Spatial Planning Model for Optimizing Conservation Priorities for Local Community Utilization on Arefi Island in the Raja Ampat Marine Protected Area (MPA) Southwest Papua, Indonesia

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Abstract

This study investigates the application of remote sensing technologies to identify the biophysical characteristics of marine ecosystems for spatial planning, focusing on optimal conservation scenarios within the Raja Ampat Marine Protected Area (MPA) on Arefi Island, Southwest Papua, Indonesia. Indigenous communities manage this area. WorldView-3 satellite imagery, combined with an object-based image analysis (OBIA) approach, was used to classify and map coastal ecosystems. A Marine Reserve Design using the Spatially Explicit Annealing (Marxan) model was applied to delineate conservation areas and propose zoning strategies. The analysis revealed that Arefi Island's coastal ecosystems cover 64.78 hectares, consisting of seagrass beds (45.41%), coral reefs (36.35%), and mangroves (18.24%), with a kappa accuracy of 0.82. Three scenarios, based on ecological values, were tested to prioritize conservation features while ensuring sustainable ecosystem use. Ecological Value III is most closely aligned with international conservation standards, designating 34.37 hectares (6.32%) as a core conservation zone. However, Ecological Scenario II provided a balanced approach, allocating larger areas for local community use while preserving conservation integrity. This study highlights the

effectiveness of remote sensing and spatial planning tools, such as Marxan, in marine conservation within indigenously managed areas, emphasizing the importance of balancing conservation efforts with sustainable community use for future planning.

Keywords: Spatial planning, remote sensing**,** marine protected area, indigenous management, marxan models.

Introduction

Indonesia harbours some of the world's richest marine biodiversity. It encompasses approximately 3,953,800 hectares of the world's coral reefs, over 3,000,000 hectares of seagrass beds, and 2,332,429 hectares of mangroves (Amkieltiela et al., 2022; Burke et al., 2011; Hamilton & Friess, 2018; Thorhaug et al., 2020). These productive ecosystems provide numerous benefits, such as filtering pollutants, supplying nutrition, offering coastal protection, supporting livelihoods, and sequestering carbon. Due to these significant benefits, Indonesia has a high conservation priority, particularly in the Raja Ampat Marine Protected Area, located in the Arefi Island Regency, Southwest Papua Province. While other regions in Indonesia, such as Komodo National Park, Wakatobi, and Bunaken, hold substantial conservation value, Raja Ampat stands out due to its unparalleled biodiversity, strategic location within the Coral Triangle, and globally significant ecosystems. The unique marine life, ecological significance, and need for sustainable management in the face of growing environmental pressures position Raja Ampat as a top conservation priority for Indonesia. The nation recognizes that safeguarding Raja Ampat is not only a national obligation but also essential for protecting global marine biodiversity. Conservation efforts in Raja Ampat have also focused on supporting the livelihoods of indigenous and local communities (Sutton, 2023).

The conservation of marine environments is crucial for maintaining the Earth's natural processes, addressing significant future challenges such as climate change, and ensuring societal well-being and benefits (Marcos et al., 2021). The Indonesian government has established 411 Marine Protected Areas (MPAs) across its archipelago, covering approximately 9% of its territorial waters—over 28 million hectares (Estradivari et al., 2022). The Ministry of Maritime Affairs and Fisheries (MMAF) of the Republic of Indonesia issued ministerial decree no. 36 in 2014, designating the Raja Ampat marine area as an MPA. This MPA is divided into five regions, totalling approximately 1,026,540 hectares. Each area includes specific zones that play a vital role in the management and conservation of natural resources, offering a framework for effective planning and sustainable development (MMAF, 2014). In this context, "zone" refers to a designated area with specific characteristics or purposes, often demarcated for conservation, resource management, or regulatory objectives. The zones in Raja Ampat include core, utilization, fisheries, and other zones. The “other zones” are further divided into two subzones: traditional use and seasonal closure, and other utilization (MMAF, 2016).

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For marine biodiversity conservation, MPAs are defined as marine, coastal, or small island areas that are protected and managed by a zoning system to achieve the sustainable management of fish resources and biodiversity conservation (Green et al., 2009). MPAs are essential tools for conserving marine biodiversity and sustaining ecosystem services (Claudet et al., 2020). Particularly, MPAs with well-designed spatial planning strategies are more effective at achieving conservation goals (Edgar et al., 2014). With the rising threats from human activities such as overfishing, habitat destruction, and climate change, spatial planning within MPAs has become vital for sustainable management (Mora et al., 2011). In recent years, MPA areas, including Arefi Island, have faced increasing pressures from sea level rise, ocean acidification, and anthropogenic impacts like overfishing and habitat destruction. To mitigate these challenges, effective spatial planning is essential (White et al., 2018). Advanced modelling techniques have positioned spatial planning as a valuable tool for optimizing conservation efforts within MPAs. Spatial planning involves the systematic allocation of marine areas for various uses while considering ecological, social, and economic objectives.

