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Abstract

The increase in sea surface temperature (SST) is one of the primary consequences of climate change and has the potential to impact tuna fisheries. This paper theoretically models and then applies the production function approach to establish a positive but non-linear relationship between catch and SST using gridded data for yellowfin and skipjack tuna catch in the Eastern Pacific Ocean. We test different forms of relationship between SST and the carrying capacity of tuna fisheries. By considering area, species and fishing methods, we provide spatially and biologically relevant information for the management of tuna in response to warming oceans. The increase in yellowfin tuna catch is higher in the Northern Hemisphere compared to the Southern Hemisphere, while the reverse is true for skipjack tuna. We also find that there is a nonlinear (i.e. logarithmic and quadratic) relationship between the SST and the carrying capacity of tuna fisheries.

JEL-Codes: Q22, Q54.

Keywords: production function, sea surface temperature, tuna.

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INTRODUCTION

The increase in ocean temperature observed in the last few decades is a direct consequence of climate change and results in decreasing sea-ice extent, rising sea level, and changing patterns of global precipitation and ocean circulation (IPCC 2019). Based on climate change projections, these changes in ocean dynamics are expected to continue into the next century. The ocean's net heat uptake is primarily stored in the upper layers of the ocean and records show that the Pacific Ocean has been warming overall (Doney et al. 2012; Bindoff et al. 2019).

Ocean warming affects the distribution of marine species including those in the Pacific Ocean (Bindoff et al. 2019). Fish populations move to higher latitudes or deeper waters as ocean temperature increases (Perry et al. 2011; Rice and Garcia 2011), such that shifts in the distribution and availability of fish species may require fishing vessels to modify their fishing behaviour. Tuna is one of the commercially important marine species in the Pacific Ocean potentially affected by climate change. Suitable habitats for tuna are expected to shift towards the poles as temperature increases; however, the effects of SST likely vary across tuna species according to their thermal tolerance (Muhling et al. 2011). The top two species in terms of share of total tuna catch in the Pacific Ocean are skipjack and yellowfin tuna (FAO 2019c). Previous research suggests that ocean warming may increase the suitability of some habitats for skipjack tuna (Muhling et al. 2015), while for yellowfin tuna temperature above a threshold may have adverse effects on cardiac functionality of spawning adults and survival of eggs and larvae (Wexler et al. 2011; Dell'Apa et al. 2018).

In this study we use catch and effort data for tuna caught using purse seine available from the Inter-American Tropical Tuna Commission (IATTC)[1] and SST data from the Japan Meteorological Agency to analyse the impact of climate change on tuna fisheries in the Eastern Pacific Ocean (EPO). We focus on the two main target species, skipjack and yellowfin tuna, and the three types of purse seine methods used to catch them, including dolphin sets, floating object sets and unassociated sets.

[1] IATTC is a regional fishery management organization for the management of tuna in the EPO.

Purse seine sets are classified based on the way the fishes are detected and encircled. Dolphin sets are made for large yellowfin tuna associated with dolphins; floating object sets have been the dominant set type for the past 20 years targeting mostly skipjack tuna; and unassociated sets catch both small yellowfin and skipjack (Hall 1998). In our analysis, we consider the set type as tuna catch may be sensitive not only to the varying biological and behavioural impacts of SST on the target species, but also the fishing methods employed (Hu et al. 2018; Asche and Guillen 2012). We contribute to the literature in two novel ways.

Firstly, we apply a production function approach to estimate the biological impact of SST increases through the growth function of tuna species. Production functions have traditionally been used to establish linkages between the habitat of a fishery and its economic productivity (Barbier 2007). We adapt Barbier and Strand's (1998) bioeconomic model to account for temperature effects on the carrying capacity, and apply annual total tuna catch and effort by 1° latitude/longitude grid cells, while controlling for time-invariant grid effects. We also test for the possibility of a linear, logarithmic and quadratic relationship between SST and the carrying capacity of tuna fisheries. The inclusion of SST in a production function allows the conduct of more studies to assess the economic impacts of climate change on fisheries.

The second contribution focuses on the use of gridded, species- and fishing method-specific data in the area under the jurisdiction of a regional fisheries management organization, the IATTC. We consider two tuna species, and three different types of purse seine sets, as opposed to most studies that focus on a spatially homogenous, single species that is caught with a specific method. By focusing on an agreement area and considering species and fishing method, we provide spatially and biologically relevant information for the management of tuna in response to warming oceans.

We show that catch of skipjack and yellowfin tuna increase with SST in the EPO. The magnitude of the increase in tuna catch as a result of a 1°C increase varies across species, types of sets and distance from the equator. For yellowfin tuna, the largest increase in catch occurs for unassociated sets followed by dolphin sets and floating object sets. A similar pattern can be observed for skipjack tuna, where largest increases in catch occur for unassociated, floating object and dolphin sets. The increase in yellowfin tuna catch is higher in the Northern Hemisphere compared to the Southern Hemisphere, while the reverse is true for skipjack tuna. We also find that there is a nonlinear (i.e. logarithmic and quadratic) relationship between the SST and the carrying capacity of tuna fisheries.

In the next section, we discuss how climate change affects the ocean and fisheries, specifically focussing on tuna. Then, a description of purse seine and the different type of sets is presented, followed by a discussion of how temperature can be included in economic models. The next section then presents the model we estimate, the data, and the estimation procedure used in the study. We then discuss the results of the analysis, and finish with some concluding remarks.

REVIEW OF LITERATURE

Climate driven changes in ocean conditions affect fisheries and their habitat, such as mangroves, seagrass, and coral reefs (Bell et al. 2013). Increasing ocean temperatures may force (some) fish populations to move to higher latitudes or deeper waters and lead to changes in marine ecosystems (Bindoff et al. 2019). These changes in the spatial distribution of fish stocks and the composition of fisheries resources may affect fishing operations and consequently the effectiveness of fisheries management measures (Sumaila et al. 2011). Therefore, the economic consequences of ocean warming vary in different areas and fisheries, e.g. negative impacts may be felt in areas where species move out. Besides declining catch in some places, higher capital costs as fishers need to improve gears and vessels and incur higher fuel, ice, and labour costs due to longer search time are also likely (Sumaila et al. 2011). On the other hand, migration of species into some areas can translate into higher revenue and lower costs. Thus, migration of species may be viewed as negative by fishers in established fisheries and positive in new fisheries (Madin et al. 2012).

Economic analysis of the impacts of ocean warming on fisheries must consider characteristics unique to the individual fisheries such as ocean dynamics, harvesting fleet, and region (Haynie and Pfeiffer 2012). For example, as described by (Hayward 1997), the warming of the ocean off California in the 1970s resulted in a decrease in biomass of anchoveta, an increase for sardines, and no change for mackerel.

Tuna is a commercially important species and it is therefore important for policymakers to understand how climate change affects it. For example, the productivity of phytoplankton is projected to decrease with the increase in ocean temperature affecting both zooplankton and micro nekton through the food chain. Zooplankton are preys of tuna larvae and juveniles and adult tuna feeds on micro nekton (Lehodey et al. 2013). Warming ocean waters may also potentially affect the reproductive success and survival of tuna. Tuna spawning occurs throughout the year in tropical waters and seasonally in subtropical waters in all major oceans (Goujon and Majkowski 2000). Sea temperature has already been shown to be an influential environmental variable affecting spawning and growth of tuna (Pecoraro et al. 2017; Ashida and Horie 2015). Indeed, Monllor-Hurtado, et al. (2017) indicate that there is a poleward movement of tropical tuna populations in response to ocean warming.

Seventy percent of the total global catch of tuna in 2010 came from the Pacific Ocean, composed of mainly skipjack, yellowfin, bigeye, and albacore tuna (Lehodey et al. 2013). Skipjack tuna and yellowfin tuna are the top two species in terms of contributions to total global tuna catch weight in 2010 at 58.1 percent and 26.8 percent, respectively (FAO 2019c). The Northern Hemisphere is the preferred habitat of yellowfin tuna while skipjack tuna prefers the Southern Hemisphere. Skipjack tuna prefer warm waters and are usually caught with surface gears such as purse seine and pole-and-line, and usually with the use of fish aggregating devices (FAD). Skipjack tuna commence spawning when surface temperature exceeds 24°C (Ashida and Horie 2015). Simulations on the effects of climate change have concluded there is a steady increase in the skipjack tuna biomass across the whole Pacific Ocean (Muhling et al. 2015) with a progressive displacement of biomass to the east (Dueri et al. 2016) and to higher latitudes (Lehodey et al. 2013).

For yellowfin tuna, Schaefer, et al. (2007) provided evidence that adults move vertically or horizontally to areas with a SST of around 18°C. Results of experiments showed that water temperatures less than 21°C and more than 33°C are lethal for the yolk sac and larvae of yellowfin tuna (Wexler, Margulies, and Scholey 2011), and water temperature above 30°C reduces the cardiac functionality of spawning adults (Dell'Apa et al. 2018).

The primary method to catch tuna in the Eastern Pacific is by purse seine, which is made of a long wall of netting framed with a lead line and a float line designed to catch schooling fish (Bayliff 2001). Purse seine sets are classified based on the way tunas are detected and encircled. The types of purse seine sets recorded in the Inter-American Tropical Tuna Commission (IATTC) dataset include dolphin sets, floating object sets, and unassociated sets.

Dolphin sets are made for tuna that associate with dolphins, mostly large yellowfin tuna. When fishers detect a group of tuna swimming with dolphins, they use the purse seine to encircle and capture them (this method is controversial due to the incidental mortality of dolphins). Floating object sets use fish aggregating devices (FAD) - man-made floating objects tethered to the ocean floor. The composition of catch using floating object sets is a mixture of skipjack, bigeye, and yellowfin, with skipjack as the dominant species (Bayliff 2001). Unassociated sets are used to target tuna in association with other species. Hall and Roman (2013) prefers to call this type of sets school sets, given that tuna are caught in association with schools of different species and seabirds. This type of set usually catches small-sized yellowfin and skipjack tuna (Hall 1998). Tuna production input and outputs are affected by the differences in the behaviour of target tuna species depending on the type of set used. There is, therefore, a need to consider both the fishing methods and the target species in any analysis of tuna catch (Hu et al. 2018; Asche and Guillen 2012).

In terrestrial systems, the link between temperature and different economic outcomes has been extensively studied The literature includes cross-country analyses that estimate the relationship between temperature and the growth of aggregate output (Hsiang and Jina, 2013), sectoral output (Hsiang 2010), and export growth (Jones and Olken 2010). Other studies use sub-national data to link temperature and agricultural profits (Deschênes and Greenstone 2007), time allocation (Zivin and Neidell 2014) and labour income (Dell et al. 2014). In studies these studies, temperature is treated as a productive input that can explain variations in the output, though most of these studies examine aggregate (macroeconomic) production.

The production function approach is, however, also used to establish the effects of temperature on the production of specific crops, which is more similar to our paper. For example, Schlenker and Roberts (2009) identify a nonlinear and asymmetric relationship between temperature and yields of corn, soybeans, and cotton in the US. Gupta et al. (2014) include temperature as an input in the production of rice, pearl millet, and sorghum in India, using both level and quadratic forms of the 12-month average of monthly temperatures as independent variables.

