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Effect of marine climate and baitfish availability on the tuna baitboat fishery CPUE OFF northwestern Mexico

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A B S T R A C T

Tunas caught by the baitboat fleet are one of the most sustainable products of the high seas. We analyzed catches of the baitboat fleet operating off northwestern Mexico from 1978 to 2013. We assessed the relationship between the standardized tuna catch and the Multivariate El Niño Index (MEI), the Pacific Decadal Oscillation (PDO), and landings of the two main species (Pacific sardine, *Sardinops sagax*, and northern anchovy, *Engraulix mordax*) used as baitfish in the Northeastern Pacific Ocean tuna fishery. Results showed a strong correlation between yellowfin tuna (*Thunnus albacares*) catches and sardine landings, and an inverse correlation between yellowfin tuna catches and both MEI and PDO. Yellowfin tunas are more abundant during colder-than-normal conditions. We hypothesized that, when the sardine population is more vulnerable to the small-pelagic fishery in the Gulf of California, environmentally ideal conditions, as well as baitfish (sardine) availability, resulted in high yellowfin tuna landings. The opposite behavior was observed for the standardized catch of skipjack tuna (*Katsuwonus pelamis*): a strong correlation with anchovy landings and a positive correlation with both MEI and PDO suggested that there is an alternation between tuna and small pelagic species.

1. Introduction

During the 1950s, most tunas caught by the world tuna fishery were obtained using the baitboat fishing method (Gillet, 2015). The billion-dollar tuna industry evolved, and by 2010 up to 60% of the world's tunas were caught by the purse seine fleet (Joseph et al., 2010), and the importance of the baitboat method decreased in most regions of the world (Gillet, 2015). Several environmental organizations were concerned by this transition because bycatch levels are greater in the purse seine tuna fishery than in the baitboat fishery (Miller et al., 2017). Beginning around the year 2000, several organizations (including the World Wide Fund for Nature (WWF), Greenpeace, and the International Pole and LineFoundation, among others) began an initiative targeting the worldwide boost and repositioning of the baitboat tuna fishing method (Gillet, 2015).

In a baitboat tuna fishery operation, large amounts of baitfish are cast into the waters adjacent to the fishing vessel, with the goal of starting a tuna feeding frenzy. Once the frenzy is initiated, the fishing operation (also known as fishing set) begins; fishermen use an artificial lure tied to a barbless hook to capture tuna until the tuna school is depleted or the tunas stop feeding on the baitfish, resulting in the end of the fishing operation. There is little information on important aspects of the baitboat tuna fleet fishing operations, such as the duration of each fishing operation, or the addition of technological devices (fish finders, bird sonars, satellite data receivers, etc.) to baitboat vessels. The Inter-American Tropical Tuna Commission (IATTC) does not receive information that could be used to include those potential changes into baitboat tuna fishery catch standardization for the Eastern Pacific Ocean (EPO; N. Vogel, pers. comm.); thus, we had to assume that changes in CPUE resulting from variations in the duration of fishing operations and

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the addition of technology were negligible.

The main limitation of the baitboat tuna fishery is its reliance on a constant and abundant supply of baitfish. For example, Gillett (2011) estimated that a total of 31,250 t/year of baitfish would be needed to account for the tuna catches of the purse seine fleet of the Pacific Islands region (islands that encompass Polynesia, Melanesia, and Micronesia), an amount that is practically impossible to harvest. The baitfish used to target tunas are caught at dusk in shallow waters, such as beaches and bights; the live bait is then loaded into tanks with continuous water flow located on the tuna vessels (Rodríguez-Marín et al., 2003). Clupeoids are a preferred bait group of the tuna baitboat fishery, because they do not scatter or dive when they are cast into the water (Hester, 1976). In the northeastern Pacific Ocean, the two main baitfish species used in the baiboat tuna fishery are the Pacific sardine (*Sardinops sagax*; hereafter sardine) and the northern anchovy (*Engraulis mordax*; hereafter anchovy) (IATTC, 1962).

Despite the known environmental advantages of the baitboat method over other tuna-targeting methods, the number of baitboat vessels continues to decrease throughout the world, and the baitboat tuna fishery of the EPO is not an exception. The tuna fleet off southern California, once one of the most important tuna fleets of the world, has disappeared (Gillet, 2015), and in 2013 only a handful of Mexican baitboat vessels remained in operation in the EPO (this study).

Standardized fishery data are used, in theory, to remove factors, other than abundance, that could affect catch rates over time, providing thus a more reliable indicator of population abundance (Maunder and Punt, 2004). The analysis of standardized catch rates of the tuna baitboat fishery could highlight important aspects of this fishery, such as trends in relative abundance, or the preference by different tuna species for certain baitfish species or for certain environmental regimes, such as El Niño years. Both the abundance of baitfish and variations in marine climate are expected to be cyclical (Chávez et al., 2003). Assessing the preference of tunas for such variables is an important task because the results of studies like ours could be used by policymakers to promote the revival of this fishery if conditions become favorable in future. Thus, the main objectives of our contribution were 1) to standardize the catch-per-unit effort (CPUE) of the tuna baitboat fishery operating off northwestern Mexico and 2) to assess the influence of baitfish availability and variations of marine climate on the tuna standardized CPUE of the baitboat fleet.

2. Materials and methods

2.1. Study area

The main large-scale oceanographic feature in the study area is the California Current (CC), a cold, nutrient-rich current that flows southeast from higher latitudes and reaches the southern tip of the Baja California Peninsula (BCP); here, the CC turns westward and becomes the North Equatorial Current (Kessler, 2006). Between the BCP and Mexico's mainland lies the Gulf of California (GC), a semi-enclosed inner sea where water masses with warm temperatures (18° - 31 °C) and high salinities (>35 UPS) form (Castro et al., 2000). The Mexican Coastal Current (MCC) carries warm water masses of tropical origin from lower latitudes to the tip of the BCP parallel to Mexico's mainland (Kessler, 2006). The Eastern Pacific Warm Pool (EPWP) is a permanent feature off central Mexico; it is caused by the strong stratification that results from poor wind mixing (Wang and Enfield, 2001) and is characterized by Sea Surface Temperature (SST) values > 27.5 °C throughout the year (Fiedler and Talley, 2006) (Fig. 1). The entrance to the GC is an area where water masses carried by the different currents converge; this results in a very dynamic area, where different mesoscale features occur, such as eddies and thermal fronts (Zamudio et al., 2008; Marín-Enríquez et al., 2018).

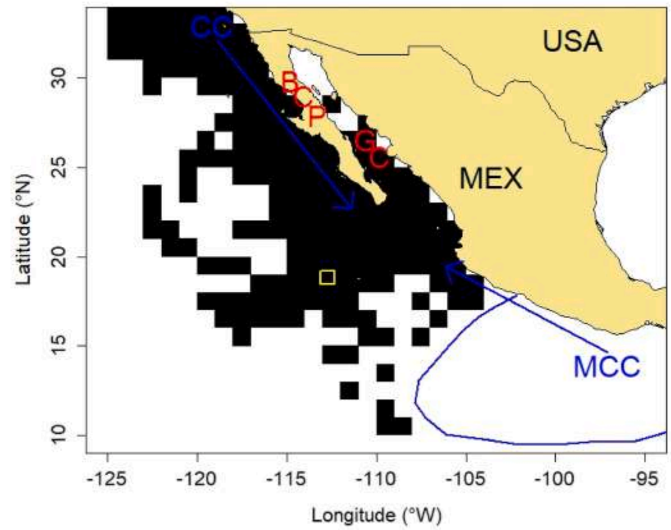

Fig. 1. Study area. The black squares depict the 1° × 1° cells where at least one fishing operation was carried out between 1978 and 2013. Geographic features are shown in red (BCP, Baja California Peninsula and GC, Gulf of California); predominant oceanographic currents are depicted with blue arrows (CC, California Current; MCC, Mexican Coastal Current). The yellow square shows the approximate location of the Revillagigedo Archipelago, and the curved blue polygon depicts the mean position of the Eastern Pacific Warm Pool according to Fiedler and Talley (2006).

