INTER-AMERICAN TROPICAL TUNA COMMISSION

SCIENTIFIC ADVISORY COMMITTEE

13TH MEETING

La Jolla, California (USA)
16-20 May 2022

DOCUMENT SAC-13-07

SKIPJACK TUNA IN THE EASTERN PACIFIC OCEAN, 2021: INTERIM ASSESSMENT

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EXECUTIVE SUMMARY

1. An integrated statistical age-structured catch-at-length stock assessment was developed for skipjack tuna in the eastern Pacific Ocean using Stock Synthesis.
2. The assessment is similar to those conduced for bigeye and yellowfin tuna and is fit to indices of relative abundance and length composition data.
3. Although the assessment is termed *interim* by the staff, the staff considers it reliable for management advice. The term *interim* results from additional improvements being expected on the skipjack assessment under the ongoing 2021-proposed methodology and workplan to develop a stock assessment for skipjack in the EPO that includes tagging data.
4. There is substantial uncertainty about several model assumptions and sensitivity analyses are conducted to determine if the management advice is robust to the uncertainty. In particular, there is uncertainty about why the large skipjack are not seen in the purse-seine fishery. This could be due to dome-shaped selectivity, high fishing mortality, high natural mortality for old fish, or a rapid decline in growth rates for older fish.
5. Several data sources are available to fit the model, but there is uncertainty about their reliability. Sensitivity analyses are conducted to determine if the management advice is robust to the use of the different data sources. Relative indices of abundance include: a) a longline index, for which the sample size is low; b) catch-per-set indices for purse-seine sets, by set type (floating objects, free swimming

schools), for which the relationship between catch-per-set and abundance is uncertain; and, c) an index based on echosounder buoy data, which has recently been developed.

6. A reference model is developed based on the most plausible assumptions and sensitivity analyses are conducted by changing the assumptions of the reference model.
7. The diagnostics indicate that a data conflict exists, and that this was reduced somewhat when the stock east of 120°W was assessed separately. However, the management results were robust to the inclusion or exclusion of the index of abundance and length composition data sets.
8. MSY-based quantities cannot be estimated 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, implying that the optimal fishing mortality should be infinite. Therefore, a conservative *proxy* for the target biomass of SBR = 0.3 based on values for bigeye and yellowfin, and the fishing mortality corresponding to that biomass, are used as the target reference points.
9. The reference model estimated that the 2021 exploitation rate was slightly above *status quo* (average level of 2017-2019) as did over half of the sensitivity models ranging from being only slightly above to being 0.1 higher (except one model that estimated high exploitation rates).
10. The reference model and most of the sensitivity analyses estimate that the current biomass is above the target reference point and the fishing mortality is below the target fishing mortality.
11. The model will continue to be improved towards the benchmark assessment in 2023, including incorporating the results of the analysis of recently collected tagging data.

RESUMEN EJECUTIVO

1. Se desarrolló una evaluación estadística integrada de captura a la talla estructurada por edad para el atún barrilete en el Océano Pacífico oriental utilizando Stock Synthesis.
2. La evaluación es similar a las realizadas para el atún patudo y el atún aleta amarilla y se ajusta a índices de abundancia relativa y datos de composición por talla.
3. Aunque el personal califica la evaluación como *provisional*, la considera fiable para el asesoramiento de ordenación. El término “*provisional*” se debe a que se espera que haya mejoras adicionales en la evaluación del barrilete conforme a la metodología y plan de trabajo propuestos en 2021 que están en curso para desarrollar una evaluación de la población de barrilete en el OPO que incluya datos de marcado.
4. Existe incertidumbre sustancial sobre varios supuestos del modelo y se realizan análisis de sensibilidad para determinar si el asesoramiento de ordenación es robusto a dicha incertidumbre. En particular, existe incertidumbre sobre por qué no se observan barriletes grandes en la pesquería cerquera. Esto podría deberse a una selectividad en forma de domo, una alta mortalidad por pesca, una alta mortalidad natural de los peces viejos o a un descenso rápido de las tasas de crecimiento de los peces más viejos.
5. Se dispone de varias fuentes de datos para ajustar el modelo, pero su fiabilidad es incierta. Se llevan a cabo análisis de sensibilidad para determinar si el asesoramiento de ordenación es robusto al uso de las diferentes fuentes de datos. Los índices de abundancia relativa incluyen: a) un índice de palangre, para el que el tamaño de muestra es bajo; b) índices de captura por lance para lances cerqueros, por tipo de lance (objetos flotantes, cardúmenes libres), para los que la relación entre la captura por lance y la abundancia es incierta; y, c) un índice basado en datos de boyas con ecosonda, que se desarrolló recientemente.

6. Se desarrolla un modelo de referencia basado en los supuestos más plausibles y se realizan análisis de sensibilidad cambiando los supuestos del modelo de referencia.
7. Los diagnósticos indican que existe un conflicto de datos, y que éste se redujo en cierta medida cuando se evaluó por separado la población al este de 120°O. Sin embargo, los resultados de ordenación fueron robustos a la inclusión o exclusión de los conjuntos de datos de composición por talla e índices de abundancia.
8. Las cantidades basadas en el RMS no pueden estimarse porque el balance entre el crecimiento y la mortalidad natural, en combinación con el supuesto de que el reclutamiento es independiente del tamaño de la población, implican que deberían capturarse a las edades más tempranas para maximizar el rendimiento, lo que implica que la mortalidad por pesca óptima debería ser infinita. Por lo tanto, se utilizan un *sustituto* conservador para la biomasa objetivo de SBR = 0.3 con base en los valores del patudo y el aleta amarilla, y la mortalidad por pesca correspondiente a esa biomasa, como puntos de referencia objetivo.
9. El modelo de referencia estimó que la tasa de explotación de 2021 fue ligeramente superior al *status quo* (nivel promedio de 2017-2019), al igual que más de la mitad de los modelos de sensibilidad, que abarcaron estar entre ligeramente y 0.1 por encima (excepto un modelo que estimó tasas de explotación elevadas).
10. El modelo de referencia y la mayoría de los análisis de sensibilidad estiman que la biomasa actual está por encima del punto de referencia objetivo y que la mortalidad por pesca está por debajo de la mortalidad por pesca objetivo.
11. Se seguirá mejorando el modelo hacia la evaluación de referencia de 2023, incluyendo la incorporación de los resultados del análisis de los datos de marcado recolectados recientemente.

1. INTRODUCTION

This report presents the results of a 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 3.30.19.00). It is the first assessment of the species based on an integrated age-structured model undertaken by the IATTC scientific staff since 2005, and it is also the first conventional stock assessment considered reliable by the staff for use in management advice. Although the assessment is termed *interim* by the staff, the staff considers it reliable for management advice. The term *interim* results from additional improvements being expected in the skipjack assessment under the ongoing 2021-proposed methodology and workplan to develop a stock assessment for skipjack in the EPO that includes tagging data (see Document SAC-12-06). All model input files and output results for this interim assessment are available in html and pdf formats.

1.1 Background

The previous benchmark assessment was carried out in 2005 using the ASCALA methodology (Maunder and Harley, 2005). This assessment was considered 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. The last attempt at evaluating the stock status of skipjack in the EPO was by Maunder (2012), in which a variety of methods were applied (fishery and biological indicators, analysis of tagging data, a length-structured stock assessment model, and a Spatial Ecosystem and Population Dynamic Model (SEAPODYM)). Again, any evaluation of the skipjack stock status relative to traditional reference points (e.g. MSY-based) was not possible.

While no form of reliable conventional assessment has been available for skipjack, the IATTC staff has relied on a Productivity and Susceptibility Analysis (PSA) rationale to make inferences about the stock 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. More recently, in 2020, the staff has 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.

An important development from the implementation of Resolution C-21-04 is that the PSA rationale previously used by the staff to assess skipjack on an *interim* basis is no longer valid. 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 IVL 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 2021, the staff put forward a plan to develop a new (*interim*) stock assessment for skipjack (IATTC 98 INF-F), the present stock assessment being the product of this plan. Although the assessment is termed *interim* by the staff, the staff considers it reliable for management advice. The term *interim* results from additional improvements being expected on the skipjack assessment under the ongoing 2021-proposed methodology and workplan to develop a stock assessment for skipjack in the EPO that includes tagging data (see Document SAC-12-06). Spatio-temporal modelling will be used to analyze the recently available tagging data obtained by the IATTC multi-year Regional Tuna Tagging Program in the EPO (RTTP-EPO 2019-2020, Project E.4.a) and address the issues of incomplete mixing of the tagged fish. Preliminary results of the spatio-temporal analysis will be presented at the 2022 SAC (SAC-13-08), and the final benchmark assessment at the 2023 SAC. The inclusion of the information from the tagging data is expected to improve the assessment results. However, the staff believes that the *interim* assessment and the analyses to evaluate the robustness of the management advice to the model assumptions can be used for management advice for skipjack (SAC-13-07).

A stock assessment is conducted for skipjack using Stock Synthesis, which is the integrated stock assessment modeling platform used for the bigeye and yellowfin tuna assessments. The goal is to evaluate alternative values for the uncertain assumptions and the different data sets to determine the absolute and relative stock status and its robustness to these assumptions. The assessment is conducted for the period 2006 to 2021, 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, and eliminates a period of the early 2000's where the longline abundance index was highly variable. 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.

The assessment provides two types of estimates that can be used for management advice: 1) absolute estimates of stock status relative to proxy reference points; and 2) stock status estimates relative to the *status quo period* (2017-2019) when the PSA rationale was still valid and the staff assessed the stock to be healthy relative to the target and limit reference points established under Resolution C-16-02.

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 assessing the stocks are obtained from the fishery including an index of abundance based on echosounder buoys that are used in the purse-seine OBJ fishery (FAD-06-03). 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. Four "surveys" were created for use in the skipjack assessment: 1) an index of abundance based on catch-per-set in the floating-object purse-seine fishery (SAC-13 INF-K); 2) an index of abundance based on catch-per-set in the unassociated purse-seine fishery (SAC-13 INF-K); 3) an index of abundance based on echosounder buoys (FAD-06-03); and, 4) catch in numbers of fish per hook for the Japanese longline fishery.

2.1.1 Fisheries

Twelve 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 (SAC-13 INF-I). The final fisheries were a compromise between explaining the spatial variability in length composition data and the complexity of the model, which is related to the number of fisheries. Seasonal variation in the length composition data was also investigated, but it explained little of the variability. The spatial variation in the length composition data was inconsistent between the OBJ and NOA fisheries, and therefore we chose to use different fishery definitions for each set type. Four spatially defined fisheries were used for OBJ sets and four fisheries 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, and a single fishery was used for longline. These fisheries definitions are very different from those used in the previous skipjack assessment (Maunder and Harley, 2005).

