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Spatial and Temporal Analysis of Scad Fish (*Decapterus* spp.) Catches in the Sulawesi Sea in Relation to Oceanography Parameters Using a Generalized Additive Models

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ABSTRACT

Accurate identification of fishing grounds (FG) is essential for optimizing the catch of scad fish, which are highly influenced by dynamic oceanographic factors. This study aims to analyze the spatial and temporal patterns of scad fish catches in the Sulawesi Sea, employing sea surface temperature (SST) and chlorophyll-a (CHL) concentration parameters via the generalized additive models (GAM). SST and CHL data were obtained from Aqua MODIS satellite imagery (January–December 2022). Meanwhile, data on scad catches were collected from 85 sampling points via the Tumumpa coastal fishing port office in Manado. The results show that scad catches were significantly influenced by SST (non-linear relationship, optimum at 29.50–30.00 °C) and CHL (positive linear relationship). The peak catches (2.78–4.96 tons) occurred in coastal areas (area 3) during March–May with SST and CHL ranging from 29.79– 30.40°C and 0.19–0.24mg/ m³, respectively. Offshore areas yielded lower catches due to suboptimal SST and CHL. The results demonstrate the potential of satellite-derived environmental variables to enhance the precision of FG predictions and contribute to more informed fisheries management practices. These findings support ecosystem-based fisheries management and real-time ocean monitoring through satellite data integration to enable adaptive and sustainable decision-making.

INTRODUCTION

The Sulawesi Sea, a crucial segment of the Indonesian Throughflow that connects the Pacific and Indian Oceans, plays an essential role in regional oceanographic dynamics. Characterized by strong water mass exchange, seasonal upwelling, and nutrient enrichment, this sea supports high primary productivity that sustains pelagic ecosystems. Such oceanographic features create favorable conditions for various pelagic species, including mackerel, skipjack, tuna, and scads (*Decapterus* spp.), making the Sulawesi Sea one of Indonesia's most productive fishing grounds and potential spawning habitats **(Gordon *et al*., 2010; Amri *et al*., 2015)**.

The scad fish (*Decapterus* spp.) fishery represents a vital socio-economic asset for coastal communities in North Sulawesi Province. Beyond its importance as a staple protein source, scad contributes significantly to local livelihoods through artisanal and commercial fisheries. It also supports value-added industries producing shredded fish, fish balls, and natural flavor enhancers that serve as alternatives to monosodium glutamate (MSG) **(Chairita *et al*., 2019; Kasmiati *et al*., 2020; Fauziah *et al*., 2021)**. Therefore, the sustainable management of this resource is essential not only for maintaining marine ecosystem balance but also for ensuring long-term food security and economic resilience in the region. Given the socio-economic importance of scad for coastal communities, improving the accuracy of fishing ground identification is essential, thereby necessitating the use of oceanographic indicators and remote sensing approaches.

Remote sensing technology offers a valuable approach for enhancing the precision of FG identification by enabling the continuous monitoring of key oceanographic parameters, such as sea surface temperature (SST) and chlorophyll-a concentrations **(Maulina *et al*., 2019; Hatidja *et al*., 2023)**. Sea surface temperature (SST) and chlorophyll-a (CHL) are critical determinants of the spatial and temporal distribution of fish populations, since they serve as indicators of environmental conditions that underpin marine ecosystem productivity and habitat suitability **(Sachoemar *et al*., 2012; Nghia & Hung, 2018; Istnaeni & Zainuddin, 2019; Hidayat *et al.*, 2021; Putri *et al.*, 2021; El-Gharbawy *et al*., 2024; Katiandagho *et al.*, 2024; Titaley *et al*., 2024)**. SST influences the thermal habitat suitability for fish species, which typically exhibit specific optimal temperature ranges that support their physiological functioning, including growth, reproduction, and survival **(Safruddin, 2013; Paillin *et al.*, 2020; Putri *et al.*, 2021; Hatidja *et al*., 2023; El-Gharbawy *et al.*, 2024)**. Meanwhile, CHL acts as an indicator of aquatic fertility because it reflects the concentration of phytoplankton as it mirrors the abundance of phytoplankton, which are the primary producers in the aquatic food web **(Daris *et al*., 2021; Putri *et al*., 2021; El-Gharbawy *et al*., 2024**). Consequently, advancing the understanding of these oceanographic indicators is fundamental to improving spatial predictions of fishing grounds in the Sulawesi Sea**.**

Despite the Sulawesi Sea's recognized high potential for fisheries, oceanographic research utilizing remote sensing data in this area remains comparatively scarce. Several prior investigations have explored the correlation between oceanographic variables and fish catch volumes in the Sulawesi Sea, such as determining the status of tuna fishing utilization and effort in North Bolaang-Mongondow waters **(Kekenusa *et al.*, 2019)**; the relationship between El Niño Southern Oscillation (ENSO) and oceanographic parameters in North Sulawesi waters **(Lasut *et al.*, 2021)**; the amount of pelagic fish catch in Sangihe Islands Regency **(Saselah & Manu, 2022)**; and the temporal distribution of scad catches with sea surface temperature (SST) in the region **(Hatidja *et al*, 2023)**. No prior research has been found that specifically investigates the spatial and temporal effects of sea surface temperature (SST) and chlorophyll (CHL) on scad catches. As a result, this study aims to analyze the spatial and temporal patterns of scad catches in the Sulawesi Sea, employing SST and CHL parameters via the generalized additive models (GAM).

MATERIALS AND METHODS

1. Study area

The research was conducted in the Sulawesi Sea, Indonesia, an area demarcated by longitudes 122°E to 126°E and latitudes 1.5°N to 4°N. Data were collected at 85 sampling sites, the coordinates of which were provided by the Tumumpa coastal fishing port office in Manado, Indonesia. The specific locations of these 85 sampling points are illustrated in Fig. (1).

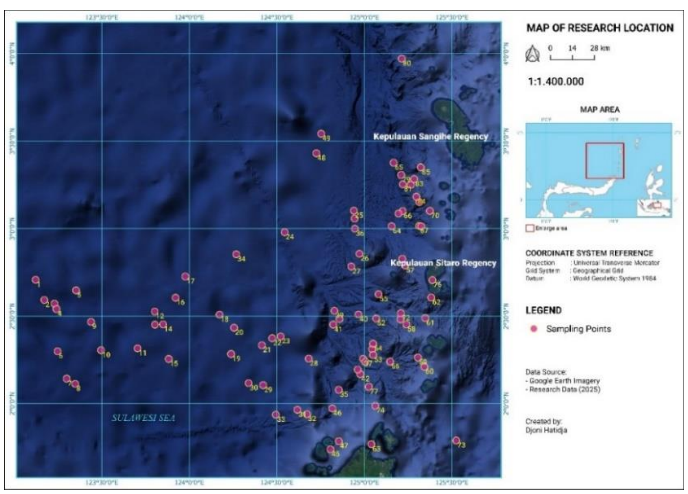


Fig. 1. Research location map

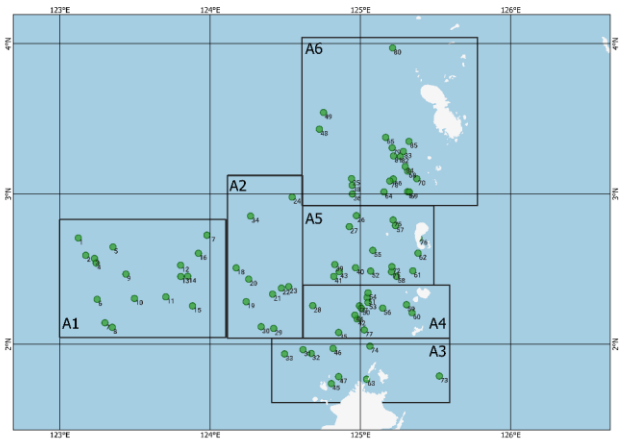


Fig. 2. Spatial map of research location

Furthermore, the 85 sampling points were divided into 6 areas, namely A1-A6 (Fig. 2). The division of areas is based on the closest distance between sampling points as well as ecological division and distance from the coast, consisting of coastal areas, transition areas, and offshore areas. Area 1 (A1) and area 6 (A6) are grouped into the offshore area, area 2 (A2) is grouped into the transition area, and areas 3, 4, and 5 (A3, A4, A5) are grouped into the coastal area. The division of area boundaries can be seen in Table (1).