The Raja Ampat Regency in Southwest Papua, Indonesia, is renowned for its natural tourism, both on land and at sea, and its rich sociocultural heritage, largely due to its extraordinary marine biodiversity (Cinner et al., 2018). However, the Raja Ampat MPAs face certain shortcomings, particularly in areas such as Arefi Island. Arefi Island and its surroundings are located within the "other zones" of the Raja Ampat marine conservation area (MMAF, 2014). While the significance of Arefi in the broader context of marine conservation is recognized, the MMAF decree lacks the specificity required to fully harness its potential. In particular, the decree fails to clearly delineate the boundaries of subzones, address the diverse ecosystems and biodiversity within the area, and optimize the use of marine resources by indigenous communities. This lack of precision hinders the realization of conservation objectives. For an MPA to be both effective and beneficial to surrounding communities, its location must adhere to four key principles: Connectedness, Adequacy, Representativeness, and Effectiveness (CARE) (Ban et al., 2011). According to various studies, the ideal proportion of coastal areas that should be protected ranges from 20-30% of the total coastal area (Krueck et al., 2017; IUCN, 2008; Green et al., 2014).

Establishing MPAs is an important step toward conservation, but the lack of precise boundary delineation and insufficient consideration of the intricate mosaic of ecosystems impede the strategic planning needed for effective conservation. This gap in applying CARE principles in Arefi Island's designation highlights a critical issue in marine conservation efforts in Indonesia and other similarly biodiverse regions worldwide. The broad approach of the MMAF decree overlooks the ecological and socioeconomic complexities of Arefi Island, leading to a disconnect between conservation objectives and on-ground realities. This oversight not only compromises the ecological integrity of the protected area but also the livelihoods and cultural heritage of indigenous communities dependent on these marine resources. Moreover, the failure to align

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with recommended coverage and core zone area standards for MPAs exacerbates challenges in achieving sustainable conservation outcomes. Addressing these gaps requires a comprehensive, data-driven approach to MPA management that emphasizes spatial planning and community involvement, ensuring both biodiversity conservation and socioeconomic resilience.

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Effective maritime planning is essential for designing marine conservation areas. In this process, analyzing spatial information is crucial. Decision-making regarding conservation costs becomes particularly important when budgets are limited (de Groot et al., 2022). Some decision-makers argue that areas designated for ecosystem services (ES) conservation should focus on meeting specific ES conservation targets at low cost, rather than prioritizing areas with the highest ES intensity (Schröter and Remme, 2016). Various spatial decision support tools, such as Marxan, have been developed to integrate socioeconomic costs into ES conservation planning (Adame et al., 2015). As conservation costs vary across different regions (Naidoo et al., 2006), Marxan iteratively selects low-cost areas until the combined ES conservation targets are achieved (Watson et al., 2019). Thus, conservation costs act as a spatial constraint for ES conservation, necessitating the prioritization of lands with lower conservation costs (Egoh et al., 2011).

Research has demonstrated that conservation prioritization based on systematic conservation planning (SCP) theory can result in cost-effective conservation efforts while meeting multiple objectives (Beger et al., 2022). SCP theory, initially a foundational paradigm in conservation biology (Margules and Pressey, 2000), is now widely applied to guide objective decision-making in the prioritization of conservation actions (Kukkala and Moilanen, 2017). There are two significant advantages to using SCP-based prioritization. First, SCP theory suggests that priority areas should be identified based on three core criteria: importance, vulnerability, and feasibility (Wilson et al., 2009). This approach ensures comprehensive coverage and balances multiple objectives during implementation (Kukkala and Moilanen, 2017). Second, SCP theory categorizes prioritization challenges into two main types of mathematical problems: minimizing costs and maximizing benefits. These offer different but effective solutions for planning and implementation (Alagador et al., 2016).

In this context, implementing maritime planning within a Geographic Information System (GIS) framework provides significant advantages. An effective maritime planning process involves evaluating various objectives, identifying conflicts or synergies in marine use, assessing risks posed by human activities, managing spatial zones, and testing different scenarios. Stelzenmüller et al. (2013) noted that conservation area planning can be efficiently evaluated using practical tools, including risk assessments, forecasting, modeling, and decision-support tools such as simulation models to explore planning options and address complex scenarios.

