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Persistence and Dynamics of Shallow Water Benthic Habitats by Multi-Temporal Sentinel-2 Observations in Mapur Island Indonesia

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Abstract

Shallow-water benthic habitats are important to tropical coastal ecosystems, yet spatial transitions and persistence in Indonesia's small islands remain insufficiently documented. This study mapped benthic habitats around Mapur Island, Riau Islands, Indonesia, and assessed changes between 2020 and 2025. Results: Sentinel-2 imagery was classified using Random Forest in Google Earth Engine, supported by field observations collected in July 2025 using 1 × 1 m photo-transects. Four classes were mapped: dead coral with algae, mixed substrate, sand, and seagrass. The 2025 classification achieved 76.9% overall accuracy and a Kappa coefficient of 0.69. Between 2020 and 2025, sand increased by 75.43 ha (11.5%) and dead coral with algae increased by 68.01 ha (10.5%), while seagrass declined by 41.8%, from 308.97 ha to 179.76 ha. Approximately 24% of the initial seagrass area persisted over the study period. Conclusions: The results indicate substantial changes in the composition of shallow-water benthic habitats around Mapur Island, with seagrass showing the largest net decline. The maps provide a temporal baseline for coastal habitat monitoring and conservation planning, while the transferred classification for 2020 should be interpreted in light of the lack of independent field validation for that year.

1 Introduction

Shallow-water benthic habitats, including coral reefs, seagrass meadows, and other benthic substrates, form the foundation of tropical coastal ecosystems. These interconnected habitats play essential ecological roles by sustaining marine biodiversity, providing habitat for a wide range of marine organisms, supporting coastal fisheries, and serving as significant blue carbon reservoirs (Alongi et al., 2016; Mansoben et al., 2024). Consequently, alterations in one habitat component may trigger cascading effects that disrupt the structure and functioning of the entire coastal ecosystem (Cattano et al., 2020). Despite their ecological importance, shallow-water benthic habitats are increasingly threatened by multiple environmental and anthropogenic stressors, including rising sea surface temperatures, sedimentation, eutrophication, and human activities. These pressures have accelerated shifts in benthic habitat composition and spatial distribution across tropical coastal regions over recent decades (Aji et al., 2024; Gove et al., 2023; Panjaitan et al., 2025; Rivadeneira and Nielsen, 2022).

Recent global seagrass mapping has revealed that approximately 4% of the world's seagrass meadows disappeared between 2019 and 2024, while many of the remaining meadows experienced declines in cover and condition due to increasing environmental pressures and anthropogenic disturbances (Peng et al., 2026). However, changes in benthic habitats are not limited to habitat loss alone; they may also occur through transitions among different habitat types. Understanding the direction and magnitude of these habitat transitions is therefore essential for assessing the condition of coastal ecosystems and establishing evidence-based conservation priorities.

Remote sensing has become an indispensable tool for large-scale benthic habitat mapping by providing cost-effective, repeatable, and spatially comprehensive observations (Hedley et al., 2016). Numerous

studies have demonstrated that Sentinel-2 imagery can achieve high mapping accuracy for shallow-water benthic habitats when combined with machine learning classification algorithms (Arifin et al., 2025; Trinh et al., 2023; Wicaksono et al., 2021). Among the available classification techniques, the Random Forest (RF) algorithm has emerged as one of the most widely adopted approaches due to its ability to model complex spectral relationships, minimize the risk of overfitting, and produce high classification accuracy for heterogeneous benthic habitats (Thanh Noi and Kappas, 2017).

This study extends beyond benthic habitat mapping by incorporating a multi-temporal change analysis to better understand ecosystem dynamics over time. Such an approach enables the identification of habitat transitions between different benthic classes as well as habitats that remain stable over successive observation periods (persistent habitats). Persistence analysis provides valuable insights into ecologically stable areas, whereas transition analysis identifies habitats that are more susceptible to environmental change. Together, these complementary analyses improve our understanding of the stability of shallow-water benthic ecosystems and the trajectories of habitat change. Despite their importance, studies that explicitly integrate benthic habitat transition and persistence analyses in shallow-water ecosystems of Indonesia's small islands remain relatively scarce.

Mapur Island, located in Bintan Regency, Riau Islands Province, Indonesia, is a typical tropical small-island ecosystem characterized by diverse shallow-water benthic habitats. The island is also part of the Eastern Bintan Marine Protected Area, which plays an important role in conserving the region's coastal biodiversity. Recent studies conducted within the Eastern Bintan Marine Protected Area have reported a decline in seagrass cover over the past decade, accompanied by changes in species composition and ecosystem quality, as indicated by the Seagrass Ecological Quality Index (SEQI). These findings suggest that the coastal ecosystems of the region are undergoing substantial ecological change (Nugraha et al., 2026). Despite these observations, no previous study has comprehensively evaluated the spatial patterns of benthic habitat transition and persistence on Mapur Island. Such information is essential for understanding ecosystem stability, identifying vulnerable habitat components, and supporting evidence-based coastal management and conservation planning. Therefore, this study aims to map the shallow-water benthic habitats of Mapur Island and analyze their transition and persistence patterns over the 2020–2025 period. The findings are expected to provide a valuable temporal baseline for monitoring benthic habitat dynamics and to support adaptive conservation and sustainable coastal management in Mapur Island and the Riau Islands region.

2 Methods

This study was conducted in July 2025 on Mapur Island, which forms part of a marine protected area in Indonesia (Fig. 1). Administratively, the island is located within Mapur Village, Bintan Regency, Riau Islands Province. The surrounding waters are influenced by four dominant monsoonal seasons, namely the northeast, southeast, southwest, and northwest monsoons. Owing to its geographical setting, Mapur Island is highly exposed to strong winds and high wave conditions, particularly during the northeast

monsoon, making its coastal ecosystems vulnerable to hydrodynamic disturbances (Apriliani et al., 2009).

According to (Nugraha et al., 2026), nine seagrass species have been recorded on Mapur Island, including *Enhalus acoroides (Ea), Thalassia hemprichii (Th), Cymodocea rotundata (Cr), Oceana serrulata (Os), Halophila ovalis (Ho), Halodule uninervis (Hu), Halodule pinifolia (Hp), Syringodium isoetifolium (Si)*, and *Thalassodedron ciliatum (Tc)*.

2.1. Field Data Collection

Field surveys were conducted from 25 to 27 July 2025 using the 1 × 1 m² photo-transect method (Roelfsema and Phinn, 2009). Sampling locations were determined using a systematic random sampling approach, in which survey sites were systematically distributed based on prior knowledge of the study area, while individual sampling points were selected randomly (Congalton and Green, 2008). Benthic habitat data were collected through direct underwater visual observations. Each ground-truth point was subsequently labeled and assigned to one of the predefined habitat classes, including seagrass, sand, mixed substrate, rubble, dead coral, and dead coral with algae (DCA), to generate the training dataset for image classification. In addition, seagrass species present at each ground-truth location were identified to characterize the spatial distribution and diversity of seagrass communities across the study area.

