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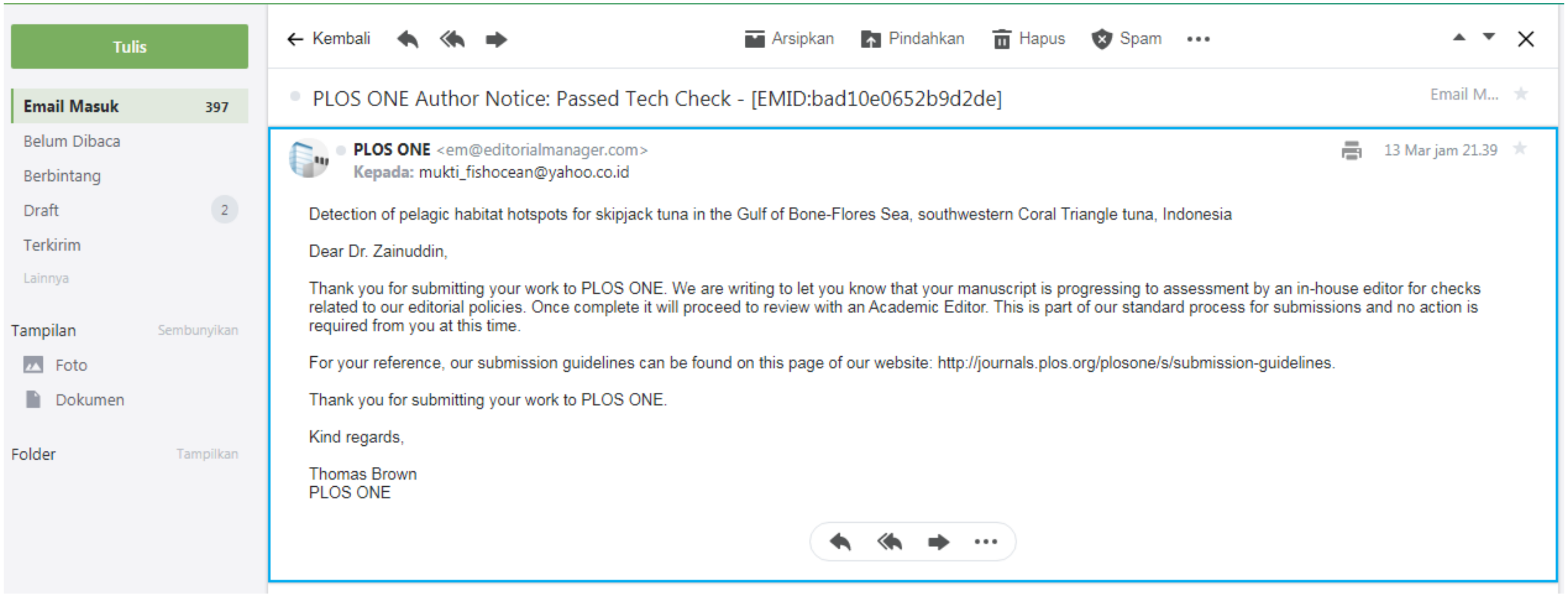

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Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia

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Cover Letter

Date: 12 March 2017

Dear Editor PLOS ONE,

I am enclosing one original manuscript entitled “Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia”, by Mukti Zainuddin, Aisyah Farhum, Safruddin Hasyim, Muhammad Banda Selamat, Sudirman Jumarung, Nurjannah Nurdin, Mega Syamsuddin, Muhammad Ridwan and Sei-Ichi Saitoh, which we would like to submit for publication as an article in the Journal of PLOS ONE.

The manuscript consists of 26 pages including 2 tables, 10 figures and 2 supporting information files.

We hope that the paper will be considered suitable for publication in your journal.

Best regards,

Mukti Zainuddin
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Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia

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Abstract

Using remote sensing data of sea surface temperature (SST), sea surface height anomaly (SSHA) and chlorophyll-a (Chl-a) together with catch data, we investigated the detection and persistence of important pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, Indonesia. We analyzed the data for the period between northwest and southeast monsoon 2007 -2011. A pelagic hotspot index was constructed from a model of multi-spectrum satellite-based oceanographic data in relation to skipjack fishing performance. Results showed that skipjack catch per unit efforts (CPUEs) increased significantly in areas of highest pelagic hotspot indices. The distribution and dynamics of habitat hotspots were detected by the synoptic measurements of SST, SSHA and Chl-a ranging from 29.5° to 31.5°C, from 2.5 to 12.5 cm and from 0.15 to 0.35 mg m^{-3}, respectively. Total area of hotspots consistently peaked in May. Validation of skipjack CPUE predicted by our model against observed data from 2012 was highly significant. The key pelagic habitat corresponded with the Chl-a front, which could stimulate the areas of relatively high prey abundance (enhanced feeding opportunity) for skipjack. We found that the area and persistence of the potential skipjack habitat hotspots for the 5 years were clearly identified by 0.2 mg m^{-3} Chl-a isopleth, suggesting that the Chl-a front provides a key oceanographic indicator for global understanding on skipjack tuna habitat hotspots in the western tropical Pacific Ocean, especially within Coral Triangle tuna.

Introduction

Pelagic habitat hotspots, which are defines as areas of high biological activity where linkages occur between physical processes, primary production, secondary consumers and higher tropic level predators, play an important role in controlling distribution, migration and abundance for commercial and wide-roaming pelagic species in many different oceans [1,2,3]. The distinct oceanographic signatures in turn stimulate enhanced trophic interactions, physiological and foraging advantages, so that providing high ecological and economic importance. Large pelagic fish as well as commercial fishing vessels recognize that prey organisms aggregate at ocean hotspots, which are mostly represented by ocean fronts, eddies and upwelling zones [2,3,4]. Thermal front has proved as an important congregating spot for many valuable pelagic species in

Baja California-Bering Sea [5]. In the western Mediterranean, the spatial pattern of bluefin tuna school distributions was determined by the key oceanic habitats (i.e. fronts and eddies) [6]. Using multi-spectrum satellite images, hotspots for albacore tuna in the western North Pacific Ocean correspond with surface fronts and eddies [7,8]. Albacore forage habitat and migration route are driven by dynamic features of a pelagic hotspot i.e. Chl-a front known as TZCF in the eastern and central Pacific Ocean [9]. Recent findings suggest the frontal area, eddy field and topographic feature (Seamount) as important habitat hotspots for pelagic species such as flying squid and tuna [10,11,12]. Therefore, detection of the ecologically significant pelagic habitats and their spatial persistence are critical for setting up the marine management strategies and potential targets for conservation.

Skipjack tuna is one of the most valuable species in the world in terms of catch weight [13]. It is a main target and exploited fisheries of high commercial value in the tropical region, it accounts for more than one half (approximately 58%) of the global tuna catch [13]. In recent years (catch proportion in average 2005-2014), the fish contributes 47% of Indonesia total tuna catch [14]. Hence, understanding of the species optimal habitats is central for evaluating fishing strategies and sustainable pelagic fisheries resources within Coral Triangle area.

Basically, potential habitat for this species inhabits the warm surface layers of tropical and subtropical oceans [15,16]. Several oceanographic studies have found that skipjack tuna migration, distribution and abundance have a link with oceanic fronts and eddies [17,18,19] and are strongly influenced by ambient temperature and dissolved oxygen concentration [20,21]. In the western North Pacific Ocean, SST and surface Chl-a are found to be more significant variables of capturing skipjack [22]. Surface temperature is one of the key oceanographic parameters to study skipjack tuna habitat in tropical region [23]. The occurrence of pelagic hotspots (salinity front and convergence zone) identified with 29°C SST isotherm provides a reasonable proxy to detect the region of highest skipjack CPUEs in western Pacific Ocean [24].

The Coral Triangle tuna, which encompasses primarily the seas of Indonesia, Papua New Guinea and the Philippines is a known tuna (skipjack, yellowfin and bigeye) nursery and migratory path, producing about 46 % of all tuna catches in Western and Central Pacific Ocean [25,26]. Gulf of Bone - Flores Sea is an important coral reef area located in the southwestern Coral Triangle tuna where many commercial tuna fisheries conduct fishing operations. Our preliminary study shows that the estimate of MSY for this study area is 49.709 tonnes per year, indicating the great potential skipjack fishing ground. Statistical data (2007-2013) from Agency For Marine and Fisheries Affairs, South Sulawesi Province indicate that trend of skipjack catch tends to increase during the period between northwest and southeast monsoon. During this period, surface temperature gradually decrease while Chl-a tend to be high, providing high biological productivity areas [27] which are in turn correlated with high catches of skipjack [28].

There are many studies, which investigate skipjack tuna habitat in the western tropical Pacific Ocean especially northern waters of Papua (Indonesia) and Papua New Guinea [15,23,24]. Those areas predominantly locate in the eastern area of Coral Triangle tuna. However, there is a critical gap of skipjack tuna distribution in the opposite area (southwestern Coral Triangle tuna, particularly in the Gulf of Bone- Flores Sea). This area is one of the most potential tuna fishing grounds in Indonesia waters [27,28]. Therefore, detection and visualization of a spatial pattern of the pelagic hotspot and its persistence in this area are the interesting challenges. The aims of the present paper are to detect a spatial pattern of pelagic habitat hotspots for skipjack tuna and to map out their persistence in the southwestern Coral Triangle tuna using remotely sensed satellite and catch data.

Data and methods

Study area

The Coral Triangle tuna, so named because of its distinct triangular shape, contains nearly 5.7 sq km of coral reefs and spans parts of six countries: Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands, and Timor-Leste [25]. The area of interest, the Gulf of Bone-Flores Sea located in the southwestern Coral Triangle tuna is one of the most biologically productive skipjack fishing grounds (Figure 1). In addition, the study area is also known as one of the main pathways of the Indonesian throughflow (ITF) and is strongly influenced by a tropical monsoon type of climate, resulting from the Asia-Australian monsoon wind systems, which change the wind direction according to the seasons, i.e. southeast monsoon and northwest monsoon [27]. The interaction between the ITF and the Asian monsoon affects the specific current circulation system, Ekman mass and heat transport, tidal mixing, wind induced upwelling and down-welling systems and environmental variability of sea surface temperature (SST) and surface Chl-a concentration (hereafter Chl-a) [27,29,30]. Dynamics of the biophysical oceanographic structures in this area, results in a highly productive pelagic habitat hotspot, which serves as a forage ground for various commercially and ecologically important pelagic species including tuna [28,31].

Fig 1. A location map of the southwestern Coral Triangle tuna showing the major oceanographic and bathymetric features. The broken lines correspond to the spatial position of 350 m isobath (shelfbreak).

Pole and line fishery data

The pole and line fishery in the study area, which extends from 118.5°E to 122.5°E longitude and 2°S-8°S latitude, captures the skipjack tuna mostly between the northwest and southeast monsoon (January-June). The fishery catch data were collected from pole and line fishing logbooks provided by the Fish Landing Bases in Luwu and Sinjai, South Sulawesi, and the and Kolaka Districts and Incorporated Company of Indonesian Government, PT. Perikanan Samudra at Kendari, Southeast Sulawesi in the period between northwest and southeast monsoon 2007-2011. The fishery data comprised daily geo-referenced fishing positions (latitude and longitude), catch in number of skipjack and effort (fishing set), from which catch per unit effort (CPUE) was determined in number of fish per fishing set, further compiled into monthly resolution datasets. To validate our model, the catch data were also collected as many as 114 sampling fishing positions from scientific pole and line fishing surveys in the study area during the same period in 2012.

Satellite remote sensing data

The physical and biological environmental data used to describe the oceanographic condition around the fishing locations are surface Chl-a concentration and sea surface temperature (SST). Terra/ MODIS (Moderate Resolution Imaging Spectroradiometer) level 3 standard mapped images (SMI) data were used to estimate sea surface Chl-a concentration and SST at all pole and line fishing ground locations. NASA distributes the level 3 binary data with HDF (*Hierarchical Data Format*) format. We obtained these data from NASA GSFC’s Distributed Active Archive Center (DAAC) (http://oceancolor.gsfc.nasa.gov/). For this study, we used Global Area

Coverage (GAC), monthly mean MODIS images with a spatial resolution of about 4 x 4 km for the study period during 2007-2011 (Table 1).

Table 1. Summary of oceanographic parameters used for developing habitat hotspot models for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia

Oceanographic variables	Abbreviation	Temporal Resolution	Spatial Footprint	Data Source
Sea surface temperature	SST	Monthly	4 km	Terra/MODIS
Surface chlorophyll-a	Chl-a	Monthly	4 km	Terra/MODIS
Sea surface height anomaly	SSHA	Daily	25 km	AVISO

In the present study, we used SSHA data distributed by AVISO (the Archiving, Validation and Interpretation of Satellite Oceanographic data). The SSHA data were global images with 0.25 º spatial resolution both longitude and latitude. Due to the different spatial and temporal resolutions with SST and Chl-a, the SSHA data were resampled into the spatial footprint (4 km) and sampling interval (monthly) spatial resolutions and then subset to the study area. Monthly values of all satellite images (SST, Chl-a and SSHA) were extracted from each pixel corresponding to the location of fishing activities using spatial analyst of ArcGIS 10.3. The result was a full matrix of the skipjack tuna CPUE as well as the environmental variables. All satellite images were processed using IDL (Interactive Data Language) software package and had the same spatial and temporal resolutions prior to the model construction.

Construction of pelagic habitat hotspot map

To detect the spatial pattern of the skipjack pelagic hotspots throughout study area, we constructed a model of fishery performance, which took into account both CPUE (index of fish abundance) and frequency of fishing effort (index of fish occurrence) in relation to the three oceanographic variables. This model was improved and developed from the albacore hotspot model [7] by adding weighting factor and SSHA variable into the model.

The habitat hotspot was determined using environmental probability indices, reflecting the high probability areas of finding skipjack tuna. Specifically, the pelagic hotspot index (PHI) was computed based on total CPUE at a given interval of histogram divided by the maximum total CPUE from all class intervals of the three variables (SST, SSHA and Chl-a) (Eq. 1), and fishing frequencies were also calculated with the same method (Eq.2). Then, we calculated the average of probability indices from the interval ranges of all variables (eq.3). The highest probability value in which the probability index is more than 0.75 (PHI > Quartile 3) indicated the pelagic habitat hotspots, showing the greatest probability areas of finding the fish. In contrast, the lowest probability denoted the least suitable locations for detecting skipjack tuna. Lastly, we combined the three satellite images to create a pelagic hotspot map for all interval ranges of the environmental conditions.

The CPUE data were then overlain on the map and the probability index of the joint environmental factors was extracted from each pixel corresponding to the fishing ground positions. The probability area was visualized using ArcGIS 10.3 Spatial Analyst software package. Then we examined the relationship between total CPUE and the level of probability index around fishing locations. Here this attempt focused on an analysis of the pelagic hot spots on the seasons of highest skipjack abundance 2007-2011. For validation, we analyzed catch and the environmental data during the same period in 2012. All the habitat hotspot images were mapped using spatial analyst toolbox in ArcGIS software package. The model used to calculate pelagic habitat hotspot index (PHI) as follows:

$$PI_{cpue} = \frac{\sum \frac{cpue_{ij}}{cpue_{i\,max}}}{n} \quad (1)$$

$$PI_{f} = \frac{\sum \frac{F_{ij}}{F_{i\,max}}}{n} \quad (2)$$

$$PHI = \frac{(PI_{cpue} + PI_{f})}{2} \quad (3)$$

Where PHI is the pelagic hotspot index; PI_{cpue} is the mean probability index for skipjack based on the relationship between CPUE and the three oceanographic variables (SST, Chl-a, SSHA) for each histogram graph; PI_{f} is the mean probability index based on the relationship between fishing frequency and the oceanographic variables for the histogram graphs; $cpue_{ij}$ is the value of CPUE in relation to oceanographic variable-i for class interval-j; $cpue_{i}$ max is the maximum value of CPUE among the oceanographic variables; F_{ij} is the value of fishing frequency in relation to oceanographic variable-i for class interval-j; $F_{i\ max}$ is the maximum value of fishing frequency among the oceanographic variables; n is the total number of variables.

Detection of persistent pelagic habitat hotspot

A persistent pelagic hotspot map was constructed based on the presence or absence of the strong environmental probability index (probability of more than 75%) in the study area. We built the persistent hotspot map by computing monthly mean composite hotspot images at the peak season between the northwest and southeast monsoon 2007-2011. The map consisted of value ranging from zero (0) to five (5). The highest value (5) indicated that the persistent hotspot at a certain spatial location took place during the period of five years. While, the lowest value (0) denoted that there was no persistent hotspot available at a given area during at least one year. Then, we overlaid the conspicuous environmental characteristics on the map to find a reliable proxy indicator for locating the persistent skipjack habitat hotspots.

Results

Temporal variation of catch data and environmental variables

During the period of April-June, skipjack CPUEs tended to be high and reached the peak in May (Fig 2A). Catch level in this month was about 170 fish/fishing set. The highest CPUEs occurred in areas of relatively high Chl-a and warmer SST ranging from 0.16 to 0.3 mg m^{-3} (0.22±0.068 mg m^{-3}) (Fig 2B) and from 29.76 to 30.86 °C (30.31±0.55 °C) (Fig 2C), respectively. At the same time, the greatest skipjack catches were obtained in waters of positive SSHA ranging from 3.04 cm to 7.96 cm (5.50 ± 2.46 cm) (Fig 2D). Whereas during January-March, the catch rates (CPUEs) appeared to be lower than those of subsequent months. During that period, the fishing sets occupied the locations where surface temperature was relative high and Chl-a as well as SSHA were highly fluctuated.

Fig 2.Temporal variability of (A) CPUE of skipjack fishery, (B) SST, (C) Chl-a concentration, and (D) SSHA, between northwest and southeast monsoon (January-Juni) 2007-2011.

Skipjack tuna in relation to environmental variables

Satellite based oceanographic data in relation to skipjack tuna fishing performance indicated the specific ranges where the fish were most abundant (Fig 3). Total CPUEs in relation to SST showed that most of the catches were concentrated in areas where SST ranged from 29.75 to 31.25ºC using histogram graph (Fig 3A). The similar trend was found in the relationship between the frequency of fishing set and SST (Fig 3D). Both histograms revealed that the preferred SST tended to center at 30.5ºC, which reflected the highest probability of finding fish in term of SST. Total skipjack CPUEs in relation to Chl-a indicated that skipjack CPUEs were mainly found in areas where the environmental variable occurred mainly from 0.15 to 0.35 mg m^{-3} (Fig 3B). The relationship between skipjack fishing frequency and the surface Chl-a also showed a similar pattern (Fig 3E). The Chl-a preference for skipjack tuna mostly concentrated at 0.2 mg m^{-3}. Whilst Skipjack catches and fishing sets were derived in substantial number in waters where SSHA varied between 0 and 12.5 cm (Fig 3C). Both fishing performance reached an average at approximately 6 cm (Fig 3C- 3F).

Fig 3. Total skipjack CPUE (skipjack/fishing set) in relation to MODIS SST (A), MODIS Chl-a (B), and SSHA (C) and fishing frequency in relation to SST *(*D), Chl-a (E) and SSHA (F) during January-June 2007-2011.

It is worth noting that Chl-a was the most important oceanographic variable to explain skipjack fishing performance. Specifically, we found that chlorophyll concentrations of about 0.2 mg m^{-3} was a good proxy for describing the highest total skipjack CPUEs (~54%) and fishing frequency (~60%) (Fig 3). Whilst, the value of SST 30.5°C was capable of exposing the catch rates of approximately 29% and frequency of the fishing set of about 35%. Whereas, the optimum SSHA value of near 6 cm accounted for the fishing productivity and frequency of fish occurrence were about 28% and 40%, respectively.

The associated highest catches with the Chl-a front well formed every year during 2007-2011 (Fig 4). The chlorophyll front consistently occurred in the specific location within the study area. This fact means that the potential habitat was constantly available for fishery every year (2007-2011) based on the environmental indicator. For the SST variable, the dynamics and position of the optimum range varied widely both in longitude and latitude and sometimes disappeared over the Flores Sea for instance in May 2008 (S1).   Likewise, from the SSHA images, the spatial position of the most suitable range was widely distributed (S2).

Fig 4. The spatial position of the Chl-a front measured by the 0.2 mg m^{-3} Chl-a concentration contour for May 2007-2011 estimated from MODIS ocean color data. The solid lines correspond to the Chl-a front along the study area.

Pelagic habitat hotspot map for skipjack tuna

Areas of potentially suitable habitat hotspots for skipjack tuna strongly developed in May and covered the waters of approximately 8971 km^2 in average (Fig 5). Mean PHI throughout the study area in the peak season was about 0.60. In contrast, the lowest pelagic habitat hotspot index occurred in January and occupied the areas of 2317 km^2 with mean hotspot index of 0.41.