The production function approach in fisheries, as opposed to terrestrial studies, is applied to establish linkages between the habitat of a fishery and its economic productivity. Most of these studies apply a static model based on the assumption that the fishery is in a long-run equilibrium (Barbier 2007). This has been applied to linkages of mangrove and shrimp catch in Mexico (Barbier and Strand 1998), mangrove and artisanal demersal and shellfish fisheries in Thailand (Barbier et al. 2002), and cold water coral and redfish catch in Norway (Foley et al. 2010). The inclusion of environmental factors in the fisheries production function is the subject of a growing body of literature (see Vondolia et al. 2019; Armstrong et al. 2017; Kahui, Armstrong, and Vondolia 2016; Armstrong et al. 2016; Hassan and Crafford 2015).

The basic model includes two key variables in the growth function of the fish species: the intrinsic growth rate, and the carrying capacity. The intrinsic growth rate defines the rate at which the stock grows at very low levels while the carrying capacity of the environment determines the largest possible fish stock size given food supplies, habitat, and other factors (Anderson and Seijo 2010). Barbier and Strand (1998) developed a model to demonstrate how an environmental factor, specifically habitat, directly affects the carrying capacity. Foley et al. (2010) extended the model and showed that the environmental factor also indirectly affects the carrying capacity through the intrinsic growth rate.

An important feature of papers examing terrestrial systems is that they establish a nonlinear relationship between temperature and economic outcomes. This suggests the possibility of a nonlinear relationship between SST and tuna catch. In fisheries, Barbier et. et al. (2002) applied a logarithmic function to model a concave relationship between the environmental input and carrying capacity, while Barbier and Strand (1998) and Foley et al. (2012) applied a linear function. There is no study in fisheries, however, that tests for a quadratic relationship.

FISHERIES PRODUCTION FUNCTION

We extend the fisheries production function pioneered by Barbier and Strand (1998) to establish a link between the SST and the catch of tuna. For this purpose, the standard static open access fishery model is modified to account for the relationship between carrying capacity and SST in the following way.

Static Fishery Model

We define X_{it} as the fish stock of tuna, T_{it} as SST, and E_{it} as fishing effort in grid *i* at time *t*. The change in the stock of tuna is expressed as

$$X_{it+1} - X_{it} = F(X_{it},\ T_{it}) - h(X_{it}, E_{it}), \qquad F_X > 0,\ \ h_X > 0. \tag{1}$$

The net change in the tuna stock is determined by the difference between biological growth, $F(X_{it},\ T_{it})$, and harvesting, $h(X_{it}, E_{it})$, where biological growth is assumed to follow a logistic growth function. Foley et al. (2012) provide an overview of bioeconomic fisheries-habitat interactions and we follow Foley et al.'s (2010) exposition of the fisheries production model to include SST (instead of habitat) to affect both the intrinsic growth rate and the carrying capacity.

$$F(X_{it},\ T_{it}) = r[K(T_{it})X_{it} - X_{it}^2] \tag{2}$$

The variables r and K denote the intrinsic growth rate and the carrying capacity, respectively. Harvesting is a function of stock and effort and we assume the basic Gordon-Schaefer function

$$h(X_{it}, E_{it}) = qX_{it}E_{it} \tag{3}$$

where q is the constant catchability coefficient.

Substituting Equations (2) and (3) into Equation (1) we get

$$X_{it+1} - X_{it} = \ \{r[K(T_{it}) - X_{it}] - \ qE_{it}\}\,X_{it}. \tag{4}$$

Long run harvest function

In equilibrium, X_{it+1}= X_{it} = X_i equation (4) can be solved for the steady state stock size, which is substituted into equation (3) and rearranged to derive the long run harvest function (Barbier and Strand (1998); Foley et al. (2010)).

$$h_{it} = qK(T_{it})E_{it} - \frac{q^2}{r}E_{it}^2. \qquad (5)$$

As mentioned above, applications in the habitat-fisheries model typically assume a linear and/or a logarithmic relationship between the carrying capacity and habitat. We restate the functional form and extend the model by developing and testing for a quadratic function as shown below.

Linear

Barbier and Strand (1998) and Foley et al. (2012) assume a proportional relationship between carrying capacity K and SST, such that $K(T_{it}) = \alpha T_{it}$ for $\alpha > 0$ and equation (5) can be expressed as

$$h_{it} = q\alpha T_{it}E_{it} - \frac{q^2}{r}E_{it}^2. \qquad (6)$$

or

$$h_{it} = b_1 T_{it}E_{it} + b_2 E_{it}^2 \qquad (7)$$

where $b_1 = q\alpha$ and $b_2 = -\frac{q^2}{r}$.

Logarithmic

Barbier, et al. (2002) apply a logarithmic function, such that $K(T_{it}) = \alpha \ln T_{it}$. Equation (5) may be expressed as

$$h_{it} = q\alpha \ln T_{it} E_{it} - \frac{q^2}{r}E_{it}^2. \qquad (8)$$

or

$$h_{it} = b_1 \ln T_{it} E_{it} + b_2 E_{it}^2. \qquad (9)$$

where $b_1 = q\alpha$ and $b_2 = -\frac{q^2}{r}$.

Quadratic

We extend the model to assume a quadratic relationship between SST and catch , such that $K(T_{it}) = \alpha_1 T_{it} + \alpha_2 T_{it}^2$.

Equation (5) may be expressed as

$$h_{it} = q\alpha_1 T_{it} E_{it} + q\alpha_2 T_{it}^2 E_{it} - \frac{q^2}{r} E_{it}^2. \qquad (10)$$

or

$$h_{it} = b_1 T_{it} E_{it} + b_2 T_{it}^2 E_{it} + b_3 E_{it}^2 \qquad (11)$$

where $b_1 = q\alpha_1$, $b_2 = q\alpha_2$ and $b_3 = -\frac{q^2}{r}$.

MODEL AND ESTIMATION PROCEDURE

Firstly, assuming the linear relationship between SST and carrying capacity, we estimate the following equation derived from Equation (7)

$$Tuna_{it} = \beta_1 Sets_{it} * SST_{it} + \beta_2 Sets_{it}^2 + \beta_3 t + \sum_{g=2}^{n} \gamma_g D_g + \varepsilon_{it} \qquad (12)$$

$Tuna_{it}$ is the amount of tuna caught in grid *i* in year *t*, $Sets_{it}$ is the number of sets in grid *i* in year *t*, which is a measure of effort, SST_{it} is the annual mean SST in grid *i* in year *t*, $Sets_{it}^2$ is the square of $Sets_{it}$, D_g is dummy for 1° latitude/longitude grid, ε_{it} is the error term, and α, β, and γ are coefficients. The values of $Tuna_{it}$ and $Sets_{it}$ are expressed in per square kilometre to account for differences in the surface area of grids. The model also includes a time trend, *t*, to account for technological progress. A year trend was preferred over a year dummy as we do not want *t* to capture the year-to-year changes from SST. The estimation also showed that models with a time trend have higher R^2 compared to models without. The grid dummy accounts for the time-invariant, grid-specific factors affecting the tuna catch such as area, location, and bathymetry.

The analysis is run as a regression through the origin (RTO) to handle the unrealistic possibility of positive output of tuna without fishing effort. RTO was also implemented in fisheries production functions by Armstrong et al. (2016), Thanh Thuy and Flaaten (2013), and Foley et al. (2010). A synthesis of the literature on RTO approach in modelling is provided in Eisenhauer (2003).

The measure of effort, *Sets*, is proportionally adjusted for the amount of yellowfin and skipjack caught within a set. This is done to isolate species-specific effort because purse seine catch different species in each set. A similar adjustment to effort was done in Foley et al. (2010). We assume that fishers give equal importance to yellowfin and skipjack tuna consistent with the effort proportion allocation procedure used in Wang et al (2015).

The marginal product of SST at means, MP_{SST}, is derived from Equation (12):

$$MP_{SST} = \frac{\partial Tuna}{\partial SST} = \beta_1 Sets. \qquad (13)$$

Secondly, we assume a logarithmic relationship between SST and carrying capacity (see Equation (9)):

$$Tuna_{it} = \beta_1 Sets_{it} * lnSST_{it} + \beta_2 Sets_{it}^2 + \beta_3 t + \sum_{g=2}^{n} \gamma_g D_g + \varepsilon_{it} \qquad (14)$$

Accordingly, the MP_{SST} at means is

$$MP_{SST} = \frac{\partial Tuna}{\partial SST} = \beta_1 \frac{Sets}{SST}. \qquad (15)$$

Finally, as derived from Equation (11), we assume a quadratic relationship between SST and carrying capacity.

$$Tuna_{it} = \beta_1 Sets_{it} * SST_{it} + \beta_2 Sets_{it} * SST_{it}^2 + \beta_3 Sets_{it}^2 + \beta_4 t + \sum_{g=2}^{n} \gamma_g D_g + \varepsilon_{it} \qquad (16)$$

and the MP_{SST} at means is computed as

$$MP_{SST} = \frac{\partial Tuna}{\partial SST} = \beta_1 Sets + 2\beta_2 SST * Sets. \qquad (17)$$

We use an unbalanced annual panel data for 1° latitude/longitude grid of fished areas in the Eastern Pacific Ocean from 1970 to 2018.[2] Only those grid cells that contained catch and effort data are included in the analysis. Separate estimations are performed for observations grouped by species, types of set, and by distance from the equator (by latitude group) with standard errors clustered on a 1° latitude/longitude grid.[3]

DATA

We focus on the agreement area of the Inter-American Tropical Tuna Commission (IATTC), which is the portion of Pacific Ocean east of 150°W up to the coastline of North, Central, and South America and between 50°N and 50°S as defined in the Antigua Convention. We refer to this area as the Eastern Pacific Ocean (EPO).

Publicly available tuna catches and effort data for purse seine were obtained from the website of IATTC, showing monthly tuna catches and number of sets by purse seine vessels in every 1°latitude/longitude grid within the EPO. Catch and effort data were disaggregated by set type and by species of tuna caught (IATTC 2018). Annual totals of both catch and effort were computed for every grid and expressed in per square kilometre to account for the differences in the area of the 1°latitude/longitude grid.

SST analyses typically use in situ observations from ships and buoys (Huang et al. 2018). Monthly SST observations for a 1° latitude/longitude grid from 1970 to 2018 were obtained from the Centennial In Situ Observation-Based Estimates of the Variability of SST and Marine Meteorological Variables, version 2.9.2 (COBE-SST2) by the Japan Meteorological Agency (JMA) (Hirahara, Ishii, and Fukuda 2014).[4] Satellite observations were used by JMA for the reconstruction of SST variability in data sparse regions. We computed the annual averages of SST for each grid using the data from COBE-SST2.

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[2] Parameter estimation was done using monthly data and including a dummy variable for the months in the model. We considered the use of monthly data as tuna spawn all throughout the year in tropical areas (Schaefer 2001), however, estimations using annual data show consistently higher R2 values compared to models that use monthly data, thus only the results of annual data are presented.

[3] Panel fixed effects estimation was also considered to control for time-invariant grid level effects and to test for robustness of the results. The use of panel fixed effects model has many advantages including its capacity to control for the effects of omitted variables (Wooldridge 2010). However, the estimation procedure for this model does not allow for an RTO model.

[4] COBE-SST2 data used in this study was taken from NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site at https://www.esrl.noaa.gov/psd/.