The division of the area was done to analyze the spatial distribution of SST, CHL and scad catches. Table (1) shows that the number of sampling points for each area is different, so the data used in the spatial analysis does not use the total scad catches, total SST, and total CHL, but uses the average of each area.

Table 1. Research location boundaries

Area	Longitude	Latitude	Number of Sampling Point
Area 1 (Offshore area)	123°0'0" E –24°0'0" E	2°0'0" N –3°0'0" N	17
Area 2 (Tran. area)	124°10'22"E –124°32'43"E	1°56'11" N –2°58'48" N	11
Area 3 (Coastal area)	124°37'4"E –125°31'31"E	1°47'21" N –2°5'46" N	10
Area 4 (Coastal area)	124°40'57"E –125°20'54"E	2°10'7" N –2°29'25" N	17
Area 5 (Coastal area)	124°49'46"E –125°23'20"E	2°30'44" N –3°3'30" N	13
Area 6 (Offshore area)	124°43'35"E –125°22'29"E	3°0'50" N –3°58'19" N	19
		Total	**85**

2. Data collection

2.1. Satellite Data

Sea surface temperature (SST) and chlorophyll (CHL) images were acquired from the Aqua MODIS satellite at level 3 & 4, with a spatial resolution of 4 km × 4 km (per pixel) and temporal resolution of monthly images from January 2022 to December 2022.

These images were obtained from the official NASA Ocean Color website: http://oceancolor.gsfc.nasa.gov/. The data were downloaded in NetCDF (nc) format as image files. Each SST and CHL image was processed using the SEADAS software to extract numerical SST or CHL data corresponding to the study area. The output numerical data from SEADAS were saved in CSV format, which can be easily read and analyzed using Microsoft Excel software **(Hatidja *et al*., 2023)**.

The SST and CHL values extracted and saved in MS Excel files encompass thousands of data points. These data were subsequently correlated with the sampling points procured from the Tumumpa coastal fishing port (Fig. 1). The correlation between the sampling points and the data points in the images was established by identifying the nearest distance between them. This process, known as point matching, utilizes the Haversine method, which is delineated as follows **(Nabilla *et al*., 2023)**:

$$d = 2r.arcsin\left(\sqrt{sin^2\left(\frac{\Delta\emptyset}{2}\right) + \cos(\emptyset_1)\cos(\emptyset_2)sin^2\left(\frac{\Delta\lambda}{2}\right)}\right)$$

Where, d: distance between 2 points; ϕ_1, ϕ_2: latitude point 1 and 2 (radian); λ_1, λ_2: longitude point 1 and 2 (radian); $\Delta\phi = \phi_2 - \phi_1$; $\Delta\lambda = \lambda_2 - \lambda_1$; r: radius of the earth (average ≈ 6371 km)

2.2. The Catches of Scad Fish

The scad catch data were obtained from the Tumumpa Coastal Fishing Port (CFP) office in Manado, Indonesia, which serves as a base for field data collection. The dataset comprises the scad catch (in kilograms) recorded at 85 sampling points during the period from January to December 2022.

2.3. Data Analysis

Sea surface temperature (SST) and chlorophyll-a concentration (CHL) data at 85 sampling points were created for spatial and temporal maps1 using QGIS 3.40.5 software. Maps were created for the months of January to December. After that, SST, CHL from 85 sampling points were averaged for each month, while the data on scad catches were summed. Described the SST, CHL and temporal catch of scad in graphical form using MS Excell software.

Performed a one-way anova (analysis of variance) to compare SST across the four seasons. The same was done for CHL and scad catches. The 4 seasons are western season (December to February), first transitional season (March to May), eastern season (June to August) and second transitional season (September to November). The one-way ANOVA linear model used is **(Montgomery, 2017)**:

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij} \quad i = 1, 2, 3, 4; \; j = 1, 2, 3$$

Where, Y_{ij} : catch of scad fish/SST/CHL in the *i*-th season and *j*-th month; μ : general average; τ_i : influence of catch of scad fish/SST/CHL in the *i*-th season; ε_{ij}: error term in the *i*-th season and *j*-th month.

Comparison testing between averages was determined using Tukey's test. One way ANOVA was analyzed using SAS OnDemand for Academics (SAS ODA) software.

Determining the correlation between catch of scad fish with SST and CHL was assessed using Pearson correlation **(Hatidja *et al*., 2024)** with the following formula:

$$r = \frac{n\sum_{i=1}^{n} x_i y_i - (\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{\sqrt{(n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2)(n\sum_{i=1}^{n} y_i^2 - (\sum_{i=1}^{n} y_i)^2)}}$$

Where, r: Pearson correlation; x_i: SST/CHL; y_i: catch of scad fish. Pearson correlation was analyzed using R Studio 2024.12.1.

The relationship between SST/CHL and catch of scad fish was tested with the hypothesis:

Ho: There is no significant relationship between SST/CHL and catch of scad fish

H_1: There is significant relationship between SST/CHL and catch of scad fish.

If the *P*-value < α, then reject Ho

To determine the relationship model and the effect of SST and CHL on the catch of scad fish, the generalized additive model (GAM) **(Wood, 2017)** was implemented. The linear model of GAM is:

$$g(\mu_i) = \alpha + f_1(SST) + f_2(CHL) + \varepsilon_i$$

Where, $g(\mu_i)$:spline smooth function; μ_i :the expected value of the catch of scad fish; α: constant coefficient; f_1, f_2 :smooth function of SST and CHL; ε_i :an error term in the *i*-th month. R Studio 2024.12.1 software was used for GAM analysis.

To test the effect of the catch of scad fish on SST/CHL, a test was conducted with the following hypothesis:

H_0: SST/CHL does not significantly affect the catch of scad fish.

H_1: SST/CHL significantly affects the catch of scad fish.

If the *P*-value is α, then reject Ho.

If the value of edf = 1, then the relationship between SST/CHL and catch of scad fish is linear, otherwise if the value of edf > 1, then the relationship is non-linear. Where α: level of significanct; edf: estimated degree of freedom.

The next data analysis is the spatial analysis of scad fish catch, SST and CHL. In the spatial analysis, the data used is the average catch of scad fish from each area. Spatial analysis is described using Heatmap plot. Heatmap plot is a data visualization that displays values in the form of colors in a two-dimensional area that describes the catch of scad fish/SST/CHL from area 1 to area 6 from January to December. Heatmap plot were created using Python 3.12.3 software.

RESULTS AND DISCUSSION

1. Temporal distribution of sea surface temperature (SST)

In the Sulawesi Sea, the minimum sea surface temperature (SST) was recorded in February at 29.14°C, whereas the maximum SST was observed in November at 30.62°C. These findings align with the results reported by **Lasut *et al*. (2022)** and **Hatidja *et al.* (2023)**. SST generally decreases from January to February, coinciding with the west season. However, it shows an increasing trend from March to November 2022, with a slight decline in December as the west season commences (Fig. 3). A similar pattern is depicted in Fig. (4), where the color intensity of the map indicates SST levels: redder hues signify higher SST, while bluer tones represent lower SST. In February, the average SST was at its lowest, as evidenced by the predominantly blue map.