Fig 5. The spatial distribution of skipjack CPUE (skipjack/fishing set) from the pole and line fishery shown as dots for May 2007-2011 overlain on pelagic hotspot maps generated from a model of satellite images (Chl-a, SST and SSHA) in relation to fishing performance.

During five years period, spatial dynamics and intensity of habitat hotspots appeared to change significantly (Fig 6). However, it is important to note that a Chl-a of 0.2 mg m^{-3} isopleth performed a good indicator for detecting spatial distribution patterns of the pelagic hotspots for all years (Figs 4 and 6). In 2007, the most suitable habitat strongly formed within Gulf of Bone and associated with the skipjack fishery distribution. The pelagic habitats were predicted in eastern Bone Gulf and western the Flores Sea in the subsequent year. We found that skipjack catches mainly concentrated in the hotspot area. In 2009, the predicted hotspots were mostly found in the western Flores Sea, whilst the skipjack tuna seemed to be captured in the hotspot areas of the northern Bone Gulf. Then, in the following year 2010, the pelagic habitat hotspots developed in agree well with the chlorophyll front and were in a good association with the fishery locations in the northern Bone Gulf. For the year of 2011, the habitat hotspots well formed again in the northern area with narrower both latitudinal and longitudinal bands and matched generally with fishing data. In all years, it seems that the potential habitat had also a good association with the shelf-break formation (at the depth of about 350 m).

Fig 6. Monthly mean temporal variability of pelagic hotspot area (km^2) and pelagic hotspot index between northwest and southeast monsoon 2007-2011.

The datasets for the period of northwest-southwest monsoon 2007-2011 showed that the total CPUEs significantly increased with the increasing probability values of joining environmental variables ($R^2=0.67$, $P<0.0001$) (Fig 7). The increasing CPUEs were substantially found when the pelagic hotspot indices were more than 60%. The first equation of the regression lines was $Y=b_0+b_1X_1$, when $X_1 \leq 0.6$ (X=0.6 indicates the point where the slope change), and the second equation was $Y=(b_0- 60b_2)+(b_0+b_1)X_1$ when $X_1>0.6$. Therefore, we suggested that the PHI of joint oceanographic variables provided a reasonable proxy for predicting pelagic hotspots for skipjack tuna.

Fig 7. The relationship between total skipjack CPUE and PHI in the southwestern Coral Triangle tuna using piecewise linear regression.

Prediction and validation of skipjack CPUE

For the spatial model validation, Fig 8 showed that spatial distribution of fishing data in May 2012 mostly occurred on predicted habitat hotspots (PHI > 0.75). The important skipjack habitats located the areas of 120.5-121.5°E longitude and 3.5-4.5°S latitude. It is interesting to see that the mean geographical position of the habitat hotspot was highly consistent with the Chl-a front position along the study area. Using pelagic habitat hotspot index as a predictor for skipjack CPUE response, we found that correlation of predicted skipjack CPUEs against that observed was highly significant ($P < 0.0001$, $R = 0.60$) (Fig 9). It inferred that the period between northwest-southwest monsoon, the pelagic hotspot model was significantly capable of predicting skipjack CPUEs.

Fig 8. The spatial distribution of skipjack CPUE (skipjack/fishing set) shown as dots for May 2012 superimposed on the pelagic habitat hotspot map and Chl-a front.

Fig 9. A scatter plot of pooled monthly observed against predicted skipjack CPUE values calculated from the pelagic hotspot index (PHI) ($P < 0.001$, $R^2 = 0.60$).

Persistence of habitat hotspots for skipjack tuna

During the period of 5 years (May 2007-2011), the persistent habitat hotspots were found only in May and June (Table 2). The greatest persistent area occurred in May and covered approximately 1.21% of the grid cells in the southwestern Coral Triangle tuna for 5 years (Fig 10 and Table 2). These cells were all concentrated along the specific areas from the western Flores Sea, surrounding the Gulf of Bone to eastern Flores Sea. Nevertheless, our analysis indicated that more than 95% of the study area had not persistent habitat hotspots. This fact means that the key skipjack habitat was not omnipresent throughout the study area. However, it was remarkable that all persistent habitat hotspot formations associated consistently with the Chl-a front indicated by 0.2 mg m^{-3}. Skipjack CPUE tended to increase at the most persistent habitat (Fig 10).

Fig 10. Spatial distribution of persistent pelagic habitat hotspots for skipjack tuna in the peak season May 2007-2011 (frequency/ 5 years) in the southwestern Coral Triangle Tuna, Indonesia (left) and the graphical relationship between average CPUE and persistent habitat hotspots (right).

Table 2. Persistence of habitat hotspot location for skipjack tuna, in number of pixel per year, in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia

Month \ Year	2007	2008	2009	2010	2011
January	3846	894	78	4	0
February	4540	966	89	5	0
March	3923	2614	170	7	0
April	3082	2738	910	43	2
May	3386	1874	1233	735	193
June	3166	2403	1004	387	119

Discussion

We have developed a model of satellite-based environmental data-fishing performance relationship to explore and map out the spatial distribution pattern and persistence of pelagic hotspots for skipjack tuna. The fishing performance data represented by CPUE and fishing frequency are low-cost fish distribution datasets commonly available to fishery scientists. CPUE data provide a good proxy as an index of fish abundance [15,32], whereas fishing frequency data act as an index of fish occurrence or fish availability [7,33]. The fishing data describe fisher's experience-based knowledge and provide invaluable supplement data to a better habitat prediction [34]. Whilst, satellite data are mostly available at no cost to the user and are capable of accurately monitoring oceanographic features over a wide area [9,35]. High performance of the fishery data in relation to satellite oceanographic information, therefore, could be considered as an important indication of finding habitat hotspots for pelagic species.

In principle, our model extracts the optimum combination of three environmental factors (SST, Chl-a and SSHA) from the high fishing performance to produce pelagic habitat hotspots. Several studies supported that a combination of these factors plays a pivotal role in explaining and exposing a pelagic tuna habitat [7,8,22,36]. The choice of Chl-a as an important variable for this study as it is central for identifying tuna forage habitat [9]. SST was selected to be important variable for detecting the habitat hotspot since skipjack tuna are sensitive to the changes of temperature on their distribution [15]. While SSHA variable is related to the changes of depth distribution of thermocline and mesoscale variability [35,37]. We combined these variables to improve a better estimate for detecting potential pelagic hotspots for skipjack tuna.

Our results show that skipjack tuna habitat associates with the areas of warm SST (~ 30.5°C), specific Chl-a concentrations (centered at 0.2 mg m^{-3}) and positive SSHA (near 6 cm), favoring fishing operations (Figs 2 and 3). The surface temperature preference for skipjack is relatively warmer than the results suggested from the other areas around the world [15,22,33]. Highest catches consistently occur in May when SST gradually decrease to about 30.5°C after reaching a peak in November-December and back to the lowest SST in July and August [30]. At the same time, skipjack tuna fishery tends to maintain within the areas of positive anomalies suggesting that food biomass aggregates mainly at the surface when thermocline depth move on the opposite direction of sea surface height [37,38]. We found that predominantly positive SSHA had a real effect on both skipjack CPUE and number of fishing set (Fig 3C), reflecting preference for areas closely associated with the warm mixed layer above the thermocline.

It is interesting to note that our finding shows Chl-a as a key oceanographic indicator of locating hotspots for skipjack tuna within the southwestern Coral Triangle tuna. This finding provides an important step to improve our understanding on distribution pattern and migration route for skipjack tuna in western Tropical Pacific Ocean, particularly within Coral Triangle tuna region. The Chl-a concentration is an index of phytoplankton biomass (principal photosynthetic organisms in the ocean) which provides valuable information about trophic interactions, forage habitat and dynamic movement of pelagic species [9,39,40]. We show that favorable Chl-a for skipjack has more specific range than the previous study [22] and clearly indicates frontal areas at the level of 0.2 mg m^{-3} Chl-a isopleth (Fig 4). Skipjack tuna fishing sets assembled in waters along Chl-a front (Figs 2 and 4), implying that this oceanographic feature plays a role for detecting skipjack habitat hotspot along study area. Previous investigations found that skipjack tuna in the tropical western Pacific (eastern Coral Triangle tuna) are caught within relatively low Chl-a (low primary production as well) which correspond to the salinity front and warm water SSTs [15,24]. Preference for 0.2 mg m^{-3} Chl-a, indeed, has important biophysical, physiological and trophic implications. This allows skipjack tuna to locate and forage along the frontal zones within preferred temperatures and SSHAs [18,22,41]. Therefore, our results suggest that pelagic habitat hotspots associate well with the Chl-a front, which in turn corresponds to the high skipjack concentrations.

In the present paper, we explore the performance of skipjack hotspots based on the three main points: (1) high PHI; (2) the area of potentially suitable habitat and (3) persistence of the most suitable habitat. For the period of 5 years, our findings show that the areas of the most potential skipjack habitat hotspot consistently peak in May corresponding to the highest PHI (Figs 5 and 6). These areas may relate strongly with enhanced feeding opportunity for skipjack. Skipjack tuna move and exploit primarily high densities of food organisms, which could be tracked by the high PHI. We consider that the skipjack forage such as anchovy, cephalopods and crustacean [42] are more abundant in the areas of increased probability index. It is more than 80% of skipjack stomach content caught in the western Coral Triangle tuna is anchovy (S*tolephorus spp.*) [43]. As visual predators, tuna need clear waters to efficiently capture the prey [44] and the silver stripe on flanks of the anchovy may be the reason for skipjack to easily catch them. We propose that the PHI provides a reasonable proxy, which is capable of detecting forage abundance, and then it is that of modifying skipjack tuna spatial distribution and abundance. Several investigations found that the distribution and abundance of tuna are strongly related to the forage availability [23,45,46]. The potential habitats in this month may have a good association with enhanced feeding opportunity for skipjack which is probably stimulated by the frontal systems [17,19] and upwelling zones [27], and ocean currents [47]. Therefore, the efforts of detection of the skipjack tuna forage habitat represented by the high PHI are the key factor to increase the commercial fishing success.

Although the formations of habitat hotspot varied spatially, however, spatial mean positions of the pelagic hotspots did not substantially change (Fig 5). Habitat hotspots in the Gulf of Bone such as in 2007 appear more pronounced than in the Flores Sea reflecting that the enhanced forage habitat supporting high tuna concentration cover a wide area. In the subsequent years, the biologically rich habitats mainly perform along the Chl-a of 0.2 mg m^{-3} (Chl-a front). Several explanations for the association of tunas with fronts include: (1) the availability of appropriate food; (2) confinement to a physiologically optimum temperature range; (3) use of frontal gradients for thermoregulation; (4) limitation of visual hunting efficiency owing to water clarity [41]; and (5) forage habitat and migration route [9,48]. The Chl-a front appears to coincide with the shelfbreak position (approximately 350 m isobath) of Both Flores Sea and Bone Gulf (Figs 1,5 and 10). Highest skipjack CPUEs are concentrated near shelfbreak location [17] during the daytime [49]. Our findings confirm that most of the empirical fishing data (2007-2011) consistently exploit the forage habitat during the daytime and, using fishing data in 2012, we feel our predictions have been substantially verified (Figs 5, 8 and 9). To improve the model performance, we suggest to taking into account the effect of upwelling and current systems on the analysis. Certainly, these factors warrant future investigation.

It is important to note that we did not show monthly temporal persistence of the habitat hotspot from January to June since there were no significant persistent areas throughout the period. At the peak season for 5-years (May 2007-2011), we find that less than 2% of the study area exhibits a persistent concentration of habitat hotpots (Fig 10). We suggest that these areas play a pivotal role since skipjack CPUEs increase significantly with increasing the habitat persistence (Fig 10) and thereby provide potential targets for marine conservation and fishing management strategies. The geographical position of the persistent habitat hotspots can be clearly predicted using spatial contour of the 0.2 mg m^{-3} Chl-a concentration detectable from satellite images. Indeed, the use of this variable has proved the key for detecting the forage habitat of several important pelagic species [9,50]. As a result, our findings could be as preliminary nature of results in providing new insight into detection of skipjack tuna distribution and abundance in either the Coral Triangle tuna region or the western tropical Pacific Ocean.

Conclusions

Pelagic habitat hotspots for skipjack tuna in the southwestern Coral Triangle tuna are influenced by the optimum combination of environmental factors (SST, Chl-a and SSHA) detectable from satellite images. Skipjack CPUEs increased significantly in the areas of highest pelagic hotspot index (PHI). We found the key pelagic habitat corresponded mainly with the Chl-a front, which could stimulate enhanced forage abundance for skipjack within a physiologically optimum temperature range above the thermocline depth. The habitat hotspot and its persistence are clearly identified by 0.2 mg m^{-3} Chl-a isopleth, suggesting that the Chl-a front provides an important step on detection of habitat hotspots, distribution pattern and abundance of skipjack tuna in the western tropical Pacific Ocean, especially within Coral Triangle tuna.

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Author Contributions

Conceived and designed the experiments: MZ SJ SS. Analyzed the data: MZ SH. Contributed reagents/materials/analysis tools: MBS AF MR MS NN. Wrote the paper: MZ.

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Supporting information:

S1 Fig. The spatial distribution of SST for May 2007-2011 estimated from MODIS ocean color data. The dash lines correspond to the approximate optimum SST range.

S2 Fig. The spatial distribution of SSHA for May 2007-2011 estimated from AVISO - altimetry. The dash lines indicate the approximate optimum SSHA range.

Figure 1.

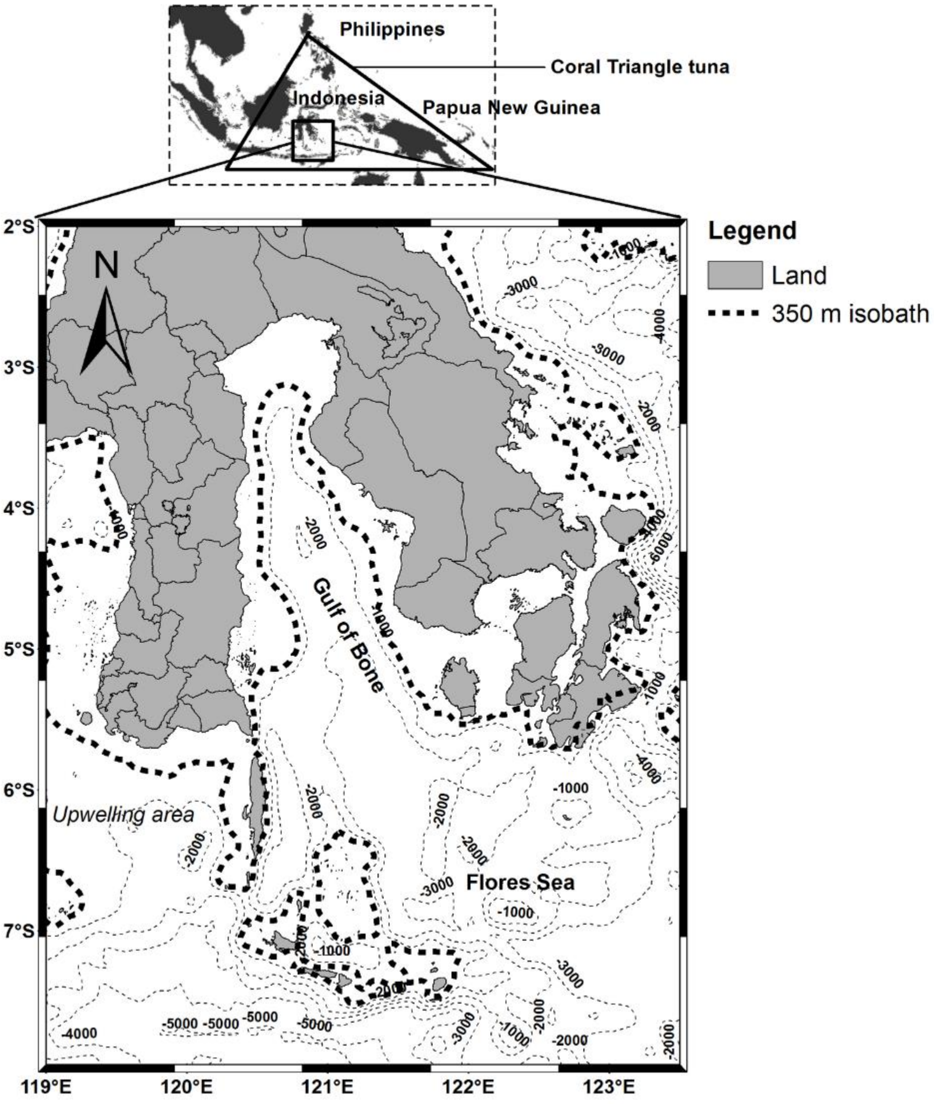

Philippines
Coral Triangle tuna
Indonesia
Papua New Guinea
Legend
Land
350 m isobath
N
Gulf of Bone
Flores Sea
Upwelling area
2°S
3°S
4°S
5°S
6°S
7°S
119°E
120°E
121°E
122°E
123°E
-1000
-2000
-3000
-4000
-5000
-6000

Figure 2.

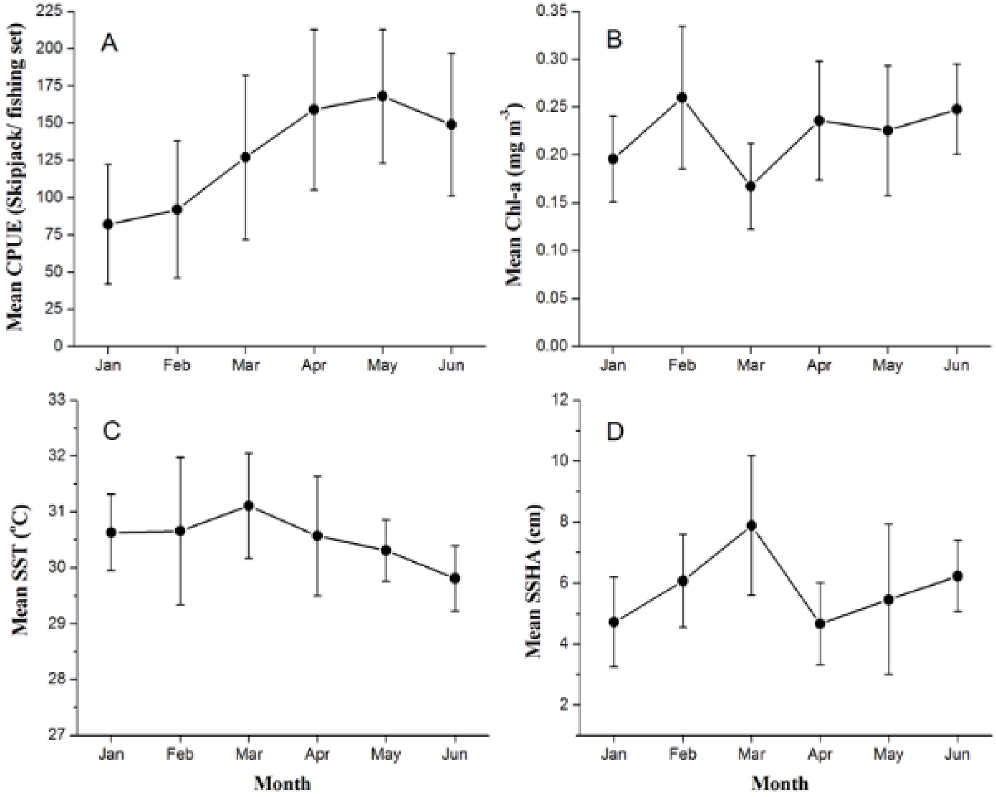
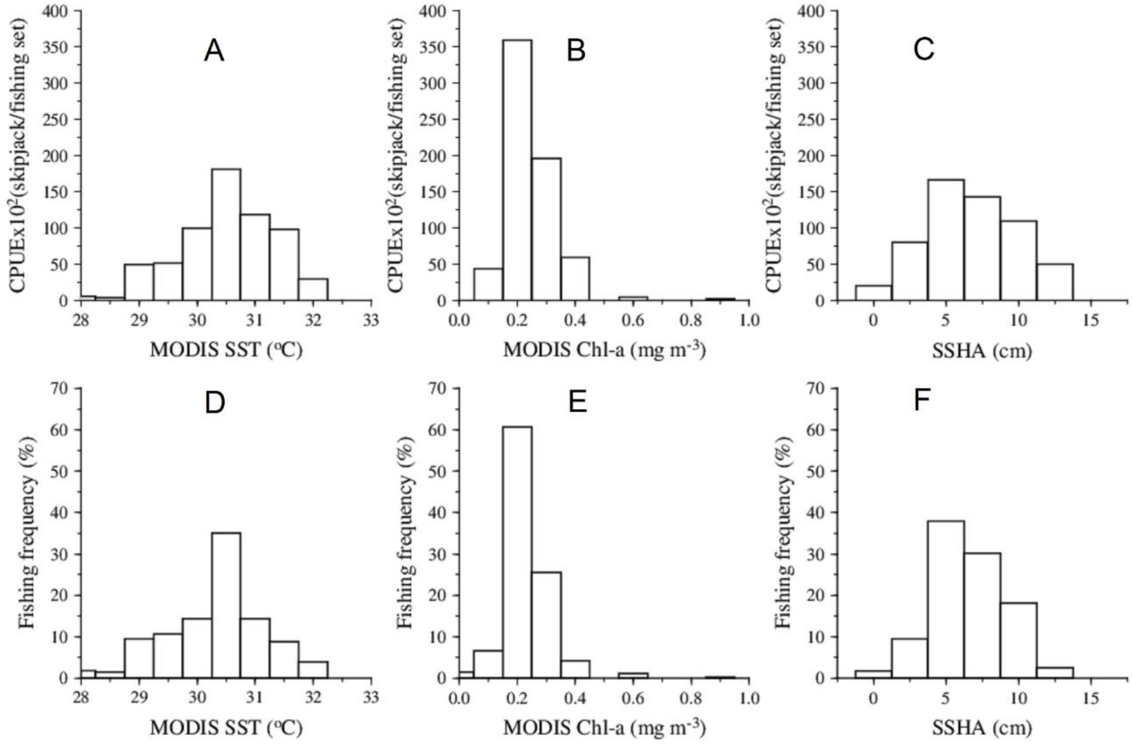

A
Mean CPUE (Skipjack/ fishing set)
0
25
50
75
100
125
150
175
200
225
B
Mean Chl-a (mg m^{-3})
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
C
Mean SST (^{o}C)
27
28
29
30
31
32
33
D
Mean SSHA (cm)
2
4
6
8
10
12
Jan
Feb
Mar
Apr
May
Jun
Month

Figure 3.