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. The longline CPUE is treated as a "survey" because it is in numbers, while the catch is in weight. Stock Synthesis has the flexibility to mirror the survey selectivity to one of the fisheries where appropriate (*e.g.,* the longline "survey" mirrors the selectivity of the longline fishery).

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: canneries, on-board observers, vessel logbooks, and in-port sampling by IATTC staff. The catch composition is estimated by strata. Briefly, the total catch of tropical tunas (yellowfin + skipjack + bigeye) for the purse-seine fleet is taken from the cannery, observer or logbook data, and prorated to catch estimation strata (set type x area x month x vessel size class category) using data on operational characteristics collected by observers and reported in logbooks. The port-sampling data are then used to calculate the species and size composition of the catch for each stratum. Detailed explanations of the sampling and estimators can be found in the appendix of Suter (2010) and in WSBET-02-06.

2.2.2 Longline

The IATTC staff does not collect data on longline catches directly; they are reported annually to the IATTC by Members and Cooperating non-Members (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 and coastal CPCs. Longline catches are reported in numbers by some fleets and in weight by others. Since the longline catch of skipjack is only a few percent of the total catch, the annual estimates of catch are simply taken as reported in the FSR and distributed evenly among the quarters.

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 coastal OBJ fishery. 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) increased starting in 2015. The discards due to sorting in the OBJ fisheries show a reduction beginning around 2001, 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

Several 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 abundance based on echosounder buoys (FAD-06-03), and 4) catch in numbers per hook for the Japanese longline fishery.

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., 2020). 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 3.7.1) (Thorson and Barnett 2017, Xu *et al* 2019). VAST fits a delta-generalized linear mixed spatio-temporal model to the data.

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 2015 and then levels off.

2.3.2 Catch per hook for the Japanese longline fishery

Few skipjack tuna are caught in the longline fisheries and therefore the sample size for calculating CPUE based indices of abundance is low. For this reason, the ratio of the sum of the catch divided by the sum of the number of hooks fished for each year-quarter is used as the index of abundance. Only the Japanese longline data is used in the analysis.

The longline index of abundance is low up until about 2006, and then increases to a higher level in 2014 (Figure 3). Afterwards, the longline index declines to 2018 and increases again.

2.3.3 Echosounder buoy index

An index of abundance (ECHO) for skipjack tuna in the EPO was derived for the period 2012-2021. This index was developed based on the signal from satellite-linked GPS tracking echosounder buoys used in the purse-seine OBJ fishery (FAD-06-03). 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 trough high and low levels (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 by the IATTC port-sampling program at ports of landing in Ecuador, Mexico, Panama, and Venezuela. The data available in the port-sampling database is determined by the governing sampling protocol (Suter 2010), which specifies that only those wells with catch from a single 'stratum' are to be sampled; the strata are defined by: type of set (DEL, NOA, OBJ), month and area of fishing (13 areas; see Figure 1 in WSBET-02-06). The catch estimation methodology additionally stratifies the catch into two vessel size class categories (Classes 1-5, 'small'; Class-6, 'large'). 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 (SAC-01-11; SAC-05-06). The sampling coverage in terms of percentage of the catch is lower (SAC-02-10). The sampling areas were designed for yellowfin prior to the development of the fishery on FADs. Since 2000, both the 5° cell and the sampling area have been recorded for almost all samples (SAC-03-10). Ideally, 50 fish of each species in the sampled well were measured, and since 2000 samplers alternate between counting fish by species and measuring fish for length. More details on the port-sampling program can be found in the Appendix of Suter (2010) and in WSBET-02-06. 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. Since 2000, the well 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 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 the OBJ fisheries and, surprisingly, the composition data for the NOA index, which is comprised of the NOA fisheries that do not have a mode at this size (except the secondary mode in the offshore NOA fishery) (Figure 4). The offshore NOA fishery catches the largest skipjack of the purse-seine fisheries (F5), followed by the southern DEL fishery (F10) and the central NOA fishery (F7). The length composition for the offshore NOA fishery is bimodal. Several of the OBJ fisheries have a long right-hand tail of the length composition distribution (*e.g.,* F1, F2, F3).

2.4.1.2 Longline

Few skipjack tuna are caught in the longline fisheries and therefore the sample size for calculating length frequencies are low. For this reason, we simply sum the length compositions for each year-quarter. Only the Japanese longline data is used in the analysis since Japan has the longest time series of length composition data.

The longline length composition shows no fish under 62 cm and the reason for this is not known (Figure 4b). The distribution increases rapidly from about 68 cm, peaks at 78 cm and drops off rapidly after that with few fish over 86 cm.

2.4.2 Survey

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 spatial weighting 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 spatial-temporal 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 purse seine fishery catch-per-set based index were also used for the echosounder buoy index (*i.e.*, they shared selectivity). The longline based index of abundance used the length composition data from the longline fishery (*i.e.*, they shared selectivity; Figure 4b).

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* (Version 3.30.19.00, Methot and Wetzel 2013). Other auxiliary quantities and graphs were computed using the *R* library *r4ss* (version 1.43.2) and original code available from the IATTC repository IATTCassessment.

The model period covers 2006 to 2021. The start year differs from the previous skipjack stock assessments, which started in 1975, and the bigeye and yellowfin assessments, for the reasons mentioned above. 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 was defined in 1-cm intervals from 2 cm to 120 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 2-cm intervals, from 60 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 were assumed to be unbiased and relatively precise and were fitted assuming a lognormal error distribution with standard error (SE) of 0.01.

3.1 Biological and demographic information

3.1.1 Growth

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. Sensitivity to these assumptions is tested.

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 a reasonable age for the size 37 cm skipjack (the smallest size seen in the tagging data) will be robust to that assumption and that a 37 cm skipjack in the EPO is 2 quarters old. A perfect correspondence is not possible due to information on natural mortality being grouped into 10 cm length bins, and therefore this assumption was tested by running sensitivity analyses to the assumed age.

The tagging data were analyzed using several assumptions about the age at 37 cm (2, 3 and 4 quarters) and the asymptotic length (75, 80, 85 cm). Growth was estimated to be linear for the sizes of fish included in the data and this was robust to the assumptions of age at 37 cm and the asymptotic length. Therefore, the medium value of the growth rate parameter across all scenarios was taken, Rmax = 26.54 cm, which was converted to a quarterly time step by dividing by four, to use in the stock assessment model. The median of the parameter controlling when the growth curve bends over was also used (K = 5.71) and divided by four. These parameters were kept constant in all the scenarios even when the asymptotic length or age at 37 cm was changed.

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. A simple assumption is taken that the peak 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 peak implies a small standard deviation (see below). Sensitivity analysis to the assumption about asymptotic length is conducted.

The variability of size at age is also important, as this will also contribute to determining the largest sizes that are plausible in the population. The growth analysis estimates both the measurement error and the individual variability in length at age. These are both relevant when predicting the length composition because the same type of measurement error is expected in the length composition data (note that no adjustments for shrinkage were done in the assessment and this should be considered in future research). The length measurements are taken from the whole time-step of the stock assessment model (quarter), whereas the tagging data is based on the exact times at release and recapture. We calculate this additional variation due to the time within a quarter when a fish is caught as the standard deviation of a uniform distribution between zero growth and a full quarters growth. The latter is constant with age for young skipjack, but there is little or no growth at the asymptotic age, so it is not added to the standard deviation for individuals at the asymptotic size.

$$sd[U(LB,UB)] = \sqrt{\frac{(UB-LB)^2}{12}} = \sqrt{\frac{(26.54/4)^2}{12}} = 1.92$$

This additional variation was added (in terms of variance) to the standard deviation estimated by the growth model (for both observation error and individual variability) for a 37cm fish [(0.0176 + 0.0222) x 37cm = 1.47 cm].

$$sd_{total} = \sqrt{sd_{tag}^2 + sd_U^2}$$

Which gives a total standard deviation of 2.42 and a CV of 0.065.

The CV of the asymptotic length is simply the sum of the coefficients for sd for the observation and process error 0.0176 + 0.0222 = 0.0398.

The standard deviation for fish at the asymptotic length was also estimated from fitting a half normal distribution to the longline length composition data while fixing the mean at the asymptotic length (78 cm). The standard deviation was estimated at 3.85 giving a CV of 0.049. This value is higher than that estimated from the tagging data. These CVs were used in 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 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 and that 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*)

We use 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). The estimate for 70+ cm fish is very high and is likely biased by the dome shape selectivity of the purse seine fishery. Therefore, we also investigate a natural mortality schedule that is constant after 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

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 ages-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). Spatio-temporal 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 assessment it is assumed that the EPO is comprised of a single stock to fulfill management requirements, but the hypothesis of a separate stock east of -120°W is also explored.

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 F1, the purse-seine fishery on floating objects in the offshore 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

Selectivities were modelled as a function of length and were assumed to be dome-shaped for all fleets except for the longline fleet which is assumed to have asymptotic selectivity. All selectivity curves are modelled using cubic splines. 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 40 cm is zero. The dome shape purse seine selectivities are constrained to have a selectivity of zero at 20 cm and at 80 cm (90 cm for F5). Sensitivity analyses were conducted to investigate the robustness of the results to the dome shape selectivity for purse seine fisheries.

3.3 Data weighting

Likelihood functions encompass not only the sampling (observation) variability, but also model misspecification and unmodelled process variability. Therefore, the CVs of the index of abundance are increased by adding a constant to the CVs estimated from the standardization model so that the average CV over the modeled period is 0.20. In the case of the longline based index, we simply use a constant CV of 0.2.

The size-composition data were assumed to have multinomial distributions. The input sample size for the purse-seine fisheries was equal to the number of wells sampled. The number of fish sampled within a well should not be used to represent the sample size because fish stored in the same well may come from the same school and not be independent samples, and their sizes may be highly correlated (Pennington *et al*. 2002). The sample size for the dolphin associated fisheries were divided by 10 because this fishery does not catch much skipjack and it is likely that despite a large number of wells being sampled, few skipjack were sampled in each well. The sample size of the longline fishery was set equal to the number of fish/10 because the catch of skipjack in the longline fishery is low and the length compositions were more variable than would normally be expected.

No further data weighting was attempted. Francis weighting (TA1.8 in Francis 2011) generally indicates further down weighting of the data, while McAllister and Ianelli (1997) weighting tended to want to increase the weighting. Rather than using data weighting methods, we looked at sensitivity analysis of including different data sets and alternative assumptions.

4. MODELS

There is substantial uncertainty in the skipjack assessment. This uncertainty includes the shape of the purse-seine 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 were conducted to test the robustness of the results to the assumptions, particularly the robustness of the estimated stock status.

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 selectivity is asymptotic and purse-seine selectivity is dome-shaped.

