BIODIVERSITAS
Volume 27, Number 5, May 2026
Pages: 12

ISSN: 1412-033X
E-ISSN: 2085-4722
https://doi.org/10.13057/biodiv/d270513

Systematic conservation planning for pelagic fish habitats in the Sulawesi Sea, Indonesia

AMEHR HAKIM[1,2], AM AZBAS TAURUSMAN[3,♥], BUDY WIRYAWAN[3], ARI PURBAYANTO[3], REGI DARMAWAN[4], IRFAN YULIANTO[3, 4]

[1]Study Program of Marine Fisheries Technology, Department of Fisheries Resource Utilization, Faculty of Fisheries and Marine Science, Institut Pertanian Bogor. Jl. Agathis, Bogor 16680, West Java, Indonesia
[2]Directorate General of Marine Spatial Planning, The Ministry of Marine Affairs and Fisheries. Jl. Medan Merdeka Timur No. 16, Central Jakarta 10110, Jakarta, Indonesia
[3]Department of Fisheries Resources Utilization, Faculty of Fisheries and Marine Science, Institut Pertanian Bogor. Jl. Agathis, Bogor 16680, West Java, Indonesia. Tel.: +62-251-8622935, ♥email: azbas@apps.ipb.ac.id
[4]Fisheries Resource Center of Indonesia-Rekam Nusantara Foundation. Jl. Sempur No. 35, Bogor 16129, West Java, Indonesia

Manuscript received: 17 July 2025. Revision accepted: 8 May 2026.

Abstract. *Hakim A, Taurusman AA, Wiryawan B, Purbayanto A, Darmawan R, Yulianto I. 2026. Systematic conservation planning for pelagic fish habitats in the Sulawesi Sea, Indonesia. Biodiversitas 27 (5): d270513. https://doi.org/10.13057/biodiv/d270513.* Mackerel scad (*Decapterus macarellus*) is a key species in pelagic fisheries, providing substantial economic value while playing an important role in pelagic food webs. However, increasing fishing pressure raises concerns regarding stock sustainability and ecosystem integrity. This study aimed to identify priority areas for offshore pelagic Marine Protected Areas (MPAs) in the Sulawesi Sea, Indonesia, by integrating ecological and socio-economic information within a systematic conservation planning framework. Spatial analyses of spawning and nursery habitats derived from larval surveys were combined with fishing-related cost data and analyzed using Marxan to optimize conservation prioritization under four alternative scenarios. The analysis identified four candidate conservation areas (Areas I-IV). Among these, Area IV that located between Sangihe and Talaud Islands, consistently emerged as the highest conservation priority, offering the most favorable balance between high ecological value and low fishing intensity. Area IV covers approximately 599,790.91 ha, with 282,364.82 ha (47.08%) identified as a core conservation zone supporting critical spawning and nursery habitats of *D. macarellus*. These findings demonstrate the value of integrating larval habitat data with spatial optimization tools to identify cost-efficient and ecologically robust offshore conservation areas. The approach provides a scientifically grounded framework for offshore pelagic MPA planning and contributes empirical evidence to support ecosystem-based fisheries management in the Sulawesi Sea.

Keywords: Biodiversity conservation planning, Marxan, offshore MPA, Sulawesi Sea

INTRODUCTION

Marine spatial planning and Marine Protected Areas (MPAs) are increasingly recognized as important tools for conserving biodiversity, maintaining ecosystem integrity, and supporting sustainable fisheries (Sini et al. 2017; Kirkfeldt and Frazão Santos 2021; Zuercher et al. 2022). Planning for pelagic fisheries is especially challenging because pelagic habitats are dynamic and three-dimensional, while key processes such as spawning, larval dispersal, and connectivity occur across variable spatial and temporal scales (Game et al. 2009; Dickey-Collas et al. 2017; Venegas-li et al. 2018). Offshore MPAs nonetheless serve as crucial sources of larval dispersal and help restore overexploited fisheries (Christie et al. 2010). Several countries have established such areas, for example the UK's Chagos Archipelago (~500,000 km²), where pelagic protection coincided with increased bigeye tuna stocks, highlighting the need to harmonize conservation and fisheries regulations (Sheppard 2010; Curnick et al. 2020). In the Bay of Biscay anchovy fishery, MPAs protected critical spawning stages but required complementary measures such as effort control and adaptive Total Allowable Catch (TAC) (Lehuta et al. 2010). Yet pelagic protected areas remain limited and are often not systematically designed to maximize biodiversity protection (Game et al. 2009). In Indonesia, conservation has concentrated on coastal systems, leaving offshore pelagic habitats underrepresented (Estradivari et al. 2024); the Banda Sea seasonal closure under MMAF Regulation No. 26 of 2020 has been criticized for lacking a rigorous academic foundation (Adam 2016).

The mackerel scad (*Decapterus macarellus*), a small pelagic species of considerable economic importance in Indonesian waters, particularly the Sulawesi Sea and eastern Indonesia, is predominantly caught with purse seines by local fishers (Suwarso and Zamroni 2014; Akerina et al. 2019). However, it is currently overfished: catches from 2020 to 2022 consistently exceeded the TAC (3,499,779 tons/year) and in 2020-2021 surpassed the Maximum Sustainable Yield (MSY) (4,374,723 tons/year), indicating an urgent need for management intervention (Gahunting et al. 2023; Setya et al. 2023). Beyond fishing pressure, the species' distribution, reproduction, and recruitment are strongly shaped by environmental conditions such as salinity, hydro-oceanography, and habitat suitability (Puspasari et al. 2016; Hou et al. 2020; Retnoningtyas et al. 2024).

Habitat protection is especially relevant for mackerel scad because critical life stages occur offshore. In the Sulawesi Sea, spawning areas were identified around the northern and western sides of Sangihe and Siau Islands, with the species generally found at 40-200 m depth (Hakim et al. 2025). Spawning is linked to local hydro-oceanographic conditions influencing larval transport, while nursery areas in the southern Sulawesi and Maluku Seas offer favorable growth conditions, including high zooplankton abundance, unlike many species whose juveniles depend on shallow coastal nurseries (Beck et al. 2001; Whitfield and Pattrick 2015). In Indonesia's thermally stable waters, factors such as salinity, habitat characteristics, larval retention, and primary productivity likely play a greater role in spawning success and juvenile survival than the temperature-driven seasonality seen at higher latitudes (Villarao and Encarnacion 2025).

A systematic spatial prioritization approach is therefore needed to identify pelagic conservation areas that support both biodiversity and fisheries sustainability. Marxan (Watts et al. 2017) offers a relevant decision-support framework, integrating multiple spatial datasets and conservation criteria to identify priority areas efficiently and transparently, incorporating ecological features such as spawning and nursery grounds into a more evidence-based process than ad hoc selection. As one of Indonesia's first offshore conservation initiatives, planning in the Sulawesi Sea underscores the need to integrate such fisheries-based parameters into MPA development within Fisheries Management Area (FMA) 716, providing input for national policy and MMAF strategies. Accordingly, this study aims to identify priority offshore areas for conserving pelagic fish habitat, particularly the spawning and nursery grounds of mackerel scad, and to develop a zoning design for the selected area to support sustainable pelagic fisheries management in the Sulawesi Sea.

MATERIALS AND METHODS

Study area

The study area for the Marxan analysis is located between 1°-6° N and 123°-128° E in the Sulawesi Sea, Indonesia, covering an approximate area of 30,760,974 hectares (Figure 1). This region encompasses the Sulawesi Sea, which is part of Fisheries Management Area (FMA) 716 under Indonesian jurisdiction. The Sulawesi Sea has been designated as a potential offshore Marine Protected Area (MPA) aimed at supporting the sustainability of pelagic fisheries. Among the key species within the small pelagic group is the mackerel scad (*D. macarellus*), which holds significant ecological and economic importance. The establishment of conservation zones in this area is critical for maintaining biodiversity, ensuring sustainable fish stocks, and supporting long-term fisheries management strategies. The characteristics of the aquatic environment in the study area, such as ocean currents and sea surface temperatures, have been described in previous research by Hakim et al. (2025).