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This study aimed to examine the complexities of conserving the Arefi subzone by utilizing existing biodiversity elements through remote sensing data, enabling the community to make optimal use of these resources. The primary objectives were to use remote sensing data to identify biophysical features (mangroves, coral reefs, and seagrass) as input for determining conservation areas on Arefi Island and to propose zoning within the MPA to protect biodiversity while supporting the sustainable management of marine resources by the local community. Through this research, we seek to provide valuable insights into marine conservation planning, contributing to the development of a robust and sustainable spatial plan for Arefi Island.

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Materials & Methods

Study Area

This research was conducted in Area III of the Marine Protected Area (MPA) in the Dampier Strait, Arefi Island, Raja Ampat Regency, Southwest Papua (Fig. 1). Raja Ampat Regency is characterized by a cluster of islands situated between 2°25′ N and 4°25′ S latitude and 130° E to 132°55′ E longitude. The regency covers approximately 6,084.5 km² and includes around 600 islands of varying sizes. The Raja Ampat conservation area is renowned for its ecological richness and is a popular tourist destination. It also holds strategic importance for fisheries due to its well-functioning aquatic ecosystem. Although categorized under "other zones" in the Raja Ampat MPAs, satellite data reveal the significant biophysical potential of Arefi Island (McKenna et al., 2002; RPZ Raja Ampat, 2018). The term "other zone" refers to the zoning classification used by the MMAF of the Republic of Indonesia for the Raja Ampat water conservation area, which includes four districts in Southwest Papua.

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Arefi Island, located at 0° 47′ 18.67″ S and 130° 42′ 27.72″ E, supports significant marine biodiversity and provides critical habitats for various species, including corals, fish, and endangered marine mammals (Kovacs et al., 2021; Trip et al., 2019). The island's characteristics make it a suitable candidate for various conservation zones, including core, fisheries, and sustainable utilization areas. Additionally, Arefi Island is home to indigenous cultures that practice the "sasi" tradition, a customary resource management system deeply rooted in their cultural heritage. This system involves periodic closures to allow ecosystem recovery and ensure resource sustainability (Sairiltiata, 2023). Under sasi, indigenous communities impose temporary bans (moratoriums) on the use of marine resources, such as coral reefs and fish, in specific areas for designated periods (Rachma Persada et al., 2018). This highlights the need for a comprehensive and nuanced zoning strategy to fully protect and utilize the island's diverse ecosystems.

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Figure 1. Study area map in Arefi Island, Raja Ampat District

Data Used

The data used in this research primarily consists of remote sensing data, supported by secondary data sources (Table 1). Specifications of the multispectral bands of the Worldview 3 imagery are detailed in Table 2. The research framework and stages are illustrated in Figure 2.

Figure 2: Research Framework

The first step involved analyzing satellite imagery to map biophysical parameters, including mangroves, seagrass, and coral reefs. These biophysical parameters serve as breeding grounds for numerous fish species with both commercial and ecological significance (Weeks, 2017; Sutrisno et al., 2021) and are integral to conservation efforts. In the second step, the locations of biophysical parameters were used as inputs for determining conservation features. Cost features were calculated based on the current usage? of the area, as presented in Table 3.

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Table 1: Types and Sources of Data

Table 2: Multispectral Bands of the WorldView-3 Satellite Imagery (Source: Choudhury et al., 2021)

Method of Biophysical Analysis

The biophysical parameters were mapped using high-resolution Worldview 3 satellite images from 2021, provided by the Center for Data and Information, National Innovation and Research Agency (BRIN). The spatial resolution of these images is approximately 0.6 meters, allowing detailed analysis and mapping of terrestrial and aquatic ecosystems.

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Due to the high resolution of the satellite images, thorough image analysis is essential. Traditional pixel-based classification methods are limited due to spectral similarities. To address this, Object-Based Image Analysis (OBIA) was employed, which differs from pixel-based methods by using image objects as the basic unit of analysis rather than individual pixels (Hossain and Chen, 2019). OBIA is an iterative process that starts with segmenting satellite images into cohesive and contiguous segments. These image objects are then classified using either supervised or unsupervised approaches (Belgiu and Csillik, 2018).
According to Ventura et al. (2018), the OBIA workflow begins with image segmentation, a process based on pixel parameters with similar spectral values. In this study, we used the Multi-resolution Segmentation (MRS) algorithm to create image objects that minimize average heterogeneity and maximize homogeneity. The three key parameters in the MRS algorithm are shape, compactness, and scale (Darmawan et al., 2022). OBIA analysis was performed using eCognition Developer 64 software.