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

c) The asymptotic length is 78 cm.

d) The age at 37 cm is 2 quarters.

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

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 longline and the echosounder buoy-based indices of relative abundance are proportional to the population abundance selected by the longline and purse-seine OBJ, respectively, and the other indices (catch-per-set on OBJ and NOA fisheries) are not used.

i) Length compositions for all the fisheries are used in the analysis, but those constructed for the purse-seine index for the NOA fishery are not (those constructed for the purse-seine OBJ index are used for the echosounder buoy index).

4.2 Sensitivity models

Several sensitivity analyses are conducted to determine the robustness of the results to model assumptions and inclusion of different data sets. In particular, the assumptions about why large skipjack are not seen in the purse-seine fishery are investigated. The reference model assumes it is because of dome-shaped selectivity since large fish are seen in the longline fishery. The following describes how the sensitivity models differ from the reference model.

a) Lower asymptotic length. The asymptotic length is set at 73 cm.

b) Higher asymptotic length. The asymptotic length is set at 83 cm.

c) Lower variation of length at age. The CV for variation at the asymptotic length is fixed at 0.05.

d) Higher variation of length at age. The CV for variation at the asymptotic length is fixed at 0.07.

e) Including the improved estimates of catch for 2020 and 2021.

f) Excluding the echosounder buoy index of abundance. The echosounder buoy index of abundance and the associated length composition data are excluded from the model and the associated selectivity not estimated.

g) No longline index of abundance. The longline index of abundance and its associated length composition data are excluded from the model. The selectivity of the longline fishery is fixed at that estimated by the reference case.

h) Inclusion of the purse-seine OBJ catch-per-set index. The index of abundance based on the OBJ catch-per-set is included in the model. The associated length composition data is already included in the model for the echosounder index and the selectivity is shared between these two "surveys".

i) Inclusion of the purse seine NOA catch-per-set index. The index of abundance based on the NOA catch-per-set and associated length composition data is included in the model and the selectivity estimated.

j) NOA asymptotic selectivity. The offshore NOA fishery is constrained to have asymptotic selectivity and the asymptotic length is equal to the mode of the length distribution for this fishery (75 cm). The longline index of abundance and its associated length composition data are excluded from the model. The selectivity of the longline fishery is fixed at that estimated by the reference case. The NOA catch-per-set index of abundance and composition data are used.

k) OBJ asymptotic selectivity. The coastal OBJ fishery is constrained to have asymptotic selectivity and the asymptotic length is equal to the mode of the length distribution for this fishery (65 cm). The longline index of abundance and its associated length composition data are excluded from the model. The DEL and NOA length composition data are excluded from the analysis. The selectivity of the longline, DEL, and NOA fisheries are fixed at that estimated by model p. The OBJ catch-per-set index of abundance is used.

l) Eastern assessment. The assessment is conducted for the EPO area east of -120°W. This involves setting the catch in the offshore fisheries (F1 and F5) to zero, not using their length composition data, and not estimating their selectivities. The ECHO index is from data mainly west of -120°W and therefore it is not used. The OBJ index and its composition data are used instead, but are adjusted to appropriately represent the area east of -120°W. The longline index and composition data are recalculated for the areas east of -120°W. The longline catch is not adjusted because it is small.

m) High natural mortality for old fish. The constant natural mortality after 65 cm assumption is replaced with the higher natural mortality for 75 cm fish as estimated by Hampton (2000), a linear trend between 65 cm and 75 cm, and natural mortality after size 75 cm is assumed to be at this level. Several analyses are carried out: 1) including or 2) excluding the longline data and 3) not constraining the purse-seine fisheries to be dome-shaped (with and without higher M for the old fish).

n) High fishing mortality for old individuals. The selectivity curve for the offshore NOA fishery (F5) is constrained to be constant after the asymptotic length. The longline index and composition data are still fit in the model.

o) Rapid reduction in growth rate for older individuals. The asymptotic length is fixed at 70 cm. Several analyses are carried out: 1) including or 2) excluding the longline data, 3) not constraining the purse-seine fisheries to be dome-shaped, and 4) making the offshore NOA fishery (F5) to have constant selectivity after the asymptotic size.

5. RESULTS

Although there are many models and aspects of the results that are available from this stock assessment, all of this information cannot possibly be presented on this report. Therefore, this report is focused on presenting the results for the reference case and then on results from models that are substantially different from the reference case, or those that provide better diagnostics. Results that provide insight into the reasons for these differences are also presented.

The model is run on a quarterly basis and therefore the labeling of many of the figures use a quarterly time step. In these figures the first period is the first quarter of 2000. This is not the start of the model period, but is a consequence of the period initially considered for the assessment. The table below can be used to convert from elapsed quarter to year (first quarter), when necessary. For example, the start of the model, quarter 1 of 2006 is elapsed quarter 25 and the 4th quarter of 2021 is elapsed quarter 88.

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Elapsed quarter	25	29	33	37	41	45	49	53	57	61	65	69	73	77	81	85	89

5.1 Model diagnostics of the Reference Model

5.1.1 Model convergence

The reference model converged with a low maximum gradient component of 7.89e-05 and a positive definite hessian. No parameters were on the bounds.

5.1.2 Fit to purse-seine indices of abundance

Both the echosounder buoy index and the longline index we included in the model to have average CVs of 0.2. The RMSE for both were much higher (ECHO = 0.34 and 0.46) indicating poor fits. However, they visually provided temporal patterns consistent with the data (Figure 9). The high RMSE, particularly for the longline index, is probably due to extreme values that are low values with a small standard deviation or high values. Interestingly, even though the reference model does not fit to the purse-seine catch-per-set indices, the model estimates similar trends (Figure 10) and the RMSEs are lower (0.26 and 0.31 for the OBJ and NOA, respectively).

5.1.3 Fits to length-frequency data

The reference model fits the average length composition well for all fisheries and for the ECHO index (Figure 4). The latter being 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 this data are not fit 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 Age-structured production model (ASPM) and catch-curve analyses

The age-structured production model without recruitment deviates (ASPM) shows a larger more stable population indicating that the index of abundance does not contain information about absolute abundance without accounting for recruitment variation (Figure 11). 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.

The catch-curve analyses (CCAs) estimates a higher biomass at the start of the time period, but similar abundance at the end. This also suggests that the composition data is controlling the absolute biomass level, but the index constrains the trend.

5.1.4.2 Likelihood profile on R_0

This diagnostic is helpful in determining the relative importance of different data components on the estimates. The likelihood profile on R_0 (in log scale) indicates that there is substantial conflict in the data with the ECHO index preferring larger biomass (larger R_0) and the longline index preferring smaller biomass (Figure 12a). There is also conflict in the composition data and even within the same purse seine set type (Figure 12b and c).

5.1.4.3 Retrospective analyses

The retrospective analyses show the behavior of the models when new data are added. The estimated spawning biomass and spawning biomass ratio shows little influence of eliminating years of data and no systematic pattern (Figure 13).

5.1.5 Parameter estimates

5.1.5.1 Initial conditions

The reference model estimates that the stock was substantially depleted in 2006 (Figure 16), which was a consequence of the high estimated initial fishing mortality (1.05).

5.1.5.2 Selectivity

The use of cubic splines and the long right-hand tails of the length composition data for some fisheries produces bimodal selectivities for many of the purse seine fisheries (Figure 14). Bimodal selectivities indicate that the fishery may combine two or more fishing approaches or that the model is misspecified. The cubic spline is flexible enough to approximate the average length composition, but if the amount of each of the different fishing approaches changes over time, the model may not be taking the fish out of the population at the right size and the information provided about abundance may be biased. This may cause biased results, particularly if the changes are systematic over time. There does not appear to be a lot of systematic pattern in the residuals of the fits to the composition data (Figure 5)

The longline selectivity is made constant after the asymptotic length (78 cm) and is estimated to have a very steep ascending (left) limb (Figure 14). The steep slope is because the composition data for this fishery does not spread much to the left above what the standard deviation of length at age predicts around the asymptotic length. The small bump in selectivity at small sizes is below the truncated length (60 cm) used to fit the length composition and is a consequence of using the cubic splice. Since the skipjack catches by the longline fishery are low, this will not influence the model results.

5.2 Results of the reference model

5.2.1 Recruitment

Estimated recruitment is presented in Figure 15. There are some short-term patterns in recruitment, but no long-term trends.

5.2.2 Fishing mortality (*F*)

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, peaking at the start of the period and around 2016 (Figure 17). There is no indication of increased fishing mortality over time. Although, fishing mortality appeared to be lower in the period 2010 – 2014 and 2018-2021.

5.2.3 Fisheries impacts

The fisheries have had a moderate impact on the spawning biomass (Figures 16 and 18). The impact in the first year is misleading (Figure 18) because the parameterization of the initial age-structure 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 lost after a few years. The fishery impact plots form the basis for calculating the dynamic depletion levels.

5.3 Results of the senstivity analysis

The estimates of depletion level are robust to several of the sensitivity analyses. These include the asymptotic length (Figure 19), CV of the variation of length at age for the oldest individuals (Figure 19), improved catch estimates for 2020 and 2021 (Figure 20), the age at 37 cm (Figure 21), adding the OBJ catch-per-set index of abundance (Figure 22), adding the NOA catch-per-set index of abundance (Figure 22), forcing the NOA offshore fishery (F5) to have constant selectivity after the asymptotic length (78 cm) (Figure 26).

When forcing the NOA offshore fishery (F5) to have constant selectivity after the asymptotic length (78 cm), the selectivity does not go to zero for the oldest ages like the reference case, but it also is not asymptotic (Figure 27). The selectivity for large fish is just over 40% of full selectivity.

The estimates of depletion level are moderately or highly sensitive to several of the sensitivity analyses. These include eliminating the longline index of abundance (Figures 22, 25, 28), eliminating the ECHO index of abundance and its length composition data (Figure 22), which fishery is assumed to have asymptotic selectivity (Figure 23), increasing the natural mortality for old fish (Figure 25), constraining the offshore NOA fishery to have constant selectivity after 70 cm and using a Linf of 70 cm (Figure 28), and when only modelling the stock east of -120°W (Figure 24).

Removing the longline based index of abundance causes the stock to be less depleted at the start of the time series (*e.g.* Figure 22). The ECHO index starts in 2012 and therefore when the longline index is removed, there is no index constraining the biomass trend in the early years. This is also confirmed by the catch curve analysis (Figure 11), which illustrates that the composition data prefer higher biomass in the early years.

Removing the echosounder buoy index causes the depletion level to be less depleted at the end of the time period (Figure 22). The catch curve analysis (Figure 11) estimates the stock to increase at the end of the time period supporting that the length composition data is providing the information on increased biomass at the end of the time period.