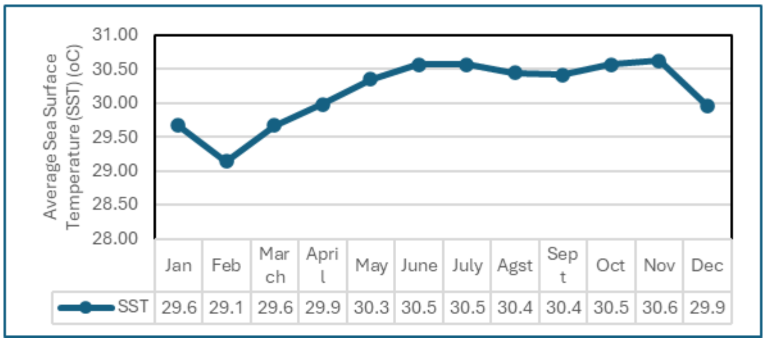


Fig. 3. Sea surface temperature (SST) per month (^{0}C) in the Sulawesi Sea in 2022

Table (2) indicates that the minimum sea surface temperature (SST) occurs during the west season (W) and subsequently rises until the second transitional season (ST). The SST in the second transitional season (ST) is significantly higher than that in the west season (W), yet it does not exhibit a significant difference compared to the east season (E) and the first transitional season (FT).

During the west season (W), which spans from December to February, the southwesterly monsoon winds drive cooler surface waters into the Sulawesi Sea, thereby lowering the SST. From March to May, the Sulawesi Sea transitions into the first transitional season (FT), bridging the gap between the west season (December–February) and the east season (June–August). During this first transitional season (FT), alterations in wind direction and intensity have a notable impact on the distribution of sea surface temperatures, as documented by **Yusuf *et al.* (2022)**. In the second transitional season (ST), the monsoon winds weaken, leading to a reduction in upwelling and a subsequent increase in sea surface temperatures. Research by **Andeleu *et al.* (2019)** has demonstrated that during the second transitional season, the sea surface level (SPL) tends to be higher than in the east season due to diminished upwelling processes.

Table 2. Average SST per season (°C) in the Sulawesi Sea in 2022

Season	(Mean ± St.Dev)	CI 95%
Second Transitional Season (ST)	(30.537±0.103)^{a}	(30.434; 30.640)
East Season (E)	(30.523±0.071)^{a}	(30.452; 30.594)
First Transitional Season (FT)	(30.004±0.341)^{ab}	(29.663; 30.345)
West Season (W)	(29.672±0.536)^{b}	(29.136; 30.208)

Note:Notation with different letters was significant diference between the means (P<0.05) with Tukey Test.

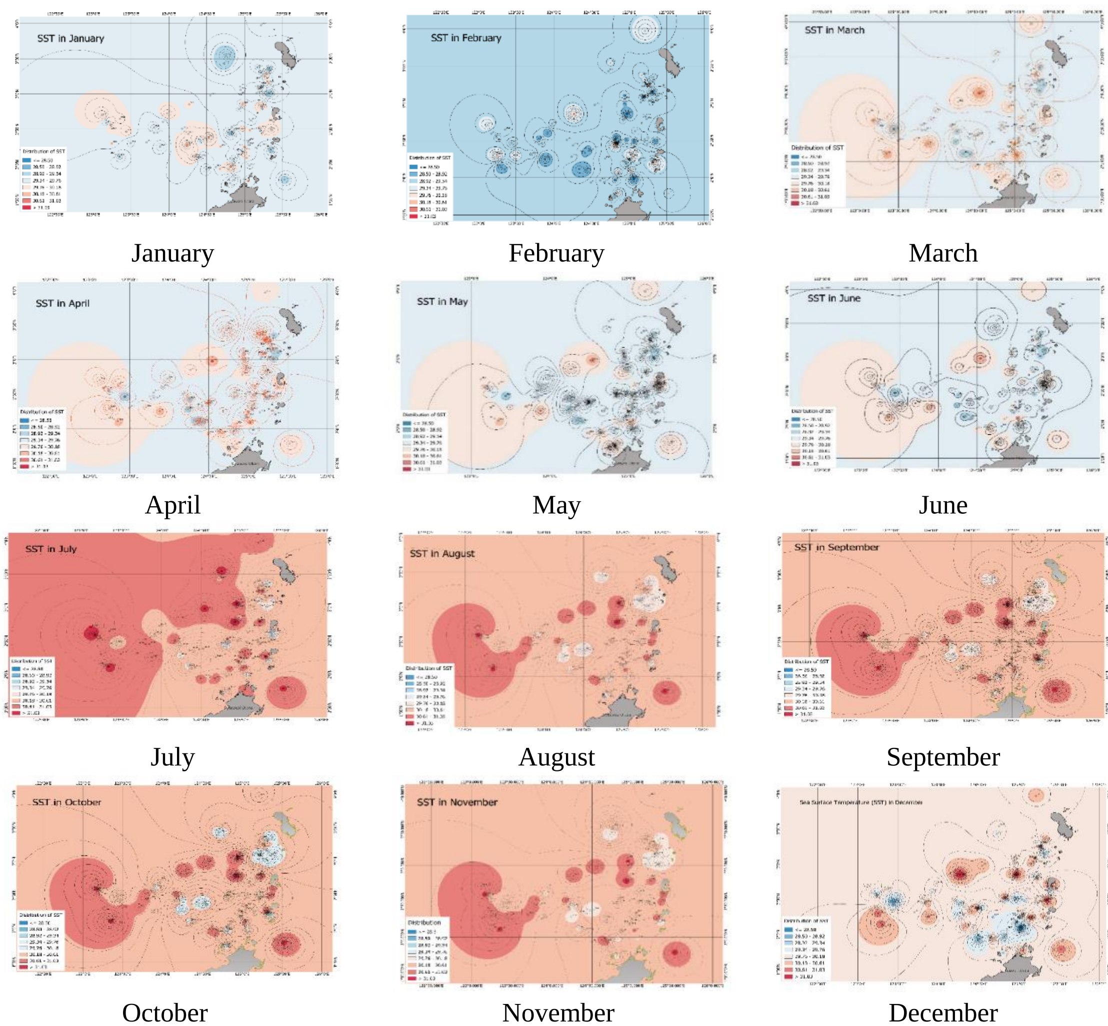


Fig. 4. Spatial and temporal map of sea surface temperature (°C) January-December 2022

The Sulawesi Sea serves as the primary conduit for the influx of water masses from the Pacific Ocean into the Sulawesi Sea region, as noted by **Munandar *et al.* (2021)**. The Pacific Ocean exerts a substantial influence on sea surface temperature (SST) in the Sulawesi Sea, particularly through the dynamics of El Niño and La Niña events, which are integral components of the El Niño-Southern Oscillation (ENSO) circulation system. These phenomena modulate SST in the region by altering Pacific temperatures and influencing the Indonesian Throughflow and seasonal wind patterns, as documented by

Alfiqri *et al.* (2024). La Niña events occur when the eastern Pacific Ocean cools, leading to increased rainfall and a decrease in SST in the Sulawesi Sea. In contrast, during El Niño events, warming in the eastern Pacific results in an increase in SST in the Sulawesi Sea, as reported by **Lasut *et al.* (2021)** and **Puspasari *et al.* (2021)**.

2. Temporal distribution of chlorophyll-a (CHL)

Chlorophyll-a (CHL) is an important indicator of primary productivity in aquatic ecosystems, which usually reflects the presence of phytoplankton. Phytoplankton productivity is influenced by various environmental factors such as light, nutrient availability, temperature, and ocean circulation **(Kunarso *et al.*, 2022)**. Chlorophyll-a concentrations in the Sulawesi Sea varied from 0.088 to 0.176mg/ m^3. The highest average chlorophyll-a concentration occurred in January (0.176mg/ m3) and tended to decrease until October and increased again in November (Fig. 5). Changes in chlorophyll-a concentrations from January to December indicate that there were changes in environmental conditions affecting phytoplankton growth. Similarly, Fig. (6) shows that the map tends to be red. The redder the map, the higher the concentration of chlorophyll-a.

