INTER-AMERICAN TROPICAL TUNA COMMISSION

SCIENTIFIC ADVISORY COMMITTEE

TENTH MEETING

San Diego, California (USA)
13-17 May 2019

DOCUMENT SAC-10 INF-J

EXPLORATORY ANALYSIS OF AVAILABLE DATA OF PACIFIC BONITO (*Sarda chiliensis lineolata*) IN THE NORTH PACIFIC OCEAN

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SUMMARY

This report discusses an overview of Pacific bonito (*Sarda chiliensis lineolata*) biology and aspects of its historical fishery. Pacific bonito is an epipelagic species distributed in temperate waters over the continental shelf from southern Alaska, U.S.A. to the Revillagigedo Islands, Mexico. The most economically productive area is from Magdalena Bay, in Baja California Sur, Mexico to Point Conception, California, U.S.A. The main spawning area is in waters of the Baja California Peninsula from Thetis Bank to Hutchins Bank (Gulf of Ulloa) during spring and summer. Tagging studies have shown that this species moves from California northward in late summer and early fall and down southern California and the Baja California Peninsula coasts during winter months. Historically USA sport-fishing fleets have been catching this species off California waters while commercial catches have come from two areas: off California from the Mexican border to Point Conception and off the western coast of the Baja California Peninsula from Cedros Island to Magdalena Bay, mainly by purse-seiners that target mackerel and sardines and those that target yellowfin tuna. Along these historical catches, a great variability has been recorded, which has not been explained yet with low landings for some years interspersed with high yield years. Although efforts have been dedicated to obtain indicators of abundance (Squire 1972; MacCall et al. 1976; Collins et al. 1980) through production models (equilibrium approximation) and yield per recruit models using catch data from commercial fishery and sport-fishing, the estimates have not been reliable and seem to overestimate abundance and maximum sustainable yield. Preliminary exploration data and future steps

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are discussed.

1. INTRODUCTION

The Pacific bonito (*Sarda chiliensis lineolata*) belongs to the Scombridae family that forms the tribe Sardini, whose taxonomic position is between mackerels and tunas (Collete and Chao 1975). They are normally heterosexual organisms and do not display apparent external anatomical differences between males and females. Young fish are found nearshore in close association with giant kelp *(Macrocystis* sp.) beds, and older fish are found in open waters and over nearshore banks (Collins et al. 1980). It is an epipelagic species distributed in temperate waters over the continental shelf from southern Alaska, U.S.A. to the Revillagigedo Islands, Mexico, being most economically productive from Magdalena Bay in Baja California Sur, Mexico to Point Conception, California, U.S.A. (Campbell and Collins 1975; Collins and MacCall 1977; Larinto 2010).

This species started to be an economic impact in California waters after 1957, mainly for sport-fishing fleet and for commercial catch in 1966 (Glenn 1979). Historically, Pacific bonito commercial catches have come from two areas: off California from the Mexican border to Point Conception and off the western coast of the Baja California Peninsula from Cedros Island to Magdalena Bay (Collins et al. 1980). Although commercial capture of this species in California waters has been recorded since 1916, it was mainly for sport-fishing fleet after 1957 and until 1966 when commercial catch started to be an economic impact (Glenn 1979), usually performed within 12 miles off shore. In the 60s and 70s, 50 to 90% of Pacific bonito that landed in the United States was caught off the coast of Baja California, but Mexico began restricting foreign vessel access to its nearshore fisheries in 1982.

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Pacific Bonito are caught commercially by troll gear, gillnets, pole and line gear, and purse seiners, of which this last fleet is the most effective method to catch them. The purse-seine fleet consists of two general groups: (a) “wet fish” vessels that operate off California waters and which have a as target mackerel and sardines but seasonally catch bonito. These vessels are based in San Pedro and fish in the Santa Barbara and San Pedro channels; (b) tuna purse seiners that operate in the Eastern Pacific Ocean and have as a target mainly yellowfin tuna (Leet et al. 2001).

Catches from U.S. waters occur primarily from July to January, peaking in September through November, but quite variable in the months of July, August, December and January. Catches off Mexico are also concentrated inshore, primarily on banks from Cedros Island to Cape San Lazaro from June through September with both June and September being months of variable catch (Collins et al. 1980).

