INTER-AMERICAN TROPICAL TUNA COMMISSION

SCIENTIFIC ADVISORY COMMITTEE

15TH MEETING

La Jolla, California (USA)
10 - 14 June 2024

DOCUMENT SAC-15-04 REV

STOCK ASSESSMENT OF SKIPJACK TUNA IN THE EASTERN PACIFIC OCEAN: 2024 BENCHMARK ASSESSMENT

Rujia Bi, Mark N. Maunder, Haikun Xu, Carolina Minte-Vera, Juan Valero, and Alexandre Aires-da-Silva

Contents

EXECUTIVE SUMMARY

1. A benchmark stock assessment for skipjack tuna in the eastern Pacific Ocean (EPO) is conducted using an integrated statistical age-structured catch-at-length model in Stock Synthesis.
2. This assessment represents a significant improvement from the initial interim assessment conducted in 2022. It reflects major advancements in the assessment methodologies and incorporates new data sets, including tagging data collected through the Regional Tuna Tagging Program in the EPO.
3. Several data sources are available to fit the model, including data from sixteen defined fisheries and five "surveys". The fisheries are classified by gear type (purse-seine, longline) and purse-seine set type, which includes dolphin-associated (DEL), floating-object associated (OBJ), and unassociated (NOA) sets, as well as by geographical area of operation. The "surveys" data include: a) catch-per-set indices for purse-seine sets, by set type (OBJ, NOA), where the relationship between catch-per-set and abundance remains uncertain; b) an index based on recently developed echosounder buoy data; c) absolute biomass from a spatiotemporal Petersen-type model applied to tag-recapture data; and d) an index of relative biomass from a tagging biomass model that uses a flexible effort assumption.
4. A reference model is developed based on the most plausible assumptions and sensitivity analyses are conducted by changing the assumptions of the reference model.
5. There is substantial uncertainty about several model assumptions and sensitivity analyses are conducted to determine if the management advice is robust to the uncertainty, especially concerning model assumptions about growth and selectivity.
6. There is also uncertainty about the reliability of different data sources, and there is conflict in the information they provide about absolute abundance. Sensitivity analyses are conducted to determine if the management advice is robust to the use of the different data sources.
7. The diagnostics indicate that a data conflict exists. However, the management results are robust to the model assumptions about growth and selectivity, as well as to the inclusion or exclusion of indices of abundance and length-composition data sets.
8. MSY-based quantities are unreliable because the tradeoff between growth and natural mortality, in combination with the assumption that recruitment is independent of stock size, implies fish should be caught at the youngest ages to maximize yield, and that the optimal fishing mortality should be infinite. Therefore, a conservative *proxy* for the target biomass of spawning biomass ratio (SBR) = 0.3, as used in the interim assessment, and the fishing mortality corresponding to that biomass, are used as the target reference points.
9. The reference model estimated that the current fishing mortality is below the level corresponding to the MSY *proxy* and the spawning biomass is above the dynamic level corresponding to the MSY *proxy*. In addition, the spawning biomass does not have a 10% or more probability of exceeding the limit point. This is also true for all the sensitivity models.
10. The reference model estimated that the exploitation rates for 2022 and 2023 were below the *status quo* (average level of 2017-2019). This is also true for all but one of the sensitivity models, with the exception being the model that removes the echosounder buoy index.
11. The improvement of the stock assessment for skipjack and future management advice will continue to strongly rely on the implementation of a comprehensive tagging program.

1. INTRODUCTION

This report presents the results of a benchmark stock assessment of skipjack tuna (SKJ; *Katsuwonus pelamis*) in the eastern Pacific Ocean (EPO) using an integrated statistical age-structured catch-at-length stock assessment conducted using Stock Synthesis (Methot and Wetzel 2013; version 3.30.22.beta). This marks a significant update from the initial interim assessment conducted in 2022, reflecting substantial advancements in the assessment methodologies and incorporation of new data sets, including extensive tagging data collected under the Regional Tuna Tagging Program in the EPO (RTTP-EPO 2019-2020, Project E.4.a). All model input files and output results for this benchmark assessment are available in html format.

1.1. Background

The previous benchmark assessment was carried out in 2005 using the ASCALA methodology (Maunder and Harley 2005). This assessment was preliminary and not considered reliable for management advice because it was not known whether catch-per-day fished for purse-seine fisheries was proportional to abundance nor whether the purse-seine selectivity was dome-shaped. Subsequently, evaluations of the skipjack stock status, such as the comprehensive analysis by Maunder (2012) using various methods including fishery and biological indicators, tagging data analysis, and a Spatial Ecosystem and Population Dynamic Model (SEAPODYM), could not definitively assess the stock relative to traditional MSY-based reference points.

In the absence of a reliable conventional assessment, IATTC staff utilized a Productivity and Susceptibility Analysis (PSA) to infer the status of skipjack. Through this PSA assessment rationale, since skipjack and bigeye have about the same susceptibility to the purse-seine gear in the EPO PSA (Duffy *et al*. 2019), and skipjack is the most productive of the two species, if bigeye is healthy skipjack can be inferred to be healthy. In 2020, the staff combined the PSA rationale with the quantitative elements of the risk analysis for tropical tuna in the EPO. This combined PSA-risk analysis assessment indicated that the skipjack stock status at the start of 2020, reflecting the stock status associated with *status quo* fishing mortality conditions (2017-2019), was healthy.

Following the implementation of Resolution C-21-04, the PSA rationale previously used to assess skipjack on an *interim* basis became untenable. Since the additional measures established under C-21-04 were specifically designed to prevent the *status quo* conditions to be breached for bigeye (the species with the strictest need for management measures), these measures do not necessary prevent increased fishing mortality for the other two species, in particular skipjack. For example, the new Individual Vessel Threshold (IVT) scheme for bigeye catches could result in a change of fishing strategies by purse-seine vessels with increased fishing mortality for skipjack. Therefore, the stock status of skipjack can only be evaluated through a conventional stock assessment.

In 2022, an interim assessment was conducted using Stock Synthesis to bridge the gap between the previous assessments and the planned comprehensive benchmark assessment (SAC-13-07). This interim assessment was considered reliable for management advice, even though it was understood that further improvements were anticipated as part of a continued effort to integrate additional data, including recent tagging data. The present report details the benchmark assessment conducted following the development plan set out in 2021 (SAC-12-06), employing refined methodologies and integrating new data to provide a robust evaluation of the skipjack stock status in the EPO.

The benchmark assessment is conducted for the period 2006 to 2023, which avoids the period where the floating-object fishery expanded after the mid-1990s, covers a period where the purse-seine data collection methods were more consistent, avoids the potential influence of the 1998 El Niño on catchability and selectivity. Skipjack is a short lived, and as a result, abundance of the stock tends to be highly variable, so information from prior years is less relevant for assessing its current status.

2. DATA

2.1. Fisheries and "surveys"

The fisheries are defined by gear type, purse-seine set type [dolphin-associated (DEL), floating-object associated (OBJ), and unassociated (NOA)], and geographical area of operation. This is consistent with the 'areas-as-fleets' approach and allows spatial information to be taken into account without explicitly constructing a spatial model. All data available for the stock assessment are obtained from the fishery, including an index of abundance based on echosounder buoys that are used in the purse-seine OBJ fishery (FAD-08-02). The echosounder buoy index is fishery dependent but independent of the catch, and therefore should be less influenced by changes in the fishing strategy. The fisheries defined in this assessment are illustrated in Figure 1 and summarized in Table 1. A description of these fisheries is provided below.

"Surveys" are a construct in Stock Synthesis that allow the use of data that is not associated with catch. These do not have to be strictly surveys but can be based on fishery-dependent data and the index constructed in a way that does not need to be or should not be associated with catch. Five "surveys" were created for use in the skipjack assessment: 1) an index of abundance based on catch-per-set in the purse-seine OBJ fishery (SAC-13 INF-K); 2) an index of abundance based on catch-per-set in the purse-seine NOA fishery (SAC-13 INF-K); 3) an index of abundance based on echosounder buoys (FAD-08-02); absolute biomass from a spatiotemporal Petersen-type model applied to tag-recapture data (SAC-15 INF-G); and 5) an index of relative biomass from a tagging biomass model that uses a flexible effort assumption (SAC-15 INF-G).

2.1.1. Fisheries

Sixteen fisheries are defined for the stock assessment of skipjack tuna in the EPO, classified by gear (purse-seine, longline), purse-seine set type, and geographical area of operation (Figure 1; Table 1). One of the fisheries is used to represent fish that are discarded due to the size of the fish and has full selectivity for fish between 30 cm and 40 cm.

Fisheries in the areas-as-fleets approach are defined to group data that have similar selectivity, which is a combination of contact selectivity and spatial availability. The fisheries defined for purse-seine OBJ and NOA sets were identified using regression tree analysis of the length-composition data (Lennert-Cody *et al*. 2013; Lennert-Cody *et al*. 2010). The regression tree algorithm uses recursive partitioning to search for hierarchical binary decision rules that divide the data into more homogeneous subgroups. The binary decision rules are selected to provide the greatest decrease in the heterogeneity of length composition data, which is measured based on the Kullback–Leibler divergence. The regression tree algorithm has been recently included in an R package *FishFreqTree*, where fisheries length-frequency data, separated by gear (longline/purse-seine) and purse-seine set type (OBJ/NOA/DEL), are grouped by latitude, longitude, quarter, and cyclical-quarter. This R package is open-source and can be accessed at: https://github.com/HaikunXu/FishFreqTree.

The analysis is based solely on length frequency and is conducted for each set type to provide uncompromised set type-specific fishery definitions. The habitat preference of skipjack tuna is size-specific, so fish caught by different set types are likely to have distinct spatial patterns of age/size composition. As such, independent fishery definitions are more appropriate for this assessment model that utilizes the 'areas-as-fleets' approach.

In the regression tree analysis, the length measurements of skipjack tuna taken in the first and third months of a quarter are adjusted based on the growth curve to reflect the value they would represent if fish were measured in the middle of the quarter. Furthermore, to remove the influence of recruitment variation on observed length frequency, each length frequency observation is divided by the EPO-wide average length frequency for the corresponding quarter. These two data processing steps were not included in the previous regression tree analysis.

Based on the regression tree analysis, five spatially defined fisheries were used for OBJ sets, and four fisheries for NOA sets. It was found that in three fisheries, some sets caught only small fish while others caught only large fish, resulting in a bimodal pattern in the observed length frequency. Consequently, this fishery was separated into two distinct fisheries, corresponding to the small and large fish groups. Three fisheries, including the offshore OBJ fishery, the central OBJ fishery, and the offshore NOA fishery, were divided into smaller and larger fisheries. As a result, seven fisheries were used for OBJ sets and five fisheries were used for NOA sets. Few skipjack are caught in the DEL purse-seine fishery or the longline fishery. Therefore, the DEL fishery was split into two areas, north and south of the equator.

A single longline fishery Is defined in this benchmark assessment using observer data reported by four Members of the IATTC — China, Chinese Taipei, Japan and Korea — covering the period from 2013 to 2023, and reported effort data from all available CPCs during the period 2006-2023.

2.1.2. "Surveys"

A "survey" in Stock Synthesis is created for each of the purse-seine catch-per-set indices of abundance used in the assessment. This was done because the index represents the abundance in the whole EPO while the fisheries are separated by spatial areas to better model the size or age of the fish removed. The index cannot be associated with any particular fishery and has its own length-composition data, which is weighted by abundance (CPUE) rather than catch (SAC-13 INF-K). The echosounder buoy index is also an index of the whole population and is therefore also treated as a "survey" and its selectivity is determined by fitting to the length-composition data from the OBJ catch-per-set index. Similarly, the absolute biomass estimated from the spatiotemporal Petersen-type model applied to the tag-recapture data, and the relative biomass index from the tagging biomass model using a flexible effort assumption, are treated as "surveys." The selectivities of the tagging-based surveys are also determined by fitting to the length-composition data from the OBJ catch-per-set index. Stock Synthesis has the flexibility to mirror the survey selectivity to others where appropriate (e.g., the echosounder and one tagging "surveys" mirror the selectivity of the OBJ catch-per-set index).

2.2. Catch

Catch is estimated for each of the fisheries as described below.

2.2.1. Purse seine

The information used to estimate the total catch by species comes from four main sources. Those sources are canneries, on-board observers, vessel logbooks, and in-port sampling by IATTC staff. The observer and logbook databases also contain other information about the catches, such as the location, date, and set type. Year is the only ancillary information available for the cannery data. Additionally, the port-sampling program for collecting length composition data has also provided information on species composition since 2000.

For this assessment, total catches were estimated by catch stratum (area, month, set type, and vessel carrying capacity) and then aggregated across catch strata to obtain quarterly estimates for each fishery. Since 2000, port-sampling data have been used to determine the species composition of the total catch. The total catch of all three species combined (from cannery, observer, and logbook data)[1] is prorated to catch strata, using the information in the observer and logbook databases. The port-sampling data on the

[1] If landing information from canneries is unavailable, catch information in the observer or vessel logbook databases, in that order, is used instead.

species and size composition of the catch are then used to estimate the catch of each species by catch stratum. Detailed explanations of the estimators can be found in Tomlinson (2002, 2004), Suter (2010) and in WSBET-02-06. Details of the port-sampling protocol in use since 2000 can be found in the appendix of Suter (2010). This catch estimation methodology, which is a design-based approach, is used to obtain the fleet-level Best Scientific Estimates (BSEs) of species composition of the catches for each purse-seine fishery fleet. The methodology has been integrated into a R package *BSE* that can be accessed at: https://github.com/HaikunXu/BSE.

Bias-adjustment was made for the estimated OBJ catches derived from the BSE algorithm for the two years affected by the COVID-19 pandemic (2020 and 2021). The pandemic disrupted the collection of species and size composition data by IATTC port-samplers, leading to a systematic loss of port-sampling data from ports where much of the EPO bigeye tuna catch is unloaded (SAC-13 INF-L). Given that the BSE algorithm relies heavily on the port-sampling data to predict the species composition of purse-seine catches, it is likely that the purse-seine catches estimated for the two COVID-19 years by the BSE algorithm are biased. Recent research suggests that the BSE algorithm overestimates skipjack catches in the OBJ fishery by 0.6% for 2020 and underestimates them by 6% for 2021 (SAC-13-05). Consequently, adjustments were made to reduce each BSE-estimated quarterly OBJ catch for 2020 by 0.6% and to increase each BSE-estimated quarterly OBJ catch for 2021 by 6%.

2.2.2. Longline

The IATTC staff does not collect data on longline catches directly; they are reported annually to the IATTC by CPCs, pursuant to Resolution C-03-05 on data provision. Catches are reported by species, but the availability and format of the data vary among fleets: the principal fleets report catch and effort aggregated by 5° cell-month. IATTC databases include data on the spatial and temporal distributions of longline catches of skipjack in the EPO by the fleets of distant-water CPCs (China, Chinese Taipei, French Polynesia, Japan, Korea, and Vanuatu) and EPO coastal CPCs (principally Mexico and the United States).

Longline catches are reported in numbers by some fleets and in weight by others, and only a small proportion of skipjack catch was reported (only from observed vessels). The annual estimates of the longline catch are calculated by multiplying the number of hooks reported by the nominal CPUE, which is derived using observer data from four Members of the IATTC — China, Chinese Taipei, Japan, and Korea. If nominal quarterly CPUE data are not available, the quarterly-average CPUE in the same year is used instead. For years prior to the observed period (2006-2012), the quarterly CPUE is assumed to be equal to the quarterly-average CPUE in 2013.

In the last interim assessment, the annual estimates of longline catch were simply taken as reported in the Fishery Status Report (FSR) and distributed evenly among the quarters. The new approach in this benchmark assessment is considered an improvement because no longline skipjack catches were reported by fishers; therefore, the value in the FSR may be negatively biased.

2.2.3. Other catch

The pole-and-line catch of skipjack only makes up a few percent of the total catch over the assessment period and there has been little or none in recent years. Therefore, the catch is taken from the FSR, divided evenly among quarters, and added to the northern coastal OBJ fishery (F7). Recreational catch is unknown and not included in the model.

2.2.4. Discards

Two types of discards are considered, those resulting from inefficiencies in the fishing process and those related to the sorting of catches. Examples of inefficiency are catch from a set exceeding the remaining storage capacity of the fishing vessel or discarding unwanted bycatch species, while catch sorting is assumed to occur when fishers discard tuna that are under a certain size. The former is added to the fisheries and the latter are combined into a separate fishery with an assumed selectivity curve (full selectivity between 30 and 40 cm). Discards by the longline fisheries cannot be estimated with the minimal data available due to the low observer coverage, so it is assumed that the retained catch represents the total catch.

2.2.5. Catch and discard trends

Skipjack tuna is the main target species of the OBJ and NOA purse-seine fisheries. The catches of the DEL purse-seine fishery and the longline fishery represent only a small proportion of the total catches of skipjack tuna in the EPO.

The purse-seine OBJ fishery has been important since the 1970s in areas north of the equator and close to the coast of South America, between 10°S and the equator. However, the OBJ fishery had a widespread expansion in the EPO after 1992. The number of OBJ sets has been steadily increasing since 2005, up until the onset of the COVID-19 pandemic (SAC-13-06). Over the period covered by the model, there is a large seasonal variation in the purse-seine catch (Figure 2). The catch in the offshore OBJ fishery (F1 and F2) increased starting in 2015. The discards due to sorting in the OBJ fisheries show a reduction beginning around 2003, and ceased almost completely beginning in 2006 (Figure 2) following resolutions adopted by the IATTC which prohibited discarding of juvenile tunas (*e.g.*, C-04-05).

2.3. Indices of abundance

Indices of abundance are a crucial input to stock assessment models as they directly inform the changes in population abundance over time (Francis 2011). Ideally, indices of abundance should be calculated using fishery-independent survey data, collected using the same fishing gear and operation across time to assure constant catchability and selectivity, and have a random or fixed sampling design in space. However, for most tuna species worldwide, including skipjack tuna in the EPO, survey data are not available. Therefore, indices of abundance are derived solely from fishery-dependent CPUE data. These data need to be standardized so that the abundance index is approximately proportional to population abundance (Maunder and Punt 2004). To achieve this, the standardization model needs to remove the part of the variation in the CPUE data that is not driven by changes in population abundance. Furthermore, the standardization model should impute fish abundance for unfished locations and use an area-weighting approach to compute the abundance index for the population for the entire spatial domain of the fishery (Thorson *et al*. 2015).

Five indices of abundance are considered for inclusion in the skipjack assessment. These include 1) an index of abundance based on catch-per-set in the OBJ purse-seine fishery (SAC-13 INF-K), 2) an index of abundance based on catch-per-set in the NOA purse-seine fishery (SAC-13 INF-K), 3) an index of abundance based on echosounder buoys(FAD-08-02), 4) absolute biomass from a spatiotemporal Petersen-type model applied to tag-recapture data (SAC-15 INF-G); and 5) an index of relative biomass from a tagging biomass model using flexible effort assumption (SAC-15 INF-G).

The catch in number per hook for the Japanese longline fishery was treated as a "survey" in the interim assessment. A standardized CPUE was derived from a spatiotemporal model fitted to observer data from four Members of the IATTC (*i.e.*, China, Chinese Taipei, Japan, and Korea) this year. However, the uncertainty around the derived CPUE is high (average CV = 0.62), so it is not included in the reference model of this benchmark assessment. This information on the uncertainty in the index was not available in the previous assessment which used nominal CPUE and assumed a CV. It should be noted that the CPUE used in the previous assessment was biased because all effort was used in the calculation when only observed trips report skipjack catch. Since an absolute estimate of abundance is available from the tagging analysis, the longline index is no longer needed to provide information about abundance.

2.3.1. Catch-per-set in the purse-seine fishery

The data used to construct the index are the set-by-set catch data from purse-seine vessels. On-board observers of the Agreement on the International Dolphin Conservation Program (AIDCP) observer program have been collecting these data for large purse-seine vessels (fish-carrying capacity >363 t) since 1992 (Joseph 1994, Scott *et al*. 2016). Logbook data are used for trips for which no observer data are available.

It is not possible to separate searching effort by set type and fishing using floating objects does not have a reliable measure of search time, so catch-per-set is used to compute the index of abundance. The index should represent the whole population (*e.g.,* cover the spatial extent of the population). It is preferable to calculate the index based on summing up spatially explicit catch rates (see Maunder *et al*. 2020a). However, there is temporal variation in the spatial distribution of the effort, which sometimes results in areas with no data. Therefore, spatial modelling of the catch-per-set data is used to "fill in missing data" and the region over which the index is computed is restricted to that portion of the EPO that is fished frequently (see SAC-13 INF-K). The catch-per-set data were standardized using the R library *VAST* (version 3.11.0) (Thorson and Barnett 2017, Xu *et al.* 2019).

2.3.1.1. Standardization procedure

Our current approach to CPUE standardization for skipjack tuna in the EPO involves the utilization of a spatiotemporal delta-generalized linear mixed model (GLMM). This type of model has gained prominence in recent years for standardizing fishery-dependent CPUE data, including for highly migratory species (Ducharme-Barth *et al*. 2022, Xu *et al*. 2019). Spatiotemporal GLMMs can account for time-area interaction by including a spatiotemporal term to both encounter probability and positive catch rate. The spatiotemporal GLMMs explicitly consider spatial and temporal autocorrelation in spatial and spatiotemporal terms. An additional advantage of the spatiotemporal GLMM is its capacity to impute fish abundance in unfished areas based on spatial and temporal autocorrelation. Moreover, it can compute an area-weighted index of relative abundance over the entire spatial domain of the population of interest.

VAST (Thorson and Barnett 2017) is chosen as the platform to standardize the fishery-dependent CPUE. VAST is an open-source R package (https://github.com/James-Thorson-NOAA/VAST) and has recently gained increasing popularity in standardizing fishery-dependent CPUE data for tunas (Ducharme-Barth *et al*. 2022, Maunder *et al*. 2020b, Satoh *et al*. 2021, Xu *et al*. 2019). As a delta-generalized linear mixed model, VAST separately models encounter probability and positive catch rate to account for zero-inflated catch rate observations. We specify VAST to utilize the logit link function for the linear predictor of encounter probability, which is modeled as following a Bernoulli distribution, and the log link function for the positive catch rate, which is modeled as following a Gamma distribution. In VAST, all four quarters are treated equally.

Both the linear predictors of encounter probability and positive catch rate include an intercept (year-quarter) term, a time-invariant spatial term, a time-varying spatiotemporal term, and a vessel effect term. The intercept terms are estimated as fixed effects; the spatial terms, the spatiotemporal terms, and the vessel effect terms are estimated as random effects. Given that values at nearby locations are usually more similar than those at remote sites, the spatial and spatiotemporal random effects are both assumed to be autocorrelated in space. Specifically, VAST applies the Matérn function to describe the rate at which the correlation between random effects declines over space.

VAST computes the standardized CPUE by using an area-weighting approach. It first predicts fish density for each spatial knot and time and then sums the product of fish density and area of the knot over spatial to derive the index. Choosing the number of spatial knots needs to consider the trade-off between model accuracy and model efficiency. A total of 50 spatial knots is used in this spatiotemporal model to balance the two components. A bias-correction algorithm (Thorson and Kristensen 2016) is applied to remove the re-transformation biases in VAST-derived quantities.

Given that the spatial domain of the CPUE standardization model extends beyond the core fishing ground to encompass locations with relatively sparse CPUE data, the abundance index for this exploratory assessment is subject to greater influence by imputed fish densities for unfished locations. As such, it is crucial to address potential biases associated with the imputation process, particularly in this case where fishery-dependent CPUE data is likely preferentially sampled.

In this CPUE standardization model, spatiotemporal terms are assumed to be correlated in both space and time. Specifically, the spatiotemporal terms are assumed to be spatially correlated according to the Matérn function and to follow a random-walk process in time. Under this assumption, the spatiotemporal terms for the unfished eastern EPO are interpolated based on data collected not only from the fished western EPO in the same year-quarter but also from the eastern EPO in adjacent fished years.

The index of abundance for the OBJ fishery shows a steady decline over time until about 2015, with variability from quarter to quarter, and then it levels off (Figure 3). In contrast, the NOA index of abundance shows a steady increase until about 2020 and then levels off (Figure 3).

2.3.2. Echosounder buoy index

An index of abundance based on echosounder buoys (ECHO) for skipjack tuna in the EPO was derived for the period 2012-2023. This index was developed based on the signal from satellite-linked GPS tracking echosounder buoys used in the purse-seine OBJ fishery (FAD-08-02). The echosounder buoys provide a single biomass value without discriminating species or size composition of the fish. Therefore, the echosounder buoy data was combined with fishery data on catch species composition and average size to obtain the skipjack index. The ECHO index cycles through high and low levels (Figure 3).

2.3.3. Tagging-based absolute biomass

Absolute biomass were derived for the period 2000-2023 from a spatiotemporal Petersen-type model applied to tag-recapture data (SAC-15 INF-G). However, most of these estimates are highly uncertain, and only five are associated with low CVs (0.3-0.6) and low correlation coefficients (<0.13). For this benchmark assessment, only the estimate with lowest CV (quarter 2 of 2020, CV = 0.3) was used as an absolute biomass estimate (Figure 3).

2.3.4. Tagging-based relative biomass

An index of relative biomass was derived for the period 2000-2022 from a tagging biomass model using flexible effort assumption (SAC-15 INF-G). This method used effort data to estimate fish biomass and movement patterns through a "flexible effort" approach. It allowed for variable relationships between effort and fishing mortality, adjusting with multiple breakpoints and slopes. This model provided relative biomass estimates by combining these relationships with the Baranov catch equation and accounting for observation noise. The index is relatively stable but fluctuates over time (Figure 3).