Data collection

The dataset used in this study consists of catch data of mackerel scad (*D. macarellus*) collected from May 2019 to December 2023 (n = 1479 data). The data includes detailed information on fishing effort, fishing gear, fishing boat, catch volume (expressed in weight), Fish Aggregating Device (FAD), number of crews, fishing ground, fishing trip, and total setting. All data was obtained from the North Sulawesi Provincial Marine and Fisheries Agency. This study utilized spatial vessel position data to improve the accuracy of fishing activity mapping and the estimation of fishing intensity. Vessel position data were obtained from the Vessel Monitoring System (VMS) managed by the MMAF, which provides time-stamped geographic positions of licensed fishing vessels. These data were integrated with fisheries catch statistics by matching vessel identifiers and fishing dates, allowing each fishing trip and associated catch record to be spatially referenced.

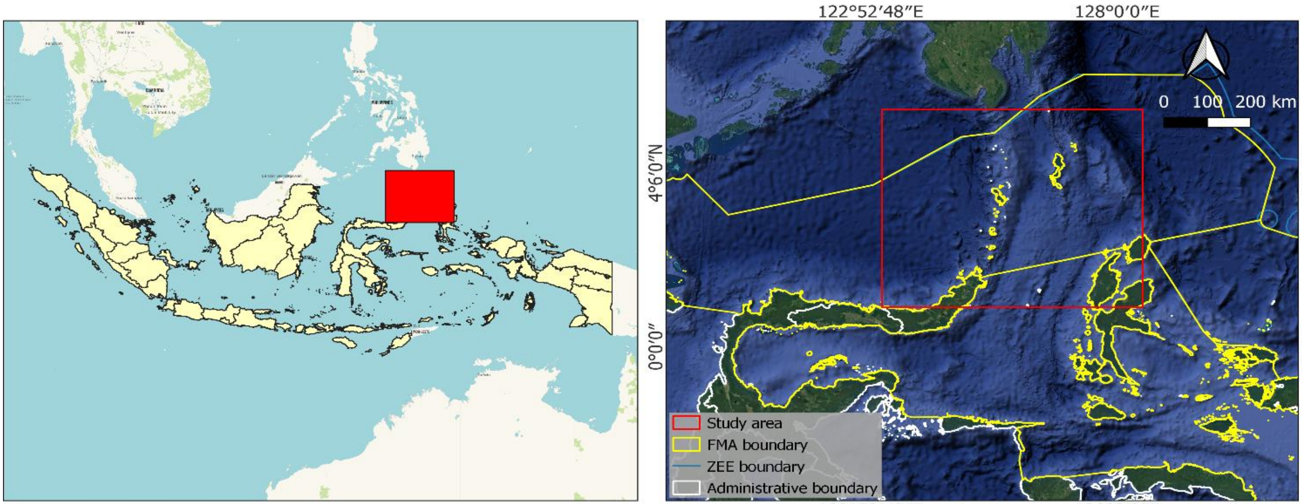

Figure 1. Study area to design a conservation area for pelagic fish in the Sulawesi Sea, Indonesia

To complement VMS coverage and reduce potential gaps arising from incomplete reporting or inactive transponders, satellite-based vessel detection data from the Visible Infrared Imaging Radiometer Suite (VIIRS) were incorporated. VIIRS detections were accessed through the Global Fishing Watch and VIIRS Boat Detection (VBD) platforms and used to identify additional fishing activity based on nighttime light emissions associated with fishing vessels. Spatial and temporal filtering was applied to VIIRS detections to ensure consistency with known fishing periods and areas.

Fishing intensity was estimated by overlaying VMS tracks and VIIRS detections onto a predefined spatial grid and aggregating vessel presence by time unit. These spatially derived fishing effort indicators were then linked to corresponding catch data to enhance the representation of fishing activity distribution. The combined use of VMS, VIIRS detections, and catch statistics improved the robustness of fishing effort characterization and supported a more accurate interpretation of CPUE variability in relation to spatial fishing patterns.

In addition to fisheries and spatial effort data, seamount distribution was incorporated as a conservation input in the MARXAN systematic conservation planning analysis. Seamount data were obtained from the PANGAEA global seamount database developed by Yesson et al. (2011), which provides a comprehensive spatial inventory of predicted and confirmed seamount features worldwide.

Data analysis

Standardized Catch Per Unit Effort (CPUE) in this study was estimated using Generalized Additive Models (GAMs), which provide a flexible framework for modeling complex and non-linear relationships commonly found in fisheries data. GAMs allow for improved representation of temporal and operational effects influencing CPUE compared to traditional linear models. In a previous study by Darmawan et al. (2025b), standardized CPUE predictor variables included year, month, fishing boat (GT), length of all fishing boat, fishing gear, number of crew, and fishing ground, capturing both temporal and operational variability in fishing activities. In the present study, CPUE estimation was refined by prioritizing predictors that more directly represent fishing effort and operational characteristics. Accordingly, the selected predictors consisted of year, month, fishing boat (GT), fishing gear, number of crew, and fishing trip (Table 1). To ensure comparability and reduce technological bias, CPUE was standardized using mini purse seine as the reference fishing gear. The fitted model indicated that 27.1% of the deviance explained, suggesting that a meaningful proportion of the variability in CPUE was captured by the model structure. In addition, the model produced an Akaike Information Criterion (AIC) value of 21,376.42, reflecting an adequate trade-off between model fit and complexity under the generalized additive modelling framework. Standardized CPUE were conducted using R Studio, with a set of specialized packages employed to support model fitting, inference, and data visualization. Generalized Additive Models (GAMs) were fitted using the mgcv package (Wood 2025), which provides robust tools for capturing non-linear relationships between CPUE and predictor variables. Post hoc analyses, including the estimation of marginal means and pairwise comparisons among factor levels, were carried out using the emmeans package. Visualization of model outputs and standardized CPUE trends was performed using the ggplot2 package (Wickham 2016), enabling clear and interpretable graphical representations across temporal and spatial dimensions. The standardized CPUE model is presented as equation [1].

The selection and spatial design of marine conservation areas were conducted using the Marxan that a widely used decision-support tool in systematic conservation planning and optimally fulfills the minimum representation targets of existing conservation features while minimizing costs or conflicting interests that could hinder implementation (Ball et al. 2009; Watts et al. 2017; Agnew et al. 2024). In this study, the analysis was performed using Marxan v.4.0.6 through the QMarxan Toolbox v.2.0.1 integrated with QGIS 3.18.3, which enabled spatial data preparation, parameter configuration, and scenario evaluation within a geographic information system environment. The study area was divided into hexagonal Planning Units (PUs), each covering 123.21 ha. This spatial resolution was selected to provide a practical balance between ecological representation, spatial detail, and computational efficiency. Hexagonal PUs were preferred because they maintain consistent neighborhood relationships and reduce edge effects relative to square grids, thereby improving the representation of spatial continuity and connectivity in prioritization outputs. The selected PU size was considered appropriate for capturing the main ecological and fisheries-related features available for this study, while avoiding excessive fragmentation and computational burden. Nevertheless, planning unit size may influence prioritization outcomes, as finer resolutions may capture ecological heterogeneity more precisely, whereas coarser resolutions may generalize spatial patterns and obscure smaller but ecologically important features. Hexagonal PUs were preferred because they maintain consistent neighborhood relationships and reduce edge effects relative to square grids, thereby improving the representation of spatial continuity and connectivity in prioritization outputs.

Table 1. The input parameter standardized CPUE of mackerel scad (*Decapterus macarellus*) in Sulawesi Sea, Indonesia

Parameter	**Information**
CPUE	Catch per unit effort
Year	Fish landing data from 2019 to 2023
Month	January, February, March, April, May, June, July, august, September, October, November, December
GT fishing boat	The size of fishing boat’s tonnage (GT)
Fishing gear	The fishing gear was used to catch mackerel scad (i,e. mini purse seine, encircling gill net)
Crew	The number of crew in fishing vessel
Fishing trip	The total of day trip of fishing vessel operation in the sea

Spatial inputs were classified into conservation features and cost features. Conservation features included spawning areas, nursery areas, fish migration areas, and seamounts. Spawning and nursery habitats of mackerel scad (*D. macarellus*) were identified from larval survey data, while migration areas were derived from field observations (Hakim et al. 2025). Seamount and seahill features were obtained from the PANGAEA global seamount dataset, reflecting their ecological importance as structurally complex habitats. Each conservation feature was assigned a representation target and a Species Penalty Factor (SPF) based on its conservation importance and vulnerability. Cost features represented existing fisheries use and potential socio-economic conflict and included fishing grounds, fish aggregating devices (FADs), fishing effort, Vessel Monitoring System (VMS) vessel positions, and Visible Infrared Imaging Radiometer Suite (VIIRS) vessel detections. Fishing effort and vessel activity were classified into low, moderate, and high categories and scored accordingly to represent variation in fishing intensity. To improve the spatial representation of fishing intensity, fish catch data was integrated with VMS and VIIRS data. VMS records provided time-stamped vessel positions that were linked to catch data using vessel identity, fishing date, and trip information. VIIRS detections were used to support VMS coverage, particularly for nighttime fishing activity. Integrated vessel activity data were aggregated within the planning unit grid to generate a spatial proxy of fishing intensity for the cost layer.

