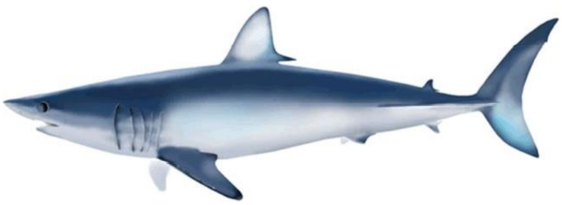
ISC/24/SHARKWG-1/11

Update on standardized catch rates for mako shark (*Isurus oxyrinchus*) in the 2006-2022 Mexican Pacific longline fishery based upon a shark scientific observer program[1]

José Ignacio Fernández
Méndez[2,]
Luis Vicente González-Ania[2,]
Georgina Ramírez Soberón[2,,]
José Leonardo Castillo-Géniz[3,]
Horacio Haro-Ávalos[3,]

[2]Instituto Nacional de Pesca
(National Fisheries Institute)
[1]Oficinas Centrales
Av. México 190, Col. Del Carmen,
Coyoacán, C.P. 04100, Ciudad de
México, México
e-mail: luis.gania@inapesca.gob.mx
e-mail: ignacio.fernandez@inapesca.gob.mx
e-mail: georgina.ramirez@inapesca.gob.mx
[3]Centro Regional de Investigación Acuícola y
Pesquera de Ensenada, Baja California
Carr. Tijuana-Ensenada, km 97.5, El Sauzal de Rodríguez
C.P. 22760, Ensenada, Baja California, México
e-mail: leonardo.castillo@inapesca.gob.mx
e-mail: horacio.haro@inapesca.gob.mx



---

[1] Working document submitted to the ISC Shark Working Group Workshop, 29-30 November-1-2, 4-7 December 2023, Yokohama, Kanagawa, Japan. **Document not to be cited without author's permission.**

SUMMARY

Abundance indices for shortfin mako shark (*Isurus oxyrinchus*) in the northwest Mexican Pacific for the period 2006-2022 were estimated using data obtained through a pelagic longline observer program, updating similar analyses made in 2014 and 2021. Individual longline set catch per unit effort data, collected by scientific observers, were analyzed to assess effects of environmental factors such as sea surface temperature, distance from land coast, including islands and time-area factors, year, area fished, quarter and fraction of night hours in the fishing set. Standardized catch rates were estimated by applying hurdle (delta) models. The first part of the model estimates the probability of a positive observation using a binomial likelihood, and a logit link function. The second part of the model (the “count” or “positive” model) estimates the mean response for those non-zero observations, assuming a negative binomial distribution with a log link function. The importance of factors included in the models is discussed. The results of this analysis point at the abundance index trends being close to stability in most of the analyzed period, with a low value in the last year of the series.

INTRODUCTION

The presence of more than 111 species of sharks in Mexican waters has allowed the development of commercial fisheries in both coastal and oceanic waters (Del Moral–Flores *et al*. 2016; Ehemann, *et al*. 2018). The main Mexican shark fisheries are the coastal artisanal fishery (along both Pacific and Gulf of Mexico coastlines) and the pelagic longline fisheries using medium size vessels in the northern Pacific region (Castillo-Géniz *et al.* 2008).

The average annual Mexican national shark production (including small sharks, called “cazones”) from 2011 to 2021 (most recent official data) was 34,590 t, which places Mexico as one of the top five shark producer nations in the world (FAO FishStat update data to 2020, cited by CONAPESCA, 2021). In 2018 the total domestic shark reached a historic peak of 47,873 t (2.2% of the total national fisheries production), with a market value of 948 million pesos (aprox. 53 k USD). The average annual shark production in Mexican Pacific for 2011-2021 was 20,053 t. In 2021 the Pacific shark production reached 29,625 t which comprised 79.7% of the total Mexican shark production.

Pelagic shark fisheries in the Mexican Northwest Pacific began in the mid 80's with the creation of an industrial fishing fleet. That was the result of the successful driftnet fishery in California, USA, which began in 1978, targeting common thresher shark (*Alopias vulpinus*) and shortfin mako (*Isurus oxyrinchus*, locally known as bonito shark).

In 1986 a small fleet of driftnet vessels appeared in northern Baja California, Mexico. This fishery was stimulated both by the reduction in longline permits and by the local abundance of swordfish and other marketable by-catch products, including several species of large pelagic sharks. These vessels were fiberglass or steel built, with an overall length of 18-25 m and a fish hold capacity of 50-70 t.

The number of vessels had grown to 20 by 1990, and to 31 by 1993 (Holts and Sosa-Nishizaki 1998). These vessels operated out of Ensenada, Baja California, and were similar in design and size (18-25 m) to the U.S. driftnet vessels, operating just 100 km to the north. This fleet targeted sharks, swordfish, tuna, and other pelagic fish. Sosa-Nishizaki *et al.* (1993), Holts *et al.* (1998), Ulloa-Ramirez *et al.* (2000), and Sosa-Nishizaki *et al.* (2002) described in detail the growth of swordfish and shark fishery along the west coast of Baja California (BC).

During the first 20 years, this fleet used surface gillnets as its primary fishing gear. The Mexican Official Standard NOM-029-PESC-2006 (DOF 2007) banned driftnets in medium-size vessels (10-27 m length). By the end of 2009, all vessels switched to longlines and the operational dynamics of the fleet changed drastically. With longlines the main shark species caught were blue (*Prionace glauca*) and short-fin mako (*Isurus oxyrinchus*) sharks (Godinez-Padilla *et al*. 2016).

In the last decade, the Mexican shark fisheries conducted by medium size commercial longliners from Ensenada, Baja California and particularly from Mazatlán, Sinaloa had expanded their fishery operations towards more oceanic waters in the Mexican Pacific Economic Exclusive Zone (EEZ).

Management of Mexican shark fisheries

Shark fisheries in Mexican waters are managed mainly through three instruments:

1) The Mexican Official Standard NOM-029-PESC-2006. Shark and Ray Responsible Fisheries. Specifications for their Exploitation;
2) The National Fisheries Chart (Carta Nacional Pesquera, CNP) and
3) The Shark and Ray Fishery Closure Agreements for both coastlines (vedas).

The NOM-029 (DOF 2007) established several regulations for shark and ray fisheries in order to achieve sustainability, among them the establishment of specific fishing zones according to vessel characteristics, refuge zones, specifications for fishing gears, mandatory participation in the satellite vessel tracking program (Vessel Monitoring System, VMS), the banning of gillnets on medium size boats and the implementation of a scientific observer program.

The National Fisheries Chart includes the description and the current exploitation status of shark populations as well as their availability in Mexican waters. At present, all shark fisheries are considered to be fully exploited (DOF 2010).

Finally, in 2012 the fisheries authority established closed seasons for shark and ray fisheries in the Pacific and only for sharks in the Gulf of Mexico, with the aim of protecting the main reproductive season for most species (DOF 2012 and 2014). Those closed periods include shark by-catch in other fisheries. The closed season in the Mexican Pacific was established between May 1st and July 31st.

Mexican shark fishery scientific observer program

The shark scientific observer program (POT, acronym in Spanish) was established in August 2006 by the Fisheries and Aquaculture Commission (CONAPESCA), in offshore and pelagic waters of the Mexican Pacific, as established in the Shark and Ray Responsible Fisheries Mexican Official Standard NOM-029-PESC-2006. The POT was designed by Mexico's National Fisheries Institute (INAPESCA) and implemented by the National Research Trust for the National Program for Tuna Utilization and Dolphin Protection and Other Programs Related to Protected Aquatic Species (FIDEMAR). The shark scientific observers, trained by INAPESCA shark biologists and technicians, report numerical catches by species and operational details (e.g. time, geographical position, number of sets per trip, number of hooks per set, setting times, target species, bait type), catch and by-catch composition and catch trends of species caught by shark vessels. They also collect biometric (size and sex) and biological data (maturity stage) for shark target species. INAPESCA is responsible for analyzing data generated by the POT.

The fishing boats participation in the observer program is voluntary so fishing trips with observer onboard are conducted according to the availability and willingness of fishing companies. The sampling coverage of fishing trips by the POT has been very variable, with a maximum of 20% in 2007 and a minimum of 1% in 2012 (Castillo-Géniz *et al.* 2014).