A
B
C
D
E
F
CPUEx10^2(skipjack/fishing set)
Fishing frequency (%)
MODIS SST (°C)
MODIS Chl-a (mg m^{-3})
SSHA (cm)
0
50
100
150
200
250
300
350
400
10
20
30
40
60
70
28
29
31
32
33
0.0
0.2
0.4
0.6
0.8
1.0
5
15

Figure 4.

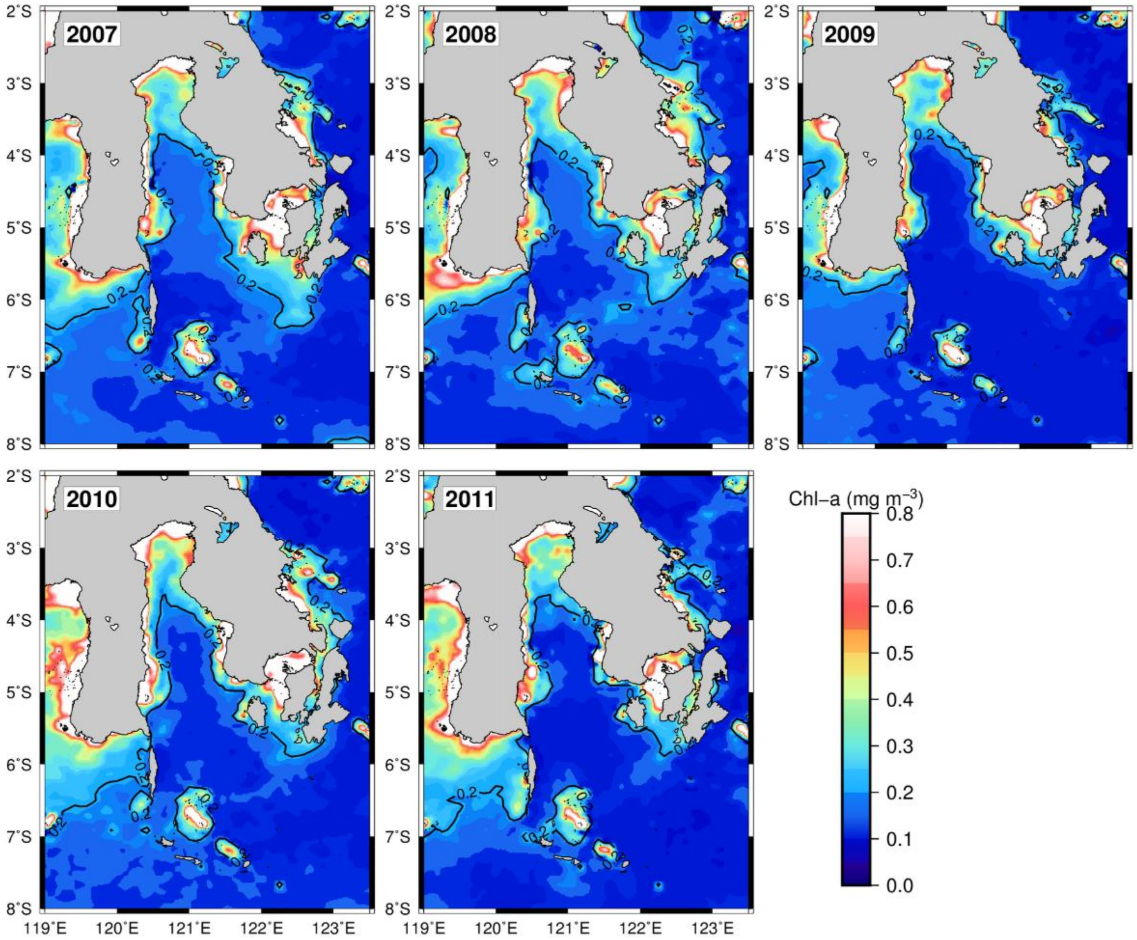

2007
2008
2009
2010
2011
2°S
3°S
4°S
5°S
6°S
7°S
8°S
119°E
120°E
121°E
122°E
123°E
0.2
Chl–a (mg m^{-3})
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

Figure 5.

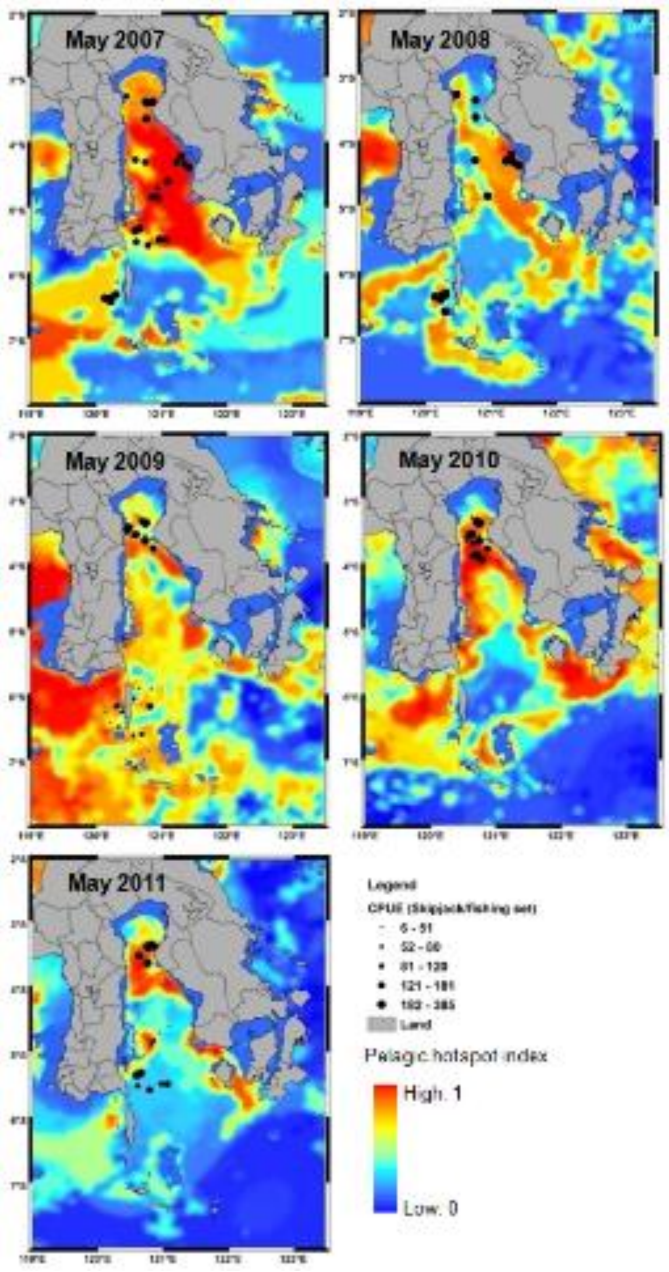
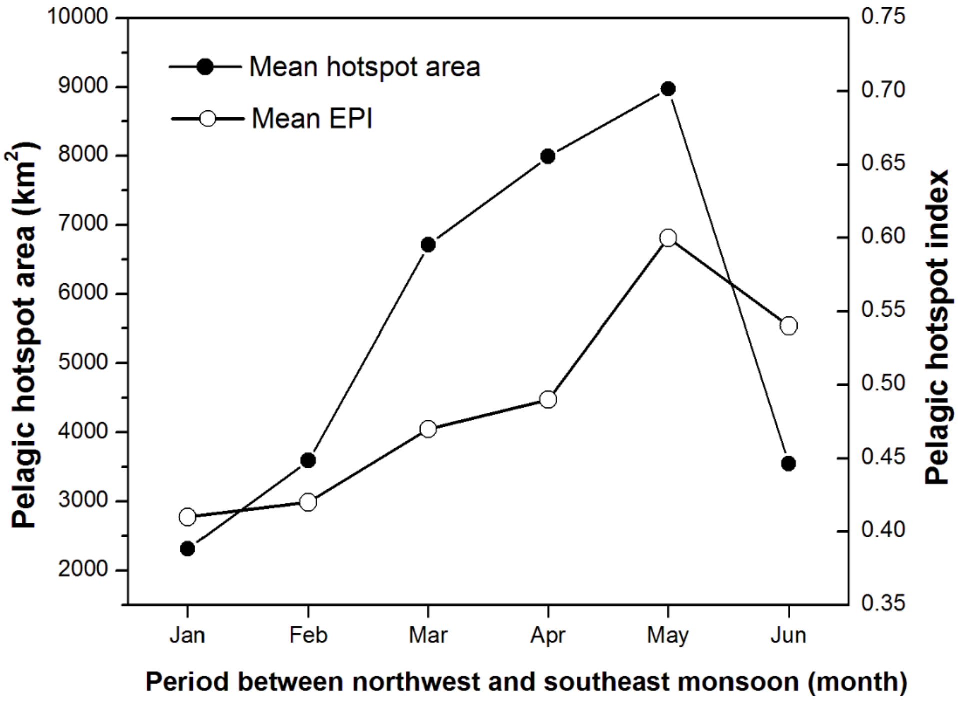
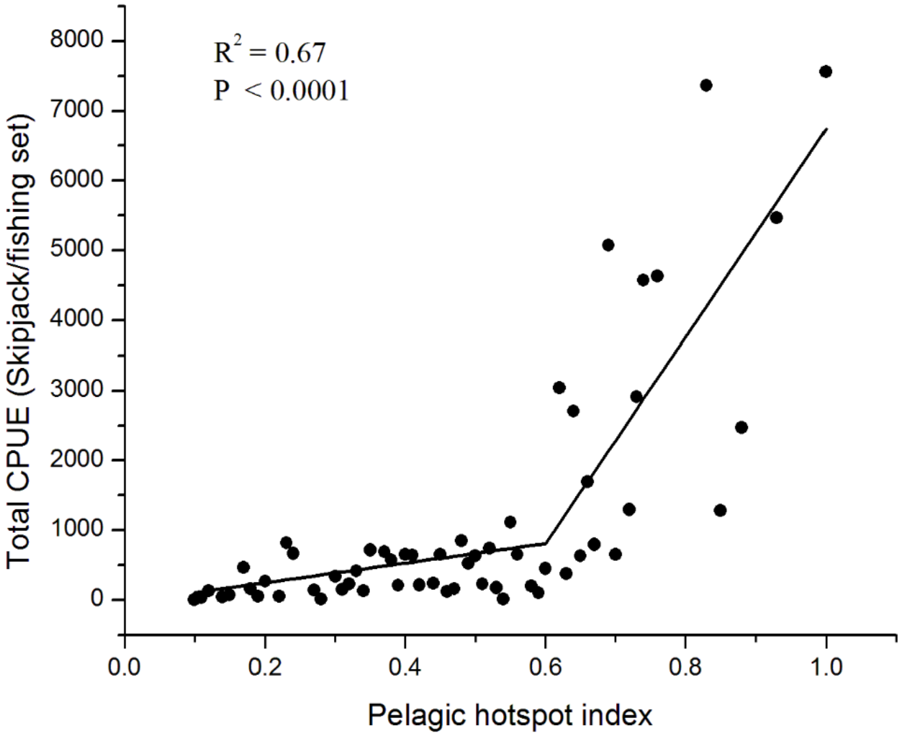

May 2007
May 2008
May 2009
May 2010
May 2011
Legend
CPUE (Skipjack/fishing set)
6 - 51
52 - 80
81 - 120
121 - 181
182 - 385
Land
Pelagic hotspot index
High. 1
Low. 0

Figure 6.



10000
9000
8000
7000
6000
5000
4000
3000
2000
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
Mean hotspot area
Mean EPI
Pelagic hotspot area (km^2)
Pelagic hotspot index
Jan
Feb
Mar
Apr
May
Jun
Period between northwest and southeast monsoon (month)

Figure 7.



$R^2 = 0.67$
$P < 0.0001$
Total CPUE (Skipjack/fishing set)
8000
7000
6000
5000
4000
3000
2000
1000
0
0.0
0.2
0.4
0.6
0.8
1.0
Pelagic hotspot index

Figure 8.

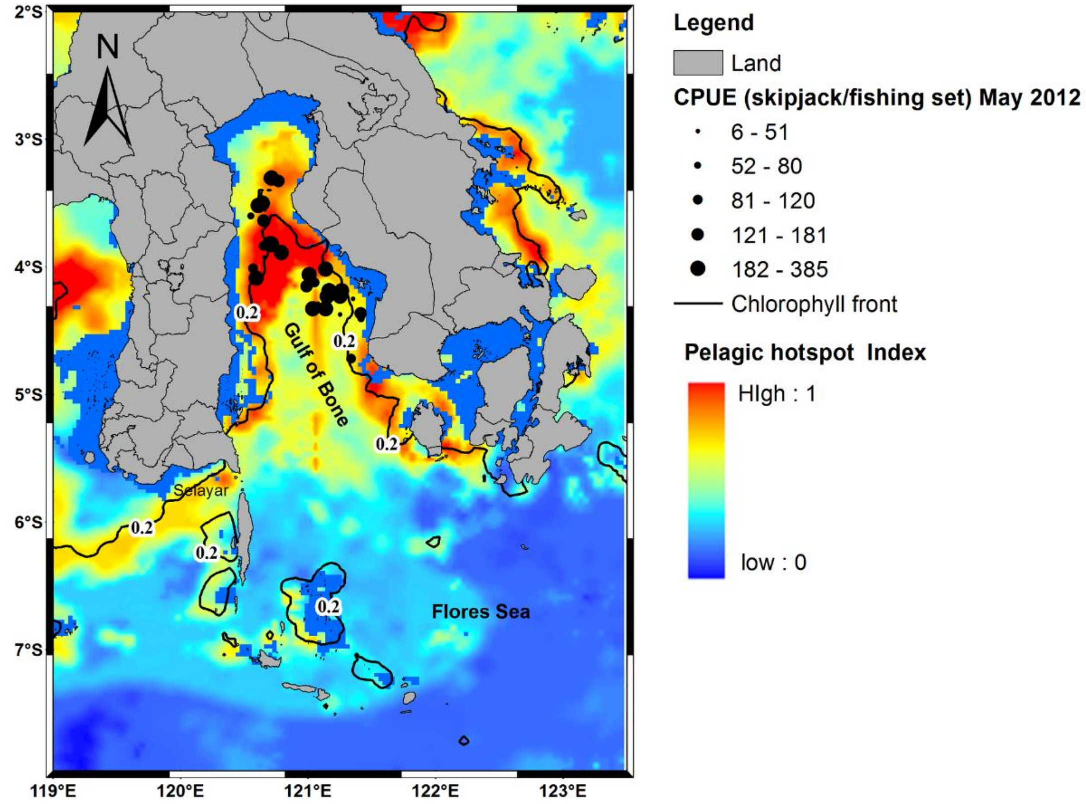
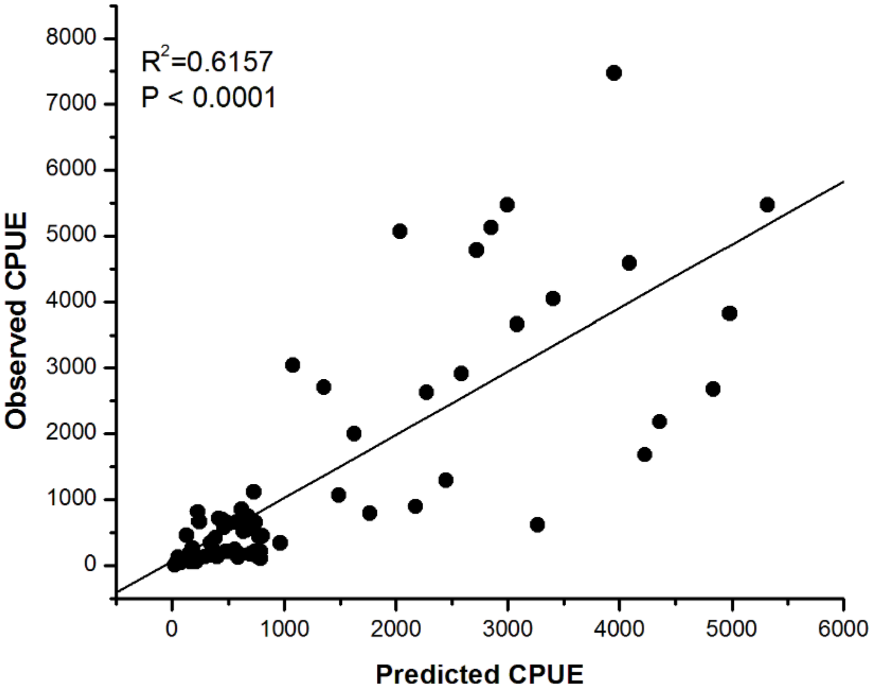
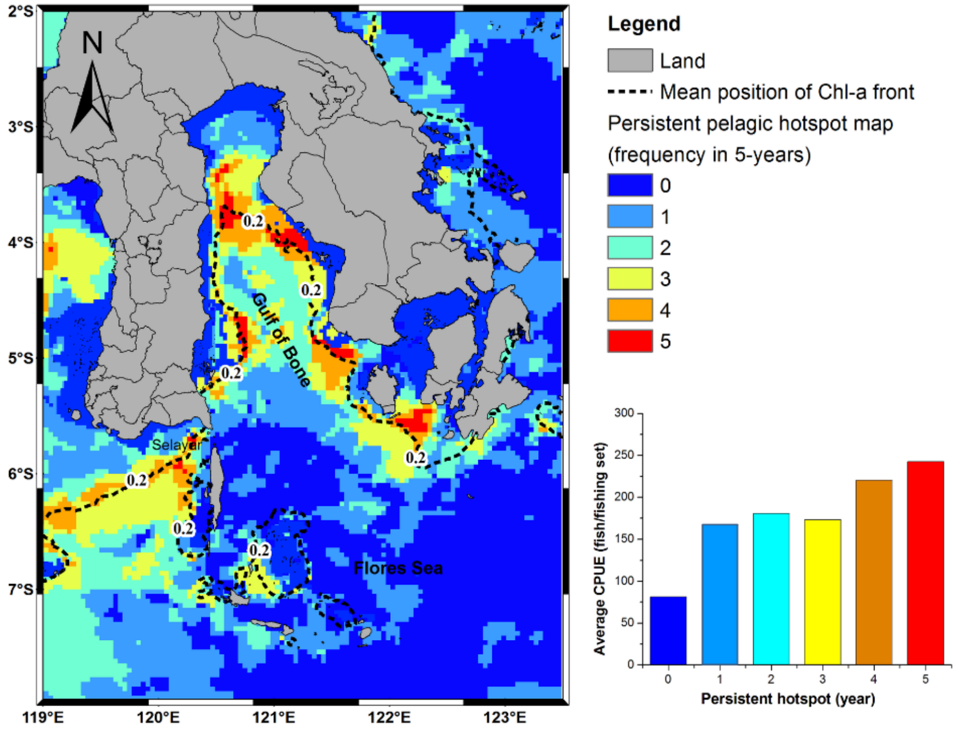

2°S
3°S
4°S
5°S
6°S
7°S
119°E
120°E
121°E
122°E
123°E
N
0.2
Gulf of Bone
Selayar
Flores Sea
Legend
Land
CPUE (skipjack/fishing set) May 2012
6 - 51
52 - 80
81 - 120
121 - 181
182 - 385
Chlorophyll front
Pelagic hotspot Index
HIgh : 1
low : 0

Figure 9.

