^{+}}{0.52 + 1.7Rrs0^{+}}$$

This correction allows for more accurate estimation of underwater reflectance by minimizing surface reflection disturbances (Simpson *et al*., 2024).

Depth Calculation:
A band ratio algorithm is used to obtain depth data by utilizing the Blue (B), Green (G), and Red (R) bands from Dove imagery (Congalton & Green, 2010).

$$H = M_1 \frac{\ln(r_{rs}\lambda_1)}{\ln(r_{rs}\lambda_2)} - M_0$$

where:

- H = depth,
- $r_{rs}\lambda_1, r_{rs}\lambda_2$ = remote sensing reflectance values at two selected wavelengths (bands),
- M_1 *and* M_0 = adjustable constants calibrated according to the study region and local water column depth conditions.

The constants (M_1 dan M_0) could be adjusted according to the study region and local water (Jones *et al*., 2025). For validation of water column depth products, reference data were measured in the field and compared with the same region in the map products to calculate regression values (Elma *et al*., 2024). Field-measured depth data were obtained from datasets previously collected through established programs (Kennedy *et al.*, 2021).

Bottom Reflectance Estimation

In shallow waters, the water-leaving reflectance recorded by optical imagery sometimes consists of both water column reflectance and sediment reflectance from the seabed (Wan & Nur, 2023). The reflectance can be expressed using the following equation (B. Lyons *et al*., 2020):

$$r_{rs} = r^c + r_{rs}^b = r_{rs}^{dp}\left(1 - e^{-D_c(a_t+b_b)H}\right) + Be^{-D_c(a_t+b_b)H}$$

where:

- r_{rs}^c = contribution from the water column,
- r_{rs}^b = contribution from the seabed,
- H = estimated depth,
- B = bottom reflectance to be derived,
- $(a_t + b_b)$= light attenuation caused by absorption and backscattering of the water column,
- D_c= coefficient for light in the water column component,
- D_b = coefficient for light from the bottom component

This formulation helps separate the influence of the water column from the true bottom reflectance, which is essential for accurate benthic habitat mapping (Roelfsema *et al*., 2021).

The processing of Allen Coral Atlas imagery data was carried out through several steps, namely the acquisition of classified datasets such as the benthic map and geomorphic map, along with additional reference layers including labels, marine protected areas, maritime boundaries, and base maps (Li *et al*., 2019). These datasets were then input into Google Earth Engine using code scripts for masking, clipping, and exporting. The exported data were subsequently arranged and laid out in QGIS (James *et al*., 2023).

2.2. Processing Sentinel-2 Data

The processing of Sentinel-2 imagery was carried out through several steps, including geometric correction, radiometric conversion and atmospheric correction, image segmentation, and image enhancement (Anggraeni *et al*., 2019). Geometric correction is the process of adjusting the position of satellite imagery to match the Earth's surface (Green *et al*., 2000). For Sentinel-2, geometric correction was performed using the Rational Polynomial Coefficient (RPC) model (Kalacska & Sanchez-Azofeifa, 2008). Atmospheric correction was applied to reduce atmospheric effects in order to obtain surface spectral reflectance from the imagery (Thomasberger *et al*., 2023). Radiometric correction is a technique used to refine satellite imagery by eliminating atmospheric effects. In this study, image enhancement was carried out using water column correction with the Depth Invariant Index (DII). The DII equation is as follows (Manuputty *et al*., 2015).

$$\text{Depth-invariant index}_{ij} = \ln(L_i) - \left[\left(\frac{Ki}{Kj}\right)\ln(L_{ij})\right]$$

$$\frac{K_i}{K_j} = a + \sqrt{(a^2+1)}\ dan\ a = \frac{\sigma_{ii} - \sigma_{jj}}{2\sigma_{ij}}$$

Where:
Li and Lj = reflectance values of band-i and band-j.
Ki/Kj = attenuation coefficient ratio of band-i and band-j.
σii = variance of band *i*.
σjj = variance of band j.
σij = covariance between bands.