2.2. Fisheries databases

We analyzed a 36-year historical database (1978–2013) of the international tuna baitboat fleet operating in the EPO. The database was gathered and compiled by the IATTC, and it includes the number of fishing operations, flag (country of register of the vessels), temporal (Month, Year) and spatial (Lon, Lat) variables, and the retained tuna catch (in t) in cells with 1° × 1° spatial resolution. Six tuna species are included in the database: yellowfin tuna (*Thunnus albacares*), skipjack tuna (*Katsuwonus pelamis*), albacore tuna (*Thunnus alalunga*), bigeye tuna (*Thunnus obesus*), Pacific bluefin tuna (*Thunnus orientalis*), black skipjack (*Euthynnus linneatus*), as well as a group identified as "Pacific bonitos" (*Sarda* spp.), and unidentified tunas. More than 95% of the total retained catch for 1978–2013 was represented by yellowfin and skipjack tunas (Suppl. Fig. 1), so we decided to focus all further analyses on these two species.

We obtained yearly landings data of sardine and anchovy from FAO's major fishing area 77 (http://www.fao.org/fishery/area/Area77/en, last accessed September 3, 2021) to assess the relationship between tuna catches and small pelagic landings. Unfortunately, the FAO databases do not include any measure of fishing effort; however, Izquierdo-Peña et al. (2019) suggested that the small pelagic database used in the present work is a good proxy of small pelagic fish abundance, at least for the analyzed scale.

2.3. Environmental database

Pacific Decadal Oscillation (PDO) data were downloaded from NOAA's National Center for Environmental Information (https://www.ncdc.noaa.gov/teleconnections/pdo/). The PDO is a climate index that affects the Northern Pacific Ocean, and it is often interpreted as a "long-lived" El Niño (Mantua and Hare, 2002); it was used here as a proxy for decadal variations in the marine environment.

To assess year-to-year temperature variations, we obtained data of the Multivariate El Niño Index (MEI) from NOAA's Physical Science Laboratory website (https://psl.noaa.gov/enso/mei/). The MEI is the first Empiric Orthogonal Function (EOF) of a multivariate environmental database that contains five variables: sea level pressure, sea surface temperature, zonal and meridional components of surface winds, and outgoing long wave radiation, all obtained for the Tropical Pacific Ocean (30°S – 30°N and 100°E − 70°W).

2.4. Statistical procedure

First, we calculated nominal Catch-Per-Unit Effort (CPUE) by dividing the number of tons caught in each 1° × 1° cell, using the following equation:

$$CPUE_i = \frac{Catch_i}{NOper_i} \quad (1)$$

Where CPUE is the nominal CPUE, Catch is the retained catch (in t), and NOper is the number of fishing operations in the ith 1° × 1° cell. We used Generalized Additive Models (GAMs) to standardize the CPUE of yellowfin and skipjack tunas. A common approach for standardizing fisheries datasets that have an excess of zeros is to use a zero-inflated Poisson or zero-inflated negative binomial GAM (e.g., Lennert-Cody et al., 2019). Neither Poisson nor negative binomial distributions were suitable for our particular case, because both are discrete probability distributions, and our response variable (CPUE) was continuous. Thus, we decided to use a delta lognormal approach, which has proven to be useful when standardizing fishery datasets that are highly skewed and that contain a large proportion of zeros (Ortiz and Arocha, 2004). The delta lognormal approach uses two different GAMs for the standardization of CPUE; a GAM with lognormal distribution was first fitted to model the probability of non-zero (positive) catch:

$$\log(CPUE_i) = \alpha + s(month_i) + s(year_i) + s(Lon_i) + s(Lat_i) + \varepsilon_i \quad (2)$$

where CPUE is the nominal CPUE for either yellowfin or skipjack tuna, s are smooth functions for the temporal (month, year) and spatial (Lon, Lat) variables, and ε is the error term assuming that $\varepsilon \sim N(0,\sigma)$, for the ith 1° × 1° cell. A GAM with binomial distribution was then fitted to the binomial-transformed nominal CPUE (zero if the retained catch was zero, and one otherwise) (Ortiz and Arocha, 2004):

$$logit(P_i) = \log\left(\frac{P_i}{1-P_i}\right) = \alpha + s(month_i) + s(year_i) + s(Lon_i) + s(Lat_i), \quad (3)$$

Where P_i is the probability of catch (binomial-transformed CPUE) for either yellowfin or skipjack tuna, and s are smooth functions as in (2). Thin plate regression splines were used for all continuous variables except for month; month is a cyclical temporal variable, so we decided to use a cyclic cubic regression in that case. Thin plate regression splines have shown to be a good smoothing method for large datasets and avoid the issues associated with the placement of "knots" (where two curves or lines are "glued" together), all at a low computational cost (Wood, 2003). The Standardized Catch Rate Index (SCRI) was then calculated by multiplying the predictions of the two GAMs (Su et al., 2008). We used standard validation techniques (QQ-plot, frequency histograms, scatterplot of residuals vs. quantiles) to assess whether the underlying assumptions of the models were met. Using predictors that are highly correlated with each other can result in biased partial effect curves of the fitted GAM. Concurvity, a non-linear extension of multicollinearity (Wood, 2017), was assessed to ensure that the predictors were not correlated with each other. Concurvity takes values between 0 and 1, where 0 represents a null dependency, and 1 indicates complete dependency between predictors. The modelling process was carried out using the "gam" and "concurvity" functions of the mgcv package ver. 1.8–31 (Wood, 2017) in the R environment ver. 4.0.2 (R Core Team, 2020).

2.5. Spatial variation of the Standardized Catch Rate Index

Monthly maps of the SCRI were constructed for yellowfin and skipjack tunas by summing monthly the SCRI calculated for the entire study period for each tuna species. A monthly SCRI standard error was also calculated for each tuna species by summing the standard error monthly. The monthly-summed standard error is included in the monthly SCRI maps of both tuna species as 5 and 10 t/operation contours.

2.6. Temporal variation of the Standardized Catch Rate Index and its relationship with MEI, PDO, and small pelagic landings

We calculated a yearly SCRI for yellowfin and skipjack tunas, following Lennert-Cody et al. (2019): we predicted the SCRI using the Delta lognormal GAMs for each year of the study period, using fixed values at the centroids (their median) for each of the rest of the predictors (Month, Lon, and Lat) to predict the yearly catches for the times and space conditions in which the fleet operated the most. The yearly SCRI was used to build a correlation matrix between the SCRI of the two tuna species, the small pelagic landings, and the mean year of the PDO and the MEI. 95% confidence intervals (CI) were calculated for the correlation coefficients, following Lennert-Cody et al. (2019): to assess the uncertainty in the SCRI resulting from spatial and temporal differences in how tunas were harvested in our study area, we simulated 500 different yearly SCRI scenarios by randomly selecting 500 different values of Month, Lat, and Lon; these values were used to predict 500 yearly SCRI time series for yellowfin and skipjack tunas. Each of the 500 SCRI values was correlated to the small pelagics and PDO yearly time series, and 95% CI were calculated using the quantile method (Lennert-Cody et al., 2019).

2.7. Ethical statements

No live animals were manipulated during our study.

3. Results

3.1. Temporal variation of fishing effort

Most of the fishing effort prior to 1999 was undertaken by the U.S.A. tuna baiboat fleet; the mean range of fishing operations varied from 8.8t in 1983 to 1.73t in 1997. The Mexican fleet was responsible for the entire fishing effort after 1999, with a mean of fishing operations ranging from 6.8t in 2005 to 2.8t in 2011 (Fig. 2).