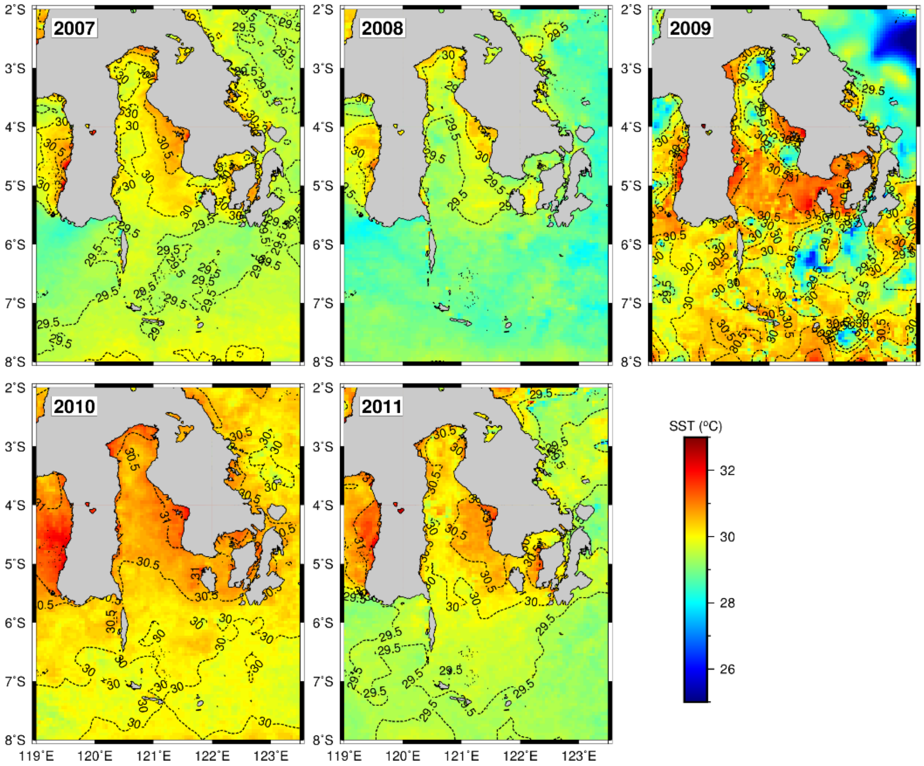


R^2=0.6157
P < 0.0001
Observed CPUE
Predicted CPUE
0
1000
2000
3000
4000
5000
6000
7000
8000
0
1000
2000
3000
4000
5000
6000

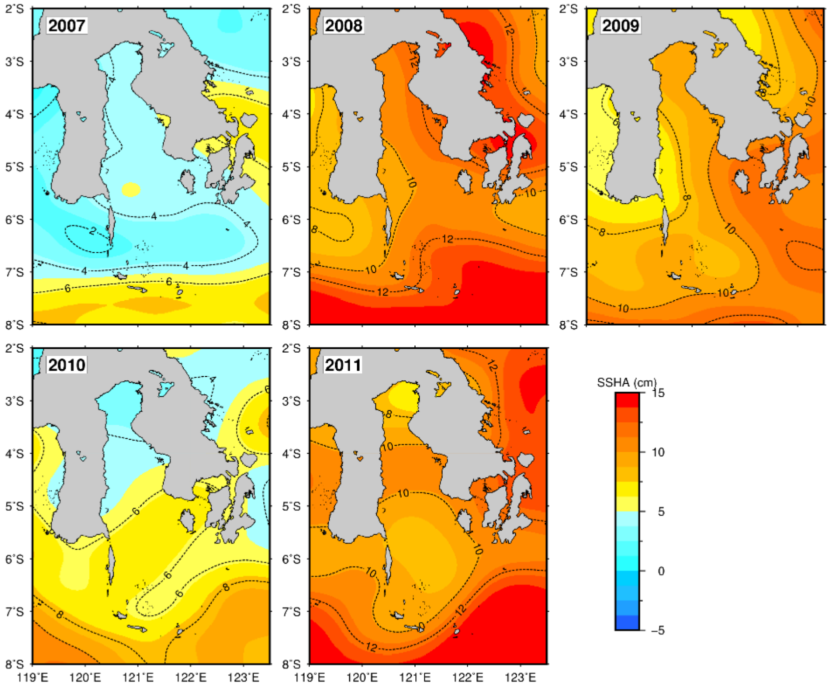
Figure 10.


N
2°S
3°S
4°S
5°S
6°S
7°S
119°E
120°E
121°E
122°E
123°E
0.2
Gulf of Bone
Selayar
Flores Sea
Legend
Land
Mean position of Chl-a front
Persistent pelagic hotspot map
(frequency in 5-years)
0
1
2
3
4
5
Average CPUE (fish/fishing set)
300
250
200
150
100
50
0
Persistent hotspot (year)
0
1
2
3
4
5

S1:


2007
2008
2009
2010
2011
2°S
3°S
4°S
5°S
6°S
7°S
8°S
119°E
120°E
121°E
122°E
123°E
SST (°C)
32
30
28
26

S2:


2007
2008
2009
2010
2011
2˚S
3˚S
4˚S
5˚S
6˚S
7˚S
8˚S
119˚E
120˚E
121˚E
122˚E
123˚E
SSHA (cm)
15
10
5
0
−5

PLOS ONE Decision: Revision required [PONE-D-17-09790] - [EMID:fb472967737f0aca]

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Reviewers' comments:

Reviewer's Responses to Questions

Comments to the Author

1. Is the manuscript technically sound, and do the data support the conclusions?

The manuscript must describe a technically sound piece of scientific research with data that supports the conclusions. Experiments must have been conducted rigorously, with appropriate controls, replication, and sample sizes. The conclusions must be drawn appropriately based on the data presented.

Reviewer #1: Partly

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2. Has the statistical analysis been performed appropriately and rigorously?

Reviewer #1: Yes

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3. Have the authors made all data underlying the findings in their manuscript fully available?

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5. Review Comments to the Author

Please use the space provided to explain your answers to the questions above. You may also include additional comments for the author, including concerns about dual publication, research ethics, or publication ethics. (Please upload your review as an attachment if it exceeds 20,000 characters)

Reviewer #1: In the manuscript of Zainuddin et al, on the “Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia”, the authors examined the relationship between the remote sensing oceanographic data and skipjack tuna CPUE and fishing effort, and explored their habitat hotspots. I agree with the value of this manuscript, but I've identified some major issues below that I'd like to authors to address either in a revision or in a rebuttal before considering publication.

・ It is very important to understand variations in fish habitat hotspots influenced by specific environmental variables. However, the same topic has been studied by various methods in the past decade for skipjack tuna. I do not understand the novelty of this particular study. The authors should clarify your novelty on your topic in the introduction section.

・The method in this study was basically similar to Zainuddin et al (2006, 2008) as below. Is there any new or improvement of this method in your study? Furthermore, the statistical methods in this manuscript are poorly described and totally absent in some cases, such as for regression and correlation analyses for the hotspots index and CPUE.

Zainuddin, M., Kiyofuji, H., Saitoh, K., & Saitoh, S. I. (2006). Using multi-sensor satellite remote sensing and catch data to detect ocean hot spots for albacore (thunnus alalunga) in the northwestern north pacific. Deep-Sea Research Part II, 53(3), 419-431.
Zainuddin, M., Saitoh, K., & Saitoh, S. I. (2008). Albacore (thunnus alalunga) fishing ground in relation to oceanographic conditions in the western north pacific ocean using remotely sensed satellite data. Fisheries Oceanography, 17(2), 61–73.

・ Did the three environmental variables used in developing the probability index correlate to each other? You calculated the pelagic hotspot index (PHI) by averaging three environmental variables, which mean each variable contributed equally to the PHI. Actually, how do they contribute to your prediction model? It should be useful to provide substantial information on this calculation approach and discuss its effects on the prediction results.

・ Why only the data in May 2012 was used to validate the prediction model? How about the prediction performance in other months in 2012?

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6. If you would like your identity to be revealed to the authors, please include your name here (optional).

Your name and review will not be published with the manuscript.

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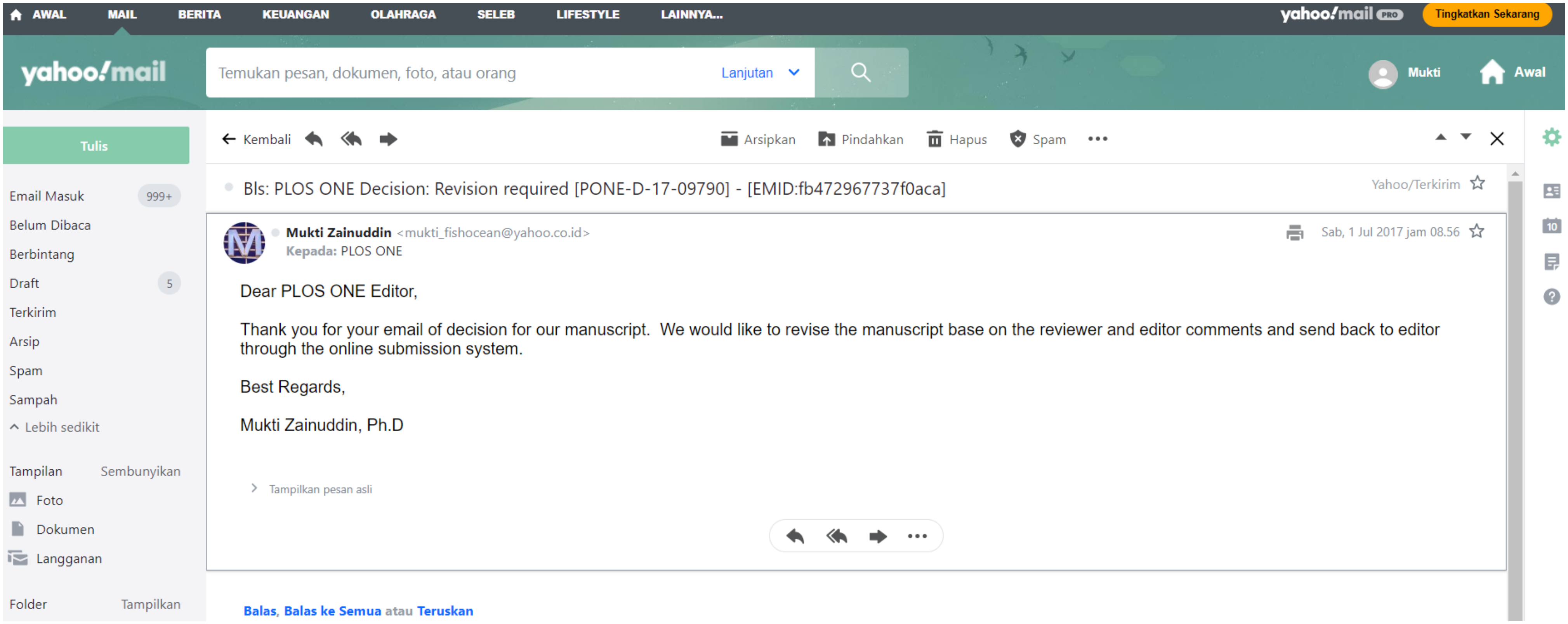
RESPONSE : 1st JULY 2017



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Mukti Zainuddin <mukti_fishocean@yahoo.co.id>
Kepada: PLOS ONE

Sab, 1 Jul 2017 jam 08.56

Dear PLOS ONE Editor,

Thank you for your email of decision for our manuscript. We would like to revise the manuscript base on the reviewer and editor comments and send back to editor through the online submission system.

Best Regards,

Mukti Zainuddin, Ph.D

REVISED PAPER SUBMITTED (ACCEPTED PAPER) TO PLOS ONE JOURNAL
ON 6 AUGUST 2017

AS THE RESPONSES TO REVIEWER, EDITOR DAN PROOF READER (PROF. SUSAN WILLIAM) COMMENTS

Cover Letter 2

Date: 11 August 2017

Dear Editor PLOS ONE,

Here I am sending one revised manuscript entitled “Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia”, by Mukti Zainuddin, Aisyah Farhum, Safruddin Safruddin, Muhammad Banda Selamat, Sudirman Sudirman, Nurjannah Nurdin, Mega Syamsuddin, Muhammad Ridwan and Sei-Ichi Saitoh, to accommodate the reviewers’ comments.

The manuscript consists of 27 pages including 2 tables, 10 figures (including two revised figures) and 2 supporting information files.

To improve the clarity and readability of this manuscript, this revised manuscript has also been proofread by Prof. Susan Williams, Ph.D, UC (University of California) DAVIS, Department of Evolution & Ecology, Bodega Marine Laboratory.

Financial Disclosure:

This work was partly supported to MZ by the National Competitive Research Grant (HIKOM, 2016 and PTUPT, 2017), Ministry of Research, Technology and Higher Education of the Republic of Indonesia.

The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

We hope that this manuscript is now suitable for publication in the journal of PLOS One.

Best Regards,

Mukti Zainuddin
Faculty of Marine Science and Fisheries,
Hasanuddin University
Jl. P. Kemerdekaan KM 10 Kampus UNHAS
Tamalanrea, Makassar, 90245, Indonesia

Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia

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Abstract

Using remote sensing ~~data~~ of sea surface temperature (SST), sea surface height anomaly (SSHA) and chlorophyll-a (Chl-a) together with catch data, we investigated the detection and persistence of important pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, Indonesia. We analyzed the data for the period between the northwest and southeast monsoon 2007 -2011. A pelagic hotspot index was constructed from a model of multi-spectrum satellite-based oceanographic data in relation to skipjack fishing performance. Results showed that skipjack catch per unit efforts (CPUEs) increased significantly in areas of highest pelagic hotspot indices. The distribution and dynamics of habitat hotspots were detected by the synoptic measurements of SST, SSHA and Chl-a ranging from 29.5° to 31.5°C, from 2.5 to 12.5 cm and from 0.15 to 0.35 mg m^{-3}, respectively. Total area of hotspots consistently peaked in May. Validation of skipjack CPUE predicted by our model against observed data from 2012 was highly significant. The key pelagic habitat corresponded with the Chl-a front, which could ~~stimulate~~ be related to the areas of relatively high prey abundance (enhanced feeding opportunity) for skipjack. We found that the area and persistence of the potential skipjack habitat hotspots for the 5 years were clearly identified by the 0.2 mg m^{-3} Chl-a isopleth, suggesting that the Chl-a front provides a key oceanographic indicator for global understanding on skipjack tuna habitat hotspots in the western tropical Pacific Ocean, especially within Coral Triangle tuna.

Introduction

Pelagic habitat hotspots, which are ~~defines~~ defined as areas of high biological activity where linkages occur between physical processes, primary production, secondary consumers and higher tropic level predators, play an important role in controlling distribution, migration and abundance for commercial and wide-roaming pelagic species in many different oceans [1,2,3]. The distinct oceanographic signatures in turn ~~stimulate~~ signify enhanced trophic interactions, physiological and foraging advantages, ~~so that providing~~and thus provide high ecological and economic importance. Large pelagic fish as well as commercial fishing vessels recognize that prey organisms aggregate at ocean hotspots, which are mostly represented by ocean fronts, eddies and upwelling zones [2,3,4]. Thermal fronts are ~~has proved as an~~ important congregating spots for many valuable pelagic species in Baja California-Bering Sea [5]. In the western Mediterranean, the spatial pattern of bluefin tuna school distributions was determined by the key oceanic habitats (i.e. fronts and eddies) [6]. Using multi-spectrum satellite images, hotspots for albacore tuna in the western North Pacific Ocean correspond with surface fronts and eddies [7,8]. Albacore forage habitat and migration routes are driven by the dynamic features of a pelagic hotspot ~~i.e~~namely a. Chl-a front known as the TZCF in the eastern and central Pacific Ocean [9]. Recent findings suggest that the frontal area, eddy field, and topographic features (~~Seamount~~seamount) ~~as~~ are important habitat hotspots for pelagic species such as flying squid and tuna [10,11,12]. Therefore, detection of the ecologically significant pelagic habitats and their spatial persistence ~~are~~ is critical for ~~setting up the~~ marine management strategies and identifying potential targets for conservation.

Skipjack tuna (*Katsuwonus pelamis*) is one of the most valuable species in the world in terms of catch weight [13]. It is a main target ~~and~~ of ~~exploited fisheries of high commercial value~~ a high-value commercial fishery in the tropical region, ~~it accounts~~accounting for more than one half (approximately 58%) of the global tuna catch [13]. ~~In recent years (catch proportion in average~~Between 2005-2014~~)~~, the fish contributed~~s~~ 47% of Indonesia total tuna catch [14]. Hence, understanding of the species optimal habitats is central ~~for~~ to evaluating fishing strategies and sustainable pelagic fisheries resources within Coral Triangle area.

~~Basically,~~The potential habitat for this species ~~inhabits~~ is within the warm surface layers of tropical and subtropical oceans [15,16]. Several oceanographic studies have found that skipjack tuna migration, distribution and abundance ~~have a link~~are linked with oceanic fronts and eddies [17,18,19] and are strongly influenced by ambient temperature and dissolved oxygen concentration [20,21]. In the western North Pacific Ocean, Sea Surface temperature (SST) and surface Chl-a ~~are~~ were found to be more ~~significant~~ important variables of ~~capturing~~ skipjack [22]. ~~Surface~~

~~temperature~~SST is one of the key oceanographic parameters to study skipjack tuna habitat in tropical region [23]. The occurrence of pelagic hotspots (salinity front and convergence zone) identified with 29°C SST isotherm provides a reasonable proxy to detect the region of highest skipjack CPUEs in western Pacific Ocean [24].

There are many studies that assess skipjack tuna habitat around the world using various methods. Skipjack forage habitats in the Pacific Ocean have been predicted based on Spatial Ecosystem and Populations Dynamics Model [15,23,25]. To characterize the spatial pattern of skipjack tuna habitat in the western North Pacific, generalized additive models (GAMs) and GIS techniques have been combined [22]. Using boast regression trees, the potential impact of climate change on skipjack tuna habitat in the Intra Americas Sea (IAS) has been discussed [26]. In the eastern central Atlantic and western Indian Oceans, favorable feeding habitats for skipjack have been investigated using a single ecological niche model [27]. The recent findings show that skipjack tuna habitats in different El Nino events can be identified based on the optimal model of Habitat Suitability Index (HSI) [28]. Most of the previous analyses of the preferred skipjack tuna habitat use statistical, ecological and spatial population dynamics models. The spatial persistence of the fish’s habitat has rarely been presented. In the present paper, we develop a model to explore not only habitat hotspots for skipjack tuna but also their persistence using multi-spectrum satellite images and high resolution of fishing performance data. This paper also highlights the important association between chlorophyll front and the skipjack habitats in the western Equatorial Pacific (southwestern Coral Triangle tuna).

The Coral Triangle ~~tuna~~, which primarily encompasses ~~primarily~~ the seas of Indonesia, Papua New Guinea and the Philippines is a known tuna (skipjack, yellowfin and bigeye) nursery and migratory path, producing about 46 % of all tuna catches in Western and Central Pacific

Ocean [~~25~~29,~~26~~30]. The Gulf of Bone - Flores Sea is an important coral reef area located in the southwestern Coral Triangle ~~tuna~~ where many commercial tuna fisheries conduct fishing operations. Our preliminary study ~~shows that the estimate of~~estimated the MSY (Maximum Sustainable Yield) for this study area is 49~~.~~,709 tonnes per year, indicating the great potential skipjack fishing ground. Statistical data (2007-2013) from Agency For Marine and Fisheries Affairs, South Sulawesi Province indicate that trend of skipjack catch tends to increase during the period between northwest and southeast monsoon. During this period, surface temperature gradually decrease while Chl-a tends to be high, providing high biological productivity ~~areas~~ [~~27~~31] which are in turn ~~correlated~~ correlates with high catches of skipjack [~~28~~32].