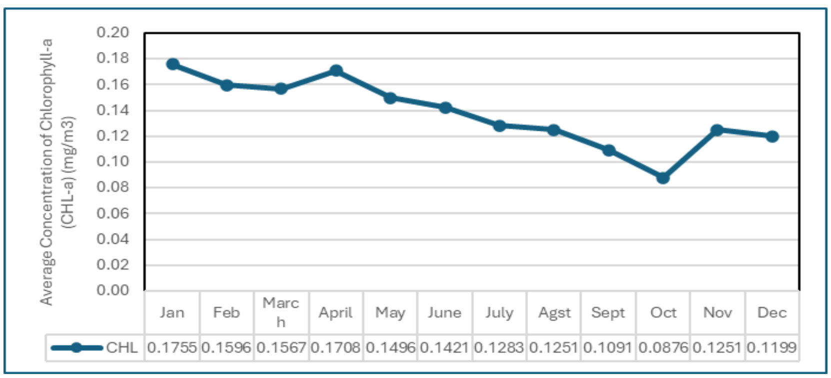
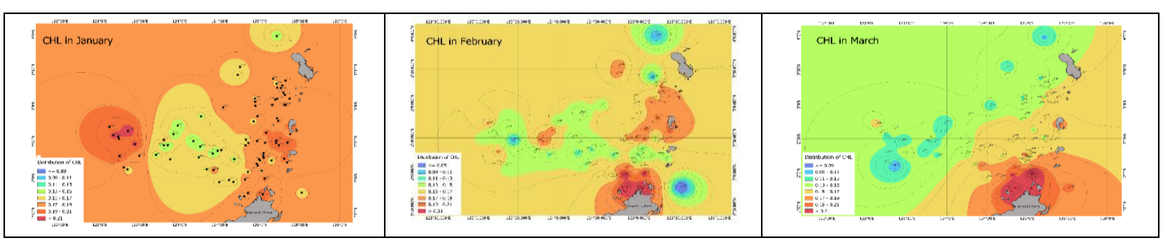
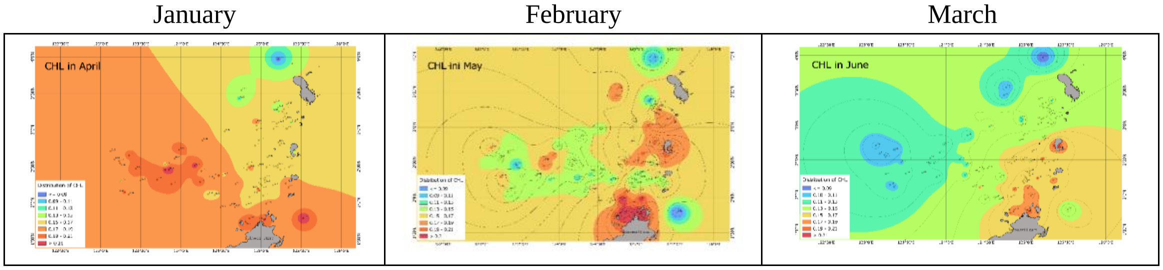


Fig. 5. Concentration of chlorophyll-a (CHL) per month (mg/m^3) in the Sulawesi Sea in 2022



January February March



April May June

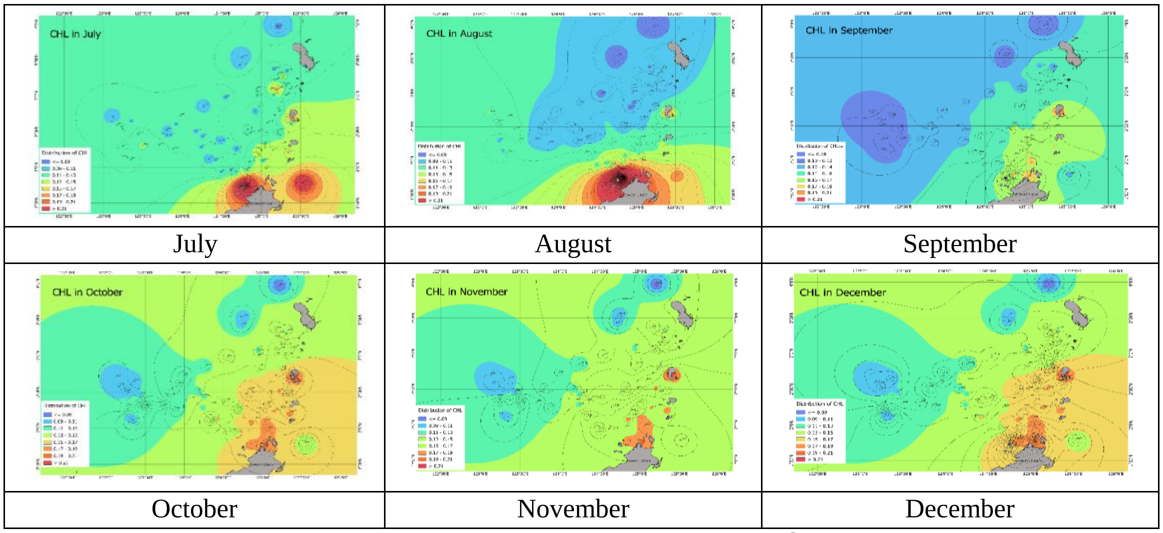


Fig. 6. Spatial and temporal map of chlorophyll-a (mg/m^3) January-December 2022

During the west season (December–February), CHL was higher than during the first transition season (FT), the east season (E), and the second transition season (Table 3). This phenomenon was mainly caused by significant increases in rainfall in the Sulawesi Sea during the west season. High rainfall causes runoff from land to sea, carrying nutrients such as nitrogen and phosphorus that support phytoplankton growth, as indicated by high chlorophyll-a concentrations **(Kunarso *et al*., 2022; Zulfa *et al*., 2024)**. The highest chlorophyll-a concentration occurred in the west season with a concentration of (0.179±0.021) mg/m^3. Chlorophyll-a concentration in the west season was not significantly different from the first transition season, but was significantly different from the eastern season and the second transition season. Chlorophyll-a concentrations in the east season were not significantly different from those in the east and second transition seasons (Table 3).

Table 3. CHL per season (mg/m^3) in the Sulawesi Sea in 2022

Season	(Mean ± St.Dev)	CI 95%
West Season (W)	(0.179±0.021)^a	(0.158; 0.200)
First Transitional Season (FT)	(0.159±0.011)^{ab}	(0.148; 0.170)
East Season (E)	(0.132±0.009)^{bc}	(0.123; 0.141)
Second Transitional Season (ST)	(0.107±0.019)^c	(0.088; 0.126)

Note: Notation with different letters was significant diference between the means (P<0.05) with Tukey Test

3. Temporal distribution of scad fish (*Decapterus* spp.) catches

The total catches of scad fish in the Sulawesi Sea in 2022 tends to vary from 60.73 tons (June) to 141.9 tons (January). Scad fish catches tends to decrease from January to June, but from July to December it tends to increase (Fig. 7).

The average catches of scad fish in the west season (December-February) was not significantly different from the first transitional season and the second transitional season, but significantly different from the average catches in the east season (Table 4).

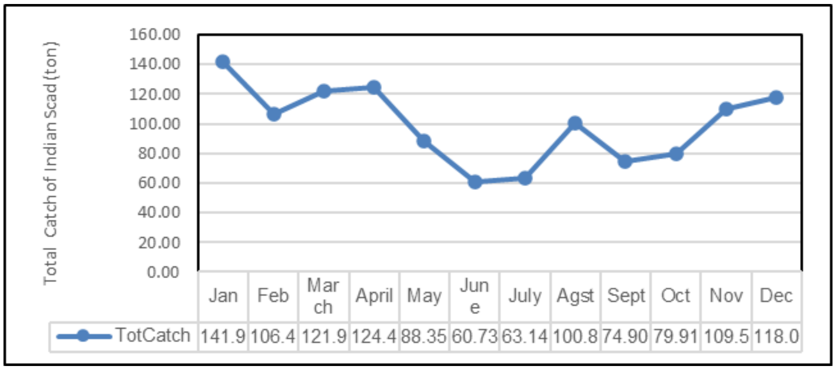


Fig. 7. Total catch of scad fish per month (ton) in the Sulawesi Sea in 2022

Table 4. The average catch of scad fish (ton) in the Sulawesi Sea in 2022

Season	(Mean ± St.Dev)	CI 95%
West Season (W)	(130.068±20.471)[a]	(109.597; 150.539)
First Transitional Season (FT)	(111.593±20.168)[ab]	(91.425; 131.761)
Second Transitional Season (ST)	(88.110±18.706)[ab]	(69.404; 106.816)
East Season (E)	(74.905±22.493)[b]	(52.412; 97.398)

Note: Notation with different letters was significant diference between the means (P<0.05) with Tukey Test

4. Temporal relationship between SPL, chlorophyll-a and scad fish catches

Fig. (8) shows that relatively high SST (more than 30^{0}C) from May to November (East season and second transition season) causes fish to migrate to cooler locations, resulting in low scad fish catches in both seasons. Changes in SST may allow fish to always adapt to SST and to migrate from areas that are suitable for their optimum temperature. Therefore, SST can control the presence and distribution of fish **(Kassi *et al*., 2018; Paillin *et al*., 2020)**.

