

Habitat modeling of little tuna (*Euthynnus affinis*) in Makassar Strait (Indonesia) using MaxEnt

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Abstract. Abudarda ARF, Zainuddin M, Hidayat R, Sriktoviana SK. 2026. Habitat modeling of little tuna (*Euthynnus affinis*) in Makassar Strait (Indonesia) using MaxEnt. *Biodiversitas* 27 (1): d270142. <https://doi.org/10.13057/biodiv/d270142>. *Euthynnus affinis*, commonly known as little tuna, is an ecologically and economically important pelagic species that supports artisanal and commercial fisheries across the Indo-Pacific region. The Makassar Strait, a major pathway of the Indonesian Throughflow, exhibits pronounced seasonal and interannual variability in oceanographic conditions, which strongly influences the spatial and temporal distribution of pelagic fishes. This study presents the first application of the Maximum Entropy (MaxEnt) modeling framework to predict habitat suitability for *E. affinis* in the Makassar Strait. Presence-only occurrence records were related to key environmental variables derived from satellite observations, including sea surface temperature (SST), sea surface chlorophyll concentration (SSC), and sea surface salinity (SSS). SST and SSC data were obtained from the MODIS Aqua sensor (NASA Ocean Color) at a spatial resolution of 4 km, while SSS data were sourced from the Copernicus Marine Environment Monitoring Service. All environmental variables were compiled at a monthly temporal resolution from January 2019 to December 2023. The MaxEnt models showed strong predictive performance, with area under the curve values ranging from 0.78 in July to 0.92 in April, indicating good to excellent model accuracy. SST emerged as the most influential predictor, contributing 57.4 percent to model gain, followed by SSC and SSS. Habitat suitability was highest in the central and southern sectors of the strait, particularly during periods characterized by moderate SST and elevated SSC. *Euthynnus affinis* showed a preference for SST of approximately 29.31°C, SSC of 0.22 mg m⁻³, and SSS of 33.7 psu. Optimal habitats were largely concentrated in the southern Makassar Strait, especially around 4 to 5°S. These results demonstrate a clear association between regional oceanographic dynamics and the distribution of *E. affinis*. The findings provide essential baseline information for ecosystem-based fisheries management and support adaptive strategies for small-scale fisheries. Integrating these spatio-temporal habitat patterns into regional fisheries planning may improve resilience to environmental variability and help sustain tuna fisheries in the Makassar Strait.

Keywords: Catch per unit effort, fisheries management, MODIS, oceanographic conditions, Species Distribution Modeling

INTRODUCTION

Makassar Strait, functions as a key biogeographic corridor under the influence of the Indonesian Throughflow, a major ocean current that transports warm Pacific Ocean waters into the Indian Ocean (Gordon et al. 2019). This throughflow generates pronounced seasonal and interannual variability in regional oceanographic conditions, thereby shaping marine productivity and species distributions (Fan et al. 2018; Lu et al. 2023; Wang et al. 2023; Wiyono et al. 2024). *Euthynnus affinis* (Cantor, 1849), commonly known as little tuna, is an ecologically and economically important pelagic species distributed widely across the Indo-Pacific region (McClellan et al. 2019). The spatial distribution of *E. affinis* is closely associated with oceanographic conditions, particularly temperature, salinity, and productivity-related indicators such as chlorophyll-a (Syamsuddin et al. 2018a). These environmental factors regulate key biological processes, including feeding, migration, and reproduction (Liu et al. 2020; Vayghan et al. 2020).

Globally, species distribution models have become an essential tool for understanding and predicting the spatial ecology of tuna fisheries, with applications in conservation

planning and fisheries management. These models are widely used to assess climate-driven shifts in species distributions, identify optimal fishing grounds, and reduce bycatch (Hazen et al. 2012; Lehodey et al. 2015). Recent studies have examined climate change impact on the distribution of highly exploited tuna species in the Atlantic Ocean (Silva et al. 2025) and modeled suitable habitats for mature albacore tuna (*Thunnus alalunga*) in the Indian Ocean (Mondall and Lee 2023). However, many existing studies rely on regression-based or mechanistic frameworks, and relatively few have applied maximum entropy modeling to tuna species.

Maximum entropy modeling is a presence-only approach that estimates habitat suitability by relating species occurrence records to environmental predictors (Merow et al. 2013). In Indonesia, MaxEnt has been applied to predict potential fishing grounds for yellowfin and bigeye tuna (Syah et al. 2020; Yati et al. 2024). Nevertheless, no study has yet applied this approach to *E. affinis* in the Makassar Strait or across the broader Indonesian Throughflow region.

This gap is important because *E. affinis* differs ecologically from larger tuna species, exhibiting shorter migration ranges, stronger responses to seasonal productivity

pulses, and higher sensitivity to localized environmental variability. Examining its habitat preferences in the Makassar Strait, one of the most dynamically variable oceanographic regions in the Indo-Pacific, can improve understanding of how pelagic tuna species respond to changing environmental conditions. The novelty of this study lies in the integration of multi-year satellite-derived oceanographic data with fisheries occurrence records to generate high-resolution habitat suitability maps for *E. affinis* in the Makassar Strait. Unlike previous studies that focus primarily on larger tuna species, this research addresses a smaller pelagic species that is particularly important for small-scale fisheries and more responsive to short-term environmental variability. By focusing on *E. affinis*, this study broadens the application of species distribution modeling within tuna fisheries research in the Indo-Pacific and strengthens the integration of fisheries-dependent and environmental datasets for applied marine management.

We hypothesize that sea surface temperature is the primary environmental driver of *E. affinis* habitat suitability in the Makassar Strait, given its strong influence on tuna physiology and behavior. We further expect that optimal habitats will occur mainly in the southern part of the strait during periods characterized by moderate sea surface temperature and elevated chlorophyll concentration, reflecting combined thermal preference and feeding opportunity. Accordingly, the objectives of this study are to apply a MaxEnt model to map the spatial and temporal distribution of suitable habitats for *E. affinis* in the Makassar Strait, to quantify the relative contributions of sea surface temperature, sea surface chlorophyll concentration, and sea surface salinity to habitat suitability, and to provide management-relevant insights that support ecosystem-based fisheries management and enhance the adaptive capacity of small-scale fishers to environmental change. By addressing this knowledge gap, the study contributes to a better understanding of tuna ecology within the Indonesian Throughflow region and supports the development of informed fisheries management strategies in Indonesia.