~~There are many~~Several ~~studies, which investigate~~ investigations have assessed skipjack tuna habitat in the western tropical Pacific Ocean especially northern waters of Papua (Indonesia) and Papua New Guinea [15,23,24]. Those areas are predominantly located in the eastern area of Coral Triangle tuna. However, there is a critical gap of information about skipjack tuna distribution in the opposite area (southwestern Coral Triangle tuna, particularly in the Gulf of Bone- Flores Sea). This area is one of the most potentially great tuna fishing grounds in Indonesia waters [~~27~~31,~~28~~32]. ~~Therefore, detection and visualization of a spatial pattern of the pelagic hotspot and its persistence in this area are the interesting challenges.~~ The aims of the present paper are to detect a spatial pattern of pelagic habitat hotspots for skipjack tuna and to map out their persistence in the southwestern Coral Triangle tuna using remotely sensed satellite and catch data.

Data and methods

Study area

The Coral Triangle tuna, so named because of its distinct triangular shape, contains nearly 5.7 ~~sq~~ km^2 of coral reefs and spans parts of six countries: Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands, and Timor-Leste [~~25~~29]. The area of interest, the Gulf of Bone-Flores Sea located in the southwestern Coral Triangle tuna is one of the most biologically productive skipjack fishing grounds (Fig~~ure~~ 1). In addition, the study area is also known as one of the main pathways of the Indonesian throughflow (ITF) and is strongly influenced by a tropical monsoon type of climate, resulting from the Asia-Australian monsoon wind systems, which change the wind direction ~~according to~~with the seasons, i.e. southeast monsoon and northwest monsoon [~~27~~31]. The interaction between the ITF and the Asian monsoon affects the specific current circulation system, Ekman mass and heat transport, tidal mixing, wind induced upwelling and down-welling systems and environmental variability of sea surface temperature (SST) and surface Chl-a concentration (hereafter Chl-a) [~~27~~31,~~29~~33,~~30~~34]. Dynamics of the biophysical oceanographic structures in this area, results in a highly productive pelagic habitat hotspot, which serves as a forage ground for various commercially and ecologically important pelagic species including tuna [~~28~~32,~~31~~35].

Fig 1. A location map of the southwestern Coral Triangle tuna showing the major oceanographic and bathymetric features. The broken lines correspond to the spatial position of 350 m isobath (shelfbreak).

Pole and line fishery data

The pole and line fishery in the study area, which extends from 118.5°E to 122.5°E longitude and 2°S-8°S latitude, captures the skipjack tuna mostly between the northwest and southeast monsoon (January-June). The fishery catch data were collected from pole and line fishing logbooks provided by the Fish Landing Bases in Luwu and Sinjai, South Sulawesi, and the and Kolaka Districts and Incorporated Company of Indonesian Government, PT. Perikanan Samudra at Kendari, Southeast Sulawesi in the period between northwest and southeast monsoon 2007-2011. The fishery data comprised daily geo-referenced fishing positions (latitude and longitude), catch in number of skipjack and effort (fishing set), from which catch per unit effort (CPUE) was determined in number of fish per fishing set, further compiled into monthly resolution datasets. To validate our model, the catch data were also collected from as many as ~~114~~ 140 sampling fishing positions from scientific pole and line fishing surveys in the study area during the same period in 2012.

Satellite remote sensing data

The physical and biological environmental data used to describe the oceanographic condition around the fishing locations are surface Chl-a concentration and sea surface temperature (SST). Terra/ MODIS (Moderate Resolution Imaging Spectroradiometer) level 3 standard mapped images (SMI) data were used to estimate sea surface Chl-a concentration and SST at all pole and line fishing ground locations. NASA distributes the level 3 binary data with HDF (*Hierarchical Data Format*) format. We obtained these data from NASA GSFC's Distributed Active Archive Center (DAAC) (http://oceancolor.gsfc.nasa.gov/). For this study, we used Global Area Coverage (GAC), monthly mean MODIS images with a spatial resolution of about 4 x 4 km for the study period during 2007-2011 (Table 1).

Table 1. Summary of oceanographic parameters used for developing habitat hotspot models for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia

Oceanographic variables	Abbreviation	Temporal Resolution	Spatial Footprint	Data Source
Sea surface temperature	SST	Monthly	4 km	Terra/MODIS
Surface chlorophyll-a	Chl-a	Monthly	4 km	Terra/MODIS
Sea surface height anomaly	SSHA	Daily	25 km	AVISO

In the present study, we used SSHA data distributed by AVISO (the Archiving, Validation and Interpretation of Satellite Oceanographic data). The SSHA data were global images with 0.25 º spatial resolution in both longitude and latitude. Due to the different spatial and temporal resolutions with SST and Chl-a, the SSHA data were resampled into the spatial footprint (4 km) and sampling interval (monthly) spatial resolutions and then subset to the study area. Monthly values of all satellite images (SST, Chl-a and SSHA) were extracted from each pixel corresponding to the location of fishing activities using spatial analyst of ArcGIS 10.3. The result was a full matrix of the skipjack tuna CPUE as well as the environmental variables. All satellite images were processed using IDL (Interactive Data Language) software package and had the same spatial and temporal resolutions prior to the model construction.

Construction of pelagic habitat hotspot map

To detect the spatial pattern of the skipjack pelagic hotspots throughout study area, we constructed a model of fishery performance, which took into account both CPUE (index of fish abundance) and frequency of fishing effort (index of fish occurrence) in relation to the three oceanographic variables. This model was improved and developed from the albacore hotspot model [7] by adding a weighting factor, allowing the contribution of each variable on the pelagic hotspot index (PHI) was taken into account. In addition, we added SSHA variable into the model to address the relationship between skipjack tuna and mesoscale variability. ~~and SSHA variable into the model.~~

The habitat hotspot was determined using environmental probability indices, reflecting the high probability areas of finding skipjack tuna. Specifically, the ~~pelagic hotspot index (~~PHI~~)~~ was computed based on total CPUE at a given interval of histogram divided by the maximum total CPUE from all class intervals of the three variables (SST, SSHA and Chl-a) (Eq. 1), and fishing frequencies were also calculated with the same method (Eq.2). The variable which has the highest CPUE or fishing frequency (maximum value) was used a standard. Then, we calculated the average of probability indices from the interval ranges of all variables (eq.3). The highest probability value in which the probability index is more than 0.75 (PHI > Quartile 3) indicated the pelagic habitat hotspots, showing the greatest probability areas of finding the fish. In contrast, the lowest probability denoted the least suitable locations for detecting skipjack tuna. Lastly, we combined the three satellite images to create a pelagic hotspot map for all interval ranges of the environmental conditions.

The CPUE data were then overlain on the map and the probability index of the joint environmental factors was extracted from each pixel corresponding to the fishing ground positions. The probability area was visualized using ArcGIS 10.3 Spatial Analyst software package. Then, based on the distribution of data points, we employed the piecewise regression technique ~~we~~ to examine~~d~~ the relationship between total CPUE and the ~~level of probability~~hotspot index around fishing locations. To evaluate the strength of the relationship, we used the correlation coefficient (r). Here this attempt focused on an analysis of the pelagic hot~~-~~spots ~~on~~ in the seasons of highest skipjack abundance from 2007-2011. For validation, we analyzed catch and the environmental data during the same period in 2012 using both spatial distributions of fishing data on the hotspot map and the correlation analysis. All the habitat hotspot images were mapped using spatial analyst toolbox in ArcGIS software package. The model used to calculate pelagic habitat hotspot index (PHI) as follows:

$$\mathrm{PI}_{cpue} = \frac{\sum \frac{cpue_{ij}}{cpue_{i\,max}}}{n} \tag{1}$$

$$\mathrm{PI}_{f} = \frac{\sum \frac{F_{ij}}{F_{i\,max}}}{n} \tag{2}$$

$$\mathrm{PHI} = \frac{(\mathrm{PI}_{cpue} + \mathrm{PI}_{f})}{2} \tag{3}$$

Where PHI is the pelagic hotspot index; PI_{cpue} is the mean probability index for skipjack based on the relationship between CPUE and the three oceanographic variables (SST, Chl-a, SSHA) for each histogram graph; PI_{f} is the mean probability index based on the relationship between fishing frequency and the oceanographic variables for the histogram graphs; $cpue_{ij}$ is the value of CPUE in relation to oceanographic variable-i for class interval-j; $cpue_{i}$ max is the maximum value of CPUE among the oceanographic variables; F_{ij} is the value of fishing frequency in relation to oceanographic variable-i for class interval-j; $F_{i\,max}$ is the maximum value of fishing frequency among the oceanographic variables; n is the total number of variables.

Detection of persistent pelagic habitat hotspot

A persistent pelagic hotspot map was constructed based on the presence or absence of the strong environmental probability index (probability of more than 75%) in the study area. We built the persistent hotspot map by computing monthly mean composite hotspot images at the peak season between the northwest and southeast monsoon 2007-2011. The map consisted of value ranging from zero (0) to five (5). The highest value (5) indicated that the persistent hotspot at a certain spatial location took place during the period of five years. While, the lowest value (0) denoted that there was no persistent hotspot available at a given area during at least one year. Then, we overlaid the conspicuous environmental characteristics on the map to find a reliable proxy indicator for locating the persistent skipjack habitat hotspots.

Results

Temporal variation of catch data and environmental variables

During the period of April-June, skipjack CPUEs tended to be high and reached the peak in May (Fig 2A). Catch level in this month was about 170 fish/fishing set. The highest CPUEs occurred in areas of relatively high Chl-a and warmer SST ranging from 0.16 to 0.3 mg m^{-3} (0.22±0.068 mg m^{-3}) (Fig 2B) and from 29.76 to 30.86 °C (30.31±0.55 °C) (Fig 2C), respectively. At the same time, the greatest skipjack catches were obtained in waters of positive SSHA ranging from 3.04 cm to 7.96 cm (5.50 ± 2.46 cm) (Fig 2D). ~~Whereas during~~During January-March, the catch rates (CPUEs) appeared to be lower than those of subsequent months. During that period, the fishing sets occupied the locations where surface temperature was relative high and Chl-a as well as SSHA ~~were highly~~ fluctuated highly.

Fig 2.Temporal variability of (A) CPUE of skipjack fishery, (B) SST, (C) Chl-a concentration, and (D) SSHA, between northwest and southeast monsoon (January-Juni) 2007-2011.

Skipjack tuna in relation to environmental variables

Satellite based oceanographic data in relation to skipjack tuna fishing performance indicated the specific ranges where the fish were most abundant (Fig 3). Total CPUEs in relation to SST showed that most of the catches were concentrated in areas where SST ranged from 29.75 to 31.25ºC using histogram graph (Fig 3A). The similar trend was found in the relationship between the frequency of fishing set and SST (Fig 3D). Both histograms revealed that the preferred SST tended to center at 30.5ºC, which reflected the highest probability of finding fish in term of SST. Total skipjack CPUEs in relation to Chl-a indicated that skipjack CPUEs were mainly found in areas where the environmental variable occurred mainly from 0.15 to 0.35 mg m^{-3} (Fig 3B). The relationship between skipjack fishing frequency and the surface Chl-a also showed a similar pattern (Fig 3E). The Chl-a preference for skipjack tuna mostly concentrated at 0.2 mg m^{-3}. Whilst ~~Skipjack~~ skipjack catches and fishing sets were derived in substantial number in waters where SSHA varied between 0 and 12.5 cm (Fig 3C). Both fishing performance reached an average at approximately 6 cm (Fig 3C- 3F).

Fig 3. Total skipjack CPUE (skipjack/fishing set) in relation to MODIS SST (A), MODIS Chl-a (B), and SSHA (C) and fishing frequency in relation to SST (D), Chl-a (E) and SSHA (F) during January-June 2007-2011.

It is worth noting that Chl-a was the most important oceanographic variable to explain skipjack fishing performance. Specifically, we found that chlorophyll concentrations of about 0.2 mg m^{-3} was a good proxy for describing the highest total skipjack CPUEs (~54%) and fishing frequency (~60%) (Fig 3). Whilst, the value of SST 30.5°C was capable of exposing the catch rates of approximately 29% and frequency of the fishing set of about 35%. ~~Whereas, the~~The optimum SSHA value of near 6 cm accounted for the ~~fishing productivity~~skipjack CPUE and frequency of the fish occurrence were about 28% and 40%, respectively.

The associated highest catches with the Chl-a front ~~well~~ formed every year during 2007-2011 (Fig 4). The chlorophyll front consistently occurred in ~~the~~ a specific location within the study area. ~~This fact means that~~Thus, the potential habitat was constantly available for the fishery every year (2007-2011) based on the environmental indicator. For the SST variable, the dynamics and position of the optimum range varied widely both in longitude and latitude and sometimes disappeared over the Flores Sea for instance in May 2008 (S1). Likewise, from the SSHA images, the spatial position of the most suitable range was widely distributed (S2).

Fig 4. The spatial position of the Chl-a front measured by the 0.2 mg m^{-3} Chl-a concentration contour for May 2007-2011 estimated from MODIS ocean color data. The solid lines correspond to the Chl-a front along the study area.

Pelagic habitat hotspot map for skipjack tuna

Areas of potentially suitable habitat hotspots for skipjack tuna strongly developed in May and covered the waters of approximately 8971 km^2 ~~in~~ on average (Fig 5). Mean PHI throughout the study area in the peak season was about 0.60. In contrast, the lowest pelagic habitat hotspot index occurred in January and occupied the areas of 2317 km^2 with mean hotspot index of 0.41.

Fig 5. The spatial distribution of skipjack CPUE (skipjack/fishing set) from the pole and line fishery shown as dots for May 2007-2011 overlain on pelagic hotspot maps generated from a model of satellite images (Chl-a, SST and SSHA) in relation to fishing performance.

During five years period, the spatial dynamics and intensity of habitat hotspots appeared to change significantly (Fig 6). However, it is important to note that a Chl-a of 0.2 mg m^{-3} isopleth ~~performed~~ was a good indicator for detecting spatial distribution patterns of the pelagic hotspots for all years (Figs 4 and 6). In 2007, the most suitable habitat strongly formed within the Gulf of Bone and was associated with the skipjack fishery distribution. The pelagic habitats were predicted to be in the eastern Bone Gulf and western ~~the~~ Flores Sea in the subsequent year. We found that skipjack catches mainly concentrated in the hotspot area. In 2009, the predicted hotspots were mostly found in the western Flores Sea, whilst the skipjack tuna seemed to be captured in the hotspot areas of the northern Bone Gulf. Then, in the following year 2010, the pelagic habitat hotspots developed ~~in agree well~~ with the chlorophyll front and were ~~in a good association~~associated closely with the fishery locations in the northern Bone Gulf. For the year of 2011, the habitat hotspots were well formed again in the northern area but with narrower both latitudinal and longitudinal bands and they matched generally with fishing data. In all years, it seems that the potential habitat ~~had~~ also had a good association with the shelf-break formation (at the depth of about 350 m).

Fig 6. Monthly mean temporal variability of pelagic hotspot area (km^2) and pelagic hotspot index between northwest and southeast monsoon 2007-2011.

The datasets for the period of northwest-southwest monsoon 2007-2011 showed that the total CPUEs significantly increased with the increasing probability values of joining environmental variables ($R^2=0.67$, $P<0.0001$) (Fig 7). The increasing CPUEs were substantially found when the pelagic hotspot indices were more than 60%. The first equation of the regression lines was $Y=b_0+b_1X_1$, when $X_1 \leq 0.6$ (X=0.6 indicates the point where the slope change), and the second equation was $Y=(b_0- 60b_2)+(b_0+b_1)X_1$ when $X_1>0.6$. Therefore, we suggested that the PHI of joint oceanographic variables provided a reasonable proxy for predicting pelagic hotspots for skipjack tuna.

Fig 7. The relationship between total skipjack CPUE and PHI in the southwestern Coral Triangle tuna using piecewise linear regression.

Prediction and validation of skipjack CPUE

For the spatial model validation, Fig 8 showed that the spatial distribution of the fishing data ~~in~~ during ~~May~~ March-June 2012 mostly occurred on predicted habitat hotspots (PHI > 0.75). The important skipjack habitats located the areas of 120.5-121.5°E longitude and ~~3.5~~3.25-4.5°S latitude. It is interesting to see that the mean geographical position of the habitat hotspot was highly consistent with the Chl-a front position along the study area. Using pelagic habitat hotspot index as a predictor for skipjack CPUE response, we found that the correlation of predicted skipjack CPUEs against ~~that~~ the observed was highly significant ($P < 0.0001$, $R^2 = 0.$~~60~~6157) (Fig 9). It inferred that during the period between the northwest-southwest monsoon, the pelagic hotspot model was significantly ~~capable of predicting~~predicted skipjack CPUEs.

Fig 8. The spatial distribution of skipjack CPUE (skipjack/fishing set) shown as dots ~~for~~ ~~May~~from March to June 2012 superimposed on the pelagic habitat hotspot map and Chl-a front. There is no fishing data during January-February 2012.

Fig 9. A scatter plot of pooled monthly observed against predicted skipjack CPUE values calculated from the pelagic hotspot index (PHI) ($P < 0.0001$, R^2 = ~~0.60~~0.6157).

Persistence of habitat hotspots for skipjack tuna

During the period of 5 years (May 2007-2011), the persistent habitat hotspots were found only in May and June (Table 2). The greatest persistent area occurred in May and covered approximately 1.21% of the grid cells in the southwestern Coral Triangle tuna for 5 years (Fig 10 and Table 2). These cells were all concentrated along the specific areas from the western Flores Sea, surrounding the Gulf of Bone to eastern Flores Sea. Nevertheless, our analysis indicated that more than 95% of the study area ~~had~~ did not have persistent habitat hotspots~~. This fact means that the key skipjack habitat was not omnipresent~~ throughout the study area. However, ~~it was remarkable that~~ all persistent habitat hotspot formations associated consistently with the Chl-a front indicated by 0.2 mg m^{-3}. Skipjack CPUE tended to increase at the most persistent habitat (Fig 10).

Fig 10. Spatial distribution of persistent pelagic habitat hotspots for skipjack tuna in the peak season May 2007-2011 (frequency/ 5 years) in the southwestern Coral Triangle ~~Tuna~~tuna, Indonesia (left) and the graphical relationship between average CPUE and persistent habitat hotspots (right).

Table 2. Persistence of habitat hotspot location for skipjack tuna, in number of pixel per year, in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia

Month \ Year	2007	2008	2009	2010	2011
January	3846	894	78	4	0
February	4540	966	89	5	0
March	3923	2614	170	7	0
April	3082	2738	910	43	2
May	3386	1874	1233	735	193
June	3166	2403	1004	387	119

Discussion

We have developed a model of satellite-based environmental data-fishing performance relationship to explore and map out the spatial distribution pattern and persistence of pelagic hotspots for skipjack tuna. The fishing performance data represented by CPUE and fishing frequency are low-cost fish distribution datasets commonly available to fishery scientists. CPUE data provide a good proxy as an index of fish abundance [15,~~32~~36], whereas fishing frequency data act as an index of fish occurrence or fish availability [7,~~33~~37]. The fishing data describe fisher's experience-based knowledge and provide invaluable supplement data to a better habitat prediction [~~34~~38]~~.~~, ~~Whilst,~~while satellite data are mostly available at no cost to the user ~~and are capable of accurately~~ monitoring oceanographic features over a wide area [9,~~35~~39]. ~~High performance of the fishery data in relation to satellite oceanographic information, therefore, could be considered as an important indication of finding habitat hotspots for pelagic species.~~Therefore, the strong correlation between the fishery data with the satellite oceanographic information provides an important means to identify habitat hotspots for pelagic species.

In principle, our model extracts the optimum combination of three environmental factors (SST, Chl-a and SSHA) from the areas of high fishing performance to produce pelagic habitat hotspots. Several studies supported that a combination of these factors plays a pivotal role in explaining and exposing a pelagic tuna habitat [7,8,22,~~36~~40]. Our results found that ~~The choice of~~ Chl-a ~~as~~ is an important variable for ~~this study as it is central for~~ identifying tuna forage habitat [9]. SST was selected to be another important variable for detecting the habitat hotspot since skipjack tuna are sensitive to the changes of temperature on their distribution [15]~~.~~ ,~~While~~ while SSHA ~~variable~~ is related to the changes ~~of~~ in the depth ~~distribution~~ of the thermocline and mesoscale variability [~~35~~39,~~37~~41]. We combined these variables to improve ~~a better estimate for detecting~~detection of potential pelagic hotspots for skipjack tuna.