Evolution of the catch

Swordfish landings from Mexican driftnet vessels were first reported in 1986. They increased steadily to 831 t in 1991, and averaged annually 535 t in 1988-93. The low catch in 1993 forced some fishing vessels to look for alternate resources, including coastal and pelagic sharks, in the Gulf of California. The number of vessels operating driftnetting for swordfish in the first half of 1994 fell to 16 (Holts and Sosa-Nishizaki 1998).The information recorded by the Federal Fisheries Delegation in Baja California for 1990-1999 indicated an average catch per boat of 15.3 t and an average catch per trip of 2.73 t for the whole driftnet and longline fleet.

The shortfin mako shark, *Isurus oxyrinchus*, is a pelagic-coastal specie of great fishing importance due to its wide distribution in the northern Pacific region and the center of the Mexican coast where medium-sized and artisanal fleets capture it. The shortfin mako shark is probably the fastest shark and the most active fish among the so-called large pelagic sharks.

From capture and effort information collected by scientific observers on vessels of the fishing fleet of Manzanillo, Colima, in the period 1986-2003, Vélez-Marín and Márquez-Farías (2009) described the spatio-temporal distribution of mako in that region. In particular The western coast of Baja California has been recognized as a Biological Activity Center (BAC) with strong upwelling activity where the mixture of masses of the California Current and the Costa Rica Current characterizes its oceanographic conditions (Luch-Belda *et al*, 2000). The high level of biomass produced in the area supports large fisheries of minor pelagic fish (clupeids). The presence of these sharks and other highly migratory predatory pelagic fish coincide with the presence of small pelagic fish that probably serve as their prey. The numerous presence of juvenile *I. oxyrinchus* individuals in the region suggests the presence of a breeding area.

Medellín-Ortiz (2008) used information from 23 shortfin mako sharks tagged with SPOT and PAT tags on the western coast of the Baja California Peninsula between 2004-2006. The data recorded by these satellite tags indicated that the sharks experienced depths between 0-500 m, spending 60% of their time in surface waters. While some sharks remained within the California Basin throughout the year, a pattern of movement was observed northward during June-October and southward during November-May.

From 2006 to 2022, the official capture records of the short-finned mako shark, from the different entities of the Mexican Pacific coast of the central and northwest area, show that the state with the highest average catches in these 17 years has been Baja California South, followed by Baja California and Sinaloa. Likewise, important fluctuations have been observed in total catches in which the years 2020, 2019, 2015 and 2014 have reached historical maximums with 1877, 1795, 1653 and 1467 t respectively. (Figure 1).

Catch composition

Based on the analysis of 683 fishing logbooks from the Ensenada longline fleet reported between 2011 and 2015, Godínez-Padilla *et al*. (2016) reported a specific catch composition of 18 shark species. The species with the highest numerical catch were: blue shark, *P. glauca* (89.25%); and the shortfin mako shark, *I. oxyrinchus* (7.77%). With a lower proportion the thresher shark, *A. vulpinus* (1.06%); silky shark, *Carcharhinus falciformis* (0.63%); smooth hammerhead shark, *Sphyrna zygaena* (0.56%); pelagic thresher, *A. pelagicus* (0.19%); the big-eye thresher, *A. superciliosus* (0.02%); and other species that represented 0.52% of the total numerical catch.
Recently, Corro-Espinosa (unpublished data) conducted an analysis of the commercial logbooks from the Mazatlan longline fleet for years 2009-2012. Corro-Espinosa documented a total catch of 182,482 sharks from 11 species, caught in 8,447 longline sets. Blue shark (*P. glauca*) 64.6%, thresher (*A. vulpinus*) 9.4%, bigeye thresher (*A. superciliosus*) 9.3%, pelagic thresher (*A. pelagicus*) 7.7% and mako (*I. oxyrinchus*) 1.7% were the most frequently caught pelagic sharks. (Figure 2).

Catch rate standardization

The primary indices of abundance for many of the world's valuable and vulnerable species are based on catch and effort. These indices, however, should be used with care because changes over space and time in catch rates can occur because of factors other than real changes in abundance (Gavaris 1980, Walters 2003, Maunder and Punt 2004, Haggarty and King 2006, Campbell 2015). Nominal catch rates obtained from fishery statistics or observer programs require standardization to correct for the effect of factors not related to regional fish abundance but assumed to affect fish availability and vulnerability, usually by using statistical regression methods (Bigelow *et al.* 1999, Ortiz and Arocha 2004).

Generalized Linear Models (**GLM**, Nelder and Wedderburn 1972, McCullagh and Nelder 1989) are the most common method for standardizing catch and effort data and their use has become standard practice because this approach allows identification of the factors that influence catch rates and calculation of standardized abundance indices, through the estimation of the year effect (Goñi *et al.* 1999, Maunder and Punt 2004, Brodziak and Walsh 2013). GLMs are defined mainly by the statistical distribution for the response variable (in this case, catch rate) and the relationship of a linear combination of a set of explanatory variables with the expected value of the response variable. Its use is based upon the assumption that the relationship between a function of the expected value of the response variable and the explanatory variables is linear. A variety of error distributions of catch rate data have been assumed in GLM analyses (Lo *et al.* 1992, Bigelow *et al.* 1999, Goñi *et al.* 1999, Punt *et al.* 2000, Maunder and Punt 2004).

Catches of non-target species are relatively unusual (resulting in many catch records being zero, even though effort is recorded to be non-zero) and catch and effort data are often characterized by left-skewed distributions, with a high proportion of zero catches, and few observations with high catch rates that resemble the distributions of highly aggregated species. The presence of a high proportion of zeros can invalidate the assumptions of the analysis and make inferences based on them dubious. The presence of zeros can also result in computational difficulties, as the logarithm of zero is undefined (Maunder and Punt 2004, Ortiz and Arocha 2004).

Alternatives to deal with this kind of data can include using zero-inflated models (Minami *et al.* 2007, Zuur *et al.* 2009), models based on the Tweedie distribution (Tweedie 1984, Shono 2008), or hurdle (or zero-altered, also called delta models) modeling separately the probability of obtaining a positive catch and the catch rate, given that the catch is non-zero, using a standard distribution defined for positive values (Pennington 1983, as proposed by Lo *et al.* 1992, Harding and Hilbe 2012). The probability of obtaining a positive observation is usually modeled using the binomial distribution (Stefansson 1996, Maunder and Punt 2004), with logit or probit link when assuming approximately an equal number of zeros and ones (positive observations) or complementary log-log (c log-log) when there is a predominance of negative or positive observations (Myers *et al.* 2002, Zuur *et al.* 2009). A variety of distributions could be used to model the catch rate given that it is non-zero (Dick 2004). Most commonly selected distributions are the log-normal (Brown 1998, Porter *et al.* 2003), Gamma (Punt *et al.* 2000), poisson (Ortiz and Arocha 2004), negative binomial (Punt *et al.* 2000) and inverse gaussian (Walker *et al.* 2012). The final index of abundance is the product of the back transformed year effects from the two GLMs (Lo *et al.* 1992, Stefánsson 1996).

MATERIAL AND METHODS

This study is focused on the longline component of the shark fishery with medium size vessels in the northwest region of the Mexican Pacific. Driftnet operations were banned in 2009, while longline fishing has prevailed through the years of operation of the scientific observer program, so the longline time series June 2006-December 2022 is complete. In this first stage, data –belonging to fleets operating outside this area or scarcely sampled– were excluded from the analysis. Then, data were subjected to a preliminary analysis, looking for missing values, incomplete information and inconsistencies. In this way, just 7,822 validated sets were retained to be used in the analysis. The proportion of zero-catch sets in this subsample was 63.9%, pointing to the use of a two-part, hurdle model for the analysis, with a logit link for the binomial GLM and a negative binomial (with a log link function) for the count model.

After an initial exploratory analysis, factors which were considered as having a possible influence on the RESPONSE variable, catch rate (CTCHRATEms), were selected to be included in a “maximum model” for the analyses.