MATERIALS AND METHODS

Study area

The Makassar Strait is a major marine passage located between the islands of Borneo and Sulawesi in eastern Indonesia (Figure 1). The strait functions as the primary pathway of the Indonesian Throughflow, a large-scale ocean circulation system that transports warm Pacific Ocean waters into the Indian Ocean and strongly influences regional climate and marine ecosystems (Gordon et al. 2019). Owing to its strategic position and dynamic oceanographic conditions, the Makassar Strait supports productive pelagic fisheries and exhibits pronounced spatial and temporal environmental variability.

Procedures

Fisheries data

Presence data for *Euthynnus affinis* were collected through direct participation in purse seine fishing operations conducted in the Makassar Strait. Field observations were carried out during four representative months, March, April, July, and August, selected to capture contrasting monsoonal conditions. For each fishing operation, geographic coordinates (latitude and longitude), catch quantity, and fishing effort were recorded. Fishing effort was defined as the number of purse seine sets conducted per trip.

Fishing productivity was calculated as catch per unit effort (CPUE), expressed as:

$$\text{CPUE} = \frac{\text{Number of individuals caught}}{\text{Number of sets}}$$

Only fishing sets with positive catches were retained for analysis, while zero-catch sets were excluded. Although CPUE values were calculated to characterize fishing productivity, the MaxEnt modeling was performed using binary presence-only data rather than CPUE-weighted occurrences. Each presence record represented a unique fishing location with a positive catch to avoid spatial duplication. All fishing activities were conducted with the informed consent of participating fishers, ensuring ethical compliance in data collection.

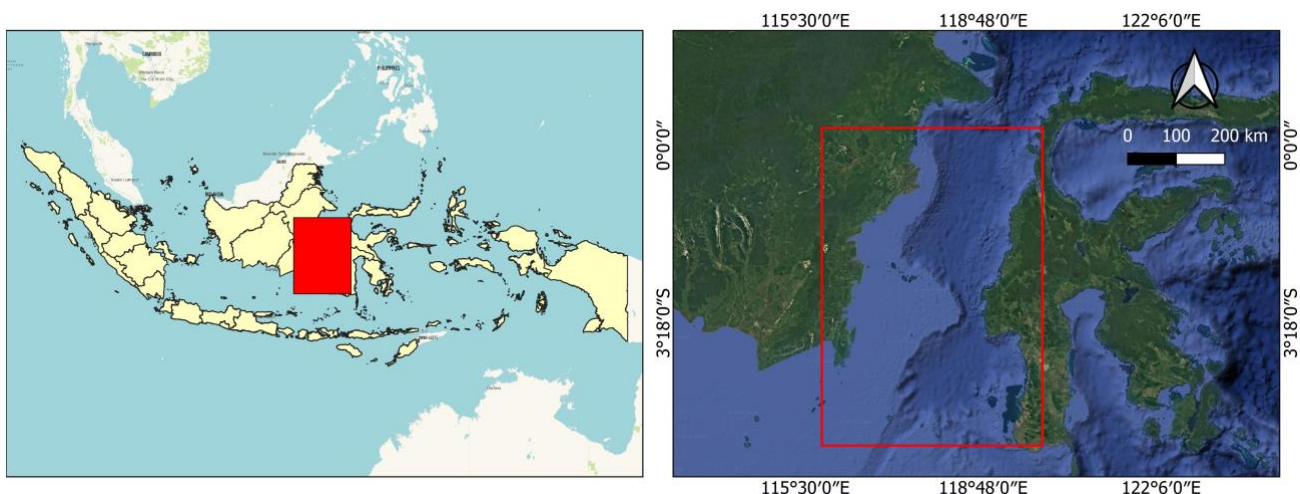


Figure 1. Location of the study area in the Makassar Strait, Indonesia

Environmental data

Environmental variables included sea surface temperature, sea surface chlorophyll concentration, and sea surface salinity. Sea surface temperature and chlorophyll concentration were obtained from the MODIS Aqua sensor through NASA Ocean Color, with a spatial resolution of 4 km. Sea surface salinity data were sourced from the Copernicus Marine Environment Monitoring Service. All environmental datasets were acquired at a monthly temporal resolution covering the period from January 2019 to December 2023.

Satellite data processing was performed using SeaDAS software version 7.5.1, developed by NASA for the visualization and processing of ocean color and remote sensing data. This processing ensured the conversion of raw satellite observations into georeferenced, quality-controlled environmental layers suitable for spatial analysis.

Data analysis

Environmental variable processing

All environmental variables were reprojected to a common spatial reference system and standardized to a consistent spatial resolution. Monthly environmental values

were interpolated using the Inverse Distance Weighting method in ArcGIS version 10.8, which has been shown to provide reliable spatial estimates for marine environmental parameters (Lu and Wong 2008). Fishing locations were overlaid on the interpolated environmental layers, and corresponding environmental values were extracted at each occurrence point to enable spatial matching between species presence and environmental conditions. Environmental predictors were selected a priori based on their documented ecological relevance to *Euthynnus affinis*, representing thermal, productivity, and salinity gradients that influence habitat suitability (Syamsuddin et al. 2018b; Fadhilah et al. 2022).

Maximum entropy (MaxEnt) modelling

Species distribution modeling was conducted using MaxEnt version 3.4.4 (Elith et al. 2011; Merow et al. 2013) based on 75 georeferenced presence records. The background area was defined as the spatial extent of the Makassar Strait corresponding to the observed fishing grounds. This approach restricted background sampling to areas regularly accessed by purse seine fisheries, thereby reducing sampling bias and maintaining ecological realism.