Our results show that skipjack tuna habitat is ~~associates~~ associated with the areas of warm SST ~~(~ 30.5°C)~~, specific Chl-a concentrations ~~(centered at 0.2 mg m^{-3})~~ and positive SSHA ~~(near 6 cm)~~, favoring fishing operations (Figs 2 and 3). The surface temperature preference for skipjack is relatively warmer than ~~the results suggested~~reported from the other areas around the world

[15,22,27,28,~~33~~37]. ~~Highest~~ The highest catches consistently occur in May when SST gradually decrease to about 30.5°C after reaching a peak in November-December and back to the lowest SST in July and August [~~30~~34]. At the same time, the skipjack tuna fishery tends to ~~maintain~~ occur within the areas of positive SSHA anomalies suggesting that food ~~biomass~~ aggregates mainly at the surface when the thermocline depth moves ~~on~~ in the opposite direction of sea surface height [~~37~~41,~~38~~42]. We found that predominantly positive SSHA had an ~~real~~ effect on both skipjack CPUE and number of fishing set (Fig 3C), reflecting preference for areas closely associated with the warm mixed layer above the thermocline. The positive SSHA values are preferred for the skipjack tuna habitat [22,27], indicating the important anticyclonic eddy fields [43,44] where skipjack catches increase significantly [45].

It is interesting to note that our finding shows Chl-a as a key oceanographic indicator of locating hotspots for skipjack tuna within the southwestern Coral Triangle tuna. ~~This finding provides an important step to improve our understanding on distribution pattern and migration route for skipjack tuna in western Tropical Pacific Ocean, particularly within Coral Triangle tuna region. The~~ Satellite derived Chl-a concentration is an index of phytoplankton biomass ~~(principal photosynthetic organisms in the ocean)~~ which provides valuable information about trophic interactions, forage habitat and dynamic movement of pelagic species [9,~~39~~46,~~40~~47]. Skipjack feed on both the small epipelagic fish and zooplankton which all of them graze on phytoplankton [46]. The Chl-a concentrations control the skipjack abundance (CPUE) in the food web system through the linkages between phytoplankton and, zooplankton and small pelagic fish. Therefore skipjack tuna enable to take advantage of a short food-web which is probably efficient from the energetic point of view [48]. We show that favorable Chl-a for skipjack has more specific range than the previous study [22] and clearly indicates frontal areas at the level of 0.2 mg m^{-3} Chl-a isopleth (Fig 4). Skipjack tuna fishing sets assembled in waters along Chl-a front (Figs 2 and 4), implying that this oceanographic feature plays a role for detecting skipjack habitat hotspot along study area (Figs 5 and 8). ~~Previous investigations found that skipjack tuna in the tropical western Pacific (eastern Coral Triangle tuna) are caught within relatively low Chl-a (low primary production as well) which correspond to the salinity front and warm water SSTs [15,24].~~ Preference for 0.2 mg m^{-3} Chl-a~~, indeed,~~ has important biophysical, physiological and trophic implications. ~~This allows skipjack~~ Skipjack tuna ~~to~~ locate and forage along the frontal zones within the preferred temperatures and SSHAs [18,22,~~41~~49]. ~~Therefore, our results suggest that pelagic habitat hotspots associate well with the Chl-a front, which in turn corresponds to the high skipjack concentrations.~~

In the present paper, we explore the performance of skipjack hotspots based on the three main points: (1) high PHI; (2) the area of potentially suitable habitat and (3) persistence of the most suitable habitat. For the period of 5 years, our findings show that the areas of the most potential skipjack habitat hotspot consistently peak in May corresponding to the highest PHI (Figs 5 and 6). These areas may relate strongly with enhanced feeding ~~opportunity~~ opportunities for skipjack. Several investigations found that the distribution and abundance of tuna are strongly linked with the forage availability [23,50,51]. Skipjack tuna move and exploit primarily high densities of food organisms, which could be tracked by the high PHI. ~~We consider that the~~The skipjack forage on species such as anchovy, cephalopods and crustacean [~~42~~48], which are more abundant in the areas of increased probability index. ~~It is~~Anchovy (*Stolephorus spp.*) represent more than 80% of skipjack stomach content when caught in the western Coral Triangle tuna~~ is anchovy (S*tolephorus spp.*)~~ [~~43~~52]. ~~As visual predators, tuna need clear waters to efficiently~~

~~capture the prey [44] and the silver stripe on flanks of the anchovy may be the reason for skipjack to easily catch them.~~ We propose that the PHI provides a reasonable proxy~~, which is capable of~~ detecting forage abundance, and ~~then it is that of modifying~~thus skipjack tuna spatial distribution and abundance. ~~Several investigations found that the distribution and abundance of tuna are strongly related to the forage availability [23,45,46].~~ The ~~potential~~ key skipjack habitats in ~~this month~~the peak season (May) may have a good association with enhanced feeding opportunity for skipjack which is probably stimulated by the ~~frontal systems~~Chl-a front ~~[17,19]~~(Figs 4,8,10), ~~and~~ upwelling zone~~s~~ [~~27~~31,43], ocean current and ~~ocean currents~~eddy fields [~~47~~43,44,53]. ~~Therefore, the efforts of detection of the skipjack tuna forage habitat represented by the high PHI are the key factor to increase the commercial fishing success.~~

Although the formations of habitat hotspot varied spatially (Fig 5), however, the spatial mean position~~s~~ of the pelagic hotspots did not substantially change (Fig ~~5~~10). Habitat hotspots in the Gulf of Bone such as in 2007 appear more pronounced than in the Flores Sea reflecting that the enhanced forage habitat supporting high tuna concentration cover a wide area. In the subsequent years, the biologically rich habitats mainly perform along the Chl-a of 0.2 mg m^{-3} (Chl-a front). Several explanations for the association of tunas with fronts include: (1) the availability of appropriate food; (2) confinement to a physiologically optimum temperature range; (3) use of frontal gradients for thermoregulation; (4) limitation of visual hunting efficiency owing to water clarity [~~41~~49]; and (5) forage habitat and migration route [9,~~48~~54]. The Chl-a front appears to coincide with the shelfbreak position (approximately 350 m isobath) of Both Flores Sea and Bone Gulf (Figs 1,5 and 10). Highest skipjack CPUEs are concentrated near the shelfbreak location [17] during the daytime [~~49~~55]. Our ~~findings confirm that most of the~~ empirical fishing data (2007-

2011) confirm that fishermen consistently exploit the forage habitat during the daytime and, using the fishing data in 2012, we ~~feel~~ showed that our prediction~~s~~ models have been substantially verified (Figs 5, 8 and 9). To improve the model performance, we suggest ~~to taking into account~~that ~~-~~the effect of upwelling and current systems should be added ~~on~~ to the analysis. ~~Certainly, these factors warrant future investigation.~~

It is important to note that ~~we did not show monthly temporal persistence of the habitat hotspot from January to June since there were no significant persistent areas throughout the period. At~~at the peak season for 5-years (May 2007-2011), ~~we find that~~ less than 2% of the study area exhibits a persistent concentration of habitat hotpots (Fig 10: left). We suggest that these areas play a pivotal role since skipjack CPUEs increase significantly with increasing the habitat persistence (Fig 10: right) and thereby provide potential targets for marine conservation and fishing management strategies. ~~The geographical position of the persistent habitat hotspots can be clearly predicted using spatial contour of the 0.2 mg m^{-3} Chl-a concentration detectable from satellite images. Indeed, the use of this variable has proved the key for detecting the forage habitat of several important pelagic species [9,50].~~ As a result, our findings could be as preliminary nature of results in providing new insight into detection of skipjack tuna distribution and abundance in either the Coral Triangle tuna region or the western tropical Pacific Ocean.

Conclusions

Pelagic habitat hotspots for skipjack tuna in the southwestern Coral Triangle tuna are influenced by the optimum combination of environmental factors (SST, Chl-a and SSHA) detectable from satellite images. Skipjack CPUEs increased significantly in the areas of highest pelagic hotspot index (PHI). We found the key pelagic habitat corresponded mainly with the Chl-a front, which could stimulate enhanced forage abundance for skipjack within a physiologically optimum temperature range above the thermocline depth. The habitat hotspot and its persistence are clearly identified by 0.2 mg m^{-3} Chl-a isopleth, suggesting that the Chl-a front provides an important step on detection of habitat hotspots, distribution patterns and abundance of skipjack tuna in the western tropical Pacific Ocean, especially within Coral Triangle tuna.

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Author Contributions

Conceived and designed the experiments: MZ SJ SS. Analyzed the data: MZ SH. Contributed reagents/materials/analysis tools: MBS AF MR MS NN. Wrote the paper: MZ.

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Supporting information:

S1 Fig. The spatial distribution of SST for May 2007-2011 estimated from MODIS ocean color data. The dash lines correspond to the approximate optimum SST range.

S2 Fig. The spatial distribution of SSHA for May 2007-2011 estimated from AVISO - altimetry. The dash lines indicate the approximate optimum SSHA range.

Figure 1.

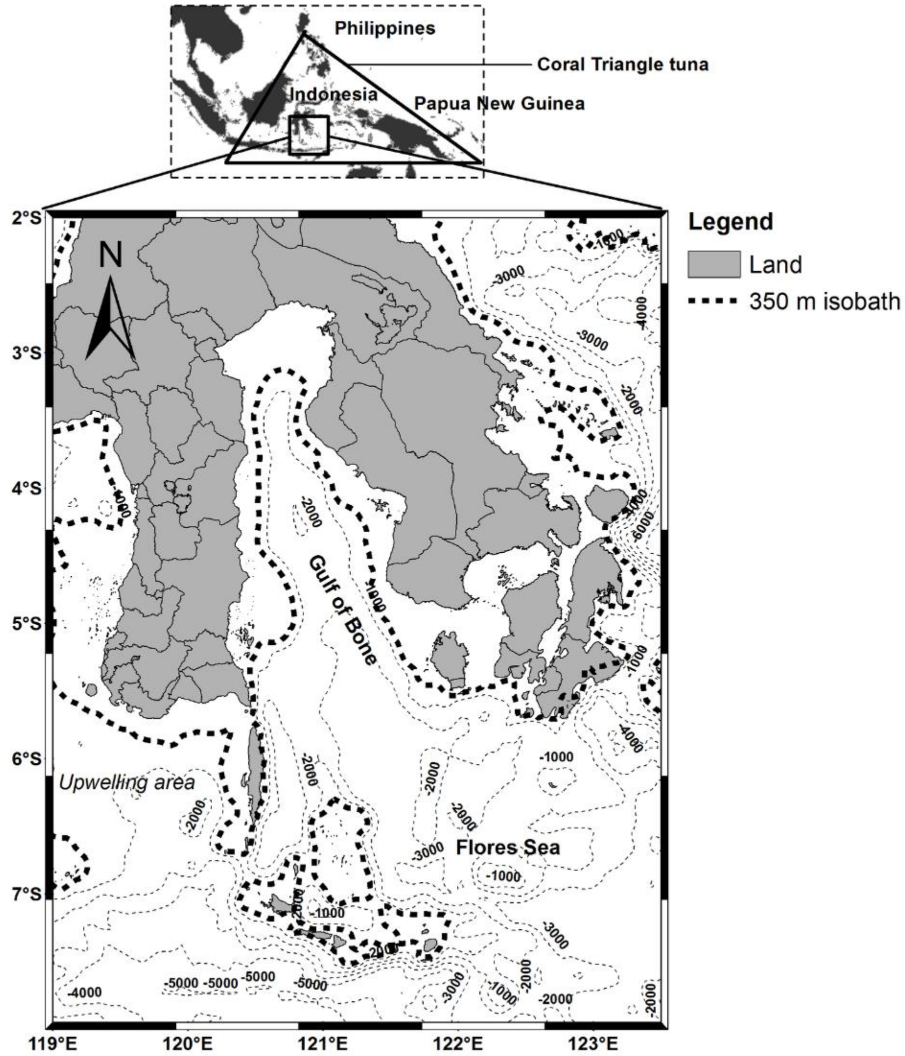

Philippines
Coral Triangle tuna
Indonesia
Papua New Guinea
Legend
Land
350 m isobath
N
Gulf of Bone
Flores Sea
Upwelling area
2°S
3°S
4°S
5°S
6°S
7°S
119°E
120°E
121°E
122°E
123°E
-1000
-2000
-3000
-4000
-5000
-6000

Figure 2.

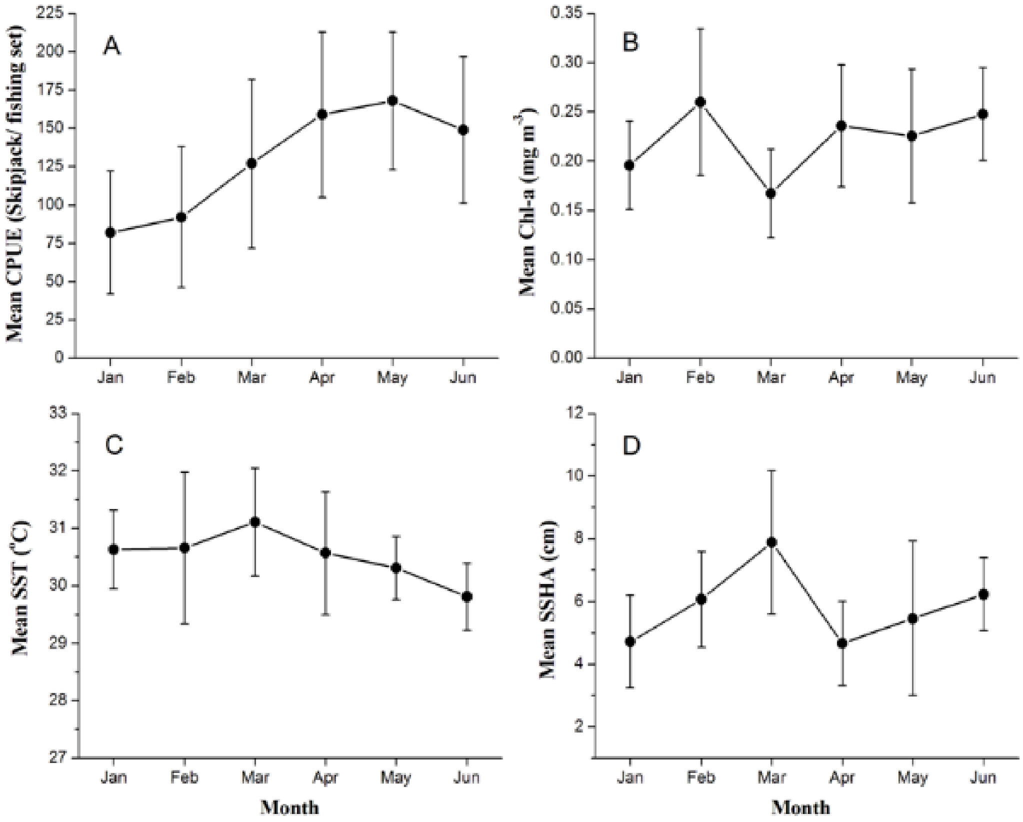

A
Mean CPUE (Skipjack/ fishing set)
0
25
50
75
100
125
150
175
200
225
B
Mean Chl-a (mg m^{-3})
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
C
Mean SST (°C)
27
28
29
30
31
32
33
D
Mean SSHA (cm)
2
4
6
8
10
12
Jan
Feb
Mar
Apr
May
Jun
Month

Figure 3.

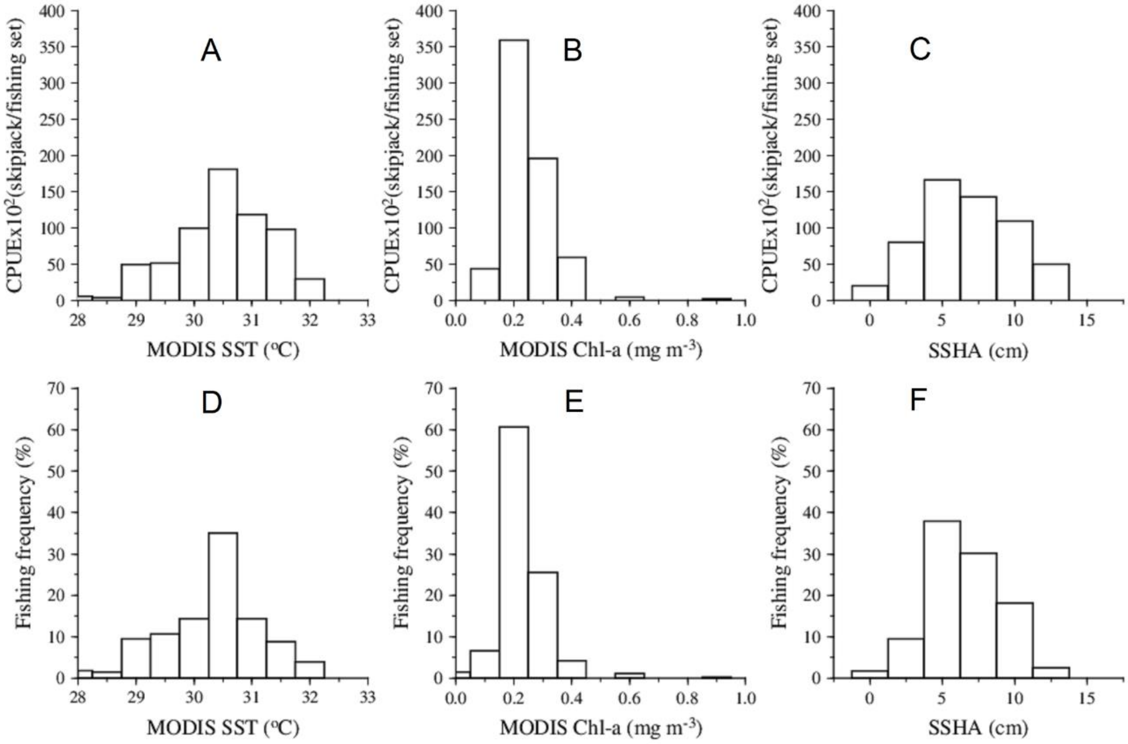

A
B
C
D
E
F
CPUEx10^2(skipjack/fishing set)
Fishing frequency (%)
MODIS SST (°C)
MODIS Chl-a (mg m^{-3})
SSHA (cm)
0
50
100
150
200
250
300
350
400
10
20
30
40
60
70
28
29
30
31
32
33
0.0
0.2
0.4
0.6
0.8
1.0
5
15

Figure 4.

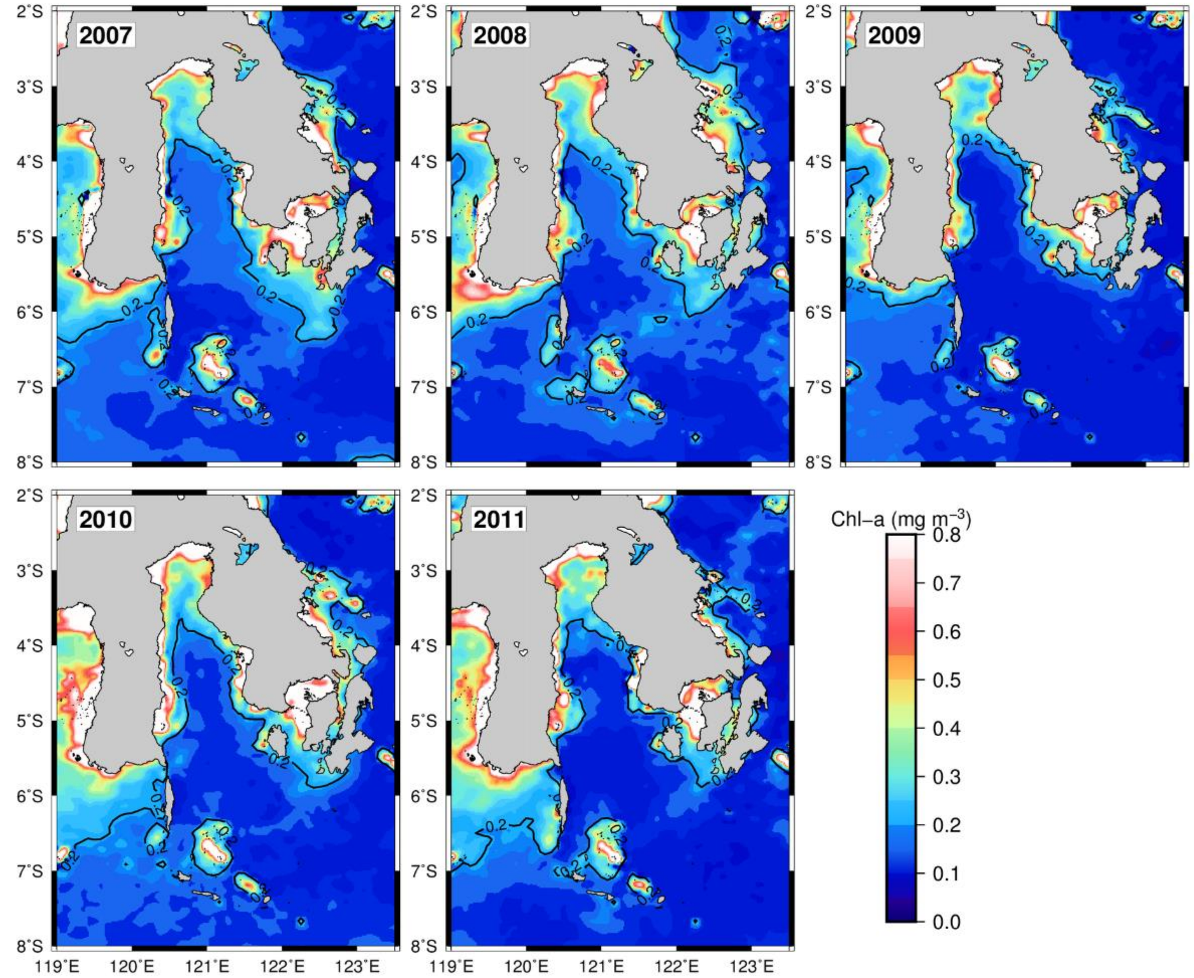

2007
2008
2009
2010
2011
2°S
3°S
4°S
5°S
6°S
7°S
8°S
119°E
120°E
121°E
122°E
123°E
0.2
Chl−a (mg m^{-3})
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

Figure 5.