3.2. Standardization of the catch-per-unit effort

For the standardization of yellowfin tuna CPUE, the two GAMs of the Delta lognormal approach yielded a total explained deviance of ~13%, and concurvity was low (<0.43) for all predictors in both models. No violation of GAM assumptions (normality and homogeneity of residuals) was observed for the lognormal GAM fitted to yellowfin tuna CPUE (Suppl. Fig. 2).

Higher yellowfin tuna nominal CPUE and probability of capture were observed in August–September. Yearly, the highest peak of yellowfin tuna CPUE was observed in 2001–2002, and higher probability of yellowfin tuna capture was observed in 2009. Spatially, higher yellowfin tuna CPUE occurred east of 100°W and higher probability of capture occurred east of 115°W. Yellowfin tuna nominal CPUE and probability of capture were greater north of 22°N (Fig. 3).

The GAMs used to standardize skipjack tuna nominal CPUE explained 12% and 15% of the total deviance for the lognormal and binomial models, respectively. Concurvity was low (<0.42) for all predictors of the lognormal model. Although a relatively high concurvity was observed for the Lat and Lon predictors (0.66 and 0.57, respectively) of the binomial model, the higher concurvity value was lower

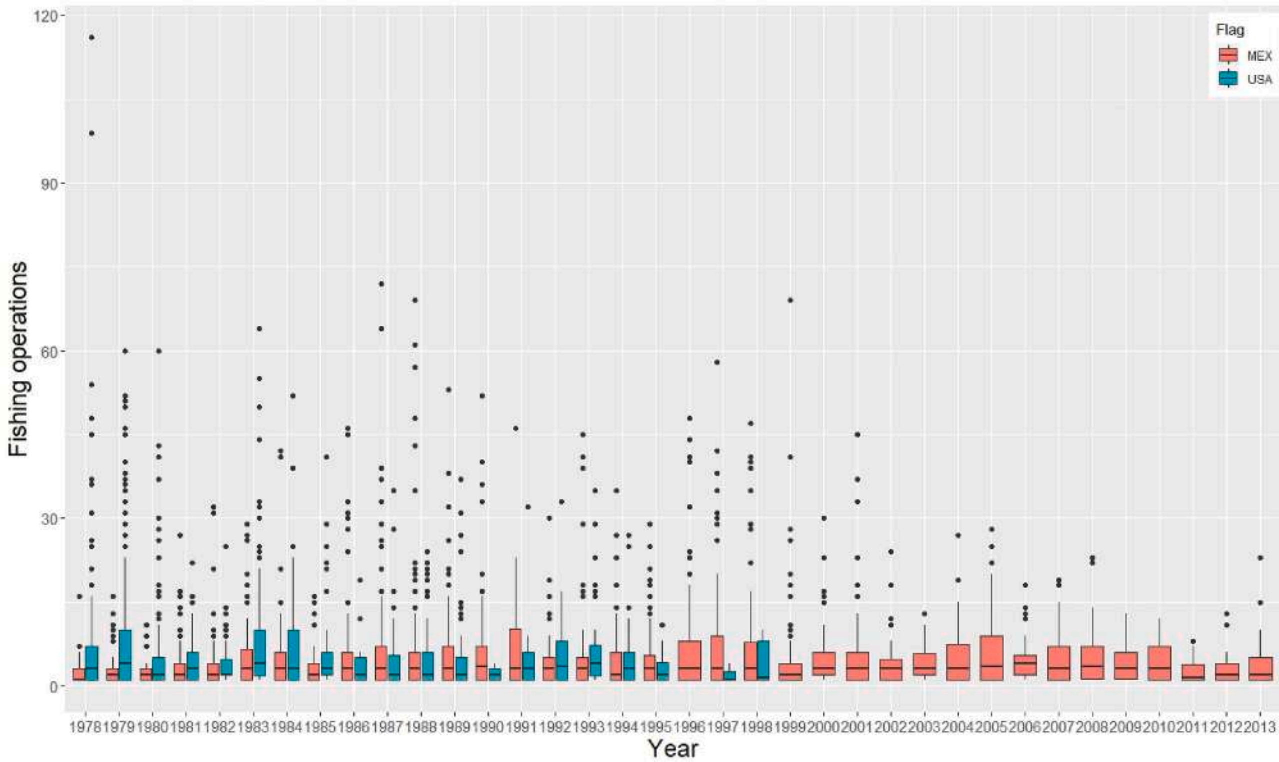

Fig. 2. Yearly boxplots of the number of fishing operations of the baitboat tuna fishery, by nation, operating in the Pacific Ocean off northwestern Mexico between 1978 and 2013. The boxes depict the 25% and 75% quantiles, and the median is represented by a thick horizontal black line inside each box. The whiskers expand 1.5 times the inter-quartile range, and the dots are values that can be considered outliers.

than the usually accepted tolerance threshold of 0.7 (Cheah et al., 2018). The validation process of the lognormal model fitted to skipjack tuna nominal CPUE was also satisfactory (i.e., no evident violation of the assumptions was observed) (Suppl. Fig. 3). The time series of the observed, smoothed, and standardized catch rates for both yellowfin and skipjack tuna are presented in Suppl. Fig. 4.

Greater skipjack tuna CPUE and probability of capture were observed in August–September. The nominal CPUE and probability of capture displayed a cyclical pattern; while no high nominal CPUE peak was evident, probability of skipjack tuna capture was greater from 1978 to 1981. High skipjack tuna CPUE was observed at the westernmost part of the study area, and the greatest longitudinal peak of probability of capture was observed at around 116°W. The curves of the partial effect of latitude on both skipjack tuna CPUE and probability of capture were similar, with two main peaks around 15° and 21°N in each case (Fig. 4).

3.3. Spatial variation of yellowfin and skipjack tuna standardized CPUE

High yellowfin standardized monthly CPUE (>10 t/operation) was observed during the first quarter of the year near the Revillagigedo Archipelago (RA) (~17°N, 110°W) (Fig. 5A–C). A patch of cells with high standardized monthly CPUE was observed in May in the southwestern portion of the BCP; this patch was also associated with high variability (S.E. > 10 t/operation) of standardized monthly CPUE (Fig. 5E).Most of the cells with high yellowfin tuna standardized monthly CPUE (>30 t/operation) were observed from July through November in the central part of the BCP, an area where the standardized monthly CPUE variability was also high (>10 t/operation) (Fig. 5F–K). An area with high standardized monthly CPUE (10–30 t/operation) and high standardized monthly CPUE variability (S.E. > 10 t/operation) was also observed in November near the RA (Fig. 5K).

The spatial distribution of the skipjack tuna standardized monthly CPUE showed a similar pattern to the distribution of yellowfin tuna standardized monthly CPUE: cells with high standardized monthly CPUE (>30 t/operation) were detected around the RA during the first 3–4 months of the year, a patch of cells with high standardized monthly CPUE (>30 t/operation) was observed in May in the southwestern part of the BCP (Fig. 6E), and a large patch of cells with high standardized monthly CPUE was observed from June to November in the south and middle of the BCP; the patch observed from June to November was associated with large variability in summed standardized monthly CPUE (S.E. > 10 t/operation) (Fig. 6F–K).

3.4. Temporal variation of the Standardized Catch Rate Index

An increase in yellowfin tuna SCRI was observed from 1986 to 2011, with the highest peak (~4.7 t/operation) observed in 2002, and lower peaks in 2010 (~4.4 t/operation) and 1993 (~3.4 t/operation). Skipjack tuna SCRI, on the other hand, declined from 1981, when the highest SCRI peak (~2.2 t/operation) was observed. Lower peaks of skipjack tuna SCRI (~2 t/operation) were observed in 1995 and 2005, and a small peak of ~1.2 t/operation occurred in 2013 (Fig. 7).