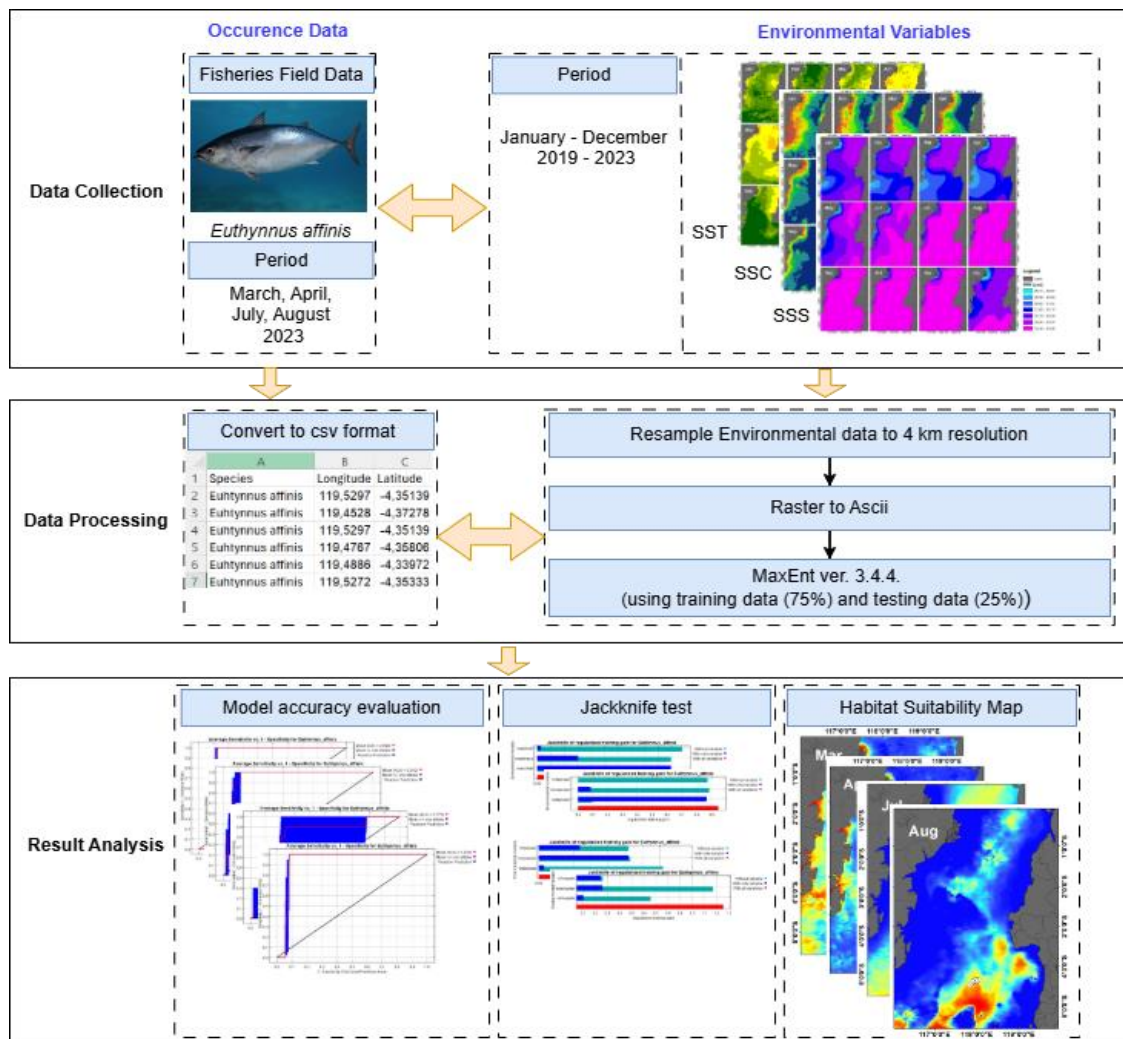


Figure 2. Flowchart of MaxEnt modeling process

The model was run using a default regularization multiplier of 1.0 to balance model complexity and reduce overfitting. Feature classes, including linear, quadratic, and hinge features, were automatically selected by MaxEnt based on sample size. Five replicate model runs were performed using the subsample method, with a maximum of 500 iterations and a convergence threshold of 1.0×10^{-5} . Clamping was enabled to restrict predictions to the observed environmental range, and logistic output was selected to produce habitat suitability values ranging from 0 (unsuitable) to 1 (highly suitable).

Occurrence data were randomly partitioned into training (75 percent) and testing (25 percent) datasets (Vayghan et al. 2020). Model performance was evaluated using the area under the receiver operating characteristic curve, with values greater than 0.7 considered acceptable and values greater than 0.9 considered excellent. Variable importance was assessed using percent contribution and jackknife tests (Alabia et al. 2015). A conceptual overview of the modeling framework is presented in Figure 2.

The temporal representativeness of the dataset represents a limitation, as occurrence records were available for only four months. Although this restricts full interannual interpretation, the selected months capture contrasting monsoonal phases and provide insight into seasonal habitat variability. Environmental predictors were deliberately limited to minimize redundancy and reduce the risk of multicollinearity.

RESULTS AND DISCUSSION

Oceanographic parameters in the Makassar Strait

The analysis of variance indicates significant differences in mean values of the examined oceanographic parameters among the sampled months (Table 1). Sea surface temperature exhibited the strongest effect ($F = 49.7$, $p < 0.05$), followed by sea surface chlorophyll concentration ($F = 10.9$, $p < 0.05$) and sea surface salinity ($F = 3.8$, $p < 0.05$). These results suggest that temperature variability is the primary factor distinguishing environmental conditions among sampling periods, while changes in chlorophyll concentration and salinity also contribute meaningfully. These comparisons are presented for descriptive purposes, as spatial and temporal autocorrelation in environmental data may violate the assumptions of classical analysis of variance.

Figure 3 illustrates the spatial and temporal variability of oceanographic conditions in the Makassar Strait from January 2019 to December 2023. Sea surface temperature ranged from 28.9 to 31.6°C, with relatively low annual variability typical of tropical waters. At the beginning of the year, sea surface temperature conditions aligned closely with the optimal thermal range reported for *E. affinis*. Temperature increases during March and April are likely to support feeding, migration, and spawning activity (Syahdan et al. 2021). In contrast, a decline in temperature from May to August, associated with the southeast monsoon, may reduce primary productivity and prey availability, thereby

lowering habitat suitability. Temperature increases again from September to December during the rainy season (Kusmardiyanti et al. 2022). A pronounced warming event was observed in late 2023 to early 2024, with temperatures reaching approximately 31.6°C. This seasonal and interannual variability is strongly influenced by the Indonesian Throughflow, which regulates temperature distribution and indirectly shapes the movement of *E. affinis* toward favorable habitats (Gordon et al. 2019; Putri and Zainuddin 2019; Abudarda et al. 2021; Putri et al. 2021). Given the relatively stable thermal regime of the Makassar Strait compared with temperate regions, even small temperature fluctuations may exert substantial ecological effects on species distribution (Istnaeni et al. 2023; Ningsih et al. 2023; Zainuddin et al. 2023).