The factors selected for inclusion in the analysis were the following: Mean Sea Surface, Temperature (MEANTEMP as a three level factor, H, M and L for “high”, “medium” and “low”), calculated for each set as the average of temperature data measured *in situ*, at the beginning and the end of both gear setting and retrieval. MEANTEMP levels were defined as L<=21°C, 21<M<=25, and H>25°C, on the basis of the mean sea surface temperature in all validated sets.

Mean Sea Surface Temperature Anomaly (MEANSSTANOM) was defined as a three level factor, MEANSSTANOMML (<=-1), MEANSSTANOMMM (>-1,<+1), MEANSSTANOMMH (>=+1) for “low”, “medium” and “high” mean SST anomaly. Data on this factor were obtained from the Multi-scale Ultra-high Resolution (MUR) SST Analysis Anomaly fv04.1, Global, 0.01°, 2002-present, Daily, Lon0360 data base, available in the ERDDAP data server (https://coastwatch.pfeg.noaa.gov/erddap/griddap/jplMURSST41anom1day_Lon0360.html) using the rerddapXtracto R package (Mendelssohn 2021).

The proportion of night hours in the fishing set for sets being carried out mostly in daylight or at night (PNH, a two level factor, “DAY” < 0.5 and “NIGHT” >=0.5) was calculated using the data from each fishing set and calculating the time of dawn and sunset for the corresponding dates and coordinates, using the suncalc R package (Thieurmel and Achraf 2022).

Fraction of the Moon Illuminated (MP, a three level factor, “NEW”<0.3, “PART”>=0.3 <=0.7, and “FULL” >0.7), were calculated for the dates of the fishing sets , using the suncalc R package (Thieurmel and Achraf 2019).

Distance to the nearest coastline, including islands, (DIST as a two level factor, N for “near” for distances less than 200 km and F for “far” from the coast for distances above that number), was calculated using the raster R package (Hijmans 2019).

Time-area factors such as YEAR, QUARTER and fishing area were included. Three fishing areas (LATF) were defined, NORTH above the 25° parallel, CENTRAL between 21° and 25° of latitude and SOUTH below 21° (Figure 3).

The levels of the above mentioned factors were selected matching approximately the inflexion points of a LOESS smoother on a scatterplot of catch rate against the values of the corresponding variable. The fishing areas were defined based on that LOESS – scatterplot procedure and on observed fleet operations patterns.

As a noticeable trend for catching swordfish in detriment of shark catches has been detected in the last years, a variable was included in the analysis as a predictor (CTCHRATEposswo, with levels 1 and 0 for swordfish appearing or not in fishing sets, respectively). The change in fishing strategy (a shift from diurnal to nocturnal fishing sets) to increase swordfish catch has been different in the two main fleets involved in the fishery. A two-level predictor, FLEET, was included (with two levels, EN for Ensenada and MZ for Mazatlán, after their respective home ports).

Both probability of catch and catch rates were modeled as a function of these factors and several two-way interactions, QUARTER:DIST, LATF:DIST, MEANTEMP:MEANSSTANOM, FLEET:PNH, FLEET:CTCHRATEposswo.

Catch probability and positive catch rates were modeled as a function of these factors, with a hurdle model, using the pscl package (Jackman, 2020, Zeileis *et al.*, 2008) in the *R* programming language and environment version 4.2.1 (*R* Core Team 2022).

The first part of the model estimates the probability of a positive observation using a binomial likelihood, and a logit link function. The second part of the model (the “count” or “positive” model) estimates the mean response for those non-zero observations, assuming a negative binomial distribution.

The formulas of the maximum (initial) models were:

For the “counts” or “positive”, model:
CTCHRATEms ~ YEAR+ QUARTER + LATF + DIST + MEANTEMP + MEANSSTANOM + PNH + FLEET + CTCHRATEposswo + QUARTER:DIST + LATF:DIST + MEANTEMP:MEANSSTANOM + FLEET:PNH + FLEET:CTCHRATEposswo

For the binomial model:
CTCHRATEposms ~ YEAR + QUARTER + LATF + DIST + MEANTEMP + MEANSSTANOM + PNH + FLEET + CTCHRATEposswo + QUARTER:DIST + LATF:DIST + MEANTEMP:MEANSSTANOM + FLEET:PNH + FLEET:CTCHRATEposswo

The significance of the included variables and interactions was assessed through tests of Hypothesis in one-term deletion tests using the likelihood-ratio tests (Agresti, 2019) in order to prevent the potential effects of collinearities, as described by Crawley (2013). The effect of the term was determined to be significant at least at the 0.05 level. The K-fold Cross Validation procedure (James et al. 2021) using the boot R package (Canty and Ripley 2020), the Akaike Information Criterion, and the Bayesian Information Criterion (Burnham and Anderson, 2002) were used as additional criteria of model simplification.

The estimated marginal means and their standard errors for the YEAR factor (the standardized abundance indices) were obtained by using the emmeans routine contained in the emmeans R package (Lenth 2021).

Although we are conscious that inter annual variations in spatial or temporal patterns could occur (v. gr. the species and/or effort distribution, seasonal changes in temperature or other factors among years), we preferred not including interactions involving the factor YEAR at this stage of the analysis with fixed effects models. Including interactions involving the factor YEAR, as well as treating it as a random factor by using Generalized Linear Mixed Effects Models (GLMM) as suggested by Maunder and Punt (2004) and Campbell (2015), could be considered at later stages of the analysis.

RESULTS AND DISCUSSION

Table 1 shows the results of the model simplification process. The final (“minimum adequate”) model was:

For the “counts” or “positive”, model:

CTCHRATEms ~ YEAR + QUARTER + LATF + DIST + MEANTEMP + MEANSSTANOM + PNH + FLEET + CTCHRATEposswo + QUARTER:DIST + LATF:DIST + MEANTEMP:MEANSSTANOM + FLEET:PNH

For the binomial model:
CTCHRATEposms ~ YEAR + QUARTER + LATF + DIST + MEANTEMP + MEANSSTANOM + PNH + FLEET + QUARTER:DIST + LATF:DIST + MEANTEMP:MEANSSTANOM

The results of estimated marginal means procedure, the standardized abundance indices for the mako shark (2006-2022) from the model are shown in Table 2. The re-scaled values of the estimated indices are shown in table 3. **Figure 4** show the estimated values of the relative index and their 95% confidence intervals, together with the nominal catch rates for years 2006-2022.

It is possible that the largest confidence intervals in the abundance index (for example in the years 2006 and 2012), could be a result, at least in part, from inter-annual differences in sample sizes.

Figure 5 shows the residuals of the model as well as the marginal-model plots for each factor. The residuals show an asymmetrical distribution with many positive residuals with relatively high values. The Hosmer-Lemeshow (Agresti 2019) test did not indicate a significant lack of fit (p-value >= 0.05) nor an overdispersion test showed any evidence of that kind of problem in the binomial part of the model. The Theta estimate of the counts part of the model (1.6037) didn't appear to show signs that overdispersion remained after fitting the model.

That pattern in the residuals led to repeating the process several times, including several subsets of the data, excluding particular areas or fleets and trying different weights vectors. The best results, in regards of residuals behavior was obtained using a weights vector based on variance of nominal CPUE for each year. The residuals for that model are shown in figure 6. Although the residuals distribution looks more symmetrical, the tails at the lower and upper ends of the qqplot are still evident. This particular model didn't differ in the binomial part from the one presented above but only had two significant predictors (YEAR and latitude). The same residuals pattern is apparent in the results shown by Hazin *et al.* (2018) in their abundance indices standardization of mako shark in the Atlantic.

However, the standardized indices of those trials didn't differ much of the ones obtained using the model shown (falling in every case within its 95% confidence intervals), so we decided to keep the ones produced by the model described above.

Spatial-temporal heterogeneity in the marine environment greatly affects the biology, dynamics, and availability of fish stocks, as well as their vulnerability to fishing gear, thus introducing a source of variability in nominal catch rates (Bigelow *et al.* 1999). Sea surface temperature is one of the most important physical factors because it modifies the geographical and vertical aggregation patterns of fishes, through its effect on feeding, reproductive and migratory behavior, and body thermoregulation (Fonteneau 1998).