3.5. Relationship between tuna Standardized Catch Rate Index, small pelagic fish landings, and PDO

Suppl. Fig 5 shows an example of the 500 simulations performed with the yellowfin tuna landings SCRI. Although the simulations suggested a noticeable variation in yellowfin tuna SCRI, they also suggested that 95% of the simulated scenarios agreed with SCRI data used to assess the relationship between tuna SCRI, baitfish availability, and environmental variables. Correlations were significant ($p_{(r = 0)} < 0.05$) between all pairs of variables. The relationship between pairs of variables is shown in Suppl. Fig. 6. Strong direct correlations were found between yellowfin tuna and sardine (r~0.61, 95% C.I. [0.60, 0.63]), skipjack tuna and anchovy (r~0.49, 95% C.I. [0.43, 0.57]), skipjack tuna and

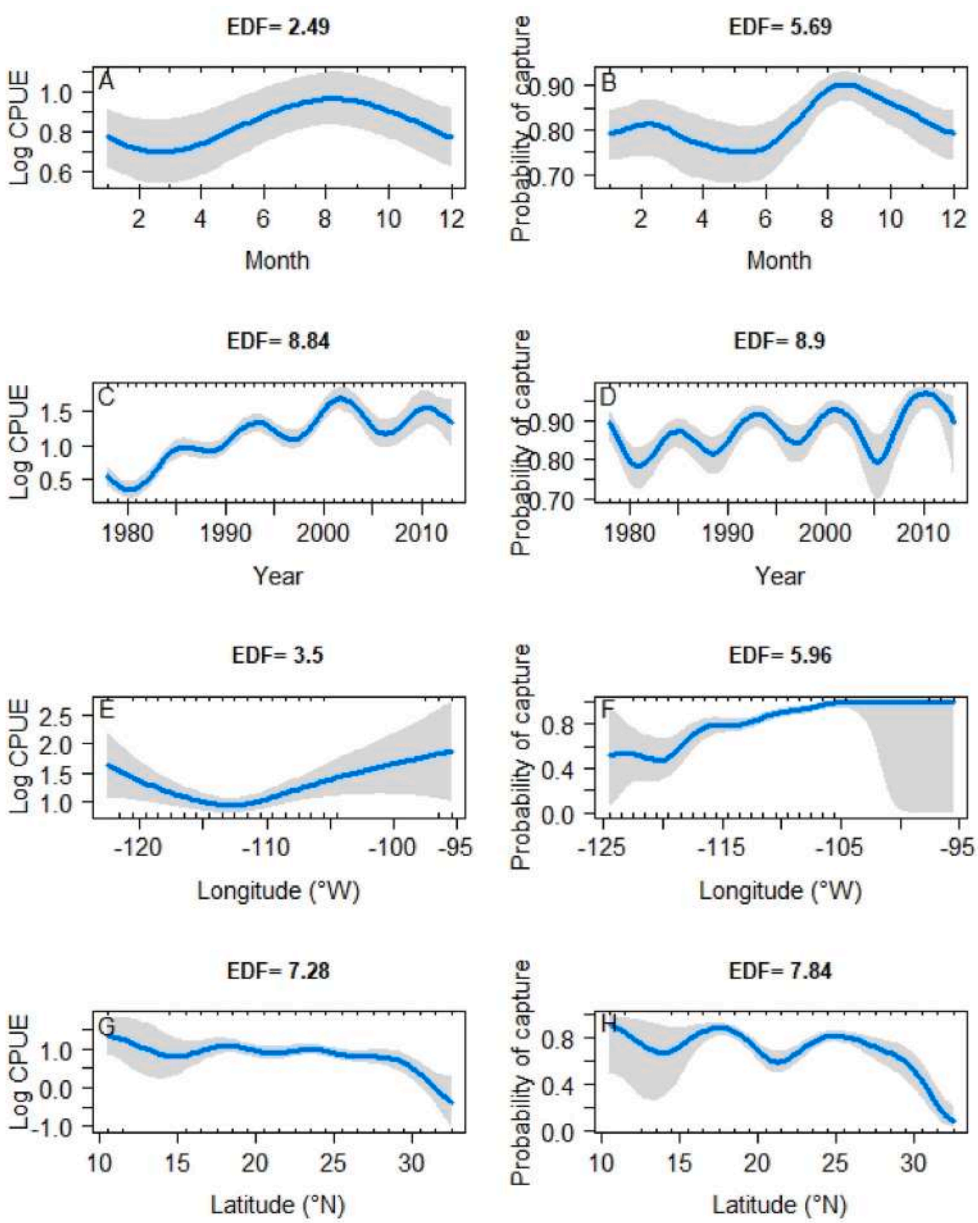

Fig. 3. Partial effect plots of the Generalized Additive Models (GAMs) used to standardize the catch rates of yellowfin tuna. Panels in the left column (A, C, E, G) represent the effect plots of the lognormal GAM, and panels in the right column (B, D, F, H) represent the effect plots of the binomial GAM. The name of each covariate is presented on the x-axis of each panel, and the Effective Degrees of Freedom (EDF) of each smoother is presented at the top of each corresponding variable.

PDO (r~0.52, 95% C.I. [0.50, 0.53]), skipjack tuna and MEI (r~0.41, 95% C.I. [0.39,0.42]), and anchovy and PDO (r~0.31, 95% C.I. [0.31, 0.32]). Strong inverse correlations were observed between yellowfin tuna and anchovy (r ~ -0.70, 95% C.I. [−0.74, −0.61]), skipjack tuna and sardine (r ~ -0.61, 95% C.I. [−0.61, −0.59]), yellowfin tuna and PDO (r ~ -0.55, 95% C.I. [−0.58, −0.53]), MEI and sardine (r ~ -0.34, 95% C.I. [0.34, 0.34]), and yellowfin tuna and skipjack tuna (r ~ -0.62, 95% C.I. [−0.66, −0.56]).

The relationship between tuna SCRI, small pelagic landings, and environmental proxies is presented in Fig. 8. Only the PDO is included, because PDO and MEI showed a strong correlation (r~0.68). The two main peaks of yellowfin tuna SCRI in 2001–2007 and 2008–2009 (~5 t/operation in both cases) coincided with two peaks of high (7×10^5 t) sardine landings (Fig. 8). The two peaks of skipjack tuna SCRI (~2 t/operation in 1995 and 2005–2006) coincided with two lower peaks of anchovy landings (~1×10^5 t) (Fig. 8).

4. Discussion

4.1. *Temporal variation of fishing effort*

The number of fishing operations undertaken by the baitboat fleet in the study area declined steadily from the late 70s to the early 00s. Yoshida et al. (1977) suggested that the baitboat tuna fleet of the EPO entered a transition in 1957, when most baitboat vessels converted to purse-seiners. Muhlia-Melo (1987) suggested that the Mexican baitboat fishery reached a maximum between 1978 and 1986, mainly because Mexico declared its Exclusive Economic Zone in the early 70s (Muhlia-Melo, 1987). After 1998, all tuna fishing in our study area was conducted by Mexican baitboat vessels. At the time of writing of our article, the IATTC had only 13 baitboat vessels registered, most of low fishing capacity (<130 t). Three of the 13 registered vessels were listed as inactive (https://www.iattc.org/VesselRegister/VesselList.aspx?List=RegVessels&Lang=ENG#Mexico accessed 22 sept 2021). The country of registry of some baitboat vessels changed from U.S.A. to Mexico (for example the Ana Maria, who changed in 1998: https