Seasonal variability in sea surface chlorophyll concentration is shown in Figure 3.B. Chlorophyll concentration ranged from approximately 0.14 to 0.7 mg m⁻³ during January and February, with higher values observed along the eastern coast of Kalimantan, likely driven by terrestrial nutrient inputs (Syahdan et al. 2014). Concentrations increased to around 0.6 mg m⁻³ during March and April, coinciding with warming temperatures and enhanced nutrient availability. Higher chlorophyll concentrations were consistently observed in the southern Makassar Strait, possibly influenced by monsoonal circulation and nutrient-rich waters originating from the Kalimantan coast. This pattern is consistent with findings by Hanansyah et al. (2024), who reported increased phytoplankton growth associated with river runoff during the west monsoon.

From May to June, chlorophyll concentrations increased further, ranging from 0.49 to 0.94 mg m⁻³, likely reflecting nutrient enrichment associated with monsoon-driven processes (Utama et al. 2017; Wijaya et al. 2020). In July and August, concentrations declined to between 0.29 and 0.68 mg m⁻³, potentially due to reduced upwelling and cooler surface waters. A marked decrease occurred during September and October, followed by low values from November to December. Time-series analysis revealed greater variability in chlorophyll concentration compared with temperature and salinity, with episodic peaks during 2021 and 2022 and reduced levels in early 2020 and late 2023. These fluctuations likely reflect complex interactions among seasonal circulation, terrestrial inputs, and broader oceanographic processes (Atmadipoera and Widyastuti 2014; Utama et al. 2017; Triyulianti et al. 2023). As chlorophyll concentration serves as a proxy for phytoplankton biomass, these variations directly influence prey availability for *E. affinis*.

Table 1. Anova test of oceanographic parameters

Oceanographic parameters	F	P value
SST	49.7	2.47e-08
SSC	10.9	0.000377
SSS	3.8	0.0311

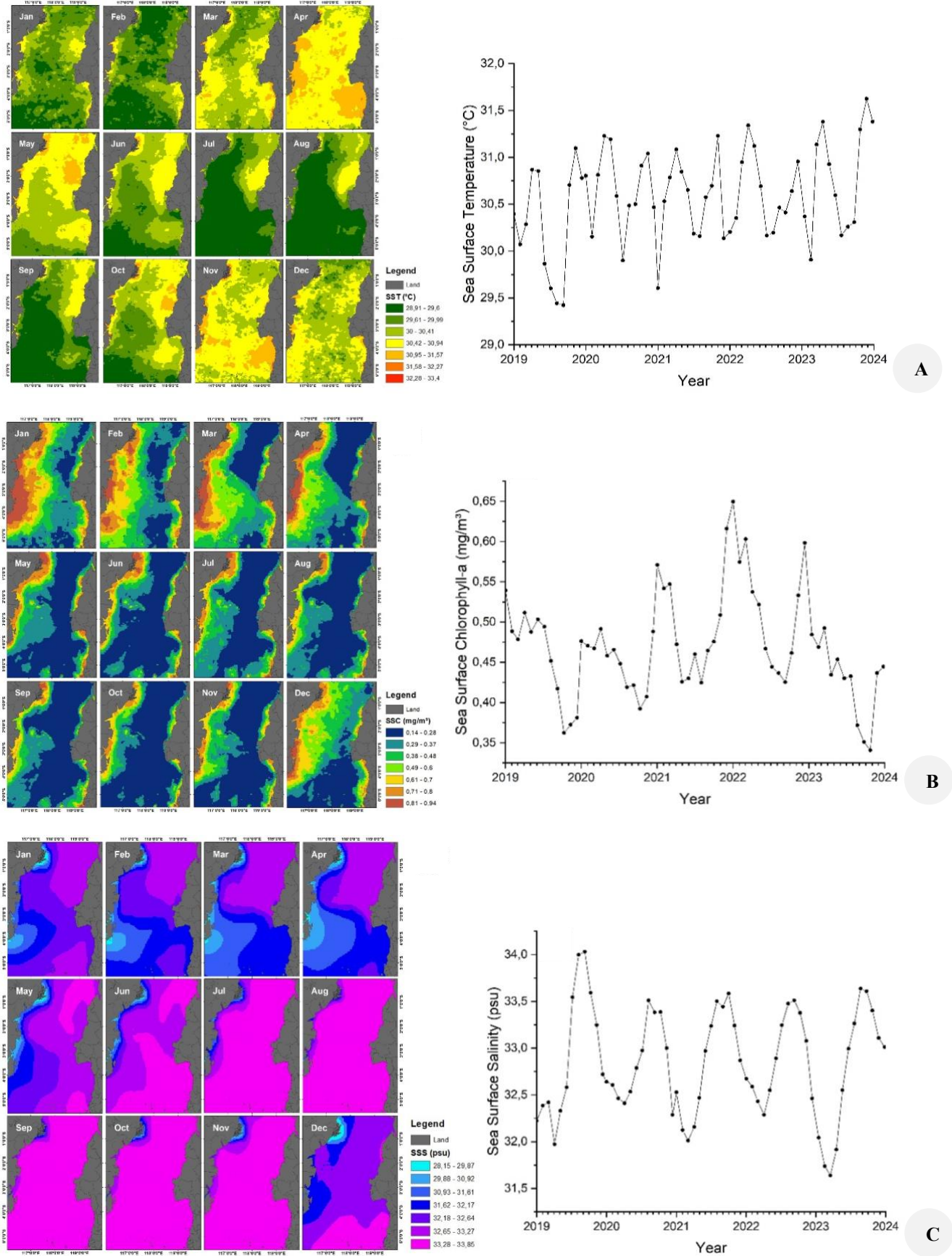


Figure 3. Maps showing spatial distribution of average oceanographic parameters in the Makassar Strait from January to December 2019-2023 and corresponding monthly mean time series. A. SST, B. SSC, C. SSS