Since its inception in California waters, this fishery has shown a high variability in catches, recording low landings for some years interspersed with high yield years (Figure 1). Studies have intended to explain this behavior by factors, such as market demand, price, and availability of desirable species. Other causes of landing fluctuations could be attributed to the migratory movements of these fish and some to oceanic changes. These changes include long term environmental seasonal variations, local water temperatures, ocean currents, and water masses from year to year; the strength of recruiting year classes of both predator and prey populations, local availability of prey, effects of pollution on spawning and variable fishing pressure throughout the species range. For instance, during El Niño events, more of the stock may move northward, becoming more available to California fisheries while during La Niña events, fewer fish may move into California waters (Karpov et al. 1995; Leet et al. 2001; Larinto 2010).

2. BIOLOGICAL INFORMATION

2.1. Spawning

Based on collections of eggs and larvae (Klawe 1961; Pinkas 1961; Sokolovskii 1971), bonito spawn off southern California and Baja California within the 200-m isobath and in shallow waters ranging in temperature from 16 °C to 20 °C.

Black (1979) determined through external examinations of male gonads and from egg diameter measurements of female gonads that Pacific bonito spawn primarily in Baja California waters from Thetis Bank and Hutchins Bank (Gulf of Ulloa) during spring and summer. The study also found that 100% of the males larger than 50 cm and at least 2-year old individuals and 97.5% of the females larger than 55 cm and older than age 2 were mature. Males are ready to spawn before females that limit the duration of the spawning season. Collins and MacCall (1977) reported a positive relationship between strong upwelling off Baja California and reproductive success of bonito, as measured by relative recruitment into the southern California partyboat fishery. Evidence suggested that even one-year-old individuals may spawn in cold-water areas influenced by thermal discharges. Older bonito specimens, approximately 69 cm long or 3-year old at first spawning (Larinto 2010) mature earlier in the season and tend to distribute further offshore as compared to younger fish.

An analysis of the ovum diameters in spawning fish indicated that bonito spawned more than once each season. Fecundity estimates were unreliable.

2.2. Feeding habits

Although interannual and seasonal variation in their feeding habits has been reported (Fields 1965), anchovy *Engraulis mordax* is the major food item in the diet of Pacific bonito; common squid, *Loligo opalescens* forms an important part of its diet from January through June; and miscellaneous fish, such as sardines and a few crustaceans make up a small portion of their diet (Pinkas et al. 1971).

2.3. Size, age and growth

Pacific bonito are vulnerable to the inshore recreational fleet in California waters from 35 to 58 cm (4 to 18 months of age), very few over 60 cm occur in sport-fishing, in general age 0 and 1. On the other hand commercial landings consisted almost exclusively of fish 2 years and older (> 60 cm).

Kuo (1970) and Campbell and Collins (1975) determined age through growth increments of otoliths; however, the results were quite discrepant, especially in L_∞; while the first estimation was very large (266. 1 cm), the second (76.87 cm) one seemed to be small, and there was an unverified report of an organism of greater size (Yoshida 1980). Campbell and Collins (1975) assigned the age to over 3000 bonitos that ranged from 23 to 79 cm (1-6 years). They determined that this species grows rapidly during their first three years of life with much slower growth from three to six years old. The mean length of each age group in the fishery is age I-51.5 cm, age II 63.3 cm, age III-69.5 cm, age IV 72.9 cm, age V-74.8 cm and age VI 75.7 cm. Kuo (1970) assigned the age to 121 otoliths of bonito (1-8 years) and suggested almost linear growth. The mean length of each age group is age I-15.2, age II-25.2 cm, age III-34.7, age IV-43.3 cm, age V-50.9 cm, age VI-58.5 cm, age VII-65.2 cm and age VIII-75.6 cm. The ages at the different lengths as given by Campbell and Collins are larger for all the ages than those given by Kuo. The von Bertalanffy growth model parameters are displayed in Table 1.

Table 1. Von Bertalanffy growth parameters of *Sarda chiliensis lineolata*

Authors	L_∞	k	t_0
Kuo, 1970	266.1	0.038	-0.60
Campbell and Collins, 1975	76.87	0.6215	-0.410

The estimations performed by Campbell and Collins (1975) were validated by several techniques (otoliths edge analysis, back-calculated fish length and growth rates from length-frequency and tagging data).

Campbell and Collins (1975) also determine the length-weight relationships for males, females and combined sexes: $W = 7.26083 \times 10^{-6} L^{3.09749}$ (males); $W = 7.93187 \times 10^{-6} L^{3.08338}$ (females) and $W = 7.62728 \times 10^{-6} L^{3.08962}$ (sexes combined).