$$\text{CPUE} \sim \text{year} + \text{month} + s\,(\text{GT fishing boat}) + \text{fishing gear} + s\,(\text{Crew}) + \text{fishing trip} \quad [1]$$

Model calibration was performed using SPF and the Boundary Length Modifier (BLM). SPF values were adjusted to penalize solutions that failed to meet conservation targets, while BLM was tuned to balance spatial compactness and cost efficiency (Keen et al. 2024). The Boundary Length Modifier (BLM) was set to 0 to allow the optimization process to prioritize conservation target achievement and cost efficiency without imposing additional constraints on spatial compactness. Three conservation scenarios were evaluated using habitat protection targets of 40%, 70%, and 100%, with each scenario run 1,000 times to ensure solution stability. Outputs were evaluated using the sum solution, which indicates the frequency of planning-unit selection across runs and was used to identify areas of high conservation priority. Areas with high selection frequency (output sum solution) indicate zones of significant ecological value and low relative cost, making them ideal candidates for core zones (Chan et al. 2011; Delavenne et al. 2012). The information of conservation and cost feature, target conservation, score and species penalty factor, and data source information is presented in Tables 2 and 3.

RESULTS AND DISCUSSION

Catch Per Unit Effort (CPUE)

According to catch data reported by the North Sulawesi Province Marine and Fisheries Agency, the Catch Per Unit Effort (CPUE) for mackerel scad exhibited an overall increasing trend during the 2019-2023 period (Figure 2). In 2019, CPUE was recorded at 324.28 kg.trip^{-1}, rising to 375.66 kg.trip^{-1} in 2020. A slight decline occurred in 2021, with CPUE decreasing to 344.79 kg.trip^{-1}. Nevertheless, CPUE increased substantially in subsequent years, reaching 490.34 kg.trip^{-1} in 2022 and further rising to 511.86 kg.trip^{-1} in 2023. Changes in CPUE over time may arise from temporal variation in the level of fishing effort exerted across different years. Differences in the number of fishing trips, operational intensity, and the number of fishing vessels actively operating each year can lead to fluctuations in CPUE values.

Table 2. Conservation features, as in the Marxan scenario, are used for designing the marine conservation area

Conservation feature	Target (%)	Species Penalty Factor (SPF)	Data source
Spawning area	70	10	Hakim et al. (2025)
Nursery area	40	7	Hakim et al. (2025)
Sea mount	100	10	PANGAEA data (Yesson et al. 2011)
Fish migration data	100	7	Field observation

Table 3. Cost features as input in the Marxan scenario for designing the marine conservation area

Cost feature	Classification	Value	Data source
Fishing grounds		7	North Sulawesi Province Marine and Fisheries Agency (2023)
Fish Aggregating Devices (FADs)		10	North Sulawesi Province Marine and Fisheries Agency (2023)
Fishing effort	Low	5	North Sulawesi Province Marine and Fisheries Agency (2023)
	Moderate	7	
	High	10	
Vessel position (Vessel Monitoring System)	Low	5	MMAF (2024)
	Moderate	7	
	High	10	
Vessel position provided by VBD-VIIRS satellite	Low	5	https://globalfishingwatch.org/ and https://eogdata.mines.edu/vbd/
	Moderate	7	
	High	10	

An increase in the number of vessels and fishing effort generally results in higher exploitation pressure, which may affect catch efficiency per unit of effort. Conversely, reduced fishing activity or a smaller active fleet may produce changes in CPUE that reflect shifts in operational dynamics and exploitation pressure on fish stocks over time.

In addition, based on the CPUE modeling showed that several operational predictor variables were found to have a significant influence on CPUE variability. These variables included the use of mini purse seine fishing gear, number of crew, and fishing boat tonnage. The effect of mini purse seine gear highlights the importance of fishing technology in determining catch efficiency. Meanwhile, the number of crew reflects labor capacity supporting fishing operations, and fishing boat tonnage is associated with the vessel's ability to access fishing grounds and accommodate catch volume. Therefore, these findings suggest that changes in mackerel scad CPUE are influenced not only by temporal factors but also strongly shaped by the operational characteristics and fishing capacity of the fishing boat.

Design of conservation area by Marxan

The conservation area design in this study focused on the northern Sulawesi Sea, where Marxan was used to identify spatial priorities for protecting key habitats of pelagic fish, particularly mackerel scad (*D. macarellus*). The northern coastal waters of Sulawesi and adjacent offshore areas contain important oceanographic features, including seahills and seamounts, which are likely to support pelagic fish habitat. In contrast, the waters between Sangihe Island and Karakelong Island showed no documented presence of seahills or seamounts, whereas the northern offshore waters near the Philippine maritime boundary contained a relatively broad distribution of these features (Figure 3.A). At the same time, spatial fishing-ground data indicated that most of the northern Sulawesi Sea is actively used for pelagic fisheries, particularly for mackerel scad (Figure 3.B), while fishing-intensity analysis based on VIIRS and VMS showed very high vessel activity in the northern coastal zone and comparatively lower activity around Sangihe and Karakelong Islands (Figure 3.C). Together, these patterns provide the ecological and socio-economic basis for defining conservation and cost features in the Marxan analysis (Figure 3).

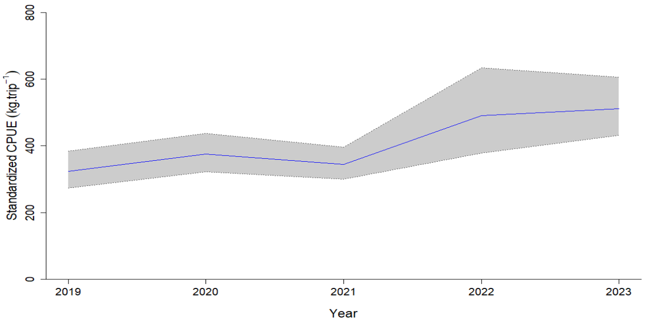

Figure 2. Standardized CPUE trend of mackerel scad (*Decapterus macarellus*) in the Sulawesi Sea, Indonesia, from 2019 to 2023. The blue line represents the mean standardized CPUE (kg.trip^{-1}), while the shaded grey area indicates the 95% confidence interval