SUMMARY STATISTICS

The waters of the Eastern Pacific Ocean are warming over time as shown by the upward trend in the annual mean SST in the IATTC convention area based on the COBE-SST2 data (Figure 1). Four of the highest five annual average SSTs were recorded in the last five years. This trend is consistent with records of increased sea temperature driven by anthropogenic climate change.

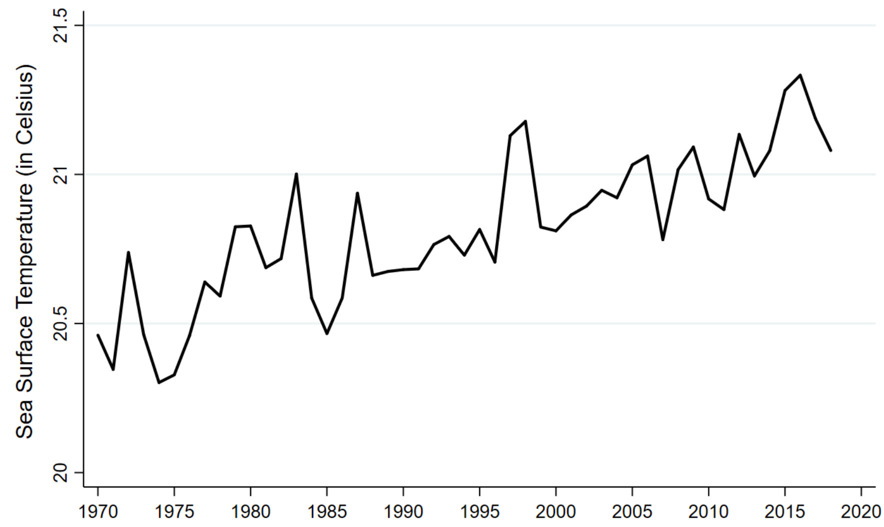

Figure 1. Average annual sea surface temperature in IATTC Convention Area

Source: COBE-SST2.

The tuna catch of purse seine in the EPO based on the IATTC data is composed of skipjack, yellowfin, bigeye, black skipjack, bonito, Pacific bluefin tuna, albacore tuna, and some unidentified tuna. Tuna is caught mostly in areas near the equator and closer to the shore (Figure 2). Catch within 10° latitude distance from the equator accounts for 64 percent of the catch in the EPO from 1970 to 2018. The average annual catch of tuna is highest near coastal areas in the Southern Hemisphere. Yellowfin comprise 58.7 percent while skipjack tuna comprise 30.8 percent of the total tuna catch. Between 1970 and 2004, yellowfin tuna accounted for the biggest share in terms of total catch, however, since 2003 the share of skipjack tuna catch has started to dominate yellowfin (Appendix Figure 2a).

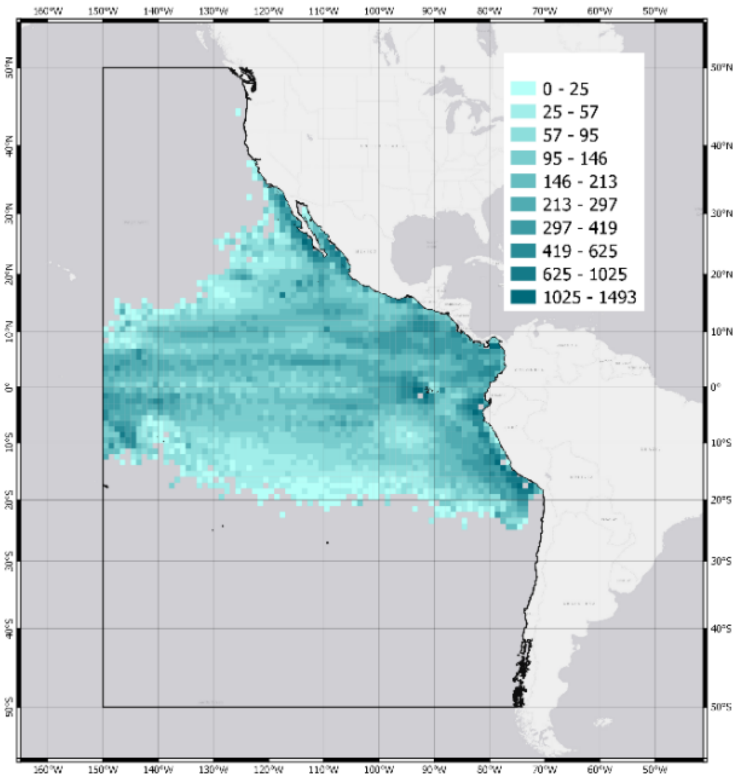

Figure 2. Average Annual Tuna Catch in Eastern Pacific (in metric tons), 1970-2018[5]

The differences in the spatial distribution of catch are apparent when we examine yellowfin and skipjack separately (Figure 3). The average annual catch of yellowfin tuna is higher in areas in the Northern Hemisphere compared to areas in the Southern Hemisphere while for skipjack tuna the opposite is true, i.e. the skipjack catch is higher in the Southern Hemisphere. The differences in the distribution of catch across space support the need to conduct separate analysis by species and location group.

[5] We used geospatial data from United Nations Food and Agriculture Organization GeoNetwork for the IATTC Convention Area (FAO 2019b) and 1° latitude/longitude grids (FAO 2018).

a) Yellowfin Tuna **b) Skipjack Tuna**

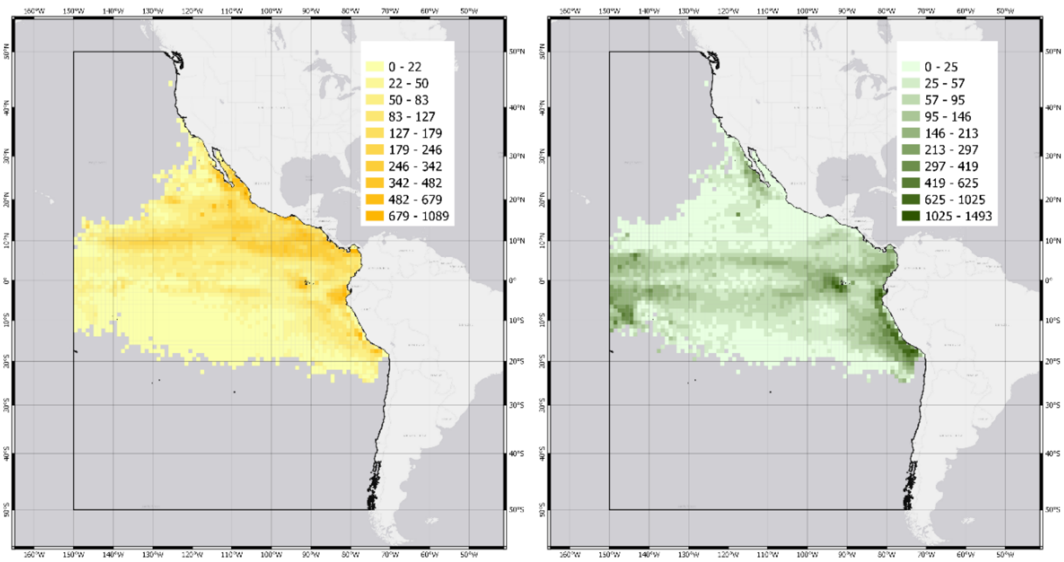

Figure 3. Average Annual Catch of Yellowfin and Skipjack Tuna in Eastern Pacific (in metric tons), 1970-2018

The largest proportion of purse seine sets are recorded in grids closer to the shore (Figure 4). A high concentration of dolphin sets are recorded in the Northern Hemisphere, while most of the floating objects sets are in areas close to the equator. For unassociated sets, effort is distributed across latitudes but clustered near the shores.

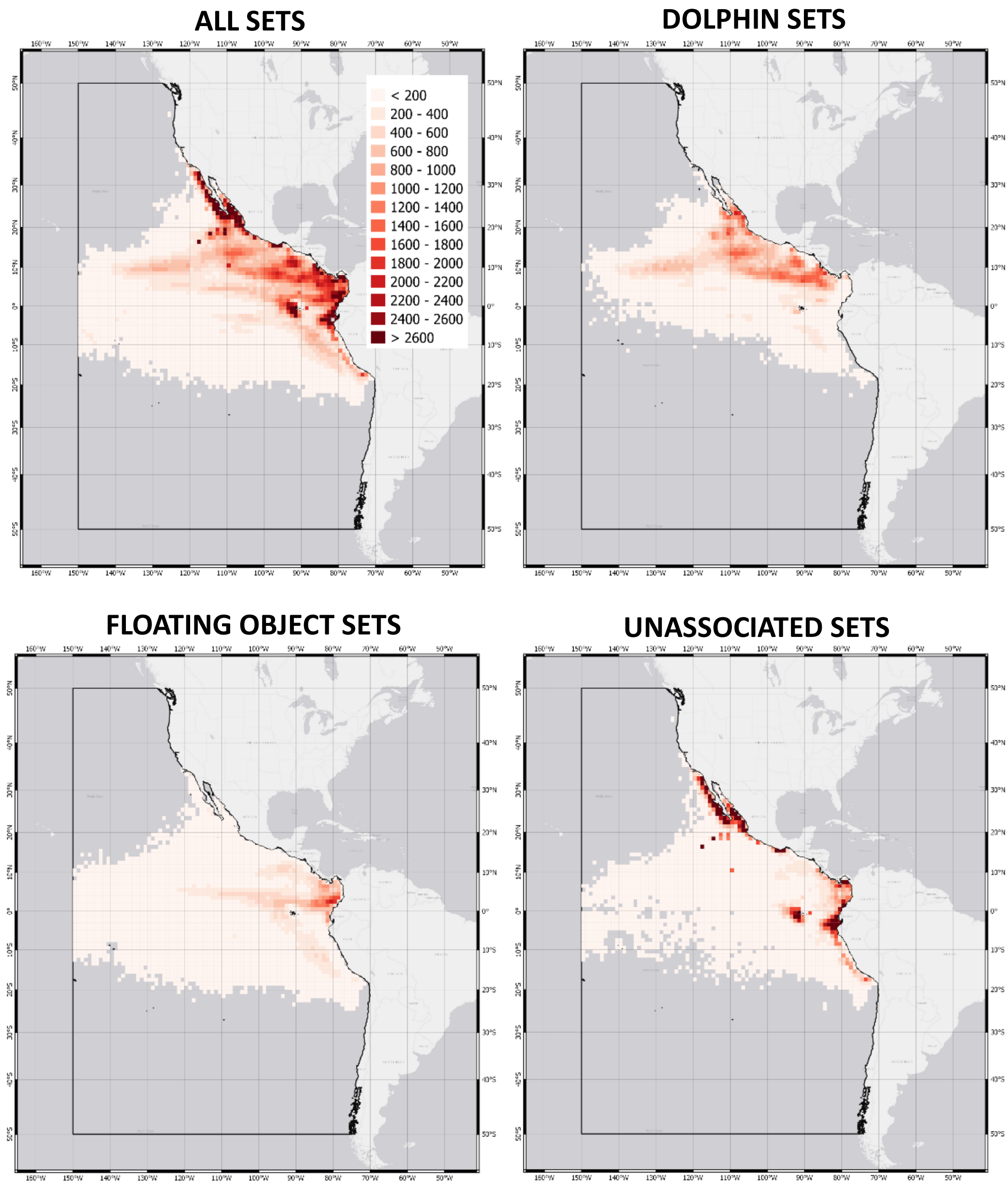

Figure 4. Total Number of Purse Seine Sets in Eastern Pacific, 1970-2018

Table 1 shows the summary statistics for catch and effort data by species, types of set, and location. Unassociated sets have the highest count in terms of effort, but the lowest catch per unit effort, making it a less preferred method more recently. In the early 1970s, most of the sets were made for unassociated schools of tuna, but their share has been decreasing over time (see Appendix Figure 1). The share of dolphin associated sets increased until 1992, after which floating-object associated sets have become the dominant set type due to the introduction of FADs in purse seine fishing in the EPO (IATTC, 2018b; Bayliff, 2001). The high catch per set for floating objects sets explains the dominance of this type of set in the later years, i.e. floating object sets have the highest catch per set at 25.9 metric tons followed by dolphin sets and unassociated sets at 15.3 and 11.7 metric tons, respectively.