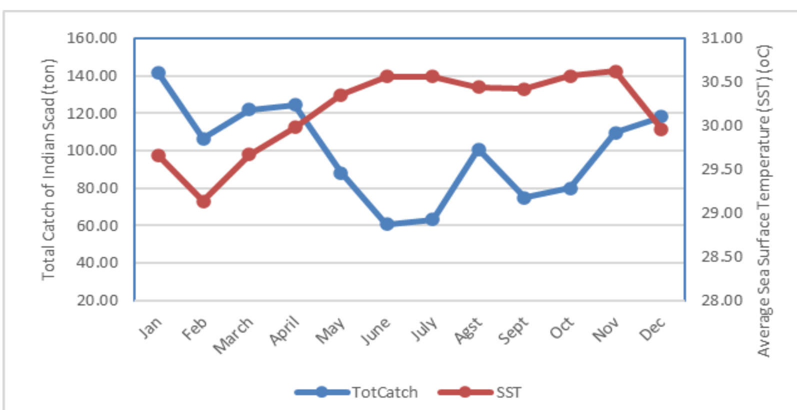


Fig. 8. Relationship between catch of scad fish and sea surface temperature

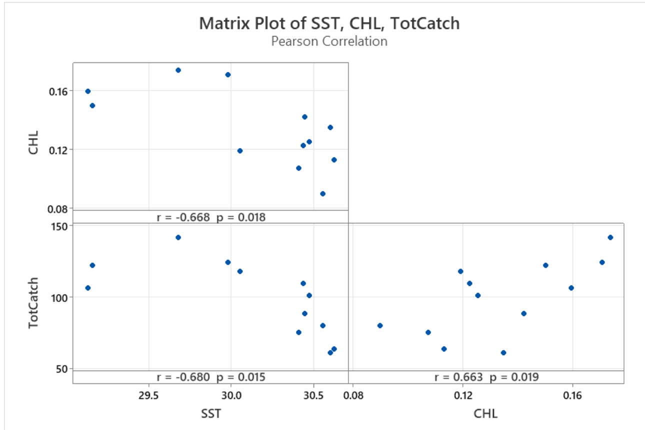


Fig. 9. Correlation between scad fish catch with SST and CHL

Fig. (9) shows that the correlation between SST and scad fish catches is -0.680 with a *P*-value of 0.015 (*P*< 0.05). This indicates a strong negative relationship between SST and scad fish catch, meaning that as SST increases, scad fish catch tends to decrease, and vice versa. The optimal temperature for scad fish in the Sulawesi Sea was determined using GAM analysis.

Table (5) shows the results of GAM analysis of three models, consisting of two models with one predictor variable and one model with two predictor variables. If the EDF = 1, the model is linear; otherwise, if the EDF > 1, the model is nonlinear. The smaller the AIC value and the larger the CDE value, the better the model.

Sea surface temperature (SST) is a significant factor influencing scad fish catch, although it exhibits a non-linear relationship (model 1: edf = 2.355; *P*-value = 0.00118), as detailed in Table (5). Fig. (10) illustrates a quadratic relationship between scad fish catch and SST, with catch volumes increasing within the temperature range of 29.5 to 30°C but declining when temperatures surpass 30°C. This suggests that the optimal temperature range for maximizing scad fish catch is 29.5– 30.0°C. This finding aligns with prior research by **Nelwan (2010)**, **Safruddin (2013)** and **Hatidja *et al.* (2023)**,who reported that the highest scad fish catches occurred at SST ranges of 29.37– 30.88°C, 29.8 °C, and 25.0– 30.0°C, respectively.

Table 5. Results of GAM analysis: Effect of SST and CHL on catch of scad fish

No.	Model	Variable	*P*-value	edf	AIC	CDE (%)
1	SST	Sea Surface Temperature	0.00118**	2.355	98.777	82.6
2	CHL	Chlorophyll-a	0.0188*	1	110.135	43.9
3	SST +	Sea Surface Temperature	0.0265*	2.241	100.688	82.4
	CHL	& Chlorophyll-a	0.6348			

Note: '**':significant with α=0.01; '*':significant with α=0.05; ' ': not significant; edf: estimated degree of freedom; AIC: Akaike Information Criterion; CDE: cumulative deviance explained

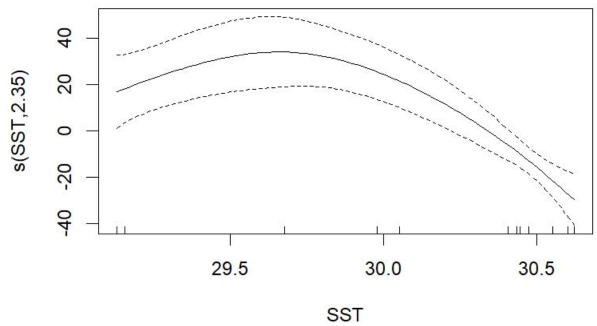


Fig. 10. Pattern of relationship between catch of scad fish and sea surface temperature using GAM analysis

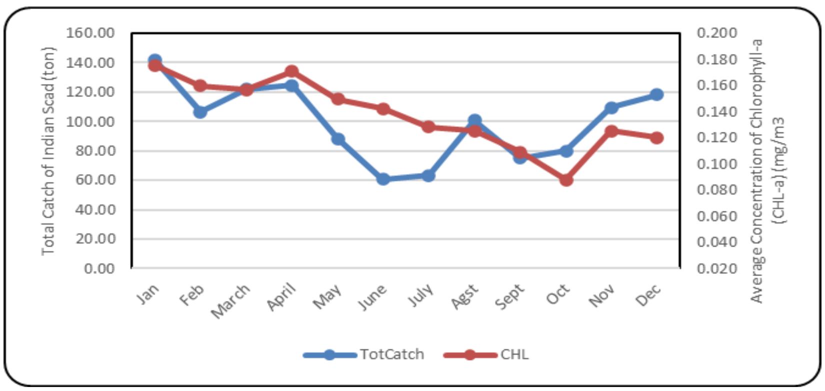


Fig. 11. Relationship between catch of scad fish and chlorophyll-a concentration

Chlorophyll-a concentrations from January to April tended to be high, resulting in higher scad fish catches from January to April (Fig. 11). From May to December, scad fish catches tended to follow the same pattern as chlorophyll-a concentrations. The highest total scad fish catch occurred in January with a chlorophyll-a concentration of 0.176mg/ m^3.

The correlation between the catch of scad fish and chlorophyll-a concentration was 0.663 with a *P*-value of 0.012 (*P*-value < 0.05) (Fig. 9). This indicates a strong positive relationship between chlorophyll-a and scad fish catch. In other words, the higher the chlorophyll-a concentration in the Sulawesi Sea, the greater the scad fish catch (Fig. 11).

The results of the GAM analysis indicate that chlorophyll-a concentration influences the catch of scad fish and has a linear relationship (model 2: edf=1 and *P*-value=0.0188) (Table 5). This result is further clarified by Fig. 12, which shows that the relationship between chlorophyll-a concentration and scad fish catch forms a straight line (linear). Chlorophyll-a serves as the primary indicator of marine ecosystem productivity and is closely associated with phytoplankton biomass, which in turn strongly correlates with fish production **(Hidayat *et al.*, 2021; Putri *et al.*, 2021; Katiandago *et al.*, 2024)**.