2.4. Size-composition data

2.4.1. Fisheries

2.4.1.1. Purse-seine

The length frequency data for the purse-seine fisheries are collected through the sampling program conducted by IATTC personnel at ports of landing in Ecuador, Mexico, Panama, and Venezuela. The ancillary information available in the port-sampling database is determined by the governing protocol (Suter 2010, Tomlinson 2002), which specifies the strata from which samples are collected: fish-carrying capacity of the vessel, set type, month, and area of catch (area definition can be found in WSBET-02-06). Wells are the primary sampling unit within a stratum, with unequal numbers of wells sampled per stratum, and fish within a well are the secondary sampling unit. Sampling at both stages is largely opportunistic, except that a well is sampled only if all the catch within it came from the same stratum. This restriction can result in sets with large catches predominating in the samples (Lennert-Cody and Tomlinson 2010). More than one well may be sampled per vessel if the catch in the other wells comes from different strata, but typically only one or two wells per trip are sampled. For large and small purse-seine vessels, about 50%-60% and 10-20% of trips, respectively, have typically been sampled per year, for a total of over 800 wells sampled in most years (IATTC 2010; Vogel 2014). The sampling coverage in terms of the percentage of the catch is lower (SAC-02-10). The sampling areas were designed for yellowfin tuna before the development of the OBJ fishery. Since 2000, both the 5° cell and the sampling area have been recorded for most samples (Lennert-Cody *et al*. 2012); the 5° cell has been recovered for many samples before 2000. Ideally, fifty fish of each species in the sampled well were measured, and samplers have alternated between counting fish by species and measuring fish for length since 2000. The protocol varies to some extent with the set type associated with the catch in the well and with the species composition of the catch in the well, as recorded by the observer or in the vessel's logbook. More details on the port sampling program can be found in WSBET-02-06 and the Appendix of Suter (2010).

As with the species composition, the size composition of the catch, in numbers of fish by 1-cm length interval, is estimated by stratum and then aggregated across strata to obtain quarterly estimates for each fishery. The estimated number of fish is then converted to the proportion of fish at length for the assessment. The estimated numbers at length are obtained by multiplying the well-level estimates of the proportion at length, combined across sampled wells, by the estimated total catch in numbers for the species in the stratum. Since 2000, the estimates of proportions at length make use of both the species counts and the length-measurement data. Details of the estimators can be found in WSBET-02-06. The staff developed a design-based algorithm (Best Scientific Estimates or BSE) to calculate length compositions for each purse-seine fishery fleet. This algorithm has been integrated into a R package *BSE* that can be accessed at: https://github.com/HaikunXu/BSE.The input sample size of purse-seine length composition data is specified to be the number of wells sampled to indirectly account for over-dispersion in length composition data.

The purse-seine fisheries start to catch skipjack around 25-30 cm and the mode of the length-frequency distribution is at about 40 cm for those fisheries that catch the smallest skipjack, which is all OBJ fisheries and most NOA fisheries, surprisingly, the composition data for the offshore NOA fishery (F9) does not have a mode at this size (Figure 4). The F9 catches the largest skipjack of the purse-seine fisheries, followed by the southern DEL fishery (F14) and the central NOA fishery (F11). Several of the purse-seine fisheries were divided into smaller and larger fisheries (*e.g.,* F1 and F2, F3 and F4, F8 and F9).

2.4.1.2. Longline

In the last interim assessment, the computation of length composition data for longline fishery fleets relied solely on Japanese longline data, simply summing the length compositions for each year-quarter. However, concerns have been raised about the representativeness of the Japanese longline length composition data due to its small spatial coverage (Figure 5). As the composition data for fishery fleets should be weighted spatially by catch amount, it is reasonable to expand the source of composition data for longline fishery fleets to other CPCs.

In this benchmark assessment, we also include longline length composition data collected by observers from China, Chinese Taipei, and Korea to provide joint length frequencies for longline fishery fleets. The longline length composition data for skipjack from the four Members of the IATTC covers the period from 2013 to 2023. However, only one fish was observed in the second quarter of 2013, leading to high uncertainty, so we use data starting from the third quarter of 2013. Length measurements were recorded at the operational level.

The methodology for computing length composition data for longline fishery fleets has been improved. Previously, for other tropical tuna species (*i.e.*, bigeye and yellowfin), length composition data for longline fishery fleets were computed by spatially raising raw length compositions to catch amount. This methodology has a significant limitation, as a large proportion of longline catches do not contribute to the computation of length frequencies for fishery fleets. This is due to the sparse distribution of longline length composition data in space. As a result, length frequencies computed by raising raw length compositions spatially to catch may not adequately represent fishery removal.

To overcome this issue, we develop length-specific spatiotemporal models to impute length frequency for the catches without corresponding length compositions. This new approach allows the computation of length frequencies for longline fishery fleets based on all, rather than a small percentage, of longline catches. The joint longline length frequencies are based on data collected by the four Members of the IATTC, and the length-specific spatiotemporal model is fitted to the four-member length composition data simultaneously.

VAST is also chosen as the platform to standardize longline length frequency. We specify VAST to use the logit and log link functions for the linear predictors of encounter probability and positive catch rate, respectively, for each length bin. Both linear predictors include an intercept (year-quarter) term, a time-invariant spatial term, and a time-varying spatiotemporal term. All three terms are assumed to be independent and identically distributed among length bins. Of the three terms, the intercept term is estimated as fixed effects and the other two terms are estimated as random effects. The spatial and spatiotemporal random effects are both assumed to be autocorrelated in space according to the Matérn function. Neither the catchability covariate term nor vessel effects term is included in this model because they are not available in this dataset. This VAST model also treats the four quarters equally.

Due to the high dimensions of the length-specific spatiotemporal model, several simplifications are made to make the model computationally more feasible: 1) only 100 spatial knots are used to estimate the spatial and spatiotemporal random effects in the EPO; 2) length bins are regrouped from the original resolution to 5 cm; 3) length frequencies for < 40 cm are negligible and are assumed 0 (length bins in the model: 40-45 cm, 45-50 cm, …, 100+ cm); and 4) all hyperparameters are assumed to be shared among length bins. It should be noted that the predicted length frequencies (lf) for each knot and time do not necessarily sum to 1 across length bins, as the spatiotemporal field of length frequency is predicted for each 5 cm length bin without a multinomial constraint. To solve this problem, we scale the predicted length frequencies to have a sum of 1 for each knot and time**.**

The length compositions of a fishery fleet are catch raised within the spatial domain of the fishery. Specifically, the length frequency for a fishery fleet ($LF(F)$) in time t and length l is computed as:

$$LF(F)_{t,l} = \frac{\sum_s (c_{s,t} \times lf_{s,t,l})}{\sum_l \sum_s (c_{s,t} \times lf_{s,t,l})}$$

where c_s is the fleet-specific total catch in grid s and time t, and $lf_{s,t,l}$ is the length frequency in grid s, time t, and length l predicted by the length-specific spatiotemporal model. The fleet-specific total catch, reported in the number of fish, is calculated by multiplying the number of hooks reported by the nominal CPUE derived from the observer data (details please see section 2.2.2), and has a spatial resolution of 5° x 5°. To match with this spatial resolution, we aggregate the predicted length frequencies from the length-specific spatiotemporal model from the operational level to 5° x 5°. For consistency, since the longline length composition data are model-based, model-based input sample size is also used for the longline length composition data. Specifically, the input sample size is calculated by the length-specific spatiotemporal model to approximate the estimated imprecision for predicted length frequency (Thorson and Haltuch 2018).

The longline length composition increases rapidly from about 65 cm, peaks at 75 cm and drops off rapidly after that with few fish over 90 cm (Figure 4b).

2.4.2. Surveys

The indices of abundance are designed to represent the whole population selected by the fishing gear used to create the index. Simply summing up the data will cause the length composition to be weighted by the sampling, which is usually related to the spatial distribution of the catch. The fishery may not be operating proportionally to the abundance. Therefore, where practical, the length-composition data is spatially weighted by the index of abundance.

The length frequencies of skipjack associated with the purse-seine catch-per-set indices of abundance ("survey") were obtained by summing raw length-frequency observations across 5° areas, weighted by the catch-per-set predicted by the spatiotemporal model used to create the index for the same fishing gear (SAC-13 INF-K). The length-frequency classes were defined by 1 cm intervals, from 20 cm to 100 cm.

The length compositions for the two purse-seine indices of abundance show a typical length-composition distribution, but with a long right-hand tail (Figure 4a). The length-frequencies of skipjack associated with the OBJ purse-seine fishery catch-per-set based index were also used for the echosounder buoy index, the tagging-based absolute biomass, and the tagging-based relative biomass index (*i.e*., they shared selectivity).

3. Assumptions and parameters

An integrated statistical age-structured catch-at-length stock assessment was developed for skipjack tuna in the EPO using Stock Synthesis (Methot and Wetzel 2013; version 3.30.22.beta), a framework capable of fitting diverse types of data and accommodating models of varying complexity. Other auxiliary quantities and graphs were computed using the R library *r4ss* (version 1.49.2) and original code available from the IATTC repository IATTCassessment.

The model period covers 2006 to 2023. The time step of the model is a quarter, 21 age classes are defined, from 0 quarters to 20+ quarters (5 years). The population size structure is defined in 1-cm intervals from 2 cm to 110 cm. The model aggregates females and males. The size compositions are defined using 1-cm intervals, from 20 cm (aggregating all smaller lengths) to 100+ cm, for the purse-seine fisheries and "surveys", and 5-cm intervals, from 40 cm (not aggregating all smaller sizes) to 100+ cm, for the longline fishery. The models are fitted to catches, relative abundance indices, and size-composition data. The observed total catches are assumed to be unbiased and very precise. The uncertainties for relative abundance indices are taken from their corresponding analyses.

3.1. Biological and demographic information

3.1.1. Growth

The growth settings in this benchmark assessment are those used in the last interim assessment (SAC-13-07). The mean length-at-age for skipjack in the EPO was estimated by fitting the growth cessation model to tagging data (SAC-13 INF-J; Figure 6). Since reliable aging is not available and tagging data are not available for old fish, the age of fish at a given length had to be assumed and the asymptotic growth was estimated from the length-composition data.

Since recruitment is assumed to be independent of stock size for skipjack (*i.e.,* steepness of the Beverton-Holt stock-recruitment relationship is set at h = 1), the age of individuals is not needed to model the lag between spawning and entry into the fishery, and if the population processes (*e.g.,* natural mortality and selectivity) are defined in terms of length, absolute age is irrelevant. It is assumed that the assessment results based on a growth curve that assumes that size 37 cm skipjack (the smallest size seen in the tagging data) are 2 quarters old will be robust to that assumption.

The asymptotic length was determined using the length-frequency data for the Japanese longline fishery. The longline fishery captures the largest skipjack tuna and is therefore assumed to have asymptotic selectivity. We assume that the 75% quantile of the longline length composition is equal to the asymptotic length. This is supported by the fact that the distribution to the right of the 75% quantile implies a small standard deviation (see below). Sensitivity analysis to the assumption about asymptotic length is conducted.

The CVs were based on the linear relationship between the coefficient of variation and length (use of the growth cessation model in Stock Synthesis requires setting the CV for age zero and this was extrapolated using the linear relationship). Initial analyses of the previous stock assessment found that the CV for young individuals was too small and caused modes in the predicted length-composition distributions that were not in the observations. In addition, the CV for old individuals was also too small and the model could not fit the right-hand side of the longline length-composition distribution. Estimation of the CVs within the stock assessment encountered numerical errors. Therefore, the CVs were increased to levels that provided reasonable fits and were fixed at those levels (CV at age zero = 0.09 and CV at age 20 quarters = 0.06). Sensitivity analysis is conducted for the CV at age 20 quarters.

The weight at age w_a is obtained from the average length at age L_a in the length-weight equation for skipjack tuna in the EPO (Hennemuth 1959):

$$w_a = 5.53 \times 10^{-6} L_a^{3.336}$$

3.1.2. Natural mortality (*M*)

The settings on *M* in this benchmark assessment are those from the last interim assessment (SAC-13-07). Specifically, the assessment assumes the natural mortality by length class for skipjack tuna estimated by Hampton (2000) with linear interpolation between the mid points of the length classes (Figure 7). Natural mortality is constant after a length of 65 cm.

The natural mortality is high for young individuals. The assumed level of *M* for age 0 has little impact on the assessment results because there are few data for these size fish and only arbitrarily scales the recruitment at age 0.

3.1.3. Reproductive biology and recruitment

The settings on reproductive biology and recruitment in this benchmark assessment are those from the last interim assessment (SAC-13-07). Information on the reproduction of skipjack in the EPO is given by Anonymous (1998: 26), Schaefer (2001), and Schaefer and Fuller (2019). Spawning is fairly widespread from about 19°N to 12°S and from 79°W to 136°W, and continuous throughout the year between about 15°N and 10°S (Schaefer and Fuller 2019). Spawning occurs from 24°C to 30°C, with the majority taking place between 26°C and 29°C (Schaefer and Fuller 2019). It is assumed that skipjack tuna can be recruited to the fishable population during every quarter of the year. No strong assumptions are made about the relationship between adult biomass and recruitment in the historical stock assessments of skipjack (*i.e.,* steepness of the stock-recruitment relationship h = 1). The maturity and batch fecundity relationships with length are taken from Schaefer and Fuller (2019). The maturity schedule was taken from the central area and represented by a Richards function and the batch fecundity from the whole EPO and represented by a power function.

$$m_l = [1 - (1 - 3.977)e^{-0.355(l-55.122)}]^{1/(1-3.977)}$$

$$f_l = 1.0756 l^{2.9838}$$

The age-specific reproductive output, which is the product of maturity and fecundity, is shown in Figure 8.

3.1.4. Movement and stock structure

Skipjack occur throughout the tropical and subtropical waters of the Pacific Ocean, and it is known that there is considerable exchange of fish among areas. The stock structure of skipjack has been studied by various methods, including analyses of catch statistics, life history, tagging, biochemical genetic data, and data on the chemical composition of the otoliths of the fish. Argue (1981) and Anonymous (1984: 88-91) examined the information and there are two principal hypotheses for skipjack in the Pacific Ocean. The separate-subpopulation hypothesis stated that there are two or more genetically distinct subpopulations of skipjack in the Pacific Ocean, and the clinal hypothesis stated that separate subpopulations of skipjack do not exist in the Pacific Ocean, but that there is isolation by distance, *i.e*., the probability of any two fish interbreeding is an inverse function of their distance from one another. It was concluded by Argue (1981) that the available data did not favor either hypothesis. Subsequent studies, described by Anonymous (1995: 69-71) have not furnished information that would serve better as the basis for management decisions.

Schaefer (2009) examined all the available information and concluded that the results from tagging experiments, along with investigations of geographic variation in length at maturity of skipjack in the EPO, demonstrate restricted movements, with fidelity to northern and southern regions of the EPO. He suggested two regions of the EPO, separated at about 15°N, probably represent spatially segregated northern and southern sub-stocks with limited mixing between them.

Analysis of length-composition data to define fisheries found a consistent first split at -120°W for both the OBJ and NOA set types (SAC-13 INF-I). Spatiotemporal analysis of OBJ catch-per-set found lower catch-per-set between -110°W and -130°W (SAC-13 INF-K). This suggests separate stocks east and west of -120°W.

For the purposes of stock assessment and management of skipjack across the Pacific Ocean by Western and Central Pacific Fisheries Commission (WCPFC) and the IATTC, it is typically assumed that skipjack in the EPO do not interact with skipjack in the western and central Pacific Ocean. Although for the purpose of some historical analyses, it has been assumed that there are six non-interacting sub-populations in the EPO. However, since skipjack in the EPO has been managed as a single stock, in this benchmark assessment it is assumed that the EPO is comprised of a single stock to fulfill management requirements, consistent with the last interim assessment.

3.2. Stock assessment model assumptions

3.2.1. Initial conditions

The model is assumed to start from a non-virgin (fished) equilibrium state, with R_{init}, the initial recruitment as an offset of the virgin recruitment (currently modelled in SS as a regime shift in average recruitment), and F_{init}, the initial fishing mortality, being estimated, with no penalty associated with initial equilibrium catches. F_{init} was assumed to correspond to fishery F7, the purse-seine fishery on floating objects in the northern coastal area. This fishery was chosen because it catches a large amount of skipjack. Additionally, 10 recruitment (quarter) deviations before the start of the model initial quarter are estimated.

3.2.2. Selectivity and data weighting

In this benchmark assessment, the decision regarding how to specify selectivity (including the form of the curve, whether to estimate the curve, and whether to add time blocks to the curve) and how to weight composition data is guided by a decision tree developed by the staff (Figure 9). Simulation studies in Privitera-Johnson *et al*. 2022 found that the double-normal selectivity is most robust to uncertainty in selectivity form, so in this benchmark assessment, all fishery and survey fleets have double-normal selectivities, except for the longline, which is assumed to have asymptotic selectivity and is modeled using a cubic spline. The asymptotic longline selectivity assumes selectivity above the asymptotic length is constant (this does not necessarily have to be asymptotic; it can be at a constant level below the peak occurring at a smaller size and this is a consequence of using the cubic spline selectivity rather than a logistic) and selectivity at 20 cm is zero.

For each fleet, there are three options regarding the combination of selectivity and data weighting. Fleets with high catch amounts, can fit a double-normal selectivity curve to their composition data closely, and having rich composition data should use time-varying selectivity along with the Francis weight (TA1.8 in Francis 2011). Fleets with low catch amounts, unable to fit a double-normal selectivity curve to fit to its composition data closely, or having poor composition data, should not estimate selectivity (*e.g.*, fix or mirror selectivity) and should not fit to its composition data. Fleets not falling into either category above use constant selectivity and 20% of the Francis weight.

The decision regarding selectivity and data weighting for each fleet included in the assessment model is outlined in Table 2. Size compositions for fishery fleets are spatially weighted by catch within the respective area of operation. Here, fishery selectivity is defined as the combination of gear selectivity and availability, so any variation in fish availability or fleet distribution over time can result in time-varying fishery selectivity. In contrast, size compositions for the survey fleet are spatially weighted by fish abundance across the EPO, allowing survey selectivity to be treated as gear selectivity and approximately constant over time. In this assessment model, the trend of population abundance is primarily dictated by the index of relative abundance, whereas the scale of population abundance is heavily influenced by composition data. Mis-specifying selectivity can thus lead to a biased estimation of the population scale. The key philosophy behind the design of the decision tree is that the estimation of the population scale should rely mainly on the composition data of the survey fleet rather than that of fishery fleets, as the degree of misspecification tends to be higher for time-varying fishery selectivity than time-invariant survey selectivity.

In theory, all data-rich fishery fleets should use time-varying selectivity to minimize the extent of selectivity mis-specification and consequently improve estimation accuracy (Martell and Stewart 2014, Xu *et al*. 2018). This, however, will lead to estimating a substantial amount of additional selectivity parameters in this assessment model, which includes sixteen fishery fleets. Considering the trade-off between estimation accuracy and model efficiency/stability, time-varying selectivity with consecutive decadal time blocks is only applied to fishery fleets with high catch amounts, rich composition data, and can fit a double-normal selectivity curve to its composition data closely (Table 2). Of those fleets, the F1, F6, F7, and F11 have two selectivity time blocks (2006-2015; 2016-2023). All other fishery fleets for which selectivity is estimated use time-invariant selectivity, with their composition data down-weighted by 80% to greatly reduce their influence on the scale of estimated population abundance (Table 2). F14 has low catch amounts and poor composition data, so its selectivity mirrors the other DEL fishery (F13) with similar observed length frequencies and its composition data is excluded from the assessment model.

4. MODELS

A reference model is defined that represents the most plausible assumptions and then sensitivity analyses are defined as modifications to the reference model. Similar to the model terminology recently used in the staff's 2020 risk analysis for the tropical tuna fishery, the term "reference model" is used rather than "base case" as used in previous IATTC assessments. Since a risk analysis is still not available for skipjack, the reference model is considered by the staff to represent the most plausible set of assumptions (*states of nature*) and the other models are termed "sensitivity" models. Below, the reference model is first defined followed by the sensitivity models.

4.1. Reference model

The reference model assumes that the reason that large fish are seen in the longline fishery, but not in the purse-seine fishery, is because the large fish are not available to the purse-seine fishery (*i.e.,* the purse-seine fisheries have dome-shaped selectivity). The reference model has the following assumptions and uses the following data.

a) Longline fishery selectivity is modeled using a cubic spline with selectivity constant after 80 cm.

b) Natural mortality is constant after a length of 65 cm.

c) The asymptotic length is 83 cm.

d) The age at 37 cm is 2 quarters.

e) The CV of the length-at-age is a linear function of length (0.09 for age zero fish and 0.06 for age 20 quarters).

f) Recruitment is independent of stock size (*i.e.,* the steepness of the stock-recruitment relationship is h = 1) and is estimated for each quarter.

g) Quarterly recruitment is assumed to vary around the average level and is specified by a lognormal distribution with a standard deviation of 0.6. The bias correction ramp and full bias correction were estimated using a single iteration of the approach of Methot and Taylor (2011) as implemented in r4ss.

h) The echosounder buoy-based index of relative abundance and tagging-based absolute biomass are proportional to the population abundance selected by the purse-seine OBJ "survey", and the other indices (catch-per-set on OBJ and NOA fisheries, and tagging-based index of relative biomass) are not used.

i) Only the most precise tagging-based absolute biomass (quarter 2 of 2020, CV = 0.3) is used in the assessment.

j) Length compositions constructed for the purse-seine index for the NOA fishery are not used in the analysis (those constructed for the purse-seine OBJ index are used for the echosounder buoy index and tagging-based absolute biomass).

4.2. Sensitivity models

There is substantial uncertainty in the skipjack assessment. This uncertainty includes the shape of the fishery selectivity curves, the relationship between the indices of abundance and the population abundance, the rate of natural mortality, particularly for old fish, the growth for old fish, and the stock structure. There is also uncertainty in the aging of skipjack, but it is expected that if dealt with appropriately, the model will not be sensitive to the assumptions related to aging. Therefore, many diverse sensitivity analyses are conducted to test the robustness of the results to these assumptions, particularly the robustness of the estimated stock status.

Several sensitivity analyses are conducted to determine the robustness of the results to model assumptions and the inclusion of different data sets. We investigate different settings on five aspects, including growth, selectivity, tagging index, indices and steepness. The following description outlines how the sensitivity models differ from the reference model.

Growth:

a1) Estimating asymptotic length.

a2) Lower asymptotic length. The asymptotic length is set at 78 cm.

a3) Higher asymptotic length. The asymptotic length is set at 88 cm.

a4) Estimating CV of the variation of length-at-age for the oldest individuals.

a5) Lower CV of the variation of length-at-age for the oldest individuals. The CV is fixed at 0.03.

a6) Higher CV of the variation of length-at-age for the oldest individuals. The CV is fixed at 0.09.

a7) Estimating growth shape parameter (Cessation_Fem_GP_1).

Selectivity:

b1) Longline fishery selectivity is constant after 78 cm.

b2) Longline fishery selectivity is constant after 83 cm.

b3) Longline fishery selectivity is constant after 88 cm.

b4) The selectivity of fleet F9 is asymptotic, defined through a double-normal function. The selectivity of the longline fishery is fixed as in the reference model, and its size composition is not used in the analysis (*i.e.*, λ = 0).

Tagging-based absolute biomass:

c1) The most precise tagging-based absolute biomass (quarter 2 of 2020, CV = 0.3) is used in the analysis and is upweighted by ten times (*i.e.*, λ = 10).

c2) Four tagging-based absolute biomass indices with low CVs (0.3-0.6) and low correlation coefficients (<0.13) during 2006-2023 are used in the analysis and are fully weighted (*i.e.*, λ = 1).

Indices:

d1) Excluding the tagging-based absolute index from the assessment model.

d2) Excluding the echosounder buoy index from the assessment model.

d3) Inclusion of the longline survey index, obtained from a VAST model fitted with observer data from the four Members of the IATTC (CV = 0.2; the estimated CV is much higher than 0.2, so this index is not included in the reference model). Inclusion of the longline survey size composition, derived from a VAST model fitted with observer data from the four Members of the IATTC, weighted by CPUE.

Steepness:

e1) Steepness = 0.75.

5. RESULTS

In this report, the latest version (3.30.22.beta) of Stock Synthesis was used to assess the status of skipjack in the EPO. Similar to the previous interim assessment, a sensitivity analysis framework is used to determine the robustness of the results with respect to model assumptions and the inclusion of different data sets. The model is run on a quarterly basis.

5.1. Model diagnostics of the Reference Model

5.1.1. Model convergence

The reference model converged with a low maximum gradient component of 9.60e-05 and a positive definite hessian. No parameters were on the bounds.

5.1.2. Fit to indices of abundance

Both the echosounder buoy index and the tagging-based absolute biomass were included in the model. The average input CV for the echosounder buoy index is 0.23, and the input CV for the tagging-based absolute biomass is 0.3. The RMSE for both were much higher (ECHO = 0.33 and tagging-based absolute = 0.44) indicating worse fits than assumed in the likelihood (*i.e.*, the RMSE > input CVs). However, they visually provided temporal patterns consistent with the data and associated confidence intervals (Figure

10). Interestingly, even though the reference model does not fit to the purse-seine catch-per-set indices and the tagging-based relative index, the model estimates similar trends (Figure 11) and the RMSEs are lower for the OBJ index (0.24) and the tagging-based relative index (0.30). The RMSE for the NOA, which was not fit in the model, was 0.42 indicating the model is inconsistent with this index.

5.1.3. Fits to length-frequency data

The reference model fits the average length composition well for all fisheries, as well as for the ECHO index, and the tagging-based absolute and relative biomass (Figure 4). The latter refers to the length-composition data for the OBJ catch-per-set index. The model also fits the average length-composition data for the NOA catch-per-set index even though these data are not fitted in the model (the selectivity was taken from a model that did fit to the data).

