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RESEARCH ARTICLE

Estimation of Albacore Tuna Potential Fishing Grounds in the Southeastern Indian Ocean

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ABSTRACT To maintain sustainable fisheries, albacore tuna is one of the commercial fish species whose management is regulated globally by the Regional Fisheries Management Organizations. Generally, sea surface temperature (SST) and chlorophyll-a (SSC) are used to determine fish suitability based on the catch data. In this research, we attempt to identify optimal habitats for albacore tuna in the southeastern Indian Ocean by analyzing in situ data based on onboard observers on tuna long line vessels from 2006–2019 and optimum interpolation sea surface temperature from NOAA-Advanced Very High-Resolution Radiometer and sea surface chlorophyll-a from Aqua MODIS satellites. The albacore tuna's habitat suitability index was examined using the generalized additive model. The results suggested that albacore tuna inhabited waters with an SST range of 15-26 °C and SSC concentration of 0.075–0.125 mg/m^3. In the Indian Ocean, most albacore tunas were captured at higher latitudes of 20°-30° S.

INDEX TERMS Albacore tuna, chlorophyll-a, sea surface temperature, habitat suitability, Indian Ocean.

I. INTRODUCTION

Since the 1950s, global tuna catches have expanded dramatically, from approximately 500,000 tons to approximately 5,100,000 tons in 2018 [1]. The Pacific Ocean has the highest tuna capture, accounting for 65% of the entire global harvest, followed by the Indian Ocean (21%) and the Atlantic Ocean (11%) [1]. The average tuna capture in the Indian Ocean over the past five years (2014–2018) has been approximately 1 million tons, composed of skipjack (46.8%), yellowfin (40.5%), bigeye (9%), and albacore (3.7%) [2].

In the Indian Ocean, albacores account for the smallest proportion of the catches among the tunas. However, it is one of the important target species in commercial tuna fisheries, as indicated by the continued increase in the albacore catch in the Indian Ocean from around 3,000 tons in 1950 to 41,000 tons in 2018 [2]. The species is found in tropical and subtropical seas up to 40°S [3]. Albacores in the Indian Ocean are caught using tuna longline fishing gear. Despite the species not having been overfished yet, the status of the species is already at a level that starts to threaten the sustainability of the resource [4].

The Indian Ocean is one of the most profitable tuna fishing regions and has a long history of albacore fishing. However, information about the relationship between oceanographic conditions and the abundance of albacore has not been widely known. One of the obstacles experienced by Indonesian fishermen while attempting to catch albacore is

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their inadequate ability to determine the correct fishing spots or potential fishing grounds (PFGs). PFGs can be estimated by analyzing oceanographic parameters such as sea surface temperature (SST) and sea surface chlorophyll-a (SSC) concentration. One of the data that may be utilized to define PFGs is remote sensing data, which can be examined further using geographic information system (GIS) technology and the generalized additive model (GAM) statistical method to identify fish habitats. GAM analysis has proven reliable for identifying PFGs. [5] created GAM for the first time in 1986. In earlier research, the model has been used to estimate PFGs for *Sardina pilchardus* [6], tuna [7], swordfish [8], and salmon [9].

In the Indian Ocean, PFGs for bigeye tuna have been estimated using GAM [10]. According to [10], the PFGs of bigeye tuna were at SSTs between 24.8° and 28.7°C and SSC concentrations between 0.05 and 0.17 mg/m^3. GAM has been used to characterize bigeye catch south of Java [11]. However, as far as we know, there is no GAM-based research on the estimation of albacore PFGs in the Indian Ocean. In this study, we aim to investigate the characteristics of albacore tuna habitat in the southeastern Indian Ocean based on ocean surface conditions and tuna catch data collected over 14 years using GAM method. The findings of this research can assist fishermen in locating productive fishing spots.

II. MATERIALS AND METHODS

A. STUDY SITE

The studied area is in the southeastern Indian Ocean, 0°-35°S and 75°-122°E (Fig. 1).