2.4. Migration

During 1968 a Pacific bonito tagging project was launched. Over 13,000 tagged fish were released and approximately 13% of them were recaptured. In general fish tagged in California go northward in late summer and early fall and down southern California and Baja California coasts during winter months. Several bonito tagged off Baja California in June were recaptured by purse seiners near Santa Barbara four to six months later. Bonito tagged near Santa Barbara have been recovered a year and a half later off Baja California. This study also indicated that heated water discharges from coastal electric generating stations strongly influenced the migration of young bonito in southern California waters. These fish either remained in the discharge area or tended to migrate to another heated discharge area (Campbell and Collins, 1975; Collins and MacCall, 1977; Collins et al. 1980)

3. ENVIRONMENTAL INFLUENCES

Similar to species like the Pacific chub mackerel, Pacific barracuda and dolphinfish, Pacific bonito abundance increases or shows northward shifts during El Niño events (Mearns 1988; Karpov et al. 1995). Pacific Bonito populations also fluctuate on a decadal scale in a similar manner as the northern anchovy, which is their main prey (Pinkas et al. 1971).

Radovich (1983) suggested that Pacific bonito moved northward into California waters during warm years, pointing out that during these years, bonito spawned successfully in California waters, increasing the local population. With data recorded by recreational fishing in southern California waters where Pacific bonito represented 5.3% of the total catches, Jarvis et al. (2004) related it with oceanic temperature and upwelling index as indicators of environmental trends, and power-generating station during the period 1980-2000. However, despite the fact that range extensions have been reported during the El Niño event (Karpov et al. 1995) and the presence of this species near heated water discharges from coastal electric generating stations (Collins et al. 1980), Pacific bonito did not show responses to environmental trends.

In a recent study, Bellquist (2015) compared mean annual trophy size with five different environmental variables and found that these variables ranked by order of importance were upwelling (53%), Pacific Decadal Oscillation (PDO, 33%), offshore sea surface temperature (SST, 11%), and the EL Niño Southern Oscillation (ENSO, 3%) indexes.

4. STOCK ASSESSMENT

Although dedicated efforts have been made to obtain indicators of abundance (Squire 1972; MacCall et al. 1976; Collins et al. 1980) through production models (equilibrium approximation) and yield per recruit models using catch data from commercial fishery and sport-fishing, the estimates have not been reliable yet and seem to overestimate the abundance and maximum sustainable yield (MSY).

The production curves indicate MSY to be about 13000 t, occurring at an abundance index of 22% (the abundance index was scaled such that 100% is equal to a value of 2.0). The production curves are skewed with peak production occurring at less than one-half maximum abundance. This production model tends to reflect the extent of actual fishing which occurred rather than the potential yield which could occur. For these reasons, yield recommendations arising from the literal interpretation of these production curves probably err on the side of over-exploitation. Accordingly, optimum yield is likely to occur at lower catch levels and higher abundances than given by these production models (Collins et al. 1980).

5. STOCK STATUS

Maintaining tuna stocks at levels that permit the MSY is the management objective specified by the Inter-American Tropical Tuna Commission (IATTC) Convention. According to the last assessment done by Collins et al. (1980), the bonito resource appeared to have been overfished beginning in 1973, when the commercial landings had declined and continued to decline until 1978. However, during the following years, the fishery behavior continued with low landings for some years interspersed with high yield years (e.g. 1990, 2007; Figure 2). Since 2007 again the catches have recorded a gradual decline, so it is necessary to look for other factors that help explain the variability that this fishery has been through along its history.

6. DATA

The data to analyze are the Pacific bonito catches (metric tons) of the purse-seiners for the period 1959 – 2018, including number and type of set and days fishing. This last one represented the total number of days for trips with any bonito catch during the trip, including days when no bonito was caught on a fishing day. Taking species distribution into account, the area to analyze corresponded to catches north 22° latitude and west to 110° longitude. Information of baitboat vessel catches for 1978 to 2011 is available. Size length sampling of 573 organisms for the main spawning area were also available, which were sampled in 2006 and for the 2014-2017 period.

7. PRELIMINARY RESULTS

7.1. Catches

Because 99.7% of Pacific bonito was caught in no associated sets, this type of set data was used in the subsequent analysis.

For the analyzed period, the interannual variation was significant ($F_{(57,1831)} = 2.89$ P <.05), recording the maximum values in 2007 with almost 14,000 t (Figure 2). The total monthly catch for the total period and the maximum values were recorded from June to September with an average for these months of 40,536 t (Figure 3).

The spatial distribution of Pacific bonito catches in areas of one degree square are shown in Figure 4. It is clear that the maximum values have been recorded from Magdalena Bay northward to Isla Cedros BC, in waters of southern California and in Point Concepcion CA, U.S.A.

The average catch per fishing day and per unassociated sets of Pacific bonito are shown in Figures 5 and 6, respectively.