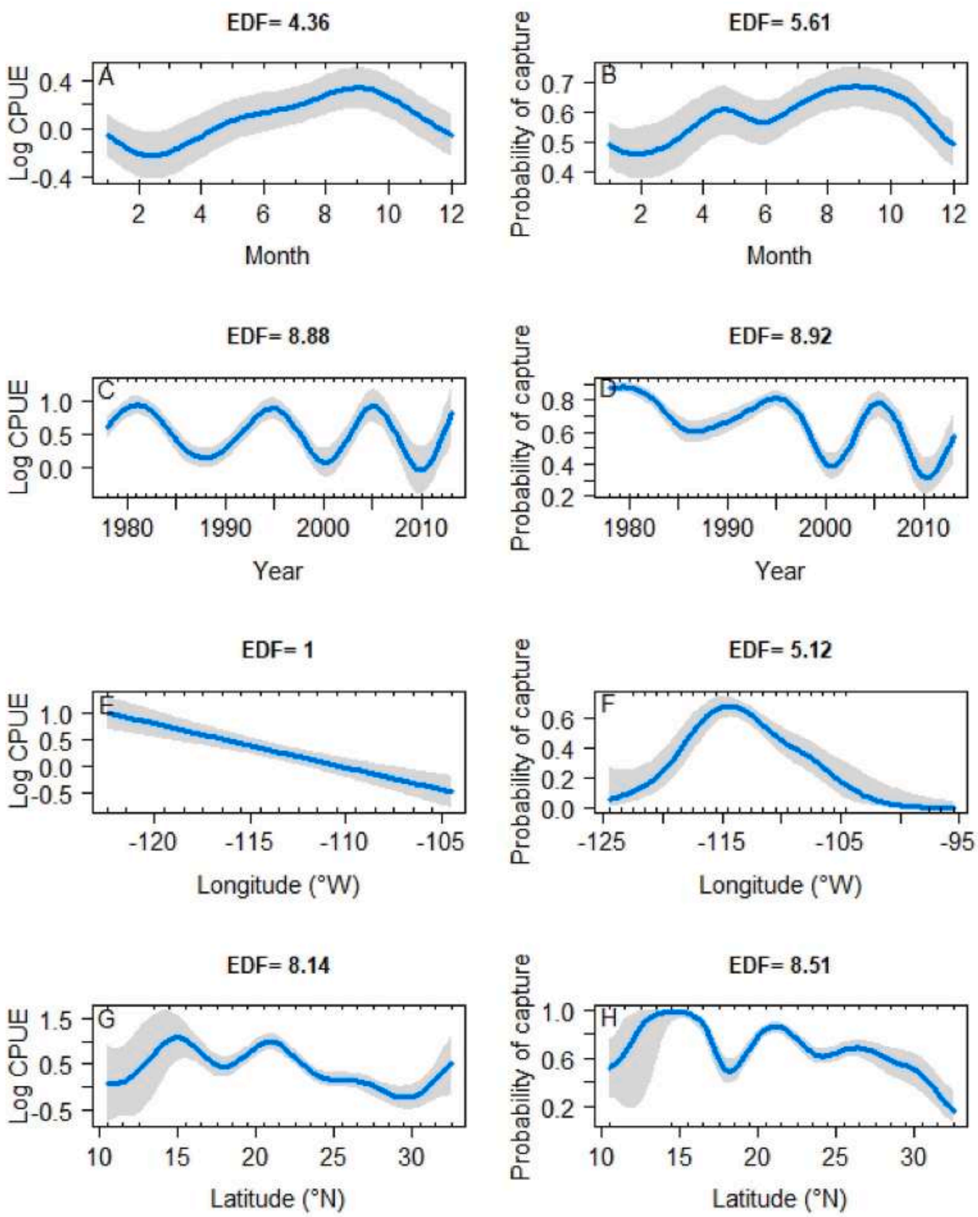

Fig. 4. Partial effect plots of the Generalized Additive Models (GAMs) used to standardize the catch rates of skipjack tuna. Panels in the left column (A, C, E, G) represent the effect plots of the lognormal GAM, and panels in the right column (B, D, F, H) represent the effect plots of the binomial GAM. The name of each covariate is presented on the x-axis of each panel, and the Effective Degrees of Freedom (EDF) of each smoother is presented at the top of each corresponding variable.

://www.iattc.org/VesselRegister/VesselDetails.aspx?VesNo=2311&Lang=en, accessed 21 sept 2021). The observed decline in our study is likely a result of the change from baitboats to purse seiners, and some of the remaining baitboat vessels of the U.S.A. fleet likely moved to the Mexican fleet. This vessel re-flagging explains why the low fishing effort after 1998 was carried-out exclusively by Mexican-registered vessels.

4.2. *Caveats of the standardization procedure*

The authors are aware that there are factors that could influence the standardization of CPUE that were not considered in the present contribution; those factors include variations in the number of fishermen, duration of each fishing operation, and addition of technological devices (sonars, bird radars, satellite data receivers) to the fishing vessels. As stated before, the IATTC does not include such information in their databases, and there is apparently no study by the IATTC tackling those factors (N. Vogel, Pers. Comm.). Kiyofuji (2016) used a similar approach to ours, using Generalized Linear Models (GLM) to standardize the CPUE of the Japanese baitboat tuna fleet. Kiyofuji (2016) found that the predictor number of fishing poles was significant in 14 of 22 GLMs, and that at least one predictor that accounts for technological devices (sonar, bird radar, bait tank, or satellite data receiver) was significant in less than half (10) of the GLMs. Some technological devices are used to locate tuna schools (Torres-Irineo et al., 2014), and one would expect an increase in probability of capture of at least one tuna individual when a technological device is added to a baitboat vessel. Apparently, this was not the case for our data, because Figs. 3 and 4 suggested that the yellowfin tuna probability of capture was relatively stable (although some cycles were detected) and that it decreased for skipjack tuna. When it comes to fishing power, Kiyofuji (2016) classified baitboat fishing vessels as a function of gross tonnage, with vessels 20–199t in the category of "offshore vessels" and those >199 t categorized as "distant fishery vessels". At the time of writing of this paper, the tonnage of the 13 vessels registered in the IATTC website (https://www.iattc.org/en-US/Management/vessel-register, accessed October 20, 2022) ranged between 53 and 180t, so all vessels of the baitboat tuna fishery in the Eastern Pacific Ocean fall in the category of "offshore vessels"; moreover, only two of the 13 vessels had a tonnage below 95t. If one assumes