The importance of sea surface temperature as an explanatory variable in the present analysis is reflected in the effects graphs (figures 7 and 8). Higher temperatures have a negative effect, both in the probability of capture and in the number of fish caught.

Variability in nominal catch rates can also be related to other physical, chemical, and biological processes or factors in the ocean (e.g. water transparency, circulation patterns, frontal zones, salinity, plankton, nekton), which together with temperature define the identity, structure, and interaction of water masses and can affect the availability of potential prey and the capture efficiency of predatory fishes (Laurs *et al.* 1984, Bigelow *et al.* 1999). High primary productivity on the Pacific coast of the Baja California Peninsula is usually related to coastal upwelling activity that injects nutrients into the euphotic zone. The upwelling intensity changes in accordance with local combinations of wind conditions and bottom topography, modulated by the influence of mesoscale meanders of the California Current (Zaytsev *et al*. 2003). As upwelling results in the appearance on the surface of cold water masses from the bottom, water temperature is indirectly related to these local high productivity areas but no direct causal relationships exist between these two factors.

The coastal nature of upwellings could explain, at least in part, the significance of terms containing the distance to the coast (DIST). In this updating, similar to analyses made in 2014, 2017 and 2021 (González-Ania *et al.* 2014, 2017, 2021). Those coastal upwelling phenomena are not present at lower latitudes of the Mexican coast which explains the significance of the LATF:DIST interaction included in the model, both in its binomial and negative binomial parts. Other significant interaction, QUARTER:DIST, points at the importance of specific seasons, in particular certain areas of the Baja California peninsula, relatively near to the shore.

These circulation patterns mentioned above are affected by warming events that are not uncommon in this area of the ocean. It should be noted that the last years of the period under study registered the occurrence of two unusual and consecutive warming events known as The Blob (TB2013–2015) and the 2015–2016 El Niño (Jiménez-Quiroz *et al.* 2019). That the effect of those events differs according to the particular marine area that is affected could be seen in the significance of the MEANTEMP:MEANSSTANOM interaction of both parts of the model. Birkmanis *et al.* (2020) predict shifts in suitable habitat for blue and mako sharks, related with higher SST anomalies in the Southern Hemisphere.

Fishery-related factors like hook size and type, fishing depth or bait type were not included in this analysis, as data on these factors were not available in the data set we used but could be available in the observer data base. However, the inclusion in the model of the interaction of fleet with the fraction of night hours in the fishing set (FLEET:PNH, that was significant in the count part of the model) was aimed at assessing the effect of an apparent shift to night sets in the Mazatlán fleet. This change in fishing strategy is apparently related to fishermen looking for species other than sharks, like swordfish (*Xiphias gladius*). Figure 9 shows a graph containing the fraction of fishing sets with zero catch of swordfish, mako and blue shark by year in the available data set. A clear negative trend in the fraction of zero swordfish catch coincides with a rise in the ones for mako and blue sharks. A shift in the target species, with the possible corresponding change in blue and mako sharks CPUE, could not be excluded at this time and should be attentively evaluated in future analysis.

The results of this analysis point at the abundance index trends being close to stability in most of the analyzed period, taking into account the uncertainty involved. The lower abundance index in the last year of the series could be related to the change in the target species mentioned above.

The present study is the result of recently initiated work, aiming to merge fishery and environmental information from the distribution range of the shortfin mako, and other shark species, in the Mexican Pacific, to estimate the best available relative abundance indices, and model recent trends in CPUE. Results may be improved by adding other predictor variables to the model, extending the time series, and taking into account the size-age and sex structure of the catches. Variable transformation and use of generalized additive models (GAMs) may also increase the explanatory power of the model, due to the likely nonlinearity of many of the functional relationships between probability of catch or catch rate and the predictor variables.

REFERENCES

Agresti, A. 2019. An introduction to categorical data analysis Third edition. John Wiley & Sons, Inc.

Bigelow, K.A., C.H. Boggs, X. He. 1999. Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery. Fish. Oceanogr. 8 (3), 178–198.

Birkmanis C.A., J.J. Freer, L.W. Simmons, J.C. Partridge and A.M.M. Sequeira. 2020. Future Distribution of Suitable Habitat for Pelagic Sharks in Australia Under Climate Change Models. Front. Mar. Sci. 7:570. doi: 10.3389/fmars.2020.00570

Brodziak, J., W.A. Walsh. 2013. Model selection and multimodel inference for standardizing catch rates of bycatch species: a case study of oceanic whitetip shark in the Hawaii-based longline fishery. Can. J. Fish. Aquat. Sci. 70, 1723–1740.

Brown, C.A. 1998. Standardized catch rates for yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) in the Virginia - Massachusetts (U.S.) rod and reel fishery. Int. Comm. Conserv. Atl. Tunas, Col. Vol. Sci. Pap. 49(3), 357–369.

Burnham, K.P. and Anderson, D.R. 2002. Model Selection and Inference: A Practical Information-Theoretic Approach. 2nd Edition, Springer-Verlag, New York.

Campbell, R.A. 2015. Constructing stock abundance indices from catch and effort data: Some nuts and bolts. Fisheries Research 161, 109–130.

Canty A. and B. Ripley 2020. boot: Bootstrap R (S-Plus) Functions. R package version 1.3-25.

Castillo-Géniz, J.L., S.R. Soriano-Velásquez, R. Villaseñor-Talavera. 2008. Capítulo No. 9 “Pesquerías mexicanas de tiburón en el Océano Pacífico”, Pp 211-241. In: Pesquerías Latinoamericanas, Machii, T y O.J. Flores, (eds), Comisión Nacional de Acuacultura y Pesca, SAGARPA, México.

Castillo-Géniz, J.L., C.J. Godinez-Padilla, H.A. Ajás-Terriquez, L.V. González-Ania. 2014. Catch data for shortfin mako shark reported by fishery observers from Mexican shark longline and driftnet fisheries in the North Pacific in 2006-2014. Documento de Trabajo (Working paper) ISC/14/SHARKWG-3/02. Taller del Grupo de Trabajo de Tiburones del Comité Científico Internacional para el Atún y Especies Afines del Pacífico Norte (ISC Shark Working Group Workshop), noviembre 19-26, 2014, Puerto Vallarta, Jalisco, México. 19 p.

CONAPESCA 2021. Anuario Estadístico de Acuacultura y Pesca Edición 2021.

Crawley, M. 2013. The R Book. John Wiley & Sons. England. 942 p.

DOF. 2007. Norma Oficial Mexicana nom-029-pesc-2006, pesca responsable de tiburones y rayas. Especificaciones para su aprovechamiento. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. Diario Oficial de la Federación. México. 14 de febrero de 2007.

DOF. 2010. Acuerdo mediante el cual se da a conocer la actualización de la Carta Nacional Pesquera. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. Diario Oficial de laFederación. México. 2 de diciembre de 2010.

DOF. 2012. Acuerdo por el que se modifica el Aviso por el que se da a conocer el establecimiento de épocas y zonas de veda para la pesca de diferentes especies de la fauna acuática en aguas de jurisdicción federal de los Estados Unidos Mexicanos, publicado el 16 de marzo de 1994 para establecer los periodos de veda de pulpo en el Sistema Arrecifal Veracruzano, jaiba en Sonora y Sinaloa, tiburones y rayas en el Océano Pacífico y tiburones en el Golfo de México. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación, México. Diario Oficial de la Federación. México. 11 de junio de 2012.

DOF. 2014. Acuerdo por el que se modifica el Aviso por el que se da a conocer el establecimiento de épocas y zonas de veda para la pesca de diferentes especies de la fauna acuática en aguas de jurisdicción federal de los Estados Unidos Mexicanos, publicado el 16 de marzo de 1994 para modificar el periodo y zonas de veda de tiburones en el Golfo de México y Mar Caribe. Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. Diario Oficial de la Federación. México. 15 de mayo de 2014.

Dick, E.J. 04. Beyond 'lognormal versus gamma': discrimination among error distributions for generalized linear models. Fisheries Research 70, 351–366.

Fonteneau, A. 1998. Introduction aux problèmes des relations thons-environnement dans l'Atlantique. Int. Comm. Conserv. Atl. Tunas, Col. Vol. Sci. Pap. 50(1), 275–317.