7.2. Sampling length data

The 5-degree and 1-degree areas where length data were sampled are shown in Figure 7. The length-frequency distribution of Pacific bonito is shown in Figure 8. Taking into account the von Bertalanffy growth parameters determined by Campbell and Collins (1975), the age structure of length data sampled is shown in Figure 9.

8. FUTURE DIRECTIONS

Considering the high catch fluctuations that have been observed in this species, Generalized Additive Models (GAMs) will be used trying to determine the main environmental factors that affect its abundance. GAMs are semi-parametric extensions of generalized linear models with the underlying assumption of additive effects and smooth components (Guisan et al. 2002).

The response "catch or catch-per-unit-effort (CPUE)" (μi) will be modeled as follows:

$$\log(\mu_i) \sim f_1(\text{Year}_i) + f_2(\text{Month}_i) + f_3(\text{SST}_i) + f_4(\text{Chla}_i) + f_5(\text{ENSO Index}_i) + f_6(\text{UW Index}_i) + f_7(\text{PDO Index}_i) + f_8(\text{longitude}_i, \text{latitude}_i)$$

where μ_i is the expected value of the catch or CPUE.

The f_{1-7} are smooth functions for the covariates: Year, Month, SST, Chl*a*, ENSO Index, PDO Index, Upwelling Index, and longitude-latitude (interaction term). All the GAMs will be fitted using the "mgcv" package (Wood 2011) of R software (R Core Team 2018).

The spatial distribution of catch or CPUE will be estimated on a homogeneous grid of the area of study covering the spatial range of the available data. Cell size will be of one degree square. The average annual spatial distribution of catch will be estimated as the mean monthly values per cell, and those cells without data will be estimated interpolating the data using kriging (Isaacs and Shrivastava 1989; Petitgas 1996; Hengl 2009). These estimations will be done using the "gstat" package (Pebesma 1999) and "RGeostats" (Renard et al, 2016) in R (R Core Team 2018); the graphical representation will be done in QGIS an open-source Geographic information system (QGIS.org). The dependency of catches on environmental variables will be estimated using GAMs as stated in the previous paragraph.

The analysis will be performed with catch and effort data independently for purse-seine and other fishing gear.

For many species, like bonito, to our knowledge, the information required for formal stock assessment models is not available; therefore, other simple indicators of stock status should be used or investigated (Maunder 2018). Rather than using reference points based on MSY, the objective is to compare current values of these simple indicators to the distributions of the indicators observed historically (Maunder and Deriso 2007). Indicators based on the available data (e.g., catch, size, vessel and field) will be used to explore which of them can best explain the available information about the stock status, such as total catch, catch per set or catch per day fishing for purse-seine and other fishing gear (effort or catch-per-unit-effort, like an index of relative stock abundance), CPUE per grid cell, and average weight.

The Monte Carlo method (CMSY) proposed by Froese et al. (2017) will be explored for estimating fishery reference points from catch, resilience and qualitative stock status information on data-limited stocks. Through this method we will be able to estimate maximum sustainable yield (MSY), biomass, exploitation rate and related fishery reference points, as fishing mortality corresponding to MSY (F_{msy}), biomass corresponding to MSY (B_{msy}), among others and finally present a Kobe plot to show the stock status.

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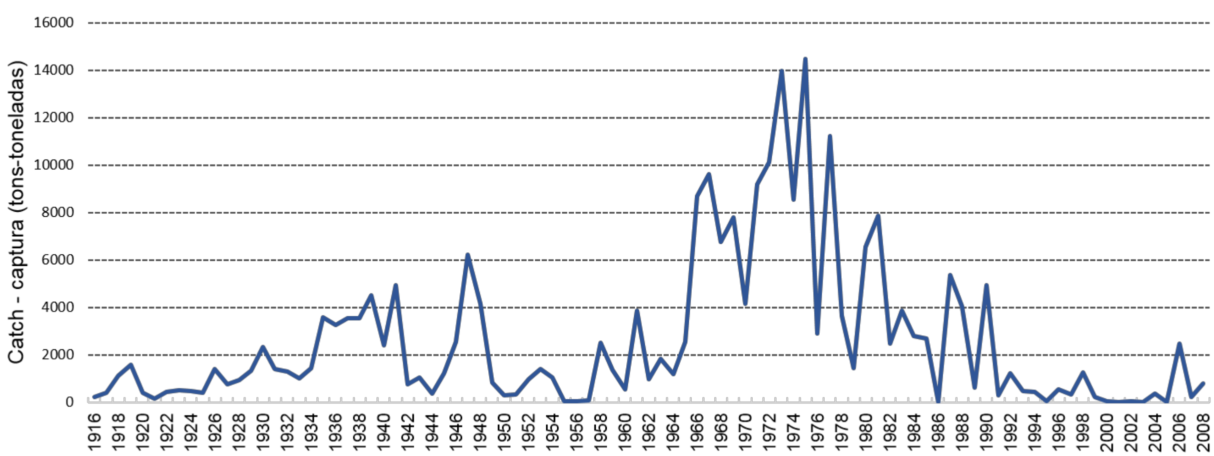