Yellowfin tuna is the primary target species of dolphin sets, comprising 98 percent of the total catch from 1970 to 2018 (Table 1). For floating object sets, skipjack tuna accounts for 55 percent of the total catch. Skipjack and yellowfin are the also the main species caught by unassociated sets, however, the species composition has changed from a majority of yellowfin to skipjack over time (see Appendix Figure 2d).

Table 1. Descriptive statistics of Tuna Catch in Eastern Pacific, 1970-2018

	Number of Sets	Catch (metric tons)	Catch per Set (metric tons)	Percentage Distribution of Catch by Species		
				Yellowfin	Skipjack	Other Species
TYPE OF SET						
All sets	**1,222,829**	**20,097,086**	**16.4**	**58.7**	**30.8**	**10.5**
Dolphin sets	451,112	6,884,432	15.3	98.0	2.0	0.0
Unassociated sets	477,009	5,593,239	11.7	44.9	48.8	6.3
Floating object sets	294,708	7,619,415	25.9	25.2	55.0	19.8
LATITUDE GROUP						
40°N to 50°N	1	3	3.0	0.0	0.0	100.0
30°N to 40°N	18,782	167,548	8.9	13.9	17.7	68.5
20°N to 30°N	170,117	1,635,520	9.6	75.9	16.7	7.3
10°N to 20°N	267,778	3,737,941	14.0	89.2	10.3	0.4
0° to 10°N	443,459	8,028,779	18.1	59.6	32.9	7.5
0° to 10°S	258,861	4,846,237	18.7	34.5	49.0	16.5
10°S to 20°S	62,824	1,646,735	26.2	30.0	48.3	21.7
20°S to 30°S	1,007	34,323	34.1	21.3	47.9	30.8

Table 1 also shows that there are more sets and a higher total catch in the Northern Hemisphere but catch per set is higher in the Southern Hemisphere. Yellowfin is the dominant species caught by purse seine in the Northern Hemisphere. The total share of yellowfin tuna catch is higher in subtropical areas (10°N to 20°N and 20°N to 30°N) compared to areas close to the equator (0° to 10°N). In the Southern Hemisphere, skipjack tuna is the dominant species caught by purse seine.

RESULTS

The computed MP_{SST} at means for yellowfin and skipjack tuna by type of sets using all data for the EPO and period covered are presented in Figure 5. The values presented are in metric tons per square kilometre of fished area. The MP_{SST} is computed using Equation 13 for an assumed linear relationship between SST and carrying capacity, Equation 15 for logarithmic, and Equation 17 for quadratic. Only the parameter estimates which are statistically significant at 5 percent are considered in the calculation of the marginal products.

The results of the estimation of parameters of the production function, mean SST, and mean number of sets are presented in Appendix Tables 1 to 3. The coefficients were estimated separately for yellowfin and skipjack tuna using observations for fished areas with reported dolphin sets, floating object sets, unassociated sets, and all sets. The R^2 for all specifications are high (>0.78). Models assuming logarithmic and quadratic relationships between the SST and carrying capacity, however, have higher R^2 compared to models assuming a linear relationship.

Figure 5 shows that the MP_{SST} are mostly positive for the models using the three assumed relationship between SST and the carrying capacity, and for the different set types. The exceptions are the MP_{SST} for skipjack tuna assuming a quadratic relationship. The MP_{SST} is highest for a linear relationship and lowest for a quadratic relationship.

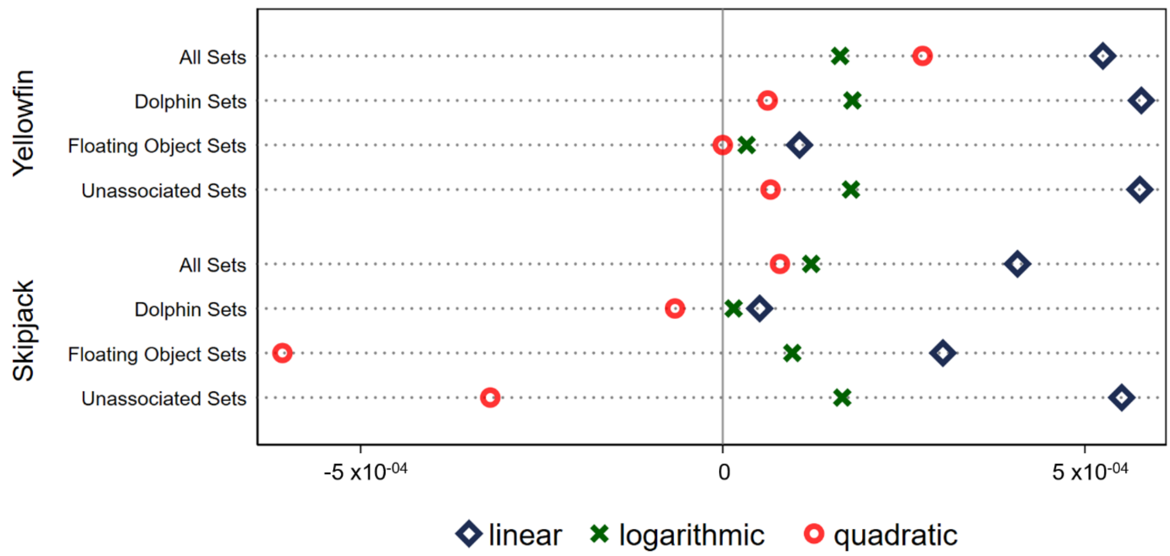

Figure 5. Marginal product of SST at means per square km

The increase in SST has a bigger effect on the catch of yellowfin tuna compared to skipjack tuna if we consider all sets. Assuming a logarithmic relationship between SST and carrying capacity, a one-degree Celsius increase in SST results in an increase of 1.62 x10^{-4} metric tons of yellowfin tuna catch per square kilometre of fished area per year for all sets made. This is equivalent to 25.2 thousand metric tons (60.7 million USD)[6] per year for the fished area in EPO. Even though the MP_{SST} per square kilometre for floating object sets (0.03) is lower compared to dolphin sets (0.18), the total MP_{SST} for the fished area is almost the same at 30 thousand metric tons (73 million USD) per year. This is because the area fished with floating objects sets is far greater than the area fished with dolphin sets.

For skipjack tuna, the MP_{SST} is 1.22 x10^{-4} metric tons of skipjack tuna per square kilometre, equivalent to 20 thousand metrics tons (29 million USD) per year for the EPO. The highest MP_{SST} for the fished area is for floating objects set at 28 thousand metric tons (42 million USD) per year, followed by dolphin sets at 20 thousand metric tons (30 million USD) per year and unassociated sets at 17 thousand metric tons (25 million USD) per year.

The MP_{SST} at means computed by latitude group for both yellowfin and skipjack tuna are presented Figure 6. The results for the estimation, mean SST, and mean number of sets for observations grouped by type of set and latitude groups are presented in Appendix Tables 4 to 6 for yellowfin tuna and Appendix Tables 7 to 9 for skipjack tuna. Only latitude groups with substantial observations (N>300) are presented in the figures and appendix tables.

Assuming a linear or logarithmic relationship between SST and carrying capacity, the MP_{SST} is positive for all types of sets and latitude groups. The results change, however, if we assume a quadratic relationship. Even though there are still areas where the MP_{SST} is positive, there are also areas where the MP_{SST} is either zero or negative. The values of MP_{SST} vary across space, with higher values recorded in areas farther away from the equator (Figure 6).

For yellowfin tuna, the MP_{SST} in areas in the Northern Hemisphere is higher compared to the areas in the Southern Hemisphere. This is true across all types of sets, with highest values in areas between

[6] Based on ex-vessel prices of whole yellowfin (2.40 USD per kilogram) and whole skipjack (1.48 USD per kilogram) Ecuador as of January 2019 as reported in the FAO (2019a).

20°N and 30°N. The MP_{SST} in the Southern Hemisphere are higher compared to areas north of the equator for skipjack tuna.

The MP_{SST} at means for the all sets in Eastern Pacific Ocean 1° latitude/longitude grid are mapped in Figure 7 for yellowfin tuna and Figure 8 for skipjack tuna. The values presented are the computed MP_{SST} multiplied by the area of the grid in square kilometre. Values are presented in thousand metric tons. The MP_{SST} are computed assuming linear, logarithmic, and quadratic relationships between SST and carrying capacity.

Figure 6. Marginal product of SST by latitude group

Figures 7 and 8 clearly highlight the spatial variation in the MP_{SST} for both yellowfin and skipjack tuna. Higher values are recorded in areas above the equator for yellowfin tuna and below the equator for skipjack tuna. The figure also shows areas closer to the coast have higher MP_{SST} compared to areas in the high seas. The highest MP_{SST} for all sets are reported if we assume a linear relationship between SST and carrying capacity both for both tuna species