Gavaris, S. 1980. Use of a multiplicative model to estimate catch rate and effort from commercial data. Can. J. Fish. Aquat. Sci. 37, 2272–2275.

Godínez-Padilla CJ, J.L. Castillo-Géniz, and Ortega-Salgado, I. 2016. Diversidad y abundancia relativa de tiburones pelágicos capturados por la flota industrial palangrera de Ensenada, Baja California, México. Ciencia Pesquera 24 (Número especial): 97-111

González-Ania, L.V., J.I. Fernández-Méndez and J.L. Castillo-Géniz. 2014. Standardized catch rates for mako shark (*Isurus oxyrinchus*) in the 2006-2014 Mexican Pacific longline fishery based upon a shark scientific observer program. Working paper. ISC/14/SHARKWG-3/16. ISC Shark Working Group Workshop, 19-26 November 2014, Puerto Vallarta, Jalisco, Mexico.

González-Ania, L.V., J.I. Fernández-Méndez, J.L. Castillo-Géniz, L. Hidalgo-García and H. Haro-Ávalos. 2017. Update on standardized catch rates for mako shark (*Isurus oxyrinchus*) in the 2006-2016 Mexican Pacific longline fishery based upon a shark scientific observer program. Working document. ISC/17/SHARKWG-3/20 submitted to the ISC Shark Working Group Workshop, 28 November4-December, 2017, NRIFSF Shimizu, Shizuoka, Japan.

González-Ania, L.V. J. I. Fernández-Méndez, J. L. Castillo-Géniz, G. Ramírez-Soberón and H. Haro-Ávalos 2021. Update on standardized catch rates for mako shark (Isurus oxyrinchus) in the 2006-2019 Mexican Pacific longline fishery based upon a shark scientific observer program. Working document submitted to the ISC Shark Working Group Workshop, 22 – 26 February, 2021. ISC/21/SHARKWG-1/07.

Goñi, R., F. Alvarez, S. Adlerstein. 1999. Application of generalized linear modeling to catchrate analysis of Western Mediterranean fisheries: the Castellón trawl fleet as a case study. Fisheries Research 42, 291–302.

Haggarty, D.R., J.R. King. 2006. CPUE as an index of relative abundance for nearshore reef fishes. Fisheries Research 81, 89–93.

Harding, J.W., J.M. Hilbe. 2012. Generalized Linear Models and Extensions. Third Edition. Stata Press. 455 p.

Hazin, F.H.V., H.G. Hazin, R. Sant'Ana, and B. Mourato 2018. Standardized Catch Rates of Shortfin Mako Sharks Caught by the Brazilian Tuna Longline Fleet (1978-2016) Using Generalized Linear Mixed Models (GLMM). SCRS/2018/101 Collect. Vol. Sci. Pap. ICCAT, 75(3): 498-510 (2018)

Hijmans, R.J. 2016. Raster: Geographic Data Analysis and Modeling. R package version 2.5-8. https://CRAN.R-project.org/package=raster

Holts, D.B., O. Sosa-Nishizaki. 1998. Swordfish, *Xiphias gladius*, fisheries of the Eastern North Pacific Ocean. *In*: Barrett, I., O. Sosa-Nishizaki, N. Bartoo (eds.), Biology and fisheries of swordfish, *Xiphias gladius*, 63-76. U.S. Dep. Commer., NOAA Technical Report NMFS, 142.

Holts, D.B., A. Julian, O. Sosa-Nishizaki, N.W. Bartoo. 1998. Pelagic shark fisheries along the west coast of United States and Baja California, Mexico. Fisheries Research 39: 115-125.

Jackman S (2020). pscl: Classes and Methods for R Developed in the Political Science Computational Laboratory. United States Studies Centre, University of Sydney, Sydney, New South Wales, Australia. R package version 1.5.5.1, https://github.com/atahk/pscl/

James, G., D. Witten, T. Hastie and R. Tibshirani. 2021. An Introduction to Statistical Learning with Applications in R. Second Edition. Springer.

Jiménez-Quiroz M. del C., R. Cervantes-Duarte, R. Funes-Rodríguez, S.A. Barón-Campis, F. de J. García-Romero, S. Hernández-Trujillo, D.U. Hernández-Becerril, R. González-Armas, R. Artell Dubois, S. Cerdeira-Estrada, J.I. Fernández-Méndez, L.V. González-Ania, M. Vásquez-Ortiz and F.J. Barrón-Barraza. 2019. Impact of "The Blob" and "El Niño" in the SW Baja California Peninsula: Plankton and Environmental Variability of Bahia Magdalena. Front. Mar. Sci. 6:25. doi: 10.3389/fmars.2019.00025.

Laurs, R.M., P.C. Fiedler, D.R. Montgomery. 1984. Albacore tuna catch distributions relative to environmental features observed from satellites. Deep-Sea Research 31(9), 1085–1099.

Lenth, R. V. 2021. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.7.0. https://CRAN.R-project.org/package=emmeans.

Lluch-Belda, D., J. Elorduy-Garay, S.E. Lluch-Cota and G. Ponce-Díaz. 2000. Centros de Actividad Biológica del Pacífico mexicano. Centro de Investigaciones Biológicas del Noroeste, S.C. Centro Interdisciplinario de Ciencias Marinas. Consejo Nacional de Ciencia y Tecnología.

Lo, N.C.H., L.D. Jacobson, J.L. Squire. 1992. Indices of relative abundance from fish spotter data based on delta-lognormal models. Can. J. Fish. Aquat. Sci. 49, 2515–2526.

Maunder, M.N., A.E. Punt. 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research 70, 141–159.

McCullagh, P., J.A. Nelder. 1989. Generalized Linear Models, 2nd ed. Chapman and Hall, London. 511 p.

Medellín Ortiz, A.2008.Movimientos del tiburón mako (lsurus oxyrinchus) en el Pacífico Noreste.Tesis de Maestría en Ciencias. Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California.76 pp.

Minami, M., C.E. Lennert-Cody, W. Gaoc, M. Román-Verdesoto. 2007. Modeling shark bycatch: The zero-inflated negative binomial regression model with smoothing. Fisheries Research 84, 210–221.

Myers, R.H., D.C. Montgomery, G.G. Vining, T.J. Robinson. 2002. Generalized linear models with applications in engineering and the sciences. John Wiley & Sons. 496 p.

Nelder, J.A., R.W.M. Wedderburn. 1972. Generalized linear models. Journal of the Royal Statistical Society, Series A 135, 370–384.

Ortiz, M., F. Arocha. 2004. Alternative error distribution models for standardization of catch rates of non-target species from a pelagic longline fishery: billfish species in the Venezuelan tuna longline fishery. Fisheries Research 70, 275–297.

Pennington, M. 1983. Efficient Estimators of Abundance, for Fish and Plankton Surveys. Biometrics 39 (1), 281–286.

Porter, J.M., M. Ortiz, S.D. Paul. 2003. Updated standardized CPUE indices for Canadian bluefin tuna fisheries based on commercial catch rates. ICCAT Col. Vol. Sci. Pap. 55 (3), 1005–1018.

Punt, A.E., T.I. Walker, B.L. Taylor, F. Pribac. 2000. Standardization of catch and effort data in a spatially-structured shark fishery. Fisheries Research 45, 129–145.

R Core Team. 2017. *R*: A language and environment for statistical computing. *R* Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Shono, H. 2008. Application of the Tweedie distribution to zero-catch data in CPUE analysis. Fisheries Research 93, 154–162.

Sosa-Nishizaki, O., P.R. De la Rosa, L.R. Castro, C.M. Grijalva, V.J. De la Rosa. 1993. Reporte anual 1992 del proyecto: Estudio biológico-pesquero del pez espada (Xiphias gladius) y otras especies de picudos (Marlines y Pez Vela). CICESE: CTCECT 9306. 44 p.

Sosa-Nishizaki, O., J.A. Furlong-Estrada, J.A. Reyes-González, J.C. Pérez-Jiménez. 2002. Blue shark (Prionace glauca) fishery in Baja California, México: An example of artisanal and middle scale fisheries interaction. Scientific Council Meeting, September 2002. Northwest Atlantic Fisheries Organization, NAFO SCR Doc 02/140, Serial No. N4762.