2.2. Satellite Image Pre-processing

This study utilized Sentinel-2 Level-2A Surface Reflectance imagery from the COPERNICUS/S2_SR_HARMONIZED image collection available through the Google Earth Engine (GEE) platform for the 2020 and 2025 acquisition periods (Fig. 2). Image processing was performed using Google Earth Engine, a cloud-based geospatial computing platform that enables efficient visualization, processing, and analysis of large-scale remote sensing datasets (Gorelick et al., 2017).

The image processing workflow began with the selection of scenes based on three criteria: minimal cloud cover, acquisition dates closely matching the field survey period, and satisfactory visual image quality. The pre-processing steps included clipping the imagery to the study area boundary, selecting the spectral bands relevant for benthic habitat mapping, Band 2 (Blue), Band 3 (Green), Band 4 (Red), and Band 8 (Near Infrared, NIR), and generating false-color and true-color composite images for preliminary visual interpretation. The overall image-processing workflow is illustrated in Fig. 2.

For each observation year, Sentinel-2 imagery was filtered using the study area boundary and a cloud-cover threshold of < 20%. A median composite was then generated from the filtered image collection for each period and subsequently clipped to the study area. To isolate shallow-water environments, a water mask was created using the Normalized Difference Water Index (NDWI = (B3 − B8) / (B3 + B8) where B3 represents the green band and B8 the near-infrared band. Pixels with NDWI values greater than 0 were retained to delineate water-covered areas.

Following the delineation of the analysis area, water-column correction was applied using the Depth Invariant Index (DII) to reduce bottom-reflectance variability associated with differences in water depth. The correction followed the empirical approach proposed by (Lyzenga, 1978) which minimizes the influence of water depth on bottom reflectance and improves the separability of shallow-water benthic habitats. The method utilizes the blue (Band 2) and green (Band 3) spectral bands, which exhibit different attenuation characteristics in the water column (Mumby and Edwards, 2000).

$$Y = \ln Li - \lfloor \frac{Ki}{Kj} \ln Lj \rfloor$$

1

where Li and Lj represent the reflectance values of spectral bands (i) and (j), respectively, while Ki/Kj denotes the attenuation coefficient ratio between the two bands. The attenuation coefficient ratio was calculated using the following equation:

$$\frac{Ki}{Kj} = a + \sqrt{a^2 + 1}$$

2

$$a = \frac{\sigma ii - \sigma jj}{2\sigma ij}$$

3

Where σii and σjj represent the variances of spectral bands (i) and (j), respectively, and σij denotes the covariance between the two bands. The resulting attenuation coefficient ratio was subsequently used to compute the Depth Invariant Bottom Index (DIBI) according to the following equation DIBI_B3_B2 = ln(B3) − (*k*i/*k*j) × ln(B2).

2.3. Random Forest Classification

The pre-processed Sentinel-2 imagery, following water-column correction, was classified using the Random Forest (RF) algorithm. Random Forest is an ensemble machine learning classifier that constructs multiple decision trees from bootstrap samples of the training dataset (Breiman, 2001). At each node, only a randomly selected subset of predictor variables is considered for data partitioning, thereby increasing model diversity and reducing correlation among individual trees. The final classification is determined through a majority voting scheme, in which each decision tree casts a vote for the predicted class, and the class receiving the highest number of votes is assigned to the output pixel (Fig. 3). The RF algorithm was selected because of its robustness in handling high-dimensional remote sensing data, its ability to model complex and non-linear spectral relationships, and its resistance to overfitting. In addition, RF has been widely demonstrated to provide reliable classification

performance for heterogeneous benthic habitats while maintaining high computational efficiency when processing large geospatial datasets.

Across various remote sensing-based classification studies, Random Forest (RF) has demonstrated strong performance due to its ability to capture complex spectral patterns and effectively discriminate between different habitat classes. In a coral bleaching detection study using Sentinel-2 imagery, the RF algorithm achieved an overall accuracy of 97% and a Kappa coefficient of 0.94, indicating very high classification reliability (Narciso et al., 2024). Similarly, in benthic habitat mapping along the coastal waters of Nongsa, Batam, RF successfully classified coral, seagrass, sand, and rubble habitats with an overall accuracy of 89.90% (Prabowo et al., 2025). Another study on seagrass mapping in Sebesi Island reported that RF outperformed the Maximum Likelihood Classifier, achieving a higher accuracy (83.3%) compared to 66.6% using the latter method (Aprizal Arifin et al., 2025). These findings highlight the robustness and effectiveness of Random Forest as a reliable classification approach for remote sensing analysis and coastal resource mapping.

Field survey data collected from Mapur Island were stored as a FeatureCollection asset within the Google Earth Engine (GEE) platform. The ground-truth samples were assigned to four benthic habitat classes: Dead Coral with Algae (DCA = 1), Mixed Substrate (Mix = 2), Sand (3), and Seagrass (4). The ground-truth dataset was randomly divided into training and validation subsets, with 67% of the samples allocated for model training and 33% for accuracy assessment. A Random Forest classifier was developed using the 2025 imagery as the baseline model. The classifier was configured with 100 decision trees and a fixed random seed (seed = 42), while the depth-invariant corrected imagery was used as the input predictor variables. To improve temporal consistency in habitat classification, the RF model was trained using mean surface reflectance values extracted from homogeneous benthic habitat polygons rather than individual pixels. The trained RF model was subsequently transferred and applied to classify the 2020 imagery. This temporal transfer classification approach assumes that the spectral characteristics distinguishing different habitat classes remain relatively consistent over time, allowing the model developed from the 2025 dataset to be applied to historical imagery (Apdillah et al., 2026).

2.4. Accuracy Assessment

Because field validation data were only available for the 2025 observation period, accuracy assessment was conducted exclusively for the 2025 classification result. This evaluation was performed to quantify the performance of the RF model prior to its application in multi-temporal change analysis. Classification accuracy was assessed using a confusion matrix by calculating the Overall Accuracy (OA), Kappa coefficient (κ), Producer's Accuracy (PA), and User's Accuracy (UA) following the approach described by (Congalton and Green, 2008).

2.5. Habitat Area Quantification and Transition Analysis

The spatial extent of each benthic habitat class was quantified in hectares (ha) for both observation years. Temporal changes were analyzed by overlaying the classified habitat maps from 2020 and 2025 using a pixel-by-pixel comparison approach. A transition matrix was generated to quantify the area (ha)

converted between each pair of habitat classes during the observation period. Habitat persistence was defined as pixels that retained the same habitat classification in both years (2020 and 2025). Based on this definition, a persistence map was generated consisting of five categories: persistent DCA, persistent mixed substrate, persistent seagrass, persistent sand, and dynamic zones. The dynamic zone category represents areas where habitat classes changed between observation periods, indicating spatial locations experiencing habitat transitions.