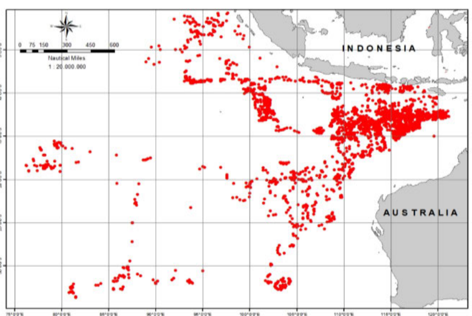

FIGURE 1. Map of the investigated area. Red dots denote the albacore fishing location.

B. CATCH DATA

The data on albacore tuna catch was obtained through direct recording activities on the vessels carried out by the observers of the Research Institute for Tuna Fisheries, the Ministry of Marine Affairs and Fisheries of the Republic of Indonesia. Data collection activities were carried out on tuna longline fishing in the Indian Ocean from 2006–2019. The data consisted of the total catches of albacore tuna, the coordinates of the fishing location, the fishing times, and the specifications of fishing gear. All collected information was compiled into a monthly database.

C. REMOTE SENSING DATA

The daily gridded optimum interpolation of SST from the NOAA Advanced Very High-Resolution Radiometer (https://www.ncei.noaa.gov/) and SSC from the Aqua Moderate Imaging Spectroradiometer (MODIS) (https://oceancolor.gsfc.nasa.gov/) were analyzed to describe ocean surface variability from January 2006 to December 2019 in the region of interest. We extracted daily SST and SSC from each pixel per the locations of albacore tuna fishing activities. The results were then used to analyze the habitat suitability of the albacore tuna using GAM.

D. CATCH PER UNIT EFFORT ANALYSIS

The analyzed fishery data included the daily capture of albacore tuna, the number of hooks, and the fishing sites. The daily data were compiled into monthly data. In addition, the fish abundance index was represented in terms of the Catch Per Unit Effort (CPUE) of tuna longline, or the number of tunas taken per one thousand fishing hooks, using the following formula [12]:

$$CPUE = \frac{E}{P} \times 1000 \tag{1}$$

where E is the total individual albacore tuna caught, and P is the total hooks used.

CPUE is an abundance index used to determine the fishing resource exploitation rate in an aquatic area [13]. In this research, CPUE was regarded as an indicator of fish availability for tuna longline fishing gear in a particular area. The calculation of CPUE was utilized to predict the fishing grounds using a GAM.

Classification of fisheries data is very useful for inferring the type of fish catch data and for determining the optimum range of oceanographic parameters and the highest catch period [10], [14], [15]. Following [14], we divided the fish catch data into three groups: (i) null catches – cases with CPUE equal to zero (1126 observations), (ii) positive catches – cases with CPUE greater than zero and less than 3.7 individual/1000 hooks (1114 observations), and (iii) high catches – cases with CPUE equal to or greater than 3.7 individual/1000 hooks (751 observations). The threshold value of a high catch number (3.7) was determined based on the lower limit of the upper quartile (Q3). The Q3 was obtained from 2991 observational data.

E. GENERALIZED ADDITIVE MODEL (GAM)

GAM is an alternative statistical model that can be used for linear and non-linear relationships and is frequently employed in habitat modeling [16]. The advantage of this statistical model is that it permits the investigation of non-parametric relationships. More generally, it can be applied to data sets with non-Gaussian distributions, including binomial, Poisson, and gamma distributions [10]. GAM uses a smoothing curve function to model the relationship between the catches (response variable) and the oceanographic variable (predictor variables) [17], [18], [19].