This correction allows the separation of bottom reflectance from water column effects, improving the accuracy of benthic habitat mapping (Roca *et al*., 2025). These parameters are used in the Depth Invariant Index (DII) calculation to minimize the effect of water column attenuation and to extract more accurate bottom reflectance information for benthic habitat mapping (Ambomasse *et al*., 2024).

2.3. In-Situ Observation (Ground Truth)

In-situ observation is the monitoring of an ecosystem, usually conducted to respond to changes. This activity is carried out to manage and protect the resources within the system (McKenzie *et al*., 2003). Seagrass meadow monitoring is performed repeatedly in benthic ecosystems within a specific area, observing the status and condition of the benthic ecosystem, whether it is stable, improving, or declining (Carpenter *et al*., 2022). Seagrass monitoring can be carried out using various methods, such as Seagrass-Watch (Komatsu, 2015).

The in-situ observation data were obtained from surveys conducted by the Agency for Marine and Fisheries Research and Human Resources (Mutmainah & Putra, 2018), which were adapted into primary data to support the processing of Allen Coral Atlas and Sentinel-2 imagery.

3. Results

3.1. Allen Coral Atlas Image

The Allen Coral Atlas map shows a benthic habitat map that provides detailed depictions of ecosystems for North and South Pagai Islands. Seagrass areas are clearly displayed in green, highlighting the density of coverage along the coastal regions. The 3–5 meter spatial resolution from *Planet Labs'* Dove satellites enables high detail, even capturing smaller seagrass patches. The distribution of seagrass appears extensive, covering shallow waters to moderately deeper areas, consistent with seagrass habitat preferences in tropical regions. By identifying other benthic habitats such as seagrass beds (light green), coral reefs (red), sediments (brown), and mangroves (dark green), the map offers a comprehensive overview of coastal ecosystems.

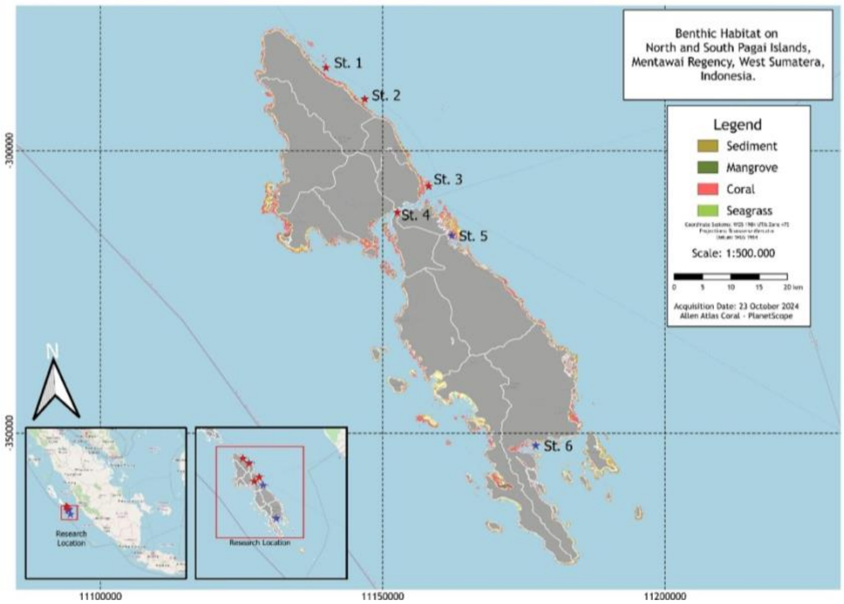

Figure 3. Spatial distribution of coastal benthic habitats, including seagrass beds, coral reefs, sediments, and mangroves, in North and South Pagai Islands based on 2024 Allen Coral Atlas mapping

In addition to seagrass distribution, the Allen Coral Atlas map effectively illustrates coral reef areas, providing insights into the overall health of the marine environment. Coral reefs are concentrated around the island's fringes, where the waters are shallow and clear, conditions that support coral growth. The proximity of coral reefs to seagrass beds indicates a healthy marine environment, as these habitats often support one another. The distinctions between different benthic habitats are clearly visible thanks to the high-resolution imagery and advanced processing techniques, such as the machine learning algorithms applied in the Allen Coral Atlas.