FIGURE 1. Commercial historical catches of Pacific bonito in California and Baja California waters (Source: Collins and MacCall 1977; Leet et al. 2001; Larinto 2010).
FIGURA 1. Capturas comerciales históricas del bonito (*Sarda chiliensis lineolata*) en aguas de California y Baja California.

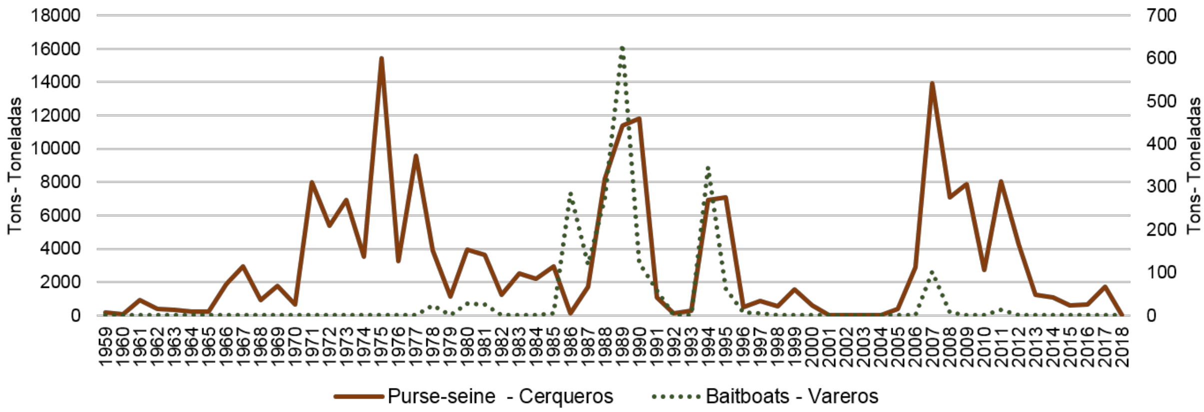

FIGURE 2. Inter-annual variation of purse-seine (1959-2018) and baitboat (1978-2011) fleets of Pacific bonito (*Sarda chiliensis lineolata*) catches recorded along California and Baja California waters.
FIGURA 2. Variación interanual de las capturas de bonito del Pacifico (*Sarda chiliensis lineolata*) registradas por las flotas de cerco (1959-2018) y vara (1978-2011) en aguas de California y Baja California.

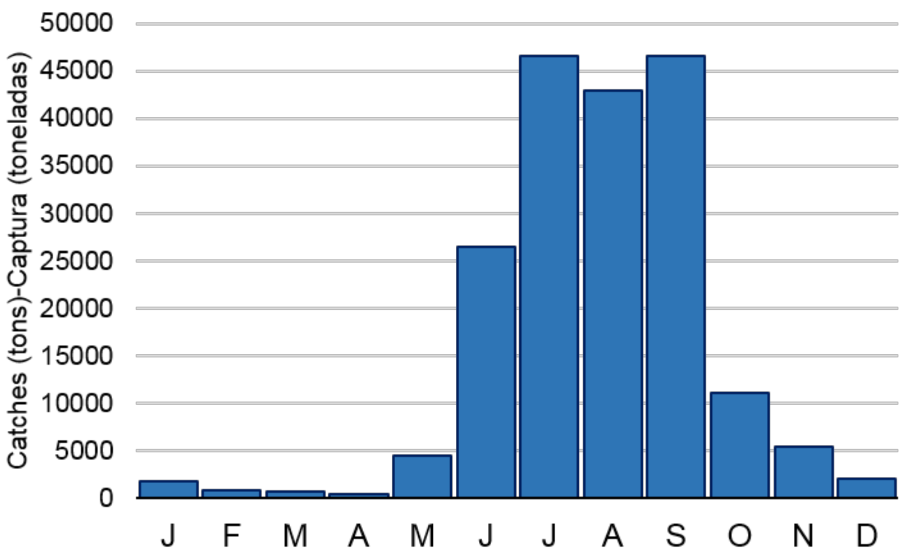

FIGURE 3. Monthly total catches of the Pacific bonito (*Sarda chiliensis lineolata*) recorded along California and Baja California waters by the purse-seine fleet during 1959-2018.
FIGURA 3. Capturas totales mensuales del bonito del Pacífico (*Sarda chiliensis lineolata*) registradas en Aguas de California y Baja California por la flota de cerco durante 1959-2018.