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The segmentation results were then classified using support vector machine (SVM) algorithms, a sophisticated non-parametric classifier widely employed in hyperspectral image classification that operates based on statistical learning theory (Tan et al. 2018). It is designed to seek an optimal decision hyperplane within a high-dimensional space, ensuring optimal separation of classes. SVM consistently performs well in challenging classification scenarios with high-dimensional features, demonstrating its effectiveness even when dealing with a limited number of training samples (Cao et al. 2018). The fundamental concept behind the SVM is to identify a hyperplane that maximizes the margin between distinct classes. This hyperplane is expressed by the following equation (Camps-Valls & Bruzzone, 2009)

$$f(x) = \sum_{i=1}^{n} \alpha_i y_i K(x, x_i) + b$$

where, $f(x)$: decision function

α_i : Coefficients obtained during the training process

y_i : class label of training sample x_i

$K(x, x_i)$: kernel function

b : bias term

The predicted class of the input data point x is determined by $f(x)$. If $f(x) > 0$ then the data point is classified as belonging to one class. If $f(x) < 0$ then the data point is classified as belonging to another class. The classified data and field and secondary observations were then input into the Marxan software.

Method of Priority Area Conservation

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Marxan Model Principle

Marine Reserve Design Using Spatially Explicit Annealing (Marxan) is software designed to support the systematic design of conservation areas (Ball et al., 2009). Marxan aids in identifying conservation areas that offer high sustainability value while maintaining relatively low management costs. It operates using a simulated annealing algorithm, which is developed to rapidly achieve optimal results through iterative optimization (Anggraeni et al., 2017).
The Marxan algorithm involves numerous random changes to the protected area system, often involving one million or more iterations. Initially, all changes to the system are accepted, regardless of their impact on the objective function score. As the annealing process progresses, the likelihood of accepting unfavourable changes (those that increase the objective function score) gradually decreases, while the acceptance of beneficial changes (those that decrease the score) becomes more likely. This approach allows the algorithm to converge on a solution that closely approximates the optimal result (Moilanen and Ball, 2009).

The optimal results represent the lowest total cost and are derived using the following equation (Watts et al., 2017):

$$Total\ Cost = \sum_{i=1}^{n} Cost + \left(BLM\ x \sum Boundary\right) + \sum_{i=1}^{n} \left(SPF\ x\ Penalty\right)$$

Cost : The combination of socioeconomic values in each planning unit within the selected solution.
BLM : Boundary Length Modifier is a value set by the user and is related to the level of connectivity between planning units. The higher the Boundary Length value, the denser the solution area.
Boundary: The boundary of the selected area.
SPF : Values set by the user and related to the importance of biodiversity target objectives. The higher the SPF assigned to a feature, the more Marxan prioritizes that feature in the solution.
Penalty: Penalty value assigned if biodiversity protection targets are not achieved (optional).
i : Unit ID in the shapefile.
n : Last Unit ID in the shapefile.

The boundary length in the protected area system was measured by counting the number of planning units that border areas outside the protected system. A fragmented protected area system will have a substantial boundary length. Modifying the boundary length or Boundary Length Modifier (BLM) aims to address connectivity issues by assigning a value based on the importance of maintaining a dense protected area network. BLM is crucial because a fragmented system is typically more challenging and costly to manage (Watts et al., 2017).

Marxan Models

To meet conservation feature targets, enhance connectivity between areas, and minimize overall management costs for priority zones, we utilized Marxan v.4.0.6. This software is designed to identify priority conservation areas. The analysis was conducted using the QMarxan Toolbox (2.0.1), a plugin for QGIS 3.18.3. The conservation features of Arefi Island include three critical ecosystems: mangroves, seagrass, and coral reefs. These features were identified using a map generated from object-based image analysis. Arefi Island served as the primary study area, with a buffer zone extending from the coastline to encompass all shallow water habitats within this zone. The study area was divided into hexagonal planning units with a side length of 15 meters, resulting in 9,531 planning units (PUs) within the area.

To estimate conservation costs, the cost feature used is based on the status of the area or region, as modified by Wijayanto et al. (2021) and Watts et al. (2017), and presented in Table 3. This includes areas with the following statuses: Resident Area (1), Land Use (3), Floating Net Cage (1), and Dock Area (3). Land use refers to the land cover on an island that is not identified as part of marine conservation areas.

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Table 3 Cost Features

This study examines the cost attributes of various human spatial utilization activities within the conservation area. Penalty scores are assigned to each cost attribute based on the significance of the activity, following Watts et al. (2017). Higher penalty scores indicate greater difficulty in designating the area as a core conservation zone. For instance, a penalty score of one is assigned to activities such as docks and floating net cages, while higher scores are given to land use and residential areas. These scores reflect the challenge of considering or reclassifying the area as a core zone (Wijayanto, 2021).

Both conservation features and cost attributes are assigned to each planning unit (PU) without normalization, ensuring that each PU contains values for both conservation features and costs. We then calibrated the Species Penalty Factor (SPF) and the Boundary Length Modifier (BLM). The SPF was calibrated to appropriately scale the penalty for missing conservation features relative to one another. The BLM was adjusted to identify the optimal value that balances area compactness with cost. As the BLM value increases, the algorithm tends to Favor a 'single large' design over 'multiple small' designs, thereby enhancing connectivity.