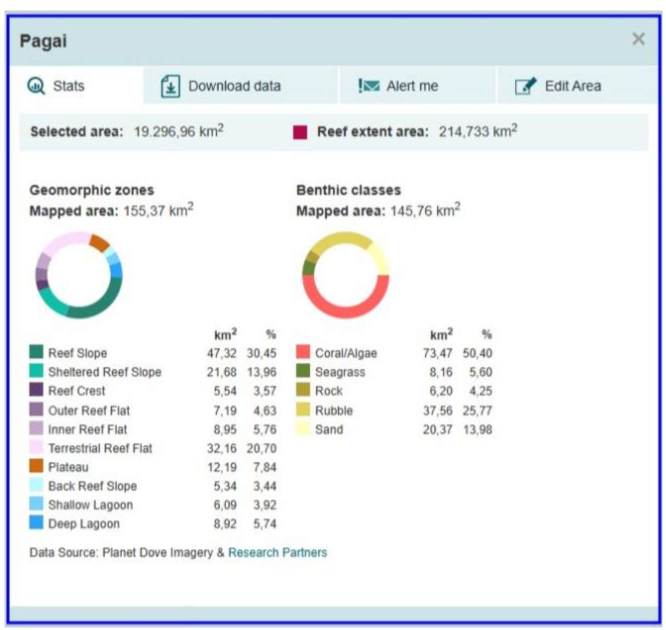

Figure 4. Pagai Islands Benthic Ecosystems Area in Allen Coral Atlas

By examining sediment and sand areas, which are often found in coastal regions where water movement is highly dynamic, the deposition of these materials can be observed. The distribution of sediments in such areas can serve as an indicator of potential seagrass growth, since seagrass often thrives on soft, sandy, or muddy substrates, for example. The presence of macroalgae in certain areas may indicate nutrient-rich waters, which are also conducive to seagrass proliferation. The clear distinction between different habitats in the Allen Coral Atlas map allows for a better understanding of their spatial relationships, which is crucial for marine conservation efforts.

The use of Dove satellites by Planet Labs not only provides high spatial resolution but also good temporal coverage, enabling the Allen Coral Atlas to capture dynamic changes in benthic habitats over time. This temporal aspect is crucial for monitoring the health and distribution of seagrass, which can be influenced by various environmental factors such as water quality, temperature, and human activities. Overall, the Allen Coral Atlas maps offer a detailed and accurate representation of seagrass distribution and other benthic habitats in North Pagai and South Pagai Islands, serving as a valuable tool for marine conservation and management.

3.2. Sentinel-2 Imagery

The Sentinel-2 imagery maps, consisting of Sentinel-2A and Sentinel-2B, provide an alternative perspective on benthic habitats in North Pagai and South Pagai Islands. Seagrass distribution is once again prominently displayed in green, covering much of the coastal areas. With Sentinel-2's spatial resolution of 10 meters, the level of detail is slightly lower compared to the Allen Coral Atlas. Smaller seagrass patches visible in the Allen Coral Atlas may be less recognizable in Sentinel-2 imagery, resulting in a more generalized representation of seagrass distribution. Nevertheless, Sentinel-2 maps are still able to effectively capture the overall extent of seagrass habitats, making them a reliable source for broader-scale studies.

The results from Sentinel-2 imagery also reveal other benthic habitats, including coral reefs (purple), mangrove forests (dark green), and sediments (brown), similar to the Allen Coral Atlas maps. Mangrove areas, in particular, appear more clearly in the Sentinel-2 imagery, likely due to the spectral bands available on the Sentinel-2 satellites, which are highly suitable for vegetation detection, with NDVI being used to distinguish vegetation. Coral reefs are displayed in slightly different locations compared to the Allen Coral Atlas maps, which may be attributed to differences in image acquisition time, cloud cover, or the processing techniques applied in SNAP.