Stefánsson, G. 1996. Analysis of groundfish survey abundance data: combining the GLM and delta approaches. ICES J. Mar. Sci. 53, 577–588.

Thieurmel B, Elmarhraoui A (2022). _suncalc: Compute Sun Position, Sunlight Phases, Moon Position and Lunar Phase_. R package version 0.5.1, <https://CRAN.R-project.org/package=suncalc>.

Tweedie, M.C K. 1984. An Index which Distinguishes between Some Important Exponential Families. *In*: Ghosh, J.K. and J. Roy (Eds.), Statistics: Applications and New Directions. Proceedings of the Indian Statistical Golden Jubilee International Conference. Indian Statistical Institute, 579–604.

Ulloa-Ramírez, P., L.V. González-Ania, O. Sosa-Nishizaki. 2000. Pez espada del Océano Pacífico. Pp 411- 433. In: Instituto Nacional de la Pesca, SEMARNAP, Editor. "Sustentabilidad y Pesca Responsableen México: Evaluación y Manejo 1997-1998". INP, México. 691 p.

Vélez-Marín, R. & J. F. Márquez-Farías. 2009. Distribution and size of the shortfin mako (Isurus oxyrinchus) in the Mexican Pacific Ocean. Pan-American Journal of Aquatic Sciences 4 (4): 490-499.

Walker, T.I., K. Giri, F.I. Trinnie, D.J. Reilly. 2012. CPUE data screening, selection and standardisation for stock assessment of southern rock lobster (*Jasus edwardsii*) in Victoria. Victorian Rock Lobster Resource Assessment Group, Meeting 7 (8 March2012).

Walters, C. 2003. Folly and fantasy in the analysis of spatial catch rate data. Can. J. Fish. Aquat. Sci. 60,1433–1436.

Zeileis A, Kleiber C, Jackman S (2008). “Regression Models for Count Data in R.” Journal of Statistical Software, 27(8). http://www.jstatsoft.org/v27/i08/.

Zuur, A.F., E.N. Leno, N.J. Walker, A.A. Saveliev, G.M. Smith. 2009. Mixed Effects Models and Extensions in Ecology with *R*. Springer. 574 p.

Table 1. Likelihood-ratio test's p values, AIC, BIC and Cross Validation MSE obtained in the model simplification process (*covariate retained in the model).

a) Binomial model:

	p LrTest	AIC	BIC	CV
FLEET:CTCHRATEposswo	0.1166	19050	19621.11	53.10894
FLEET:PNH	0.4381	19048.6	19612.74	52.9870
MEANTEMP:MEANSSTANOM*	3.37E-05	19066.47	19602.75	52.98528
LATF:DIST*	0.006106	19054.8	19605.01	53.09718
QUARTER:DIST *	5.343E-07	19074.56	19617.81	53.00432
CTCHRATEposswo	0.5072	19047.04	19604.22	53.00751
FLEET*	0.028	19049.87	19600.08	53.0964
PNH*	0.02819	19049.86	19600.08	53.13686
YEAR*	2.20E-16	19049.87	19600.08	52.94233

b) "Counts" or "positive", model:

	p LrTest	AIC	BIC	CV
FLEET:CTCHRATEposswo	0.8176	19045.1	19595.31	52.97826
FLEET:PNH*	0.006891	19050.4	19593.64	52.89923
MEANTEMP:MEANSSTANOM*	0.01662	19049.2	19571.55	53.20744
LATF:DIST *	0.001628	19053.94	19590.22	53.32253
QUARTER:DIST*	0.0003901	19057.35	19586.66	53.07155
CTCHRATEposswo*	1.142E-08	19075.68	19618.92	53.14481
YEAR*	2.2E-16	19153.72	19592.49	53.30385

Table 2. Standardized abundance indices (estimated marginal means for the YEAR factor) from the hurdle model fit, their standard errors (se), coefficient of variation (cv) and lower and upper asymptotic 95% confidence intervals.

YEAR	Index	se	cv	L CI 95%	U CI 95%
2006	1.93	0.37	0.19	1.20	2.66
2007	0.87	0.24	0.28	0.40	1.35
2008	0.94	0.23	0.25	0.48	1.39
2009	0.93	0.27	0.29	0.40	1.46
2010	0.78	0.23	0.29	0.33	1.22
2011	1.56	0.38	0.24	0.82	2.30
2012	1.88	0.55	0.29	0.80	2.95
2013	1.48	0.36	0.24	0.78	2.18
2014	0.83	0.24	0.30	0.35	1.31
2015	0.90	0.27	0.30	0.37	1.43
2016	0.89	0.25	0.28	0.40	1.38
2017	1.23	0.30	0.25	0.63	1.83
2018	0.42	0.16	0.38	0.10	0.75
2019	1.50	0.37	0.25	0.77	2.22
2020	0.73	0.26	0.35	0.23	1.23
2021	1.67	0.30	0.18	1.08	2.26
2022	0.40	0.17	0.42	0.07	0.72

Table 3. Re-scaled values of the estimated abundance indices for the hurdle model and their 95% confidence intervals.

YEAR	Re-scaled abundance index	L CI 95%	U CI 95%
2006	1.73	1.08	2.39
2007	0.79	0.36	1.21
2008	0.84	0.44	1.25
2009	0.83	0.35	1.31
2010	0.70	0.30	1.10
2011	1.40	0.74	2.07
2012	1.69	0.72	2.65
2013	1.33	0.70	1.96
2014	0.74	0.31	1.17
2015	0.81	0.34	1.29
2016	0.80	0.36	1.24
2017	1.10	0.57	1.64
2018	0.38	0.09	0.67
2019	1.34	0.69	1.99
2020	0.65	0.20	1.11
2021	1.50	0.97	2.03
2022	0.36	0.07	0.65

Year

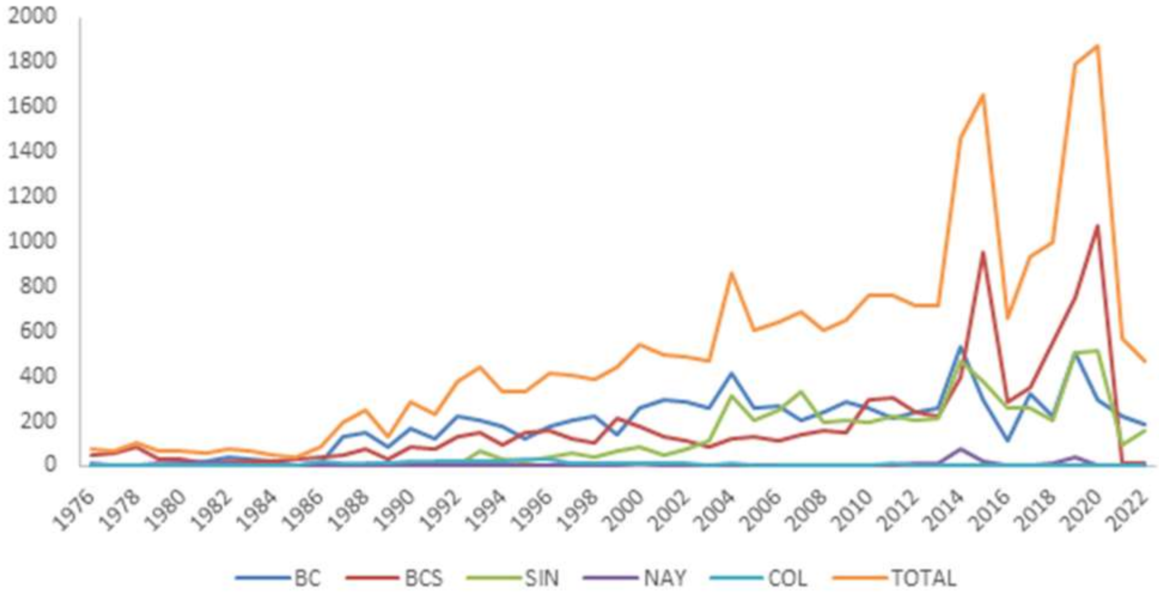


Figure 1 Mexican shortfin mako shark, *I. oxyrinchus,* landings estimation in metric tons (live weight) by state