5.1.4. Integrated model diagnostics

5.1.4.1. Jitter analysis

A Jitter analysis is conducted for the reference model to evaluate whether the negative log-likelihood of the reference model has reached global minimum. Due to time constraints, only twenty jitter runs were compared with a jittering value of 0.05 for the reference model. This is the first diagnostic analysis conducted, making sure that the reference model to be evaluated by the other diagnostics is converged at the global maximum likelihood estimation. The reference model passes the jitter diagnostics, in terms of the NLL and R_0 estimates (Figure 12).

5.1.4.2. Retrospective analysis

Retrospective analysis serves as a valuable tool for assessing the consistency of a stock assessment model from one year to the next (Mohn 1999). Inconsistencies detected through the retrospective analysis can often indicate inadequacies in the model. Typically, this analysis is carried out by progressively eliminating the last year's data from the analysis while maintaining the same methodology and assumptions. It allows for an examination of how the inclusion of additional data impacts the resulting estimates of population attributes and management quantities. Retrospective bias does not necessarily indicate the magnitude and direction of the bias in the current assessment, only that the model may be mis-specified.

In this benchmark assessment, a retrospective analysis is conducted by iteratively removing the data from the last year five times, and Mohn's rho for spawning biomass is calculated to quantify the extent of the retrospective pattern. The reference model has a negative Mohn's rho (-0.43), indicating the spawning biomass is being underestimated in the reduced time series when compared with the estimate from the full time series. The estimated spawning biomass and spawning biomass ratio shows little influence of eliminating years of data and no systematic pattern (Figure 13).

5.1.4.3. Age-structured production model

The age-structured production model (ASPM) method proposed by Maunder and Piner (2014) is a diagnostic tool to evaluate whether an assessment model is correctly specified. The ASPM is built by fixing all selectivity parameters at the values estimated by the reference model and removing all composition likelihood components from the total model likelihood. The results, particularly spawning biomass, from the ASPM with 0 recruitment deviates (ASPM_Rdev) are then compared with those from the reference assessment model. If the ASPM is not able to mimic indices of abundance, it could be because the stock is recruitment-driven, the reference model is not correctly specified, or indices of abundance are not proportional to population abundance (Carvalho *et al*. 2017, Maunder and Piner 2014).

The age-structured production model without recruitment deviates (ASPM) shows a more stable population indicating that the index of abundance does not contain information about absolute abundance without accounting for recruitment variation (Figure 14). This is expected in a short-lived highly variable species like skipjack. However, when recruitment deviates are estimated, the model estimates a much smaller population suggesting that the composition data is controlling abundance.

5.1.4.4. R_0 likelihood profile

Virgin recruitment (R_0), defined as the equilibrium recruitment in the absence of fishing, is a key parameter in the stock-recruitment relationship that scales the absolute abundance. By running the reference model several times with R_0 fixed at a range of values around the maximum likelihood estimate, the profile of model likelihood (*i.e.*, the total negative log-likelihood and its components) against R_0 is referred to as the R_0 likelihood profile (Wang *et al*. 2009). The R_0 likelihood profile is a diagnostic tool widely used to compare the influence of composition data and indices of relative abundance on absolute abundance.

The R_0 likelihood profile indicates that there is substantial conflict in the data with the ECHO index preferring higher biomass (larger R_0) and the tagging-based absolute index preferring lower biomass (Figure 15a). There is also conflict in the composition data and even within the same purse-seine set type (Figure 15b and c). The size compositions for the northern coastal OBJ fishery (F7), the central NOA fishery (F11), and catch-per-set in the OBJ purse-seine fishery (S1) support higher biomass.

5.2. Results of the reference model

5.2.1. Recruitment

Estimated recruitment is presented in Figure 16. There are some short-term patterns in recruitment, but no long-term trends.

5.2.2. Spawning biomass

The estimates of spawning biomass and spawning biomass ratio (*i.e.*, the ratio of the spawning biomass of the current stock to that of the unfished stock) are presented in Figure 17. The spawning biomass reached a low level around 2015 but has been relatively stable since.

5.2.3. Fishing mortality

Fishing mortality is difficult to represent in stock assessment models that include multiple dome shape selectivities. As the effort among the fisheries changes over time, the relative fishing mortality among ages changes over time. Therefore, we use the simple metric of catch over biomass of fish aged 2 quarters old and higher. This metric of exploitation rate within a quarter shows slow oscillations over time, and indicates an increase starting at the end of 2011 and peaking in 2016, then remaining relatively stable since (Figure 18). There is no indication of increased fishing mortality over time since then. Although, fishing mortality appeared to be lower in the period 2006-2010 and 2018-2023.

5.2.4. Fisheries impacts

The fisheries have had a moderate impact on the spawning biomass (Figures 17 and 19). The impact in the first year is misleading (Figure 19) because the parameterization of the initial age-structure is through a fishing mortality that does not include fitting to an equilibrium catch and therefore should not be interpreted as a fishery impact. However, since skipjack is short lived, this impact should be eliminated after a few years. The fishery impact plots form the basis for calculating the dynamic depletion levels.

The fishery impact plot on which the simulations are based shows that the purse-seine OBJ fishery had the greatest impact on the stock during the whole period, followed by the purse-seine NOA fishery (Figure 20). The purse-seine DEL fishery, longline fishery and discards of small skipjack in the purse-seine fishery have undetectable impacts on the depletion of the stock (Figure 20).

5.3. Results of the sensitivity analysis

The estimates of depletion level are robust to several of the sensitivity analyses. These include growth parameters, including the asymptotic length, the CV of the variation of length-at-age for the oldest individuals, and the growth shape parameter (Figure 21); selectivity settings (Figure 22); and the inclusion of more tagging-based absolute indices (Figure 23).

The estimates of depletion level are moderately sensitive to several of the sensitivity analyses. These include upweighting the tagging-based absolute index (Figure 23), eliminating the tagging-based absolute index (Figure 24), eliminating the ECHO index (Figure 24), adding the longline survey index and its size-composition data (Figure 24), and reducing the steepness from 1 to 0.75 (Figure 25).

Upweighting the tagging-based absolute index causes the stock to be more depleted during the whole period (Figure 23). Removing the tagging-based absolute index causes the stock to be less depleted (Figure 24). Removing the ECHO index causes the stock to be more depleted at the end of the period (Figure 24). These are consistent with the R_0 likelihood profile, which indicates that the tagging-based absolute index preferring lower biomass, while the ECHO index preferring larger biomass (Figure 15a). The ECHO index begins in the third quarter of 2012 and only impacts subsequent periods. Adding the longline survey index and its size-composition data caused the stock to be more depleted at the beginning of the period, and less depleted at the end of the period (Figure 24). Reducing the steepness = 0.75 causes the stock to be more depleted during the whole period (Figure 25). When the steepness is reduced from 1 to 0.75, the model will increase R_0 to get the same estimated recruitment increasing the virgin biomass and increasing the depletion level. Although the depletion level varies across these sensitivity analyses, the stock status remains healthy based on the dynamic spawning biomass ratio (Table 3).

6. STOCK STATUS

For this benchmark assessment, the staff continues to use the reference points proposed in the previous interim assessment. Following Resolution C-23-06 (amending Resolution C-16-02), an interim proxy target reference point was used. Specifically, the staff's proposed spawning biomass ratio at 0.3 (SBR; spawning biomass divided by the spawning biomass in the unfished state) and the fishing mortality corresponding to that biomass were taken (SAC-14-09). The limit reference point is defined as an SBR of 0.077. The lognormal bias correction on recruitment and dynamic SBR methods used in the previous interim assessment are maintained to improve the accuracy of recruitment estimates and better account for variability in recruitment.

6.1. Estimates of stock status

The reference model estimates that the spawning biomass is currently above the target proxy of 30% of the unexploited spawning biomass under either the static (SBR) or the dynamic (dSBR) spawning biomass ratio (Table 3). Only one of the sensitivity analyses, which removed the ECHO index, estimates that the stock is below the proxy target and only when based on the static definition (Table 3; Figure 26). None of these scenarios estimate that the stock is below the limit reference point (Table 3).

The IATTC harvest control rule takes uncertainty into consideration, particularly for the limit reference point. The estimates of uncertainty for the reference model do not exceed the limit reference point (Figure 17). The pessimistic model that excludes the echosounder buoy index comes close but does not exceeding the limit reference point by 10% for the start of 2024 (Figure 27).

The historical trajectories show that the stock size fluctuates and can go below the target reference point. It should be noted that the initial values for dSBR are misleading because the model is not fit to an initial equilibrium catch and the initial fishing mortality is just used as a way to construct the initial age-structure and therefore does not represent the real initial fishing mortality.

The current fishing mortality is lower than that corresponding to the biomass target for the reference model (Figure 18). It is also the case in all sensitivity analyses (Table 3).

Stock status relative to the *status quo* defined by the average fishing mortality over 2017-2019 was evaluated using an approximation to the exploitation rate, which was the total catch divided by the biomass of fish ages 2 quarters and older (Table 3). The reference model estimated that the exploitation rates in 2022 and 2023 were less than *status quo* (Table 3). Only the pessimistic model that excludes the echosounder buoy index estimated exploitation rates that exceeded the *status quo* in 2022 and 2023 slightly (Table 3).

7. FUTURE DIRECTIONS

7.1. Collection of new and updated information

The staff will continue the biological and tagging studies to improve the understanding of the biology of skipjack in the EPO, especially the growth, natural mortality, biomass, and length-weight relationship. In particular, a comprehensive tagging program is essential to improve the skipjack assessment and to provide management advice in the future.

7.2. Refinements to the assessment model and methods

The staff will continue developing the assessment model for skipjack tuna in the EPO. The following changes would be desirable for future assessments:

- Improve the estimates of biomass and natural mortality through further development of the tagging analysis;
- Improve estimates of growth using the tagging data and other available information;
- Explore sex-specific natural mortality, growth and selectivity;
- Continue to improve the echosounder buoy index;
- Develop a risk analysis.

ACKNOWLEDGEMENTS

Many IATTC and Member country staff provided data for the assessment. IATTC staff members, and Member country scientists provided advice on the stock assessment, fisheries, and biology of skipjack tuna. Paulina Llano provided editorial assistance and Christine Patnode aided on the figures.

REFERENCES

Anonymous. 1984. Annual Report of the Inter-American Tropical Tuna Commission 1983: 272 pp.

Anonymous. 1995. Annual Report of the Inter-American Tropical Tuna Commission 1994: 296 pp.

Anonymous. 1998. Annual Report of the Inter-American Tropical Tuna Commission 1996: 306 pp.

Argue, A.W. (editor). 1981. Report of the Second Skipjack Survey and Assessment Programme workshop to review results from genetic analysis of skipjack blood samples. South Pacif. Comm., Skipjack Survey and Assessment Programme, Tech. Rep. 6: v, 39 pp.

Carvalho, F., Punt, A.E., Chang, Y.-J., Maunder, M.N., and Piner, K.R. 2017. Can diagnostic tests help identify model misspecification in integrated stock assessments? Fisheries Research **192**: 28-40.

Ducharme-Barth, N.D., Grüss, A., Vincent, M.T., Kiyofuji, H., Aoki, Y., Pilling, G., Hampton, J., and Thorson, J.T. 2022. Impacts of fisheries-dependent spatial sampling patterns on catch-per-unit-effort standardization: A simulation study and fishery application. Fisheries Research **246**: 106169.

Duffy LM, Lennert-Cody CE, Olson R, Minte-Vera CV, and Griffiths SP. 2019. Assessing vulnerability of bycatch species in the tuna purse-seine fisheries of the eastern Pacific Ocean. Fisheries Research **219**: 105316.

Francis, R.I.C.C. 2011. Data weighting in statistical fisheries stock assessment models. Canadian Journal of Fisheries and Aquatic Sciences **68**(6): 1124-1138.

Hampton, J. 2000. Natural mortality rates in tropical tunas: size really does matter. Canadian Journal of Fisheries and Aquatic Sciences **57**(5): 1002-1010.

Hennemuth, R.C. 1959. Additional information on the length-weight relationship of skipjack tuna from the eastern tropical Pacific Ocean. Inter-Amer. Trop. Tuna Comm., Bull. **4**: 23-37.

IATTC. 2010. The IATTC program for in-port sampling of tuna catches. IATTC Document SAC-01-11. http://www.iattc.org/Meetings/Meetings2010/Aug/_English/SAC-01-11-Port-sampling-program.pdf

Joseph, J. 1994. The tuna-dolphin controversy in the eastern Pacific Ocean: Biological, economic, and political impacts. Ocean Development and International Law **25**:1-30.

Lennert-Cody, C.E., Maunder, M.N., Aires-da-Silva, A., and Minami, M. 2013. Defining population spatial units: Simultaneous analysis of frequency distributions and time series. Fisheries Research **139**: 85-92.

Lennert-Cody, C.E., Maunder, M.N., Tomlinson, P.K., Aires-da-Silva, A., and Pérez, A. 2012. Progress report on the development of postratified estimators of total catch for the purse-seine fishery port-sampling data. IATTC Document SAC-03-10. http://www.iattc.org/Meetings/Meetings2012/May/_English/SAC-03-10-Post-stratified-estimators.pdF

Lennert-Cody, C.E., Minami, M., Tomlinson, P.K., and Maunder, M.N. 2010. Exploratory analysis of spatial–temporal patterns in length–frequency data: An example of distributional regression trees. Fisheries Research **102**(3): 323-326.

Lennert-Cody, C., and Tomlinson, P. 2010. Evaluation of aspects of the current IATTC port sampling design and estimation procedures for catches of tunas by purse-seine and pole-and-line vessels. Inter-Amer. Trop. Tuna Comm., Stock Assessment Report **10**: 279-309.

Martell, S., and Stewart, I. 2014. Towards defining good practices for modeling time-varying selectivity. Fisheries Research **158**: 84-95.

Maunder, M.N., and Harley, S.J. 2005. Status of skipjack tuna in the eastern Pacific Ocean in 2003 and outlook for 2004. Inter-Amer. Trop. Tuna Comm., Stock Assess. Rep. **5**: 109-167.

Maunder, M.N., and Piner, K.R. 2014. Contemporary fisheries stock assessment: many issues still remain. ICES Journal of Marine Science **72**(1): 7-18.

Maunder, M.N., and Punt, A.E. 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries research **70**(2-3): 141-159.

Maunder, M.N., Thorson, J.T., Xu, H., Oliveros-Ramos, R., Hoyle, S.D., Tremblay-Boyer, L., Lee, H.H., Kai, M., Chang, S.-K., and Kitakado, T. 2020a. The need for spatio-temporal modeling to determine catch-per-unit effort based indices of abundance and associated composition data for inclusion in stock assessment models. Fisheries Research **229**: 105594.

Maunder, M.N., Xu, H., Lennert-Cody, C., Valero, J.L., Aires-da-Silva, A., and Minte-Vera, C.V. 2020b. Implementing reference point-based fishery harvest control rules within a probabilistic framework that considers multiple hypotheses. Inter-Amer.Trop. Tuna Comm., 11th Scient. Adv. Com. Meeting: SAC-11 INF-F.

Methot, R.D., and Wetzel, C.R. 2013. Stock synthesis: a biological and statistical framework for fish stock assessment and fishery management. Fisheries Research **142**: 86-99.

Mohn, R. 1999. The retrospective problem in sequential population analysis: An investigation using cod fishery and simulated data. ICES Journal of Marine Science: Journal du Conseil **56**(4): 473-488.

Privitera-Johnson, K.M., Methot, R.D., and Punt, A.E. 2022. Towards best practice for specifying selectivity in age-structured integrated stock assessments. Fisheries Research **249**: 106247.

Satoh, K., Xu, H., Minte-Vera, C.V., Maunder, M.N., and Kitakado, T. 2021. Size-specific spatiotemporal dynamics of bigeye tuna (Thunnus obesus) caught by the longline fishery in the eastern Pacific Ocean. Fisheries Research **243**: 106065.

Schaefer, K.M. 2001. An assessment of skipjack tuna (*Katsuwonus pelamis*) spawning in the eastern Pacific Ocean. Fishery Bulletin **99**(2): 343-350.

Schaefer, K.M. 2009. Stock structure of bigeye, yellowfin, and skipjack tunas in the eastern Pacific Ocean. Inter-Amer. Trop. Tuna Comm., Stock Assess. Rep. **9**: 203-221.

Schaefer, K.M., and Fuller, D.W. 2019. Spatiotemporal variability in the reproductive dynamics of Skipjack Tuna (*Katsuwonus pelamis*) in the eastern Pacific Ocean. Fisheries Research **209**: 1–13.

Scott, M.D., Lennert-Cody, C.E., Gerrodette, T., Skaug, H.J., Minte-Vera, C.V., Hofmeister, J., Barlow, J., Chivers, S.J., Danil, K., Duffy, L.M., Olson, R.J., Hohn, A.A., Fiedler, P.C., Ballance, L.T., and Forney, K.A. 2016. Data available for assessing dolphin population status in the eastern tropical Pacific Ocean. Inter-Amer.Trop. Tuna Comm., Workshop on Methods for Monitoring the Status of Eastern Tropical Pacific Ocean Dolphin Populations: DEK-01 (Available at www.iattc.org/Meetings/Meetings2016/DEL-01/PDFs/_English/DEL-01_Data-Available-for-AssessingDolphin-Population-Status-in-the-Eastern-Tropical-Pacific-Ocean.pdf).

Suter, J.M. 2010. An evaluation of the area stratification used for sampling tunas in the eastern Pacific Ocean and implications for estimating total annual catches. IATTC Special Report 18.

Thorson, J.T., and Barnett, L.A.K. 2017. Comparing estimates of abundance trends and distribution shifts using single- and multispecies models of fishes and biogenic habitat. ICES Journal of Marine Science **74**(5): 1311-1321.

Thorson, J.T., and Haltuch, M.A. 2018. Spatiotemporal analysis of compositional data: increased precision and improved workflow using model-based inputs to stock assessment. Canadian Journal of Fisheries and Aquatic Sciences **76**(3): 401-414.

Thorson, J.T., and Kristensen, K. 2016. Implementing a generic method for bias correction in statistical models using random effects, with spatial and population dynamics examples. Fisheries research **175**: 66-74.

Thorson, J.T., Shelton, A.O., Ward, E.J., and Skaug, H.J. 2015. Geostatistical delta-generalized linear mixed models improve precision for estimated abundance indices for West Coast groundfishes. ICES Journal of Marine Science **72**(5): 1297-1310.

Tomlinson, P.K. 2002. Progress on sampling the Eastern Pacific Ocean tuna catch for species composition and length-frequency distributions. In: Inter-American Tropical Tuna Commission Stock Assessment Report **2**: 339-356.

Tomlinson, P.K. 2004. Sampling the tuna catch of the Eastern Pacific Ocean for species composition and length-frequency distributions. In: Inter-American Tropical Tuna Commission Stock Assessment Report **4**: 311-324.

Vogel. 2014 http://www.iattc.org/Meetings/Meetings2014/May/_English/SAC-05-06-Fishery-in-the-EPO-2013-PRES.pdf

Wang, S.-P., Maunder, M.N., Aires-da-Silva, A., and Bayliff, W.H. 2009. Evaluating fishery impacts: application to bigeye tuna (*Thunnus obesus*) in the eastern Pacific Ocean. Fisheries Research **99**(2): 106-111.

Xu, H., Lennert-Cody, C.E., Maunder, M.N., and Minte-Vera, C.V. 2019. Spatiotemporal dynamics of the dolphin-associated purse-seine fishery for yellowfin tuna (Thunnus albacares) in the eastern Pacific Ocean. Fisheries research **213**: 121-131.

Xu, H., Thorson, J.T., Methot, R.D., and Taylor, I.G. 2018. A new semi-parametric method for autocorrelated age-and time-varying selectivity in age-structured assessment models. Canadian Journal of Fisheries and Aquatic Sciences **76**(2): 268-285.

FIGURES

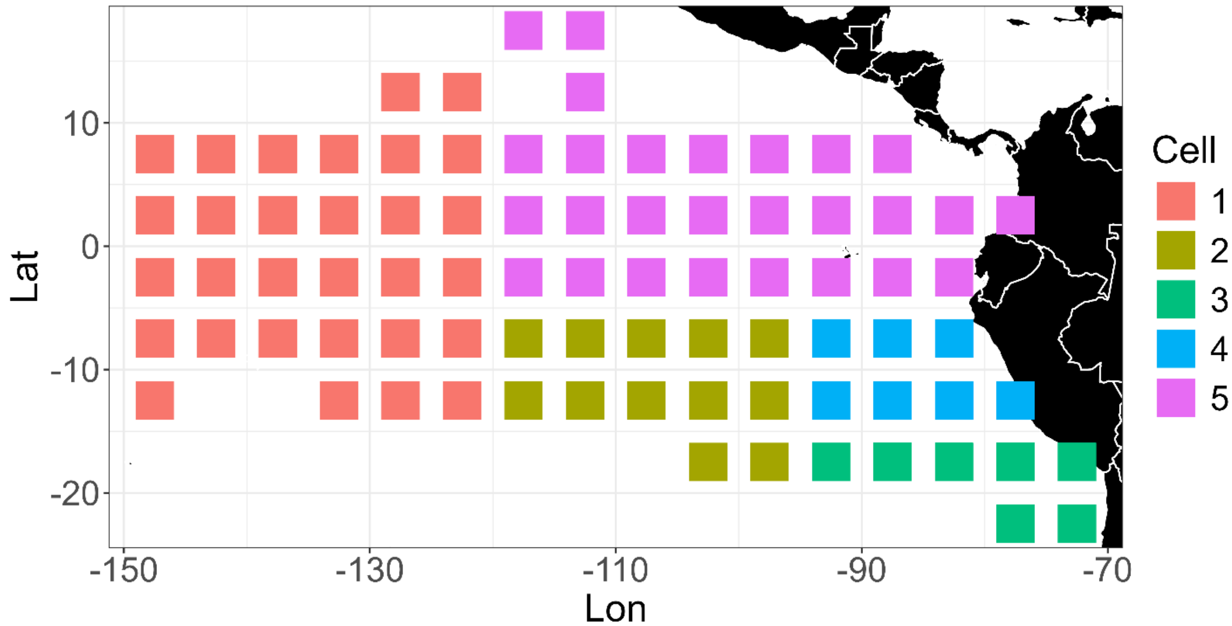

FIGURE 1a. Areas corresponding to the floating-object fishery definitions used in the stock assessment of skipjack tuna in the EPO in 2024 (Table 1). The fisheries in area 1 and 2 are divided into smaller and larger fisheries.

FIGURA 1a. Áreas correspondientes a las definiciones de pesquerías sobre objetos flotantes usadas en la evaluación de la población de atún barrilete en el OPO en 2024 (Tabla 1). Las pesquerías de las áreas 1 y 2 se dividen en pesquerías más pequeñas y más grandes.

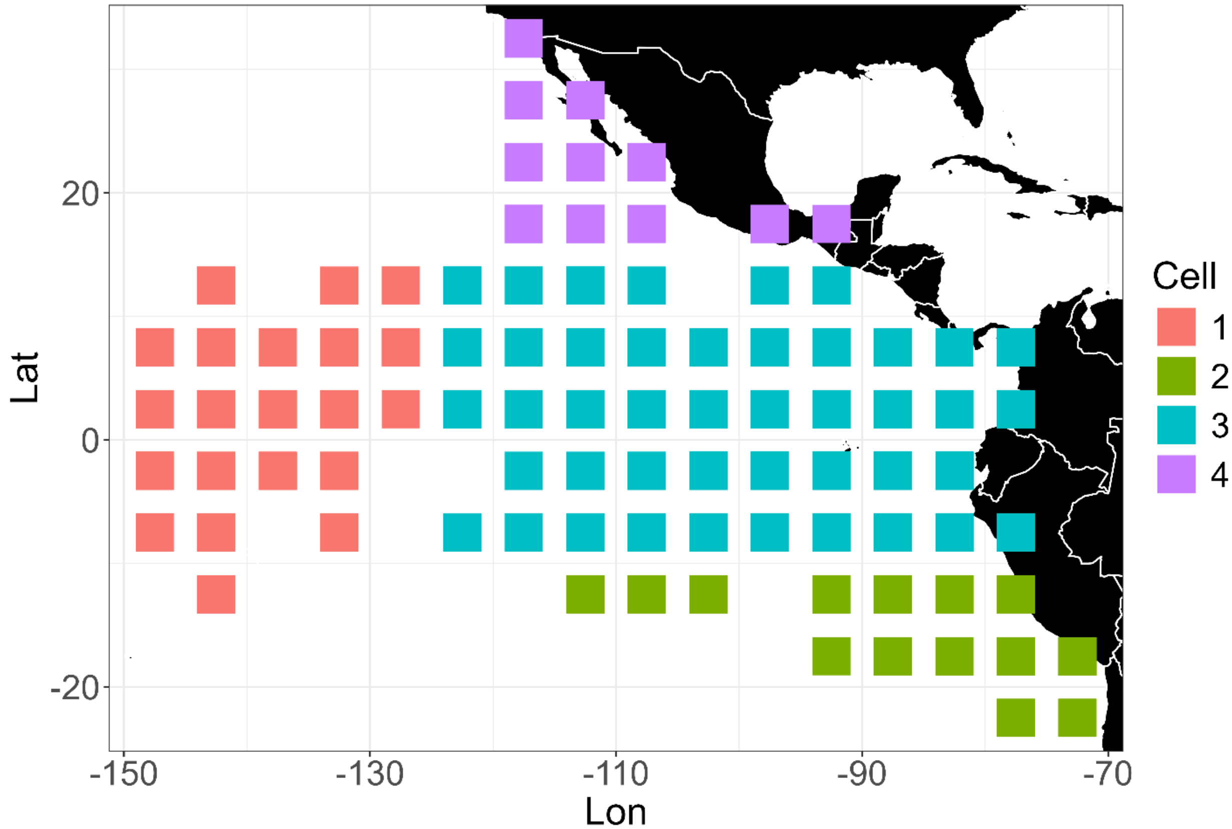

FIGURE 1b. Areas corresponding to the unassociated fishery definitions used in the stock assessment of skipjack tuna in the EPO in 2024 (Table 1). The fishery in area 1 is divided into smaller and larger fisheries.
FIGURA 1b. Áreas correspondientes a las definiciones de pesquerías no asociadas usadas en la evaluación de la población de atún barrilete en el OPO en 2024 (Tabla 1). Las pesquerías del área 1 se dividen en pesquerías más pequeñas y más grandes.