Cloud cover, represented in light blue, is more clearly visible in the Sentinel-2 map. This is a significant factor that can affect the accuracy of benthic habitat mapping. The presence of clouds can obscure important details on the Earth's surface, leading to data gaps or habitat misclassification. The fact that cloud cover is more noticeable in the Sentinel-2 map may indicate that the data were acquired on a day with higher cloud cover, which could have influenced the overall accuracy of seagrass mapping.

The use of Sentinel-2 data from multiple spectral bands, including near-infrared, allows for better differentiation between water and vegetation, which is crucial for accurate seagrass mapping. However, the larger pixel size may limit the detection of smaller or sparse seagrass beds, potentially leading to less accurate estimates of seagrass coverage. Nevertheless, Sentinel-2 data provide a valuable overview of benthic habitats and serve as a complementary dataset to the higher-resolution Allen Coral Atlas.

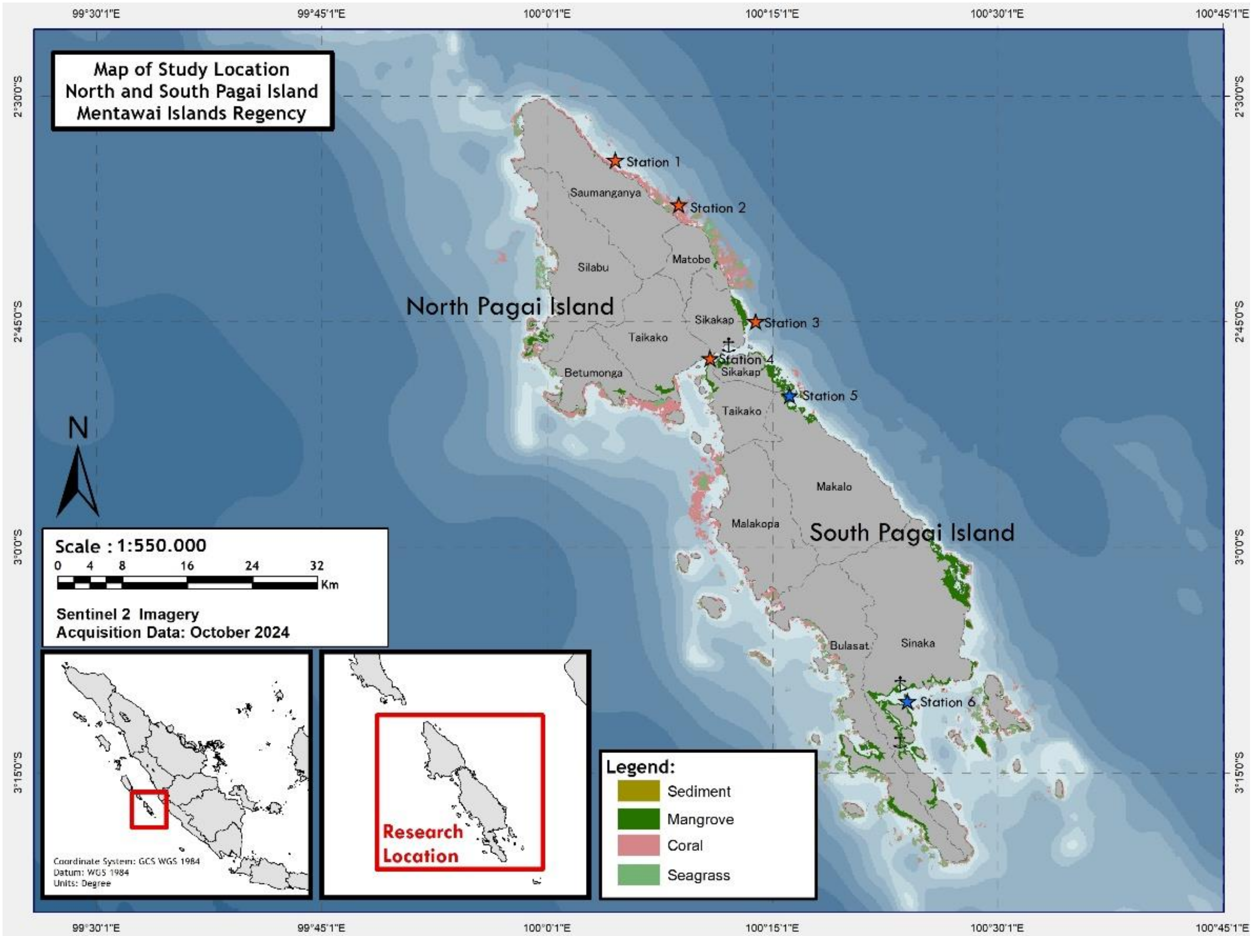

Figure 5. Spatial distribution of coastal benthic habitats in North and South Pagai Islands derived from 2024 Sentinel-2A and Sentinel-2B imagery, illustrating seagrass beds, coral reefs, mangroves, sediments, and cloud cover at 10-m spatial resolution

3.3. Data In-Situ Observation

It is important to note that the field validation data were collected in 2024, consistent with the period of the satellite imagery acquisition. The in-situ observations conducted on North Pagai and South Pagai Islands are an integral part of this study, serving as the basis for validating the benthic ecosystem maps derived from the Allen Coral Atlas and Sentinel-2 imagery. This research was carefully designed, with six observation stations strategically placed to capture the diversity of coastal environments in the region. Four stations are located on North Pagai Island, specifically in Saumangaya Village, Matoba Village, Sikakap Village and Taikako Village while the other two stations are situated on South Pagai Island, in Makalo Village and Sinaka Village.