Spatial patterns of sea surface salinity are shown in Figure 3.C. During January and February, salinity ranged from 28.15 to 30.92 psu, reflecting increased rainfall and freshwater runoff. Salinity increased during March and April to values between 29.88 and 32.17 psu as rainfall decreased, creating conditions favorable for adult *E. affinis*. High salinity conditions persisted from May to June, followed by a decline during September and October with the onset of the rainy season. Time-series analysis showed salinity values ranging from 31.64 to 34.03 psu, with a pronounced peak in late 2019 and a notable low event in mid-2023. These cycles reflect monsoon-driven precipitation patterns and variability in the Indonesian Throughflow (Atmadipoera and Widyastuti 2015; Lu et al. 2023). The consistency of these patterns suggests predictable seasonal changes in water mass characteristics that influence habitat suitability for *E. affinis*, which exhibits preferences for specific salinity ranges that optimize physiological performance (Yunus et al. 2019).

This study provides a descriptive assessment of *E. affinis* habitat preferences based on seasonal variability represented by four selected months. The analysis does not capture continuous monthly dynamics or fully represent interannual variability and should therefore be interpreted as indicative of seasonal patterns within the observation period. Future research incorporating longer and more continuous time series of occurrence data is recommended

to better resolve interannual trends and long-term habitat dynamics.

Relationship between *Euthynnus affinis* CPUE and oceanographic parameters

The relationship between *E. affinis* catch data and sea surface temperature indicates that higher CPUE values generally occur at lower temperature ranges, with a pronounced peak of approximately 6,736 individuals per set at an average SST of 29.31°C (Figure 4.A). CPUE declines at temperatures around 29.9°C and subsequently stabilizes at moderate levels of approximately 400 to 500 individuals per set within the range of 30.55 to 31.79°C. These patterns indicate a clear association between catch rates and thermal conditions, suggesting that waters near 29°C represent favorable habitat for *E. affinis* in the Makassar Strait. This observation is consistent with previous studies reporting that eastern little tuna preferentially occupy warm surface waters, particularly within an SST range of 29 to 30°C (Puspita et al. 2023). The persistence of moderate catch rates at higher temperatures indicates thermal tolerance rather than optimal preference. Notably, the dominance of SST identified in the MaxEnt model aligns with the CPUE-based patterns, with both approaches indicating a similar thermal window that supports the aggregation and availability of *E. affinis* in the Makassar Strait (Putri et al. 2022; Puspita et al. 2023).

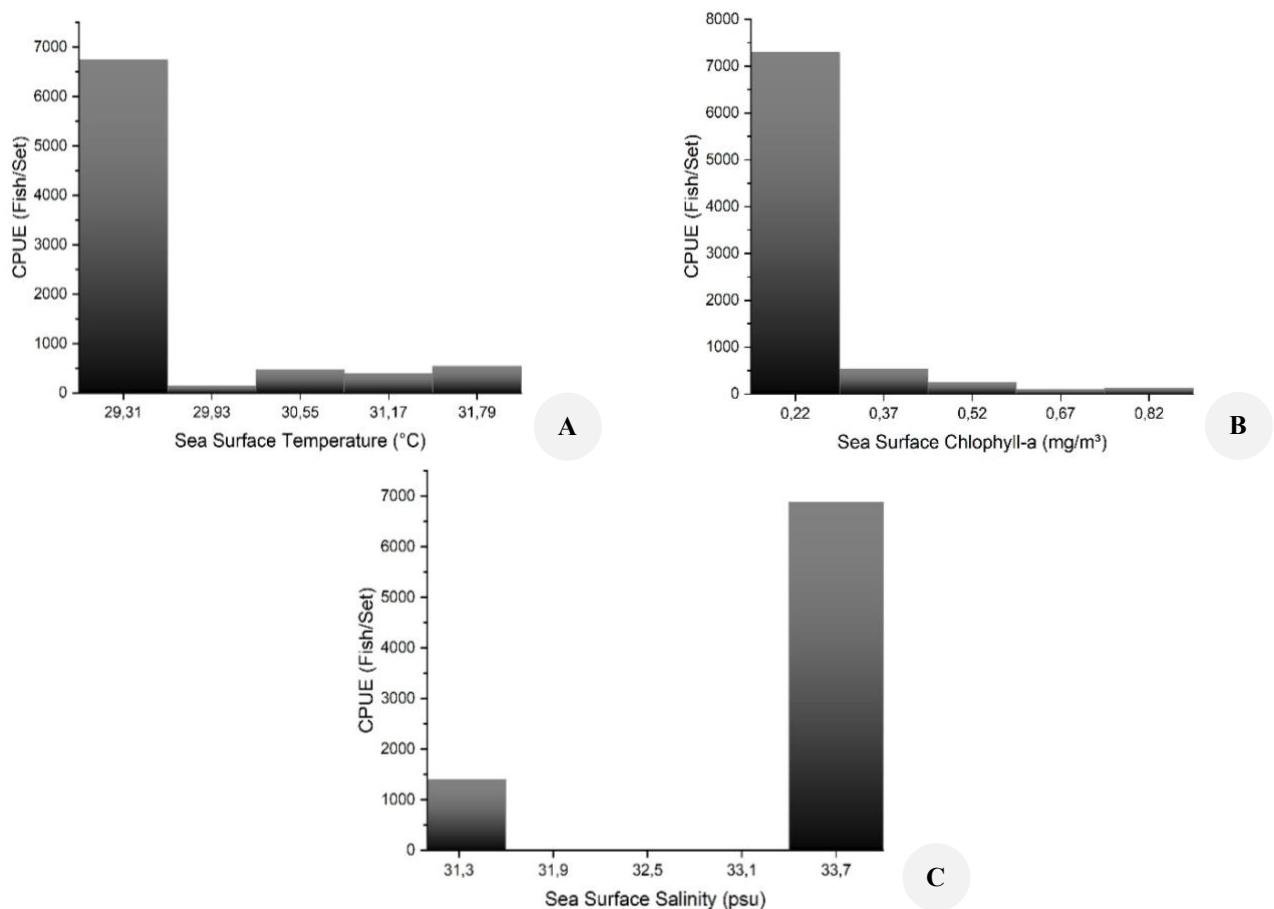


Figure 4. Relationships between oceanographic parameters with *Euthynnus affinis* catch data. A. SST, B. SSC, C. SSS

The relationship between CPUE and sea surface chlorophyll concentration shows that the maximum CPUE, approximately 7,300 individuals per set, occurs at the lowest observed chlorophyll concentration of 0.22 mg m⁻³ (Figure 4.B). Catch rates decrease sharply as chlorophyll concentration increases. While earlier studies have reported optimal chlorophyll ranges for *E. affinis* between 1 and 2 mg m⁻³ (Puspita et al. 2023), the present results suggest that, in the Makassar Strait, *E. affinis* may be associated with relatively oligotrophic surface conditions. This pattern implies that prey aggregation processes, such as frontal zones or localized productivity hotspots, may be more influential than uniformly high background productivity in determining catch rates.