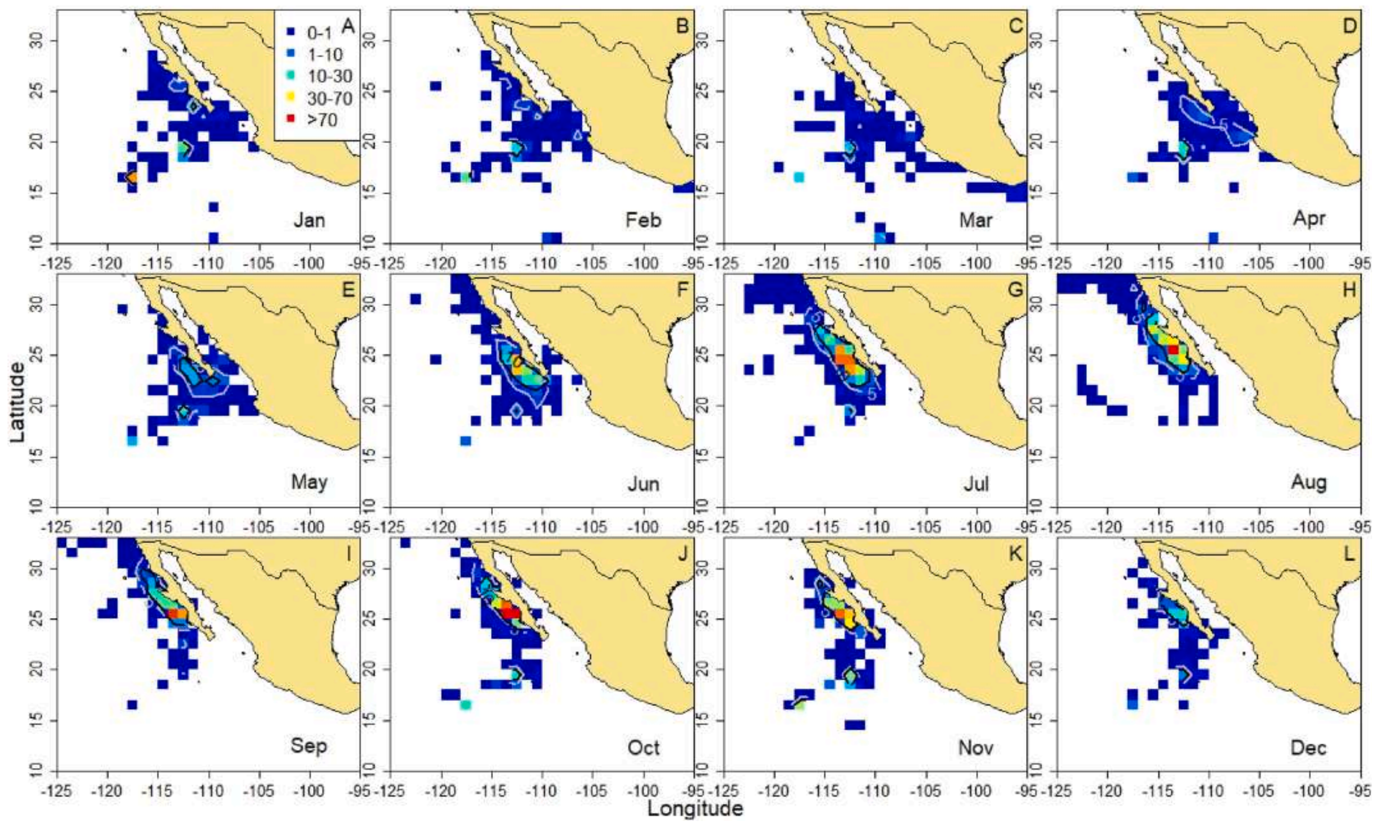

Fig. 5. Spatial seasonal distribution of the standardized catch of yellowfin tuna captured by the baitboat fishery operating in the Pacific Ocean off northwestern Mexico between 1978 and 2013 by month (A–L). Colors represent the summed standardized catch by month (in t/operation). Contours of standard deviation of 5 and 10 t/operation are shown as gray and black lines, respectively.

that the number of poles/fishermen is limited by vessel size, variations in the number of fishermen in the fishing operations throughout the study period should be small. Thus, although we are conscious that there are other factors that were not considered in our study, our assumption that the main variations in CPUE are forced by the spatial and temporal dynamics of the fishing fleet appears to be reasonable, at least as a first approximation. However, our results and recommendations should be interpreted with caution because they are based on a series of hypotheses that need to be corroborated.

4.3. Spatial distribution of tuna standardized catch

According to Fink and Bayliff (1970), there are two stocks for each tuna species in the Eastern Pacific: a 'northern' stock that migrates in summer from the RA to the western coast of the BCP and into the GC, and a 'southern' stock that includes yellowfin and skipjack tunas that are harvested in the area ranging from the Tres Marias Islands (~21.5°N, 106.4°W) to northern Chile. The yellowfin and skipjack tuna individuals caught near the RA and off the BCP are part of the same northern stock. Most of the standardized catch of skipjack and yellowfin tunas was observed in the vicinity of the RA during the first quarter of the year. During the boreal winter months, the habitat of the stocks of the two tuna species retracted to the south in the EPO, at approximately 20°N and around the RA (Fink and Bayliff 1970). The local enhancement of biological productivity around oceanic islands has been long recognized (i.e., "the island effect"; Doty and Oguri, 1956) and is a result of the turbulence created when oceanic currents encounter an island mass, explaining thus the great abundance of large pelagic fish around oceanic islands. Tagging studies suggest that yellowfin tuna individuals remain relatively close to the RA (Schaeffer et al., 2013).

For the second, third, and throughout most of the fourth quarter of the year, most of the standardized catch of yellowfin and skipjack tunas was observed off the western BCP, a known fishing ground of the Mexican tuna fishery. Strong wind-driven upwelling events occur from April to June off the western coast of the BCP. Such events are known to promote very large aggregations of pelagic red crabs (*Pleuronocodes planipes*) (Aurioles-Gamboa et al., 1994), one of the favorite prey of both yellowfin (Olson et al., 2010) and skipjack tunas (Fuller et al., 2021) in the area. The seasonal migration of the northern stocks of the two tuna species is most likely the cause of the spatial variation of the standardized CPUE of the baitboat fleet.

4.4. Relationship between tuna SCRI, baitfish availability, and variations in marine climate

One of the more interesting results of this study was the relationship between sardines and colder-than-normal conditions (and the opposite for anchovy), a result that is contradictory with what is proposed in the "regime shift hypothesis", i.e., that sardine populations thrive under warmer-than-normal conditions (and thus, greater sardine landings are expected when such conditions occur) and that anchovies are more abundant in years with colder-than-normal conditions on a decadal scale (Chávez et al., 2003). Rodríguez-Sánchez et al. (2002) suggested that the sardine population off the BCP not only decreases in years when conditions are colder-than-normal, but that the spatial habitat of the sardines moves to the south and contracts during such conditions, and that it expands during warmer-than-normal conditions, causing a phenomenon known as the "expansion-contraction" (Rodríguez-Sánchez et al., 2002). Rodríguez Sánchez et al. (2001) suggested that one of those changes to the sardine habitat during cold conditions in the 1970s resulted in a new sardine fishery inside the GC because an important part of the population entered the Gulf. During colder-than-normal