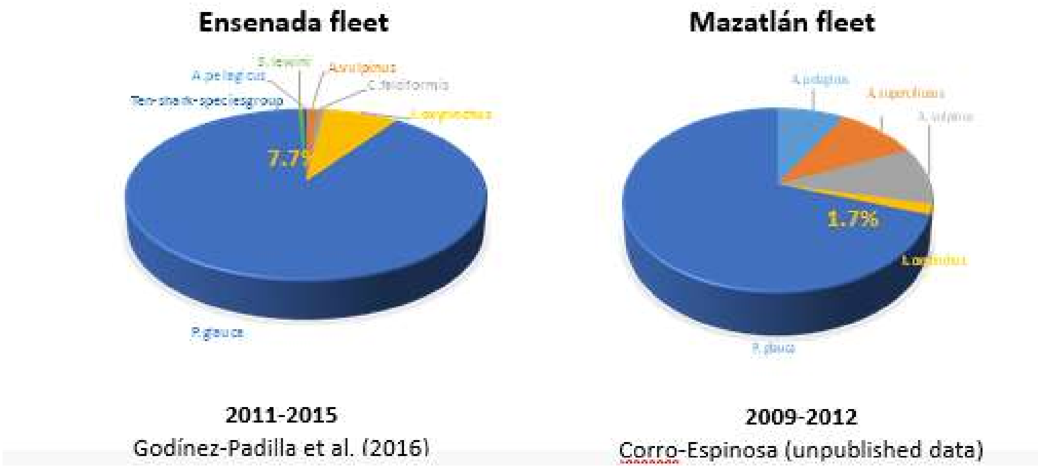


Figure 2 Sharks catch composition of the Mexican Pacific coast.

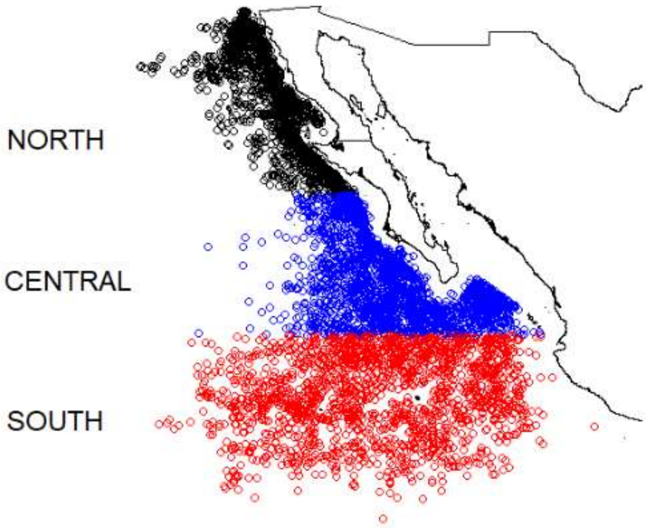


Figure 3.-The zones used in the analyses (see text for details).

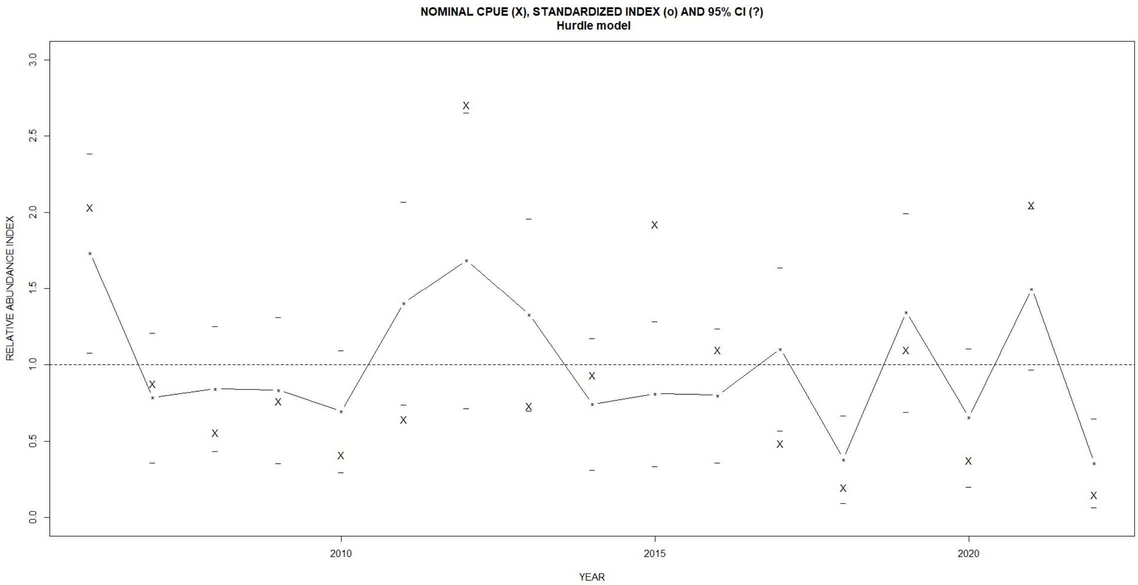


Figure 4. Relative abundance indices for the shortfin mako shark, *I. oxyrinchus,* with approximate 95% confidence intervals. X marks the nominal CPUE. Hurdle model for years 2006-2022.

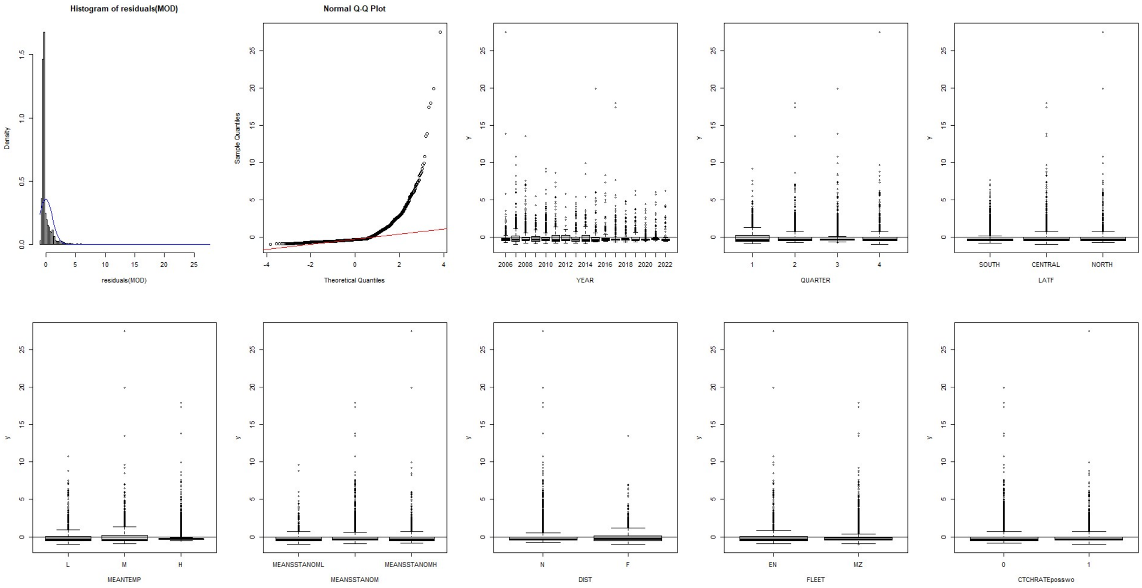


Figure 5. Residuals and Marginal-model plots of the hurdle model.