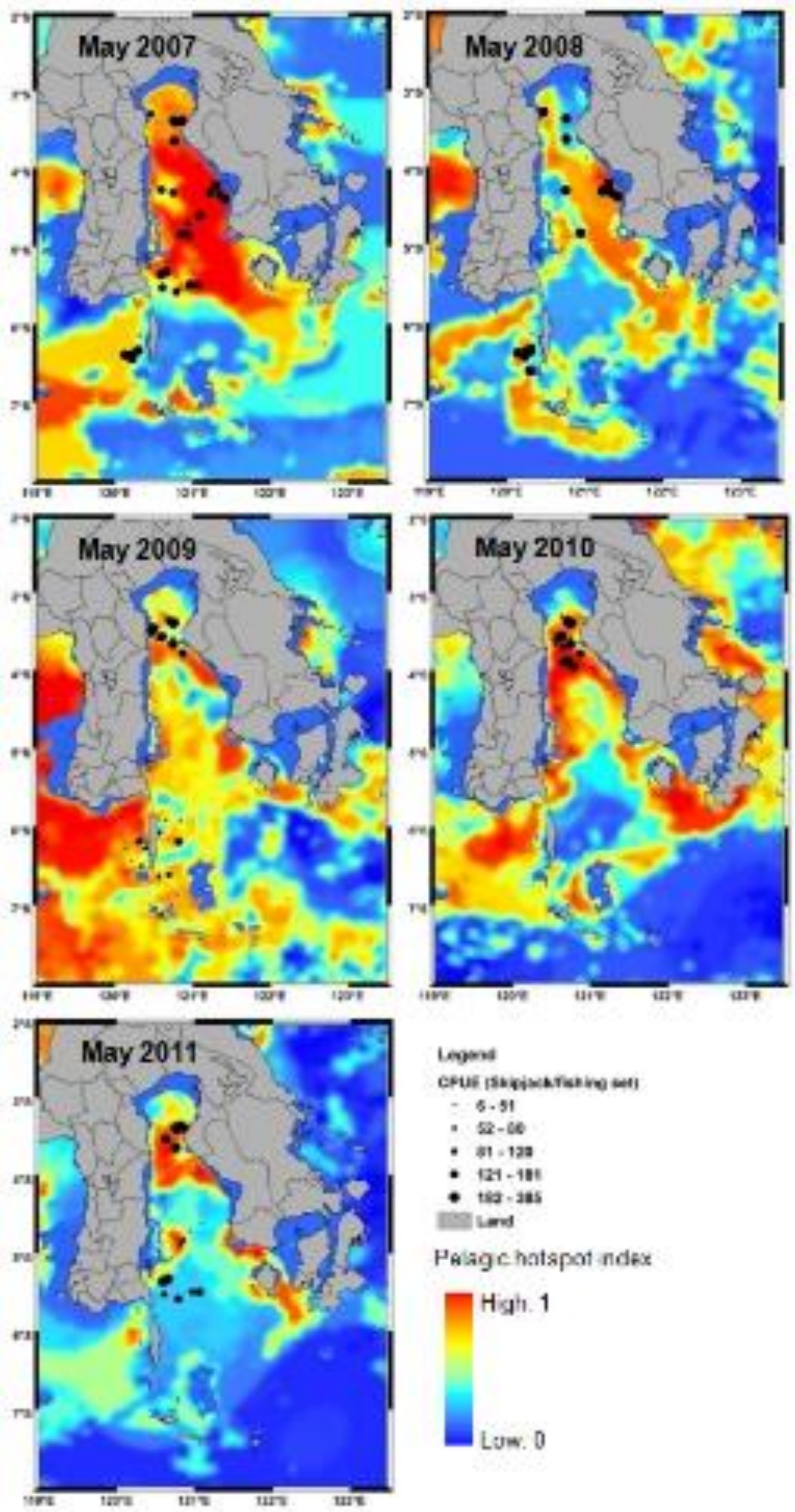
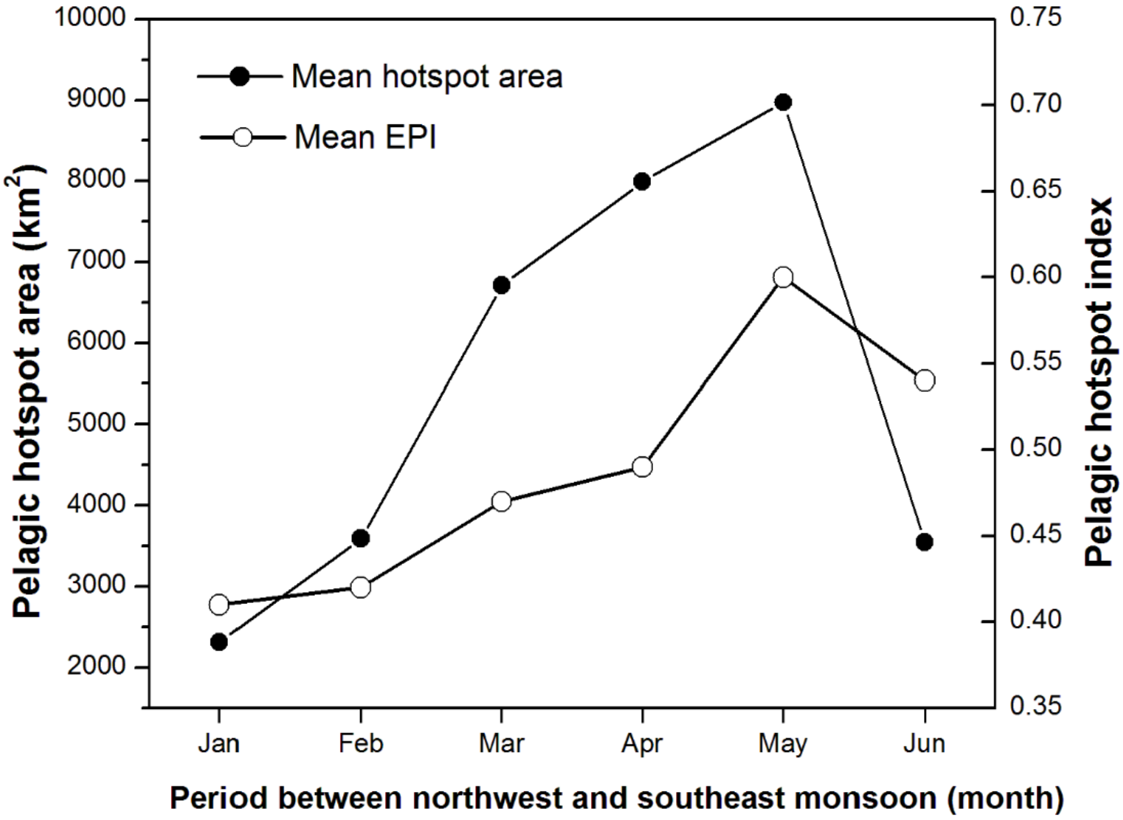
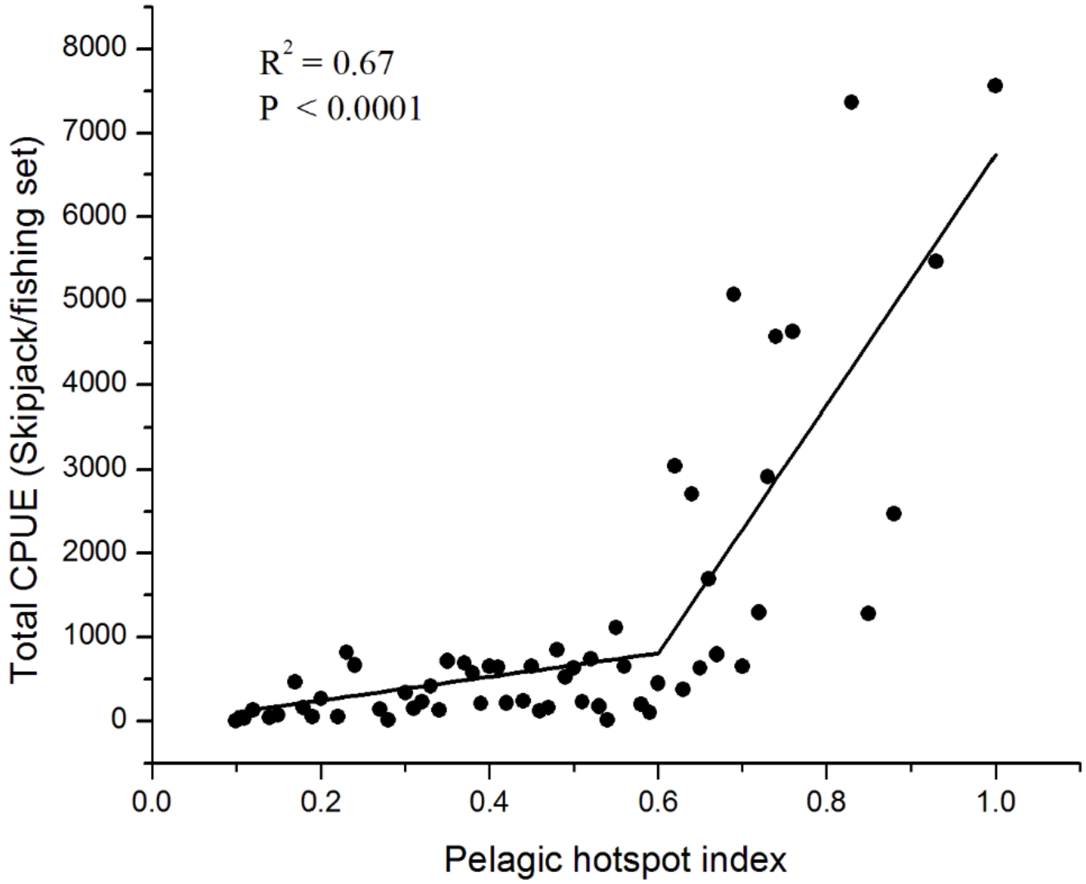

May 2007
May 2008
May 2009
May 2010
May 2011
Legend
CPUE (Skipjack/fishing set)
6 - 51
52 - 90
91 - 120
121 - 181
182 - 385
Land
Pelagic hotspot index
High. 1
Low. 0

Figure 6.



Mean hotspot area
Mean EPI
Pelagic hotspot area (km^2)
Pelagic hotspot index
Period between northwest and southeast monsoon (month)
10000
9000
8000
7000
6000
5000
4000
3000
2000
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
Jan
Feb
Mar
Apr
May
Jun

Figure 7.



R^2 = 0.67
P < 0.0001
8000
7000
6000
5000
4000
3000
2000
1000
0
Total CPUE (Skipjack/fishing set)
0.0
0.2
0.4
0.6
0.8
1.0
Pelagic hotspot index

Figure 8.

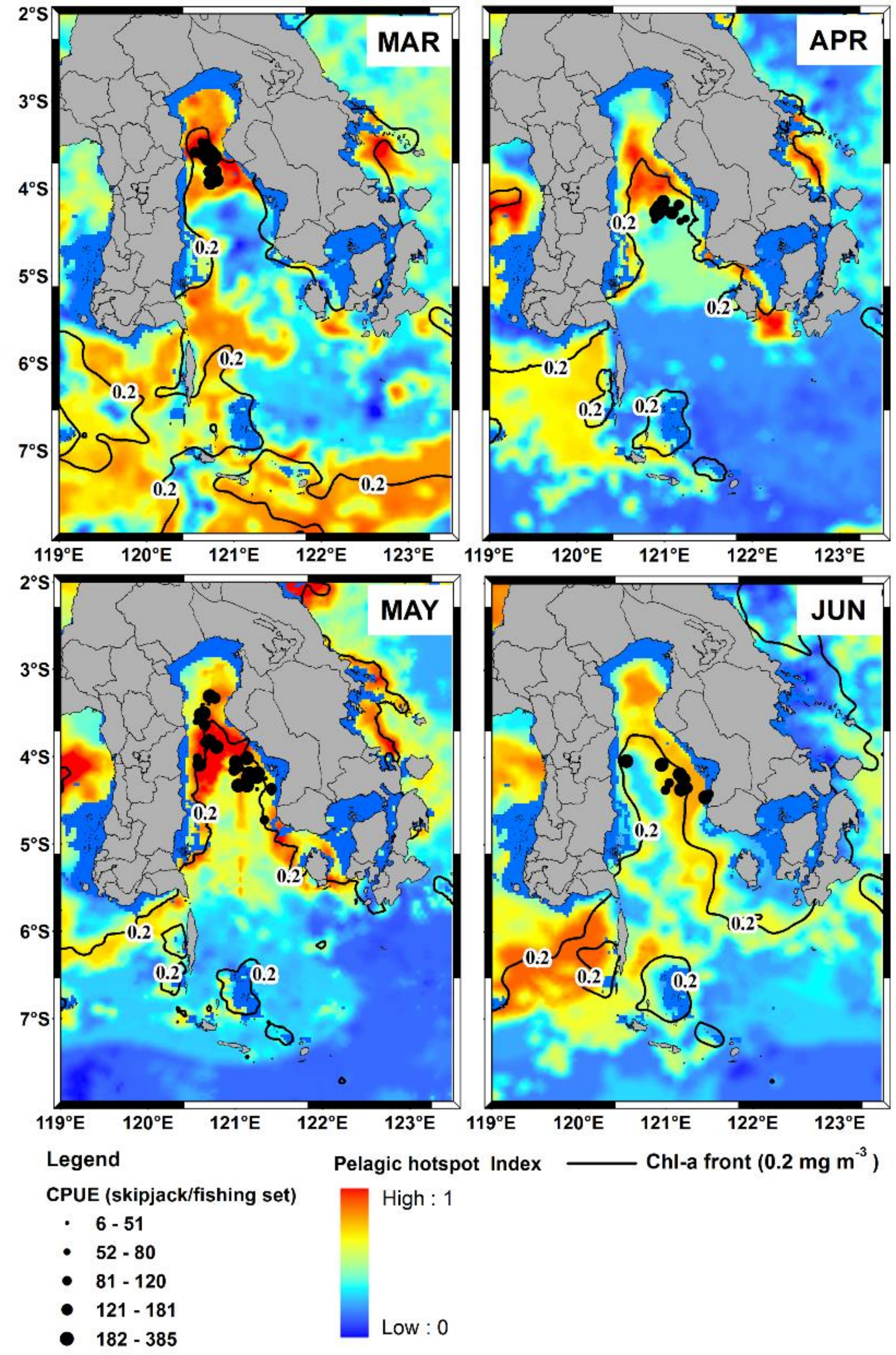
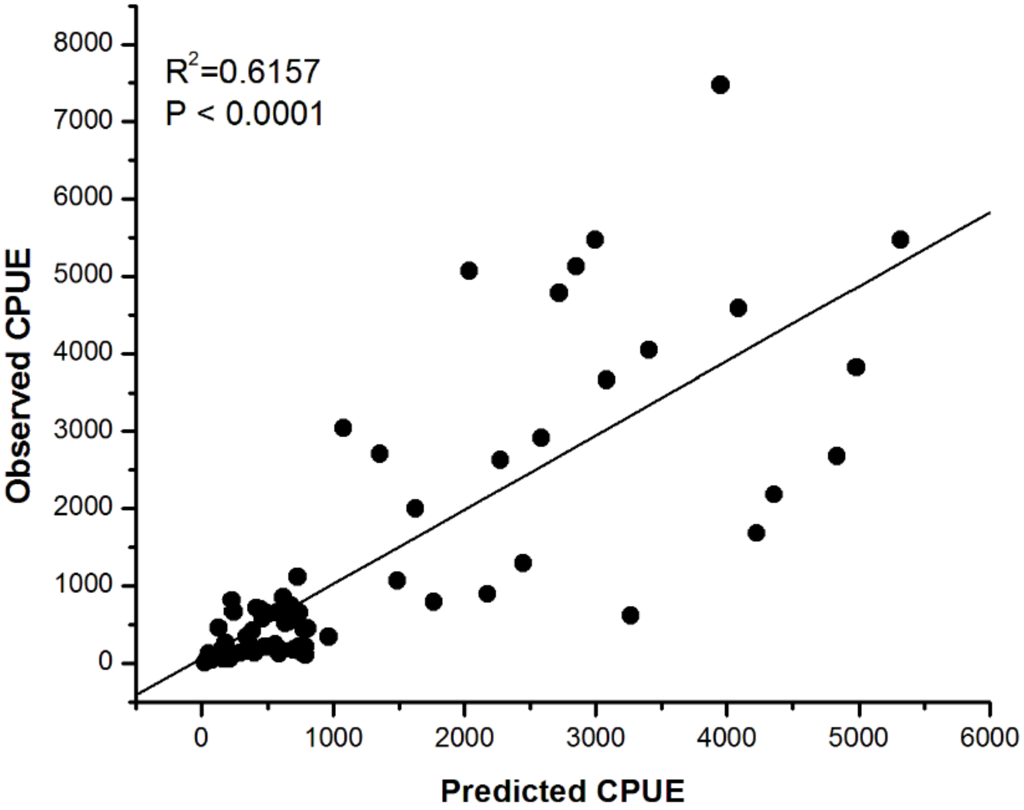
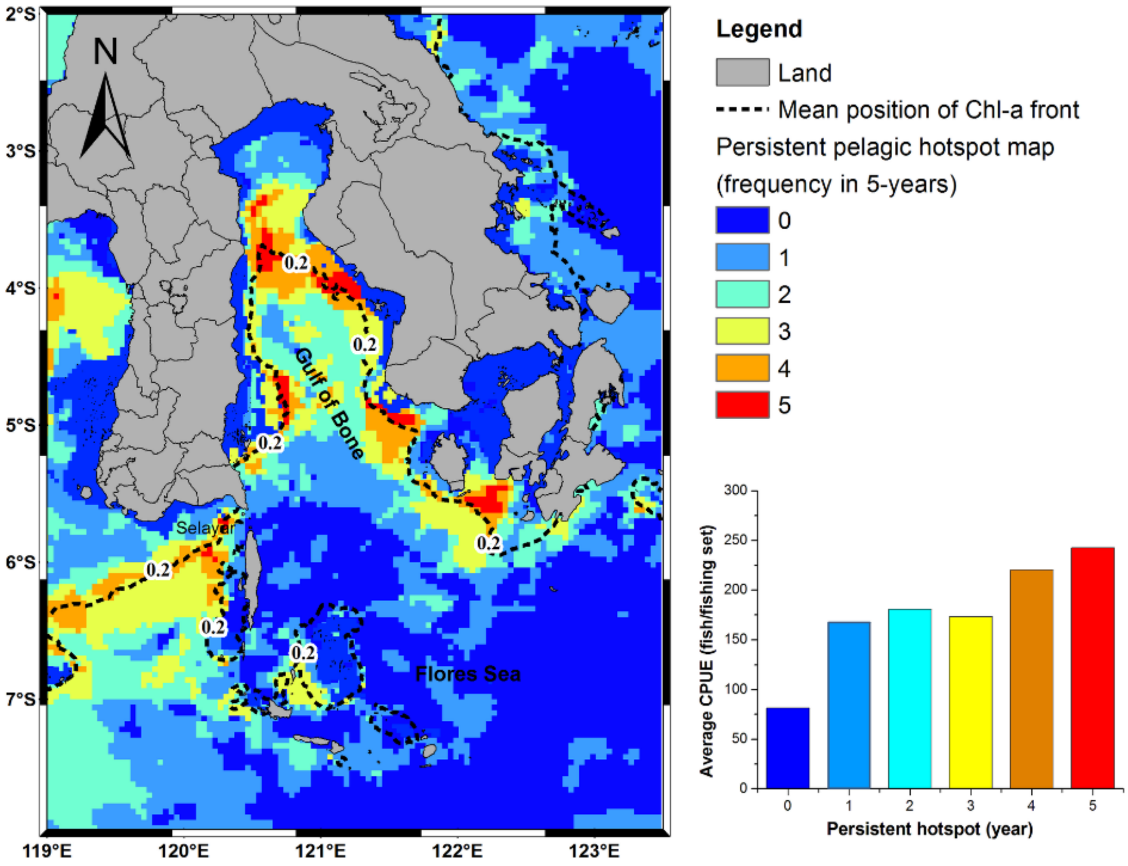

MAR
APR
MAY
JUN
2°S
3°S
4°S
5°S
6°S
7°S
119°E
120°E
121°E
122°E
123°E
0.2
Legend
CPUE (skipjack/fishing set)
6 - 51
52 - 80
81 - 120
121 - 181
182 - 385
Pelagic hotspot Index
High : 1
Low : 0
Chl-a front (0.2 mg m^{-3})

Figure 9.