Assuming that the purse seine fisheries have asymptotic selectivity results in estimates of a more depleted stock, particularly after the first few years (Figure 23), but these results should be interpreted with caution because the models had convergence problems and the run that had asymptotic selectivity for the inshore floating object fishery did not have a positive definite Hessian.

Increasing the natural mortality for old fish estimates the stock to be less depleted in the latter years (Figure 25). In contrast, if the longline data is ignored and the purse seine fisheries are not constrained to be dome shaped (although the selectivities are estimated to be dome shaped), the stock is estimated to be less depleted in the early part of the time series and more depleted at the end of the time series, which appears to be a consequence of removing the longline data. Interestingly, if the purse seine selectivity is not constrained to be dome shaped, then the increased natural mortality for old fish counteracts the loss of the longline data and does not estimate less depletion at the start of the time series. However, it is estimated to be more depleted at the end of the time series and the total abundance is much lower. None of the purse seine fisheries are estimated to have an asymptotic selectivity.

Lowering the asymptotic length to 70 cm and not constraining the purse seine selectivity to be dome shaped either with or without the longline data is dominated by the impact of eliminating the longline data, but making the offshore NOA fishery (F5) selectivity to be asymptotic causes the stock to be more depleted (Figure 28).

Only assessing the stock east of -120° W resulted in a reduced biomass as expected, but it also resulted in a more depleted stock (Figure 24). The ASPM and catch-curve diagnostics were similar to the reference model, except that the ASPM estimated a much larger biomass (Figure 29). The likelihood component profiles showed some improvement, but there is still some conflict in the data (Figure 30). The retrospective analysis showed no indication of model misspecification (Figure 31). There were still bimodal selectivities (Figure 32). The fit to the longline data is about the same and the fit to the OBJ catch-per-set is reasonable (Figure 33). The fit to the purse seine length composition data is simlar to the reference model, but the longline length frequency observations have defined modes, which the model does not fit (Figure 34).

6. STOCK STATUS

Resolution C-16-02 defines target and limit reference points, expressed in terms of spawning biomass (S) and fishing mortality (F), for the tropical tuna species: bigeye, yellowfin, and skipjack. The IATTC adopted S_{MSY} (the spawning biomass corresponding to the MSY) and F_{MSY} (the fishing mortality rate corresponding to the MSY) in 2014 as the target reference points, and the spawning biomass that produces 50% of the virgin recruitment (R_0) with the stock-recruitment relationship follows the Beverton-Holt function with a steepness (h) of 0.75, and F_{LIMIT} (the fishing mortality rate corresponding to that biomass) as limit reference points.

Previous assessments of skipjack tuna in the EPO have found estimation of target reference points problematic because recruitment is assumed to be independent of stock-size and maximum yield-per-recruit is obtained by catching fish at ages younger than the age at entry into the fishery.

The maximum yield-per-recruit is theoretically obtained when the cohort is harvested at an age when its biomass is maximized, which occurs at

$$N_{a+\Delta}w_{a+\Delta} = N_a w_a$$

Which occurs when growth balances natural mortality

$$\frac{w_{a+\Delta}}{w_a} = \frac{N_a}{N_{a+\Delta}}$$

Because of the fast growth and high natural mortality of skipjack, this theoretical age is very young.

Our analyses also found estimation of reference points problematic. The optimal yield occurs by capturing the fish as young as possible. There is only a narrow range of ages where the growth is higher than survival (3-5 quarters) and where the biomass of the cohort increases. Within this short age range the cohort's biomass is maximized at 6 quarters (Figure 35). However, since the overall selectivity of all fisheries combined includes ages older than age 6, the yield calculations estimate that increasing mortality always increases yield. Therefore, MSY based reference points are not available for skipjack and proxies will have to be used. In contrast, the limit reference points are not based on maximizing yield and can be calculated.

The **spawning biomass limit reference point (S_{LIMIT})** is the threshold value of S that should be avoided because further depletion could endanger the sustainability of the stock. The interim S_{LIMIT} adopted by the IATTC in 2014 is the spawning biomass that produces 50% of the virgin recruitment (R_0) if the stock-recruitment relationship follows the Beverton-Holt function with a steepness (h) of 0.75. This spawning biomass is equal to 0.077 of the equilibrium virgin spawning bio mass (S_0) (SAC-05-14). The HCR requires action be taken if the probability (P) of the spawning biomass (S_{current}) being below S_{LIMIT} is greater than 10%. Thus, to provide management advice, $S_{\text{current}}/S_{\text{LIMIT}}$, and the probability of $S_{\text{current}} < S_{\text{LIMIT}}$ (or P($S_{\text{current}}/S_{\text{LIMIT}}$ <1) needs to be calculated.

The **fishing mortality limit reference point (F_{LIMIT})** is the threshold value of F that should be avoided because fishing more intensively could endanger the sustainability of the stock. The interim F_{LIMIT} adopted by the IATTC in 2014 is the fishing mortality rate that, under equilibrium conditions, maintains the spawning population at S_{LIMIT}. The HCR requires action to be taken if the probability of the average fishing mortality during 2017-2019 (F_{current}) being above F_{LIMIT} is greater than 10%.

Since MSY based target reference points are not available for skipjack tuna, we use those estimated for bigeye and yellowfin as a proxy. The range for bigeye tuna is most sensitive to the steepness of the Beverton-Holt stock-recruitment relationship and the range for yellowfin is sensitive to a variety of factors (Table 2). For a steepness of h = 1, which is the assumption made in the skipjack assessment, the range for bigeye is S_{MSY}/S_0 = 0.20 – 0.24 and the range for yellowfin is S_{MSY}/S_0 = 0.23 - 0.32. Other ranges can be seen in Table 2. As a conservative reference proxy for skipjack we use 0.30.

Estimating the spawning biomass ratio (SBR; spawning biomass divided by the spawning biomass in the unfished state) has several issues that need to be addressed. First, the lognormal bias correction factor [$exp(-0.5\sigma_R^2)$] that is applied to the recruitment deviates to estimate the recruitment influences the estimated recruitment relative to the virgin recruitment parameter (R_0). Therefore, often R_0 (when recruitment is assumed to be independent of stock size) does not equal the average recruitment over the time period that is desired to represent average recruitment. To ensure that this is at least approximately true, the value of σ_R^2 has to be iteratively changed to make σ_R^2 equal to the standard deviation of the recruitment deviates. Initial model runs with $\sigma_R = 1.0$ suggested that $\sigma_R = 0.6$ is more appropriate and therefore it was used in all models, but there still may be some influence of the value of σ_R^2. The other issue is that the average level of recruitment may change over time even in the absence of fishing so that the perceived depletion level represented by the virgin recruitment may not reflect the real depletion level. Therefore, the dynamic spawning biomass in the absence of fishing, shown in the fisheries impact plots used historically by the IATTC (dynamic depletion) should be used to calculate the depletion level. The dynamic depletion level is based on the historic level of recruitment and is particularly relevant for stocks like skipjack for which recruitment is highly variable and not related to stock size. In this case, the value of σ_R does not influence the depletion level. We use dynamic depletion to evaluate the target reference point and equilibrium adjusted by the average recruitment to evaluate the limit reference point.

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 (SBR_d) spawning biomass ratio (Table 3). Only three of the sensitivity analyses estimate that the stock is below the proxy target (Figures 36 and 40). In these three sensitivity analyses, the unassociated fishery is assumed to have asymptotic selectivity and/or when the longline data are not used (sensitivities j, m3.M, and o4). None of these 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 16). Of the three pessimistic models mentioned above, only one comes close to exceeding the limit reference point by 10% (Figures 37-39) and exceeds the limit for the start of 2022 simply because it includes a recruitment that is not informed by the data and increases the estimate of uncertainty. This sensitivity analysis is the one that does not use the longline data, does not constrain the purse-seine selectivity to be dome-shaped, and allows the natural mortality to be higher for fish greater than 65 cm.

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 SBR_d 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 40). It is also lower than the fishing mortality estimated by all sensitivity analyses except the sensitivity that excludes the longline data, does not constrain the purse-seine selectivity to be dome-shaped, and has a higher natural mortality for older fish (Table 3; Figure 25).

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 2020 exploitation rates were much less than *status quo* and the 2021 exploitation rates were slightly above *status quo* (Table 3). Only one model estimated exploitation rates that exceeded the *status quo* in 2020 (Model m3 M) and over half of the models estimated it did in 2021, ranging from only slightly to by 0.1, except model m3 M (Table 3).

7. FUTURE DIRECTIONS

A benchmark assessment is planned for 2023 and work is currently underway to analyze the recent tagging data for inclusion in this assessment. In addition to the research related to the tagging data (SAC-13-07), other improvements to the assessment are possible. These may include:

- Investigations on stock structure and further evaluation of the eastern model;
- Refine the fishery definitions to remove bimodal and other undesirable length composition distributions and selectivities.
- Investigate alternative selectivity patterns to avoid bimodal and other undesirable selectivity patterns
- Consider the possibility of changes in selectivity as indicated by the catch curve analysis
- Adjusting the length composition data for shrinkage;
- Using the offshore OBJ length composition data for the echosounder buoy index of abundance;
- Improve the estimates of natural mortality using the tagging data and other available information;
- Spatio-temporal modelling of the longline CPUE and composition data.

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.