Table 2. In-situ observations of mangrove, coral reef, and seagrass habitats at each observation station

No	Location	Station	Ecosystem	Species
1	Saumangaya Village, North Pagai Island	Station 1	Seagrass	*Enhalus sp.*
2	Matoba Village, North Pagai Island	Station 2	Seagrass	*Enhalus sp.*
3	Sikakap Village, North Pagai Island	Station 3	Coral Reef	*Acropora sp.*
4	Taikako Village, North Pagai Island	Station 4	Coral Reef	*Acropora sp.*
5	Makalo Village, South Pagai Island	Station 5	Mangrove	*Rhizophora sp.*
6	Sinaka Village, South Pagai Island	Station 6	Mangrove	*Avicennia sp.*

The stations were selected for their ecological significance as well as their representativeness of the diverse coastal habitats found in the Pagai Islands. The in-situ observations focused primarily on mangrove, coral and seagrass habitats, a key component of benthic ecosystems that play a vital role in coastal protection, carbon sequestration, and serving as nursery grounds for marine life. During the field survey, the research team conducted detailed assessments of the seagrass meadows, mangrove, and coral reef documenting the species present, their density, and the coordinates of these habitats. Findings from these observations provided highly valuable ground-truth data, which were then used to evaluate the accuracy and reliability of the maps derived from satellite imagery.

Field surveys revealed that seagrass meadows were present at all six observation stations, although there were striking variations in the extent and composition of these habitats. For example, in North Pagai Island, the seagrass beds observed in Saumangaya Village and Matoba Village were dense and healthy, dominated by species such as *Enhalus acoroides*. These dense meadows play an important role in stabilizing sediments and providing habitat for a wide variety of marine organisms. On the other hand, the seagrass beds in Matoba Village, while still significant, were more fragmented, likely due to the complex coastal topography and human activities in the area.