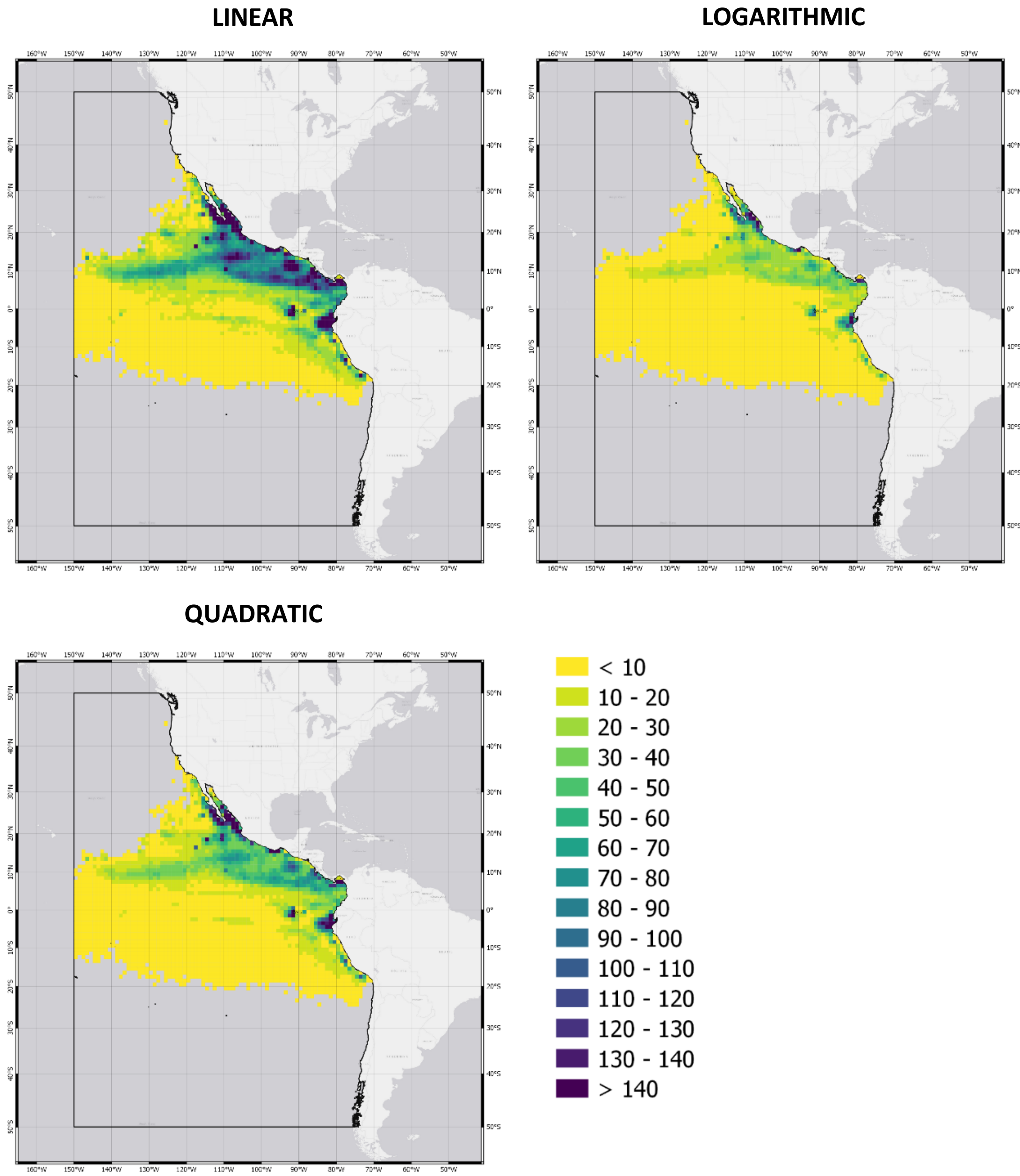

Figure 7. Marginal product of SST for Yellowfin Tuna

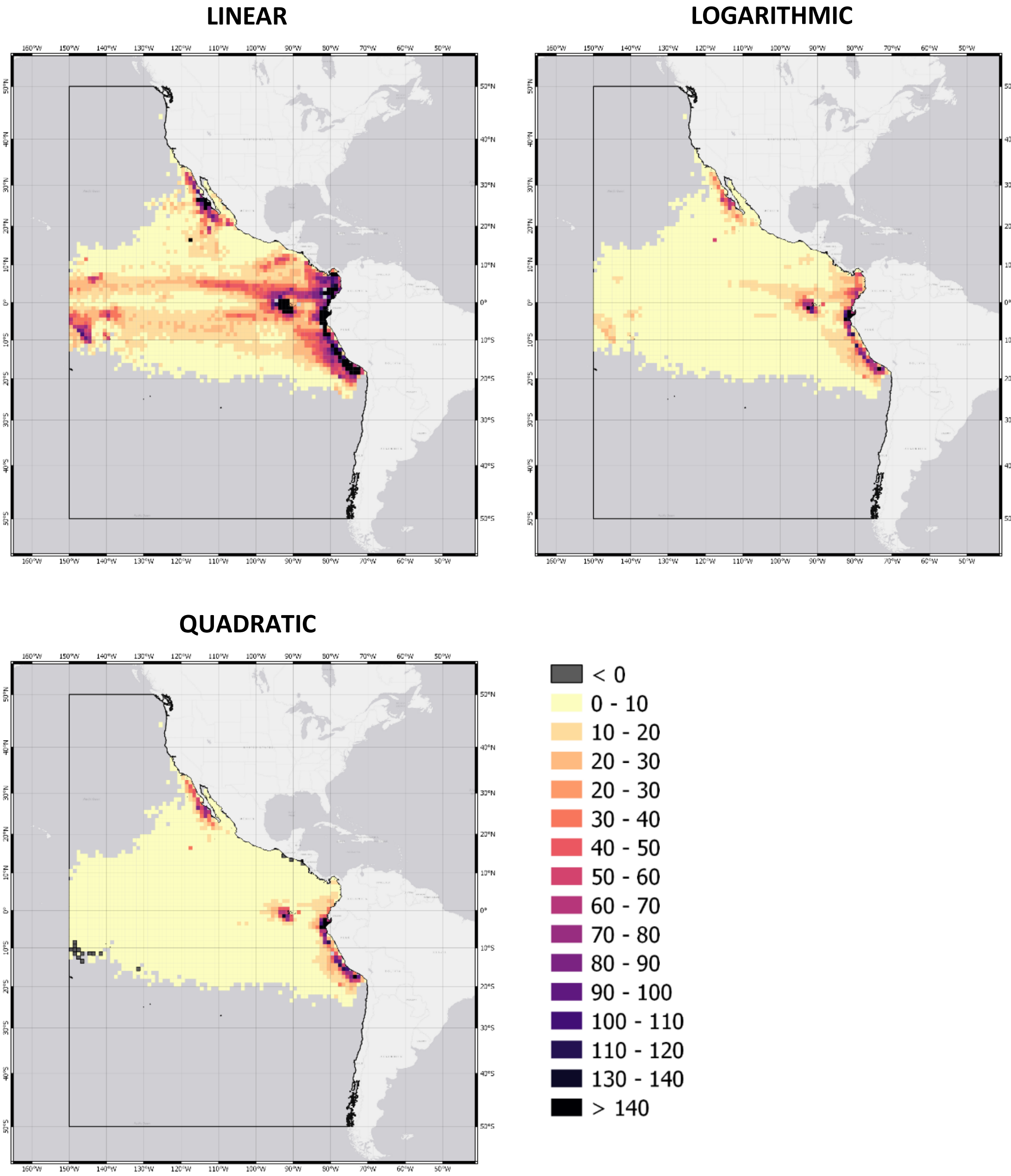

Figure 8. Marginal product of SST for Skipjack Tuna

DISCUSSION

By applying the production function approach, we show that yellowfin and skipjack tuna catch is increasing with SST in the Eastern Pacific Ocean. The magnitude of the MP_{SST} varies across species, type of set, and location of catch and effort, suggesting the need for sector- and species- specific predictions. The MP_{SST} is positive for all types of sets for both yellowfin and skipjack tuna, assuming linear and logarithmic relationships between SST and carrying capacity. These results change for a quadratic relationship, where the MP_{SST} is positive for yellowfin tuna but is negative for skipjack depending on the types of sets considered. We cannot identify the inflection point in the quadratic function with sufficient confidence because of the large variability in the values (from 18°C to 28°C) depending on the location and type of set. Mediodia (2020), which uses the same method and data but focuses on areas within exclusive economic zones of states, shows that logarithmic specification performs better compared to quadratic specification using the coefficient of determination

Our results show that the effect of ocean warming on tuna catch has a bigger effect on yellowfin tuna compared to skipjack tuna if we consider all types of purse seine sets. This implies that, collectively, fishers targeting yellowfin tuna in the EPO will benefit more compared to those targeting skipjack tuna. The results also show that the MP_{SST} varies across types of purse seine set. This highlights the importance of looking at the fishing gear in doing an analysis on the effects of SST on fisheries production, as suggested in Hu et al. (2018). The highest MP_{SST} for both yellowfin and skipjack tuna are for unassociated sets. Unassociated sets catch both yellowfin and skipjack tuna, thus both species benefit from the improved suitability of the EPO for spawning and spatial redistribution. Between dolphin sets and floating object sets for each tuna species, the MP_{SST} is higher if the species dominates the catch of that type of set. For yellowfin tuna, the MP_{SST} for dolphin sets is higher compared to floating object sets. On the other hand, the MP_{SST} for floating object sets is higher compared to dolphin sets for skipjack tuna.

The eastward redistribution of tuna in response to ocean warming in our results is consistent with the pattern established through simulations models in other studies (see Lehodey et al. 2013; Dueri et al. 2016). High values of MP_{SST} are predicted for grids on the eastern side of the Pacific Ocean close to the coastal border. Due to habitat preference, more yellowfin tuna are caught in the Northern Hemisphere while skipjack tuna is dominant in the Southern Hemisphere. In the Northern Hemisphere, fishers targeting yellowfin tuna will benefit more as ocean warms compared to those targeting skipjack tuna as MP_{SST} for yellowfin tuna is higher compared to skipjack tuna. Unassociated sets and dolphin sets which both target yellowfin tuna are expected to be the dominant types of purse seine set in this area as sea temperature increases. The MP_{SST} is higher for skipjack tuna compared to yellowfin in the Southern Hemisphere, thus there will be more unassociated and floating object sets as these types of sets target skipjack tuna.

We demonstrate a procedure for including SST in a fisheries production function approach by adopting the fisheries bioeconomic model pioneered by Barbier and Strand (1998). This novel approach allows further work on the impacts of climate change on fisheries and marine systems using an economic framework. The approach we employed is also applicable to models that will use projections of future climate scenarios. We also demonstrate the use of catch and effort data paired with temperature data for latitude/longitude grids, with the expectation that more gridded datasets of fisheries will be available in the future.

We establish that there is a nonlinear relationship between the SST and the carrying capacity of tuna fisheries. The R^2 of models that assume nonlinear (i.e. logarithmic and quadratic) relationship between SST and carrying capacity is greater compared to models that assume linear relationship. This is the result across all species, types of sets, and location. Nonlinear relationships between temperature and economic outcomes have been established in previous studies but not applied for fisheries production.

The availability of gridded catch and effort data and improvements on climate modelling opens opportunities for more research on the economic impact of climate change on fisheries. Studies that focus on a single species should consider all types of fishing gears used to catch that species. The absence of gridded catch and effort data at the same resolution limits our ability to conduct that analysis for this paper. If the focus is for the management of an area, then all target species must be included in the analysis. We show that tuna catch increases with SST, however, it is possible that the net effect for the area is negative as result of reduction in catch of other species. Use of higher resolution catch and effort and ocean temperature data may provide more useful results for fisheries management areas. Our approach in analysing the relationship of SST and tuna catch provides an enabling framework for the application of bioeconomic models to understand impacts of climate change on fisheries.

CONCLUSION

Our results show that catch of both yellowfin tuna and skipjack tuna increases with SST if we consider the whole EPO and all purse seine sets. This is consistent with the results of Dueri et al. (2016) and Bell et al (2013) were it was stated that warming ocean is favourable to tuna fisheries in EPO. However, the magnitude of increase in tuna catch vary across tuna species, type of purse seine set and location of effort. Ocean warming makes higher latitudes more suitable habitats for tuna species that already dominate the area in terms of catch and effort. Any program to manage tuna fisheries in response to ocean warming must be designed specifically for the species and should consider the different types of gears used. The policy must also be suited for the area being managed.