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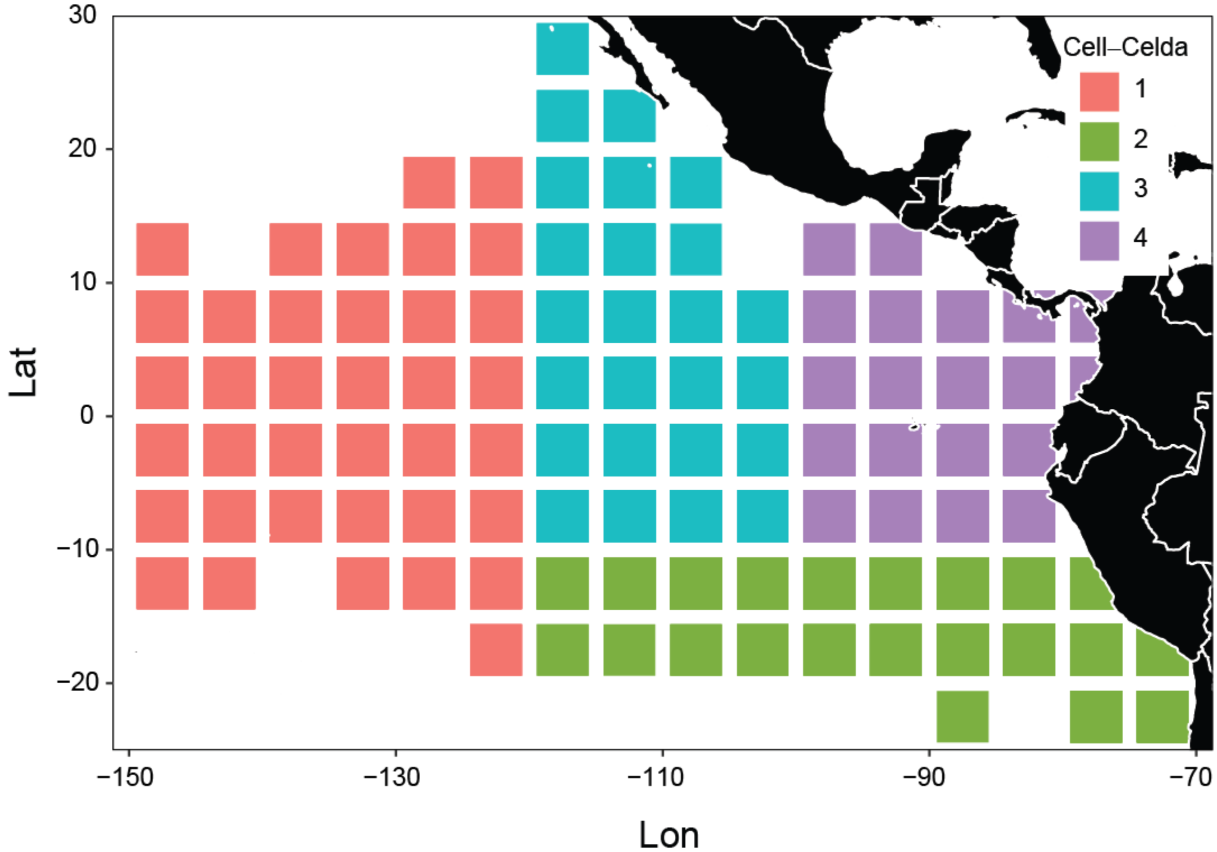

FIGURE 1a. Areas corresponding to the floating object fishery definitions used in the stock assessment of skipjack tuna in the EPO in 2022 (Table 1). The filed squares indicate the data used to conduct the analysis to define the fisheries, which is not necessarily the same as the data used in the stock assessment.

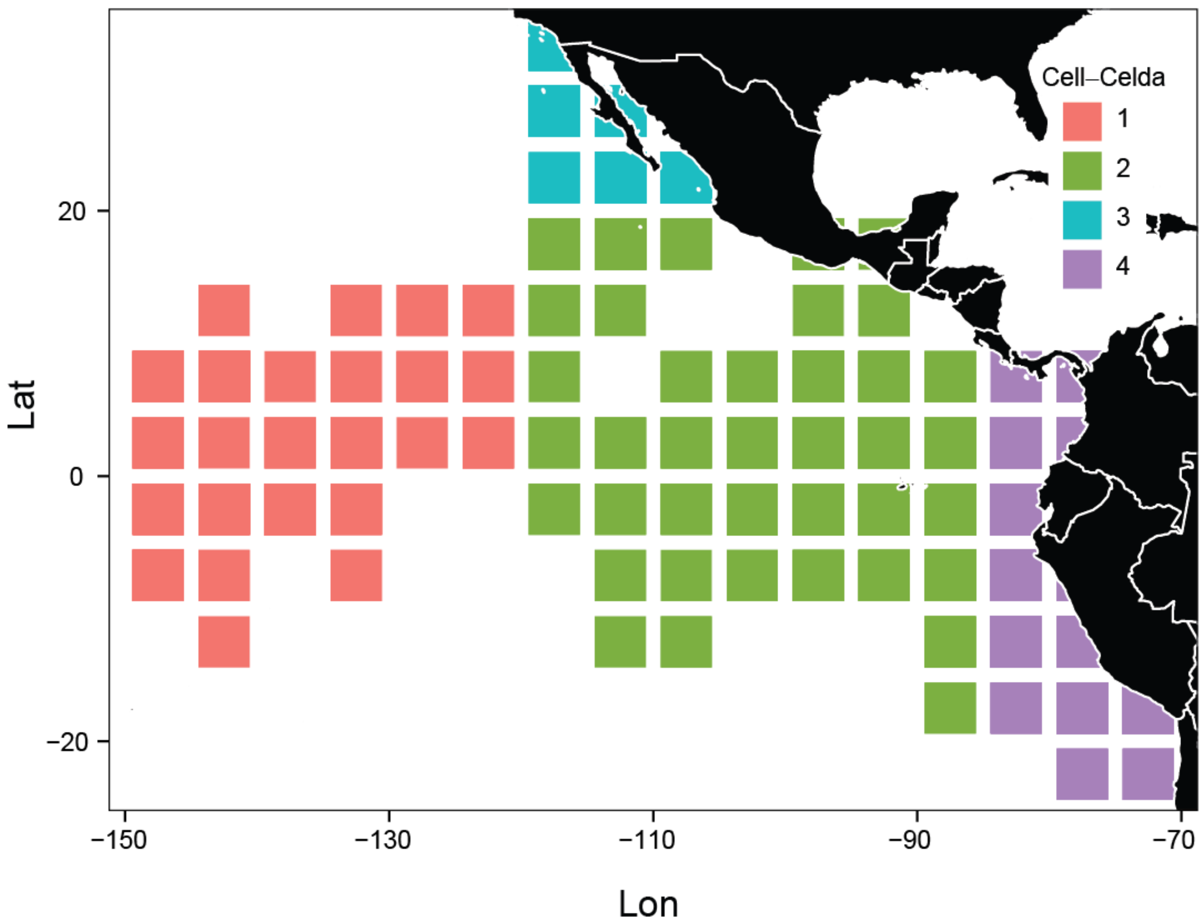

FIGURE 1b. Areas corresponding to the unassociated fishery definitions used in the stock assessment of skipjack tuna in the EPO in 2022 (Table 1). The filed squares indicate the data used to conduct the analysis to define the fisheries, which is not necessarily the same as the data used in the stock assessment.

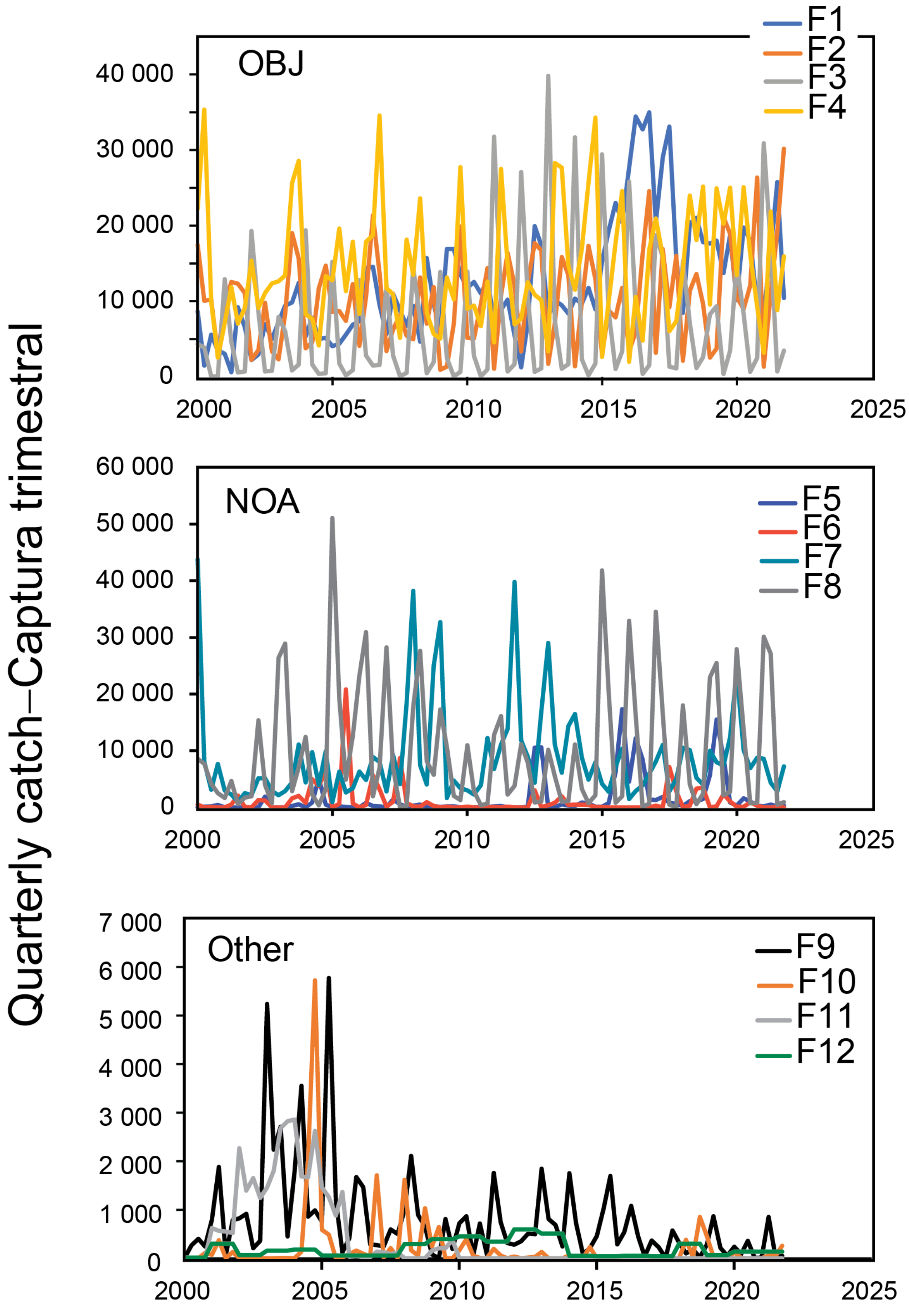

FIGURE 2. Quarterly catches of skipjack tuna, in tons, in the EPO, 2000-2021, by fishery. NOTE: The y-axis scale varies by plot.