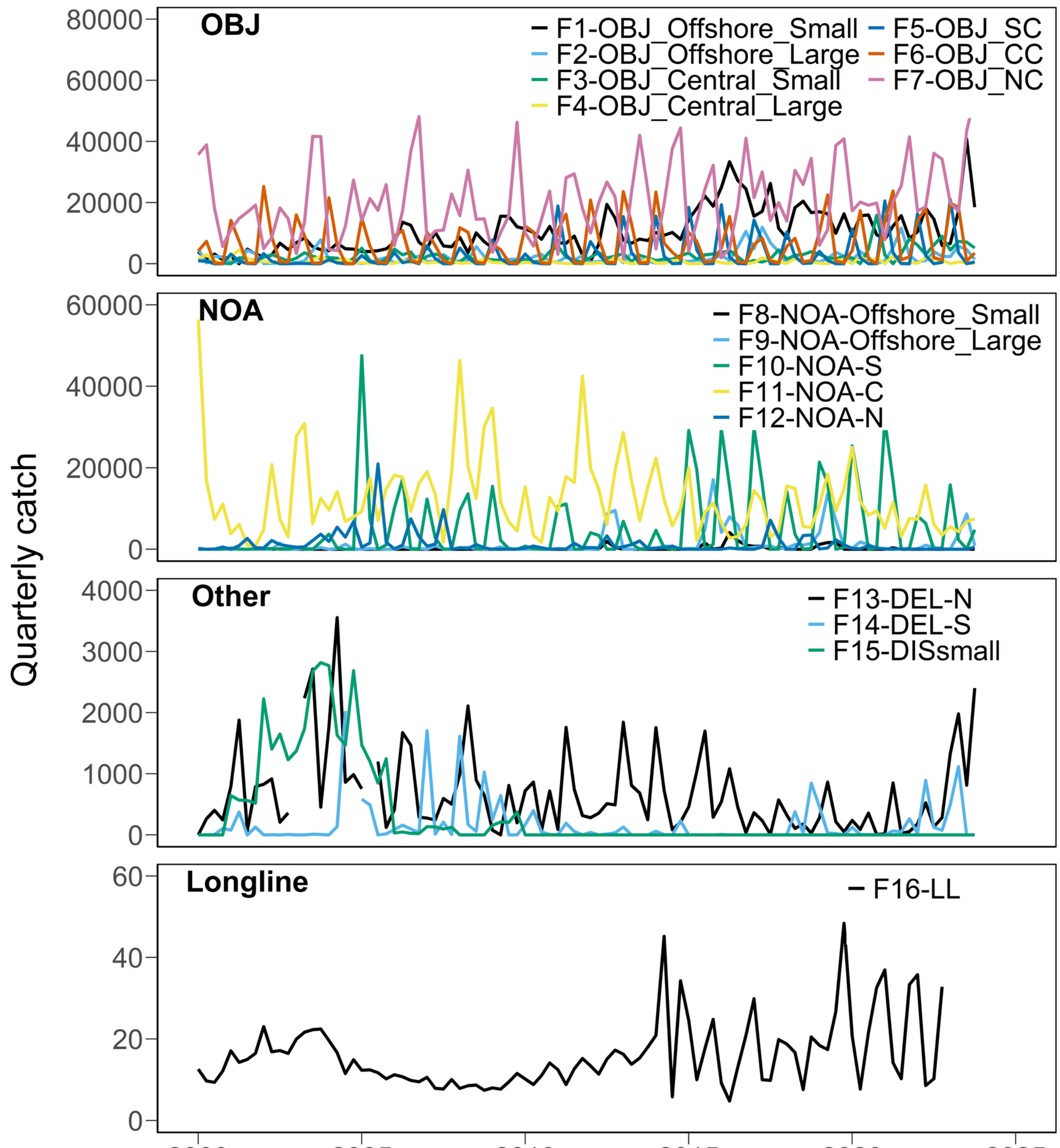

FIGURE 2. Quarterly catches of skipjack tuna, in tons, in the EPO, 2000-2023, by fishery. NOTE: The y-axis scale varies by plot. The unit for longline fishery catch is thousand fish, while it is metric tons for other fisheries. The actual data used in the assessment only includes 2006 to 2023.

FIGURA 2. Capturas trimestrales de atún barrilete, en toneladas, en el OPO, 2000-2023, por pesquería. NOTA: la escala del eje ‘y’ varía por gráfica. La unidad para la captura de la pesquería palangrera es miles de peces, mientras que para las demás pesquerías es toneladas métricas.

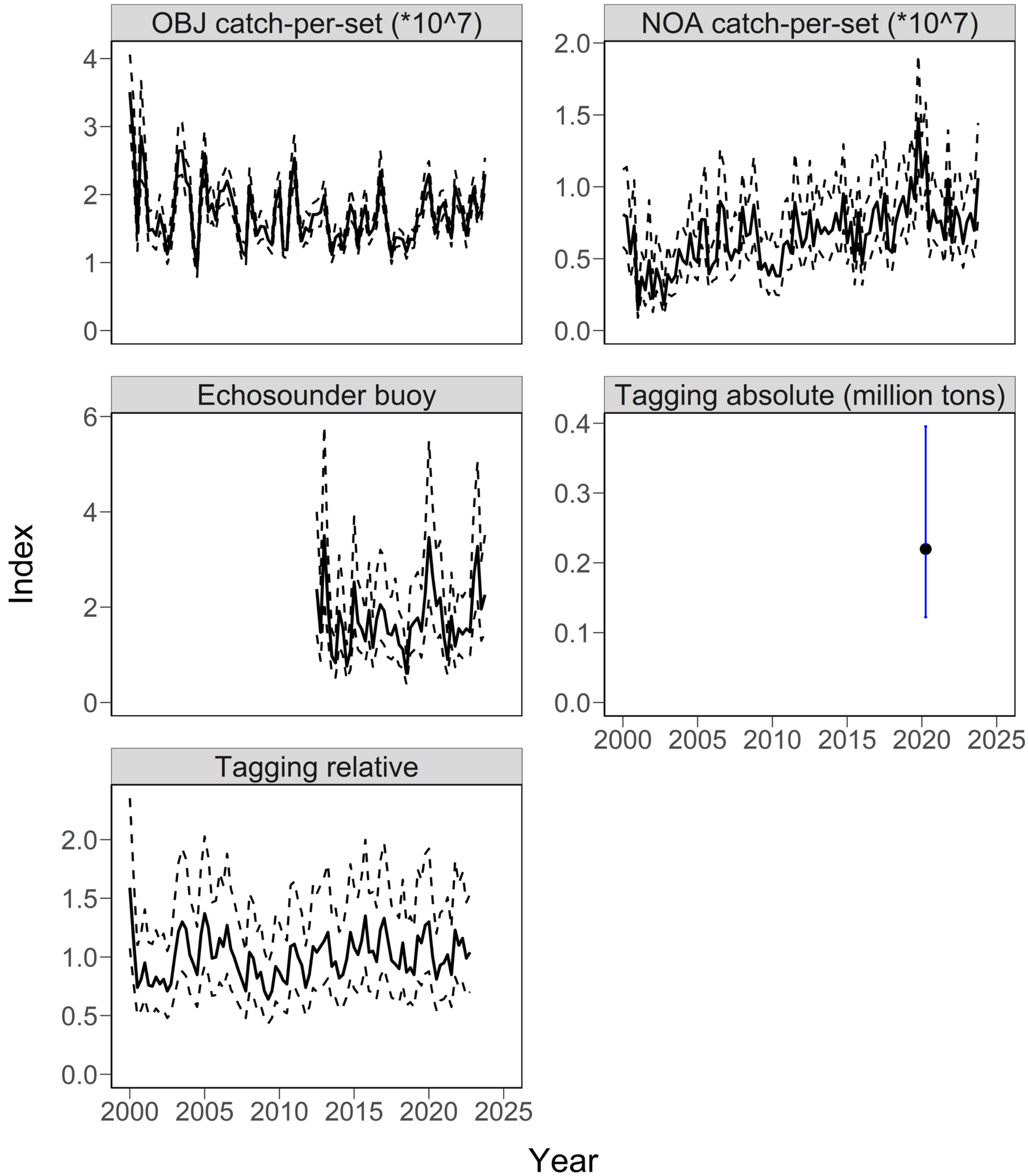

FIGURE 3. Indices of abundance used in the stock assessment of skipjack tuna in the EPO, 2000-2023 (black solid line and solid points), and their associated 95% confidence intervals (dashed lines and blue lines). The actual data used in the assessment only includes 2006 to 2023.

FIGURA 3. Índices de abundancia usados en la evaluación de la población de atún barrilete en el OPO, 2000-2023 (línea negra), y sus intervalos de confianza de 95% asociados (líneas discontinuas y líneas azules). Los datos utilizados en la evaluación solo incluyen los años 2006 a 2023.

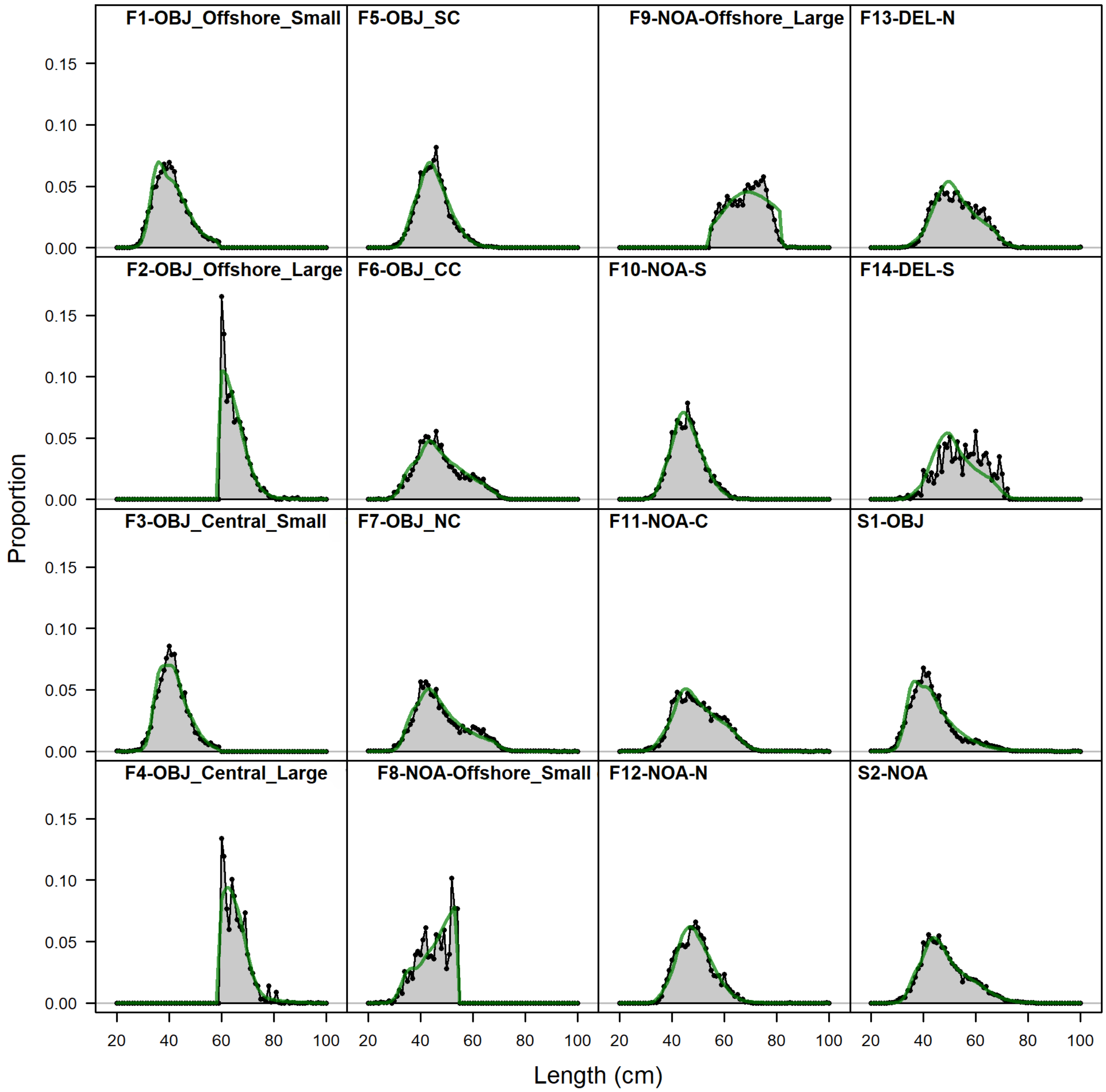

FIGURE 4a. Weighted average observed (shaded area) and predicted by the reference model (line) length-composition data, by purse-seine fishery and “survey”.

FIGURA 4a. Promedio ponderado de los datos de composición por talla observados (área sombreada) y predichos por el modelo de referencia (línea), por pesquería de cerco y "estudio".

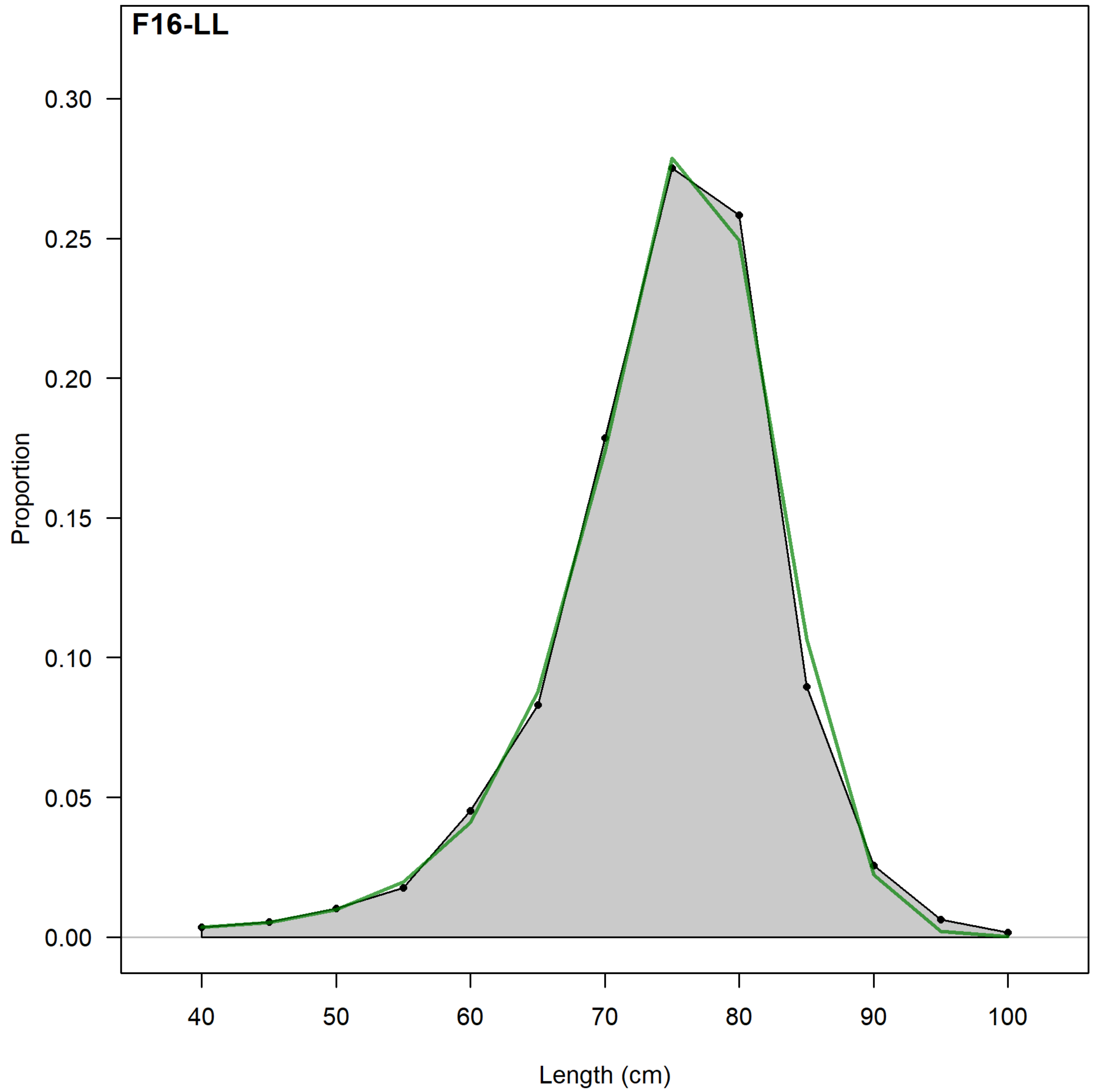

FIGURE 4b. Weighted average observed (shaded area) and predicted by the reference model (line) length-composition data for the longline fishery.

FIGURA 4b. Promedio ponderado de los datos de composición por talla observados (área sombreada) y predichos por el modelo de referencia (línea) para la pesquería palangrera.

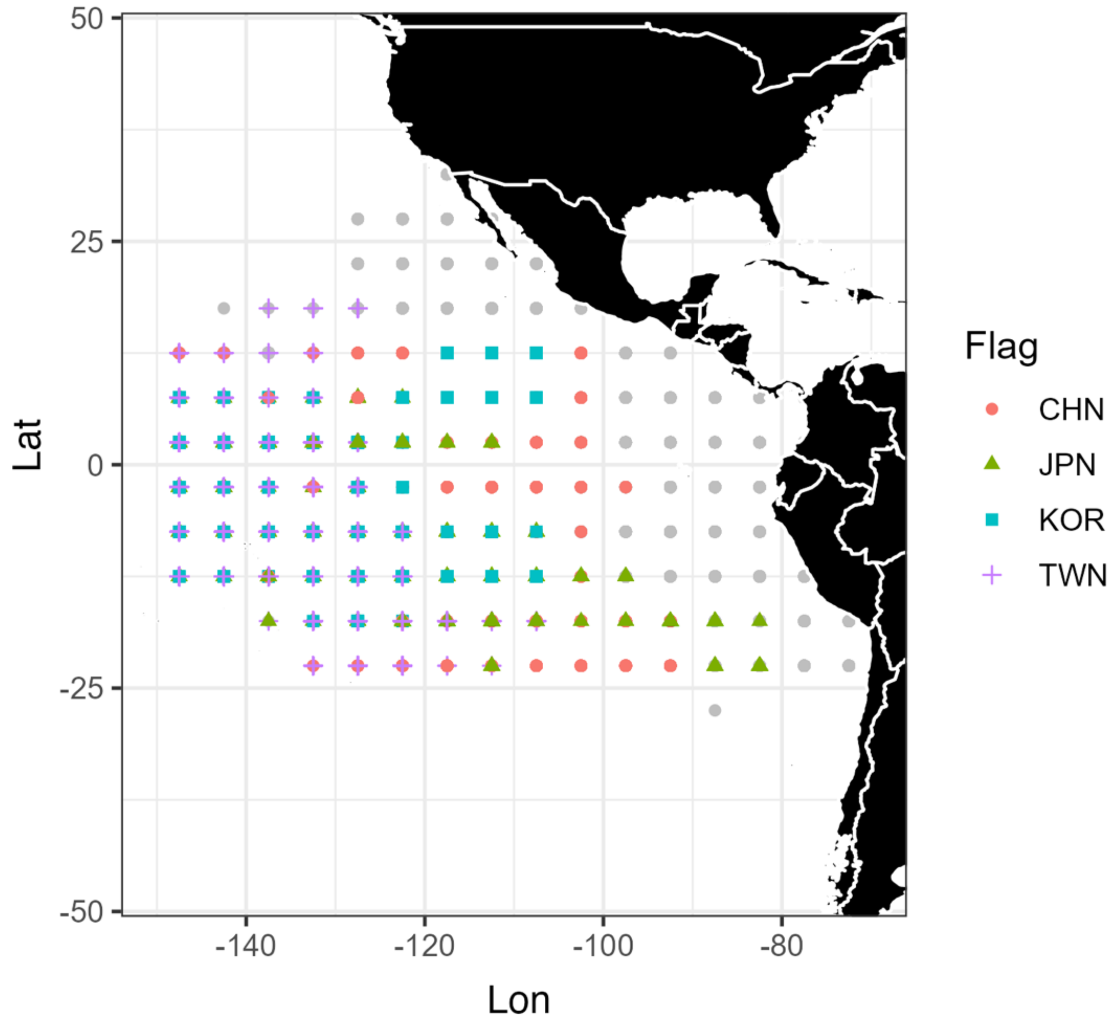

FIGURE 5. Coverage of longline observer data from the four Members of the IATTC (*i.e.*, China, Chinese Taipei, Japan and Korea). Grey points indicate the locations of purse-seine catch and effort data. Data are aggregated into a 5 by 5 grid.

FIGURA 5. Cobertura de los datos de observadores de palangre de cuatro Miembros de la CIAT (es decir, China, Taipéi Chino, Japón y Corea). Los puntos grises indican la ubicación de los datos de captura y esfuerzo de cerco. Los datos están agregados en una cuadrícula de 5 por 5.

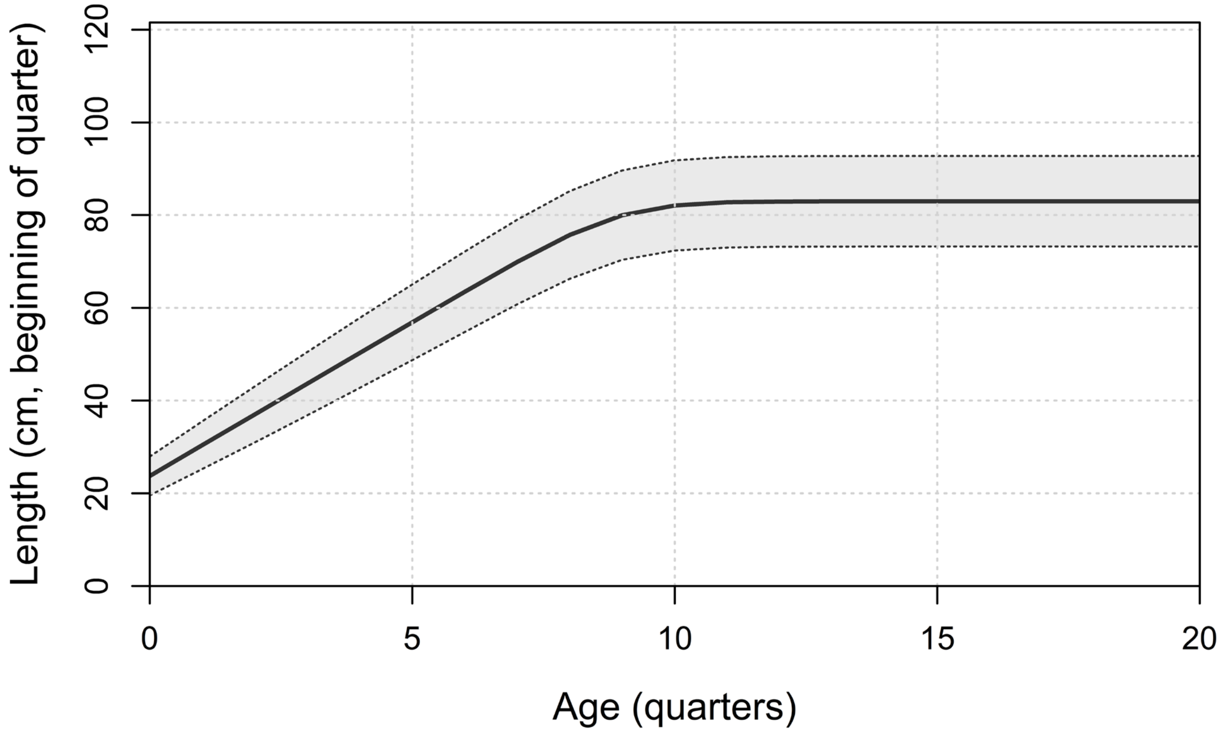

FIGURE 6. Assumed mean length-at-age in the reference model (solid line). The shaded region represents variation in length-at-age, assuming a CV = 9% at age 0 and 6% at age 20 quarters (mean ± 1.96 standard deviations).

FIGURA 6. Talla por edad promedio supuesta en el modelo de referencia (línea continua). La región sombreada representa la variación de la talla por edad, suponiendo un CV = 9% a edad 0 y 6% a 20 trimestres de edad (promedio ± 1.96 desviación estándar).