GAM was developed using the *mgcv* packages library in the R software [20], where the CPUE was the response variable, while SST and chlorophyll-a were the predictor variables. Predictor variables that influence the fishing grounds are selected based on the Akaike's Information Criteria (AIC) value, the Deviance Explained (DE) value, and the largest level of significance (P-value) of each developed GAM [21]. AIC is the residual error in a simple linear regression, whereas DE is the coefficient of determination (R^2). The *mgcv* package 'Predict GAM' uses the following equation to develop GAM.

$$g(\mu_i) = \alpha_0 + f_1(x_{1i}) + f_2(x_{2i}) + f_3(x_{3i}) + \cdots f_n(x_{ni}) \tag{2}$$

where g is the link function, μ_i is the response variable, α_0 is the model constant, x_n is the developed parameter, and f_n is the spline smooth factor function of each predictive variable.

The developed model will have AIC and DE values where each variable has its significance value (P-value). The model with the smallest AIC and the largest DE value is the best and is selected. On the other hand, the predictor variable with the smallest significance value is determined as the variable with the strongest influence on the response variable. The optimal values of each predictor variable (SST and SSC) determined by GAM are used as the main parameters to predict the habitats of albacore tuna.

F. HABITAT SUITABILITY INDEX (HSI)

The habitat suitability index (HSI) is a numerical index between 0 and 1, where 0 indicates unsuitable habitat and 1 is the optimal habitat. This index represents the capacity of habitat to support a particular species with output [10]. The output of the HSI analysis is a map of suitable albacore habitats. This study used ArcGIS's raster calculator function in the spatial analysis tool to process the HSI. The habitat factors based on GAM were combined using the additive priority function P, as shown in the following equation [22].

$$P = \sum_{i=1}^{m} ai \tag{3}$$

where P is the HSI, m is the number of factors, and ai is the relatively important factor of 'i'. In this case, 'i' is SST and SSC, where 'a' is the weighted value of each variable. The weighted value is calculated based on the proportion of essential habitat predictors for albacore tunas by GAM results.

III. RESULTS AND DISCUSSION

Albacore tuna is one of the fish resources that many Indonesian fishermen hunt. Many of them return from their fishing trips with only a few fish. Hence, it is crucial to understand the habitat preferences of the target species. Fishery information is essential for analyzing the parameters of fish habitat.

The CPUE of albacore tuna changed annually over the observation period, with the highest rate in 2012 (4 individuals/1000 hooks) and the lowest rate in 2017 (1 individual/1000 hooks) (Fig. 2). CPUE of above three individuals/1000 hooks were found in 2010, 2012, 2013, 2014, 2016, 2018, and 2019. On the other hand, in 2007, 2008, and 2011, the CPUE was around two individuals/1000 hooks. In 2006, 2009, 2015, and 2017, the rates were only around one individual/1000 hooks.

The highest CPUE of albacore tuna in the southeastern Indian Ocean occurred from April-July, as indicated in Fig. 3. In contrast, the low CPUE occurred from January to February and from September–November. We postulate that this might be an effect of seasonal reversal of easterly wind- induced upwelling along the southern coasts of the Lesser Sunda Islands from Bali to Timor (i.e., [23], [24], [25], [26]) and the enhancement of the South Equatorial Current during March-May, characterized by SST cooling [27], [28], [29].

The CPUE of albacore tuna indicated an increasing trend towards the high latitudes (Fig. 4). The highest CPUE were observed at latitudes of 31°–35°S (7 individuals/1,000 hooks) (Fig. 4) and longitudes of 80°–85°E (11 individuals/1,000 hooks) (Fig. 5).