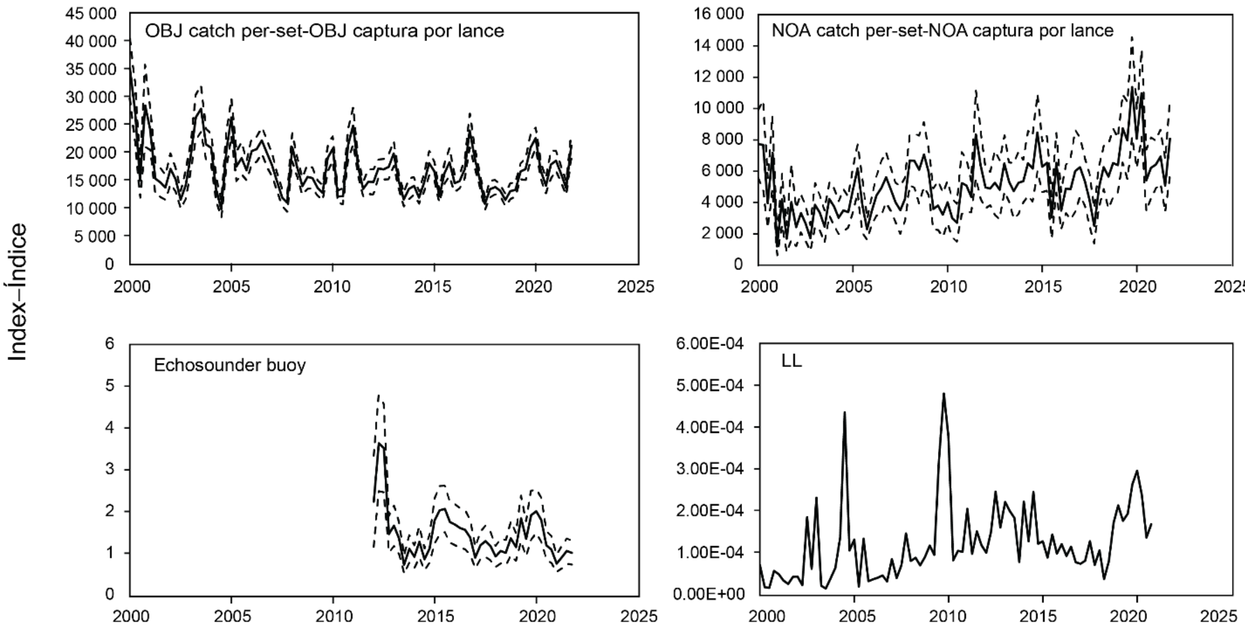

FIGURE 3. Indices of abundance used in the stock assessment of skipjack tuna in the EPO, 2000-2021 (black line), and their associated 95% confidence intervals (dashed lines). The actual data used in the assessment only include 2006 to 2021. No measure of uncertainty was calculated for the longline index.

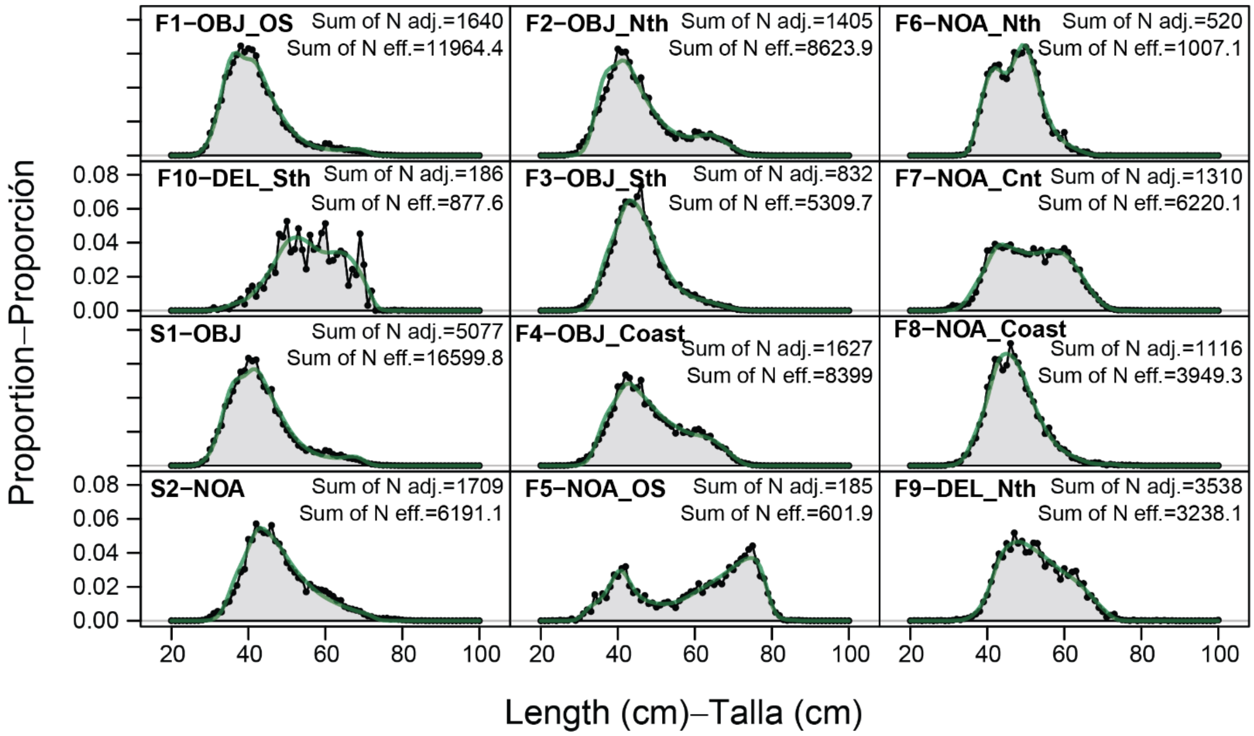

FIGURE 4a. Weighted average observed (shaded area) and predicted by the reference model (line) length composition data, by purse seine fishery and "survey".

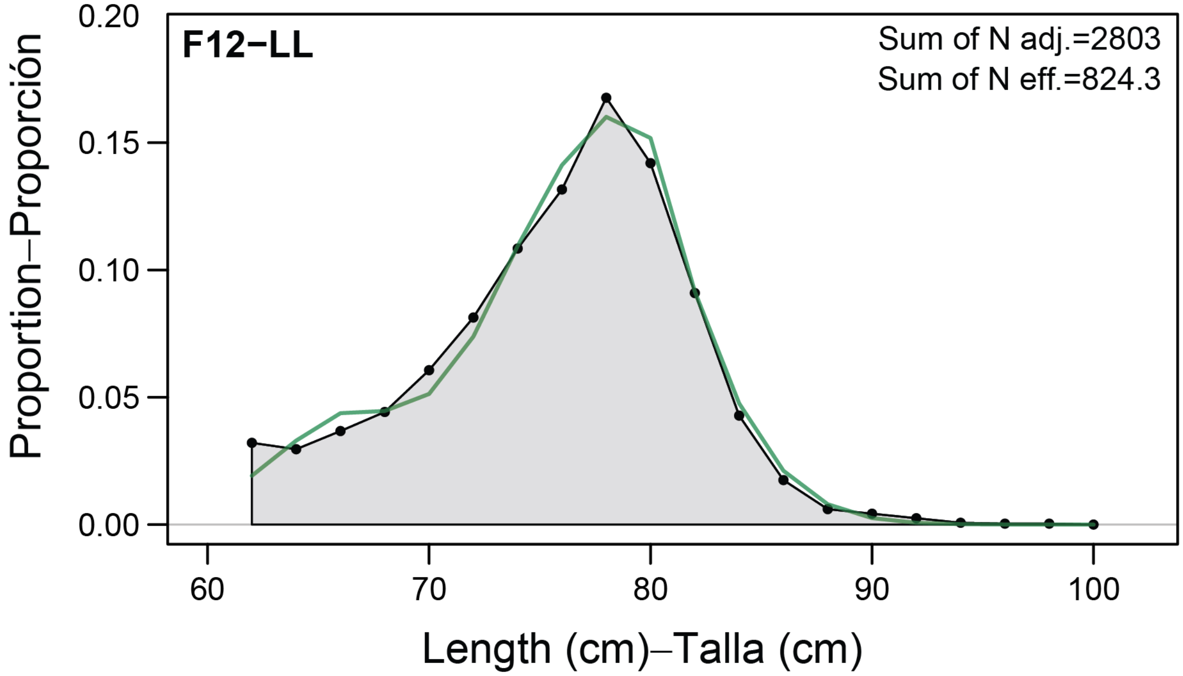

FIGURE 4b. Weighted average observed (shaded area) and predicted by the reference model (line) length composition data for the longline fishery.

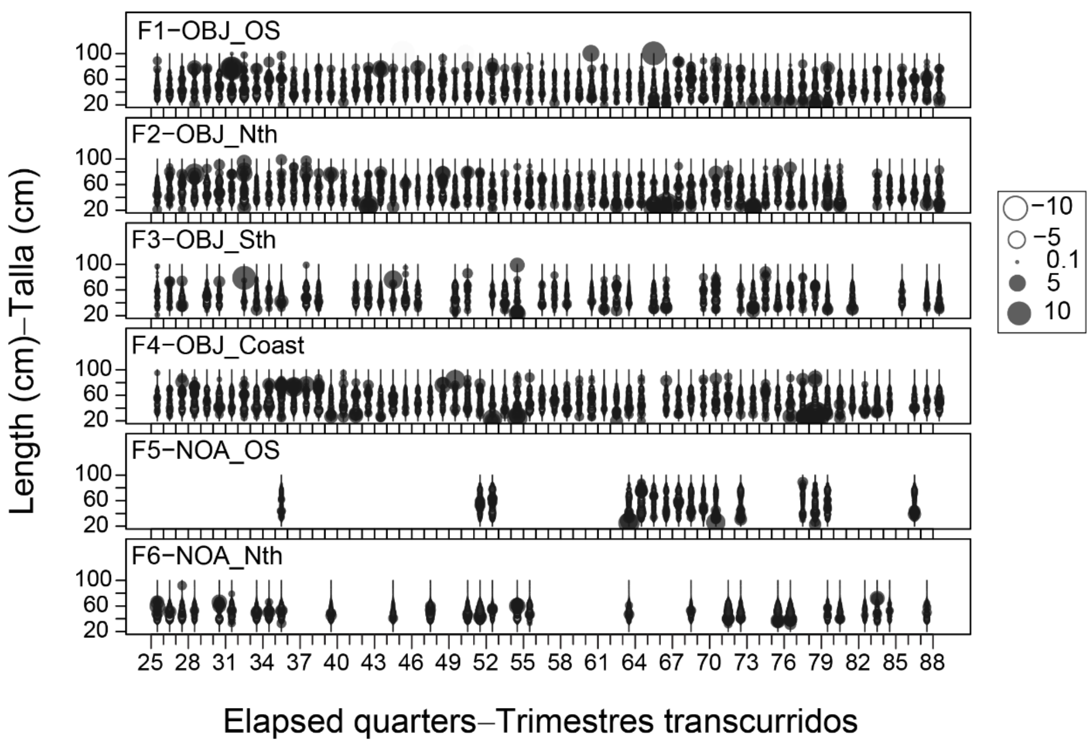

FIGURE 5a. Residual plots for the fit to the purse seine length composition data for the reference model.