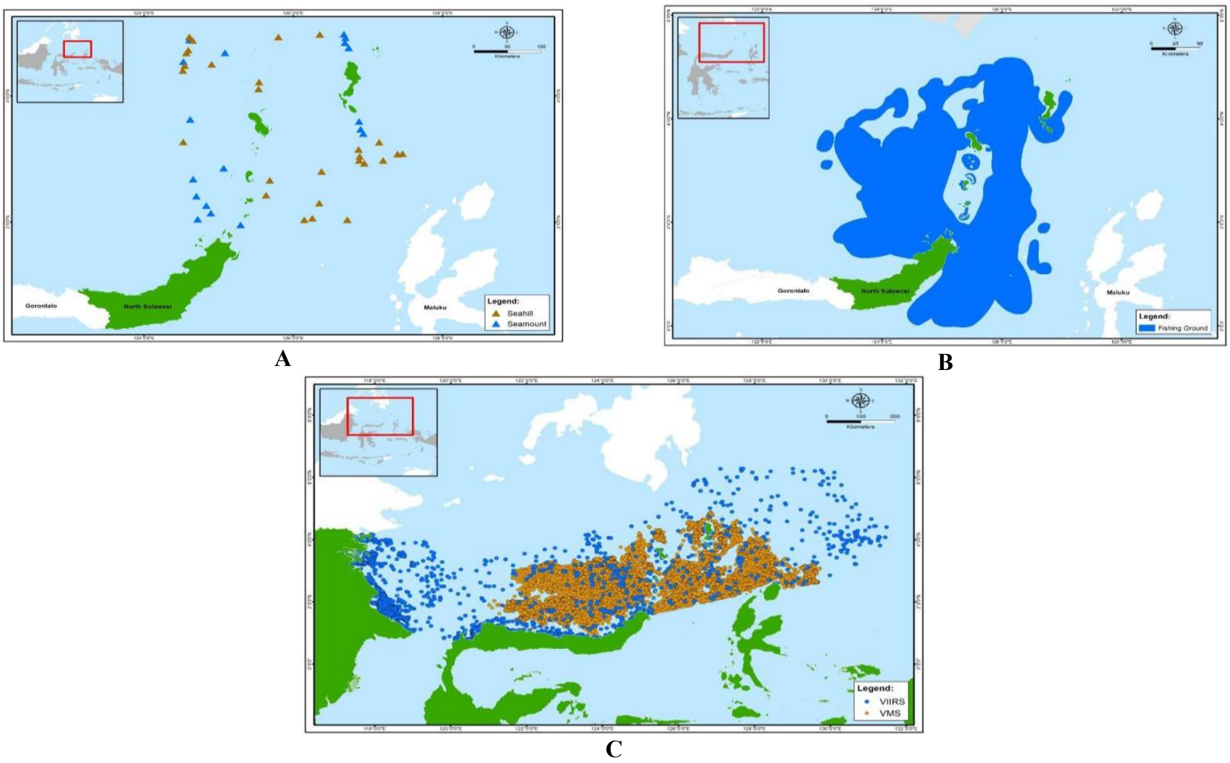

Figure 3. A. Distribution of seahill and seamount from PANGAEA data (Yesson et al. 2011), B. Fishing ground, C. Fishing intensity of pelagic fishes in Sulawesi Sea, Indonesia provided by VIIRS and VMS

Spatial analyses of spawning and nursery grounds, together with larval dispersal patterns of mackerel scad (*D. macarellus*), have been comprehensively mapped in the Sulawesi Sea, providing a robust ecological foundation for spatial conservation planning (Hakim et al. 2025). These ecological datasets identify critical life-history habitats that play a key role in sustaining recruitment and population resilience of this highly exploited pelagic species. Building on these insights, Marxan was applied to assess conservation priorities under four alternative scenarios (Table 4), allowing systematic evaluation of spatial trade-offs between ecological objectives and socio-economic constraints. Scenario-based planning is particularly valuable in data-limited and dynamic marine systems, as it enables comparison among alternative spatial configurations and supports informed decision-making under uncertainty.

The Marxan analysis delineated a total Area of Interest (AOI) of 4,387,019.82 ha, which was subsequently classified into four candidate conservation areas with distinct ecological and economic characteristics. Area I represented the largest spatial extent, covering 1,598,939.95 ha (36.45%), followed by Area II with 1,490,667.50 ha (33.98%), Area III with 697,621.46 ha (15.90%), and Area IV with 599,790.91 ha (13.67%) of the total AOI. Despite their large spatial coverage, Area I and Area II exhibited contrasting conservation attributes. Area I contained multiple high-value conservation features, including spawning grounds, nursery habitats, and seamounts, but was also associated with high socio-economic costs, as it overlapped extensively with major fishing grounds characterized by intense fishing activity. In contrast, Area II exhibited lower ecological value, being dominated primarily by seamount and seahill features, yet it incurred relatively low socio-economic costs due to limited fishing intensity.

Areas III and Area IV both encompassed ecologically important spawning and nursery habitats, underscoring their relevance for pelagic fish conservation. However, these two areas differed markedly in their socio-economic implications. Area III was associated with moderate fishing pressure, indicating potential trade-offs between conservation objectives and fisheries activities. Conversely, Area IV combined high conservation importance with comparatively low fishing intensity, resulting in the most favorable balance between ecological benefits and implementation costs. This combination rendered Area IV the most cost-efficient and strategically suitable conservation candidate among the four areas identified (Figure 4 and Table 4), highlighting its potential role as a priority zone for ensuring the sustainability of mackerel scad populations in the Sulawesi Sea.

Based on the Marxan prioritization results, Area IV, located between Sangihe Island and Talaud Island, emerged as the highest-priority conservation zone. Although it represented the smallest candidate area, its ecological importance was disproportionately high because it encompassed essential spawning and nursery habitats for *D. macarellus*. From a management perspective, Area IV also offered the most favorable trade-off between biodiversity protection and implementation cost, as it was associated with lower fishing intensity than Areas I and III. This combination of high ecological value and relatively low socio-economic conflict supports the designation of Area IV as the most suitable area for conservation action. These findings demonstrate that conservation priority in the Sulawesi Sea is determined not only by area size, but also by the spatial overlap between ecological significance and lower fisheries-use pressure.

The conservation priority of each planning unit, as illustrated in Figure 5, was determined by its selection frequency across Marxan simulations, which integrated conservation targets for mackerel scad (*D. macarellus*) spawning and nursery habitats with spatial patterns of fishing activity. Selection frequency represents the consistency with which a planning unit contributes to meeting conservation objectives under alternative optimization runs. In the priority map, a color gradient is used to visualize this pattern, where dark red indicates the highest conservation priority, medium red represents moderate priority, and light red denotes lower-priority areas.

The result showed that high-priority planning units are strongly concentrated in the central waters between Sangihe Island and Talaud Island (Zone IV). This spatial concentration reflects the ecological importance of the area, which encompasses critical habitats that support reproductive processes and early larval development of mackerel scad (Hakim et al. 2025). The dominance of high selection frequencies in Zone IV indicates that this area consistently fulfills conservation targets while minimizing associated socio-economic costs, reinforcing its suitability as a core conservation zone.

Table 4. Result of the Marxan scenario (conservation and cost features)

Area	Conservation features	Cost features	Area estimation (Ha)
I	High conservation features (spawning ground, nursery ground, and seamount)	High socio-economic cost (main fishing ground with high fishing intensity)	1.5 million
II	Low conservation features (seamount and seahill)	Low socio-economic cost (fishing ground with low fishing intensity)	1.4 million
III	High conservation features (spawning ground and nursery ground)	Moderate socio-economic cost (main fishing ground with moderate fishing intensity)	0.697 million
IV	High conservation features (spawning ground and nursery ground)	Low socio-economic cost (fishing ground with low intensity)	0.599 million

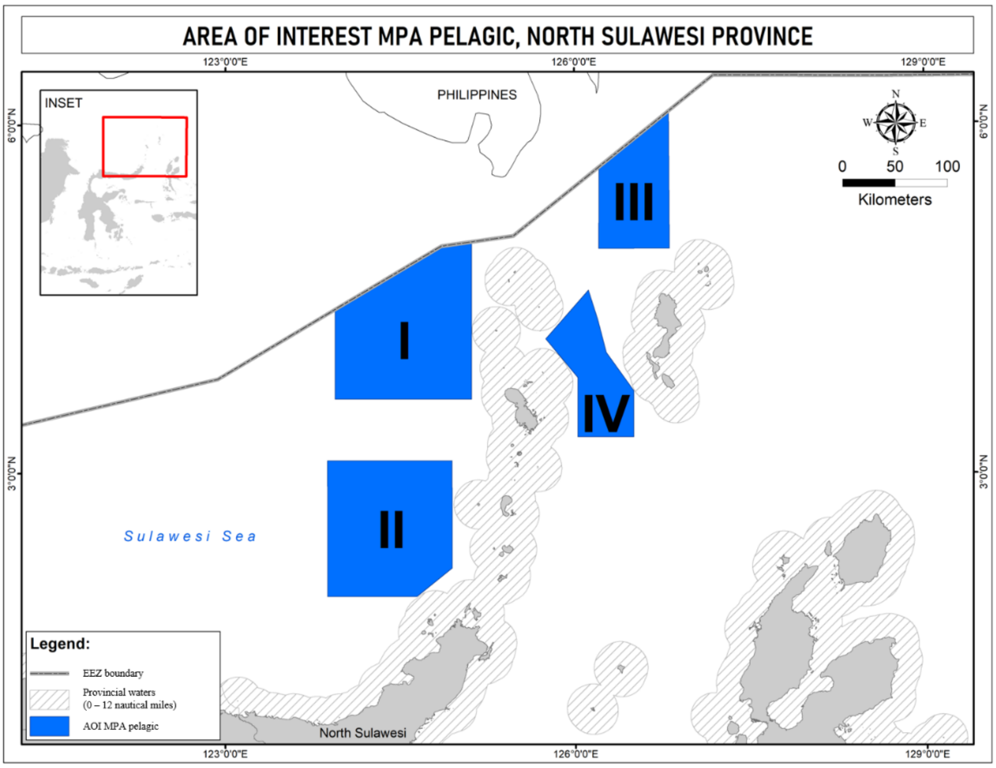

Figure 4. Area of interest (AOI) on conservation zone candidate in Sulawesi Sea, Indonesia; Zone I with high conservation features (spawning ground, nursery ground, and seamount) and high socio-economic cost (main fishing ground with high fishing intensity); Zone II with low conservation features (seamount and seahill) and low socio-economic cost (fishing ground with low fishing intensity); Zone III with high conservation features (spawning ground and nursery ground) and moderate socio-economic cost (main fishing ground with moderate fishing intensity); and Zone IV with high conservation features (spawning ground and nursery ground) and low socio-economic cost (fishing ground with low intensity)