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Deleted: The data were then converted into a format compatible with Marxan by generating the necessary files: pu.dat, bound.dat, puvspr.dat, puvspr_sporder.dat, spec.dat, and input.dat. With these files, the data were prepared for processing in Marxan software.

Next, three Ecological Value (EV) scenarios were analyzed using QMarxan. Scenario EV I, aligned with Target 3 of the post-2020 Global Biodiversity Framework and IUCN guidelines, aims to protect 30% of identified conservation targets, including coral reefs, seagrass, and mangroves. This scenario is designed to enhance connectivity within the conservation area (IUCN, 2008) while supporting fisheries in the surrounding regions (Firmansyah et al., 2018). Protecting 30% of these key habitats is intended to strike a balance between conservation efforts and sustaining benefits for the local fishery sector (Waldron et al., 2020).

Scenario EV II set a 40% protection target, following the recommendations of Noss et al. (2012), which suggest that between 25% and 75% of an area should be managed primarily for nature conservation to achieve biodiversity goals. Conservation planners often adopt targets of 10%, 30%, 40%, or 50%, consistent with Aichi Target 11 (Harris & Holness, 2023). Aichi Target 11 emphasizes the need for protected areas and other effective conservation measures across geographic regions, including strictly protected zones as well as areas where sustainable use is permitted, as long as species, habitats, and ecosystem functions are adequately protected.

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Scenario EV III adopted a 50% conservation target, following the 'Half-Earth' concept, which advocates protecting 50% of conservation targets. This ambitious scenario aligns with the ecoregional approach proposed by Dinerstein et al. (2017), which seeks to preserve 50% of the terrestrial biosphere for global ecological heritage conservation.

The irreplaceability of each planning unit was measured based on the frequency with which it was selected across 1,000 iterations, with values ranging from 0 to 1,000. Units with higher irreplaceability scores were considered more important for conservation. Planning units scoring between 750 and 1,000 were designated as Priority I, indicating their critical importance for conservation. Units scoring between 500 and 750 were categorized as Priority II, while those with scores between 250 and 500 were labelled as Priority III. Units with scores between 0 and 250 were classified as Priority IV. Any unit with a score of zero was considered a nonpriority zone. Priority I areas were designated as core conservation zones, Priority II areas were allocated for tourism, Priority III areas were identified as fisheries zones, and Priority IV areas were set aside for other uses, such as coastal development.

Finally, we validated the outputs of the Marxan model by comparing the conservation areas generated with actual field conditions to ensure that the target species and ecosystems were present in the identified priority areas. This validation was essential to confirm the feasibility of implementing Marxan's recommendations in the field. Additionally, we refined the model through iterative adjustments, such as modifying the SPF and testing various scenarios. This iterative process allowed us to develop a more robust and optimal conservation strategy.

Results

Satellite Image Analysis Results

Satellite image analysis using Object-Based Image Analysis (OBIA) identified three main coastal ecosystems on Arefi Island: mangroves, seagrasses, and coral reefs (Fig. 3). These ecosystems are vital for the conservation sustainability of Arefi Island and are interrelated in ways that support one another. Mangroves and seagrasses play a key role in controlling sediment release from land, thereby reducing excessive sediment flows that could potentially suffocate coral reefs (Golbuu et al., 2008). In turn, mangroves benefit from reduced wave impact and establish mutually beneficial biological connections with coral reefs. Consequently, preserving these three ecosystems is crucial, and efforts must be made to minimize degradation from anthropogenic activities.

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Figure 3 OBIA analysis of coastal ecosystems of Arefi Island, Raja Ampat, Southwest Papua

The total area of coastal ecosystems on Arefi Island is approximately 64.78 hectares (Table 4). Coral reefs cover 36.35% of this area, making them a significant component. Mangroves and seagrasses are also present but are distributed unevenly across the island. Mangroves, which cover 11.81 hectares (18.24% of the total area), are primarily concentrated in the southeast, while their presence is relatively sparse in residential areas. Seagrass beds, covering 29.42 hectares and constituting 45.41% of the total area, are dominant in the northern part of Arefi Island. The overall classification has a kappa accuracy value of 0.82. Additionally, the presence of a port and floating fish cages indicates local community activities such as shipping, fishing, and tourism.

Table 4 Percentage coverage of coastal ecosystems using OBIA analysis.

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Conservation Priority Area Recommendations for Arefi Island

From the analysis of the maps presented in Figure 4, three key areas with higher selection percentages were identified, even under lower target scenarios. These areas are found in the northern, southeastern, and southwestern waters of Arefi Island. Notably, the eastern part of Arefi Island showed a lack of selected areas for conservation.