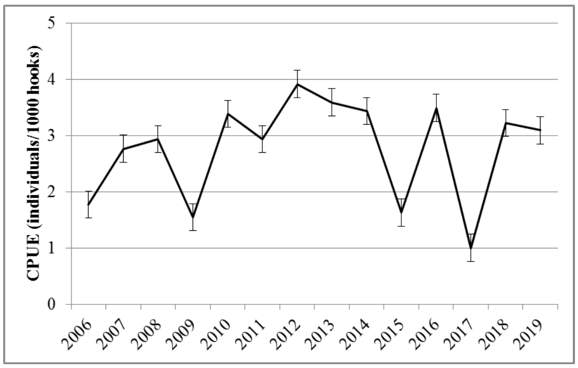

FIGURE 2. **Annual average of CPUE of albacore tuna in the study area.**

SST and SSC played a role in albacore tuna fishing. The highest CPUE corresponded to SST of 17°C (Fig. 6) and SSC concentration of 0.3 mg/m^3 (Fig. 7). Fig. 8 illustrates the habitat features of albacore tuna using GAM. The x-axis represents the explanatory variable, while the y-axis shows a more subtle influence on the associated value. The solid line indicates the observed data points, whereas the dashed line indicates the 95% confidence interval for each predictor variable. The zero value of the y-axis suggests no influence from the parameter. The percentage was higher when the developed GAM function was above the zero axis, indicating a strong influence from the parameter, while below the zero axis indicated the parameter's weak influence on the albacore tuna CPUE.

The results of GAM suggest that SSTs >25°C had no effect on the CPUE of albacore tuna in the southeastern Indian Ocean. A positive influence was found for SST of 15°–26° (Fig. 8a). SSC concentration <0.125 mg/m^3 had the greatest influence on the CPUE of albacore tuna (Fig. 8b). Furthermore, GAM analysis suggests that latitudes of 20°-30° S

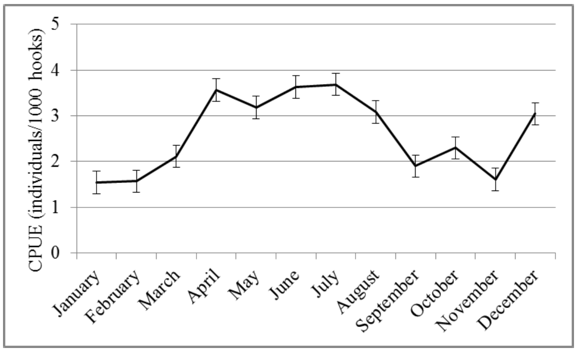

FIGURE 3. Monthly climatology (2006-2019) of CPUE albacore tuna in the study area.

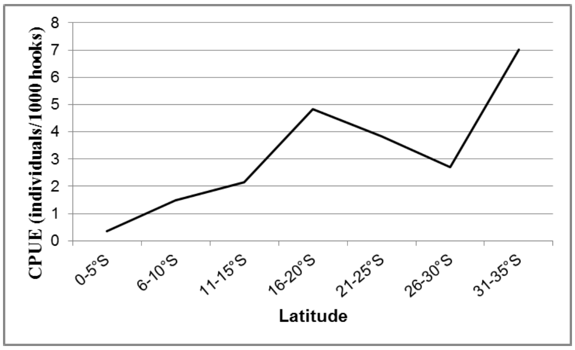

FIGURE 4. CPUE of albacore tuna (2006-2019) in the study area as a function of latitude.

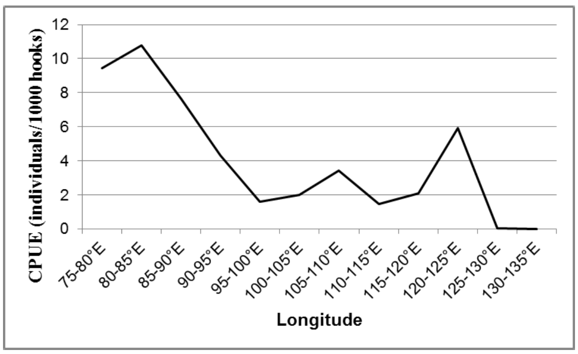

FIGURE 5. CPUE of albacore tuna (2006-2019) in the study area as a function of longitude.

(Fig. 8c) and longitude > 100°E (Fig. 8d) demonstrated strong influences on the CPUE. The longitudes of 120°–125°E also affected albacore tuna fishing; however, the data were limited.

