Effect of oceanographic conditions on skipjack tuna catches from FAD versus free-swimming school fishing in the Makassar Strait

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Abstract. Fish Aggregating Devices (FADs) have become the preferred choice in skipjack tuna fisheries rather than looking for free-swimming schools (FSS) which is considered less effective. This study aimed to identify the effect of oceanographic conditions on skipjack tuna catches in the FADs versus free-swimming schools in the Makassar Strait. We collected fishing data from vessels using purse seine fishing gear and satellite-based oceanographic data (Sea Surface Temperature (SST) and chlorophyll-a (chl-a)) from May to July 2017. The satellite and catch data were analysed using a Generalized Additive Model implemented in R and mapped using Spatial Analyst in ArcGIS 10.6. The results showed that SST ranges in the FAD areas were relatively wider (29 – 31°C) than those in free-swimming school areas (29.5 – 30.5°C). The chl-a concentrations in free-swimming school areas were relatively higher (0.25 – 0.80 mg m⁻³) than those in the FAD areas (0.15 – 0.50 mg m⁻³). It was also found that mean skipjack tuna catches in the FAD areas (337 fish/setting) were relatively higher than in the free-swimming school areas (145 fish/setting). These findings suggest that the high skipjack tuna catches in Makassar Strait were significantly affected by specific SST ranges and relatively low chl-a.

1. Introduction
Makassar Strait is a water body with unique characteristics because it is traversed by the main branch of the Indonesian Throughflow (ITF) which carries warm water masses from the Pacific Ocean to the Indian Ocean [1]. Inevitably, these characteristics will affect the dynamics of fish movement and the abundance of fisheries resources in these waters, especially schools of large pelagic fish such as skipjack tuna. Skipjack tuna is one of the fishes with a high capture fisheries production from the Makassar Strait, much of which is destined for processing by export-oriented canning businesses [2].

In the Makassar Strait, Skipjack tuna is predominantly captured using purse seine fishing gear, either around Fish Aggregating Devices (FADs) or by seeking free-swimming schools (FSS). Fishing around FADs is growing in popularity because it has a higher success rate compared to FSS fishing [2]. It has been reported that the tuna catches around FAD were smaller compared to FSS fishing areas [3]. The difference in the size of skipjack tuna caught in FADs and FSS fishing may be influenced by differences in oceanographic conditions such as SST and chl-a concentrations.
It is generally accepted that skipjack tuna distribution and abundance are influenced by oceanographic factors such as Sea Surface Temperature (SST) and chlorophyll-a (chl-a) concentrations [4–7]. Several studies in tropical areas report that chl-a is an important oceanographic factor influencing skipjack tuna habitat selection [4,8–10]. A previous study suggested that SST has a significant influence on the spatial and temporal distribution of tuna [11].

Some previous studies have attempted to identify or explain catch differences and fish distributions, and examine determinant technical factors in FAD or FSS fishing [12–14]. Catch differences are influenced by environmental factors around the fishing ground, in particular oceanographic conditions. In the Bone Bay, [13] found that differences in fish catch are most strongly influenced by chl-a concentration. There is a lack of research comparing FAD versus FSS fishing, in terms of effective areas for catching skipjack tuna in the Makassar Strait. Therefore, in this study we attempted to identify the effect of oceanographic conditions on skipjack tuna catches in FAD vs. FSS fishing.

2. Materials and Method

2.1. Study area

The study area was mapped (Figure 1), with a focus on the fishing spots in the southern reaches of the Makassar Strait. The study area (2°N - 5°S and 116 - 121°E) is located between Borneo (to the west) and Celebes (to the east). This is an area where skipjack tuna purse seiners from several fishing bases operate to catch skipjack tuna.

Figure 1. Map of the study area in the Makassar Strait showing purse seiner skipjack tuna fishing spots during May-July 2017
2.2. Data Collection and Mapping
In this study, we used two types of datasets. From May to July 2017, we collected data on the purse seine fishery in the Makassar Strait. We also obtained satellite-based oceanographic data for this area on Sea Surface Temperature (SST) and chlorophyll-a (chl-a) concentrations over the same period. Both datasets were mapped using ARCGIS 10.2.

2.2.1. Data. Daily skipjack tuna catch data was obtained by following the purse seine fishing operations in the Makassar Strait over the study period. The vessels followed operated from two fishing bases, sited in Pinrang and Barru Districts respectively. These data comprised daily fishing positions (latitude and longitude) and catch in fish/setting. The fishing position data were divided into two categories, fishing around fish aggregating devices (FADs) or seeking free-swimming schools (FSS) of fish (Figure 1).