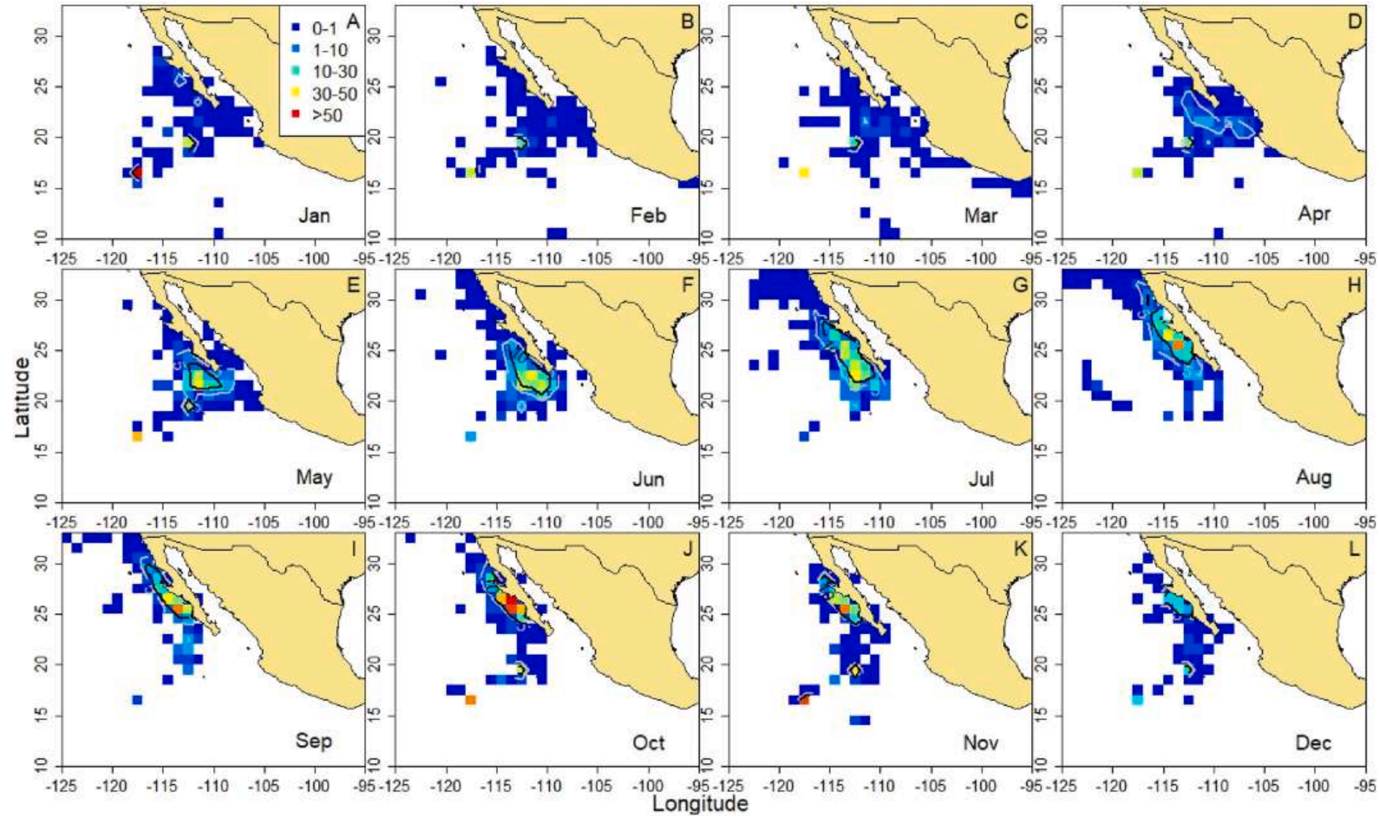

Fig. 6. Spatial seasonal distribution of the standardized catch of skipjack tuna captured by the baitboat fishery operating in the Pacific Ocean off northwestern Mexico between 1978 and 2013 by month (A–L). Colors represent the summed standardized catch by month (in t/operation). Contours of standard deviation of 5 and 10 t/operation are shown as gray and black lines, respectively.

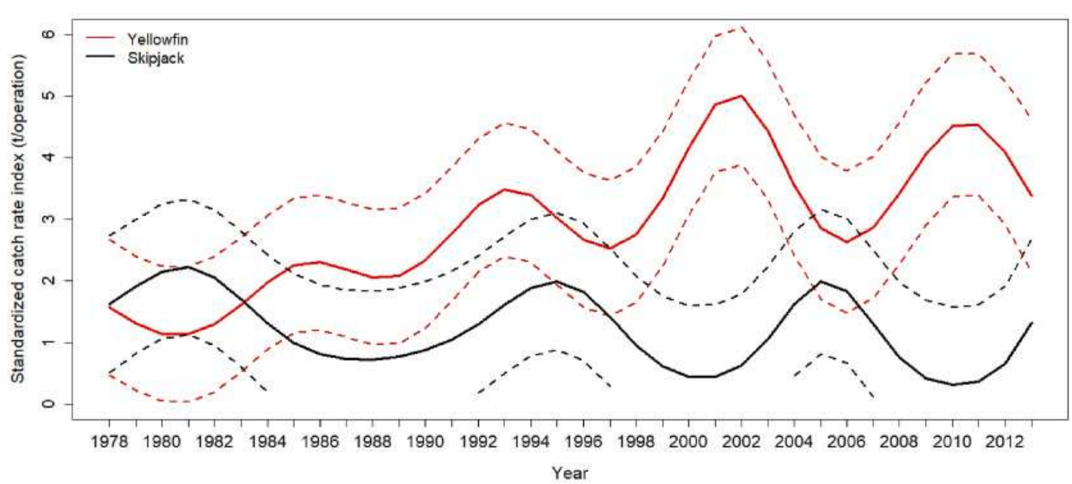

Fig. 7. Yearly Standardized Catch Rate Index (SCRI) for yellowfin and skipjack tunas captured by the baitboat tuna fleet in the Pacific Ocean off northwestern Mexico, between 1978 and 2013. The broken line depicts 95% confidence intervals.

conditions, the bulk of the sardine population is restricted to a much smaller space, which increases its catchability, thus explaining high landings during colder-than-normal conditions, both on yearly and decadal scales.

An accepted hypothesis is that sardines and anchovies found in the CC follow inverse abundance patterns (the sardine population thrives when anchovies are either absent or found at very low densities, and vice versa) (Rodríguez-Sánchez et al., 2002; Chávez et al., 2003). Thus, a similar (but inverse) phenomenon could be affecting the catchability of anchovies during warmer-than-normal conditions. For example, Rodríguez-Sánchez et al. (2002) suggested that anchovies were caught commercially in the Central GC for the first time in 1985–1986 and that catches increased almost five orders of magnitude (from 39t to 18,493t) from 1986 to 1990, when positive SST anomalies were observed in the CC, providing a plausible explanation for the direct correlation seen in this study between anchovy landings, MEI, and PDO. While some of the aspects that result in temporal and spatial changes in catchability of small pelagic fish off northwestern Mexico and in the GC are partially understood, the ecological and biological traits that are responsible for those changes are still not fully understood (Checkley et al., 2017).

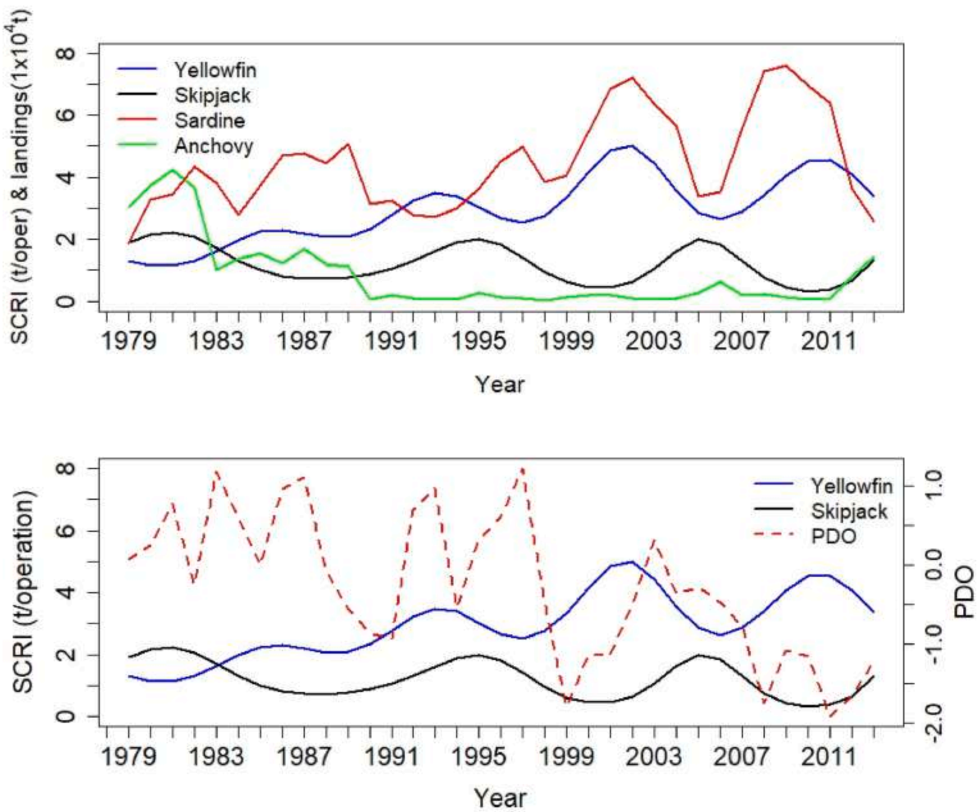

Fig. 8. Yellowfin and skipjack tuna SCRI in relation to anchovy and sardine landings (upper panel) and to the PDO (lower panel).