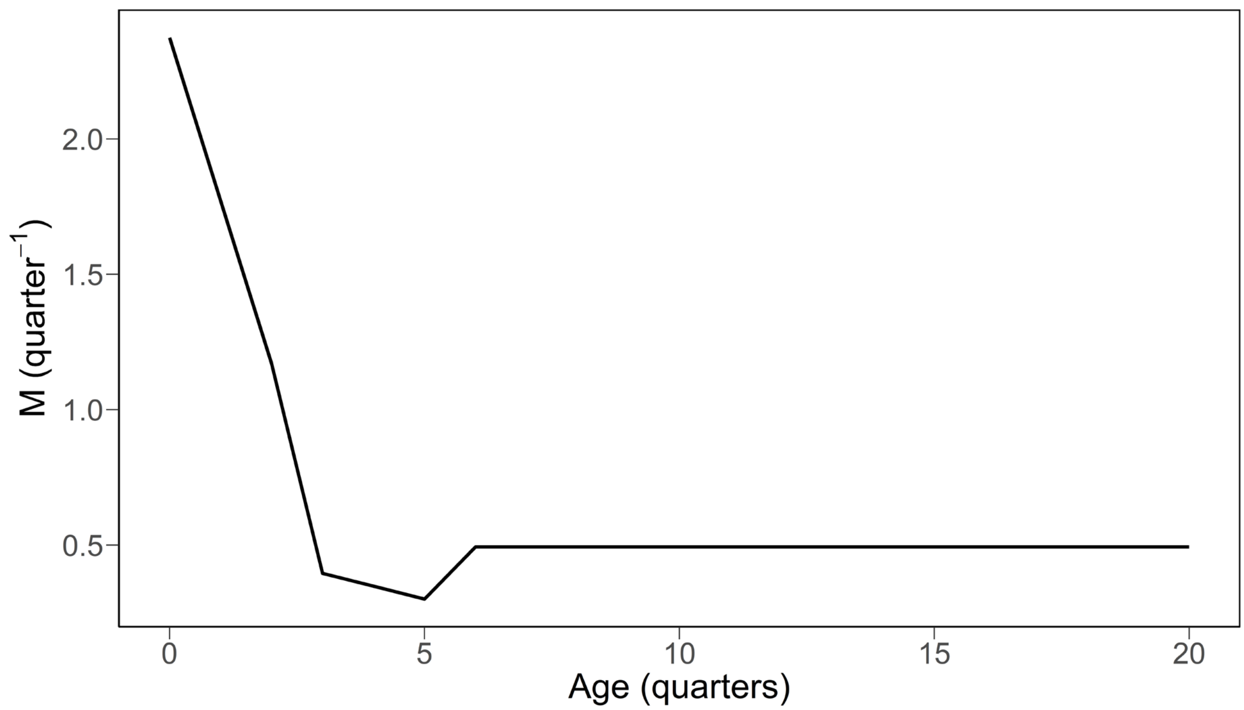

FIGURE 7. Assumed age-specific natural mortality in the reference model. It assumed constant natural mortality for fish of 65 cm and larger.
FIGURA 7. Mortalidad natural por edad supuesta en el modelo de referencia. Se supuso una mortalidad natural constante para los peces de 65 cm y más grandes.

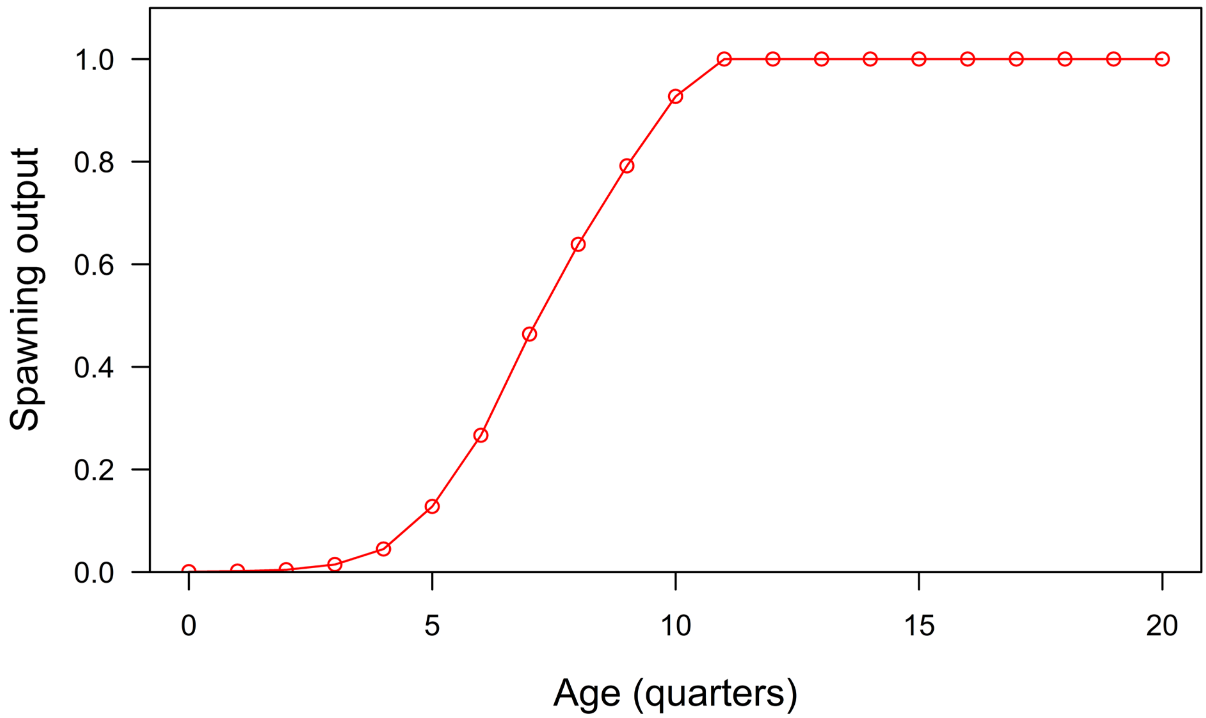

FIGURE 8. Relative contribution of each age to the reproductive output component (scaled to a maximum of one) for skipjack tuna in the EPO.
FIGURA 8. Contribución relativa de cada edad al componente de producción reproductora (escalado a un máximo de uno) para el atún barrilete en el OPO.

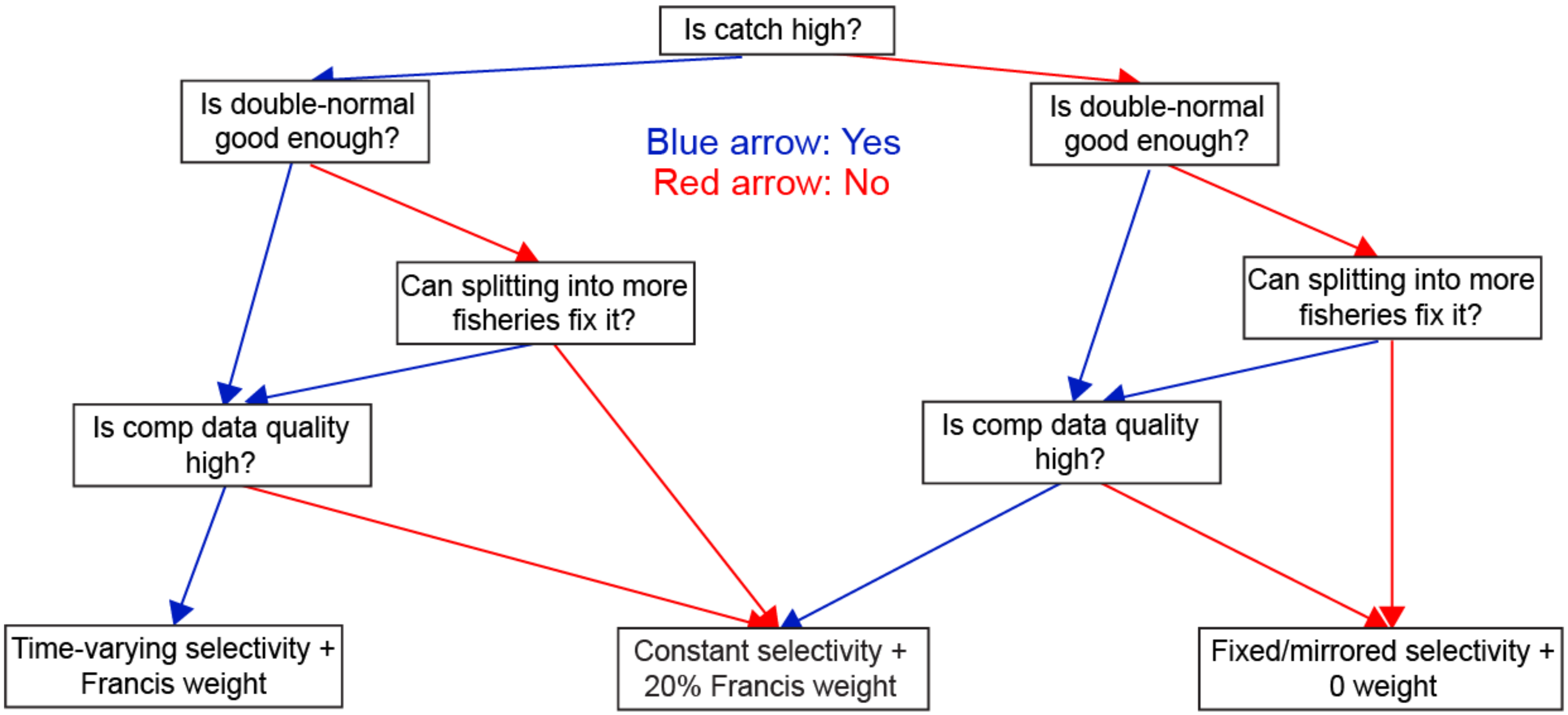

FIGURE 9. The decision tree on which the selectivity form and composition data weighting in this benchmark assessment are based.
FIGURA 9. Árbol de decisión en el que se basa la forma de la selectividad y la ponderación de los datos de composición en esta evaluación de referencia.

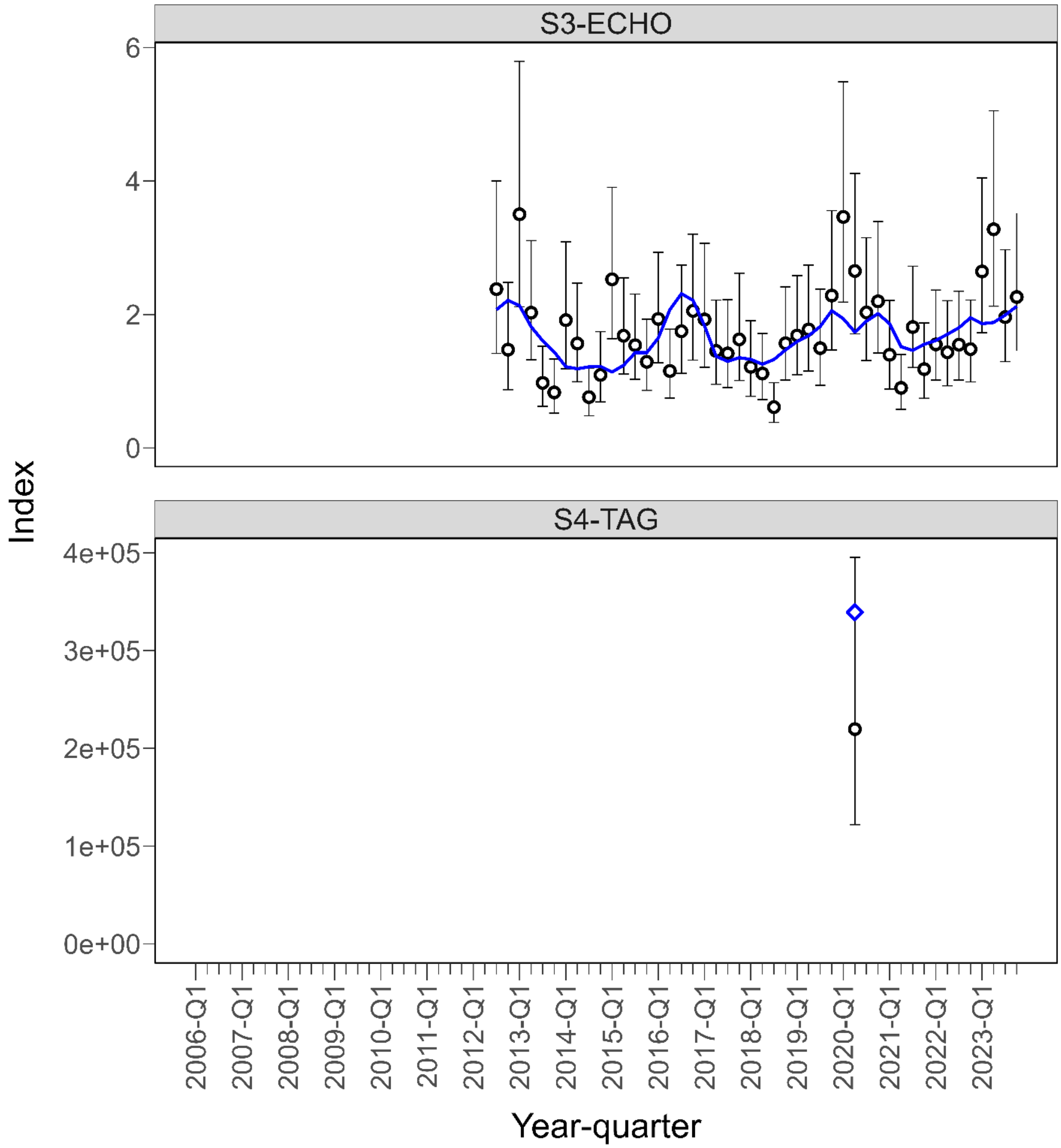

FIGURE 10. Model fits to the CPUE-based indices of abundance for the echosounder buoy index (top) and the tagging-based absolute index (bottom) by the reference model. The blue line (top) and blue diamond (bottom) represent the estimated indices, the black circles are the observed CPUE values, and the vertical lines represent the uncertainty in the observations.

FIGURA 10. Ajustes del modelo a los índices de abundancia basados en la CPUE para el índice de boyas con ecosonda (arriba) y el índice absoluto basado en marcado (abajo) por el modelo de referencia. La línea azul (arriba) y el rombo azul (abajo) representan los índices estimados, los círculos negros son los valores de CPUE observados y las líneas verticales representan la incertidumbre en las observaciones.

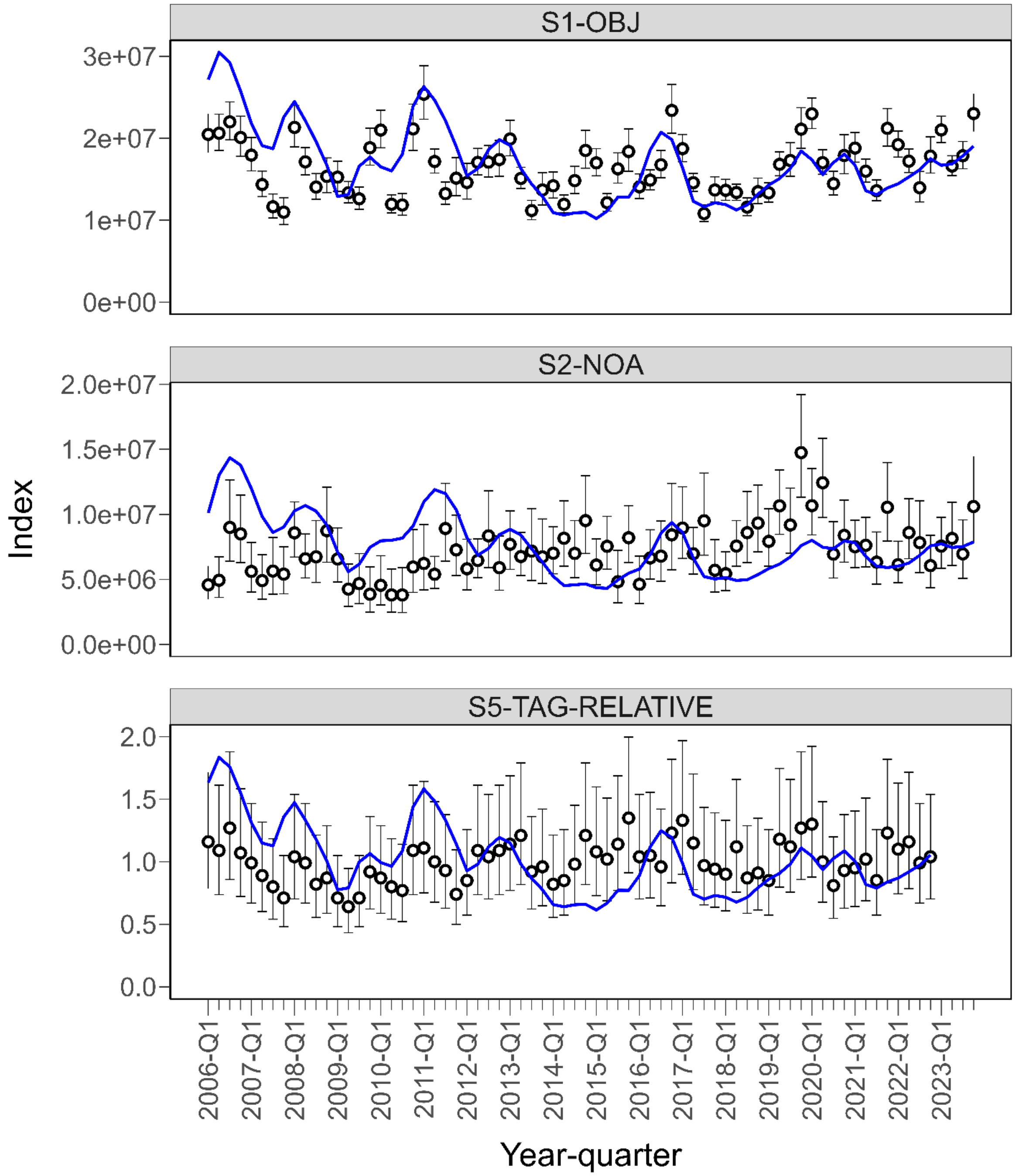

FIGURE 11. Model fits to the catch-per-set based indices of abundance for the floating object (top) and unassociated (middle) purse-seine fisheries, and the tagging-based relative index (bottom) by the reference model. These fits are not included in the objective function. The blue line represents the estimated indices, the black circles are the observed CPUE values, and the vertical lines represent the uncertainty in the observations.

FIGURA 11. Ajustes del modelo a los índices de abundancia basados en la captura por lance para las pesquerías cerqueras sobre objetos flotante (arriba) y no asociadas (medio), y el índice relativo basado en marcado (abajo), por el modelo de referencia. Estos ajustes no se incluyen en la función objetiva. La línea azul representa los índices estimados, los círculos negros son los valores de CPUE observados y las líneas verticales representan la incertidumbre en las observaciones.

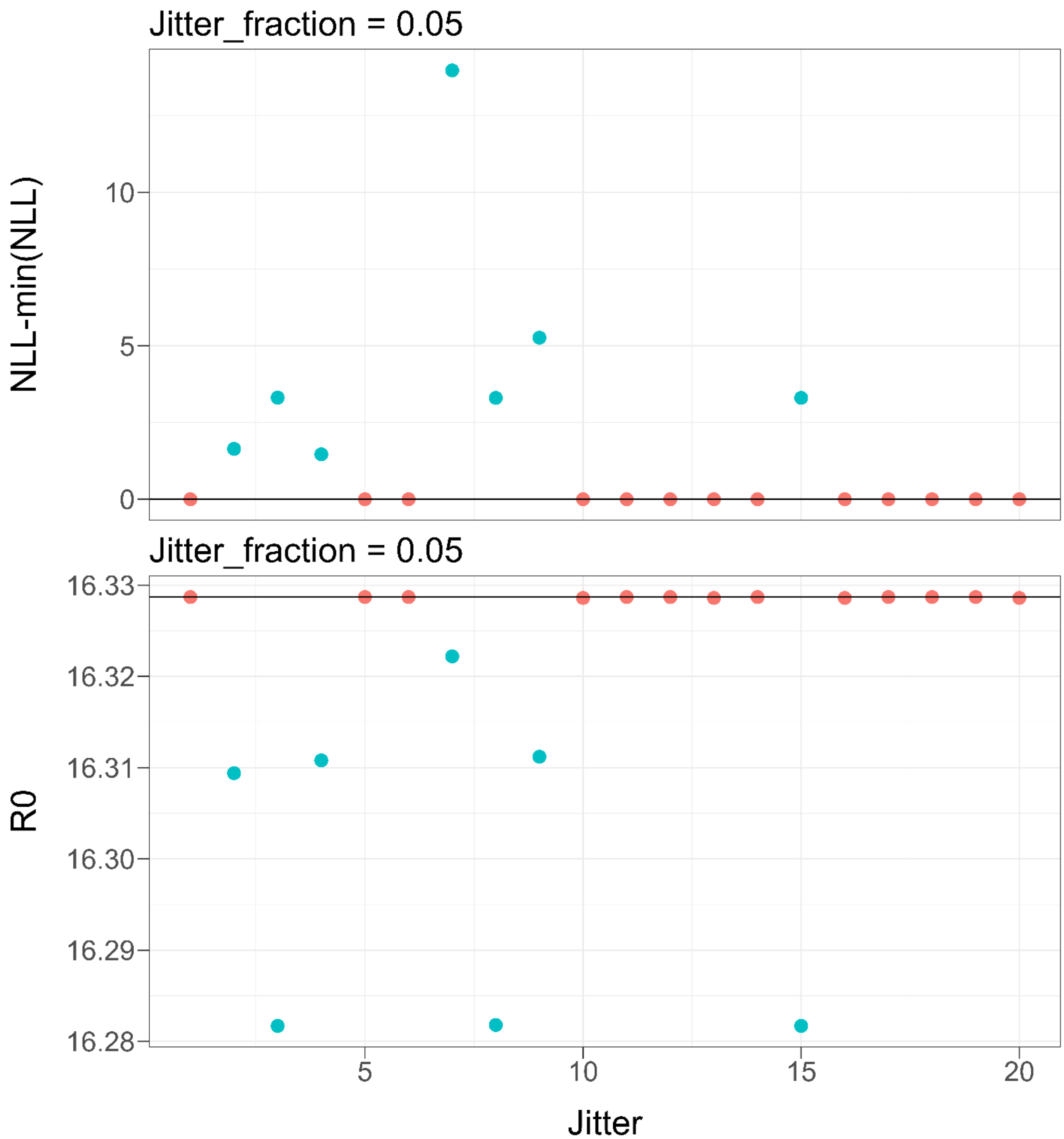

FIGURE 12. Normalized negative log-likelihood (top), and estimate of R_0, the equilibrium recruitment in the absence of fishing (bottom), for the jitter analysis from the reference model.
FIGURA 12. Verosimilitud logarítmica negativa normalizada (arriba), y estimación de R_0, el reclutamiento de equilibrio en ausencia de pesca (abajo), para el análisis de *jitter* del modelo de referencia.

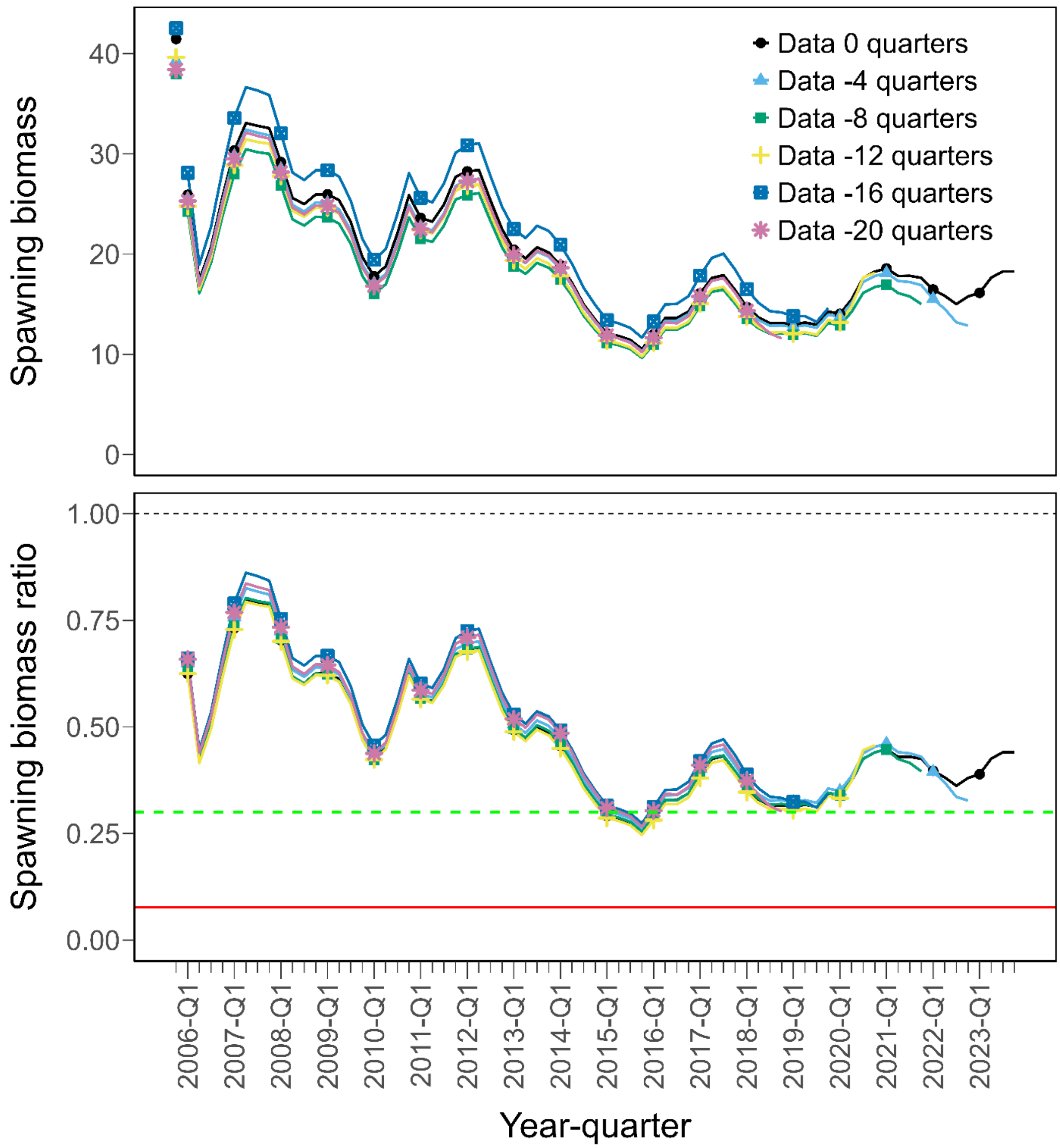

FIGURE 13. Spawning biomass (top) and spawning biomass ratio (bottom) for the retrospective analysis from the reference model. The green horizontal dashed line is the target biomass reference point (SBR = 0.3) and the red horizontal solid line is the limit biomass reference point (SBR = 0.077).