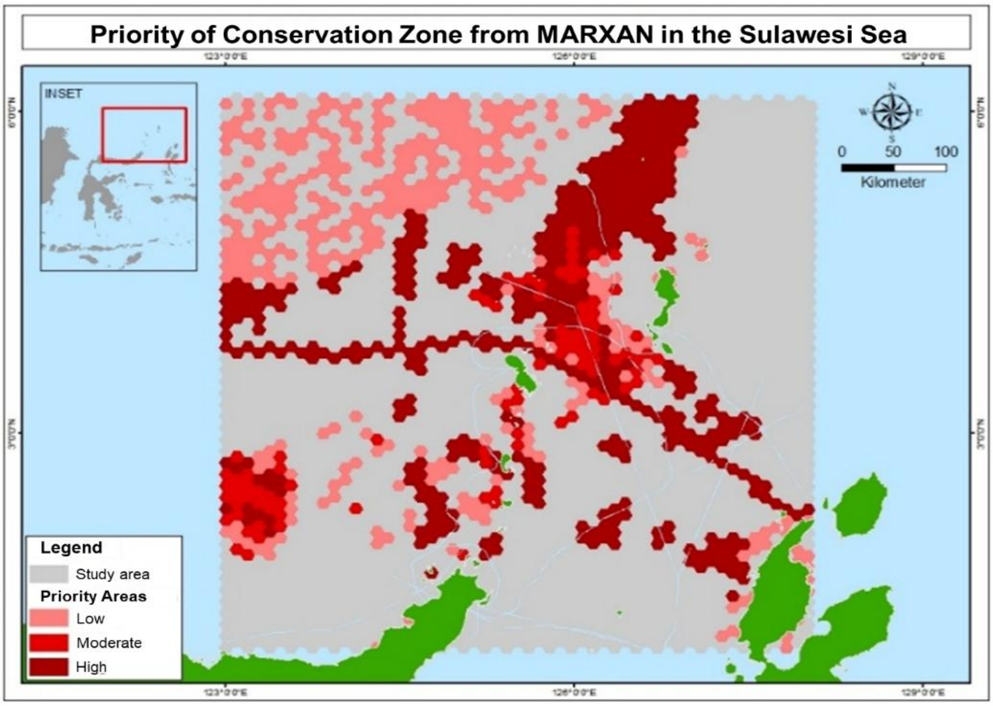

Figure 5. Priority locations for conservation zone from the Marxan analysis in the Sulawesi Sea, Indonesia. The red color pattern from light to dark showed the level of priority areas as conservation zone

Notably, the spatial distribution of high-priority units within Zone IV exhibits a clustered rather than dispersed pattern, forming a relatively connected and contiguous area. Such spatial coherence is ecologically advantageous, as it enhances habitat continuity and increases the likelihood that conservation measures will effectively support key life-history processes of pelagic species, including spawning success and larval survival. In contrast, planning units with lower priority levels are more widely distributed and occur mainly outside the core cluster, suggesting that these areas contribute less consistently to achieving conservation objectives. Overall, the clustering of high-priority planning units in Zone IV underscores its strategic importance for effective marine protected area (MPA) design and for promoting the long-term sustainability of pelagic fisheries in the Sulawesi Sea.

The Sum Solution output further confirmed the importance of Area IV by showing the frequency with which each planning unit was selected across Marxan runs. Planning units with higher selection frequencies represent areas that consistently contributed to meeting conservation targets at lower cost. Within Area IV, the highest-priority class (700-1000 selections) covered 282,364.82 ha, equivalent to 47.08% of the area, making it the dominant class in the final solution. By comparison, the lowest-priority class (0-99 selections) covered 163,282.74 ha (27.22%), while the intermediate classes 100-299, 300-499, and 500-699 occupied 11,438.45 ha (1.91%), 33,328.13 ha (5.56%), and 15,657.89 ha (2.61%), respectively. This distribution indicates that nearly half of Area IV was repeatedly selected as part of the optimal conservation solution, highlighting its robustness as a priority area (Table 5 and Figure 6).

Table 5. The area values each class interval from the output sum solution in Marxan

Interval	Areas (Ha)
0-99	163,282.74
100-299	11,438.45
300-499	33,328.13
500-699	15,657.89
700-1000	282,364.82

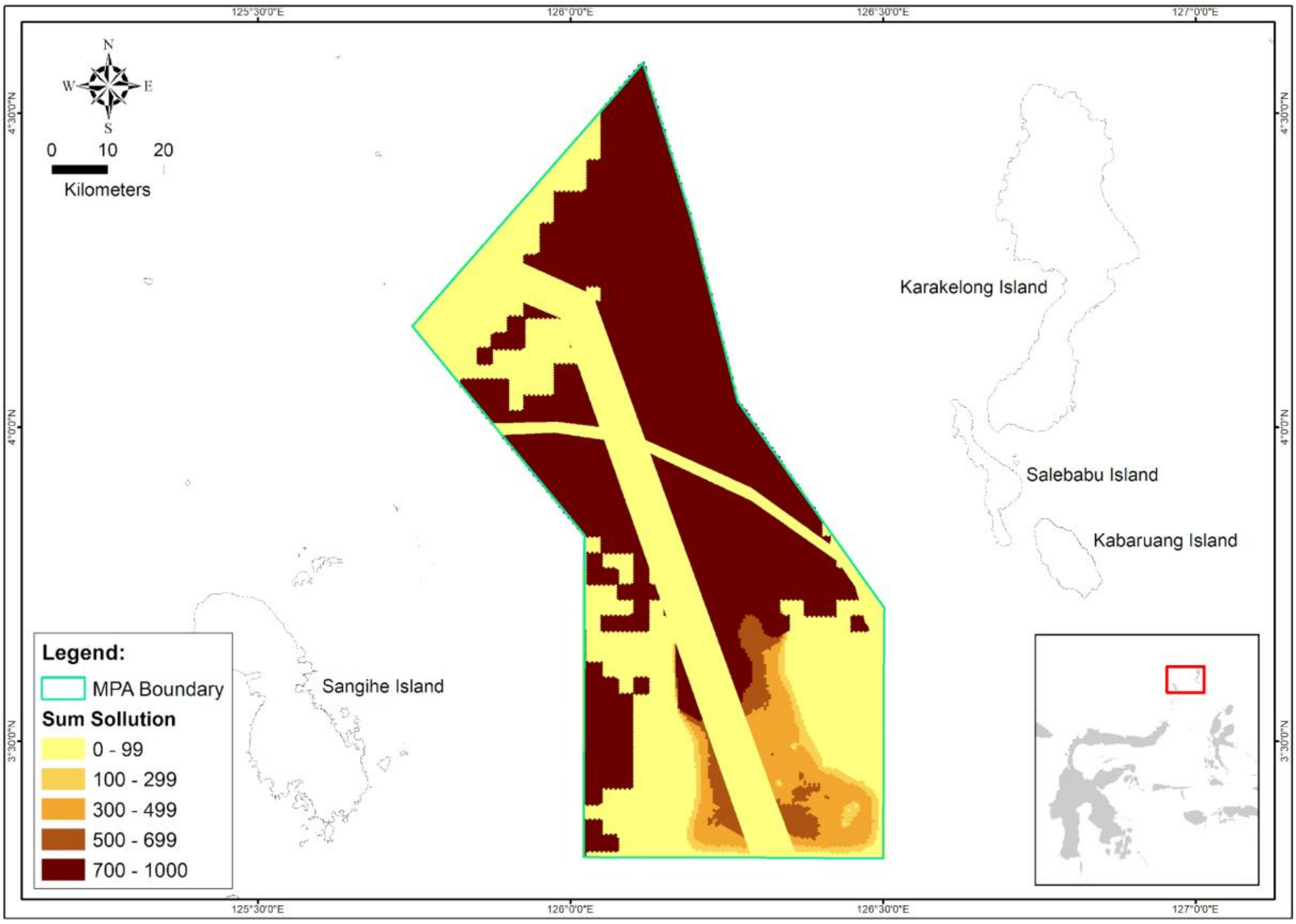

Figure 6. Output sum solution in the Marxan analysis to determine the core zone in Area IV. The areas of yellow color was 163,282.74 Ha; the areas of mustard color was 11,438.45 Ha; the areas of orange color was 33,328.13 Ha; the areas of brown color was 15,657.89 Ha; the areas of dark brown was 282,364.82 Ha. The green line showed the marine protected areas boundary