The relationship between CPUE and sea surface salinity is shown in Figure 4.C. The highest CPUE, approximately 6,876 individuals per set, occurs at a salinity of 33.7 psu, with a secondary peak of about 1,400 individuals per set at a lower salinity of 31.3 psu. These results indicate that higher catch rates are generally associated with more saline waters, while the secondary peak may reflect transitional or mixed water masses influenced by freshwater input. This

pattern is consistent with findings by Syamsuddin et al. (2023), who reported elevated CPUE values when sea surface salinity ranged between 34 and 34.5 psu.

It is important to note that CPUE was not incorporated as an input variable in the MaxEnt habitat suitability modeling. The MaxEnt analysis was conducted exclusively using presence-only occurrence records in combination with satellite-derived oceanographic parameters. The CPUE analysis was performed independently and is intended solely to provide descriptive ecological context for the observed habitat patterns. Consequently, the relationships between CPUE and environmental variables should not be interpreted as direct drivers of, or as validation for, the MaxEnt predictions. Instead, these relationships represent complementary ecological observations that aid interpretation of habitat suitability patterns. The spatial correspondence between higher CPUE values and areas predicted as highly suitable by the MaxEnt model likely reflects a shared response to underlying oceanographic gradients, rather than a direct validation of model outputs, thereby strengthening the ecological interpretation of the modeled habitat distribution (Phillips et al. 2006; Jiménez-Valverde 2012).

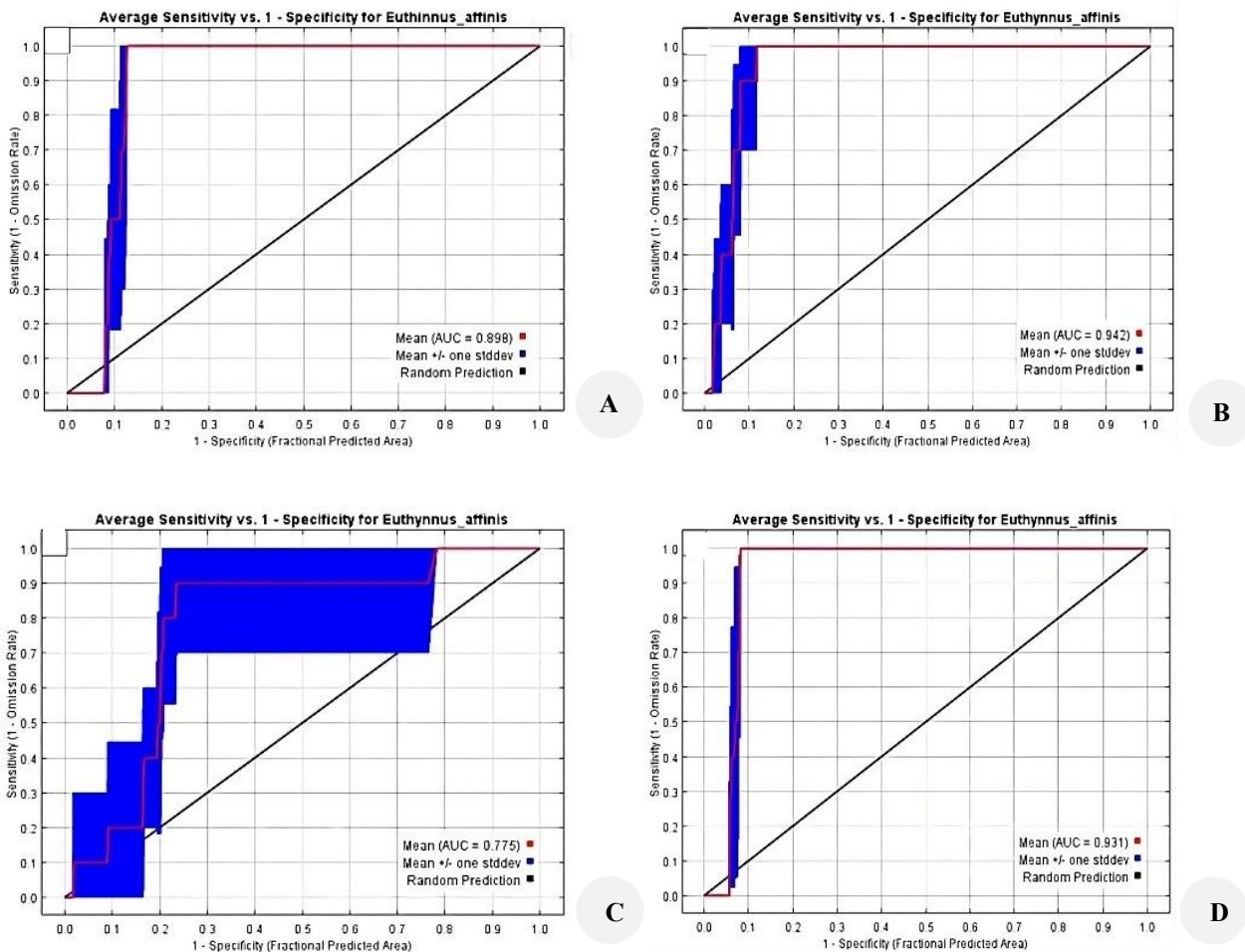


Figure 5. Receiver operating characteristic curve showing MaxEnt model performance for A. March, B. April, C. July, and D. August

Maxent model prediction of habitat suitability for *E. affinis*

Building on the observed seasonal contrasts in oceanographic conditions, habitat suitability for *E. affinis* was modeled using month-specific occurrence data. All four evaluated models (A-D) performed substantially better than random expectation, as indicated by receiver operating characteristic curves positioned well above the diagonal reference line (Figure 5). Models B and D showed excellent predictive performance, with area under the curve (AUC) values of 0.942 and 0.931, respectively, indicating high discriminatory ability. Model A also demonstrated strong performance with an AUC of 0.898, whereas Model C yielded a lower AUC of 0.775, reflecting only moderate predictive capacity and suggesting reduced model robustness during this period (Figure 5.C). The relatively narrow blue-shaded confidence envelopes surrounding the ROC curves for Models A, B, and D, representing standard deviations across replicate runs, further indicate stable and reliable model predictions. These results highlight the importance of seasonally explicit modeling for migratory pelagic species such as *E. affinis*, whose habitat associations vary across monsoonal phases (Jiménez-Valverde 2012).