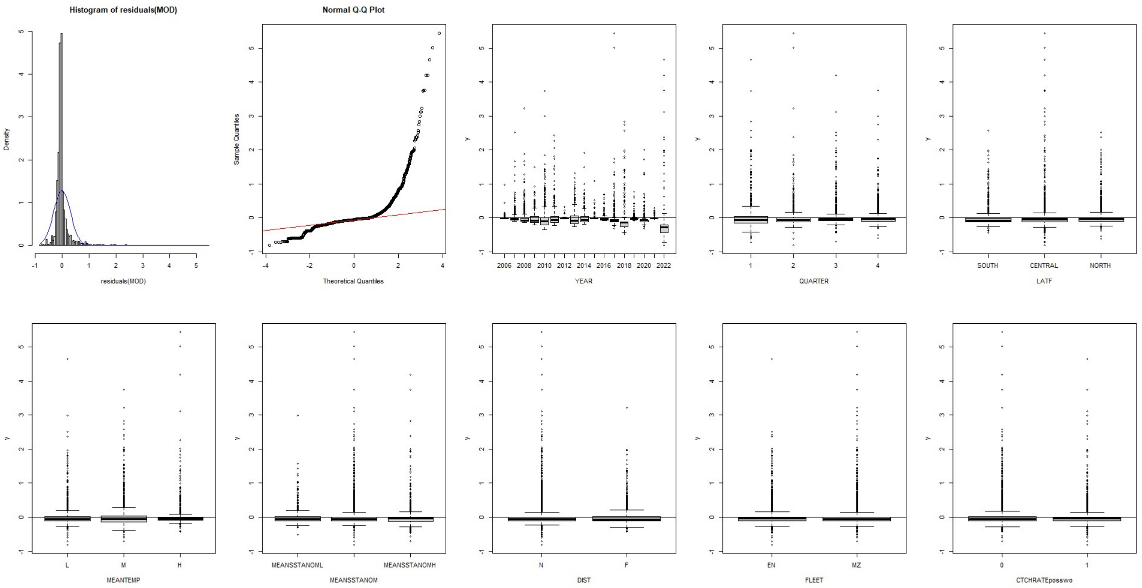


Figure 6. Residuals and Marginal-model plots of the hurdle model, using a weights vector based on variance of nominal CPUE for each year.

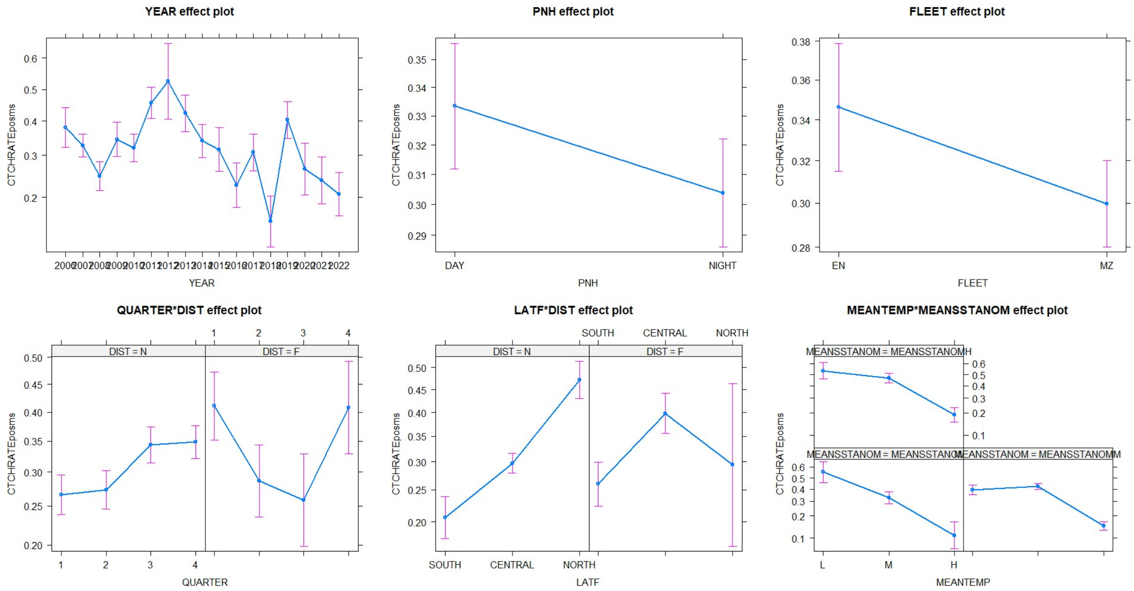


Figure 7. Effects plot for the terms included in the final model, binomial part.

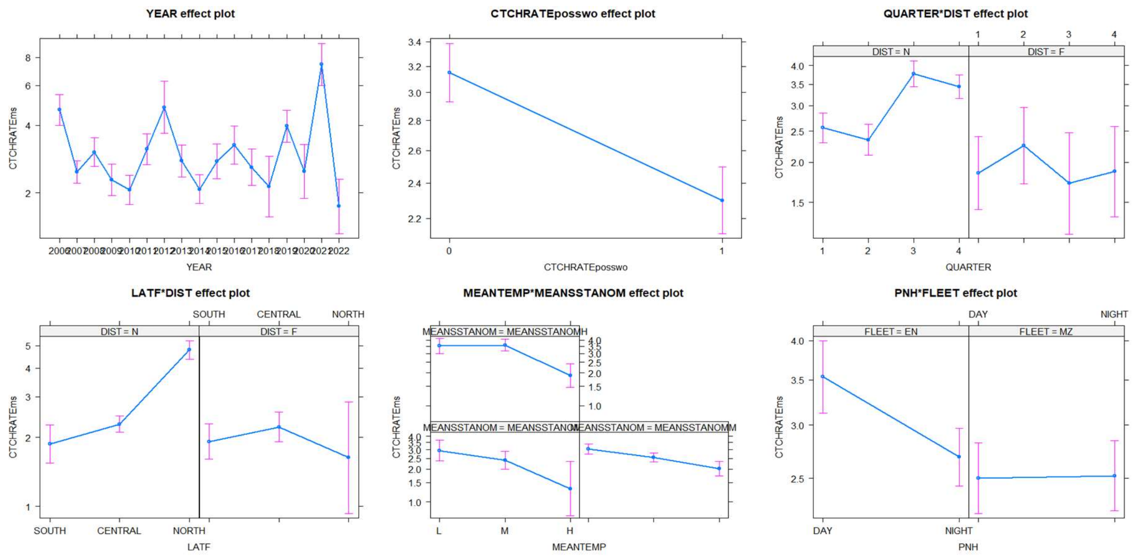


Figure 8. Effects plot for the terms included in the final model, negative binomial part.

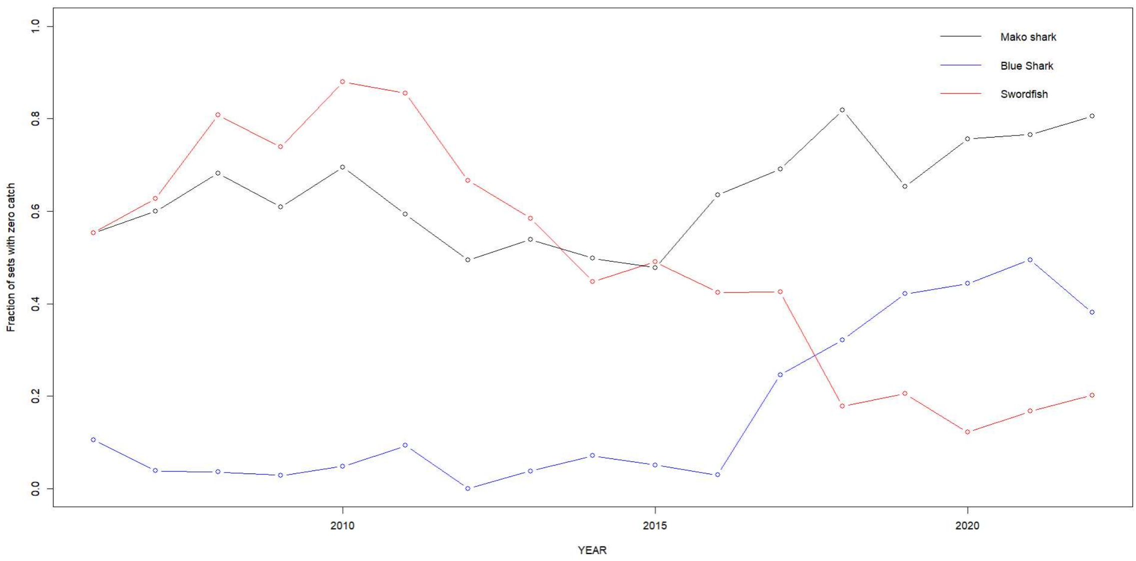


Figure 9. Fraction of fishing sets with zero catch of swordfish and shortfin mako and blue sharks by year in the available data set.