3 Results and Discussion

3.1. Multi-Temporal Benthic Habitat Mapping and Area Dynamics

The Random Forest classification of Sentinel-2 imagery identified four benthic habitat classes in the shallow waters of Mapur Island for both 2020 and 2025, namely Dead Coral with Algae (DCA), Mixed Substrate (Mix), Sand, and Seagrass (Fig. 4). Spatially, the distribution patterns of these habitat classes remained relatively consistent between observation periods. Sand and DCA habitats dominated the outer reef flat zones, whereas seagrass habitats were primarily concentrated in more sheltered and low-energy coastal waters.

The total extent of the study area remained relatively stable between observation periods; however, substantial shifts occurred in the composition of individual habitat classes (Fig. 5). The Sand and DCA classes increased by 75.43 ha (11.5%) and 68.01 ha (10.5%), respectively, whereas Seagrass exhibited the most pronounced decline, decreasing by 129.21 ha or 41.8% of its initial extent. The Mixed Substrate class also decreased by 20.49 ha during the observation period. The expansion of DCA accompanied by the decline in seagrass extent indicates a shift in benthic habitat composition toward a condition increasingly dominated by degraded coral substrates and algae-covered dead coral. Similar habitat transitions have been observed in coral reef ecosystems exposed to prolonged environmental stress, including anthropogenic disturbances and elevated sea surface temperatures, which may reduce ecosystem resilience and recovery capacity (Duarte, 2009; Gove et al., 2023).

The magnitude of seagrass loss observed on Mapur Island (41.8%) exceeds the decadal decline reported in the Eastern Bintan Marine Protected Area, where seagrass cover decreased by 33.6% across monitoring stations (Nugraha et al., 2026). This comparison suggests that Mapur Island represents one of the areas experiencing relatively high rates of benthic habitat degradation within the Riau Islands region and highlights the need for prioritized management and conservation interventions.

The accuracy assessment of the 2025 image classification against the field-based ground-truth data resulted in an Overall Accuracy (OA) of 76.9% and a Kappa coefficient (κ) of 0.69. The Producer's Accuracy (PA) and User's Accuracy (UA) values ranged from 58.1% to 93.9% across the benthic habitat classes (Table 1).

Table 1
Confusion matrix of the Sentinel-2 image classification results for 2025.

Class	***Ground Truth***				**Total**	***User accuracy (%)***
	DCA	**Mix**	**Sand**	**Seagrass**		
DCA	28	2	1	1	32	87,5
Mix	5	18	3	5	31	58,1
Sand	1	0	31	1	33	93,9
Seagrass	5	2	4	23	34	67,6
Total	39	22	39	30	130	
Producer accuracy (%)	71,8	81,8	79,5	76,7	*Overall accuracy*	76,9

The obtained accuracy is comparable to the performance of Random Forest classification reported in other Sentinel-2-based benthic habitat mapping studies in Indonesian waters, which generally achieved Overall Accuracy values ranging from 83% to 98 (Arifin et al., 2025; Narciso et al., 2024b; Prabowo et al., 2025). Furthermore, the present results are consistent with Wicaksono et al. (2021), who demonstrated that multi-temporal Sentinel-2 imagery can achieve classification accuracies exceeding 80% when supported by high-quality imagery, particularly under conditions of low cloud cover and minimal sunglint effects.

3.2. Habitat Transition Analysis (2020–2025)

The pixel-based transition analysis revealed the spatial trajectories of each benthic habitat class during the 2020–2025 period (Fig. 6). The results showed that the largest transition involved the DCA class, which increased from 647.78 ha in 2020 to 715.79 ha in 2025 (Fig. 7). During this period, DCA areas were mainly converted into Mixed Substrate (151.31 ha), Sand (147.00 ha), and Seagrass (102.71 ha).

The transition from DCA to Sand suggests that some areas previously dominated by dead coral substrates experienced increased sediment accumulation. High sedimentation can alter the surface properties of benthic substrates by covering dead coral structures, resulting in spectral characteristics that become more similar to sandy substrates in multispectral imagery (Limmon and Marasabessy, 2019; Rogers and Ramos-Scharrón, 2022; Tuttle and Donahue, 2022). This interpretation is also supported by the observed expansion of Sand habitat during the study period. Conversely, the transition from DCA to Seagrass indicates that several areas previously characterized by dead coral substrates may have developed greater benthic vegetation cover. This finding suggests that certain locations on Mapur Island may still provide suitable environmental conditions for benthic vegetation establishment, contributing to the observed increase in seagrass extent from 149.22 ha in 2020 to 179.76 ha in 2025.

However, the transition from DCA to Seagrass should not be interpreted as direct evidence of seagrass colonization in all converted areas. Instead, this pattern may represent an increase in benthic vegetation cover, including seagrass and/or algae, which can be difficult to distinguish using medium-resolution multispectral imagery. Dead coral substrates can be rapidly colonized by microalgal communities with high primary productivity (Heil et al., 2004), potentially producing spectral responses similar to vegetated benthic habitats. Furthermore, previous studies have demonstrated that seagrass and macroalgae exhibit overlapping spectral characteristics, particularly in the green, red, and near-infrared wavelengths, leading to potential classification uncertainties in multispectral remote sensing applications (Elma et al., 2024; Hou et al., 2025; Wicaksono et al., 2024).

In this study, macroalgae were not included as an independent classification class because the available field samples were insufficient to develop a reliable classification model. Therefore, the classification scheme was limited to four major habitat classes (seagrass, DCA, mixed substrate, and sand). Under this classification framework, areas potentially dominated by macroalgae may have been classified as seagrass due to their similar spectral responses. Consequently, the observed DCA to Seagrass transition should be interpreted as an indication of increasing benthic vegetation cover rather than definitive evidence of complete conversion into seagrass meadows.

In contrast, Sand represented one of the most persistent habitat classes, with approximately 485.02 ha remaining unchanged during the 2020–2025 period. However, several sandy areas experienced transitions into other habitat classes, including DCA, Mixed Substrate, and Seagrass. Approximately 13% of the initial Sand class was converted into DCA (Dead Coral with Algae). This transition may indicate the development of benthic algal cover over sandy substrates associated with the accumulation of coral rubble or scattered hard substrates on the seafloor (Connell et al., 2014).