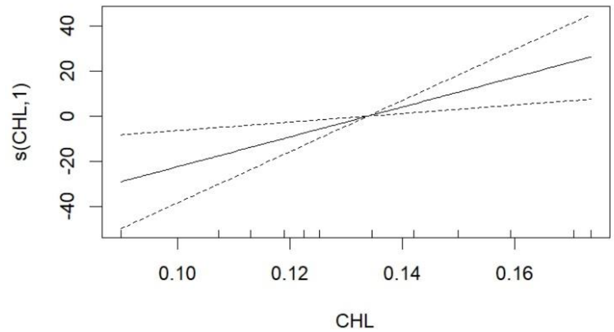


Fig. 12. Pattern of relationship between catch of scad fish and chlorophyll-a concentration using GAM analysis

5. Spatial analysis of scad fish (*Decapterus* spp.) catch and sea surface temperature (SST)

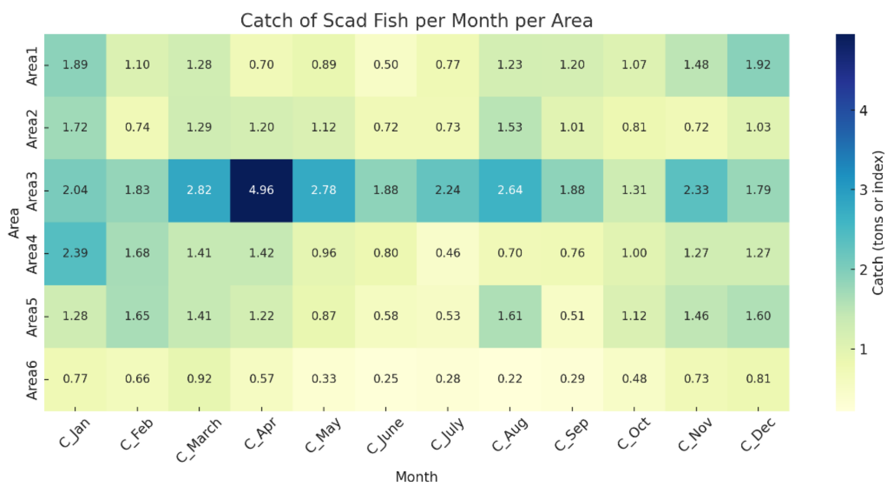


Fig. 13. Heatmap of spatial distribution of catch of scad fish (tons)

The average catch of scad fish in the Sulawesi Sea shows significant variation between areas (Area 1–Area 6), which represent various types of water zoning. Area 3, which is part of the coastal zone, emerges as the most productive area. Throughout the year, particularly in March (2.82 tons), April (4.96 tons), and May (2.78 tons), the catch in this area is significantly higher than in other areas (Fig. 13). This is consistent with the biological characteristics of scad fish (*Decapterus* spp), which generally prefer coastal areas for spawning and feeding, as these waters tend to be shallow, rich in plankton, and protected from strong ocean currents **(Dwiyanti *et al.*, 2022)**. The high consistency of catches in Area 3 makes it a priority zone for fishing activities during peak seasons such as March–May.

On the other hand, areas 4 and 5, which are also classified as coastal zones, show more stable catch results but not as high as Area 3. The average catch of scad fish in Area

4 tends to be lower, especially during the second transition season (June–August), which may be influenced by oceanographic conditions such as the strength of the east wind and rising sea waves. Area 5 showed a spike in catches in August of 1.61 tons and in November of 1.46 tons, which could be related to fish migration dynamics or favorable environmental conditions such as temperature and food availability **(Nghia *et al.*, 2018; Srioktoviana *et al.*, 2024)**. Although these two areas are not as productive as Area 3, they still hold potential for supporting the diversification of fishing locations and require adaptive management.

Meanwhile, areas 1 and 6, which represent offshore zones, showed low and inconsistent catch results. Area 6 was the area with the lowest overall catch, ranging from 0.22 to 0.92 tons throughout the year (Fig. 13). Area 1 was slightly higher but still inefficient compared to coastal areas. Offshore zones typically have greater depths, strong ocean currents, and fewer structures that support the aggregation of small pelagic fish. Therefore, the low catch in this area indicates that it is not the main habitat of catch fish, but rather serves as a migration route **(Buditama *et al*., 2017; Nghia *et al*., 2018; Srioktoviana *et al*., 2024)**. Fishing activities in this area should be restricted or shifted to research and conservation.

Area 2, located in the transition zone between the open sea and the coast, shows fluctuating catch patterns, with average catches that are not very high (0.74–1.72 tons) showing no clear seasonal patterns. This instability reflects complex environmental conditions that are not always conducive to the long-term survival of scad fish. Such transition zones generally have high variability in oceanographic parameters, making them only temporary habitats for pelagic fish (**Safruddin, 2013)**

Overall, this spatial analysis clarifies that coastal areas, especially area 3, have the highest potential to support Scad fishing. This zone needs to be managed sustainably, taking into account the season, ecosystem capacity, and potential fishing pressure. Conversely, offshore areas (areas 1 and 6) with low catch yields should be considered for alternative functions such as conservation zones or non-pelagic fisheries development. Such a zonation-based approach is crucial for ensuring the sustainability of scad fish resources in the future.

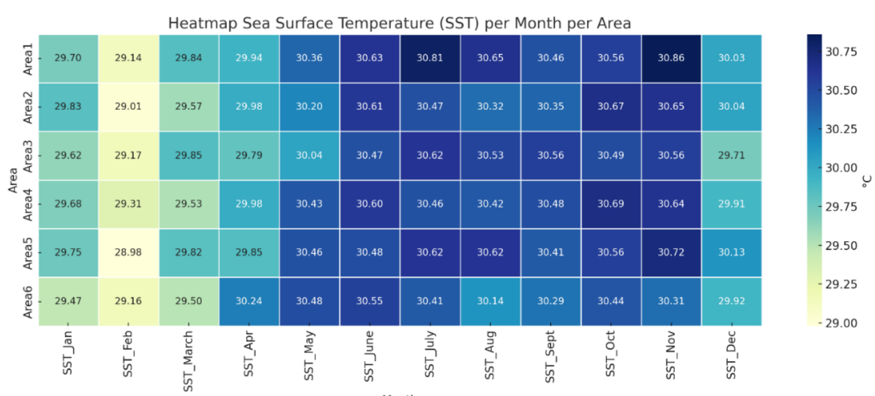


Fig. 14. Heatmap of spatial distribution sea surface temperature (^{0}C) per area

Spatially, the distribution of sea surface temperature (SST) shown in Fig. (14) shows a relatively homogeneous pattern, but a significant difference between coastal and offshore areas. Area 1, which represents the offshore zone, shows quite striking temperature fluctuations. The lowest temperature was recorded in February at 29.14°C, while the highest temperature occurred in November (30.86°C), making area 1 the region with the widest temperature range among all areas (approximately 1.72°C). These fluctuations can be attributed to oceanographic dynamics in the offshore zone, which is more open to the influence of ocean currents, upwelling, and direct solar radiation without the moderating effect of coastal structures. Although temperatures in certain months appear ideal, such thermal instability can disrupt the consistency of pelagic species presence, such as scad fish **(Buditama *et al.*, 2017)**.

On the other hand, area 2, which is the transition zone between the coastal and offshore zones, shows SST patterns similar to area 1 but with slightly narrower fluctuations. Temperatures range from 29.01°C (February) to 30.67 °C (October) (Fig. 14). Although the variation is not as large as in area 1, the inconsistent monthly temperature changes may also contribute to fluctuations in fish distribution, as small pelagic fish are highly sensitive to rapid temperature changes, even as small as 0.5°C (**Safruddin, 2013).**

Coastal areas, namely Area 3, Area 4, and Area 5, exhibit more stable temperature ranges and tend to approach the optimal range for tropical pelagic fish habitats, which is between 29.17 and 30.72°C. Area 3, as the coastal area with the highest fisheries productivity, exhibits highly favorable temperatures throughout the year, with a minimum temperature of 29.17°C (February) and a maximum of 30.62°C (July). This temperature stability significantly contributes to the presence of scad fish in the area, as constant temperatures tend to increase primary productivity (phytoplankton), which forms the foundation of the marine food chain (**Safruddin, 2013)**. Area 4 also exhibits similar temperature stability, with minimal seasonal fluctuations. The monthly average temperature in this area ranges from 29.31°C (February) to 30.69°C (October) (Fig. 14). This indicates that the waters in area 4 are also highly conducive for scad fish biological activity, although catch data from this area are lower, possibly due to anthropogenic factors or different seabed habitats **(Tangke, *et al*., 2020; Kunarso *et al*., 2022)**.