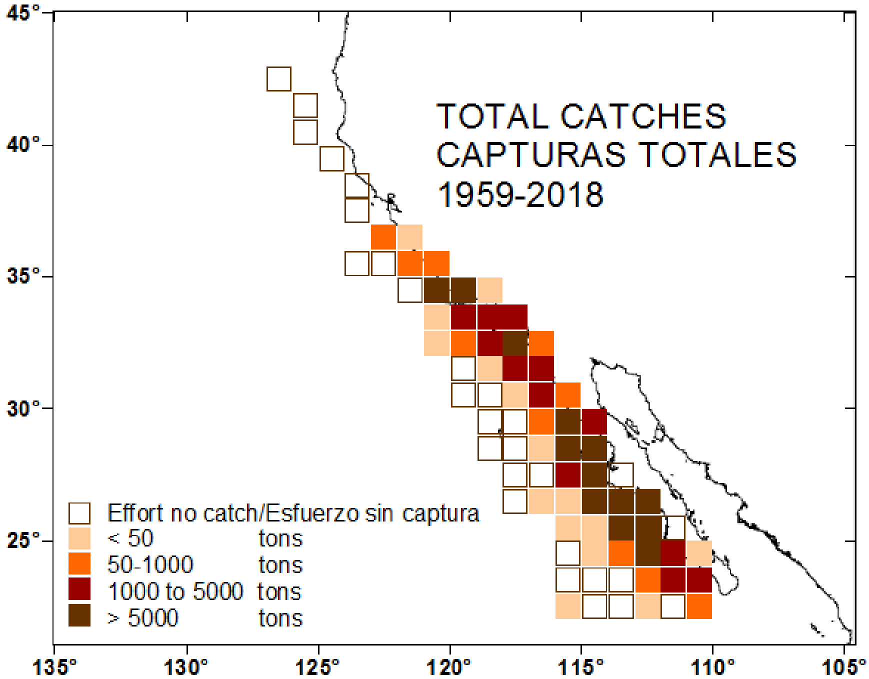

FIGURE 4. Total catches of Pacific bonito (*Sarda chiliensis lineolata*) for 1–degree areas recorded by purse-seine fleet during 1959-2018 recorded along California and Baja California waters.
FIGURA 4. Capturas totales del bonito del Pacífico (*Sarda chiliensis lineolata*) para áreas de 1 grado registradas por la flota atunera de cerco durante 1959-2018 en las aguas de California y Baja California.

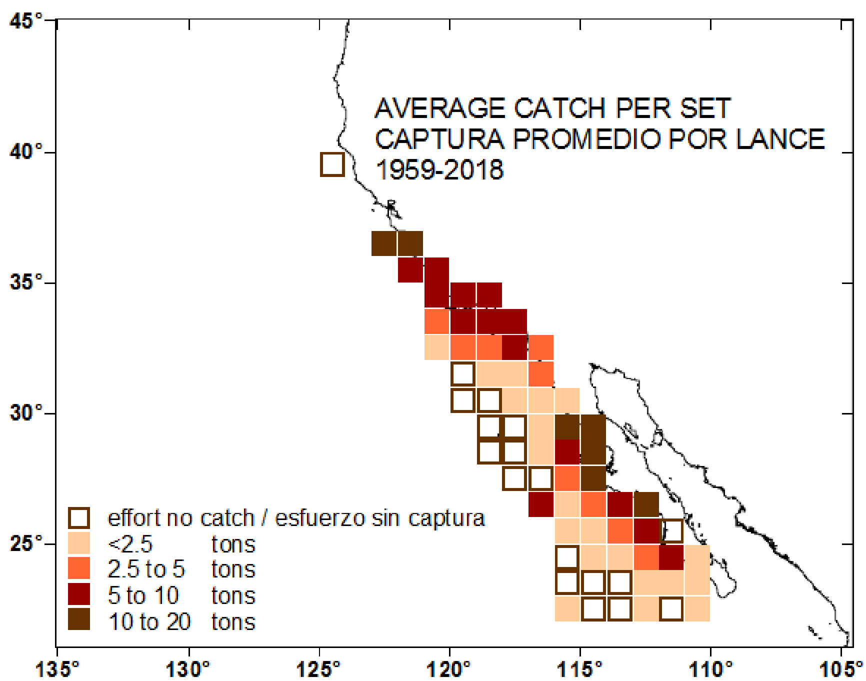

FIGURE 5. Average catch per unassociated set of Pacific bonito (*Sarda chiliensis lineolata*) for 1–degree areas during 1959-2018 recorded along California and Baja California waters.
FIGURA 5. Captura de bonito del Pacífico (*Sarda chiliensis lineolata*) promedio por lance no asociado para áreas de 1 grado durante 1959-2018 en aguas de California y Baja California.