Previous studies have shown that turf algae tend to proliferate more extensively on coral rubble substrates than on intact hard substrates and are favored by surfaces with relatively low structural complexity. These conditions suggest that fragmented coral materials and relatively flat substrates can provide suitable environments for algal colonization (Syafruddin et al., 2025). Therefore, sandy areas containing accumulated coral fragments or exposed hard substrates that become colonized by algae may exhibit spectral responses similar to DCA and consequently be classified as such in multispectral imagery. In this study, macroalgae and turf algae were not considered as separate classification classes due to the limited availability of field training samples. Consequently, some areas dominated by algal communities may have been classified as DCA because of their similar spectral characteristics in multispectral satellite imagery (Hedley et al., 2016; Knudby et al., 2010)

Approximately 12% of the area initially classified as Sand transitioned into the Mixed Substrate class, indicating that some sandy substrates developed more diverse benthic cover. This transition may occur because sandy substrates represent dynamic habitats that can support the development of multiple benthic cover types, including seagrass, algae, and coral rubble. Consequently, a single image pixel may contain a combination of different benthic habitat types (Lundquist et al., 2018). Furthermore,

sedimentation processes, the movement of coral fragments driven by waves and currents, and the gradual colonization of benthic organisms may increase substrate heterogeneity in areas previously dominated by sand (Liu et al., 2025).

The remaining 5% of the Sand class transitioned into Seagrass, indicating that some sandy areas have become colonized by seagrass. This condition may occur because stable sandy substrates facilitate the anchoring of seagrass roots and rhizomes, allowing plants to establish and expand more effectively (Essa and Geneid, 2025). Areas that were previously dominated by bare sand may potentially develop into seagrass habitats through seed dispersal or rhizome expansion from adjacent seagrass meadows (Ambo-Rappe, 2022). Seagrass represented the habitat class with the highest degree of change compared to other benthic habitats. Of the 308,97 ha of seagrass mapped in 2020, only 179,76 ha remained classified as seagrass in 2025, while the remaining areas transitioned into Dead Coral with Algae (DCA), Mixed Substrate (Mix), and Sand classes. These results indicate that the spatial distribution of seagrass on Mapur Island is highly dynamic and can undergo substantial changes within a five-year period.

This finding is consistent with the global pattern of seagrass decline, where the rate of seagrass loss increased from approximately 0.9% per year during the 1940s to around 7% per year by the end of the 20th century, making seagrass ecosystems one of the most threatened ecosystems worldwide (Chowdhury et al., 2024; de los Santos et al., 2019; Waycott et al., 2009). Similar findings were reported by Febrianto et al., 2024), who demonstrated that seagrass extent declined by up to 61% within only two years (2018–2020). These conditions indicate that seagrass ecosystems exhibit high spatial dynamics in response to the combined effects of natural processes and anthropogenic pressures, allowing substantial changes in seagrass extent to occur within relatively short time periods.

Overall, the habitat transition analysis indicates that benthic changes on Mapur Island were not solely characterized by the loss of a single habitat type but also involved simultaneous inter-habitat transitions, including habitat reduction, expansion, and conversion into other classes (DCA, Mix, Sand, and Seagrass). This pattern is consistent with findings from other multi-temporal benthic habitat studies in Indonesian waters. For example, in Ayau Island, Raja Ampat, coral habitats (9.9%) and seagrass habitats (74.9%) were reported to decline simultaneously; however, the magnitude and direction of transitions varied among observation periods, indicating that habitat changes did not occur uniformly across all habitat classes (Setiawati et al., 2024). Similarly, a study in Gili Sumber Kima, Bali, revealed three simultaneous patterns of seagrass cover change within the same observation period, including habitat expansion, decline, and persistence across different spatial areas (Lazuardi et al., 2021).

These findings indicate that shallow-water ecosystems on Mapur Island remained actively dynamic during the observation period, consistent with the characteristics of tropical benthic ecosystems that commonly experience shifts in habitat composition due to interactions between natural environmental processes and anthropogenic pressures (Aji et al., 2024; Panjaitan et al., 2025; Wayan A Karang et al.,

2022). Such multi-directional dynamics highlight the importance of continuous monitoring to better understand the future trajectory and rate of benthic ecosystem changes on Mapur Island.

To further illustrate the direction and magnitude of all benthic habitat transitions, the Sankey diagram presented in Fig. 7 depicts the proportional flows from each habitat class in 2020 to the corresponding benthic habitat classes in 2025.

The figure above highlights that changes in benthic habitat cover on Mapur Island during the 2020–2025 period did not occur uniformly across all habitat classes. DCA and Sand represented the most persistent habitat classes, retaining approximately 66% and 70% of their initial extent, respectively. In addition, both classes also received additional areas from other habitat classes, resulting in an overall increase in their extent by 2025. In contrast, the Mixed Substrate class exhibited a more dynamic pattern, with only 19% of its area remaining unchanged, while the remaining areas transitioned into DCA, Sand, and Seagrass.

The most prominent change occurred in the Seagrass class, which retained only approximately 24% of its initial extent. Most seagrass areas transitioned into Sand (33%) and DCA (28%) classes (Fig. 8), resulting in a decrease in total seagrass extent from approximately 308,97 ha in 2020 to 179,76 ha in 2025. This pattern indicates a shift in shallow-water habitat composition on Mapur Island, where areas previously dominated by seagrass tended to transition into sandy substrates or dead coral habitats. This decline requires attention because seagrass meadows are among the important coastal ecosystems that contribute to maintaining aquatic productivity and providing essential habitats for various marine organisms.

3.3. Persistence Maps of Benthic Habitats

The persistence maps for each habitat class (Fig. 9) revealed distinct spatial change patterns during the 2020–2025 period. Dead Coral with Algae (DCA) habitats (Fig. 9a) remained dominant along the reef crest and several coastal areas, consistent with the habitat extent analysis showing an increase in DCA area throughout the observation period. This pattern indicates that DCA represents one of the most persistent benthic components on Mapur Island. This finding is consistent with (Sari Sakaria, 2022), who reported that DCA cover was higher in reef crest and reef slope zones compared to other dead coral categories, including Rubble (R) and Recent Dead Coral (DC). The dominance of DCA suggests that a substantial proportion of dead coral colonies have progressed into an advanced degradation stage, characterized by coral skeleton surfaces being covered by algae. This condition may reflect prolonged environmental pressures, such as sedimentation and anthropogenic disturbances.

Seagrass (Fig. 9b) exhibited limited persistent areas that were spatially fragmented and concentrated in specific locations, particularly in the southern and southeastern parts of the island. This indicates that only a small proportion of the total seagrass extent remained stable and was consistently classified as seagrass during both observation periods (2020 and 2025), while the remaining areas transitioned into other habitat classes. This pattern is consistent with previous studies showing that seagrass meadows exposed to environmental stress tend to fragment into smaller and isolated patches, potentially reducing

their overall ecosystem functions (Riera et al., 2025). Similar patterns were reported in a decadal study of shallow waters in Eastern Bintan, Riau Islands, where only certain locations with dominant seagrass species were able to persist, while the overall seagrass cover exhibited a declining trend (Nugraha et al., 2026). Differences in habitat persistence may also be influenced by spatial variations in environmental conditions, as seagrass structural characteristics can vary considerably even at small spatial scales due to differences in microhabitat conditions (Smale et al., 2019).