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Figure 4. Conservation zones on Arefi Island under (A) Ecological Value I, (B) Ecological Value II, (C) Ecological Value III.

The spatial zoning arrangements for Arefi Island's conservation areas under the three Ecological Value (EV) scenarios revealed significant differences in how space is allocated to optimize conservation priorities, as shown in Table 5.

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Table 5**.** Zoning arrangements for Arefi Island conservation area.

This study compares three conservation scenarios (EV I, EV II, and EV III) in terms of the spatial allocation of core zones and their effectiveness in protecting key habitats, such as coral reefs, seagrass beds, and mangroves:

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- EV I designates a Core Zone of 12.33 hectares (2.27% of the total area), offering minimal protection, conserving only 5.82% of coral reefs, 16.25% of seagrass beds, and 29.55% of mangroves. Most of the area (92.43%) was left for general use.
- EV II expands the Core Zone to 15.13 hectares, increasing habitat protection to 21.74% of coral reefs, 22.16% of seagrass beds, and 29.55% of mangroves. This resulted in 23.35% of the total key habitats being safeguarded.
- EV III further expands the Core Zone to 34.37 hectares (6.32% of the total area), significantly enhancing protection to 40.85% of coral reefs, 40.79% of seagrass beds, and 29.64% of mangroves. This scenario covereds 38.76% of the key habitats, demonstrating a shift towards stronger conservation efforts.

As shown in Table 5, increasing the proportion of protected conservation features across the scenarios leads to a corresponding rise in the number of conservation planning units designated as core and utilization zones. Conversely, it results in a reduction in the areas allocated for sustainable fisheries and other zones. Using the 30% conservation scenario (EV I) as a baseline, expanding the protection targets to 40% (EV II) and 50% (EV III) increased the core zone size by 58.39% and 178.75%, respectively.

However, the growth in utilization areas under EV III (34.99%) was less significant compared to EV II (80.75%). Both EV II and EV III led to a reduction in areas designated for sustainable fisheries and other uses. This shift reflects a deliberate reallocation of spatial zones, with EV III showing a substantial reduction in these areas to accommodate an expanded Core Zone. This

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reconfiguration highlights the increased prioritization of conservation as the Other Zones decrease in size, making room for more core conservation areas.

The results for the multitarget scenario are summarized in Table 6. As shown, increasing conservation targets leads to higher conservation costs and longer boundary lengths, although the pattern of conservation efficiency remains irregular.

Table 6 Comparison of Total PU, Cost, Boundary Length and Efficiency

Discussion

This study provides an overview of remote sensing techniques for biodiversity monitoring in marine protected areas. The OBIA (Object-Based Image Analysis) method has proven effective in detecting biophysical parameters in shallow marine environments (Darmawan et al., 2022; Ventura et al., 2018). This method leverages high-resolution satellite imagery to assess shallow marine ecosystem habitats. The results underscore the potential of integrating remote sensing data with ground-based observations to enhance the accuracy of monitoring efforts (Petrou et al., 2015).

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Deleted: The application of remote sensing satellite technology to provide spatial information has been widely adopted and is continually advancing. The ongoing development of remote sensing technology is closely tied to improvements in satellite technology, particularly in natural-resource monitoring satellites. These satellites are being developed with enhanced capabilities to deliver image data related to Earth's surface features. The resulting satellite imagery varies in spatial and spectral resolutions, ranging from low to high, depending on the specific satellite and its intended application.¶

Our study found that spatial planning models can effectively identify optimal conservation priority zones on Arefi Island for local community use within the Marine Protected Area. This finding is consistent with the research by Halpern et al. (2019), which demonstrated that spatial planning modelling integrates ecological data, habitat suitability assessments, and stakeholder input to identify areas of high conservation value and vulnerability.

Applying this approach will enhance the effectiveness of conservation measures and ensure the long-term sustainability of marine ecosystems within the Raja Ampat Marine Protected Area. Smaller conservation areas with well-defined boundaries facilitate better management and monitoring, thereby improving the capacity of Marine Protected Areas (MPAs) to conserve, enhance, and restore the marine environment (Henneberg, 2023). Transparency in decision-making and active community involvement are also crucial for the long-term success of MPAs (Henneberg, 2023).

Referring to Figure 4, the absence of selected conservation areas in the eastern waters of Arefi Island is evident. This is likely due to the lower biodiversity in this region compared to other areas, justifying its exclusion from the Marxan-generated solution. Additional factors include data scarcity and the cumulative impacts of anthropogenic activities, such as tourism, shipping routes, and aquaculture practices—particularly floating net systems. These impacts are more

Commented [MM20]: What types of data? Were you unable to get satellite images from this area?

pronounced in the western and southern waters of Arefi Island, where human activities, including tourism and aquaculture, contribute to the scarcity of high-priority conservation areas.