Figure 6. Seagrass transect at Station 2

The in situ observations were then compared with the benthic ecosystem maps derived from the Allen Coral Atlas and Sentinel-2 imagery. The Allen Coral Atlas, provided a detailed and accurate representation of seagrass habitats, which closely matched the field data. The maps produced from this dataset successfully captured the continuity and density of seagrass meadows, particularly in areas such as Taikako Village, where the meadows are more fragmented. This level of detail is crucial for understanding the small-scale dynamics of seagrass ecosystems, especially in regions with complex coastal environments such as the Pagai Islands.

Conversely, Sentinel-2 imagery, provides a more general overview of seagrass distribution. While this dataset is effective in mapping larger and more continuous seagrass meadows, it tends to generalize smaller patches and is less accurate in areas with high sedimentation or cloud cover. These limitations are evident in Makalo Village on South Pagai Island, where in situ observations confirmed the presence of seagrass, but the habitat was not accurately captured in the Sentinel-2-derived maps. Despite these discrepancies, the overall between two datasets and the field observations remains relatively high, particularly in larger seagrass meadows.

The integration of in situ observations with satellite-derived maps provides a comprehensive understanding of the benthic ecosystems in the Pagai Islands. Field data not only validate the accuracy of satellite imagery but also highlight the importance of ground-truthing in remote sensing studies. Findings from this research demonstrate the effectiveness of utilizing multiple data sources to achieve detailed and accurate benthic habitat mapping, which is crucial for proper management and conservation efforts in this ecologically sensitive region. By combining the strengths of the Allen Coral Atlas and Sentinel-2 imagery, this study establishes a robust framework for future ecological research and supports the sustainable management of coastal resources in the Pagai Islands.

3.4. Image Comparison

The comparison between the Allen Coral Atlas and Sentinel-2 imagery reveals clear differences as well as complementary strengths that are important for understanding seagrass habitats in the region. The resolution and level of detail provided by the Allen Coral Atlas are among its key advantages. The Allen Coral Atlas offers a more detailed and accurate depiction of seagrass meadows and other benthic features. This level of detail is particularly useful for capturing smaller and fragmented seagrass patches, which are often found in areas with complex coastal topography. The higher resolution also allows for more precise delineation of mixed habitats, where seagrass may coexist with other benthic communities such as coral reefs or mangroves. This precision is crucial for identifying and mapping habitat boundaries, which is often challenging in regions with diverse and overlapping ecosystems like the Pagai Islands.

Table 3. Comparison of benthic habitat area estimates derived from Sentinel-2 and Allen Coral Atlas

No	Benthic Ecosystem	Area in Sentinel-2 (Km^2)	Area in Allen Coral Atlas (Km^2)
1	Mangrove	6,83	7,13
2	Seagrass	8,01	8,16
3	Coral	113,4	73,47
4	Rubble	82,3	37,56

On the other hand, Sentinel-2 imagery, provides a broader view but with less detail of seagrass habitats. While this coarser resolution is sufficient for large-scale monitoring and mapping, it tends to generalize seagrass distribution, which may overlook smaller patches or misrepresent areas with mixed habitats This makes Sentinel-2 imagery a practical choice for sustainable environmental assessment, where the primary focus is on tracking changes in seagrass distribution over time rather than capturing fine-scale details.

For Accuracy test of the benthic habitat classification with a *matrix confusion* on North Pagai Island and South Pagai Islands has a value of more than 68,5% each station, with the best one of 77,2% accuracy from Sentinel-2 data and more than 68,2% each station with the best accuracy at 84,3% from Allen Coral Atlas which means it has a high accuracy value.

Table 4. Comparison of overall accuracy of benthic habitat classification using Sentinel-2 and Allen Coral Atlas data

No	Research Station	Location	Overall Accuracy (OA) of Sentinel-2 (Km^2)	Overall Accuracy (OA) Area in Allen Coral Atlas (Km^2)
1	Station 1	Saumangaya Village, North Pagai Island	68,5%	72,4%
2	Station 2	Matoba Village, North Pagai Island	66,1%	71,1%
3	Station 3	Sikakap Village, North Pagai Island	78,8%	68,2%
4	Station 4	Taikako Village, North Pagai Island	72,1%	79,8%
5	Station 5	Makalo Village, South Pagai Island	77,2%	81,2%
6	Station 6	Sinaka Village, South Pagai Island	69,6%	84,3%

In contrast, Sentinel-2 classification, while robust and versatile, may not be specifically tuned for particular benthic habitats. This can lead to potential misclassifications, particularly in regions where habitats are mixed or where environmental conditions, such as sedimentation or cloud cover, obscure the satellite's view.