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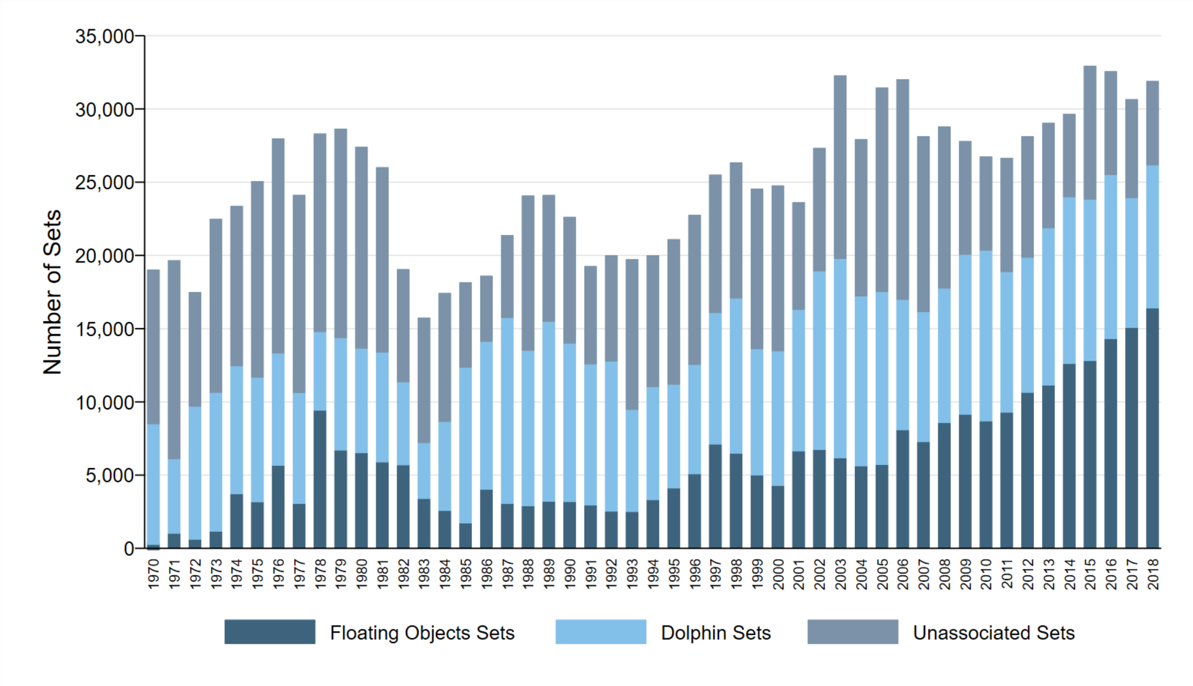
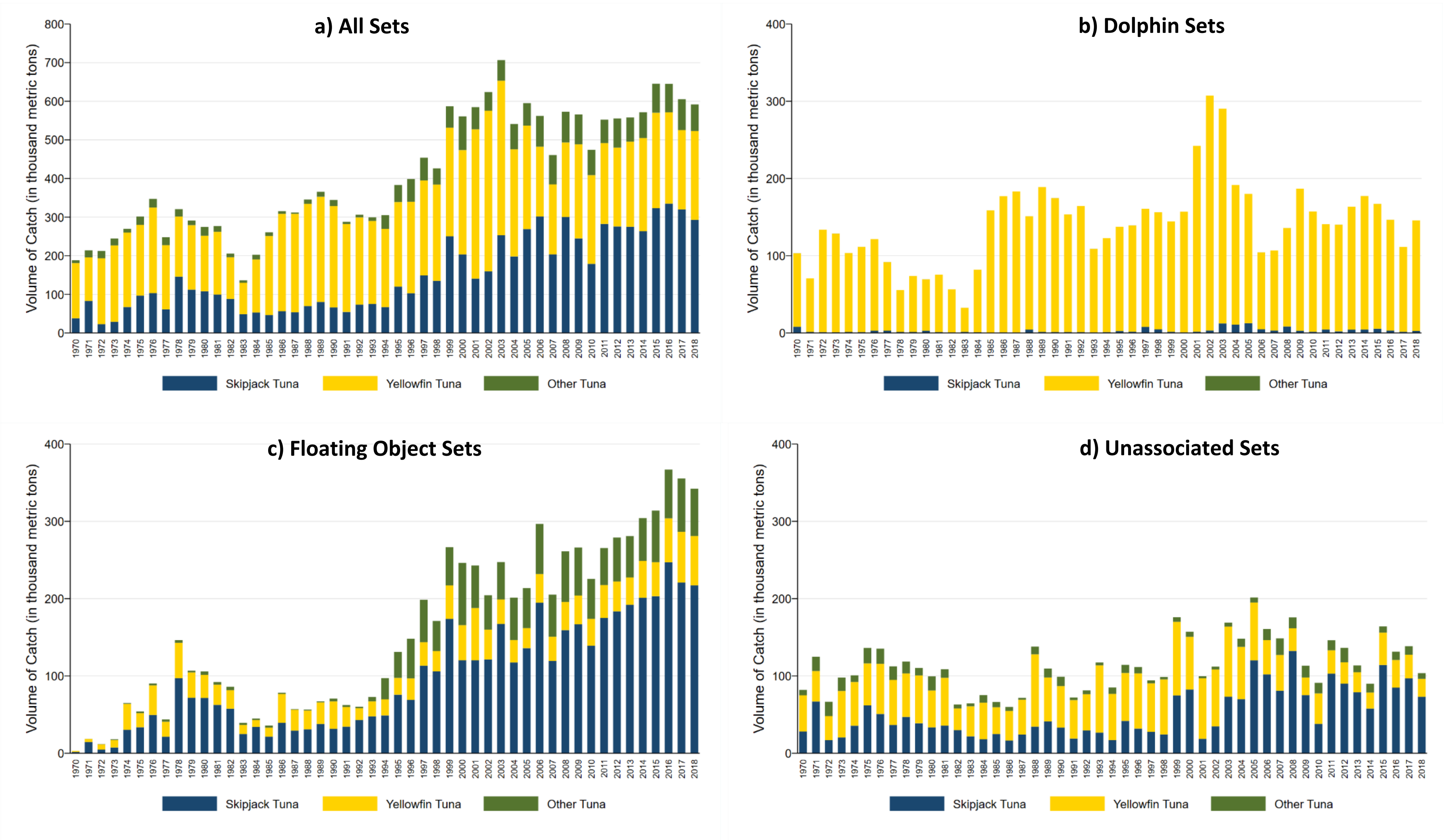


Appendix Figure 1. Total number of purse seine sets in IATTC Convention Area by set type, 1970-2018



Appendix Figure 2. Total purse seine catch in IATTC Convention Area by set type and species, 1970-2018

Appendix Table 1. Parameter estimates and marginal product of SST at means for yellowfin and skipjack tuna assuming linear relationship between SST and carrying capacity, by set type [Dependent Variable: Annual tuna catch (in metric tons)]

	Observations	R^2	β_1	p-value (β_1)	β_2	p-value (β_2)	Mean SST	Mean Number of Sets	MP_{SST}
Yellowfin									
All Sets	62,036	0.848	0.5332	0.00	-94.11	0.00	26.39	9.84 x10^{-04}	5.25 x10^{-04}
Dolphin Sets	39,581	0.857	0.6289	0.00	-325.16	0.00	26.91	9.19 x10^{-04}	5.77 x10^{-04}
Unassociated Sets	14,805	0.825	0.4436	0.00	-54.34	0.00	25.86	1.30 x10^{-03}	5.76 x10^{-04}
Floating Object Sets	36,317	0.754	0.6459	0.00	-654.21	0.00	26.13	1.64 x10^{-04}	1.06 x10^{-04}
Skipjack									
All Sets	46,808	0.818	0.5911	0.00	-28.38	0.00	26.14	6.88 x10^{-04}	4.07 x10^{-04}
Dolphin Sets	8,942	0.860	0.5763	0.00	610.34	0.12	26.93	8.79 x10^{-05}	5.07 x10^{-05}
Unassociated Sets	15,450	0.816	0.5240	0.00	-8.22	0.14	25.56	1.05 x10^{-03}	5.51 x10^{-04}
Floating Object Sets	38,323	0.782	0.8122	0.00	-446.90	0.00	26.15	3.75 x10^{-04}	3.04 x10^{-04}

Appendix Table 2. Parameter estimates and marginal product of SST at means for yellowfin and skipjack tuna assuming logarithmic relationship between SST and carrying capacity, by set type [Dependent Variable: Annual tuna catch (in metric tons)]

	Observations	R^2	β_1	p-value (β_1)	β_2	p-value (β_2)	Mean SST	Mean Number of Sets	MP_{SST}
Yellowfin Tuna									
All Sets	62,036	0.849	4.352	0.00	-109.906	0.00	26.39	9.84 x10^{-04}	1.62 x10^{-04}
Dolphin Sets	39,581	0.859	5.239	0.00	-336.464	0.00	26.91	9.19 x10^{-04}	1.79 x10^{-04}
Unassociated Sets	14,805	0.830	3.523	0.00	-64.343	0.00	25.86	1.30 x10^{-03}	1.77 x10^{-04}
Floating Objects Sets	36,317	0.754	5.236	0.00	-621.885	0.00	26.13	1.64 x10^{-04}	3.29 x10^{-05}
Skipjack Tuna									
All Sets	46,808	0.820	4.629	0.00	-41.542	0.00	26.14	6.88 x10^{-04}	1.22 x10^{-04}
Dolphin Sets	8,942	0.865	4.736	0.00	670.461	0.01	26.93	8.79 x10^{-05}	1.55 x10^{-05}
Unassociated Sets	15,450	0.821	4.022	0.00	-17.218	0.00	25.56	1.05 x10^{-03}	1.65 x10^{-04}
Floating Object Sets	38,323	0.786	6.671	0.00	-454.964	0.00	26.15	3.75 x10^{-04}	9.55 x10^{-05}

Appendix Table 3. Parameter estimates and marginal product of SST at means for yellowfin and skipjack tuna assuming quadratic relationship between SST and carrying capacity, by set type [Dependent Variable: Annual tuna catch (in metric tons)]

	Observations	R^2	β_1	p-value (β_1)	β_2	p-value (β_2)	β_3	p-value (β_3)	Mean SST	Mean Number of Sets	MP_{SST}
Yellowfin Tuna											
All Sets	62,036	0.849	0.782	0.00	-0.009	0.01	-104.060	0.00	26.39	9.84 x10^{-04}	2.91 x10^{-04}
Dolphin Sets	39,581	0.859	1.199	0.00	-0.021	0.00	-333.542	0.00	26.91	9.19 x10^{-04}	8.05 x10^{-05}
Unassociated Sets	14,805	0.829	0.817	0.00	-0.014	0.00	-64.596	0.00	25.86	1.30 x10^{-03}	8.89 x10^{-05}
Floating Object Sets	36,317	0.754	0.766	0.06	-0.004	0.77	-648.193	0.00	26.13	1.64 x10^{-04}	0.00
Skipjack Tuna											
All Sets	46,808	0.820	1.039	0.00	-0.018	0.03	-41.90	0.00	26.14	6.88 x10^{-04}	8.18 x10^{-05}
Dolphin Sets	8,942	0.869	1.880	0.00	-0.049	0.00	1060.77	0.00	26.93	8.79 x10^{-05}	-6.48 x10^{-05}
Unassociated Sets	15,450	0.823	1.278	0.00	-0.031	0.00	-24.15	0.00	25.56	1.05 x10^{-03}	-3.12 x10^{-04}
Floating Object Sets	38,323	0.792	3.350	0.00	-0.095	0.00	-433.49	0.00	26.15	3.75 x10^{-04}	-5.97 x10^{-04}