Among the three ecological values (EV), EV II and EV III were the closest to the ideal conservation scenario. According to Green et al. (2014), marine sanctuary areas should cover 20–40% of each primary habitat to optimize benefits for fisheries management and biodiversity conservation, particularly in the context of climate change. Additionally, the core zone of a marine conservation area should encompass 20–30% of the total area to ensure the sustainability of key biological stocks (Krueck et al., 2017). Indonesia's Minister of Marine Affairs and Fisheries Regulation No. 31 of 2020 on conservation area management stipulates that the core zone of a conservation area classified as a park must cover at least 10% of the ecosystem or habitat of the target species. The protection targets set in EV II meet the regulatory standards, as well as the guidelines outlined by Green et al. (2014) and Krueck et al. (2017).

Commented [MM21]: How are you defining 'ideal' here?

The study's findings on Arefi Island, where a 40% protection target was applied, yielded a conservation area covering 20–30% of the region, consistent with research by Suprianto et al. (2019) in the Thousand Islands, Jakarta. Suprianto et al. (2019) employed Marxan analysis with a 40% protection target to identify potential MPAs in the Thousand Islands. The results indicated that the selected areas had a selection probability of over 80%, covering most of the study area and demonstrating high biodiversity. The 40% protection target aligns with the minimum conservation requirement of 20–30% of the total protected habitat in the Thousand Islands of Jakarta.

Commented [MM22]: Confusing. I cannot tell which sentences are about the present study and which are about others

Similarly, Anggraini et al. (2017) conducted research in the Sunda Banda Seascape, located in the Coral Triangle of Southeast Sulawesi, Indonesia, to identify potential core, utilization, and sustainable fishing zones using Marxan analysis. The conservation targets for these habitats were set at 30%, 40%, and 50%. Analysis of nine MPAs in Southeast Sulawesi revealed that the core zones ranged from 2% to 13% of the total conservation area, while the utilization zones varied from 2.5% to 49%.

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Marxan has been effectively used to identify conservation areas, as demonstrated by research conducted of Aulia et al. (2021) in the Pulau Pinang, Siumat, and Simanaha Islands (PISISI), located in the northeastern region of Simeulue Island. The selection of no-take zones was based on conservation targets with high biodiversity values in the PISISI area. The model results indicated that these no-take zones could protect 80% of the conservation targets, with a total estimated area of approximately 2,283.89 hectares.

Yusuf et al. (2008) and Sidik (2008) conducted research in Gili-Sulat and Gili Lawang, Lombok Regency, focusing on one of Indonesia's established local marine protected areas. The Marxan approach was utilized to identify new zones within the MPA, based on in-situ data surveys and other relevant information. The target area for the no-take zone was set at 30% of the total area. As a result, Marxan identified potential zones for designation as no-take areas, including coral reef ecosystems, mangroves, and seagrass beds. It is important to note that Marxan's results serve as suggestions and recommendations for the zoning process within the MPA, rather than definitive decisions.

Firmansyah's research (2009) utilized Marxan to identify conservation areas on Maratua Island and Kakaban Island in the Berau Regency, East Kalimantan Province. The study incorporated coastal and marine habitat maps as input for the analysis, which resulted in an optimal conservation scenario targeting 30-40% of the area, covering approximately 3,204 hectares. Overall, the identified conservation areas represented 20.44–25.27% of the Area of Interest (AOI), meeting the criteria established by the International Union for Conservation of Nature (IUCN).

However, the application of Marxan does not always fully align with IUCN standards, as demonstrated by Wijayanto et al. (2021) in Southeast Sulawesi. Their study used Marxan to identify core zones under three different scenarios, with the largest zone covering 1,498 hectares—falling short of IUCN criteria. The analysis considered protection levels of 30%, 50%, and a combination of both, resulting in core zone sizes of 751, 1,008, and 1,498 hectares, respectively. While these scenarios met the critical habitat protection threshold of 30%, none encompassed more than 1% of the total conservation area. These findings provide valuable insights for managers and stakeholders, offering guidance for core zone designation, spatial planning, and sustainable development strategies.

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In another study by Tasidjawa et al. (2013), Marxan was applied to determine the core zone in the Community-Based Marine Protected Area (MPA) in Bahoi Village, North Sulawesi. The selection by the Marxan model focused on 10% of the total habitat, which had relatively low management costs and was conveniently located near the village, facilitating easy monitoring from the land.