The best model was selected based on the smallest AIC and the largest DE values (Table 1). The AIC values indicate how much information the GAM model loses when forecasting habitat suitability areas, whereas the DE values indicate how well the GAM model represented or explained the CPUE data. Table 1 suggests that SST and SSC influenced the habitats of albacore tuna in the southeastern Indian Ocean, with SST played a bigger role than SSC concentration as its DE was higher and its AIC was lower than those of SSC.

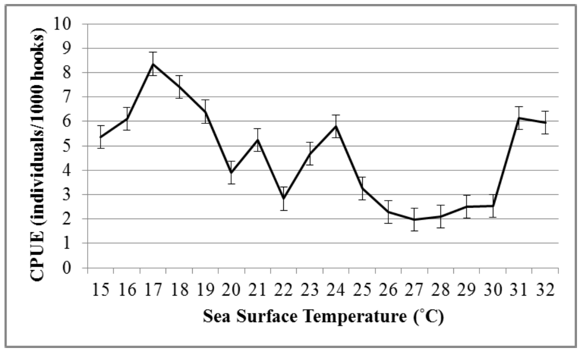

FIGURE 6. Relationship between albacore tuna CPUE and SST.

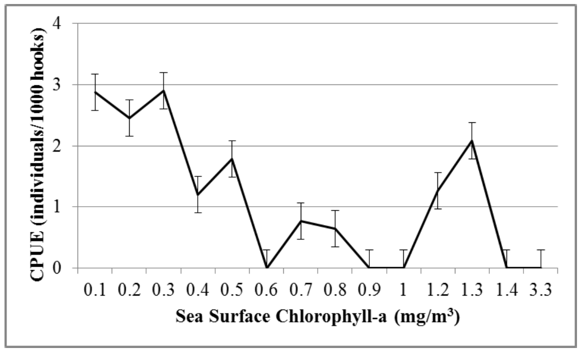

FIGURE 7. Relationship between albacore tuna CPUE and surface chlorophyll-a concentration.

Our findings also indicated that the fishing site significantly impacted the albacore tuna catches in the southeastern Indian Ocean.

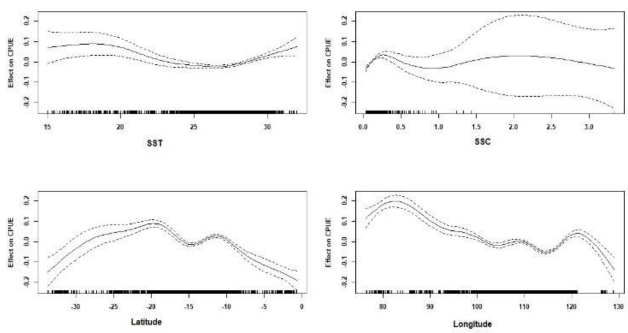

FIGURE 8. GAM analyses between albacore tuna CPUE and (a) SST, (b) surface chlorophyll-a concentration, (c) latitude, and (d) longitude.

The CPUE of albacore tuna in the southeastern Indian Ocean was affected by the SST range of 15°-26°C. According to [30], the SST range of 17°-21°C was the main factor influencing the distribution of albacore tuna in the southern Indian Ocean. The CPUE was also influenced by low surface chlorophyll-a concentration of 0.07-0.125 mg/m^3. Because albacore tuna eats secondary producers such as fish [31], [32], shrimp, squid, and octopus [33], chlorophyll-a is not

TABLE 1. Habitat characteristics of albacore tuna.

Model	Variable	P-Value	DE	AIC	edf
SST	SST	<0.001 ***	8.16%	2528.401	7.017
SSC	SSC	<0.001 ***	3.08%	2693.041	8.784
SST+SSC	SST	<0.001 ***	9.58%	2498.957	6.907
	SSC	<0.001 ***			8.745
Lat+Lon	Lat	<0.001 ***	27.8%	1828.527	8.515
	Lon	<0.001 ***			8.814