Appendix Table 4. Parameter estimates and marginal product of SST at means for yellowfin tuna assuming linear relationship between SST and carrying capacity, by set type and latitude group
Dependent Variable: Annual tuna catch (in metric tons)

	Observations	R^2	β_1	p-value (β_1)	β_2	p-value (β_2)	Mean SST	Mean Number of Sets	MP_{SST}
All Sets									
20°N to 30°N	2,785	0.882	0.4083	0.00	-43.14	0.01	24.12	3.66 $\times10^{-03}$	1.49 $\times10^{-03}$
10°N to 20°N	14,645	0.878	0.5290	0.00	-103.81	0.00	27.52	1.34 $\times10^{-03}$	7.09 $\times10^{-04}$
0° to 10°N	22,988	0.878	0.6093	0.00	-165.82	0.00	27.23	9.38 $\times10^{-04}$	5.72 $\times10^{-04}$
0° to 10°S	14,474	0.793	0.5697	0.00	-91.12	0.00	25.39	5.55 $\times10^{-04}$	3.16 $\times10^{-04}$
10°S to 20°S	6,782	0.877	1.2266	0.00	-91.74	0.56	24.49	2.02 $\times10^{-04}$	2.48 $\times10^{-04}$
Dolphin Sets									
20°N to 30°N	1,996	0.842	0.4023	0.00	43.42	0.67	24.97	1.51 $\times10^{-03}$	6.06 $\times10^{-04}$
10°N to 20°N	14,130	0.867	0.5510	0.00	-183.95	0.03	27.54	1.11 $\times10^{-03}$	6.11 $\times10^{-04}$
0° to 10°N	17,181	0.881	0.7081	0.00	-486.30	0.00	27.40	8.88 $\times10^{-04}$	6.29 $\times10^{-04}$
0° to 10°S	5,214	0.877	0.9736	0.00	929.27	0.06	24.93	3.98 $\times10^{-04}$	3.88 $\times10^{-04}$
10°S to 20°S	1,050	0.818	0.9326	0.00	1723.10	0.53	24.06	3.42 $\times10^{-04}$	3.19 $\times10^{-04}$
Unassociated Sets									
20°N to 30°N	1,906	0.863	0.3907	0.00	-36.70	0.04	23.49	3.67 $\times10^{-03}$	1.43 $\times10^{-03}$
10°N to 20°N	3,241	0.873	0.4234	0.00	-40.54	0.17	27.31	1.02 $\times10^{-03}$	4.36 $\times10^{-04}$
0° to 10°N	5,607	0.839	0.4899	0.00	-108.76	0.00	27.07	6.15 $\times10^{-04}$	3.01 $\times10^{-04}$
0° to 10°S	2,897	0.803	0.4703	0.00	-56.38	0.00	24.51	1.67 $\times10^{-03}$	7.86 $\times10^{-04}$
10°S to 20°S	937	0.901	1.1606	0.00	-26.73	0.90	24.04	4.01 $\times10^{-04}$	4.65 $\times10^{-04}$
Floating Object Sets									
20°N to 30°N	653	0.734	0.4191	0.00	1362.93	0.15	23.26	2.44 $\times10^{-04}$	1.02 $\times10^{-04}$
10°N to 20°N	3,051	0.853	0.5919	0.00	1088.48	0.00	27.35	2.49 $\times10^{-04}$	1.47 $\times10^{-04}$
0° to 10°N	14,392	0.794	0.5433	0.00	-360.66	0.01	27.11	2.26 $\times10^{-04}$	1.23 $\times10^{-04}$
0° to 10°S	11,773	0.704	0.7299	0.00	-1829.49	0.00	25.65	9.67 $\times10^{-05}$	7.06 $\times10^{-05}$
10°S to 20°S	6,259	0.781	1.2294	0.00	3532.46	0.15	24.60	1.02 $\times10^{-04}$	1.25 $\times10^{-04}$

Appendix Table 5. Parameter estimates and marginal product of SST at means for yellowfin tuna assuming logarithmic relationship between SST and carrying capacity, by set type and latitude group

Dependent Variable: Annual tuna catch (in metric tons)

	Observations	R^2	β_1	p-value (β_1)	β_2	p-value (β_2)	Mean SST	Mean Number of Sets	MP_{SST}
All Sets									
20°N to 30°N	2,785	0.885	3.169	0.00	-48.304	0.00	24.12	3.66 $\times 10^{-03}$	4.80 $\times 10^{-04}$
10°N to 20°N	14,645	0.877	4.403	0.00	-103.895	0.00	27.52	1.34 $\times 10^{-03}$	2.14 $\times 10^{-04}$
0° to 10°N	22,988	0.878	5.077	0.00	-167.756	0.00	27.23	9.38 $\times 10^{-04}$	1.75 $\times 10^{-04}$
0° to 10°S	14,474	0.799	4.334	0.00	-102.881	0.00	25.39	5.55 $\times 10^{-04}$	9.46 $\times 10^{-05}$
10°S to 20°S	6,782	0.876	9.054	0.00	-94.195	0.51	24.49	2.02 $\times 10^{-04}$	7.47 $\times 10^{-05}$
Dolphin Sets									
20°N to 30°N	1,996	0.851	3.335	0.00	-3.213	0.97	24.97	1.51 $\times 10^{-03}$	2.01 $\times 10^{-04}$
10°N to 20°N	14,130	0.866	4.545	0.00	-159.110	0.05	27.54	1.11 $\times 10^{-03}$	1.83 $\times 10^{-04}$
0° to 10°N	17,181	0.883	5.917	0.00	-477.110	0.00	27.40	8.88 $\times 10^{-04}$	1.92 $\times 10^{-04}$
0° to 10°S	5,214	0.879	7.722	0.00	798.115	0.09	24.93	3.98 $\times 10^{-04}$	1.23 $\times 10^{-04}$
10°S to 20°S	1,050	0.820	7.208	0.00	1740.722	0.51	24.06	3.42 $\times 10^{-04}$	1.03 $\times 10^{-04}$
Unassociated Sets									
20°N to 30°N	1,906	0.867	2.988	0.00	-42.331	0.00	23.49	3.67 $\times 10^{-03}$	4.67 $\times 10^{-04}$
10°N to 20°N	3,241	0.873	3.468	0.00	-36.644	0.20	27.31	1.02 $\times 10^{-03}$	1.30 $\times 10^{-04}$
0° to 10°N	5,607	0.838	4.037	0.00	-108.046	0.00	27.07	6.15 $\times 10^{-04}$	9.17 $\times 10^{-05}$
0° to 10°S	2,897	0.815	3.598	0.00	-67.812	0.00	24.51	1.67 $\times 10^{-03}$	2.45 $\times 10^{-04}$
10°S to 20°S	937	0.903	8.349	0.00	-0.703	1.00	24.04	4.01 $\times 10^{-04}$	1.39 $\times 10^{-04}$
Floating Object Sets									
20°N to 30°N	653	0.733	3.019	0.00	1440.999	0.15	23.26	2.44 $\times 10^{-04}$	3.17 $\times 10^{-05}$
10°N to 20°N	3,051	0.853	4.909	0.00	1123.106	0.00	27.35	2.49 $\times 10^{-04}$	4.46 $\times 10^{-05}$
0° to 10°N	14,392	0.794	4.465	0.00	-342.775	0.01	27.11	2.26 $\times 10^{-04}$	3.72 $\times 10^{-05}$
0° to 10°S	11,773	0.703	5.684	0.00	-1950.053	0.00	25.65	9.67 $\times 10^{-05}$	2.14 $\times 10^{-05}$
10°S to 20°S	6,259	0.777	9.221	0.00	3695.603	0.16	24.60	1.02 $\times 10^{-04}$	3.80 $\times 10^{-05}$

Appendix Table 6. Parameter estimates and marginal product of SST at means for yellowfin tuna assuming quadratic relationship between SST and carrying capacity, by set type and latitude group
Dependent Variable: Annual tuna catch (in metric tons)

	Observations	R^2	β_1	p-value (β_1)	β_2	p-value (β_2)	β_3	p-value (β_3)	Mean SST	Mean Number of Sets	MP_{SST}
All Sets											
20°N to 30°N	2,785	0.885	0.783	0.00	-0.015	0.01	-48.972	0.00	24.12	3.66×10^{-03}	2.11×10^{-05}
10°N to 20°N	14,645	0.878	0.199	0.50	0.012	0.27	-102.486	0.00	27.52	1.34×10^{-03}	0.00
0° to 10°N	22,988	0.878	0.950	0.01	-0.012	0.34	-167.530	0.00	27.23	9.38×10^{-04}	8.91×10^{-04}
0° to 10°S	14,474	0.800	1.375	0.00	-0.033	0.02	-110.730	0.00	25.39	5.55×10^{-04}	-1.80×10^{-04}
10°S to 20°S	6,782	0.877	1.263	0.34	-0.002	0.98	-92.144	0.55	24.49	2.02×10^{-04}	0.00
Dolphin Sets											
20°N to 30°N	1,996	0.858	1.460	0.00	-0.041	0.00	-9.806	0.90	24.97	1.51×10^{-03}	-8.35×10^{-04}
10°N to 20°N	14,130	0.869	-0.120	0.62	0.024	0.00	-211.853	0.01	27.54	1.11×10^{-03}	1.49×10^{-03}
0° to 10°N	17,181	0.885	2.576	0.00	-0.068	0.00	-408.731	0.00	27.40	8.88×10^{-04}	-1.01×10^{-03}
0° to 10°S	5,214	0.880	2.354	0.00	-0.054	0.00	702.850	0.15	24.93	3.98×10^{-04}	-1.31×10^{-04}
10°S to 20°S	1,050	0.821	2.947	0.00	-0.083	0.04	2255.081	0.42	24.06	3.42×10^{-04}	-3.53×10^{-04}
Unassociated Sets											
20°N to 30°N	1,906	0.868	0.823	0.00	-0.018	0.01	-43.572	0.00	23.49	3.67×10^{-03}	-4.71×10^{-05}
10°N to 20°N	3,241	0.873	0.424	0.41	0.000	1.00	-40.533	0.18	27.31	1.02×10^{-03}	0.00
0° to 10°N	5,607	0.840	-0.086	0.89	0.021	0.34	-107.997	0.00	27.07	6.15×10^{-04}	0.00
0° to 10°S	2,897	0.829	1.761	0.00	-0.054	0.00	-83.667	0.00	24.51	1.67×10^{-03}	-1.55×10^{-03}
10°S to 20°S	937	0.904	2.788	0.15	-0.073	0.38	35.385	0.86	24.04	4.01×10^{-04}	0.00
Floating Object Sets											
20°N to 30°N	653	0.735	0.339	0.53	0.003	0.88	1363.353	0.15	23.26	2.44×10^{-04}	0.00
10°N to 20°N	3,051	0.853	0.538	0.56	0.002	0.95	1084.576	0.00	27.35	2.49×10^{-04}	0.00
0° to 10°N	14,392	0.795	0.074	0.89	0.017	0.36	-374.831	0.01	27.11	2.26×10^{-04}	0.00
0° to 10°S	11,773	0.704	0.555	0.12	0.007	0.61	-1783.344	0.00	25.65	9.67×10^{-05}	0.00
10°S to 20°S	6,259	0.786	-1.514	0.21	0.112	0.02	4272.452	0.09	24.60	1.02×10^{-04}	5.57×10^{-04}