Area 5, although also classified as a coastal zone, shows the lowest absolute temperature among all areas, at 28.98 °C in February, but still rises to the optimal range during other months, especially in November (30.72 °C). The decrease in temperature at the beginning of this year may be the result of local influences such as water intrusion from rivers or seasonal wind cooling effects. Temperatures below 29°C, even for a short period, can affect the migration and feeding patterns of pelagic fish, although this does not always lead to a drastic decline in numbers **(Kassi *et al.*, 2018; Paillin *et al.*, 2020; Siswantoputri *et al*., 2024)**.

Area 6, another offshore zone, exhibits unique temperature patterns. This area did not record extreme temperatures as high as Area 1, but experienced a significant temperature drop in August (30.14 °C), which was one of the lowest SST values during the peak of the tropical summer season. Temperatures in Area 6 show a slight delay in temperature increase compared to other areas, which may be caused by cold underwater currents or local upwelling bringing cooler water masses from deeper layers. Such SST fluctuations impact thermal stratification, which can reduce plankton abundance in the surface layer, thereby indirectly affecting the presence of pelagic fish **(Kunarso *et al.*, 2022)**.

Thus, spatially, it can be concluded that the coastal zone (especially Area 3 and Area 4) has the most stable temperature profile and is closest to the optimal thermal range for catch fish, while the offshore zone shows greater temperature fluctuations and is less ideal for supporting the consistent distribution of this species. This analysis of sea surface temperature is crucial as a basis for planning fishing zone boundaries and determining adaptive fishing calendars in response to climate change.

6. Spatial analysis of scad fish (*Decapterus* spp.) catch and chlorophyll-a concentration (CHL)

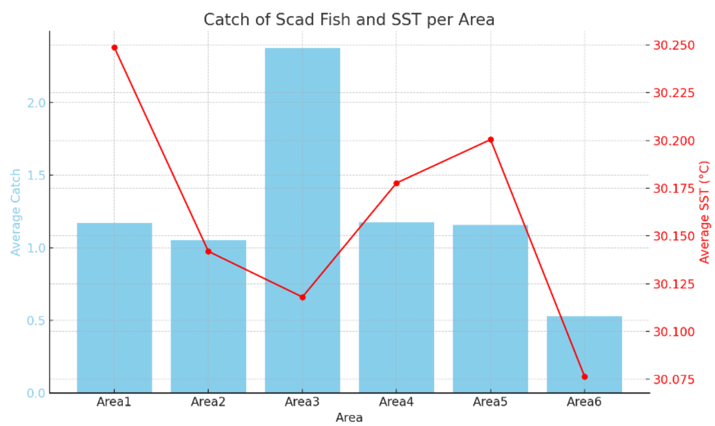


Fig. 15. Relationship between catch of scad fish and sea surface temperature per area

Table 6. Average catch of scad fish, sea surface temperature and chlorophyll-a concentration per area

	CATCH (ton/month)		**SST (°C)**		**CHL (mg/m^3)**	
AREA	**Average**	**StDev**	**Average**	**StDev**	**Average**	**StDev**
1	1.170	0.438	30.249	0.522	0.124	0.033
2	1.052	0.336	30.142	0.494	0.125	0.028
3	2.375	0.930	30.118	0.482	0.186	0.041
4	1.175	0.522	30.178	0.474	0.143	0.029
5	1.156	0.432	30.200	0.514	0.139	0.032
6	0.527	0.249	30.076	0.460	0.123	0.032

Fig. (15) shows that the average catch of scad fish and sea surface temperature

(SST) per area exhibits an interesting and non-linear spatial relationship pattern. Area 3, located in the coastal zone, stands out significantly with the highest catch, averaging above 2.375 tons per month. Uniquely, this area also has the second lowest average SST compared to other areas, around 30.118°C (Table 6). This condition reinforces the hypothesis that scad fish tend to aggregate in areas with slightly warmer but stable sea surface temperatures, which, according to **Siswantoputri *et al*. (2024)**, are optimal conditions for the metabolism and spawning of small pelagic fish such as scad fish.

Conversely, Area 1, which has the highest average SST (30.25°C), shows a much lower catch than Area 3, although it is slightly higher than Area 6 (30.08°C) (Table 6). This is consistent with the findings of **Safruddin (2013)** and **Latifah *et al.* (2024)**, who explained that excessively high SST can cause a decrease in dissolved oxygen levels, reduce plankton availability, and force fish to migrate to cooler or deeper locations. A similar pattern is observed in area 6 (another offshore zone), which has relatively high SST and the lowest catch among all areas, indicating that this zone is less supportive of scad fish presence.

Area 2, which is the transition zone between the coast and offshore, shows sea surface temperatures that are not too fluctuating but remain spatially inconsistent. Although SST in area 2 is within the optimal range, scad fish catches in this area remain low and unstable (0.72-1.72 tons) (Fig. 13). This indicates that thermally suitable SST do not necessarily guarantee the presence of scad fish if other oceanographic factors such as currents and salinity are not supportive **(Nghia *et al.*, 2018; Srioktoviana *et al.*, 2024)**. In this context, Area 2 serves as an example that the relationship between SST and catch is not linear but is influenced by the interaction of multiple environmental factors.

Areas 4 and 5 have similar catch yields, with average SST values also not significantly different, at 30.18 and 30.20°C (Table 6 & Fig. 15). Although the catch is not as high as in Area 3, the stability of SST in these areas is still within the optimal range for pelagic species. However, other oceanographic structures such as depth, local currents, or seabed substrate may also influence fish concentration **(Nghia *et al*., 2018; Srioktoviana *et al*., 2024)**. The fact that Area 4 has slightly higher catch yields than Area 2 despite similar SSTs may indicate the role of other local ecosystem factors in determining fishing success.

Overall, this graph indicates that SST influences the spatial distribution of scad fish, but it is not the only determining factor. The observed trend is that areas with slightly lower SST (around 29.79– 30.04°C) yield higher catch results, especially when located in coastal zones (Fig. 15). This can be attributed to a combination of primary productivity factors, temperature stability, and habitat characteristics suitable for scad fish. Therefore, SST can be used as a supporting indicator in fishing zone planning, but it should be combined with other oceanographic and ecological information for more comprehensive results.

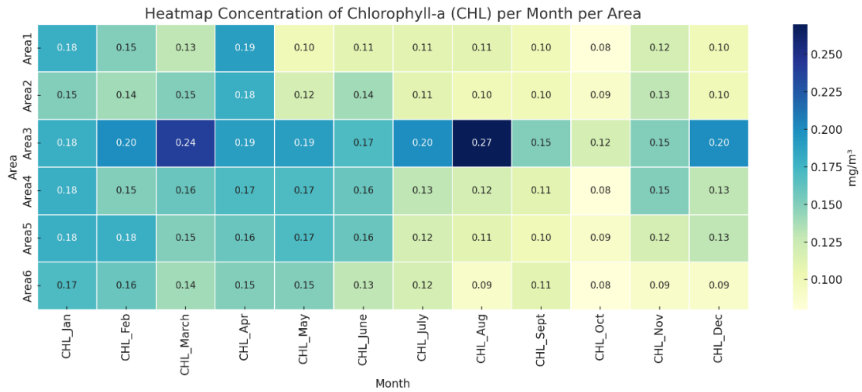


Fig. 16. Heatmap of spatial distribution chlorophyll-a concentration (mg/m^3) per area

The distribution of chlorophyll-a concentration (CHL), which is a key indicator of primary productivity and phytoplankton availability in the ocean, shows striking variations between areas. Area 3, located in the coastal zone, exhibits the highest overall CHL. Peak values were recorded in March (0.24mg/ m^3) and August (0.27mg/ m^3), with monthly averages consistently above 0.19mg/ m^3 throughout the year (Table 6 & Fig. 16). The high CHL in Area 3 indicate that this region has very fertile waters and is a plankton aggregation zone, supporting the abundance of small pelagic fish such as scad fish. According to **Hidayat *et al*. (2021)**, **Putri *et al*. (2021)** and **El-Gharbawy *et al*. (2024)**, chlorophyll-a concentrations are positively correlated with food availability for pelagic fish because plankton is the primary energy source in the marine food chain.