Although sardines and anchovies share some biological characteristics, there are some important differences too; for example, sardines are larger, and feed only by filtering small plankton. The filtering apparatus of sardines is not as coarse as that of anchovies, who can feed by filtering as well as biting (Checkley et al., 2017). Sardines are larger and therefore have the capacity to perform longer migrations, whereas anchovies are thought to perform shorter migrations (for example, from the coast to the open ocean). The fact that sardines feed on smaller particles also has important implications for habitat use: sardines inhabit mainly areas where nitrogen input occurs through wind stress curl (the open ocean) and anchovies usually live in areas where coastal upwelling is the main source of nitrogen availability (Checkley et al., 2017). Bustos-Serrano and Castro-Valdez (2006) found that there were larger nitrogen fluxes into the GC during non-El Niño conditions in 1999, compared with the El Niño event of 1997, which is likely the result of complex cores of cyclonic geostrophic eddies. Rodríguez-Sánchez et al. (2002) suggested that the sardine population migrates into the GC during colder-than-normal conditions; therefore, a plausible explanation for the observed results is that a high nitrogen input into the GC related to wind stress curl when conditions are colder-than-normal resulted in the migration of the sardine population into the GC, because sardines are capable of performing considerable migrations, and their habitat is closely linked to nitrogen supplied by wind stress curl upwelling (Checkley et al., 2017). As stated before, when sardine populations enter the GC, the catchability of the population increases, thus explaining the greater sardine landings observed when conditions were colder-than-normal. Checkley et al. (2017) suggested that the distance that anchovies are capable of migrating is shorter when compared with sardine migrations (i.e., from near the coast to the open ocean and back). When conditions are warmer-than-normal, the intensity of the coastal upwelling events in the BCP decreases (Delgadillo-Hinojosa et al., 2020), and the spatial coverage of upwelled water is also likely to decrease and be restricted to a zone near the coast. We hypothesize that anchovies migrate to waters close to the coast in search of conditions that result in coastal upwelling during warmer-than-normal conditions; the anchovy population is then restricted to a smaller area, which would increase its catchability. Unfortunately, we do not have spatial information on small pelagic fish landings, and the proposed hypotheses would need to be corroborated.

Our results suggest that more yellowfin tunas are caught during colder-than-normal years, and that sardine availability is the most important factor for catching yellowfin tuna. For skipjack tuna, an opposite trend was apparent: more skipjack tunas were caught during warmer years, and anchovy availability was the most important factor when targeting skipjack tuna. Lehodey (2000) stated that field (tags) and laboratory studies showed that skipjack tunas inhabit warmer waters (28°-32 °C) than yellowfin tunas (18°-24 °C), and that tagged skipjack tunas in the western and central Pacific Ocean moved eastwards during El Niño years and westwards during La Niña years. Lehodey et al. (2008) also suggested that the thermal surface habitat of skipjack tuna expands from the Western Pacific to the Eastern Pacific, because the Western Pacific Warm Pool, the main skipjack tuna spawning habitat, expands towards the east during El Niño events. Skipjack tunas are apparently more abundant in the Western Pacific when the warm equatorial waters are pushed to the west towards the coast of Asia by the trade winds. When warmer-than-normal conditions occur (when positive phases of El Niño and PDO are present), the trade winds weaken, which results in the intrusion of warm water masses of tropical origin to the BCP; these water masses are characterized by high temperatures and low nutrients (Fiedler and Talley, 2006). These warmer-than normal events result in a retraction of the warm water masses towards the Eastern Pacific, and a corridor of skipjack tuna preferred thermal habitat connects the Eastern and the Western sides of the Pacific (Lehodey et al., 2008), explaining the high skipjack tuna catches in the Eastern Pacific during warmer-than-normal years.

The effect of marine climate variations on the abundance and distribution of yellowfin tuna is less straightforward, and changes in the vertical thermal structure appear to be as important as horizontal variations in temperature (Lehodey, 2000). Torres-Orozco et al. (2006) suggested that high yellowfin tuna catches by the purse-seine fleet at the entrance to the GC are triggered by the arrival of positive temperature anomalies, which are a result of a decrease in the mixed layer depth in the area. Lehodey (2000) suggested that two scenarios could be possible for yellowfin tuna in the Eastern Pacific: a positive El Niño effect on catchability and recruitment, or a positive La Niña effect on catchability and recruitment. Our results support the latter. The thermal habitat of yellowfin tuna, above 10°N in our study area, remained practically unchanged in December, when comparing between El Niño and La Niña years (see Fig 11 from Lehodey, 2000). The trade winds are stronger during La Niña years, resulting in a shoaling of the mixed layer in the EPO. Wind-driven upwelling off the western BCP becomes more intense during La Niña, and in colder-than-normal conditions (such as the negative phases of El Niño and PDO), nutrient concentrations can be as much as 80% higher than in warmer-than-normal conditions (Delgadillo-Hinojosa et al., 2020). Additionally, an intensification of the upwelling events off the BCP promotes large aggregations of the red pelagic crab (*Pleuronocodes planipes*). Preferred temperatures of yellowfin tuna, large numbers of prey, and a shallow mixed layer are expected to occur during colder-than-normal years, increasing both yellowfin tuna abundance and catchability, which would help explain the inverse relationship between yellowfin tuna SCRI and MEI/PDO.

In summary, higher yellowfin tuna catches occurred when conditions were colder-than-normal (La Niña years), and when sardines were more available as baitfish, because the bulk of the yellowfin tuna population was restricted to the southern BCP (negative PDO phase) and was more vulnerable. On the other hand, higher catches of skipjack tuna occurred during warmer-than-normal conditions (El Niño years), when anchovies were the dominant small-pelagic fish species off northwestern Mexico (positive PDO phase).

4.5. Final recommendations

The baitboat tuna fishery operating off northwestern Mexico appears fated to extinction, although updated information is needed to perform a more current analysis. The demand for sustainable products is on the rise (Bonini, 2021), and the baitboat method appears to be one of the most sustainable tuna-catching methods. Yoshida et al. (1977) provided a very interesting calculation of the ratio of tuna biomass captured per ton of bait used. The mean metric tonnage of skipjack and yellowfin tuna catches ranged from 5.5t to 12.2t, with a mean value of 7.5t per metric ton of bait (Yoshida et al., 1977). At its peak, the yellowfin tuna total catch by the baitboat fleet was around 5,000t in 1987. If we make a rough calculation, according to the results of Yoshida et al. (1977), a mean total of ~670t of bait would be needed to catch ~5,000t of yellowfin tuna. A recent study by Enciso-Enciso et al. (in press) estimated a mean of ~950,000t of sardine biomass in the stock off the western coast of the BCP for 2020. Less than 1% (0.07%) of the total estimated sardine biomass off the BCP would be needed to reach the peak yellowfin tuna landings of 1987. This suggests that sardine biomass is not likely a limiting factor for the re-establishment of the Mexican baitboat fishery. To the best of the authors' knowledge, there is no recent estimate of anchovy biomass off the BCP, but results of long-term studies of sardine and anchovy landings showed similar peaks, suggesting that the biomass of these two fish species might be comparable. In years that are warmer-than-normal, skipjack tunas are more abundant in the EPO and anchovies are more available as bait, and fishermen could (theoretically) rely on those two fish species to support the baitboat fishery. Although baitfish biomass appears to be a non-limiting factor, we are aware that our calculations are very rough, and that there could be other factors that could be limiting (such as fleet dynamics and economic fluctuations) that would need to be considered for the successful re-establishment of the Mexican baitboat fleet, so our recommendations should be interpreted with care.

Marine products that are caught with sustainable methods have an aggregated market value. For example, Blomquist et al. (2015) suggested an increase of ~6% in the price of cod that was caught in a sustainable certified fishery versus cod caught in a non-certified fishery; the aggregated value of sustainable products provides an incentive to fishermen to move to sustainable fishing methods (Blomquist et al., 2015); this kind of incentive could be of interest to the Mexican tuna industry.

In summary, we suggest that Mexican policymakers promote financial programs and studies that aim to revive the Mexican baitboat fishery; doing so could have a positive ecological impact and could add an aftermarket value to harvested tunas.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2022.106418.

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