Jackknife tests of variable importance (Figure 6) further elucidate the seasonal influence of environmental drivers on habitat suitability. During March, sea surface temperature emerged as the most influential variable, yielding the highest training gain when used alone, while sea surface salinity and chlorophyll concentration contributed comparatively less (Figure 6.A). In April, sea surface temperature again dominated model performance, with chlorophyll concentration showing a notable but lower contribution (Figure 6.B). In contrast, during July, sea surface salinity became the primary driver, exhibiting the highest gain when used independently, while the importance of chlorophyll concentration increased relative to earlier months and temperature retained a secondary influence (Figure 6.C). In August, sea surface salinity remained the most influential variable, although both temperature and chlorophyll concentration also contributed meaningfully to model performance (Figure 6.D). These patterns demonstrate the dynamic nature of environmental controls on *E. affinis* distribution and reinforce the need for seasonally adaptive habitat suitability modeling approaches (Nababan et al. 2016; Syamsuddin et al. 2023).

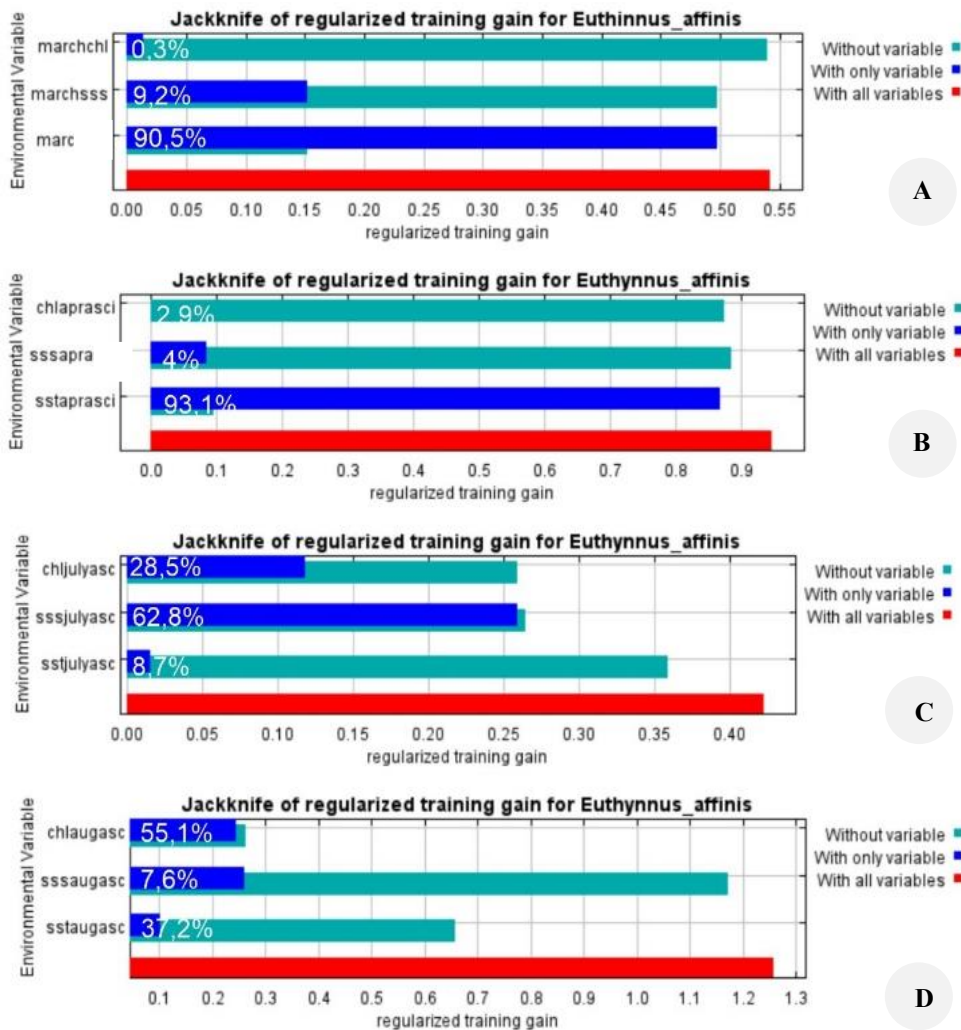


Figure 6. Jackknife analysis of variable importance for habitat suitability of *Euthynnus affinis*

Table 2 summarizes the percent contribution of key oceanographic variables to the habitat suitability models across the study period. On average, sea surface temperature contributed 57.4 percent to model performance, identifying it as the dominant environmental factor influencing *E. affinis* habitat suitability in the Makassar Strait. Sea surface chlorophyll concentration contributed an average of 21.7 percent, while sea surface salinity accounted for 20.9 percent, indicating comparable but slightly lower overall influence. Although jackknife analyses reveal clear seasonal shifts in variable importance, with temperature dominating in March and April, salinity exerting greater influence in July, and chlorophyll concentration contributing strongly in August, the aggregated results indicate that temperature remains the primary driver of habitat suitability at the annual scale. These findings are consistent with previous studies demonstrating the central role of temperature in shaping the distribution of pelagic fish species, including *E. affinis* (Putri et al. 2022; Syamsuddin et al. 2023).