Meanwhile, the Mixed Substrate class (Fig. 9c) exhibited a relatively limited distribution and was generally located between other habitat types as transition zones. These areas represent gradual habitat changes occurring along the boundaries between two different habitat types, forming intermediate zones with mixed characteristics of adjacent habitats. In addition, the Sand class (Fig. 9d) showed the widest spatial distribution, particularly in the western part of the island. Most of these areas remained classified as sand throughout the five-year observation period. This pattern indicates that sandy substrates on Mapur Island tend to be highly persistent, with only a small proportion experiencing transitions, resulting in the continued dominance of sandy substrate characteristics in the shallow-water environment. Overall, these findings demonstrate that changes in benthic habitat composition have occurred on Mapur Island over the past five years, characterized by a decline in seagrass extent accompanied by an expansion of areas dominated by sand and dead coral habitats. This condition indicates ongoing changes within shallow-water ecosystems, particularly affecting seagrass habitats, which require further attention in coastal habitat management efforts.

4 Conclusion

This study successfully mapped the dynamics of benthic habitats on Mapur Island during the 2020–2025 period using Sentinel-2 imagery and Random Forest classification, achieving an overall accuracy of 76.9%. The classification results revealed that the shallow-water ecosystems of Mapur Island experienced significant changes in habitat composition characterized by multi-directional transitions rather than movement toward a single final state.

The most concerning finding of this study was the substantial loss of seagrass habitat. From a total extent of 308,97 ha in 2020, seagrass area decreased to 179,76 ha in 2025, with only approximately 24% of the initial seagrass area remaining persistent between the two observation periods. Most of the lost seagrass areas transitioned into Sand (33%) and Dead Coral with Algae (DCA) (28%), while the Mixed Substrate class exhibited the highest instability among all habitat classes, with only 19% of its area remaining unchanged. In contrast, DCA and Sand were identified as the most persistent and expansive habitat classes, each increasing by more than 10% during the study period, primarily through transitions from areas previously occupied by seagrass. This pattern indicates that the shallow-water ecosystem of Mapur Island is shifting toward greater dominance of abiotic substrates and algae-covered dead coral habitats, with seagrass representing the most vulnerable benthic component.

Overall, these findings confirm that the shallow-water habitats of Mapur Island remain in an actively changing state rather than a stable condition, emphasizing the need for continuous monitoring to understand the direction and rate of ongoing ecosystem changes. Considering the critical role of seagrass ecosystems in providing coastal ecosystem services, the decline in seagrass extent and its low persistence rate on Mapur Island should become a priority in future coastal management and conservation planning, particularly in the southern and southeastern areas that currently represent the remaining stable seagrass habitats.

Furthermore, future studies are recommended to incorporate macroalgae as a separate classification class to reduce spectral ambiguity between seagrass and algal communities, thereby improving the accuracy and reliability of future benthic habitat dynamics assessments. The findings of this study provide an essential quantitative temporal baseline to support evidence-based coastal management in the Riau Islands.

Declarations

AUTHOR CONTRIBUTIONS

Indah Kartika: Conceptualization, Methodology, Field data collection, Mapping, Data curation, Formal analysis, Writing - original draft. Tri Edi Kuriandewa: Resources, Investigation, Formal analysis, Writing - review & editing. Aditya Hikmat Nugraha: Investigation, Writing - review & editing. All authors read and approved the final manuscript.

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Figures

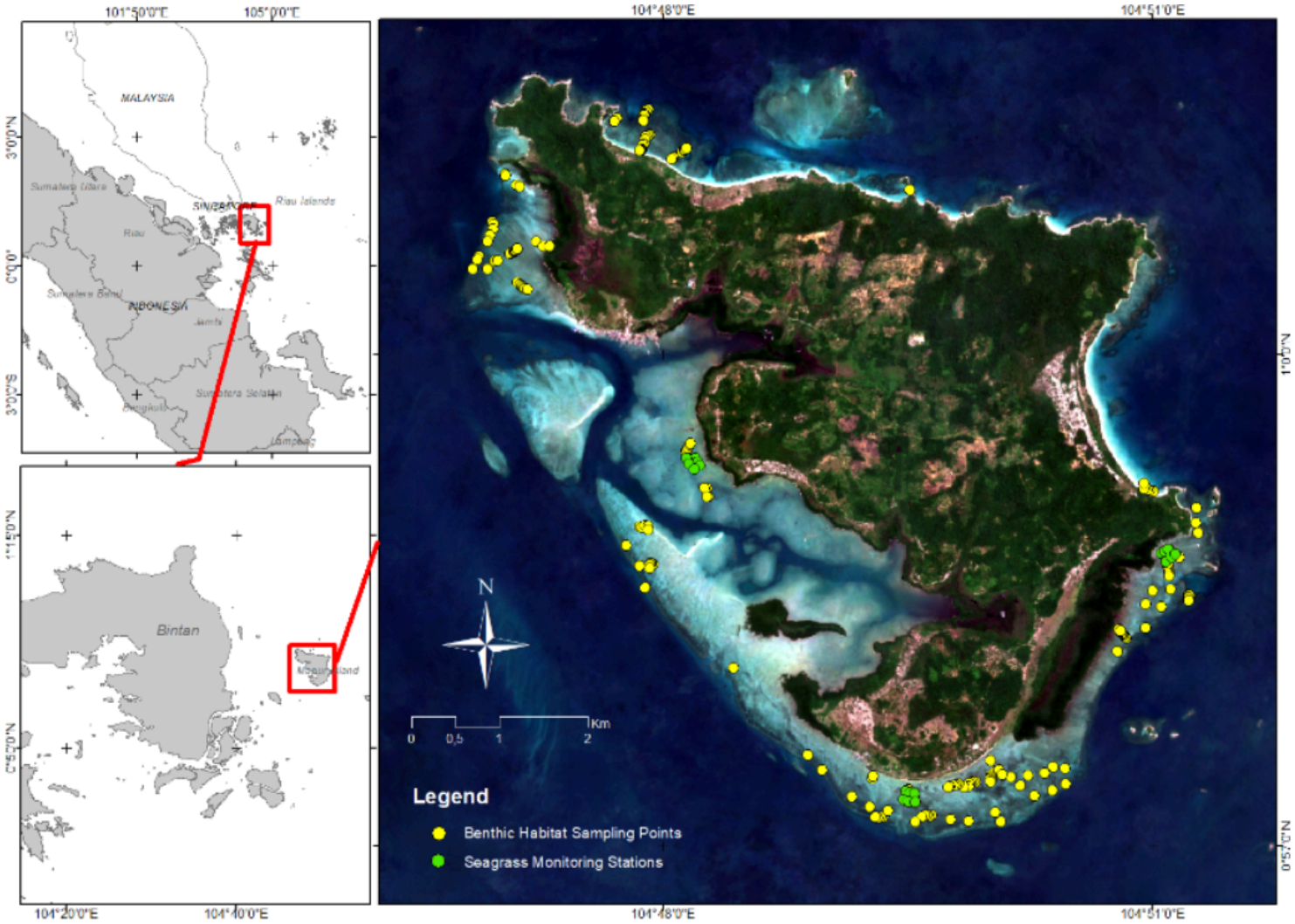


Figure 1

Location of the study area on Mapur Island, Riau Islands, Indonesia.