FIGURA 13. Biomasa reproductora (arriba) y cociente de biomasa reproductora (abajo) para el análisis retrospectivo del modelo de referencia. La línea verde horizontal discontinua es el punto de referencia objetivo de biomasa (SBR = 0.3) y la línea roja horizontal sólida es el punto de referencia límite de biomasa (SBR = 0.077).

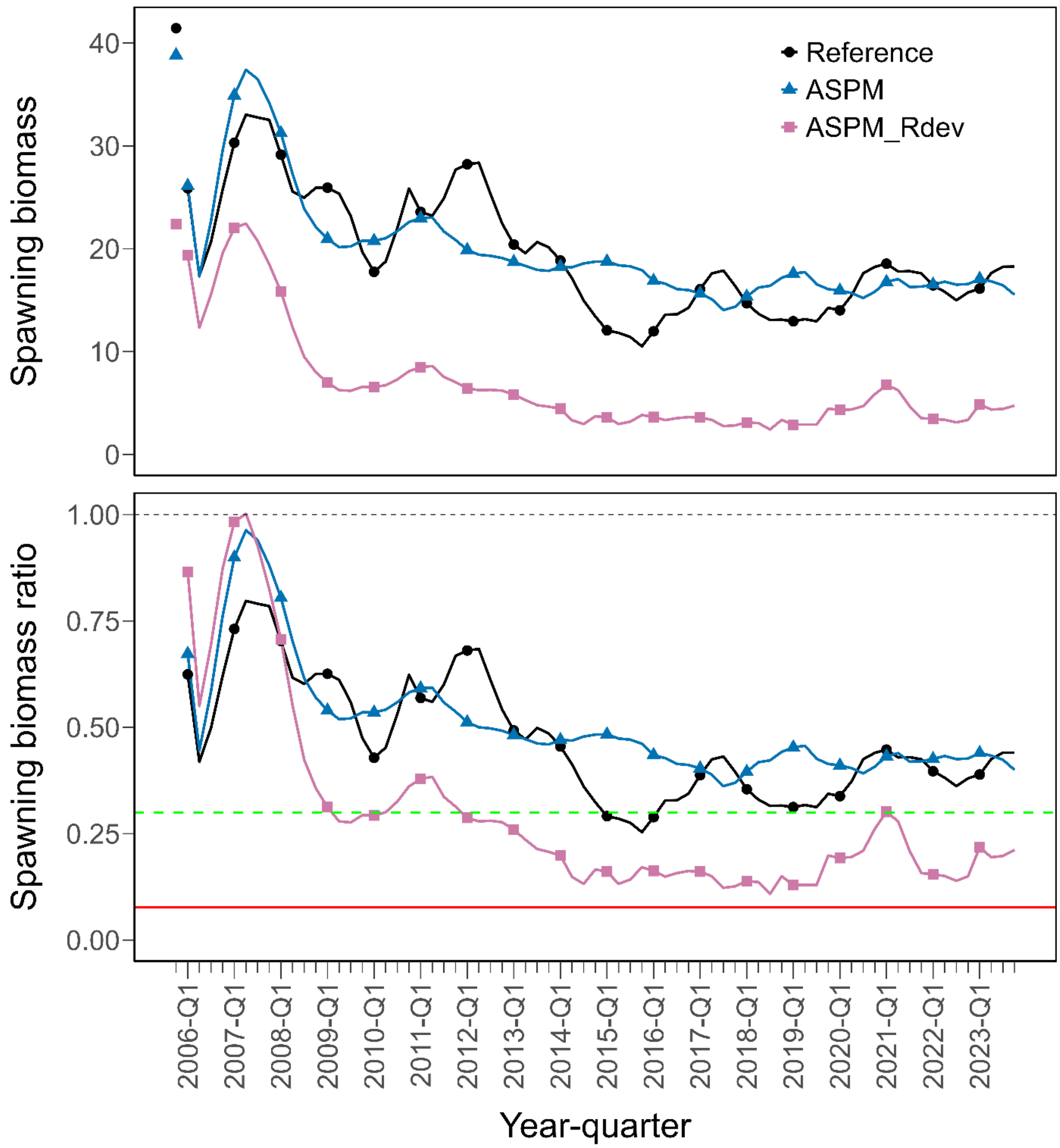

FIGURE 14. Spawning biomass (top) and spawning biomass ratio (bottom) for the age-structured production model diagnostics for the reference model. The green horizontal dashed line is the target biomass reference point (SBR = 0.3) and the red horizontal solid line is the limit biomass reference point (SBR = 0.077).

FIGURA 14. Biomasa reproductora (arriba) y cociente de biomasa reproductora (abajo) para el diagnóstico del modelo de producción estructurado por edad para el modelo de referencia. La línea verde horizontal discontinua es el punto de referencia objetivo de biomasa (SBR = 0.3) y la línea roja horizontal sólida es el punto de referencia límite de biomasa (SBR = 0.077).

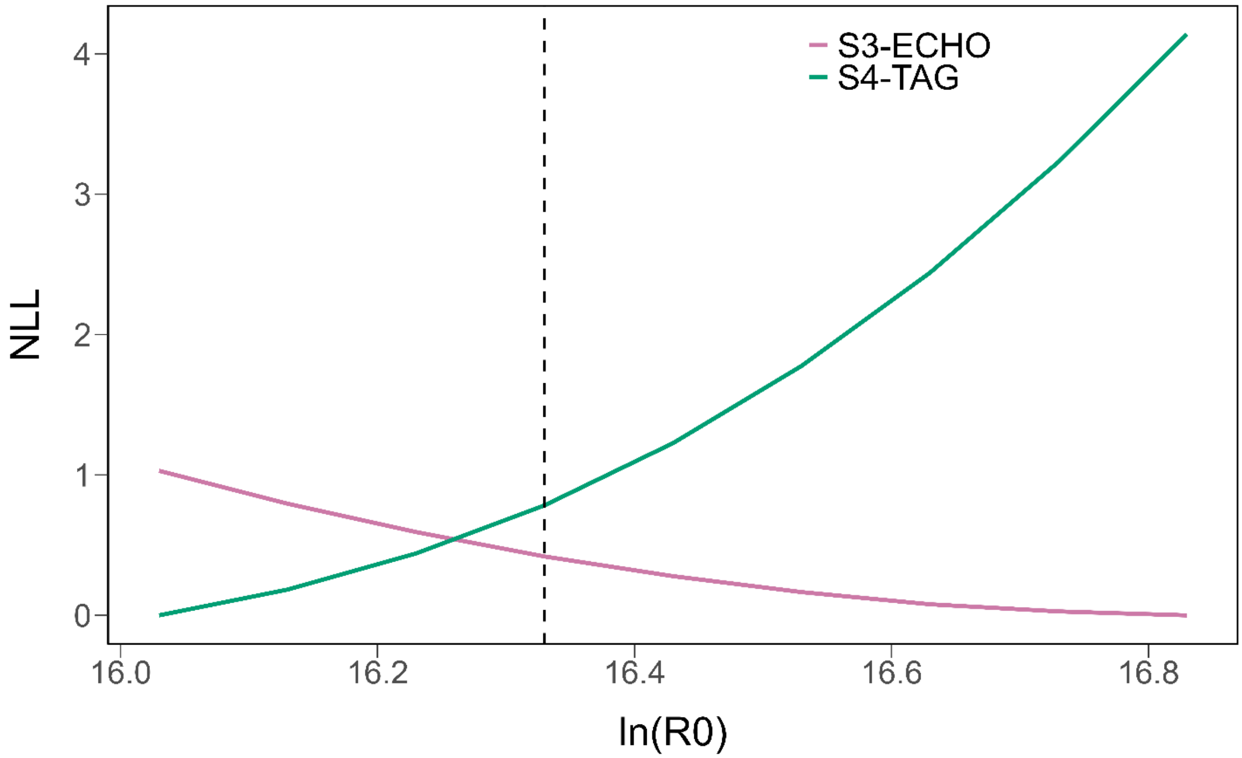

FIGURE 15a. R_0 likelihood component profile for the indices of abundance from the reference model.
FIGURA 15a. Perfil R_0 de componentes de verosimilitud para los índices de abundancia del modelo de referencia.

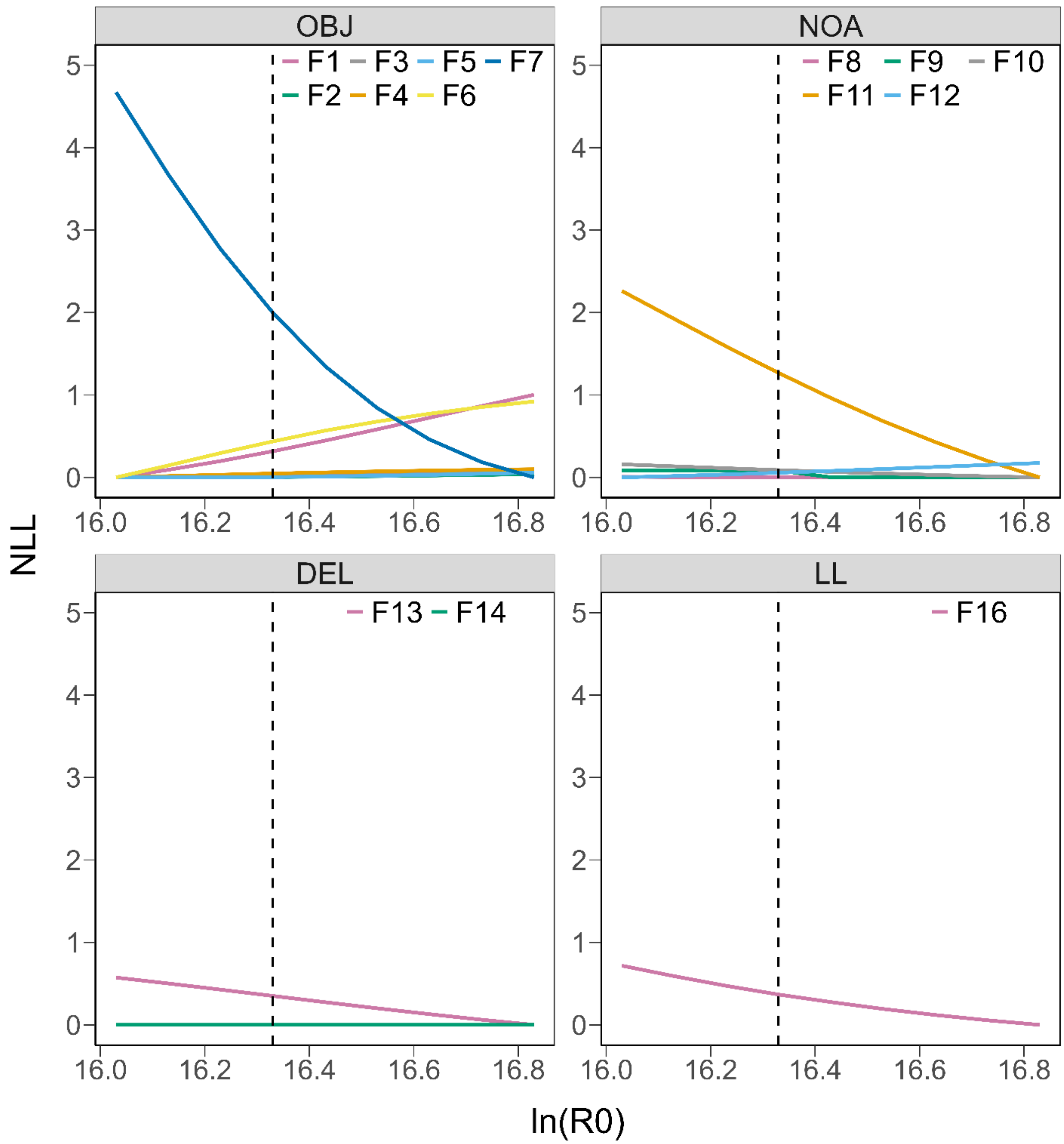

FIGURE 15b. R_0 likelihood component profile for the fishery length-composition data from the reference model.

FIGURA 15b. Perfil R_0 de componentes de verosimilitud para los datos de composición por talla de pesca del modelo de referencia.

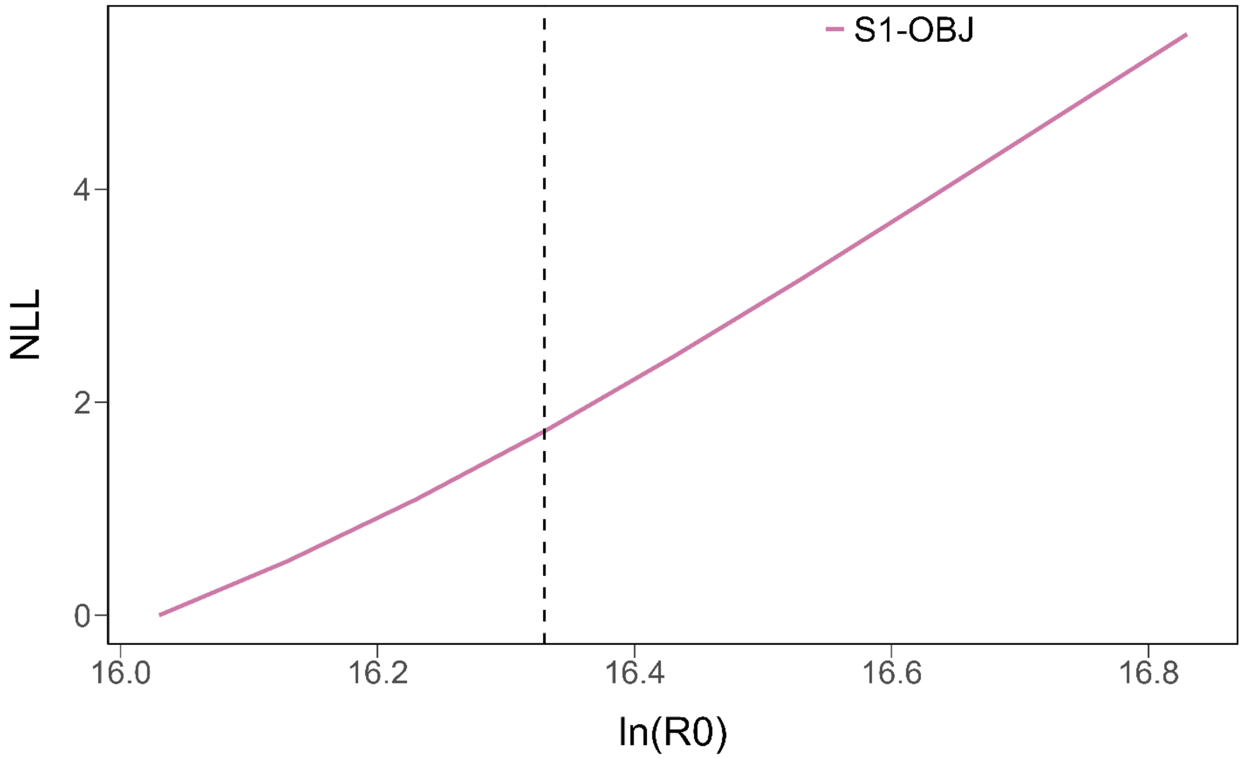

FIGURE 15c. R_0 likelihood component profile for the survey length-composition data from the reference model.

FIGURA 15c. Perfil R_0 de componentes de verosimilitud para los datos de composición por talla de estudio del modelo de referencia.

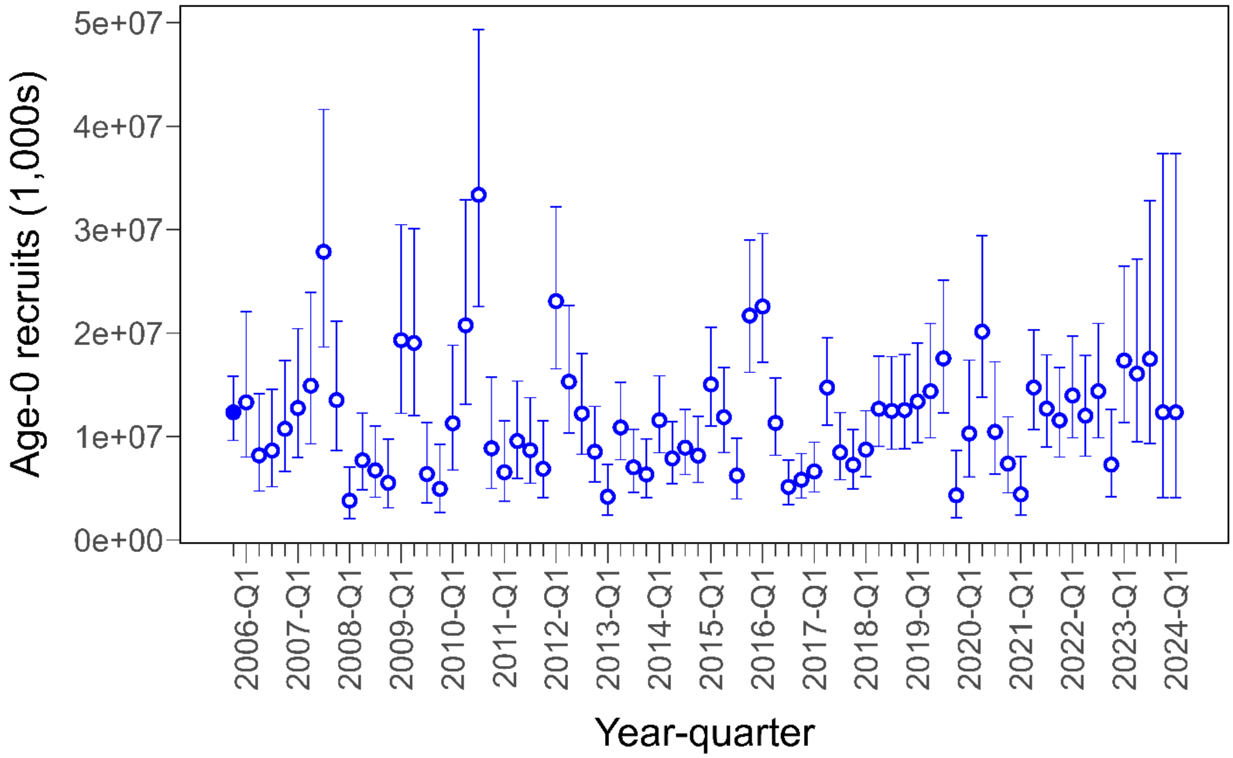

FIGURE 16. Quarterly recruitment and 95% confidence intervals of skipjack tuna estimated by the reference model.

FIGURA 16. Reclutamiento trimestral e intervalos de confianza de 95% del atún barrilete estimado por el modelo de referencia

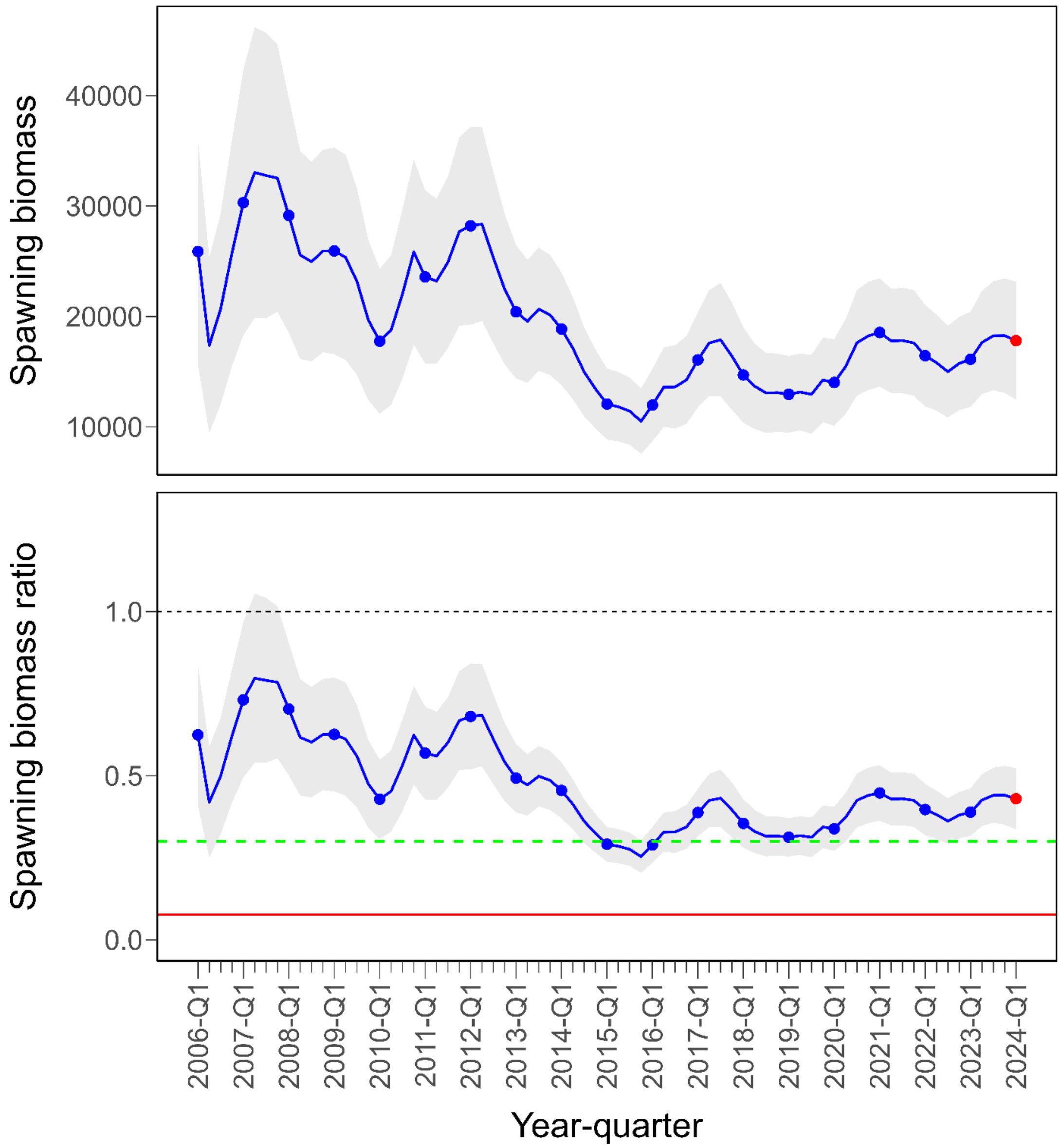

FIGURE 17. Spawning biomass (top) and spawning biomass ratio (bottom) for skipjack tuna in the EPO, 2006-current estimated by the reference model. The red points indicate the model estimates in the first quarter of 2024. The blue points represent the first quarter of each year. The solid lines represent the maximum likelihood estimates and the shaded area the approximate 80% confidence intervals (CIs) around those estimates (80% CIs would represent the 10% probability of exceeding the reference point). The green horizontal dashed line is the target biomass reference point (SBR = 0.3) and the red horizontal solid line is the limit biomass reference point (SBR = 0.077).

FIGURA 17. Biomasa reproductora (arriba) y cociente de biomasa reproductora (abajo) para el atún barrilete en el OPO, 2006-presente, estimados por el modelo de referencia. Los puntos rojos indican las estimaciones del modelo en el primer trimestre de 2024. Los puntos azules representan el primer trimestre de cada año. Las líneas continuas representan las estimaciones de verosimilitud máxima y el área sombreada representa los intervalos de confianza (IC) de 80% aproximados en torno a esas estimaciones (los IC de 80% representarían la probabilidad del 10% de rebasar el punto de referencia). La línea horizontal discontinua verde es el punto de referencia objetivo de biomasa (SBR = 0.3) y la línea roja horizontal sólida es el punto de referencia límite de biomasa (SBR = 0.077).