Discussion

The standardized CPUE results indicated an increasing trend for mackerel scad (*D. macarellus*) during the period 2021-2023, suggesting improved catch efficiency or spatial concentration of the stock. However, this trend should be interpreted cautiously, as recent stock assessments indicate that total catches during 2020-2022 exceeded allowable catch limits and surpassed Maximum Sustainable Yield (MSY) in 2020 and 2021, signalling a high risk of overexploitation (Gahunting et al. 2023). As a key small pelagic species, mackerel scad plays an important role in pelagic food webs by transferring energy from lower trophic levels to higher predators. Sustained overfishing may therefore disrupt ecosystem functioning and undermine long-term fisheries productivity, highlighting the need for ecosystem-based spatial management approaches such as Marine Protected Area (MPA). Protecting the critical area is essential to maintain reproductive success and larval development, thereby enhancing population resilience and supporting the long-term sustainability of pelagic fisheries.

Marine Protected Areas (MPAs) for pelagic fisheries remain relatively new in Indonesia, highlighting the need for research that integrates fish larval dynamics with oceanographic features to identify critical habitats for conservation (Hakim et al. 2025). According to Hakim et al. (2025) that introduces an innovative approach by examining larval distribution and dispersal patterns to delineate spawning and nursery grounds of pelagic species, which can serve as priority areas for protection. Such a method not only strengthens the ecological basis for MPA planning but also offers a replicable framework for other regions in Indonesia. This initiative aligns with the Government of Indonesia’s policy to support the Global Biodiversity Framework, which aims to conserve 30% of the world’s oceans. In line with this commitment, the Government of Indonesia has announced a new Marine Protected Area (MPA) policy, under which the country will designate at least 97.5 million hectares of its waters as MPAs by 2045. This policy is referred to as '30 by 45' (MMAF 2024).

The Marxan analysis provides a spatially explicit basis for addressing these risks by identifying conservation priorities that balance ecological benefits with socio-economic costs (Wijayanto et al. 2022). Among the four candidate conservation areas, Area IV consistently emerged as the highest-priority zone due to its combination of high ecological importance and relatively low fishing intensity. Unlike Areas I and III, which overlap with major fishing grounds and incur higher opportunity costs, Area IV encompasses essential spawning and nursery habitats while maintaining lower levels of fishing activity, resulting in a favourable cost-benefit trade-off for conservation implementation. The ecological significance of Area IV is supported by independent biological evidence indicating that the northern Sulawesi Sea functions as a principal spawning area for mackerel scad, with nursery habitats concentrated around Sangihe Island and nearby waters (Retnoningtyas et al. 2023; Hakim et al. 2025). The spatial coincidence between these critical habitats and Marxan-selected priority areas suggests that Area IV supports multiple key life-history stages of the species. Protecting such areas is particularly important for pelagic species with high mobility, as population persistence depends on safeguarding spatially predictable spawning and early-life habitats rather than continuous residency within protected boundaries.

Based on the Marxan Sum Solution output further reinforces the importance of Area IV. Approximately 47.08% of the area fell within the highest selection-frequency class (700-1000), indicating consistent selection across multiple optimization runs. Moreover, these high-frequency planning units were spatially clustered, forming a contiguous core zone rather than being dispersed across the study area. This spatial coherence enhances habitat connectivity and increases the likelihood that the conservation area will function effectively by supporting reproductive processes, larval retention, and early development. These findings demonstrate the potential role of offshore marine protected areas in the management of pelagic fisheries, which remain underrepresented compared to reef-based conservation initiatives. By targeting spatially persistent ecological hotspots identified through quantitative modelling, offshore MPAs can contribute meaningfully to stock recovery and long-term resilience, even for highly mobile species. The results of this study indicate that spatial optimization tools, when integrated with ecological and fisheries data, can effectively guide pelagic MPA design in dynamic offshore environments.

The establishment of pelagic MPAs in the Chagos Archipelago has demonstrated measurable recovery in tuna stocks, underscoring the ecological benefits of offshore habitat protection (Curnick et al. 2020). According to Aulia et al. (2021), the application of the Marxan model to identify no-take zones in Simeulue District resulted in the selection of eight areas as potential no-catch zones. These areas were prioritized based on the presence of coastal habitats, biodiversity significance, and high conservation value, with a total designated area of approximately 2,283.89 hectares (protecting 80% of the conservation target). Also, according to Darmawan et al. (2025a), successfully protecting 40% of the conservation target in Arefi Island with 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. Most MPAs remain reef-centric, with limited integration of pelagic conservation targets.

Follow-up actions for Area IV, as a candidate marine conservation area that require meticulous zoning to ensure effective ecosystem protection. In accordance with MMAF Regulation No. 31 of 2020, conservation areas must be subdivided into distinct zones, such as core zones, limited utilization zones, and other specialized zones. Core zones, which are designed to protect critical habitats like spawning, nursery, and feeding grounds, play a key role in this framework by maximizing ecological protection while balancing permitted human activities (Gutiérrez et al. 2024). According to Bograd et al. (2024), sustainable fishery resources can be achieved when Marine Protected Areas (MPAs) encompass at least 20-40% of critical habitats, with a particular focus on areas vital for the survival of vulnerable species. Restricting activities such as fishing and tourism in these critical zones is essential to maintaining biodiversity and ecological resilience (Hughes et al. 2016). The success of MPAs hinges on strict regulatory measures that prevent detrimental activities and promote the recovery of marine ecosystems, thereby supporting the regeneration of fish stocks (Gonçalves 2023; Cheung et al. 2024).

The validity of the proposed conservation area can be tested using the triangulation approach, where every aspect of the conservation area is thoroughly reviewed through focused discussions. These discussions should involve representatives from various stakeholders, including the government, parliament, academics, non-governmental organizations, and fisheries practitioners, to ensure that all perspectives are accommodated (Halim et al. 2019). Such a participatory approach not only enhances the quality of planning but also strengthens the support of all involved parties. Additionally, outreach to local communities becomes a crucial element in the process of establishing conservation areas. Raising local knowledge through education and engaging communities based on socio-cultural criteria can help promote the successful implementation of conservation policies (Jennings et al. 2024). This approach ensures that local communities not only support the establishment of conservation areas but also feel a sense of ownership and responsibility for the sustainability of marine resources in the region. Proposed marine conservation areas must be free from conflicts of interest to ensure that community and environmental priorities are not overridden by individual gains. Therefore, marine spatial allocation must be clearly defined to prevent overlapping uses that could compromise both community priorities and environmental protection (Calva 2018; Twichell et al. 2018). The potential for pelagic fishery in FMA 716 (which encompasses the Sulawesi Sea and the northern waters of Halmahera) is substantial. However, spatial studies in the Sulawesi Sea indicate that effective management of this resource requires stringent regulations to prevent continuous overexploitation.

From a management perspective, the designation of Area IV as a core conservation zone offers a practical pathway to reconcile biodiversity conservation with fisheries sustainability. Limiting extractive activities within this zone is expected to enhance stock replenishment and potentially generate spillover benefits to adjacent fishing grounds. More broadly, the spatial framework developed in this study provides a transparent and scientifically defensible basis for stakeholder engagement and adaptive management. The integration of larval ecology, fishing-effort distribution, and spatial prioritization offers a replicable approach for offshore pelagic conservation planning in Indonesia and other regions facing similar management challenges.