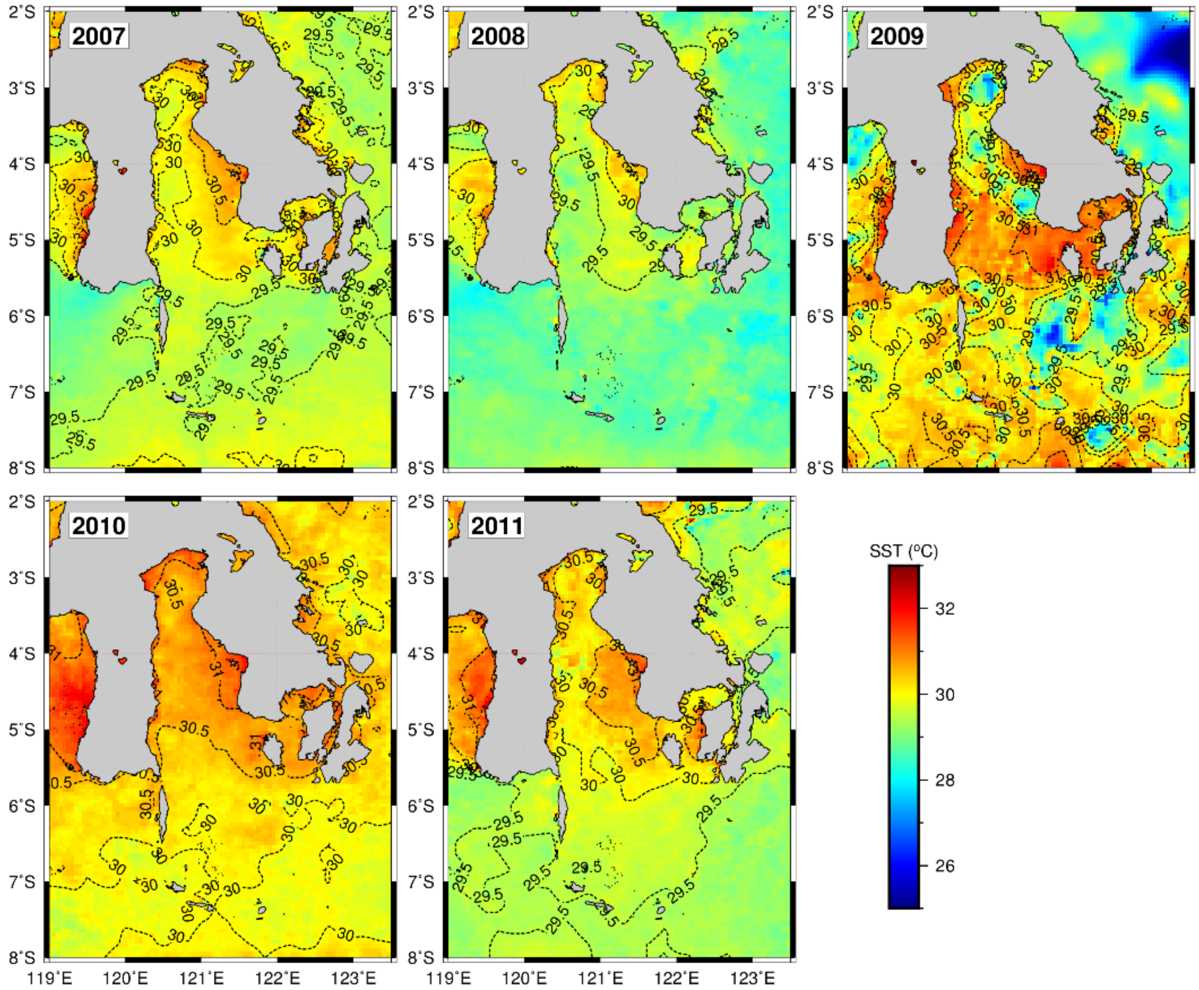


R^2=0.6157
P < 0.0001
Observed CPUE
Predicted CPUE
8000
7000
6000
5000
4000
3000
2000
1000
0
0
1000
2000
3000
4000
5000
6000

Figure 10.

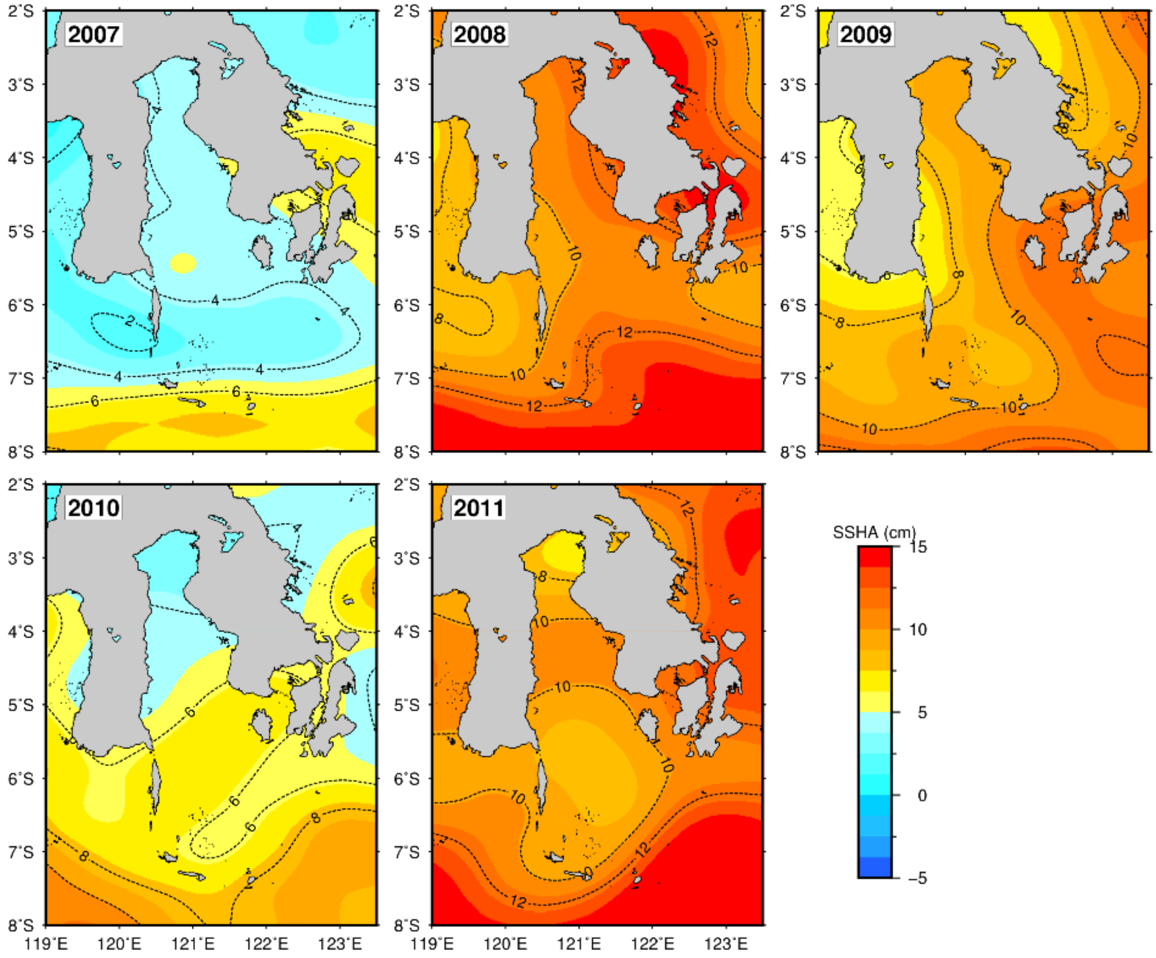

2°S
3°S
4°S
5°S
6°S
7°S
119°E
120°E
121°E
122°E
123°E
N
Gulf of Bone
Selayar
Flores Sea
0.2
Legend
Land
Mean position of Chl-a front
Persistent pelagic hotspot map
(frequency in 5-years)
0
1
2
3
4
5
Average CPUE (fish/fishing set)
0
50
100
150
200
250
300
Persistent hotspot (year)
0
1
2
3
4
5

S1:



2007
2008
2009
2010
2011
SST (ºC)
32
30
28
26
2˚S
3˚S
4˚S
5˚S
6˚S
7˚S
8˚S
119˚E
120˚E
121˚E
122˚E
123˚E

S2:



2007
2008
2009
2010
2011
2˚S
3˚S
4˚S
5˚S
6˚S
7˚S
8˚S
119˚E
120˚E
121˚E
122˚E
123˚E
SSHA (cm)
15
10
5
0
−5

RESPONSE TO REVIEWER COMMENTS

Dear Reviewers,

Thank you for your valuable comments. Here we would like to respond the reviewers' comments (some major issues) addressed in this manuscript as follow:

No	Reviewers Comments	Authors' Response
1.	It is very important to understand variations in fish habitat hotspots influenced by specific environmental variables. However, the same topic has been studied by various methods in the past decade for skipjack tuna. I do not understand the novelty of this particular study. The authors should clarify your novelty on your topic in the introduction section.	We clarified the novelty in the introduction section (Please see in the manuscript). Most of the previous studies analyzed the preferred skipjack tuna habitat using common statistical models (GAM, GLM, regression tree, HSI/arithmetic mean model), ecological model (ecological niche model) and Spatial Ecosystem and Population Dynamics Model (spatial distribution of tuna forage). They did not show the persistent skipjack tuna habitat. In the present paper, we develop a model to explore not only habitat hotspots for skipjack tuna but also their persistence observed from multi-spectrum satellite images and high resolution of fishing performance. This paper also highlighted the second important finding that Chl-a concentration of 0.2 mg m^{-3} provide a reasonable proxy indicator for detection of persistent habitat hotspot for skipjack tuna.
2.	The method in this study was basically similar to Zainuddin et al (2006, 2008) as below. Is there any new or improvement of this method in your study? Furthermore, the statistical methods in this manuscript are poorly described and totally absent	Yes, there are two points of improvement. We improved our previous model (Zainuddin et al. 2006) by using a weighting factor to take into account the contribution of each variable on pelagic hotspot index (PHI). Besides, we added SSHA variable to address the

	in some cases, such as for regression and correlation analyses for the hotspots index and CPUE.	relationship between skipjack tuna and mesoscale variability. For the method used in the other paper (Zainuddin et al. 2008), we used the statistical models (A combination of GAM and GLM) to predict albacore tuna potential fishing grounds. It is very different with the method presented in this MS. We described clearly the statistical methods used in the manuscript especially the use of both regression and correlation analyses for exploring the relationship between the hotspot index and CPUE (Please see the method section of revised manuscript).
3.	Did the three environmental variables used in developing the probability index correlate to each other? You calculated the pelagic hotspot index (PHI) by averaging three environmental variables, which mean each variable contributed equally to the PHI. Actually, how do they contribute to your prediction model? It should be useful to provide substantial information on this calculation approach and discuss its effects on the prediction results.	We did not think so. Each variable was calculated independently from each its histogram graph. So that, no correlation each other. We a weighting factor to calculate the contribution of each variable on the PHI. The variable which has the highest histogram CPUE or fishing frequency was used a standard (maximum value). This make each variable has different contribution on the prediction results, The highest PHI is obtained when the optimum combinations of all variables meet, reflecting the highest forage opportunity. In this study, we found Chl-a is the key factor (It has greatest contribution) controlling skipjack hotspots. Chl-a has the highest histogram of both in term of CPUE and fishing set frequency, So this variable was used as a standard of the weighting factor in computing all PHI.
4.	Why only the data in May 2012 was used to validate the prediction model? How about the prediction	We found that the highest PHI occur in May and has a good association with Chl-a front. The highest fishing

	performance in other months in 2012?	data CPUEs were also obtained in May (the peak season). This is the main reason for the first time making validation in this month. However, in our revised manuscript, we also added prediction performance maps in the other months (from March to June) for validation (Please see revised Figures 8 and 9). There is no fishing data in January and February 2012. The revised figures 8 and 9 also show that most of skipjack distribution and abundance occur over the highest habitat index on the maps (Fig 8) and have a good association with Chl-a front. The validation of the model was also highly significant (Fig 9).

Thank you and Best Regards

Mukti Zainuddin

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Dari: PLOS ONE (em@editorialmanager.com)
Kepada: mukti_fishocean@yahoo.co.id
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PONE-D-17-09790R1
Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia

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PLOS ONE has received your revised submission.

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Kepada: mukti_fishocean@yahoo.co.id
Tanggal: Jumat, 18 Agustus 2017 04.24 GMT+8

PONE-D-17-09790R1
Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia
PLOS ONE

Dear Dr. Zainuddin,

Thank you for submitting your revised manuscript to PLOS ONE. We have escalated your manuscript to an in-house editor for further advice and as soon as we have an update we will be in touch.

We appreciate your patience in this matter.

Kind regards,

Kate Armal
PLOS ONE

PLOS ONE: Your submission PONE-D-17-09790R1 - [EMID:4b3fc2ca69af89cd]

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PONE-D-17-09790R1
Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia
Dr. Mukti Zainuddin

Dear Dr. Zainuddin,

Thank you for submitting your manuscript entitled "Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia" to PLOS ONE. Your manuscript files have been checked in-house but before we can proceed we need you to address the following issues:

1. Thank you for stating in your Funding Statement:

"This work was partly supported to MZ by the National Competitive Research Grant
(HIKOM, 2016), Ministry of Research, Technology and Higher Education of the
Republic of Indonesia.
The funders had no role in study design, data collection and analysis, decision to
publish, or preparation of the manuscript"

Please provide an amended statement that declares *all* the funding or sources of support (whether external or internal to your organization) received during this study, as detailed online in our guide for authors at http://journals.plos.org/plosone/s/submit-now. Please also include the statement “There was no additional external funding received for this study.” in your updated Funding Statement.

Please include your amended Funding Statement within your cover letter. We will change the online submission form on your behalf.

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Please note that these changes have been requested to comply with submission guidelines and your manuscript will *not* be sent to review until you have fully adhered to our requests. Once your paper has been seen by an Editor we may return it to you for further information or amendments.

We ask that you address this request within 21 days. If you require additional time, please email the journal office. We are happy to grant extensions of up to one month past this due date. If we have not heard from you within 21 days, your manuscript will be withdrawn from Editorial Manager.

Thank you for submitting your work to PLOS ONE.

Kind regards,

Emily Jones
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Required Modifications for PONE-D-17-09790R1 - [EMID:73d0cc9b68e4395c]

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Kepada: mukti_fishocean@yahoo.co.id
Tanggal: Selasa, 19 September 2017 21.04 GMT+8

PONE-D-17-09790R1
Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia

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Once you have made all the required changes, click "Submit Task" to upload the corrected files.

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With kind regards,
PLOS ONE staff

JOURNAL REQUIREMENTS:

1. Please ensure that the author list and affiliations are correct on the title page of your manuscript, and that your author contributions, competing interests, and financial disclosure are correct as listed below. All of these sections will be indexed in PubMed and published by PLOS ONE as you have written them. Please email plosone@plos.org if any changes to this content need to be made.

Mukti Zainuddin: Conceptualization
Formal analysis
Funding acquisition
Investigation
Methodology
Supervision
Writing – original draft
Writing – review & editing

Aisjah Farhum: Data curation
Funding acquisition

Safruddin Safruddin: Data curation
Investigation
Validation

Muhammad Banda Selamat: Data curation
Software

Sudirman Sudirman: Conceptualization

Nurjannah Nurdin: Investigation

Mega Syamsuddin: Visualization

Muhammad Ridwan: Data curation
Project administration

Sei-Ichi Saitoh: Conceptualization
Formal analysis

Please see here for the full list and definition of contributor roles: http://journals.plos.org/plosone/s/authorship#loc-author-contributions

Competing Interests: The authors have declared that no competing interests exist

Financial Disclosure: This work was partly supported to MZ by the National Competitive Research Grant (HIKOM, 2016), Ministry of Research, Technology and Higher Education of the Republic of Indonesia.
The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript

2. Please confirm that all information in your Funding Information is also present in your Financial Disclosure. Only the Financial Disclosure section will be published alongside your article to describe your funding.

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HIKOM 2016 019/SP2H/LT/DPRM/II/2016 Dr. Mukti Zainuddin
PTUPT 2017 005/SP2H/LT/DPRM/IV/2017 Dr. Mukti Zainuddin
Dr Aisjah Farhum

3. Author Aisyah Farhum is listed as Aisjah Farhum in the online submission form; we are unsure which version is correct. If the name is incorrect in the manuscript, please correct this. If the name is incorrect in the submission form, please let us know so we can correct the author's profile for you. Please note that the use of middle initials/names should be consistent among the manuscript's author list, the author list in the submission form, and the Author Contributions initials.

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However, the funding information in your manuscript reads as follows:

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Tanggal: Jumat, 22 September 2017 22.57 GMT+8

Dear Dr. Zainuddin,

Thank you for your message. and for sending along this information.

I can confirm at this time that we have received the submission of your task. We are currently processing the revisions made.

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With kind regards,
Mally Espaillat
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From: Mukti Zainuddin [mukti_fishocean@yahoo.co.id]
Sent: 9/21/2017 4:37 PM
To: plosone@plos.org
Subject: Confirmation of some required points

Dear Plos One Editor,
Here we are confirming that :
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2. Since Dr. Aisjah Farhum is a member of my research grant (PTUPT 2017), so Funding Information should be:
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3. The appropriate Financial Disclosure :This work was partly supported to MZ by the National Competitive Research Grant (Hibah Kompetensi 2016 No. 019/SP2H/LT/DPRM/II/2016 and PTUPT 2017 No. 005/SP2H/LT/DPRM/IV/2017), Ministry of Research, Technology and Higher Education of the Republic of Indonesia. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

The other points are correct. For your information, we have made all required changes including (Please see the corrected manuscript):
No 3 (Journal requirements) - Author Aisyah Farhum should be Aisjah Farhum
No 4 (Journal requirements) - We completed affiliation information
No 5 (Journal requirements) - We deleted the list of author contributions in the revised manuscript
No 6 (Journal requirements) - We confirmed the discrepancy between Financial Disclosure and the funding information in the manuscript file
No 7 (Journal requirements) - We have matched the supporting information labels
No 8 (Journal requirements) - We have improved Fig 5 into suitable one and used PACE to adjusted the suitability of the figure.
No 9 (Journal requirements) - We have made a new ORCID iD and update my information in Editorial Manager.
If it is still possible, page 19 line 435 Both should be "both" (lower case).
If any some thing missing or need to be confirmed, please let us know, We would like to respond as soon as possible.
Best Regards

Mukti Zainuddin
ref:_00DU0Ifis._5000BblEQs:ref

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PONE-D-17-09790R1
Detection of pelagic habitat hotspots for skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia

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If your institution or institutions have a press office, please notify them about your upcoming paper at this point, to enable them to help maximize its impact. If they will be preparing press materials for this manuscript, please inform our press team within the next 48 hours. Your manuscript will remain under strict press embargo until 2 pm Eastern Time on the date of publication. For more information please contact onepress@plos.org.

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Thank you for submitting your work to PLOS ONE.

With kind regards,

PLOS ONE Editorial Office Staff
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