2.2.2. Oceanographic Data. There have been many studies showing that oceanographic parameters can be limiting factors for skipjack tuna distribution and abundance [4,6–8,10]. The oceanographic data used comprises primary data (for verification) and secondary data (satellite images to observe spatial and temporal variation in oceanographic data within the Makassar Strait study area). Primary data on SST and chl-a concentration were collected together with fisheries data (section 2.2.1). Secondary data were compiled for SST and chl-a concentration from Moderate Resolution Imaging Spectroradiometer (MODIS) data for May to July 2017 which we downloaded from the Ocean Color site (http://oceancolor.gsfc.nasa.gov).

2.3. General Additive Model (GAM)
This study used a general additive model (GAM) analysis to identify the effect of oceanographic conditions on skipjack tuna catches around FADs versus free-swimming schools in the Makassar Strait [14,15]. The non-parametric GAM analysis was constructed and implemented in R (version 3.5.2) software using the following formula [6,16]:

\[
\log(\text{catch} + 1) = \alpha + s(\text{SST}) + s(\text{chl} - a) + \epsilon
\]

where: \(\alpha\) is a constant

\(s(\cdot)\) denotes the spline smoothed SST and chl-a concentration functions

\(\epsilon\) is a random error term.

3. Results and Discussion
The use of FADs has become increasingly widespread in Indonesia, especially for skipjack tuna fisheries using purse seine or pole and line fishing gear. The placement of FADs can influence the spatial dynamics of skipjack tuna, making FADs a very effective tool for capturing skipjack tuna [17]. A study in 2010 reported that half of the global tuna catch came from fisheries employing the practice of fishing around FADs [2].

3.1. Oceanographic factors
3.1.1. Sea Surface Temperature (SST). By looking at the maps of skipjack tuna purse seine fishing grounds in the Makassar Strait (Figures 2 and 3), it can be seen that during the study period (May to July 2017) FAD fishing grounds were offshore whilst FSS fishing grounds were in nearshore waters. Spatially it can also be seen that the extent of the FAD skipjack tuna fishing grounds was relatively large compared to the areas used for FSS fishing.

The skipjack tuna FAD catch spots were spread over a wider area than the FSS fishing ground catch spots, and the SST range in the FAD areas (29 – 31°C) was relatively wider than in the free-swimming school fishing areas (29.5 – 30.5°C).
3.1.2. Chlorophyll-a (chl-a) concentration. Chl-a is one of the most important factors influencing skipjack tuna habitat. During the study period, as is usual in this area, the chl-a concentration was higher in nearshore than in offshore waters. As shown in Figure 3, the chl-a concentrations in FFS fishing areas (0.25 – 0.80 mg m$^{-3}$) were relatively higher compared to the FAD fishing areas (0.15 – 0.50 mg m$^{-3}$).

Figure 2. Spatial and temporal distribution of FAD vs. FSS skipjack tuna fishing locations in relation to monthly mean SST values in the Makassar Strait from May to July 2017

Figure 3. Spatial and temporal distribution of FAD vs. FSS skipjack tuna fishing locations in relation to monthly mean chl-a concentration values in the Makassar Strait from May to July 2017
In the FAD fishing areas, the highest catch (620 fish/setting) was obtained at 30.3 °C (Figure 4a) and 0.1992mg m$^{-3}$ chl-a (Figure 4c). The SST range with the highest catch frequency was 29.2 – 29.4°C, with 9 catches, representing 30% of the total sampling effort in the FAD fishing area (Figure 4b). The chl-a range with the highest catch frequency was 0.20 – 0.25 mg m$^{-3}$, with 17 catches representing 56.67% of the total sampling effort in the FAD fishing area (Figure 4d).

In the FFS fishing areas, showed that the highest catch (400 fish/setting) was obtained at 29.53 °C (Figure 5a) and a chl-a concentration of 0.3759mg m$^{-3}$ (Figure 5c). The SST range with the highest catch frequency was 29.8 – 30.0°C, with 10 catches representing 30% of the total sampling effort in the FSS fishing area (Figure 5b). The highest catch frequency was in the chl-a concentration range of 0.35 – 0.40mg m$^{-3}$ with 10 catches (30% of the total sampling in the FSS fishing area) (Figure 5d).