4. Discussion

The integration of satellite imagery with in-situ observations highlights the importance of a multi-source approach for accurately mapping benthic habitats, particularly seagrass meadows in the Pagai Islands. The Allen Coral Atlas, proved superior in capturing the complex details of benthic habitats, including small and fragmented seagrass patches. This high precision is especially useful for distinguishing boundaries between adjacent habitats, such as seagrass, coral reefs, and mangroves. In contrast, Sentinel-2, tends to provide a broader overview but with lower levels of detail. These results indicate that spatial resolution plays a key role in mapping effectiveness, particularly in coastal areas with complex topography and high biodiversity.

Nevertheless, Sentinel-2 still provides significant added value. Its main advantage lies in the wide availability of data and high image acquisition frequency, which is extremely useful for long-term monitoring and detecting temporal changes in benthic habitats. In the context of sustainable coastal management, Sentinel-2 serves as an important tool for observing seagrass dynamics in response to environmental changes such as sedimentation, water quality variations, and human activities. However, Sentinel-2's accuracy in detecting small and scattered seagrass meadows is limited, as seen in Sinaka Village, where the satellite imagery failed to represent the seagrass observed directly in the field. Field observations reinforce the importance of validating satellite data through ground-truthing approaches. In-situ observations can capture real variability in the field, including seagrass species composition and habitat conditions that are not fully depicted by satellite imagery. The combination of high-resolution data from the Allen Coral Atlas and the broad coverage of Sentinel-2, when validated with field data, provides a strong foundation for data-driven conservation strategies. Therefore, the integration of these three approaches forms a crucial basis for more adaptive and scientifically informed mapping, management, and protection of benthic habitats in the Pagai Islands and other coastal areas.

5. Conclusions

A comparative analysis of benthic ecosystem mapping in the Pagai Islands, West Sumatra, using the Allen Coral Atlas and Sentinel-2 imagery reveals the strengths and limitations of each in monitoring seagrass habitats. The Allen Coral Atlas, with its higher resolution, provides more detailed maps, which are essential for accurate conservation planning, particularly for detecting small and fragmented seagrass patches. Meanwhile, Sentinel-2, with its wider spatial coverage and more frequent revisit times, excels in monitoring changes in seagrass habitats over time, albeit at a coarser resolution. The integration of both datasets, combined with in-situ validation, successfully enhances the reliability of benthic habitat maps, supporting more effective conservation strategies in the Mentawai Islands.

Future research and conservation efforts in the Pagai Islands should integrate satellite data from both the Allen Coral Atlas and Sentinel-2 to maximize the combined strengths of these sources. This approach will provide a more accurate understanding of benthic ecosystems, aiding better decision-making for habitat conservation. Regular monitoring with Sentinel-2 is recommended to track changes in seagrass habitats and to adjust conservation strategies in response to emerging threats. Routine in-situ validation is crucial to improve the accuracy of maps derived from satellite imagery, especially in areas affected by cloud cover or sedimentation. Detailed maps from the Allen Coral Atlas should serve as a guide in the design and management of Marine Protected Areas, ensuring that critical habitats are safeguarded. Engaging local communities in conservation efforts and raising awareness about the importance of seagrass ecosystems will enhance the effectiveness of these initiatives and support the sustainable use of coastal resources.

Acknowledgments: Special mention to Marine Research Center, Marine and Fisheries Research and Human Resources Agency, Ministry of Marine Affairs and Fisheries for providing primary data for field validation.

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