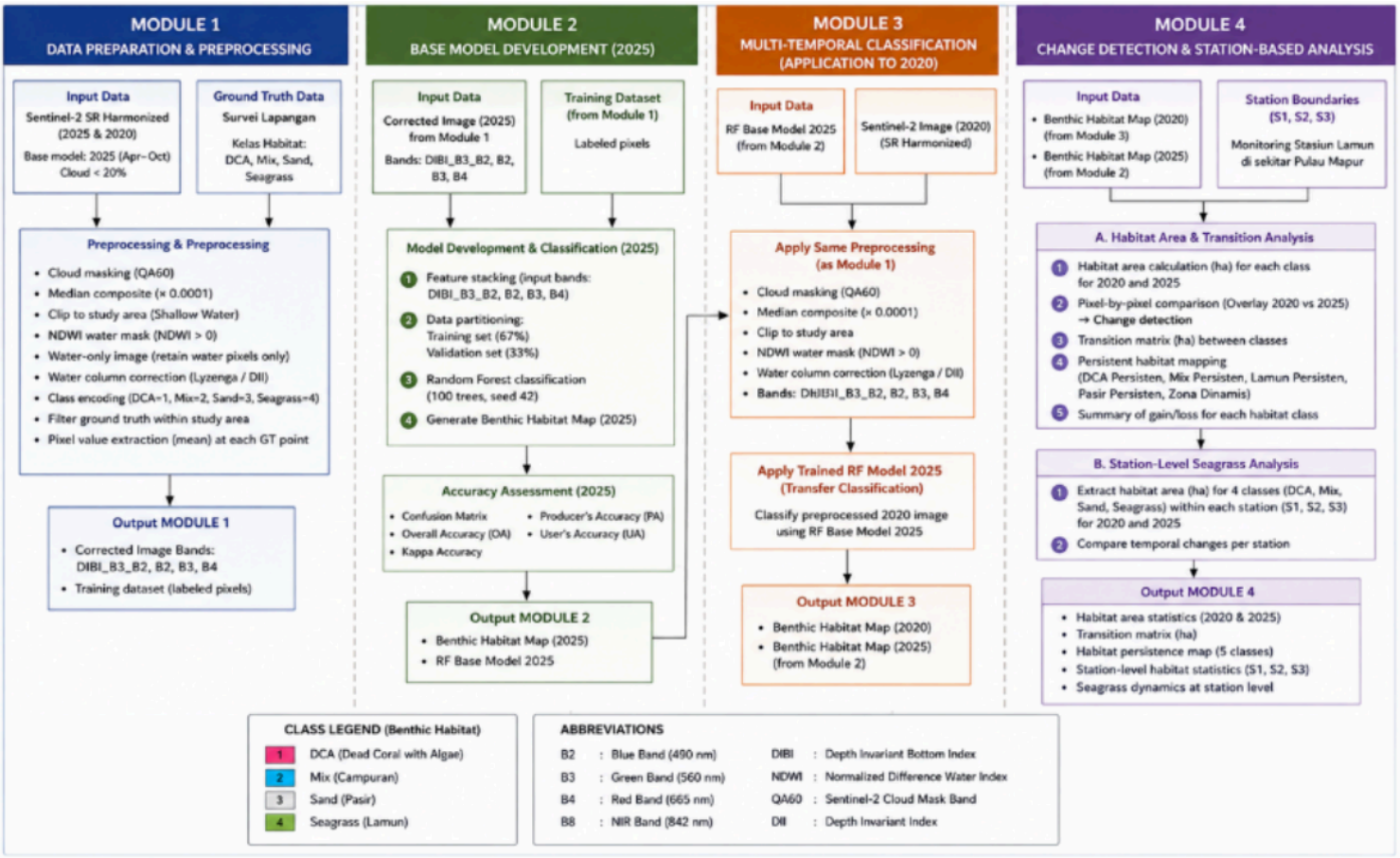


Figure 2

Workflow of the spatial data analysis.



Figure 3

Conceptual framework of the Random Forest algorithm for benthic habitat classification.