Appendix Table 7. Parameter estimates and marginal product of SST at means for skipjack tuna assuming linear relationship between SST and carrying capacity, by set type and latitude group

Dependent Variable: Annual tuna catch (in metric tons)

	Observations	R^2	β_1	p-value (β_1)	β_2	p-value (β_2)	Mean SST	Mean Number of Sets	MP_{SST}
All Sets									
20°N to 30°N	1,905	0.854	0.4187	0.00	-1.29	0.97	23.56	1.44 x10^{-03}	6.03 x10^{-04}
10°N to 20°N	6,438	0.909	0.5457	0.00	-129.96	0.03	27.29	3.96 x10^{-04}	2.16 x10^{-04}
0° to 10°N	17,392	0.824	0.6054	0.00	-125.43	0.00	27.14	7.19 x10^{-04}	4.35 x10^{-04}
0° to 10°S	14,108	0.821	0.6093	0.00	-33.11	0.04	25.51	7.70 x10^{-04}	4.69 x10^{-04}
10°S to 20°S	6,627	0.909	1.0536	0.00	-89.84	0.03	24.73	4.87 x10^{-04}	5.13 x10^{-04}
Dolphin Sets									
20°N to 30°N	772	0.832	0.3574	0.00	5717.72	0.00	24.55	1.29 x10^{-04}	4.61 x10^{-05}
10°N to 20°N	4,161	0.904	0.4779	0.00	873.54	0.00	27.29	9.58 x10^{-05}	4.58 x10^{-05}
0° to 10°N	3,262	0.877	0.6460	0.00	1938.52	0.58	27.62	7.16 x10^{-05}	4.63 x10^{-05}
0° to 10°S	690	0.885	1.0552	0.00	-1745.76	0.80	24.44	7.63 x10^{-05}	8.05 x10^{-05}
10°S to 20°S									
Unassociated Sets									
20°N to 30°N	1,378	0.855	0.4098	0.00	8.83	0.76	23.00	1.79 x10^{-03}	7.34 x10^{-04}
10°N to 20°N	1,719	0.894	0.3930	0.00	34.43	0.63	27.08	5.06 x10^{-04}	1.99 x10^{-04}
0° to 10°N	6,174	0.816	0.4590	0.00	-30.01	0.52	26.89	6.59 x10^{-04}	3.02 x10^{-04}
0° to 10°S	4,330	0.824	0.5269	0.00	-12.23	0.23	24.70	1.64 x10^{-03}	8.62 x10^{-04}
10°S to 20°S	1,609	0.917	0.9625	0.00	-41.63	0.40	24.18	9.07 x10^{-04}	8.73 x10^{-04}
Floating Object Sets									
20°N to 30°N	568	0.771	0.7982	0.00	-2592.15	0.00	23.25	2.70 x10^{-04}	2.15 x10^{-04}
10°N to 20°N	2,942	0.885	0.7025	0.00	-94.13	0.66	27.25	3.42 x10^{-04}	2.40 x10^{-04}
0° to 10°N	15,200	0.786	0.6951	0.00	-264.21	0.02	27.08	5.05 x10^{-04}	3.51 x10^{-04}
0° to 10°S	13,059	0.794	1.1506	0.00	-639.83	0.29	25.66	2.86 x10^{-04}	3.29 x10^{-04}
10°S to 20°S	6,400	0.823	1.3551	0.00	-1489.24	0.03	24.82	2.72 x10^{-04}	3.69 x10^{-04}

Appendix Table 8. Parameter estimates and marginal product of SST at means for skipjack tuna assuming logarithmic relationship between SST and carrying capacity, by set type and latitude group
Dependent Variable: Annual tuna catch (in metric tons)

	Observations	R^2	β_1	p-value (β_1)	β_2	p-value (β_2)	Mean SST	Mean Number of Sets	MP_{SST}
All Sets									
20°N to 30°N	1,905	0.856	3.088	0.00	-10.268	0.78	23.56	1.44 x10^{-03}	1.89 x10^{-04}
10°N to 20°N	6,438	0.910	4.508	0.00	-132.408	0.03	27.29	3.96 x10^{-04}	6.54 x10^{-05}
0° to 10°N	17,392	0.828	4.985	0.00	-131.069	0.00	27.14	7.19 x10^{-04}	1.32 x10^{-04}
0° to 10°S	14,108	0.816	4.578	0.00	-39.239	0.02	25.51	7.70 x10^{-04}	1.38 x10^{-04}
10°S to 20°S	6,627	0.910	7.819	0.00	-117.710	0.00	24.73	4.87 x10^{-04}	1.54 x10^{-04}
Dolphin Sets									
20°N to 30°N	772	0.837	2.925	0.00	5302.407	0.00	24.55	1.29 x10^{-04}	1.54 x10^{-05}
10°N to 20°N	4,161	0.905	3.938	0.00	1011.412	0.00	27.29	9.58 x10^{-05}	1.38 x10^{-05}
0° to 10°N	3,262	0.878	5.424	0.00	1815.660	0.60	27.62	7.16 x10^{-05}	1.41 x10^{-05}
0° to 10°S	690	0.890	8.258	0.00	-2727.786	0.69	24.44	7.63 x10^{-05}	2.58 x10^{-05}
10°S to 20°S									
Unassociated Sets									
20°N to 30°N	1,378	0.856	2.982	0.00	3.012	0.92	23.00	1.79 x10^{-03}	2.32 x10^{-04}
10°N to 20°N	1,719	0.896	3.250	0.00	21.761	0.72	27.08	5.06 x10^{-04}	6.07 x10^{-05}
0° to 10°N	6,174	0.825	3.768	0.00	-33.890	0.42	26.89	6.59 x10^{-04}	9.23 x10^{-05}
0° to 10°S	4,330	0.823	3.968	0.00	-18.038	0.10	24.70	1.64 x10^{-03}	2.63 x10^{-04}
10°S to 20°S	1,609	0.920	7.144	0.00	-71.978	0.13	24.18	9.07 x10^{-04}	2.68 x10^{-04}
Floating Object Sets									
20°N to 30°N	568	0.770	5.758	0.00	-2333.470	0.00	23.25	2.70 x10^{-04}	6.69 x10^{-05}
10°N to 20°N	2,942	0.887	5.838	0.00	-99.246	0.63	27.25	3.42 x10^{-04}	7.33 x10^{-05}
0° to 10°N	15,200	0.788	5.760	0.00	-279.519	0.02	27.08	5.05 x10^{-04}	1.07 x10^{-04}
0° to 10°S	13,059	0.792	9.181	0.00	-751.617	0.19	25.66	2.86 x10^{-04}	1.02 x10^{-04}
10°S to 20°S	6,400	0.824	10.539	0.00	-1737.681	0.00	24.82	2.72 x10^{-04}	1.16 x10^{-04}

Appendix Table 9. Parameter estimates and marginal product of SST at means for skipjack tuna assuming quadratic relationship between SST and carrying capacity, by set type and latitude group

Dependent Variable: Annual tuna catch (in metric tons)

	Observations	R^2	β_1	p-value (β_1)	β_2	p-value (β_2)	β_3	p-value (β_3)	Mean SST	Mean Number of Sets	MP_{SST}
All Sets											
20°N to 30°N	1,905	0.856	0.793	0.00	-0.016	0.12	-12.70	0.73	23.56	1.44 $\times 10^{-03}$	1.14 $\times 10^{-03}$
10°N to 20°N	6,438	0.910	1.038	0.00	-0.018	0.17	-133.00	0.03	27.29	3.96 $\times 10^{-04}$	4.11 $\times 10^{-04}$
0° to 10°N	17,392	0.832	2.376	0.00	-0.066	0.00	-134.32	0.00	27.14	7.19 $\times 10^{-04}$	-8.53 $\times 10^{-04}$
0° to 10°S	14,108	0.824	-0.074	0.79	0.028	0.03	-20.44	0.04	25.51	7.70 $\times 10^{-04}$	1.11 $\times 10^{-03}$
10°S to 20°S	6,627	0.910	2.067	0.02	-0.043	0.23	-126.38	0.00	24.73	4.87 $\times 10^{-04}$	1.01 $\times 10^{-03}$
Dolphin Sets											
20°N to 30°N	772	0.845	1.644	0.01	-0.051	0.03	5085.34	0.01	24.55	1.29 $\times 10^{-04}$	-1.09 $\times 10^{-04}$
10°N to 20°N	4,161	0.905	1.190	0.00	-0.026	0.00	1198.10	0.00	27.29	9.58 $\times 10^{-05}$	-2.30 $\times 10^{-05}$
0° to 10°N	3,262	0.879	2.320	0.03	-0.060	0.11	1754.08	0.61	27.62	7.16 $\times 10^{-05}$	1.66 $\times 10^{-05}$
0° to 10°S	690	0.907	7.556	0.00	-0.266	0.01	-4959.12	0.47	24.44	7.63 $\times 10^{-05}$	-4.17 $\times 10^{-04}$
10°S to 20°S											
Unassociated Sets											
20°N to 30°N	1,378	0.856	0.669	0.01	-0.011	0.33	2.92	0.92	23.00	1.79 $\times 10^{-03}$	1.20 $\times 10^{-03}$
10°N to 20°N	1,719	0.899	1.379	0.00	-0.036	0.03	13.72	0.81	27.08	5.06 $\times 10^{-04}$	-3.00 $\times 10^{-04}$
0° to 10°N	6,174	0.848	2.659	0.00	-0.084	0.00	-3.76	0.91	26.89	6.59 $\times 10^{-04}$	-1.21 $\times 10^{-03}$
0° to 10°S	4,330	0.824	0.645	0.04	-0.005	0.71	-14.20	0.11	24.70	1.64 $\times 10^{-03}$	1.05 $\times 10^{-03}$
10°S to 20°S	1,609	0.923	3.213	0.01	-0.097	0.06	-128.25	0.05	24.18	9.07 $\times 10^{-04}$	-2.91 $\times 10^{-03}$
Floating Object Sets											
20°N to 30°N	568	0.771	0.890	0.14	-0.004	0.88	-2554.41	0.00	23.25	2.70 $\times 10^{-04}$	0.00
10°N to 20°N	2,942	0.892	4.047	0.00	-0.122	0.00	-37.93	0.82	27.25	3.42 $\times 10^{-04}$	-8.94 $\times 10^{-04}$
0° to 10°N	15,200	0.792	3.281	0.00	-0.095	0.00	-315.17	0.01	27.08	5.05 $\times 10^{-04}$	-9.36 $\times 10^{-04}$
0° to 10°S	13,059	0.795	0.376	0.43	0.029	0.11	-474.90	0.43	25.66	2.86 $\times 10^{-04}$	0.00
10°S to 20°S	6,400	0.824	2.580	0.00	-0.049	0.10	-1770.65	0.00	24.82	2.72 $\times 10^{-04}$	7.02 $\times 10^{-04}$