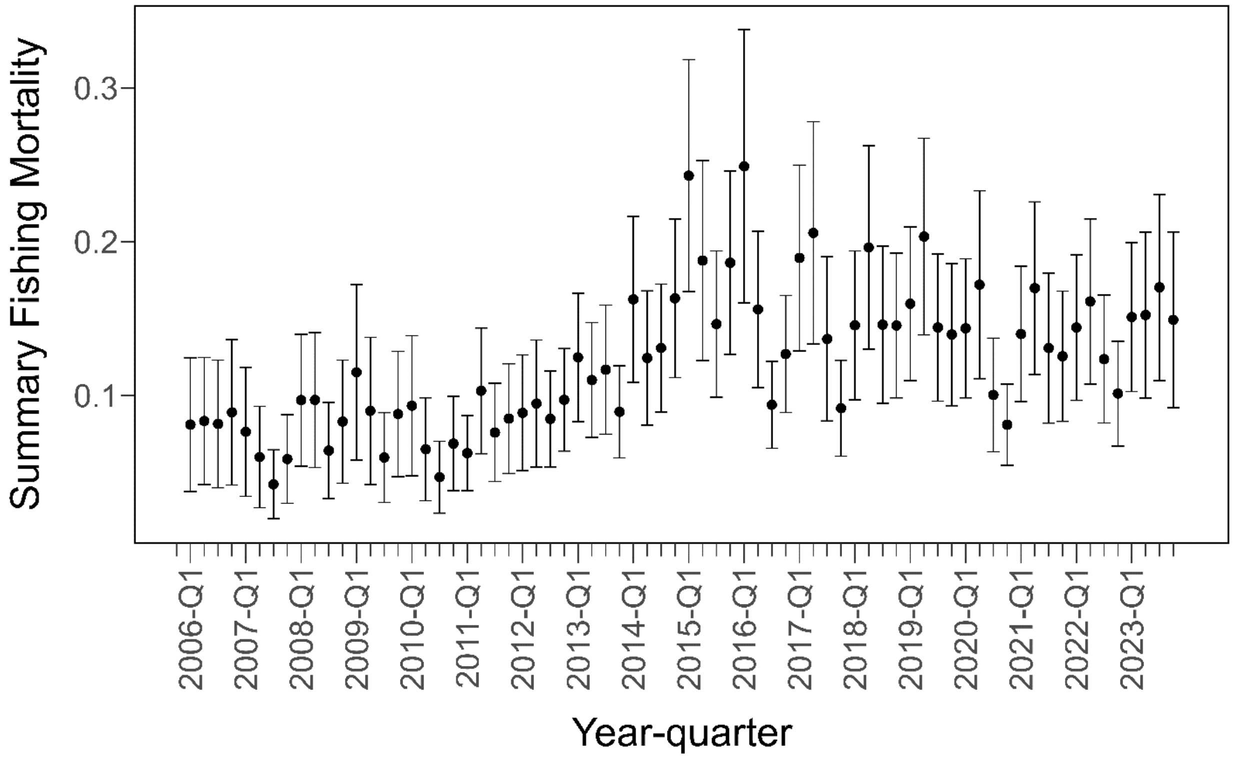

FIGURE 18. Index of quarterly exploitation rate of skipjack tuna in the EPO estimated by the reference model.

FIGURA 18. Índice de la tasa de explotación trimestral del atún barrilete en el OPO estimado por el modelo de referencia.

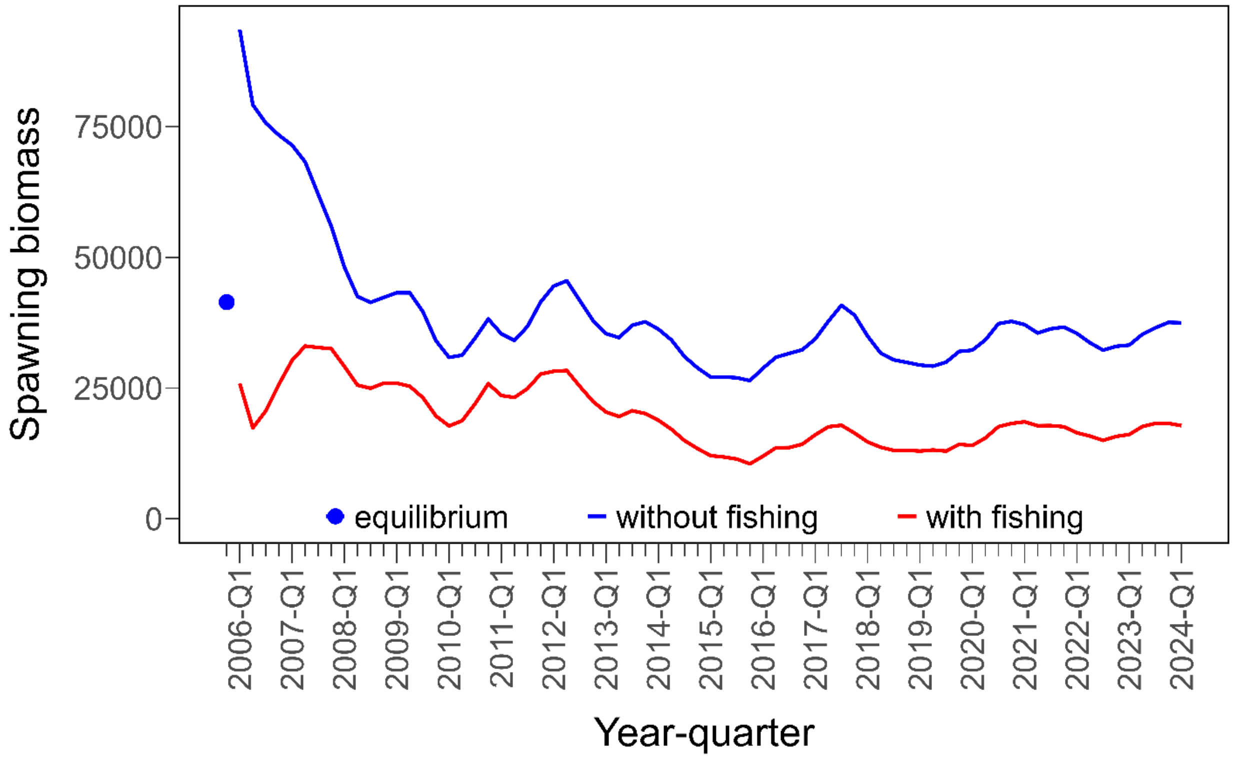

FIGURE 19. Impact of fishing, 2006-2023: trajectory of the spawning biomass (a fecundity index, see text for details) of a simulated population of skipjack tuna that was never exploited (blue line) and that predicted by the reference model (red line).

FIGURA 19. Impacto de la pesca, 2006-2023: trayectoria de la biomasa reproductora (un índice de fecundidad, ver texto para más detalles) de una población simulada de barrilete que nunca fue explotada (línea azul) y la predicha por el modelo de referencia (línea roja).

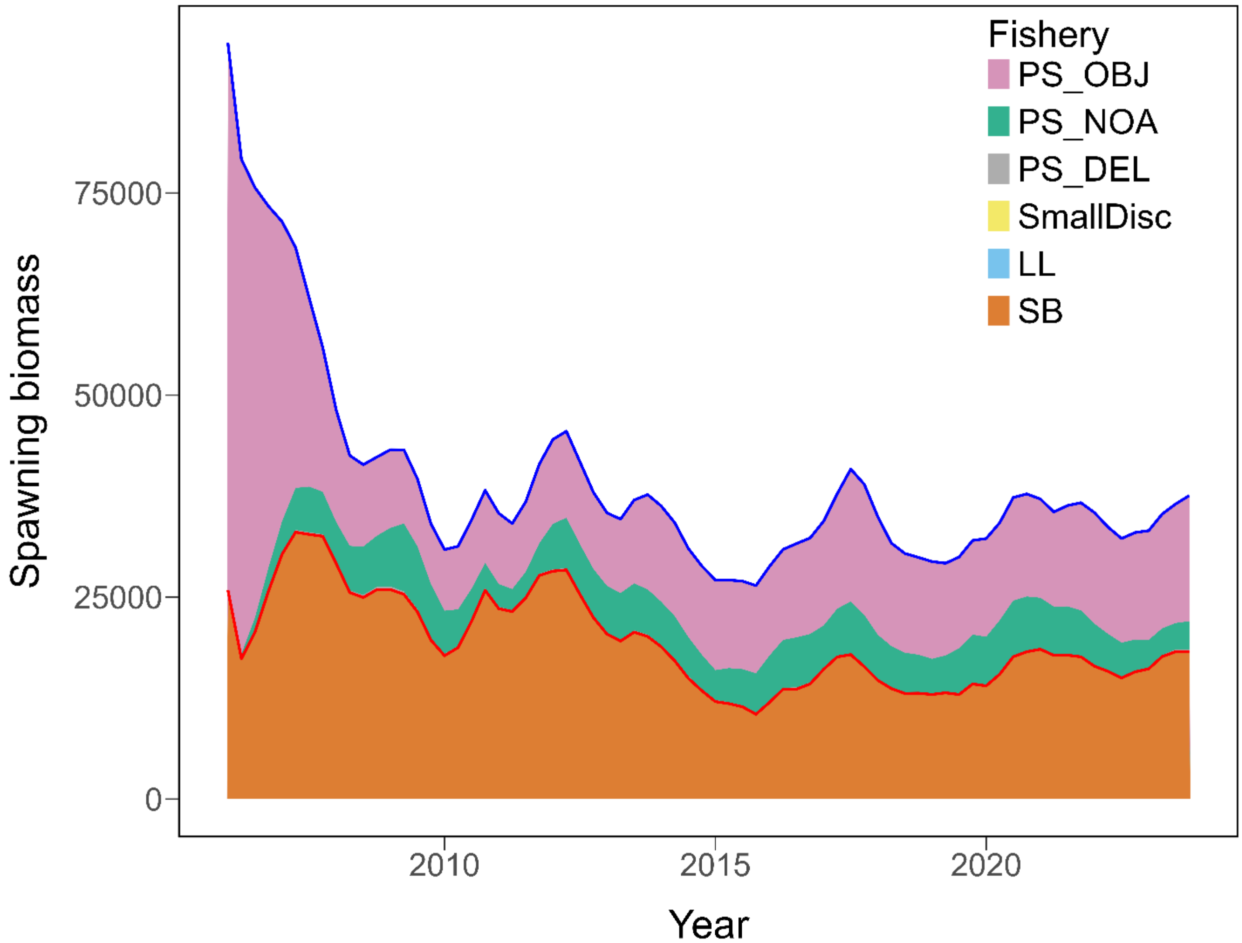

FIGURE 20. Comparison of spawning biomass trajectory of a simulated population of skipjack tuna that was never exploited (top blue line) and that predicted by the stock assessment model (bottom red line). The shaded purple, green, gray, yellow, and blue areas show the proportional impact of the purse-seine OBJ, purse-seine NOA, purse-seine DEL, small discard, and longline fishery, respectively. The impacts of the longline and small discard fisheries are undetectable, and the impact of the purse-seine DEL fishery is also hard to detect.

FIGURA 20. Comparación de la trayectoria de la biomasa reproductora de una población simulada de barrilete que nunca fue explotada (línea superior azul) y la predicha por el modelo de evaluación (línea inferior roja). Las áreas sombreadas en morado, verde, gris, amarillo y azul muestran el impacto proporcional de la pesquería de cerco OBJ, cerco NOA, cerco DEL, descartes de barrilete pequeño, y palangre, respectivamente. Los impactos de las pesquerías de palangre y de descartes de barrilete pequeño son indetectables, y el impacto de la pesquería de cerco DEL también es difícil de detectar.

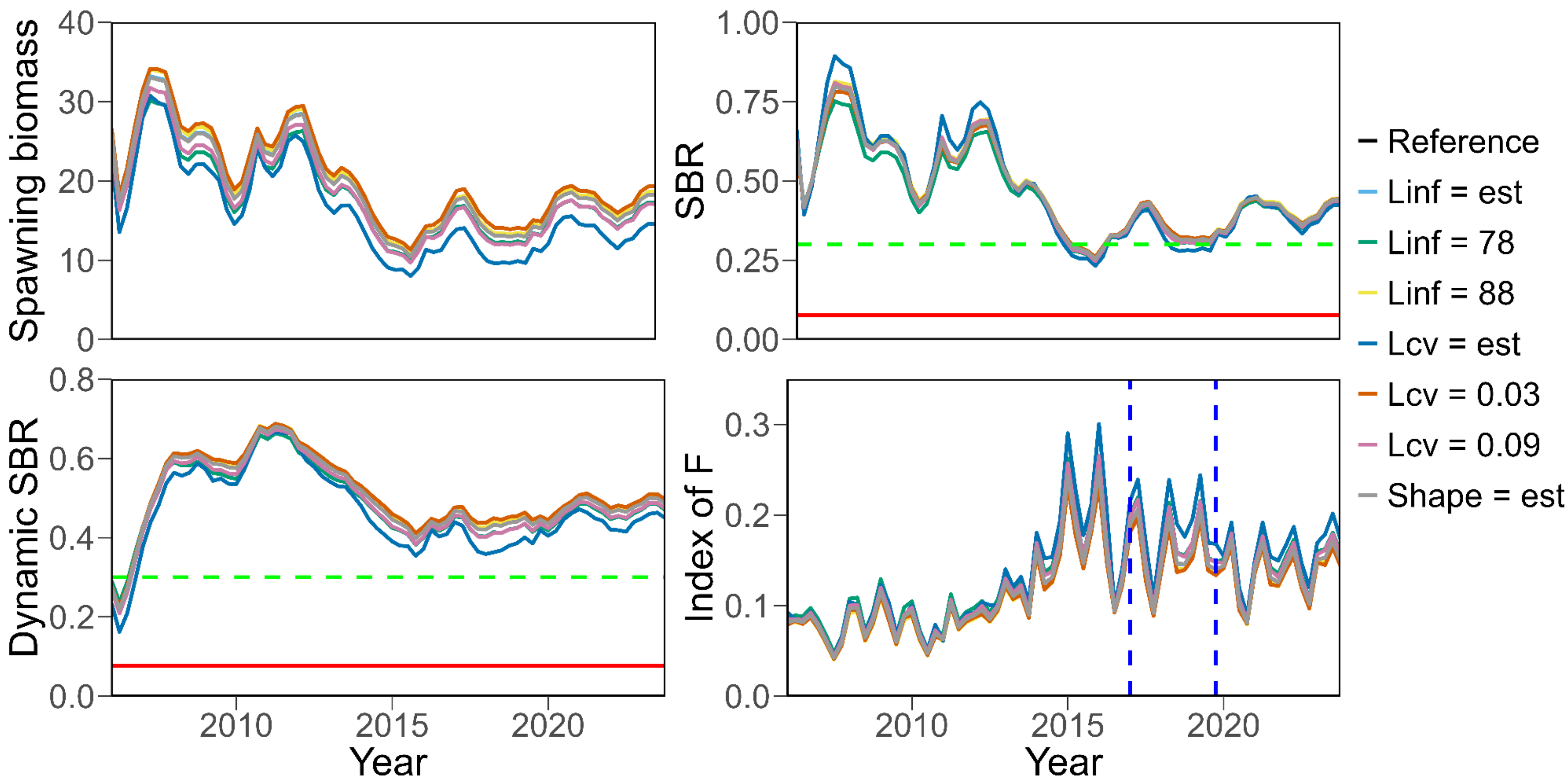

FIGURE 21. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analyses on growth parameters. The green horizontal dashed line is the target biomass reference point (SBR = 0.3) and the red horizontal solid line is the limit biomass reference point (SBR = 0.077). The two vertical lines represent the *status quo* period (2017-2019).

FIGURA 21. Biomasa reproductora, cociente de biomasa reproductora, cociente de biomasa reproductora dinámica y un índice de la tasa de explotación trimestral para los análisis de sensibilidad de los parámetros de crecimiento. La línea horizontal verde discontinua es el punto de referencia objetivo de biomasa (SBR = 0.3) y la línea roja horizontal sólida es el punto de referencia límite de biomasa (SBR = 0.077). Las dos líneas verticales representan el periodo de *statu quo* (2017-2019).

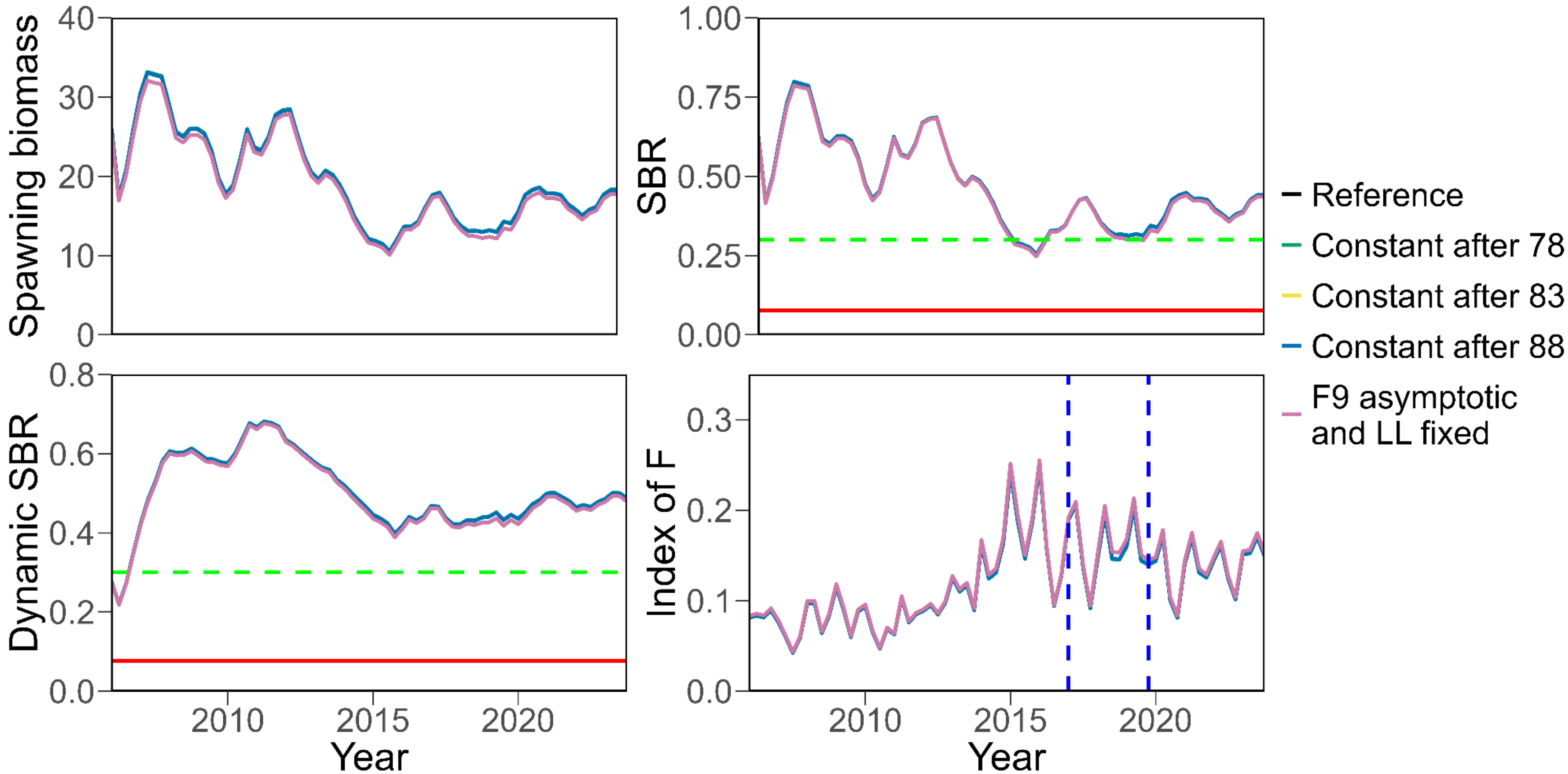

FIGURE 22. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analyses on selectivity settings. The green horizontal dashed line is the target biomass reference point (SBR = 0.3) and the red horizontal solid line is the limit biomass reference point (SBR = 0.077). The two vertical lines represent the *status quo* period (2017-2019).

FIGURA 22. Biomasa reproductora, cociente de biomasa reproductora, cociente de biomasa reproductora dinámica y un índice de la tasa de explotación trimestral para los análisis de sensibilidad de las configuraciones de selectividad. La línea horizontal verde discontinua es el punto de referencia objetivo de biomasa (SBR = 0.3) y la línea roja horizontal sólida es el punto de referencia límite de biomasa (SBR = 0.077). Las dos líneas verticales representan el periodo de *statu quo* (2017-2019).

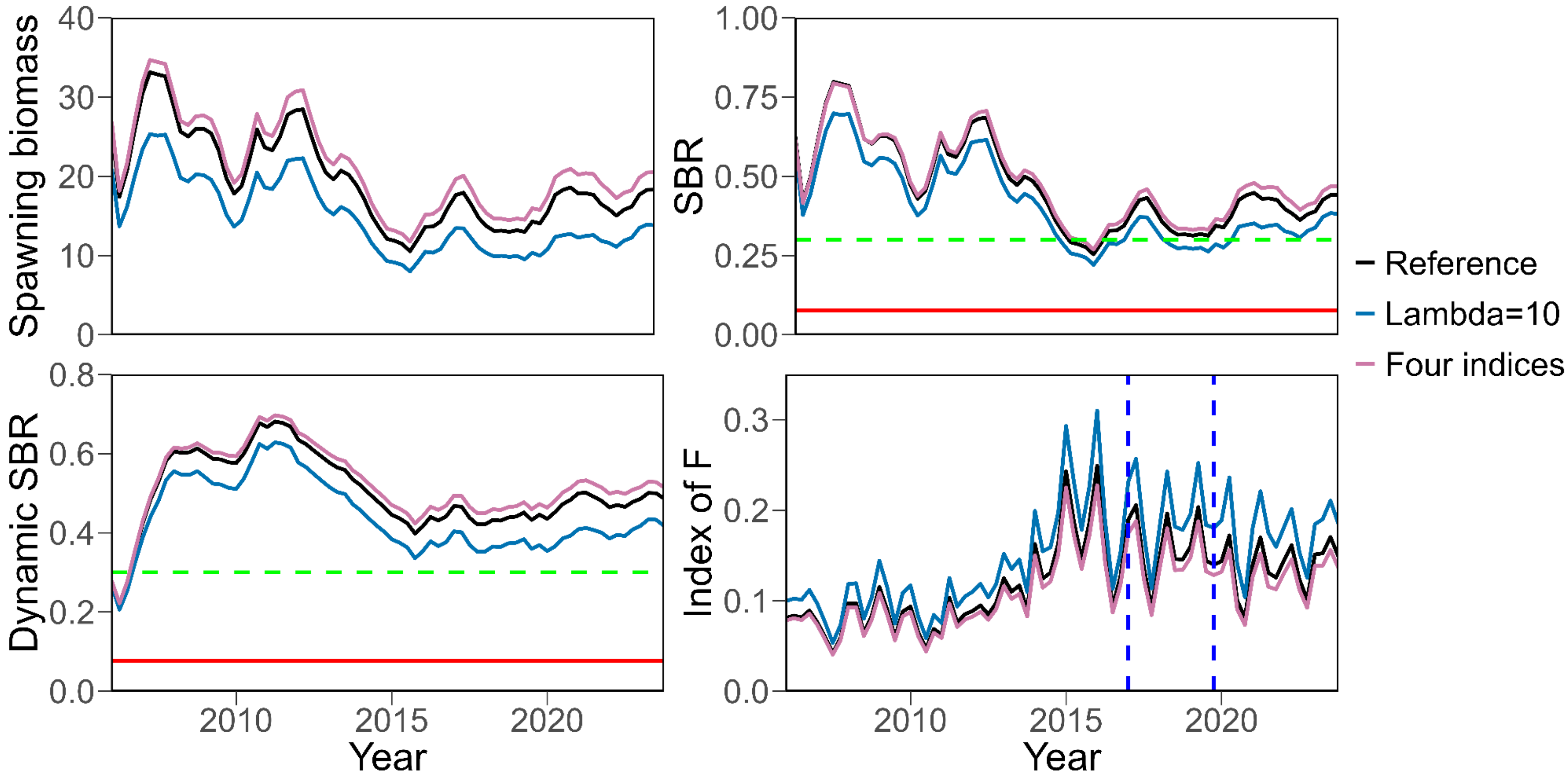

FIGURE 23. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analyses regarding treatments of tagging-based absolute index. The green horizontal dashed line is the target biomass reference point (SBR = 0.3) and the red horizontal solid line is the limit biomass reference point (SBR = 0.077). The two vertical lines represent the *status quo* period (2017-2019).

FIGURA 23. Biomasa reproductora, cociente de biomasa reproductora, cociente de biomasa reproductora dinámica y un índice de la tasa de explotación trimestral para los análisis de sensibilidad relativos a los tratamientos del índice absoluto basado en marcado. La línea horizontal verde discontinua es el punto de referencia objetivo de biomasa (SBR = 0.3) y la línea roja horizontal sólida es el punto de referencia límite de biomasa (SBR = 0.077). Las dos líneas verticales representan el periodo de *statu quo* (2017-2019).