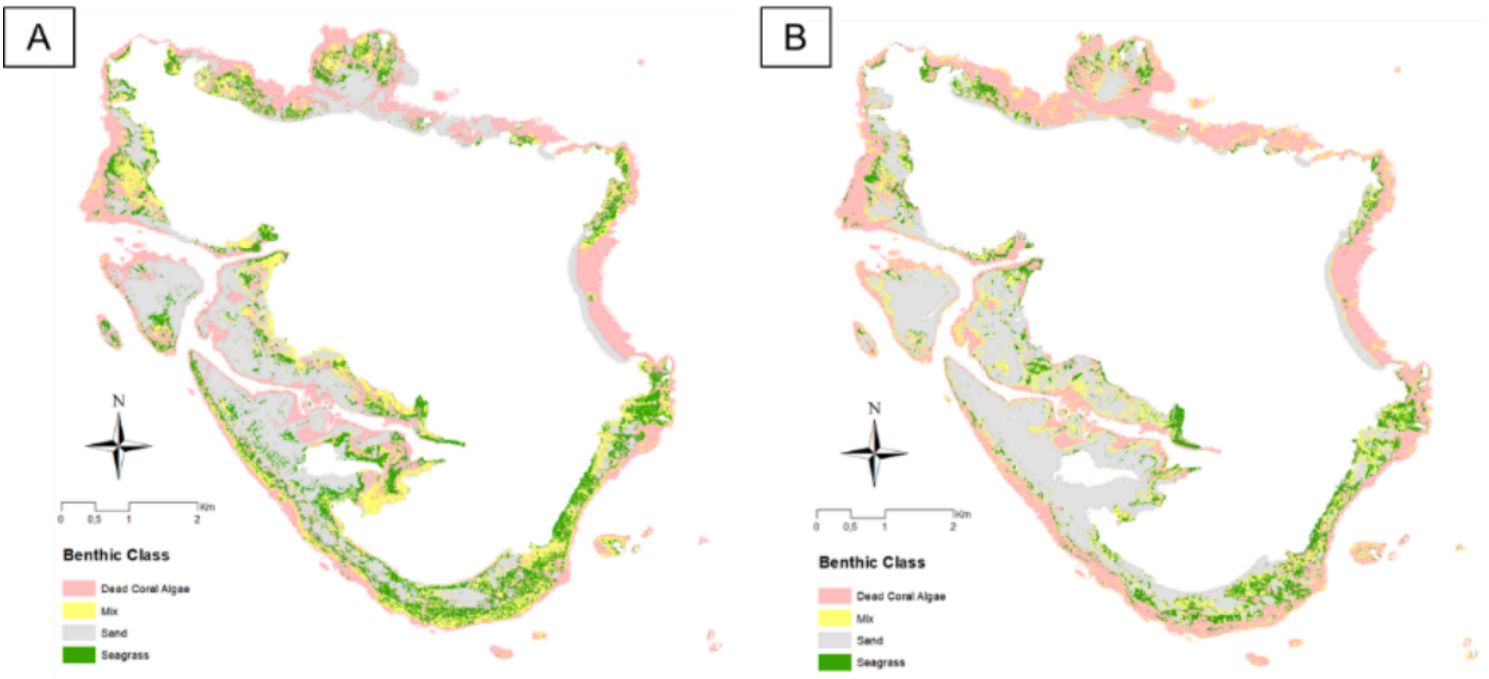


Figure 4

Spatial distribution of benthic habitats on Mapur Island in (A) 2020 and (B) 2025 based on Random Forest classification of Sentinel-2 imagery.

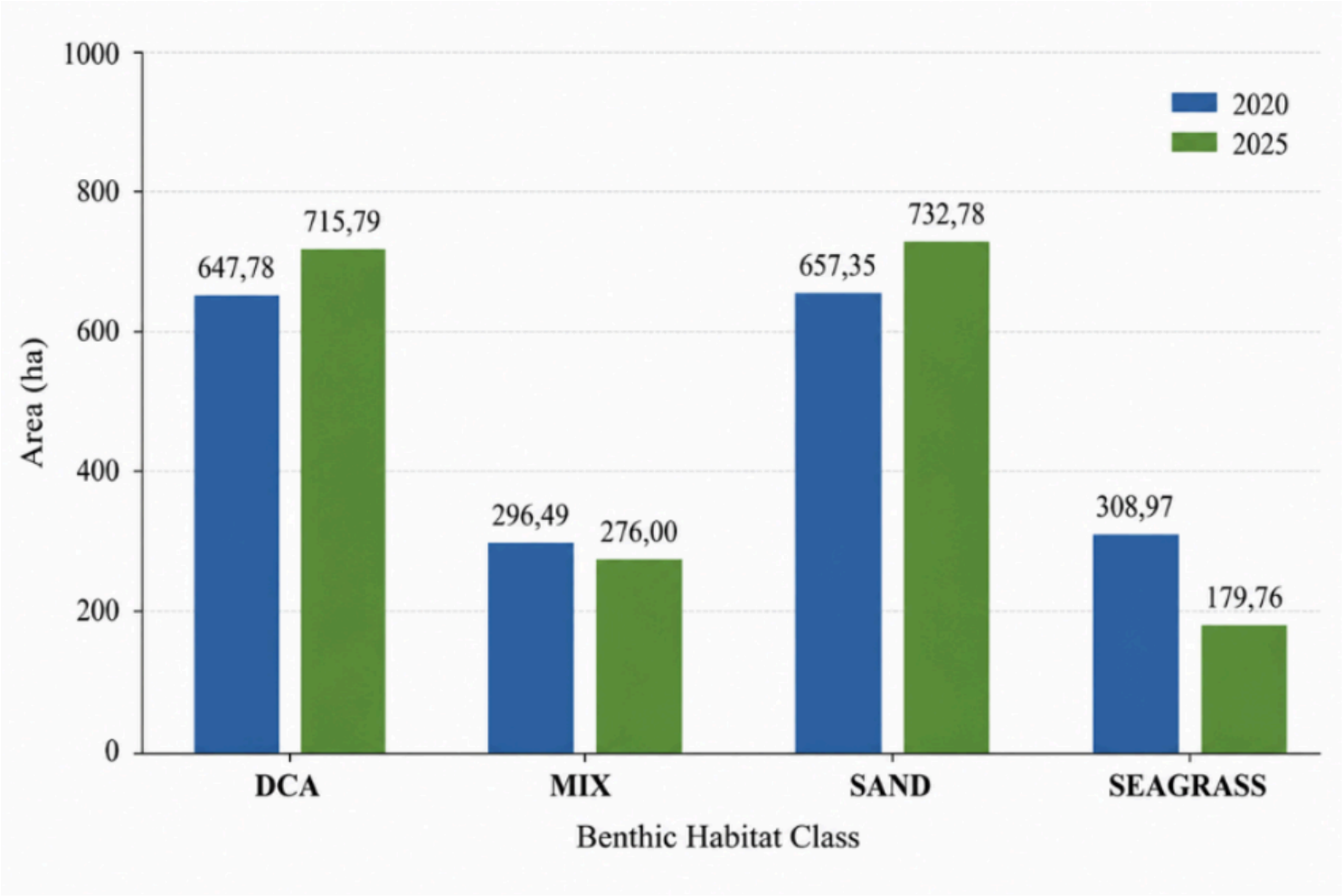


Figure 5

Spatial extent of benthic habitat classes (ha) on Mapur Island during 2020 and 2025.



Figure 6

Spatial patterns of benthic habitat transitions on Mapur Island between 2020 and 2025.