In conclusion, this study identified four candidate areas for offshore pelagic MPA development in the Sulawesi Sea, with Area IV, between Sangihe and Talaud Islands, emerging as the top conservation priority. Using Marxan spatial optimization, Area IV offered the best balance of high conservation value and low socio-economic conflict, encompassing critical spawning and nursery habitats for mackerel scad (*D. macarellus*) across ~599,790.91 ha, of which 282,364.82 ha (47.08%) formed a consistently selected core zone. By integrating ecological data, fishing-effort information, and systematic conservation planning, the study presents a robust, replicable approach to cost-efficient offshore conservation that advances MPA planning in Indonesia beyond coastal-focused management and supports the country's "30 by 45" target under the Global Biodiversity Framework. Successful implementation will ultimately depend on adaptive management and inclusive stakeholder engagement to strengthen governance, enhance compliance, and ensure long-term fisheries sustainability, while advancing broader marine conservation objectives.

ACKNOWLEDGEMENTS

We thank the Ministry of Marine Affairs and Fisheries Indonesia, the Provincial Government of North Sulawesi, Indonesia, Wildlife Conservation Society Indonesia, Institut Pertanian Bogor, Indonesia, and Rekam Nusantara Foundation, Indonesia, that their support of this research. This research was partially funded by KfW Development Bank through Wildlife Conservation Society and Oceans 5 through Indonesia MPA and OECM Consortium. We gratefully acknowledge their support, which contributed significantly to the successful completion of this study.

REFERENCES

Adam L. 2016. Policy of prohibition on fishing of yellowfin tuna: Impact analysis and solution. Jurnal Ekonomi & Kebijakan Publik 7 (2): 215-227. https://doi.org/10.22212/jekp.v7i2.577. [Indonesian]

Agnew D, Fryirs K, Leishman MR. 2024. Cost-benefit analysis of working with recovery in river management using Marxan. Front Environ Sci 12 (1425668): 1-23. https://doi.org/10.3389/fenvs.2024.1425668.

Akerina IMF, Pratasik SB, Bataragoa NE. 2019. Fly fish growth pattern (*Decapterus* spp) in Likupang Water, Nort Sulawesi. Jurnal Ilmiah Platax 7 (1): 113-120. https://doi.org/10.35800/jip.7.1.2019.22593. [Indonesian]

Aulia F, Rusdi M, Deli A, Fuadi A, Irham M, Indra I. 2021. The Marxan model for determining no-catch zones based on conservation targets in the North-eastern region of Simeulue District. IOP Conf Ser Earth Environ Sci 711: 012024. https://doi.org/10.1088/1755-1315/711/1/012024.

Ball IR, Possingham HP, Watts M. 2009. Marxan and relatives: Software for spatial conservation prioritisation. In: Moilanen A, Wilson KA, Possingham HP (eds.). Spatial Conservation Prioritisation: Quantitative Methods and Computational Tools. Oxford University Press, United Kingdom. https://doi.org/10.1093/oso/9780199547760.003.0014.

Beck MW, Heck KL, Able KW, Childers DL, Eggleston DB, Gillanders BM, Halpern B, Hays CG, Hoshino K, Minello TJ, Orth RJ, Sheridan PF, Weinstein MP. 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates: A better understanding of the habitats that serve as nurseries for marine species and the factors that create site-specific variability in nursery quality will improve conservation and management of these areas. BioScience 51 (8): 633-641. https://doi.org/10.1641/0006-3568(2001)051[0633:TICAMO]2.0.CO;2.

Bograd SJ, Anderson LC, Canonico G, Chiba S, Lorenzo ED, Enterline C, Gorecki E, Griffis R, Kleisner KM, Lachance H, Leinen M, Mills KE, Müller-Karger FE, Roskar G, Schmidt J, Seary R, Seeyave S, Hwai TS, Soares J, Tigchelaar. 2024. Advancing the climate-biodiversity-fisheries nexus in the UN decade of ocean science for sustainable development. ICES J Mar Sci 81 (9): 1705-1711. https://doi.org/10.1093/icesjms/fsae111.

Calva JC. 2018. Community-based organizations: Role on coastal resource management in the Sarangani Bay area. JHRS 1: 5-16. https://doi.org/10.34002/jhrs.v1i0.7.

Chan KMA, Hoshizaki L, Klinkenberg B. 2011. Ecosystem services in conservation planning: Targeted benefits vs. co-benefits or costs? PLoS ONE 6 (9): e24378. https://doi.org/10.1371/journal.pone.0024378.

Cheung WWL, Palacios-abrantes J, Roberts SM. 2024. Projecting contributions of marine protected areas to rebuild fish stocks under climate change. npj Ocean Sustain 3 (11): 1-11. https://doi.org/10.1038/s44183-024-00046-w.

Christie MR, Tissot BN, Albins MA, Beets JP, Jia Y, Ortiz DM, Thompson SE, Hixon MA. 2010. Larval connectivity in an effective network of marine protected areas. PLoS ONE 5 (12): e15715. https://doi.org/10.1371/journal.pone.0015715.

Curnick DJ, Collen B, Koldewey HJ, Jones KE, Kemp KM, Ferretti F. 2020. Interactions between a large marine protected area, pelagic tuna and associated fisheries. Front Mar Sci 7: 318. https://doi.org/10.3389/fmars.2020.00318.

Darmawan M, Simamora DC, Nahib I, Ramadhani F, Sutrisno D, Amhar F, Ramdhan M, Safitri S, Sutejo B, Arifin S, Agus SB. 2025a. 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. PeerJ 13: e19292. http://doi.org/10.7717/peerj.19292.

Darmawan R, Wiryawan B, Purbayanto A, Yulianto I, Kleinertz S. 2025b. Stock performance of leopard coral grouper (*Plectropomus leopardus*) and orange-spotted grouper (*Epinephelus coioides*) in Saleh Bay, West Nusa Tenggara, Indonesia. Asian Fish Sci 38 (2): 113. https://doi.org/10.33997/j.afs.2025.38.2.005.

Delavenne J, Metcalfe K, Smith RJ, Vaz S, Martin CS, Dupuis L, Coppin F, Carpentier A. 2012. Systematic conservation planning in the Eastern English Channel: Comparing the Marxan and Zonation decision-support tools. ICES J Mar Sci 69 (1): 75-83. https://doi.org/10.1093/icesjms/fsr180.

Dickey-Collas M, McQuatters-Gollop A, Bresnan E, Kraberg AC, Manderson JP, Nash RD, Otto SA, Sell AF, Tweddle JF, Trenkel VM. 2017. Pelagic habitat: Exploring the concept of good environmental status. ICES J Mar Sci 74 (9): 2333-2341. https://doi.org/10.1093/icesjms/fsx158.

Estradivari, Kartika I, Adhuri DS, Adrianto L, Agung F, Ahmadia GN, Bejarano S, Campbell SJ, Fachri FR, Kushardanto H, Marlessy C, Pane B, Puebla O, Purnama RC, Santiadji IWV, Suherfian W, Tillah M, Widodo H, Wild C, Ferse SCA. 2024. Prospective ecological contributions of potential marine OECMs and MPAs to enhance marine conservation in Indonesia. Ocean Coast Manag 258: 107411. https://doi.org/10.1016/j.ocecoaman.2024.107411.

Gahunting D, Sitanggang E, Dien H. 2023. The potency of mackerel scad (*Decapterus macarellus*) caught in WPP 716 of North Sulawesi waters by Purse Seiner landed at the coastal fishing port of Tumumpa, Manado. Jurnal Ilmiah Platax 11 (2): 589-602. https://doi.org/10.35800/jip.v11i2.49182.

Game ET, Grantham HS, Hobday AJ, Pressey RL, Lombard AT, Beckley LE, Gjerde K, Bustamante R, Possingham HP, Richardson AJ. 2009. Pelagic protected areas: The missing dimension in ocean conservation. Trends Ecol Evol 24 (7): 360-369. https://doi.org/10.1016/j.tree.2009.09.003.

Gonçalves EJ. 2023. Marine Protected Areas as Tools for Ocean Sustainability. In: Garcia MdG, Cortês A (eds.). Blue Planet Law. Sustainable Development Goals Series. Springer, Cham. https://doi.org/10.1007/978-3-031-24888-7_11.

Gutiérrez E, Letelier L, Santos-Carvallo M, Barilari F, Gutiérrez L, Pérez-Álvarez MJ, Sepúlveda M. 2024. Zoning proposal for a marine protected area in Chile: A conservation tool for large cetaceans. Ocean Coast Manag 248: (106975). https://doi.org/10.1016/j.ocecoaman.2023.106975.