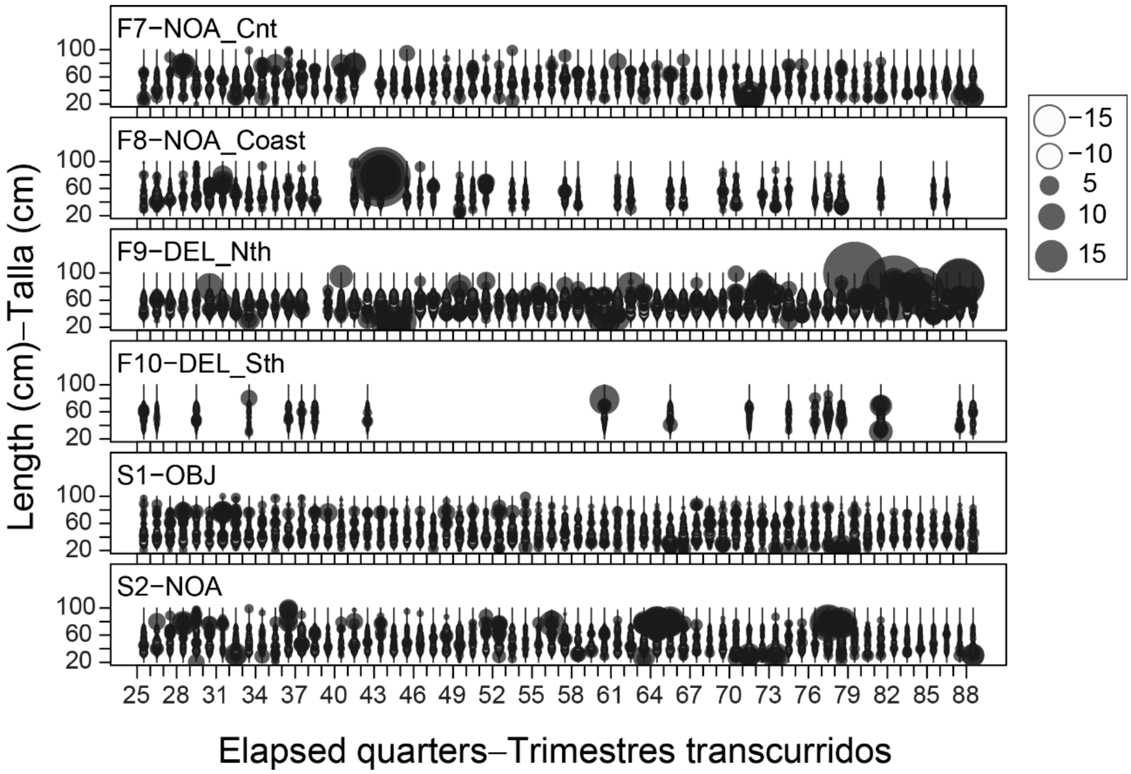

FIGURE 5b. Residual plots for the fit to the purse seine length composition data for the reference model.

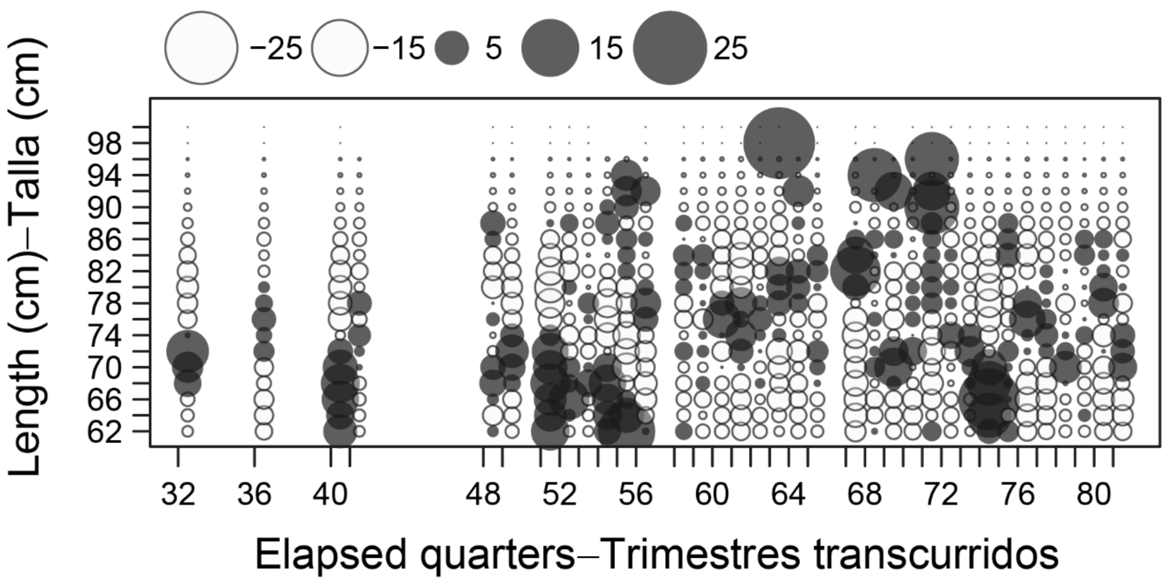

FIGURE 5c. Residual plots for the fit to the longline length composition data for the reference model.

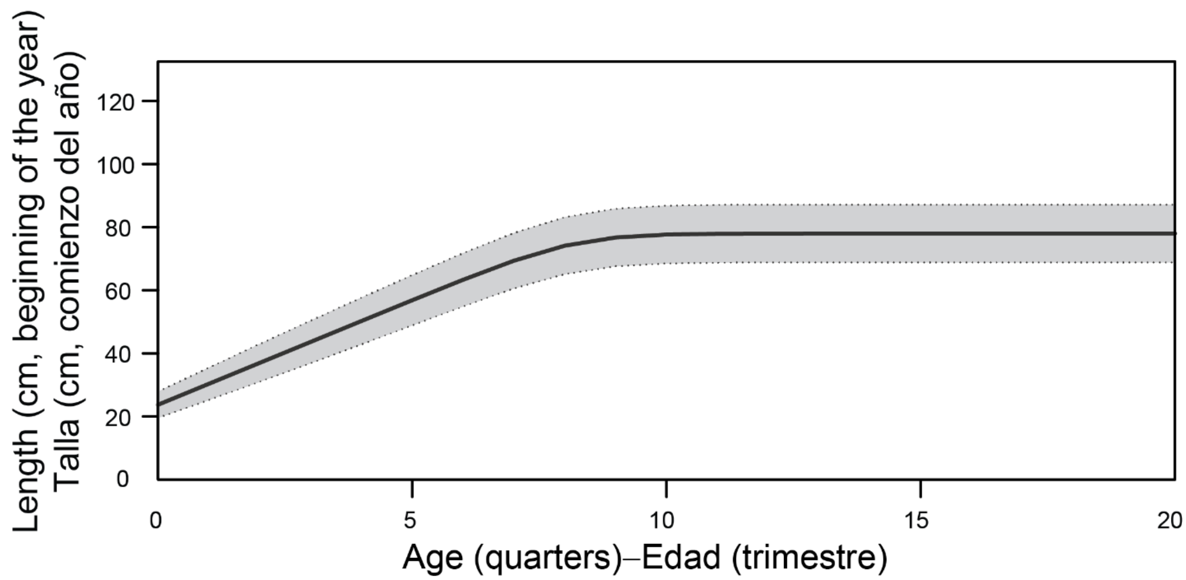

FIGURE 6. Assumed mean length at age in the reference model (solid line). The shaded region represents variation in length-at-age, assuming a CV = 9% at age 0 and 6% at age 20 quarters (mean ± 1.96 standard deviations).

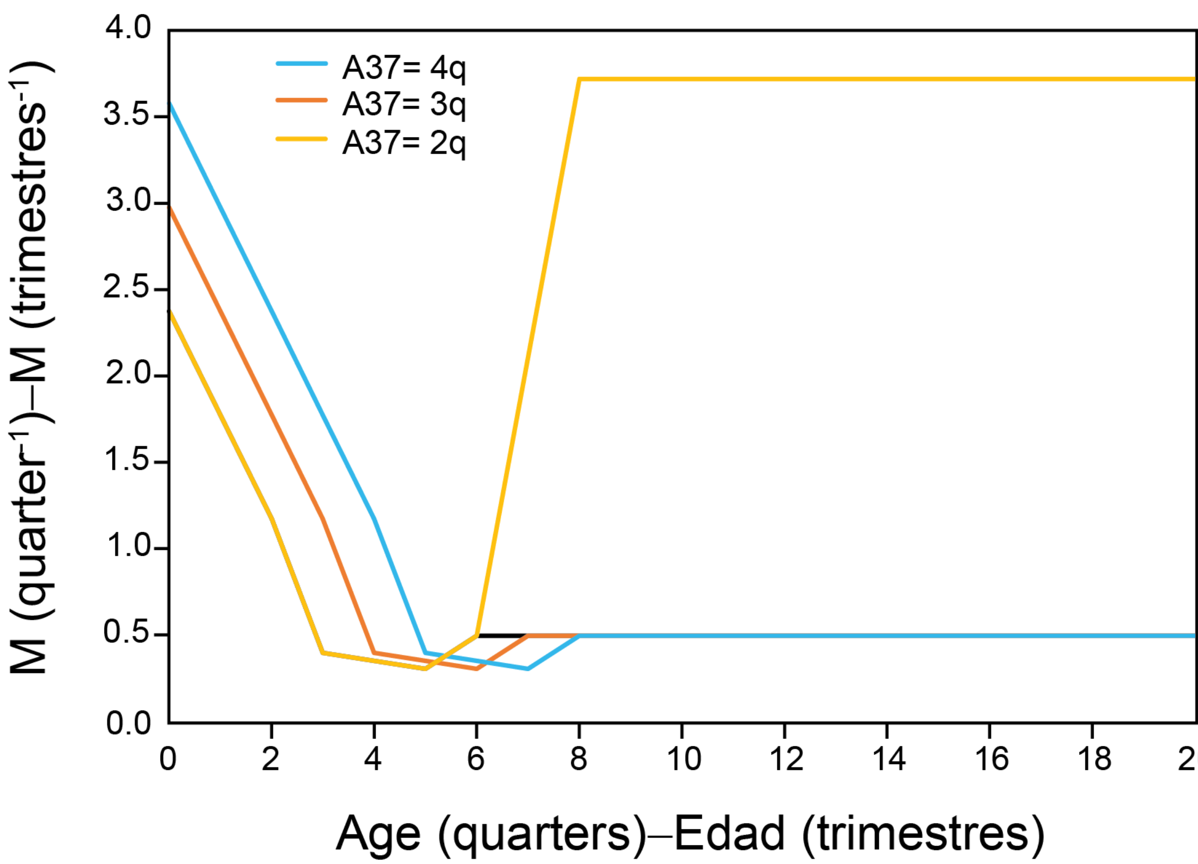

FIGURE 7. Age specific natural mortality under different assumptions of the age at 37 cm (A37). Three of the ogives assumed constant natural mortality for fish of 65cm and larger and one assumes constant natural mortality for individuals 75 cm and larger.