Figure 4. Skipjack tuna FAD fishing catches (fish/setting) and FAD fishing frequency in the Makassar Strait from May-July 2017 in relation to SST (a and b) and chl-a concentration (c and d)

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Figure 5. Skipjack tuna FSS fishing catches and skipjack tuna FSS fishing frequency in the Makassar Strait from May-July 2017 in relation to SST (a and b) and chl-a concentration (c and d)

Skipjack tuna catches in the FAD fishing areas, with a mean haul of 337 fish/setting, were in general higher than catches in the FFS fishing areas, with a mean haul of 145 fish/setting. This could indicate that fishing around FADs is more effective than FSS fishing. However, fishing activities using FADs to attract schooling fishes need to be managed wisely, taking into account the sustainability of resources and the ecological impacts [17,18].

3.2. Effect of oceanographic conditions on skipjack tuna catches in the FADs vs. FSS fishing
The GAM analysis of the fishery data collected from purse seine fishing vessels and satellite-based oceanographic data from May to July 2017 in the Makassar Strait showed that SST had a significant effect (p < 0.5 at the 95% confidence level) on skipjack tuna catch (fish/setting) in the FAD fishing area (Table 1), while the effect of chl-a concentration was not significant (p > 0.5 at the 95% confidence level). Furthermore, the R² value (0.413) indicated that the combined influence of the independent variables (SST and chl-a) on the dependent variable (skipjack tuna catches) in the FAD fishing areas could explain approximately 64% of the variation in skipjack tuna catch over the study period. This result is consistent with a study on Atlantic tunas [19], which found a significant relationship between SST and FAD fish catch volume.

Table 1. GAM analysis: effect of oceanographic conditions (SST and chl-a concentrations) on skipjack tuna catches in the FAD fishing area

|          | Edf | Ref.df | F    | p-value |
|----------|-----|--------|------|---------|
| s(SST)   | 4.502 | 5.513  | 2.757 | 0.0416* |
| S(chl-a) | 1.000 | 1.000  | 1.256 | 0.2736  |

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Significance level codes: 0 ‘****’ 0.001 ‘***’ 0.01 ‘**’ 0.05 ‘.’ 0.1 ‘ ’ 1

R² (adj) = 0.413;  n = 30
Figure 6. GAM analysis of skipjack tuna catch in FAD fishing areas. Solid lines show the fitted GAM functions describing the effect of predictor variables (a. SST; b. chl-a concentration) on the response variable (skipjack tuna catch). Gray-shaded areas indicate 95% confidence intervals. The relative density of data points is shown by the rug plot on the x-axis.

In the FSS fishing areas, SST also showed a significant effect (p < 0.5 at the 95% confidence level) on skipjack tuna catches, while the effect of chl-a concentration was not significant (p > 0.5 at the 95% confidence level) (Table 2). The $R^2$ value (0.459) indicated that combined influence of the two independent variables (SST and chl-a) could explain approximately 68% of the variation in the dependent variable (skipjack tuna catch) in the FSS fishing area.

Table 2. GAM analysis: effect of oceanographic conditions (SST and chl-a concentrations) on skipjack tuna catches in the FSS fishing area

|          | Edf | Ref.df | F   | p-value |
|----------|-----|--------|-----|---------|
| s(SST)   | 6.481 | 7.5    | 2.957 | 0.0225 * |
| S(chl-a) | 1.000 | 1.0    | 2.212 | 0.1513  |

Significance level codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '+' 0.1 ' ' 1

$R^2$ (adj) = 0.459; n = 30

Figure 7. GAM analysis of skipjack tuna catch in FSS fishing areas. Solid lines show the fitted GAM functions describing the effect of predictor variables (a. SST; b. chl-a concentration) on the response variable (skipjack tuna catch). Gray-shaded areas indicate 95% confidence intervals. The relative density of data points is shown by the rug plot on the x-axis.
4. Conclusion
Skipjack tuna catch volume was significantly influenced by sea surface temperature (SST) in both the fish aggregating device (FAD) and free-swimming school (FSS) fishing areas over the study period (May-July 2017), while the effect of chlorophyll-a (chl-a) concentrations was not significant. However, the combined effect of specific SST and relatively low chl-a was significantly associated with high catch volumes, particularly in the FAD fishing area. We conclude that SST plays and important role in shaping the skipjack tuna schools which form around FADs. The higher catch volume from FAD fishing compared to FSS fishing in this study supports the widespread perception that FAD fishing is, in general, more effective than FSS fishing.

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