Habitat suitability prediction for *Euthynnus affinis* in the Makassar Strait

The predicted spatial distribution of *E. affinis*, overlaid with observed catch locations represented by white circles (fish per set), shows a strong correspondence between model outputs and actual fishing data, particularly during July and August, when catch points are concentrated within areas of high habitat suitability in the southern Makassar Strait (Figure 7). This spatial agreement indicates that the MaxEnt model effectively captured the key environmental conditions influencing the distribution of *E. affinis* (Phillips et al. 2006).

During March and April, the model predicts moderate to high habitat suitability primarily in coastal regions, especially along the eastern and southern parts of the Makassar Strait. In March, moderate suitability dominates, with localized patches of high suitability along the western coastal zone, while the eastern boundary also exhibits limited areas of high suitability. In April, overall habitat suitability declines, with low suitability values prevailing across much of the central strait. Nevertheless, zones of high suitability persist in the southern sector of the study area, particularly around 4°S on the eastern side and in select coastal regions.

A marked increase in habitat suitability is observed in July, when extensive high-suitability zones emerge in the southwestern Makassar Strait, particularly between 4 and 5°S. This region consistently exhibits high suitability across multiple months, suggesting that it may function as a critical habitat for *E. affinis* irrespective of seasonal variability. Such persistence is likely associated with relatively stable oceanographic features, including frontal zones and mesoscale eddies, which promote prey aggregation. In August, habitat suitability becomes more spatially constrained compared to July, with a reduction in overall suitable area; however, distinct hotspots of high suitability remain concentrated in the southern part of the strait around 4 to 5°S. The negative relationship between CPUE and increasing SSC further supports the MaxEnt

prediction of higher habitat suitability under relatively low-SSC conditions, indicating that prey aggregation processes, rather than elevated background productivity, may regulate the distribution of *E. affinis* in the region (Puspita et al. 2023; Syamsuddin et al. 2023).

Table 2. Monthly percentage contribution of oceanographic variables to the MaxEnt habitat suitability models and corresponding AUC values

Month	SST Contribution (%)	SSC Contribution (%)	SSS Contribution (%)	AUC Value
March	90.5	0.3	9.2	0.898
April	93.1	2.9	4	0.942
July	8.7	28.5	62.8	0.775
August	37.2	55.1	7.6	0.931

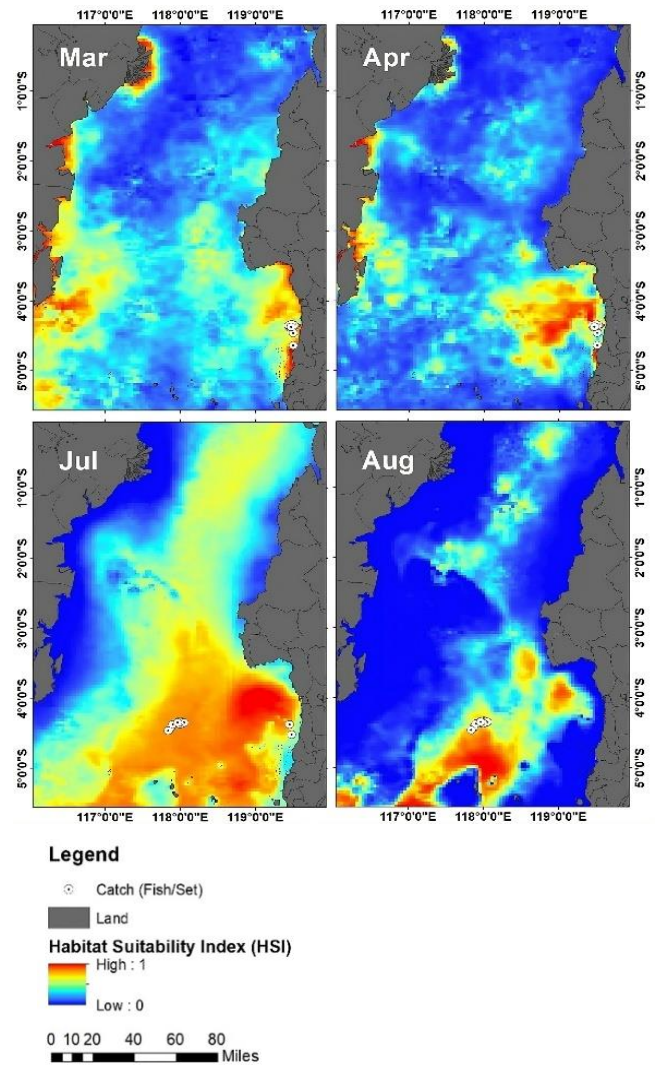


Figure 7. Spatial distribution of predicted *Euthynnus affinis* habitat suitability derived from the MaxEnt model, overlaid with observed fishing locations (white circles)

Despite its overall performance, the analytical model applied in this study has several limitations. These include sensitivity to multicollinearity among environmental predictors and a tendency toward overfitting when regularization parameters are not optimally configured (Syamsuddin et al. 2024). In addition, the model incorporated only three environmental variables. Incorporating additional oceanographic parameters, such as eddy kinetic energy, mixed layer depth, and bathymetric features, would likely improve the robustness and ecological realism of future habitat suitability assessments.

In conclusion, the MaxEnt modeling approach applied in this study demonstrated strong predictive performance, with AUC values ranging from 0.78 to 0.92, confirming its effectiveness in identifying potential habitats of *E. affinis* in the Makassar Strait. Among the environmental predictors, sea surface temperature exerted the strongest influence on habitat suitability, followed by sea surface chlorophyll-a concentration and sea surface salinity. The most suitable habitat zones were consistently identified in the central to southern parts of the Makassar Strait, particularly between 4 and 5°S. However, several limitations should be acknowledged. The analysis relied on only three oceanographic variables and was based on field observations spanning a four-month period, which may not adequately capture interannual variability or longer-term environmental dynamics. Despite these constraints, the findings provide valuable insights for fisheries management and spatial planning. First, the southern Makassar Strait should be considered a priority area for conservation and for the strategic allocation of fishing effort. Second, the implementation of real-time monitoring systems that integrate sea surface temperature and chlorophyll-a data could assist fishers in adapting their fishing strategies more efficiently. Finally, future research should incorporate additional environmental drivers, including ocean currents, bathymetry, and eddy dynamics, and should be based on longer temporal datasets to enhance model reliability and ecological interpretation.

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