The results of this study align with those of Zhang and Li (2023), who conducted research in the Beijing-Tianjin-Hebei region of China. As the conservation target increased, both conservation costs and boundary lengths exhibited growth. Notably, conservation costs rose sharply when the target shifted from 80% to 90%. The boundary length initially showed a slower rate of increase between 20% and 50% conservation targets before accelerating at higher targets. Considering its efficiency, a 40% conservation target is recommended for the Arefi Island area. This recommendation is consistent with Zhang and Li's (2023) findings, which suggest that a 40%-50% conservation target is optimal based on sensitivity analysis. Spatial priority results in this study were therefore derived from the 40% target.

Agnew et al. (2024) demonstrated the practicality of using Marxan as an accessible tool to address complex prioritization challenges and to model landscape-scale rehabilitation scenarios over time. Similarly, Chan et al. (2011) found that a 50% protection scenario effectively stabilized Marxan solutions for ecosystem services, while Delavenne et al. (2012) concluded that a 50% conservation target offers stronger ecosystem protection. This threshold is designed to provide optimal protection and ensure ecological sustainability.

A comparison of this study's findings with previous research underscores both advances in conservation planning and the ongoing need for refined spatial analysis in MPAs. For example, Jones et al. (2016) explored MPA design and effectiveness, emphasizing the importance of integrating both ecological and social data to achieve biodiversity conservation and community benefits. While Jones et al. focused on the balance between ecological and socioeconomic factors, our study concentrated on Ecological Values and their spatial distribution. This difference highlights the importance of a holistic approach that considers both ecological integrity and human well-being, suggesting that future studies should incorporate more comprehensive socioeconomic analyses to better align conservation efforts with community needs.

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The traditional practice of *Sasi*, implemented by local communities on Arefi Island, aims to enable the recovery and reproduction of marine ecosystems, preventing the depletion of resources due to overfishing. This study demonstrates that Marxan-based conservation planning can support sustainable fishing practices and preserve marine biodiversity, a crucial objective for sensitive ecosystems like Raja Ampat.

Commented [MM26]: Can you expand this line of thinking? What in your results demonstates this?

One limitation of this research is its reliance on static ecological data, which may not fully capture the dynamic nature of marine ecosystems or their responses to climate change and human activities. Although the spatial resolution and temporal scope of the data were sufficient for initial zoning and scenario planning, they may not reflect subtle but significant ecological shifts over time. Additionally, despite Marxan's effectiveness in conservation planning, the tool has limitations in modeling complex human-environment interactions. This highlights the need to integrate more adaptive and participatory planning tools that can respond to evolving ecological and social landscapes.

Conclusions

Satellite image analysis using Object-Based Image Analysis (OBIA) successfully mapped the three key coastal ecosystems on Arefi Island: mangroves, seagrasses, and coral reefs. These ecosystems are vital for the island’s conservation and sustainability, as they form an interconnected network that supports each other. Mangroves and seagrasses help control sediment release from land, protecting coral reefs from potential damage due to sedimentation.

In return, coral reefs reduce wave impacts, providing protection to mangroves, creating a mutually beneficial relationship.

Commented [MM27]: Is this a key objective of the paper? Your aims really just state that you use remote sensing as input data for the planning tools, but now your discussion and conclusions seem to be stating that this is a novel result? Did you compare these remote sensed maps to field maps or something?

Following the principles of systematic conservation planning, this study applied a straightforward remote sensing approach to map mangrove, coral reef, and seagrass ecosystems. The Marxan model was then used to analyze multi-target scenarios and identify priority areas for Marine Protected Areas (MPAs). The accuracy of this mapping was supported by a kappa value of 0.82, indicating high classification reliability.

The total coastal ecosystem area of Arefi Island is approximately 64.78 hectares, broken down as follows:

- Coral Reefs: Covering 36.35% of the total area, predominantly located around the island.
- Seagrass Beds: Dominating the northern part of the island, covering 29.42 hectares or 45.41% of the total area.
- Mangroves: Spanning 11.81 hectares or 18.24%, mainly concentrated in the southeast, with fewer mangroves in residential areas.

The presence of a port and floating fish cages indicates active shipping, fishing, and tourism by the local community. This study highlights the need to preserve these ecosystems and minimize degradation caused by human activities to maintain the island's ecological balance and long-term conservation goals.

Sensitivity analysis confirmed that a conservation objective targeting 40% of the total area (EV II) is the most effective model for Arefi Island. The zoning breakdown under this scenario includes a Core Zone of 19.53 hectares, a Utilization Zone of 15.96 hectares, a Sustainable Fisheries Zone of 15.67 hectares, and Other Zones covering 92.89 hectares. This approach underscores the importance of incorporating traditional knowledge and community participation into conservation strategies.

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These findings advocate for adaptive management strategies and underscore the vital role of geospatial technology in protecting marine biodiversity while supporting sustainable resource use in Indonesia's coastal ecosystems.

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