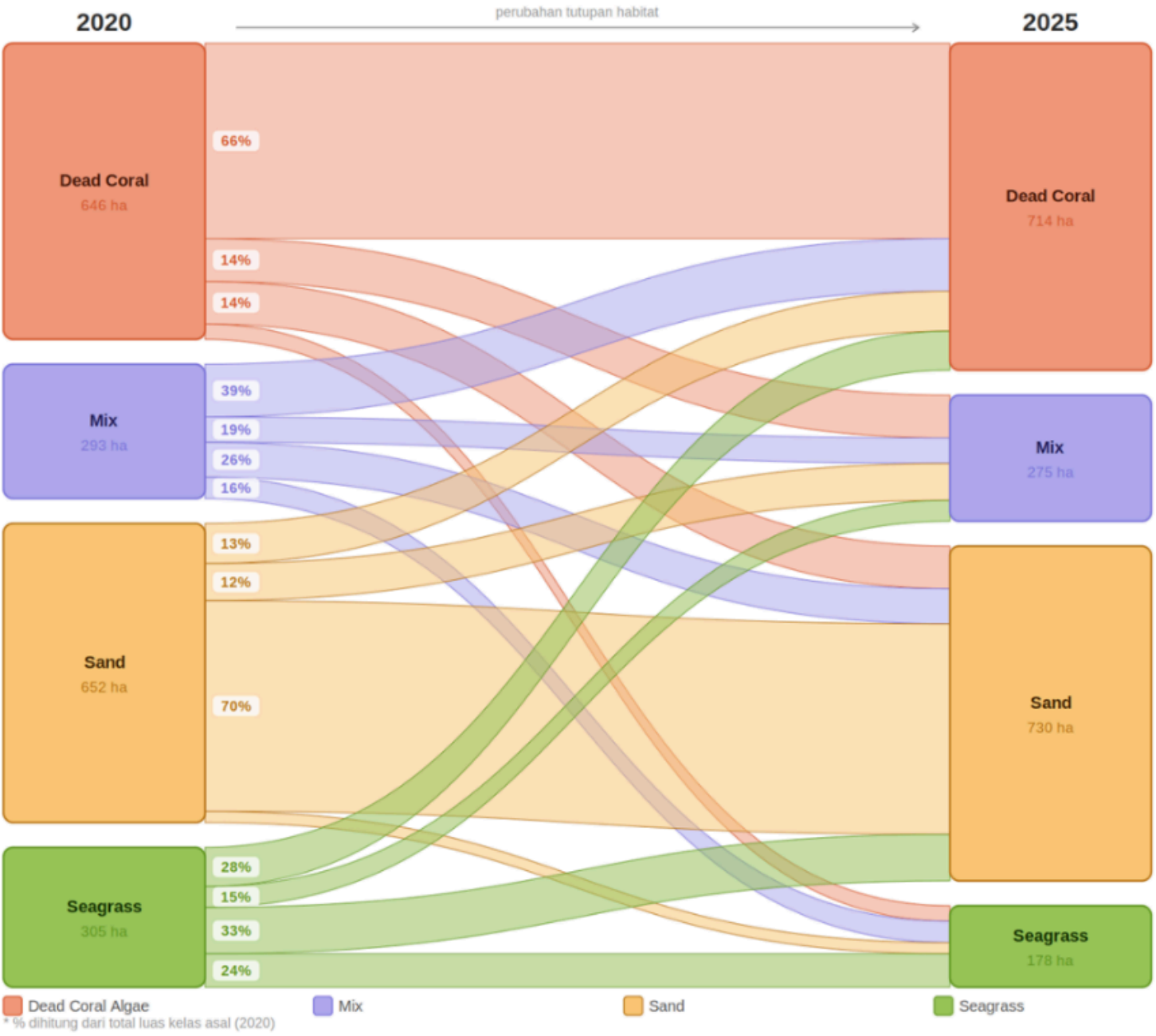


Figure 7

Sankey diagram of benthic habitat transitions on Mapur Island during the 2020-2025 period.



Figure 8

Field observation showing remaining seagrass stands growing among Dead Coral with Algae (DCA) patches in the shallow waters of Mapur Island in 2025.

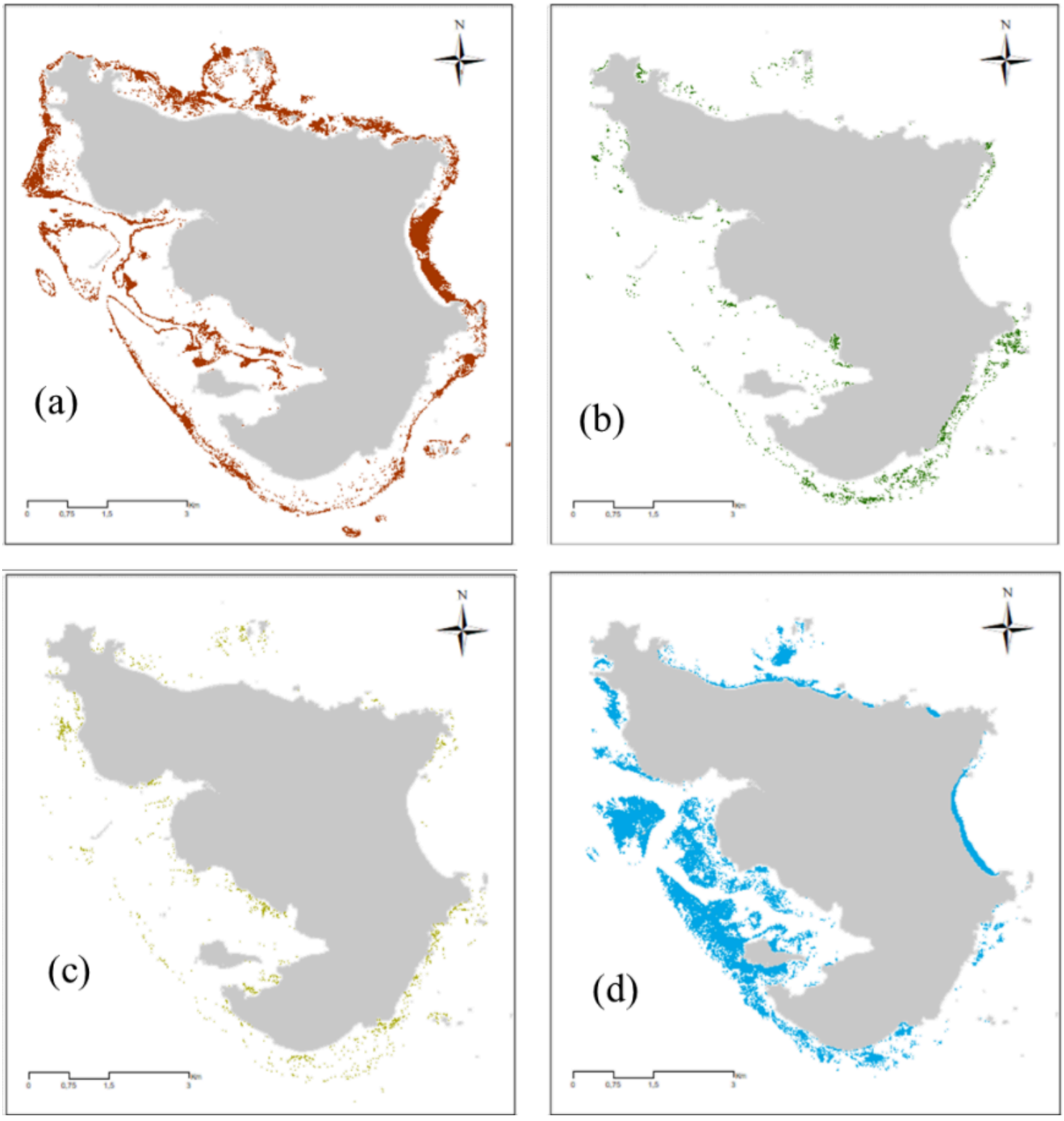


Figure 9

Individual persistence maps for each habitat class: (a) Persistent DCA, (b) Persistent Seagrass, (c) Persistent Mixed Substrate, and (d) Persistent Sand.