Note; edf – degree of freedom

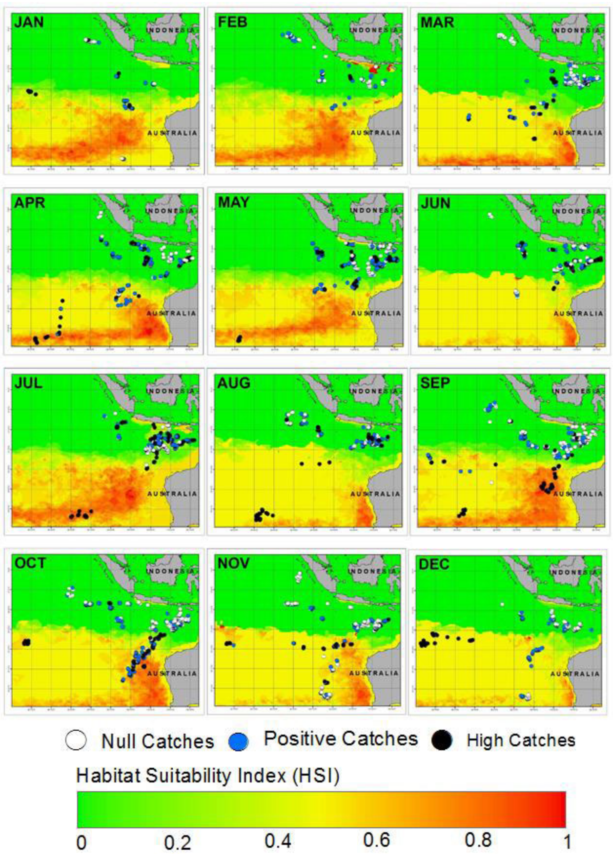

FIGURE 9. Map of habitat suitability areas and albacore fishing locations in the southeastern Indian Ocean.

directly related to the species. It takes time for secondary producers to reach high-chlorophyll areas and even longer for albacore tuna to reach secondary producers' areas. This result is consistent with an earlier study by [3] that suggests albacore tuna preferred a low chlorophyll-a concentration (0.11–0.22 mg/m^3).

Fig. 9 depicts the suitability of the albacore tuna habitat, with red indicating ideal habitats, yellow indicating moderate suitability, and green indicating an unsuitable environment. We found that most fishing activities occurred in the green area, which has environments unsuitable for albacore. However, some fishing activities were located in the suitable habitat from July to December. Moreover, the ocean region of 20°-30°S was the most suitable area for the habitats of albacore tuna. A study by [34] also found that the suitable habitat for albacore tuna in the southern Indian Ocean is at latitudes of 20°-40° S with CPUE of > 12 individual/1000 hooks. A good accordance between CPUE and latitude position revealed that the CPUE continued to rise as one traveled further south. According to the examination of CPUE and longitude coordinates, the western side of the investigated area possessed a high CPUE. Overall, the results of this study suggest that numerous fishing operations were conducted in the green area, i.e., areas with poor to no suitability, and this led to financial losses for fishermen due to high operational costs and minimal catches.

IV. CONCLUSION

Sea surface temperature, surface chlorophyll-a, and in situ observation/logbook data from 2006 to 2019 were analyzed using GAM statistical method to determine the potential fishing grounds of albacore tuna in the southeastern Indian Ocean from 0° to 35°S and 75° to 122°E. We found that oceanographic conditions significantly affected the CPUE of albacore tuna. The species preferred an SST range of 15°-26°C and a chlorophyll-a concentration of 0.075-0.125 mg/m^3. The albacore tuna habitat suitability index indicated that the fishing potential locations were between 20° and 30° S, which is in line with the logbook data trend of the fishing location.

Our results help narrow down the locations of suitable fishing ground of albacore tuna in the southeastern Indian Ocean. Given that various oceanographic parameters can be measured from satellites, this research was a first step toward more comprehensive proxy for albacore tuna. In the future, the study can be expanded to include other oceanographic data such sea surface salinity, sea surface height, winds, and in combination with ocean modelling to get profiles of salinity, temperature, density, and current that varies with depths. Finally, our research may help the government or decision makers on sustainable fisheries management.

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