Conversely, Area 6, which is an offshore zone, exhibits the lowest and most stable chlorophyll-a concentrations among all areas. CHL values in Area 6 range from 0.08 to 0.17mg/ m^3, with a decreasing trend from the beginning to the end of the year (Fig. 16). This indicates that Area 6 has very low primary productivity, likely due to deeper waters, minimal nutrient supply from land, and limited upwelling processes that distribute nutrients from the seafloor to the surface. This phenomenon is commonly found in tropical open seas with oligotrophic (nutrient-poor) conditions, where phytoplankton production is limited and directly impacts the low concentrations of pelagic fish **(Buditama *et al*., 2017; Dwiyanti *et al*., 2022)**.

Area 1, which is also classified as an offshore zone, has a pattern similar to Area 6, although slightly more varied. The highest CHL in Area 1 was recorded in April at 0.19mg/ m^3, but decreased dramatically to 0.08 mg/m^3 in October (Fig. 16). This change indicates the possible influence of seasonal ocean currents or thermal stratification affecting nutrient distribution at the sea surface. These conditions suggest that although Area 1 experiences periods of increased productivity, it is generally less productive than coastal areas **(Buditama *et al*., 2017; Dwiyanti *et al*., 2022)**.

Areas 4 and 5, which are part of the coastal zone, showed moderate and relatively stable chlorophyll-a concentrations, ranging from 0.08– 0.18mg/ m^3. Area 4 exhibited slight fluctuations, with the highest values occurring in March–May (around 0.15–0.17mg/ m^3) and a decrease during the dry season. Area 5 exhibited a similar pattern, with consistent values ranging from 0.12– 0.18mg/ m³ throughout the year (Fig. 16). Both areas demonstrated characteristics of fairly productive coastal waters, though not as robust as Area 3. This stability continued to support the presence of pelagic fish, particularly during increases in chlorophyll-a levels during the transitional season.

Area 2, as a transition zone between the coastal and open sea, shows lower CHL values than Area 3 but slightly higher than areas 1 and 6. CHL concentrations in Area 2 range from 0.10– 0.18mg/ m³, with little variation throughout the year. This reflects the characteristics of transitional waters that are not very nutrient-rich but still capable of supporting plankton productivity within limited limits.

In general, Area 3 is spatially the center of highest marine productivity based on chlorophyll-a, which is closely correlated with high scad fish catches in the region. The spatial distribution of CHL decreases from the coast to the open sea, supporting the classical theory of marine productivity gradients, where coastal waters have direct access to nutrient inputs from land and more intense vertical mixing **(Buditama *et al*., 2017; Dwiyanti *et al.*, 2022)**. The high chlorophyll-a concentration in Area 3 is the main ecological basis for why scad fish are more abundant and caught there.

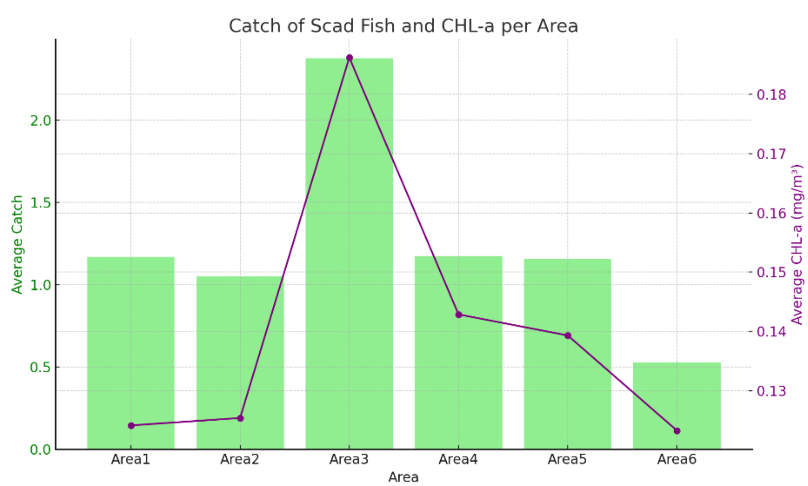


Fig. 17. Relationship between catch of scad fish and chlorophyll-a concentration

The spatial distribution of scad fish (*Decapterus* spp.) catches shows clear variations between areas, and this pattern is closely related to differences in chlorophyll-a concentrations in each region. Area 3, which is a coastal region, has the highest average catch, as well as the highest chlorophyll-a concentration (0.186mg/ m^3) compared to other areas (Fig. 17). This indicates a positive correlation between primary productivity (as indicated by chlorophyll-a) and the abundance of small pelagic fish such as scad fish. Phytoplankton, as represented by chlorophyll-a values, serve as the basis of the marine food chain; the higher the chlorophyll-a concentration, the higher the potential food availability for fish **(Hidayat *et al*., 2021; Putri *et al*., 2021; El-Gharbawy *et al*., 2024; Katiandago *et al.*, 2024)**. Coastal waters such as Area 3 are generally richer in nutrients due to the influence of land runoff and coastal current dynamics, making them productive environments.

Meanwhile, areas 1 and 6, which are offshore zones, have lower catch yields and chlorophyll-a levels (Fig. 17). Offshore waters tend to be oligotrophic, meaning they are nutrient-poor and less supportive of high phytoplankton productivity. Therefore, despite their large size, the potential for pelagic fish catches in these areas is relatively smaller compared to coastal areas **(Buditama *et al*., 2017)**.

Area 2, which is a transition zone between the coast and offshore areas, shows moderate catch and chlorophyll-a values, reflecting good mixing conditions in terms of both nutrients and ocean currents. Meanwhile, areas 4 and 5, although they are coastal areas and have fairly high chlorophyll-a concentrations, show relatively lower fish catches (Fig 17). This indicates that chlorophyll-a concentration is not the only determinant of fish abundance, and that other factors also influence the spatial distribution of scad fish, such as sea surface temperature, currents, and salinity **(Buditama *et al*., 2017; Nghia *et al*., 2018; Hatidja *et al.*, 2023; Srioktoviana *et al*., 2024)**.

Thus, this spatial pattern confirms that productive coastal areas, such as Area 3, have the potential to become prime fishing zones for scad fish. However, for sustainable fisheries zoning planning, chlorophyll-a data needs to be combined with other oceanographic parameters to obtain a more comprehensive picture of the ideal habitat of target fish.

CONCLUSION

The catch of scad fish (*Decapterus* spp) in the Sulawesi Sea is significantly affected by both sea surface temperature and chlorophyll-a concentration. Sea surface temperature has a non-linear relationship with fish catch, with the highest catch rates occurring within the temperature range of 29.50– 30.00°C. In contrast, chlorophyll a concentration demonstrates a positive linear relationship with catch. Coastal region (Area 3), especially from March to May, recorded the highest catches, attributed to favorable conditions of sea surface temperature and chlorophyll-a concentration. Conversely, offshore areas experienced lower catches due to variable sea surface temperatures and reduced chlorophyll-a concentrations. The use of satellite-derived data on sea surface temperature and chlorophyll-a concentration effectively identifies potential fishing grounds and aids in sustainable fisheries management. These findings support ecosystem-based fisheries management and real-time ocean monitoring through satellite data integration to enable adaptive and sustainable decision-making.

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