Hakim A, Wiryawan B, Purbayanto A, Taurusman AA, Agung F, Simanjuntak CP, Ningtias P, Prasetia R, Kartawijaya T, Andayani N, Natsir M, Agustina S, Retnoningtyas H, Nabil, Darmawan R, Herdiana Y, Yulianto I. 2025. Spawning and nursery areas of *Decapterus macarellus*: Siting pelagic fisheries marine protected area (MPA) in the Sulawesi Sea, Indonesia. Front Mar Sci 12: 1606963. https://doi.org/10.3389/fmars.2025.1606963.

Halim A, Wiryawan B, Loneragan NR, Hordyk A, Sondita MFA, White AT, Koeshendrajana S, Ruchimat T, Pomeroy RS, Yuni C. 2019. Developing a functional definition of small-scale fisheries in support of marine capture fisheries management in Indonesia. Mar Policy 100: 238-248. https://doi.org/10.1016/j.marpol.2018.11.044.

Hou G, Wang J, Chen Z, Zhou J, Huang W, Zhang H. 2020. Molecular and morphological identification and seasonal distribution of eggs of four *Decapterus* fish species in the Northern South China Sea: A key to conservation of spawning ground. Front Mar Sci 7: 590564. https://doi.org/10.3389/fmars.2020.590564.

Hughes TP, Cameron DS, Chin A, Connolly SR, Day JC, McCook L, McGinnity P, Mumby PJ, Pears RJ, Pressey RL, Russ GR. Tanzer J, Tobin A, Young MAL. 2016. A critique of claims for negative impacts of marine protected areas on fisheries. Ecol Appl 26 (2): 637-641. https://doi.org/10.1890/15-0457.

Jennings V, Antonio KMS, Brown MJ, Choice L, Simpson Q, Ford I, Cho HJ, Solis P, Lacey A, Robinson DM. 2024. Place-based conservation in coastal and marine ecosystems: The importance of engagement with underrepresented communities. Sustainability 16 (22) 9965. https://doi.org/10.3390/ su16229965.

Keen LH, Stortini CH, Boyce DG, Stanley RRE. 2024. Assessing climate change vulnerability in Canadian marine conservation networks: Implications for conservation planning and resilience. FACETS 9: 1-15. https://doi.org/10.1139/facets-2023-0124.

Kirkfeldt TS, Frazão Santos C. 2021. A review of sustainability concepts in marine spatial planning and the potential to supporting the UN sustainable development goal 14. Front Mar Sci 8: 713980. https://doi.org/10.3389/fmars.2021.713980.

Lehuta S, Mahévas S, Petitgas P, Pelletier D. 2010. Combining sensitivity and uncertainty analysis to evaluate the impact of management measures with ISIS-Fish: Marine protected areas for the Bay of Biscay anchovy (*Engraulis encrasicolus*) fishery. ICES J Mar Sci 67 (5): 1063-1075. https://doi.org/10.1093/icesjms/fsq002.

Ministry of Marine Affairs and Fisheries (MMAF). 2024. Spatial Planning for the Expansion of Conservation Area Coverage to Achieve the 30x45 Conservation Vision. Technical Report. Directorate General of Marine Spatial Management, Ministry of Marine Affairs and Fisheries, Jakarta. https://konservasi-id.org. [Indonesian]

North Sulawesi Province Marine and Fisheries Agency. 2023. The Fish Landing Monitoring Data. https://data.sulutprov.go.id. [Indonesian]

Puspasari R, Rachmawati PF, Wijopriono. 2016. Vulnerability analysis of small pelagic fishes in Bali Strait and Makassar Strait to the dynamic of sea surface temperature. Jurnal Penelitian Perikanan Indonesia 22 (1): 33-42. https://doi.org/10.15578/jppi.22.1.2016.33-42. [Indonesian]

Retnoningtyas H, Agustina S, Natsir M, Ningtias P, Hakim A, Dhani AK, Hartati ID, Pingkan J, Simanjuntak CPH, Wiryawan B, Taurusman AA, Purbayanto A, Palm HW, Prasetia R, Yulianto I. 2024. Reproductive biology of the mackerel scad, *Decapterus macarellus* (Cuvier, 1833), in the Sulawesi Sea, Indonesia. Reg Stud Mar Sci 69: 103300. https://doi.org/10.1016/j.rsma.2023.103300.

Retnoningtyas H, Yulianto I, Wiryawan B, Kleinertz S, Palm HW. 2023. Stock discrimination of mackerel scad *Decapterus macarellus* (Cuvier, 1833) in the Eastern Indonesia based on metazoan fish parasite composition. Reg Stud Mar Sci 61: 102840. https://doi.org/10.1016/j.rsma.2023.102840.

Setya D, Susiloningtyas D, Nurulludin. 2023. The maximum sustainable yield of mackerel scad (*Decapterus* spp) landed in Pemangkat, West Kalimantan. BAWAL Widya Riset Perikanan Tangkap 15 (1): 33. http://dx.doi.org/10.15578/bawal.15.1.2023.33-40. [Indonesian]

Sheppard C. 2010. Marine protected areas and pelagic fishing: The case of the Chagos Archipelago. Mar Pollut Bull 60 (11): 1899-1901. https://doi.org/10.1016/j.marpolbul.2010.08.023.

Sini M, Katsanevakis S, Koukourouvli N et al. 2017. Assembling ecological pieces to reconstruct the conservation puzzle of the Aegean Sea. Front Mar Sci 4: 347. https://doi.org/10.3389/fmars.2017.00347.

Suwarso, Zamroni A. 2014. Population structure analyses of three species of layang (*Decapterus* spp.) in the Java Sea and Makassar Strait: Sustainable management option of small pelagic fishes and evaluation of FMA. Jurnal Kebijakan Perikanan Indonesia 6 (2): 75-86. http://dx.doi.org/10.15578/jkpi.6.2.2014.75-86.

Twichell JH, Pollnac R, Christie P. 2018. Lesson from Philippines MPA management: Social ecological interactions, participation, and MPA performance. Environ Manag 61: 916-927. https://doi.org/10.1007/s00267-018-1020-y.

Venegas-li R, Levin N, Possingham H, Kark S. 2018. 3D spatial conservation prioritisation: Accounting for depth in marine environments. Methods Ecol Evol 9 (3): 773-784. https://doi.org/10.1111/2041-210X.12896.

Villarao MC, Encarnacion AB. 2025. Reproductive characteristics of mackerel scad *Decapterus macarellus* (Cuvier, 1833) in Northern Philippine waters. Croat J Fish 83: 167-175. https://doi.org/10.2478/cjf-2025-0018.

Watts ME, Stewart RR, Martin TG, Klein CJ, Carwardine J, Possingham HP. 2017. Systematic conservation planning with Marxan. In: Sarah EG, Monica GT (eds.). Learning Landscape Ecology: A Practical Guide to Concepts and Techniques. Springer, New York. https://doi.org/10.1007/978-1-4939-6374-4_13.

Whitfield AK, Pattrick P. 2015. Habitat type and nursery function for coastal marine fish species, with emphasis on the Eastern Cape Region, South Africa. Estuar Coast Shelf Sci 160: 49-59. https://doi.org/10.1016/j.ecss.2015.04.002.

Wickham H. 2016. ggplot2: Elegant Graphics for Data Analysis. 2nd Edition. J Stat Software 77 (2): 1-3. https://doi.org/10.18637/jss.v077.b02.

Wijayanto C, Yulianda F, Imran Z. 2022. The core zone decisive of marine conservation area in Southeast Sulawesi using marxan. IOP Conf Ser Earth Environ Sci 967 (1): 012001. https://doi.org/10.1088/1755-1315/967/1/012001.

Wood SN. 2025. Generalized additive models. Ann Rev Stat Appl 12: 497-526. https://doi.org/10.1146/annurev-statistics-112723-034249.

Yesson C, Clark MR, Taylor M, Rogers AD. 2011. List of Seamounts in the World Ocean. [Dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.757562.

Zuercher R, Ban NC, Flannery W, Guerry AD, Halpern BS, Magris RA, Mahajan SL, Motzer N, Spalding AK, Stelzenmuller V, Kramer JG. 2022. Enabling conditions for effective marine spatial planning. Mar Policy 143: 105141. https://doi.org/10.1016/j.marpol.2022.105141.