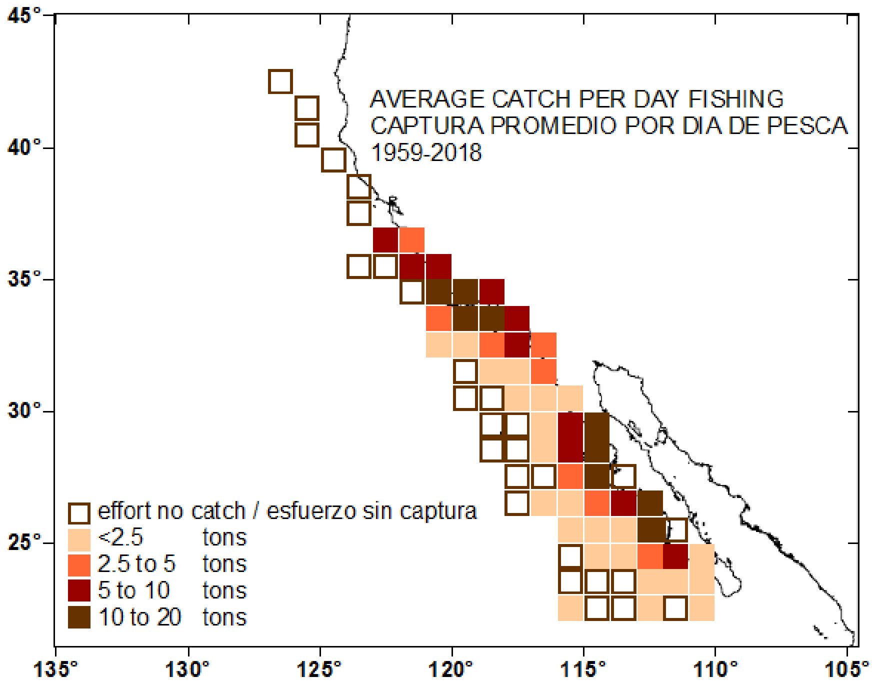

FIGURE 6. Average catch per day fishing of Pacific bonito (*Sarda chiliensis lineolata*) for 1–degree areas during 1959-2018 recorded along California and Baja California waters.
FIGURA 6. Captura de bonito del Pacífico (*Sarda chiliensis lineolata*) promedio por día de pesca para áreas de 1 grado durante 1959-2018 en aguas de California y Baja California.

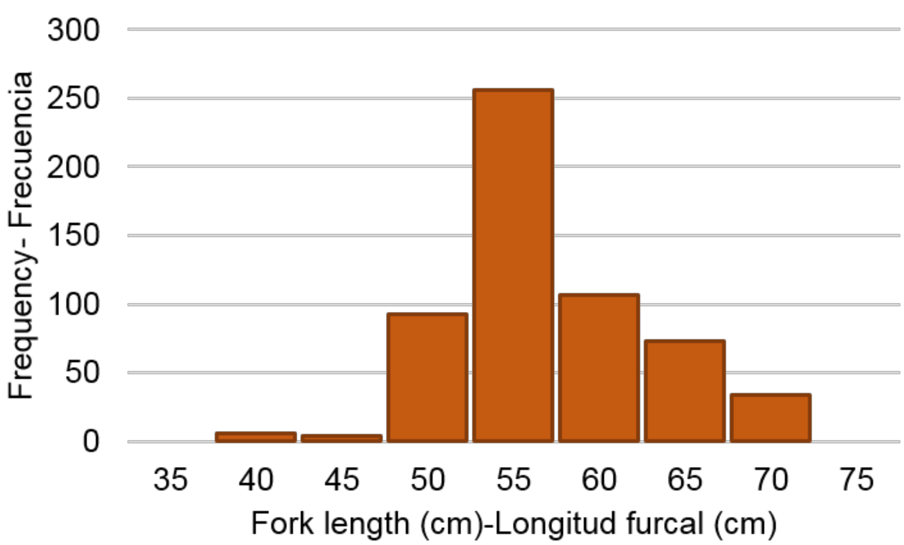

FIGURE 7. Five-degree and 1-degree areas where the length data of Pacific bonito (*Sarda chiliensis lineolata*) were sampled recorded in Baja California Sur waters.
FIGURA 7. Áreas de cinco y de un grado donde se registraron los datos de longitud del bonito del Pacífico (*Sarda chiliensis lineolata*) en aguas de Baja California Sur.