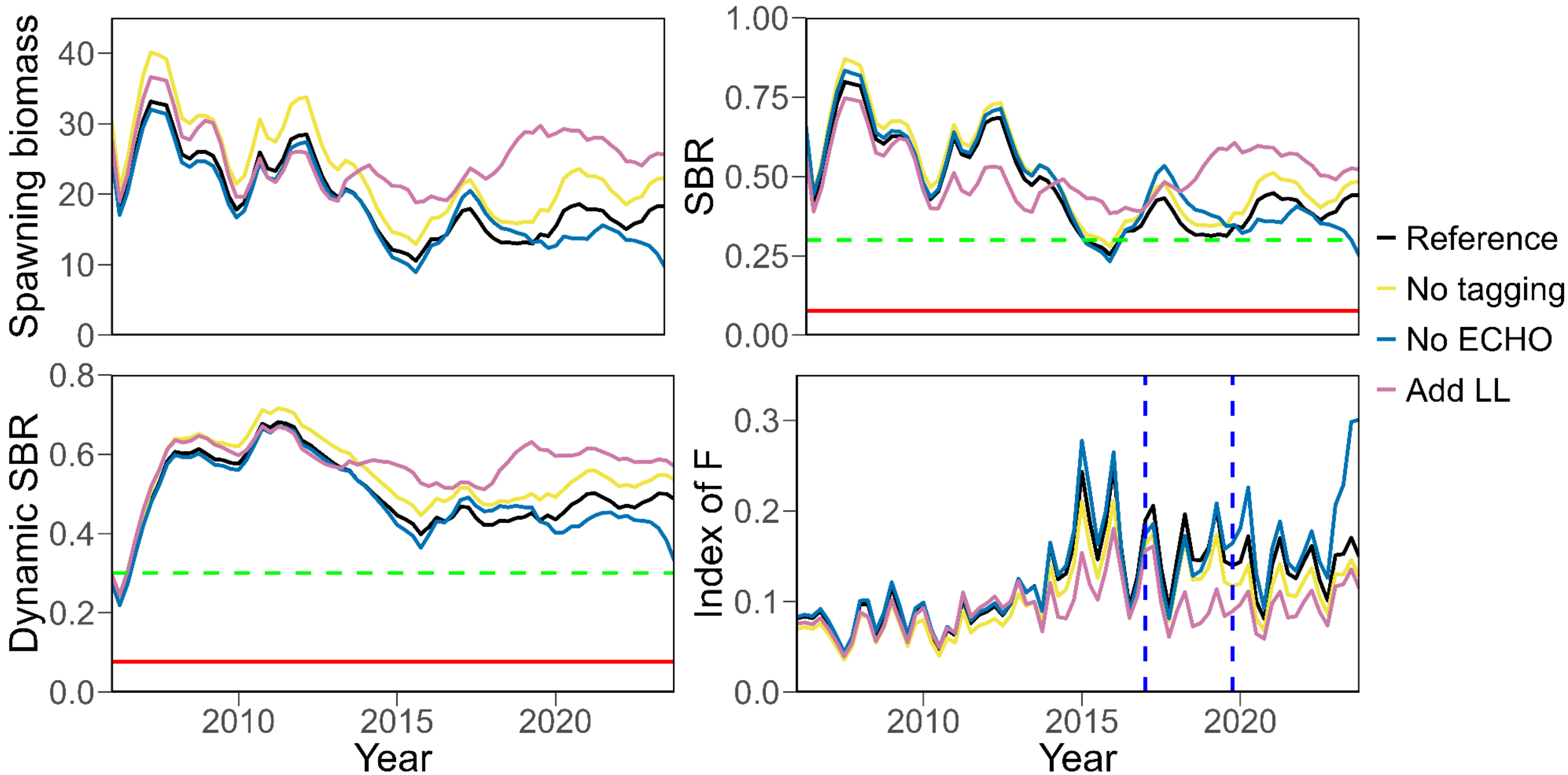

FIGURE 24. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analyses that include or exclude indices of abundance. The green horizontal dashed line is the target biomass reference point (SBR = 0.3) and the red horizontal solid line is the limit biomass reference point (SBR = 0.077). The two vertical lines represent the *status quo* period (2017-2019).

FIGURA 24. Biomasa reproductora, cociente de biomasa reproductora, cociente de biomasa reproductora dinámica y un índice de la tasa de explotación trimestral para los análisis de sensibilidad que incluyen o excluyen índices de abundancia. La línea horizontal verde discontinua es el punto de referencia objetivo de biomasa (SBR = 0.3) y la línea roja horizontal sólida es el punto de referencia límite de biomasa (SBR = 0.077). Las dos líneas verticales representan el periodo de *statu quo* (2017-2019).

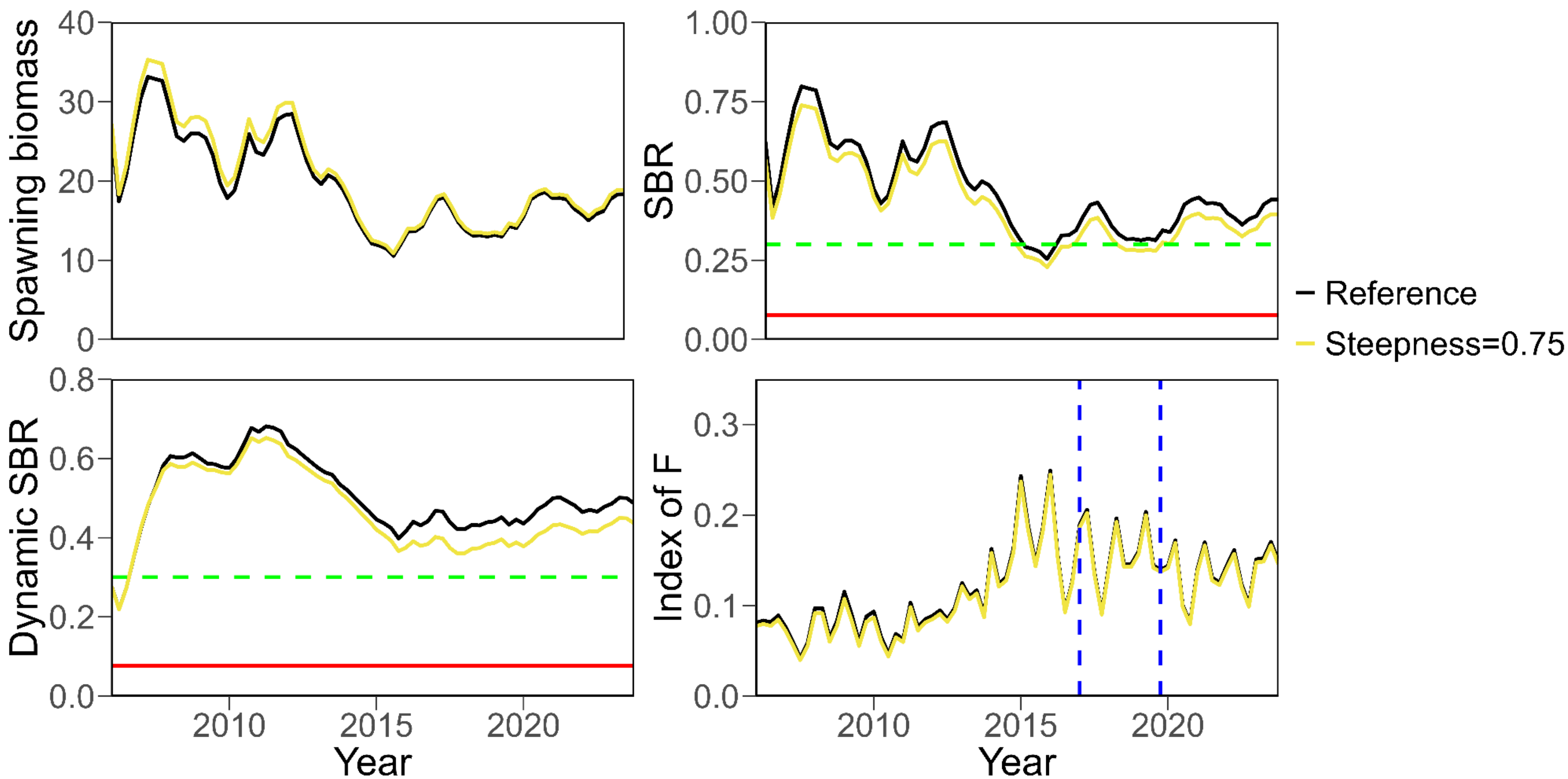

FIGURE 25. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analyses on steepness. The green horizontal dashed line is the target biomass reference point (SBR = 0.3) and the red horizontal solid line is the limit biomass reference point (SBR = 0.077). The two vertical lines represent the *status quo* period (2017-2019).

FIGURA 25. Biomasa reproductora, cociente de biomasa reproductora, cociente de biomasa reproductora dinámica y un índice de la tasa de explotación trimestral para los análisis de sensibilidad de la inclinación. La línea horizontal verde discontinua es el punto de referencia objetivo de biomasa (SBR = 0.3) y la línea roja horizontal sólida es el punto de referencia límite de biomasa (SBR = 0.077). Las dos líneas verticales representan el periodo de *statu quo* (2017-2019).

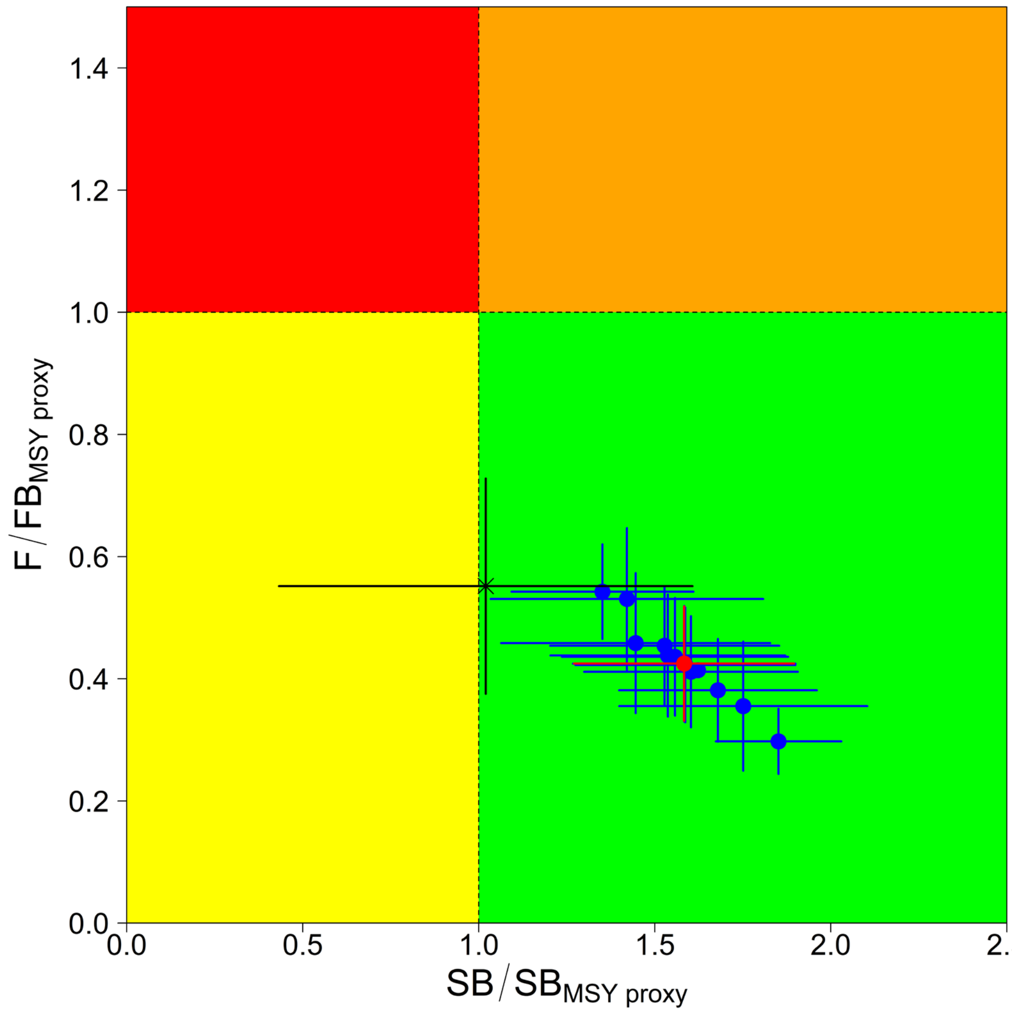

FIGURE 26. Kobe plot showing the most recent stock status estimates from all the models. The x-axis is SB_{currnt}/0.3*dynamic SB_0. Each dot is based on the average *F* over the most recent three years, 2021-2023, and the error bars represent the 80% confidence intervals of model estimates. The red dot and error bars represent the estimates from the reference model. The black cross and error bars represent the estimates from the model that removed the ECHO index.

FIGURA 26. Gráfica de Kobe que muestra las estimaciones más recientes de la condición de la población de todos los modelos. El eje *'x'* es SB_{actual}/0.3* SB_0dinámica. Cada punto se basa en la *F* promedio de los tres años más recientes, 2021-2023, y las barras de error representan los intervalos de confianza del 80% de las estimaciones del modelo. El punto rojo y las barras de error representan las estimaciones del modelo de referencia. La cruz negra y las barras de error representan las estimaciones del modelo que eliminó el índice ECO.

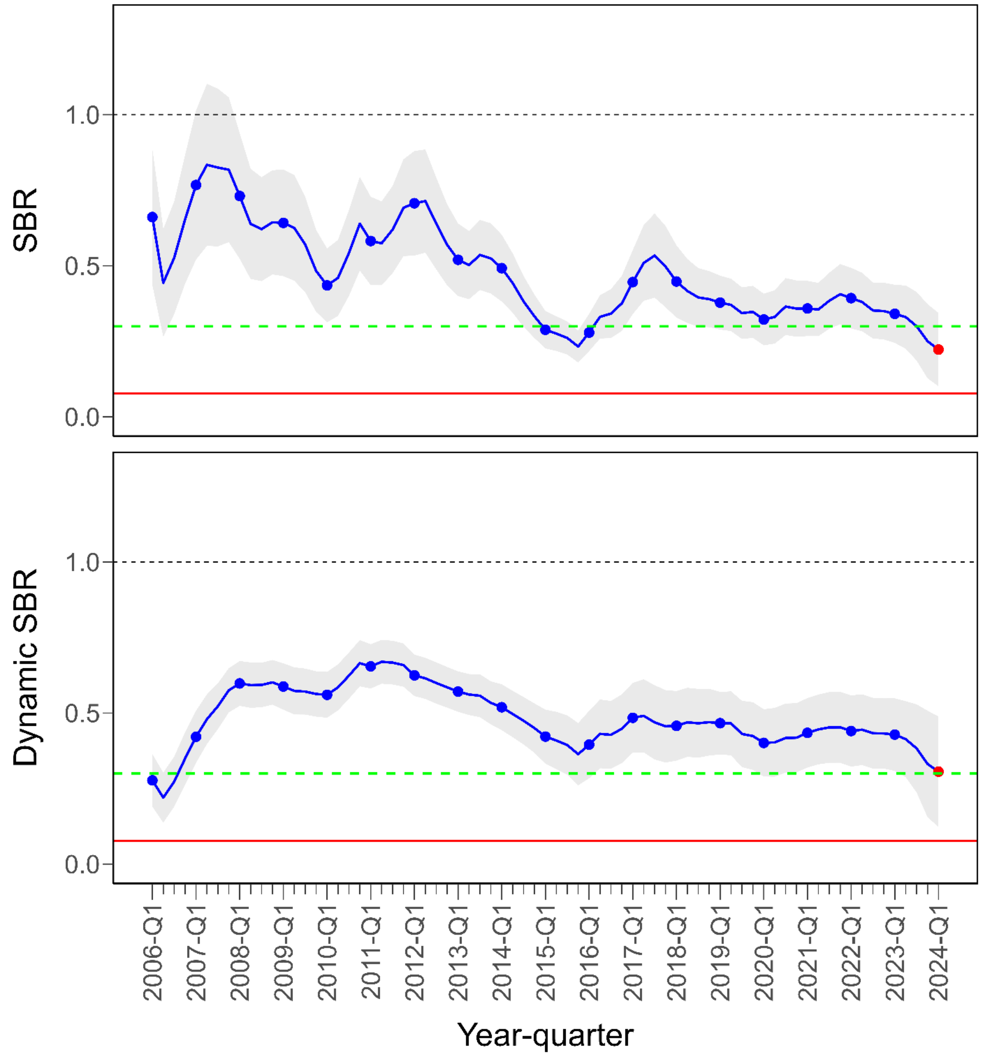

FIGURE 27. Spawning biomass ratio (SBR; top) and dynamic spawning biomass ratio (dynamic SBR; bottom) for skipjack tuna in the EPO, 2006-current estimated by the model that removed the ECHO index. The red points indicate the model estimates in the first quarter of 2024. The blue points represent the first quarter of each year. The solid lines represent the maximum likelihood estimates and the shaded area the approximate 80% confidence intervals around those estimates. The uncertainty around the dynamic spawning biomass ratio is borrowed from that around the fishery mortality. The green horizontal dashed line is the target biomass reference point (SBR = 0.3) and the red horizontal solid line is the limit biomass reference point (SBR = 0.077).

FIGURA 27. Cociente de biomasa reproductora (SBR; arriba) y cociente de biomasa reproductora dinámica (SBR dinámica; abajo) para el atún barrilete en el OPO, 2006-presente, estimados por el modelo que eliminó el índice ECO. Los puntos rojos indican las estimaciones del modelo en el primer trimestre de 2024. Los puntos azules representan el primer trimestre de cada año. Las líneas continuas representan las estimaciones de verosimilitud máxima y el área sombreada representa los intervalos de confianza (IC) de 80% aproximados en torno a esas estimaciones. La incertidumbre en torno al cociente de biomasa reproductora dinámica se toma prestada de la que existe en torno a la mortalidad por pesca. La línea horizontal discontinua verde es el punto de referencia objetivo de biomasa (SBR = 0.3) y la línea roja horizontal sólida es el punto de referencia límite de biomasa (SBR = 0.077).

TABLES

TABLE 1. Fisheries defined for the benchmark stock assessment of skipjack tuna in the EPO in 2024. **Gear**: PS: purse seine; LL: longline; **PS set type**: OBJ: floating object; NOA: unassociated; DEL: dolphin; **Area**: see Figure 1.

TABLA 1. Pesquerías definidas para la evaluación de referencia de la población de atún barrilete en el OPO en 2024. **Arte de pesca**: PS: cerco; LL: palangre. **Tipo de lance PS**: OBJ: sobre objetos flotantes; NOA: no asociado; DEL: sobre delfines. **Área**: ver Figura 1.

Fishery/survey	Gear	Set type	Area	Fish size	Units
F1	Purse seine	OBJ	Offshore	Small	Weight
F2	Purse seine	OBJ	Offshore	Large	Weight
F3	Purse seine	OBJ	Central	Small	Weight
F4	Purse seine	OBJ	Central	Large	Weight
F5	Purse seine	OBJ	Southern coastal	All	Weight
F6	Purse seine	OBJ	Central coastal	All	Weight
F7	Purse seine	OBJ	Northern coastal	All	Weight
F8	Purse seine	NOA	Offshore	Small	Weight
F9	Purse seine	NOA	Offshore	Large	Weight
F10	Purse seine	NOA	South	All	Weight
F11	Purse seine	NOA	Central	All	Weight
F12	Purse seine	NOA	North	All	Weight
F13	Purse seine	DEL	North	All	Weight
F14	Purse seine	DEL	South	All	Weight
F15	Purse seine discards	All	EPO	All	Weight
F16	Longline	NA	EPO	All	Number
S1	Purse seine	OBJ	EPO	All	Weight
S2	Purse seine	NOA	EPO	All	Weight
S3	Echosounder buoy	NA	EPO	All	Weight
S4	Tagging-based absolute	NA	EPO	All	Weight
S5	Tagging-based relative	NA	EPO	All	Weight

TABLE 2. The decisions for selectivity and composition data weighting according to each fishery's catch amount and composition data quality. The rules on which this decision table is based are illustrated as a flow chart in Figure 9. Column "Double-normal" indicates whether the length composition data of the fleet can be fit well in the assessment model by using a double-normal selectivity curve. Column "Data quality" indicates the relative quality of the fleet's length composition data. Column "Time blocks" indicates whether and how the selectivity of the fleet is time-varying. Column "Weighting scaler" indicates how the length composition data of the fleet is weighted in the assessment model in comparison to the Francis weighting method.

TABLA 2. Decisiones de ponderación de los datos de selectividad y composición en función de la cantidad de captura de cada pesquería y de la calidad de los datos de composición. Las reglas en las que se basa esta tabla de decisiones se ilustran en forma de diagrama de flujo en la Figura 9. La columna "Doble normal" indica si los datos de composición por talla de la flota pueden ajustarse bien en el modelo de evaluación utilizando una curva de selectividad doble normal. La columna "Calidad de los datos" indica la calidad relativa de los datos de composición por talla de la flota. La columna "Bloques de tiempo" indica si la selectividad de la flota varía con el tiempo y de qué manera. La columna "Escalador de ponderación" indica cómo se ponderan los datos de composición por talla en el modelo de evaluación en comparación con el método de ponderación de Francis.

Fleet Number	Fleet type	Fleet name	Catch amount	Double-normal	Data quality	Selectivity	Time blocks	Weighting scaler
1	OBJ Fishery	F1-OBJ_Offshore_Small	High	Yes	High	Estimated	2006-2015; 2016-2023	1
2		F2-OBJ_Offshore_Large	Low	Yes	High	Estimated	NA	0.2
3		F3-OBJ_Central_Small	Low	Yes	High	Estimated	NA	0.2
4		F4-OBJ_Central_Large	Low	Yes	High	Estimated	NA	0.2
5		F5-OBJ_SC	Low	Yes	Low	Estimated	NA	0.2
6		F6-OBJ_CC	High	Yes	High	Estimated	2006-2015; 2016-2023	1
7		F7-OBJ_NC	High	Yes	High	Estimated	2006-2015; 2016-2023	1
8	NOA Fishery	F8-NOA-Offshore_Small	Low	Yes	Low	Estimated	NA	0.2
9		F9-NOA-Offshore_Large	Low	Yes	Low	Estimated	NA	0.2
10		F10-NOA-S	High	Yes	Low	Estimated	NA	0.2
11		F11-NOA-C	High	Yes	High	Estimated	2006-2015; 2016-2023	1
12		F12-NOA-N	Low	Yes	High	Estimated	NA	0.2
13	DEL Fishery	F13-DEL-N	Low	Yes	High	Estimated	NA	0.2
14		F14-DEL-S	Low	Yes	Low	Mirror F13	NA	0
15	Other Fishery	F15-DISsmall	Low	No	NA	Fixed	NA	0
16		F16-LL	Low	No	NA	Estimated	NA	0.2
17	Survey	S1-OBJ	NA	Yes	High	Estimated	NA	1
18		S2-NOA	NA	Yes	High	Estimated	NA	0
19		S3-Echo	NA	Yes	High	Mirror S1	NA	0
20		S4-TAG	NA	Yes	High	Mirror S1	NA	0
21		S5-TAG-RELATIVE	NA	Yes	High	Mirror S1	NA	0

TABLE 3. Estimates of spawning biomass (SB), spawning biomass ratio (SBR) and dynamic spawning biomass ratio (dSBR) at the beginning of 2024, average recruitment over the model time period (except the 4th quarter of 2023) as a ratio of the estimated virgin recruitment for all of the models, average exploitation rate in 2022 as a ratio of the *status quo*, average exploitation rate in 2023 as a ratio of the *status quo*, and current fishing mortality (the average *F* over the most recent three years, 2021-2023) as a ratio of the fishing mortality corresponding to $B_{\text{MSY proxy}} = 0.3B_0$. R_{ave}/R_0 is a check to make sure the SBR based on B_0 is not biased due to the bias correction for recruitment residuals (this will affect the plots of SBR that are plotted with confidence intervals). The dSBR is adjusted by the ratio R_{ave}/R_0. The red highlighting and text indicate where SBR or dSBR are below the proxy target reference point (0.3) and when the *status quo* fishing mortality (average of 2017-2019) has been exceeded.

TABLA 3. Estimaciones de biomasa reproductora (SB), cociente de biomasa reproductora (SBR), y cociente de biomasa reproductora dinámica (dSBR) a principios de 2024, reclutamiento promedio a lo largo del periodo del modelo (excepto el cuarto trimestre de 2023) como razón del reclutamiento virgen estimado para todos los modelos, tasa promedio de explotación en 2022 como razón del *statu quo*, tasa promedio de explotación en 2023 como razón del *statu quo*, y mortalidad por pesca actual (la *F* promedio de los tres últimos años, 2021-2023) como razón de la mortalidad por pesca correspondiente a $B_{\text{RMS sust}} = 0.3B_0$. R_{prom}/R_0 es una comprobación para asegurarse de que el SBR basado en B_0 no esté sesgado debido a la corrección del sesgo por los residuales de reclutamiento (esto afectará a las gráficas de SBR que se trazan con intervalos de confianza). El dSBR se ajusta por la razón R_{prom}/R_0. Las celdas y el texto en rojo indican los casos en que el SBR o dSBR están por debajo del punto de referencia objetivo sustituto (0.3) y cuando se ha rebasado la mortalidad por pesca del *statu quo* (promedio de 2017-2019).

ID	Model	SB_{cur}	SBR_{cur}	$dSBR_{cur}$	R_{av}/R_0	F_{2022}/F_{sq}	F_{2023}/F_{sq}	$F_{cur}/FB_{\text{MSY proxy}}$
	Reference model	17809	0.43	0.47	0.95	0.85	0.85	0.42
a1	Eatimating L_{inf}	17873	0.43	0.48	0.95	0.85	0.85	0.42
a2	L_{inf} = 78 cm	16769	0.42	0.46	0.95	0.85	0.85	0.45
a3	L_{inf} = 88 cm	18181	0.43	0.48	0.96	0.85	0.84	0.41
a4	Estimating L_{cv}	14055	0.41	0.43	1.01	0.82	0.82	0.46
a5	L_{cv} = 0.03	18926	0.43	0.49	0.94	0.86	0.85	0.41
a6	L_{cv} = 0.09	16612	0.42	0.46	0.97	0.84	0.84	0.44
a7	Estimating growth shape parameter	17814	0.43	0.48	0.95	0.85	0.85	0.42
b1	Constant longline selectivity after 78 cm	17873	0.43	0.48	0.95	0.85	0.85	0.42
b2	Constant longline selectivity after 83 cm	17818	0.43	0.48	0.95	0.85	0.85	0.42
b3	Constant longline selectivity after 88 cm	17826	0.43	0.48	0.95	0.85	0.85	0.42
b4	F9 asymptotic selectivity, fixed longline selectivity and no fit for longline size composition	17263	0.42	0.47	0.96	0.85	0.85	0.44
c1	Using the most precise tagging-based absolute index and upweight by ten times	13357	0.37	0.41	0.95	0.90	0.87	0.54
c2	Using four tagging-based absolute indices with low CVs and weight by one	20018	0.46	0.50	0.96	0.83	0.83	0.38
d1	No tagging-based absolute index	21849	0.47	0.53	0.96	0.83	0.83	0.36
d2	No echosounder buoy index	8543	0.22	0.31	0.96	1.00	1.07	0.55
d3	Including longline survey index and size composition	24444	0.50	0.56	0.95	0.80	0.85	0.30
e1	Steepness = 0.75	18420	0.39	0.43	0.92	0.85	0.84	0.53