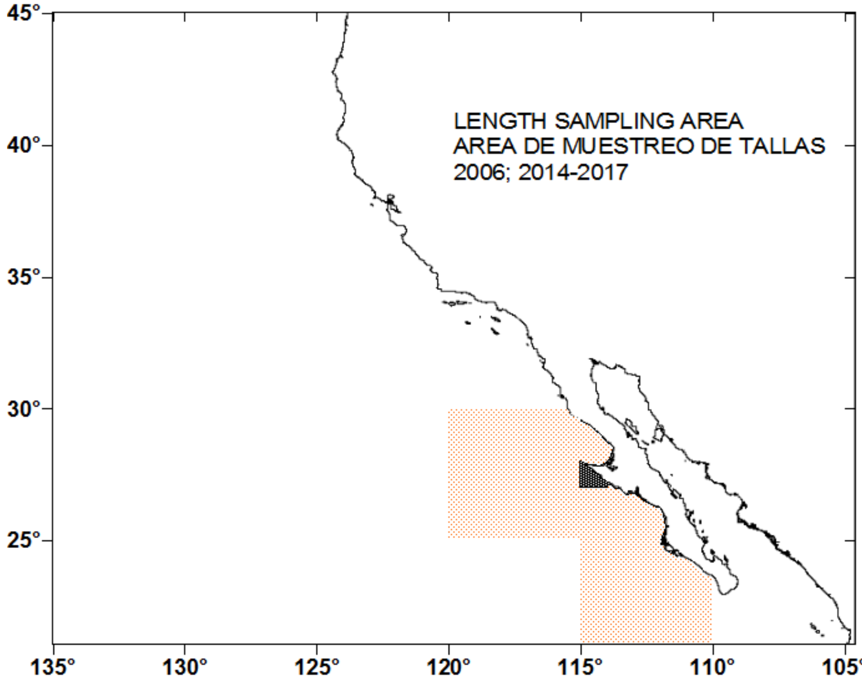

FIGURE 8. Length-frequency distribution of Pacific bonito (*Sarda chiliensis lineolata*) sampled during 2006 and 2014-2017 period recorded in Baja California Sur waters.
FIGURA 8. Distribución de frecuencias de longitud del bonito del Pacífico (*Sarda chiliensis lineolata*) muestreado durante el período 2006 y 2014-2017 en aguas de Baja California Sur.

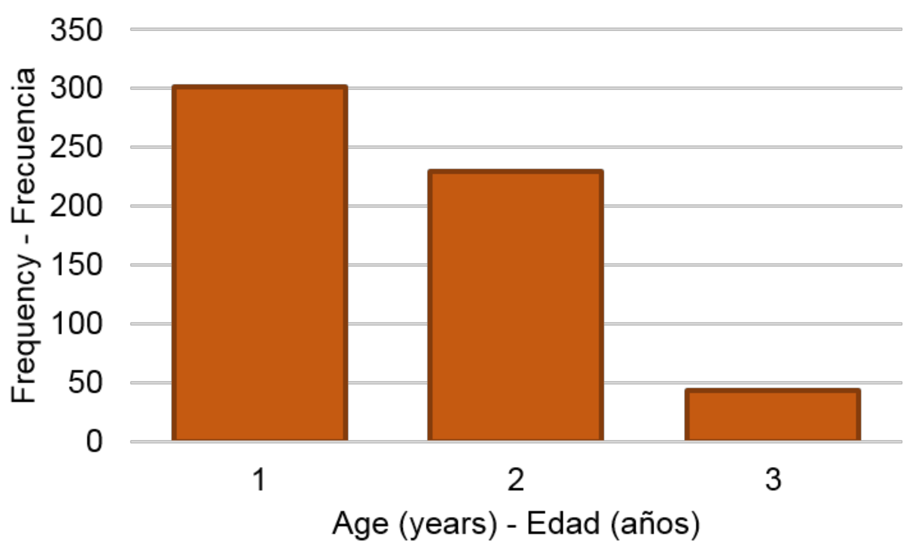

FIGURE 9. Age structure of Pacific bonito (*Sarda chiliensis lineolata*) sampled during 2006 and 2014-2017 period recorded in Baja California Sur waters.
FIGURA 9. Estructura de edad del bonito del Pacífico (*Sarda chiliensis lineolata*) muestreada durante el período 2006 y 2014-2017 en aguas de Baja California Sur.