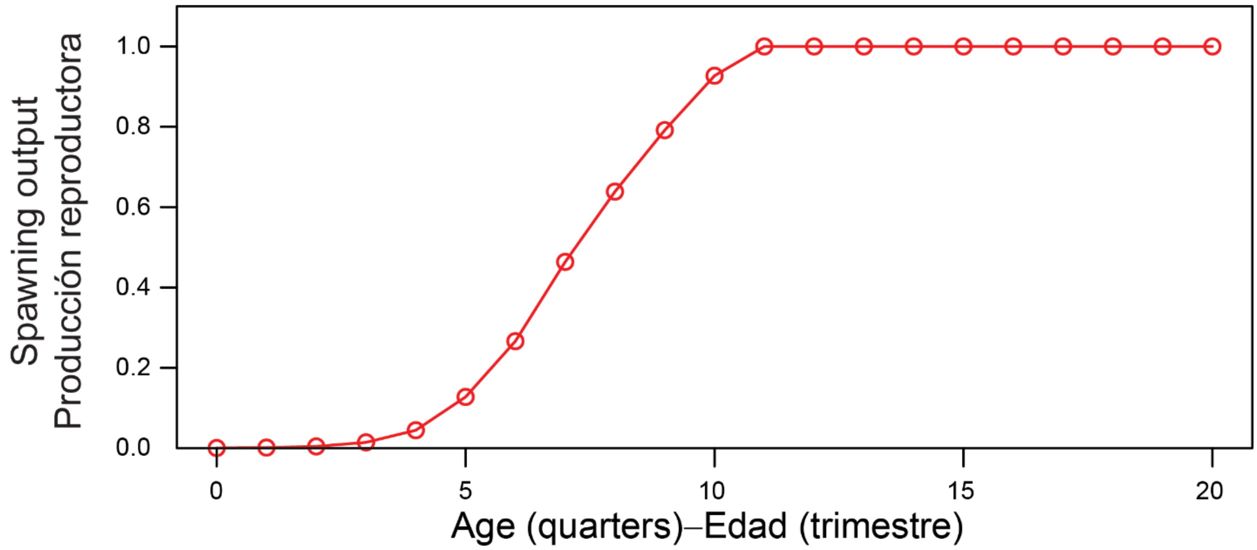

FIGURE 8. Top: Relative contribution of each age to the reproductive output component (scaled to a maximum of one) for skipjack tuna in the EPO

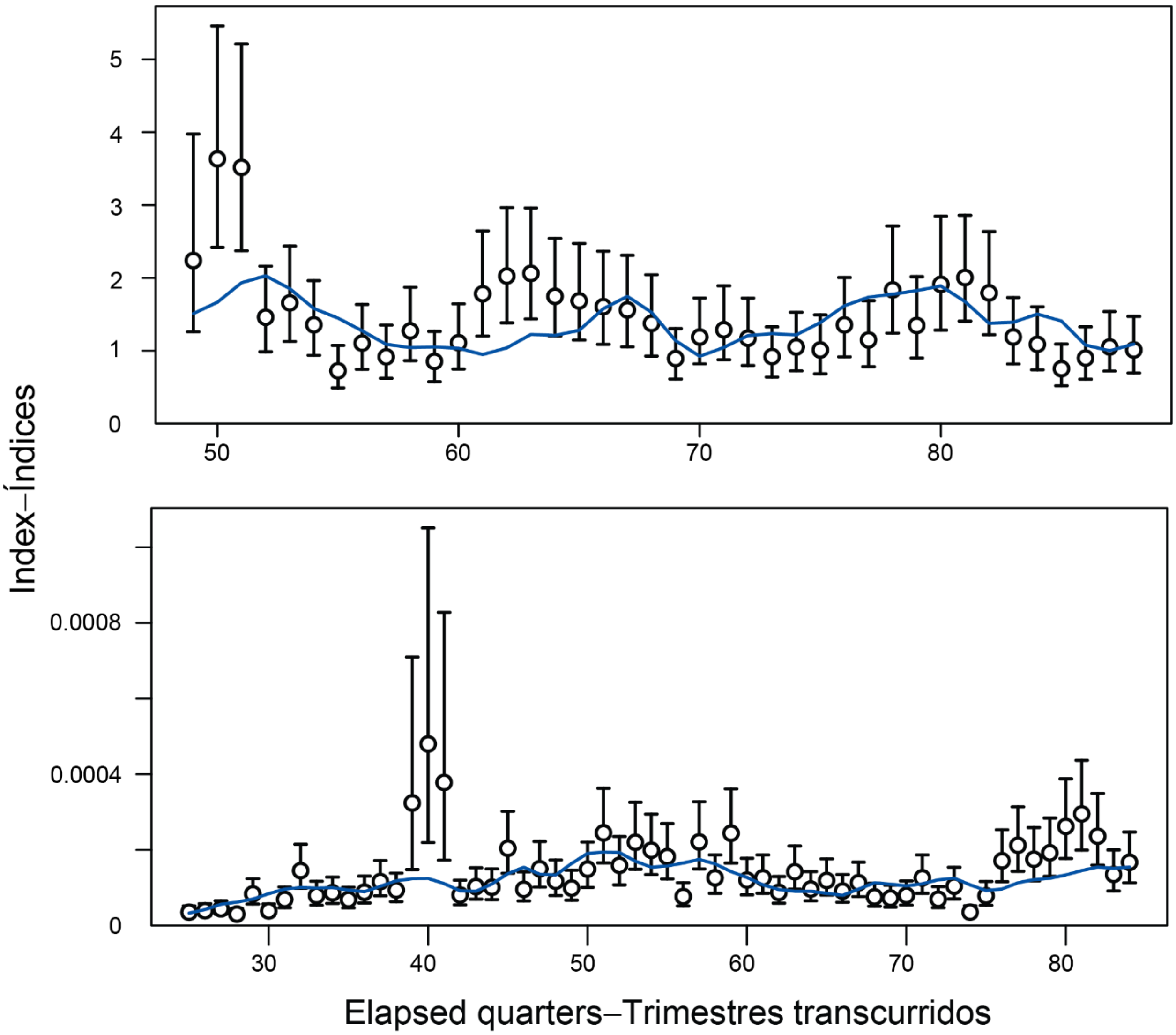

FIGURE 9. Model fits to the CPUE-based indices of abundance for the ecosounder buoy index (top) and the longline index (bottom) by the reference model. The blue line represent the estimated indices, the circles are the observed CPUE values, and the vertical lines represent the uncertanty in the observations.

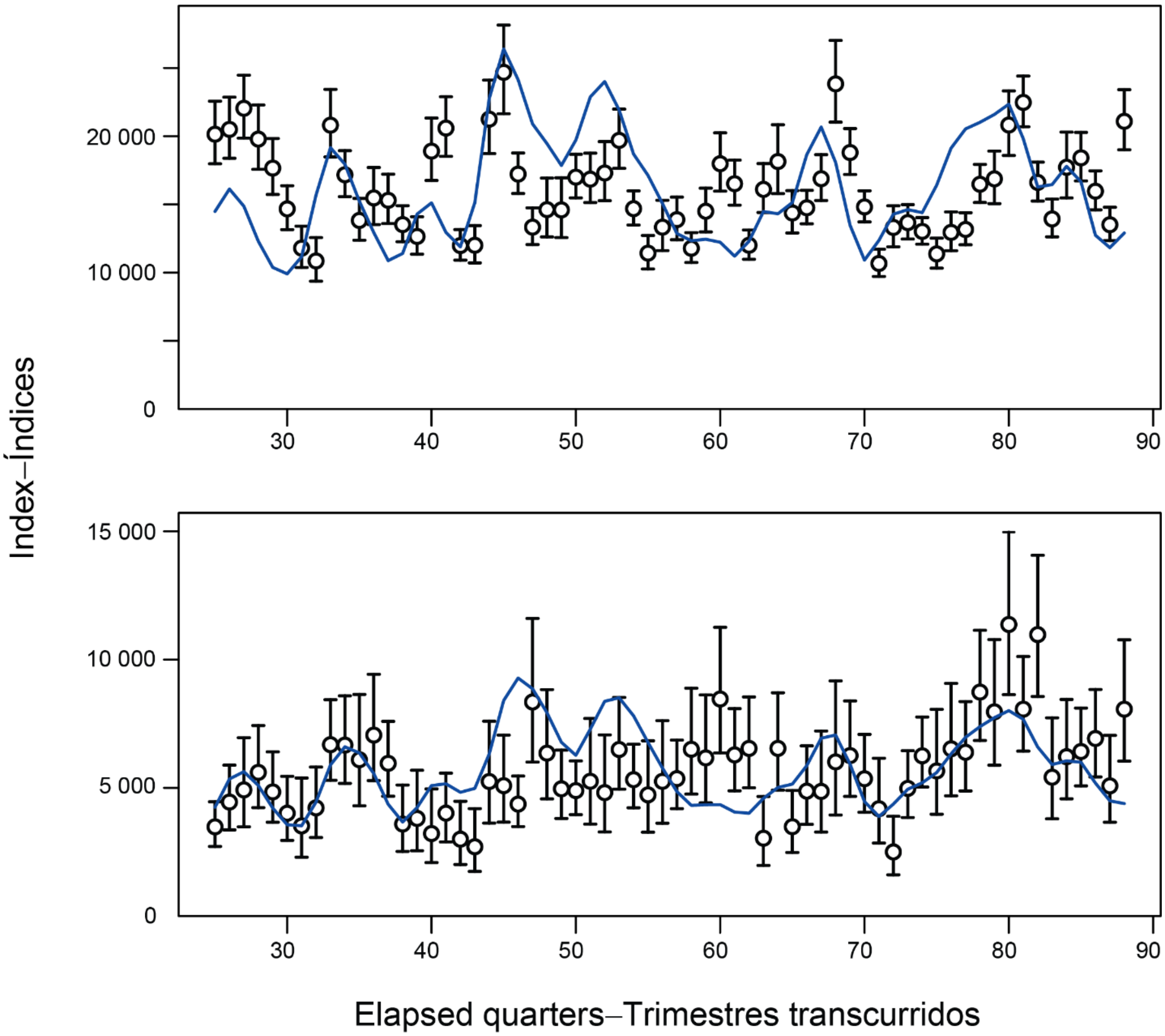

FIGURE 10. Model fits to the catch-per-set based indices of abundance for the floating object (top) and unassociated (bottom) purse seine fisheries by the reference model. These fits are not included in the objective function. The blue line represents the estimated indices, the circles are the observed CPUE values, and the vertical lines represent the uncertanty in the observations.

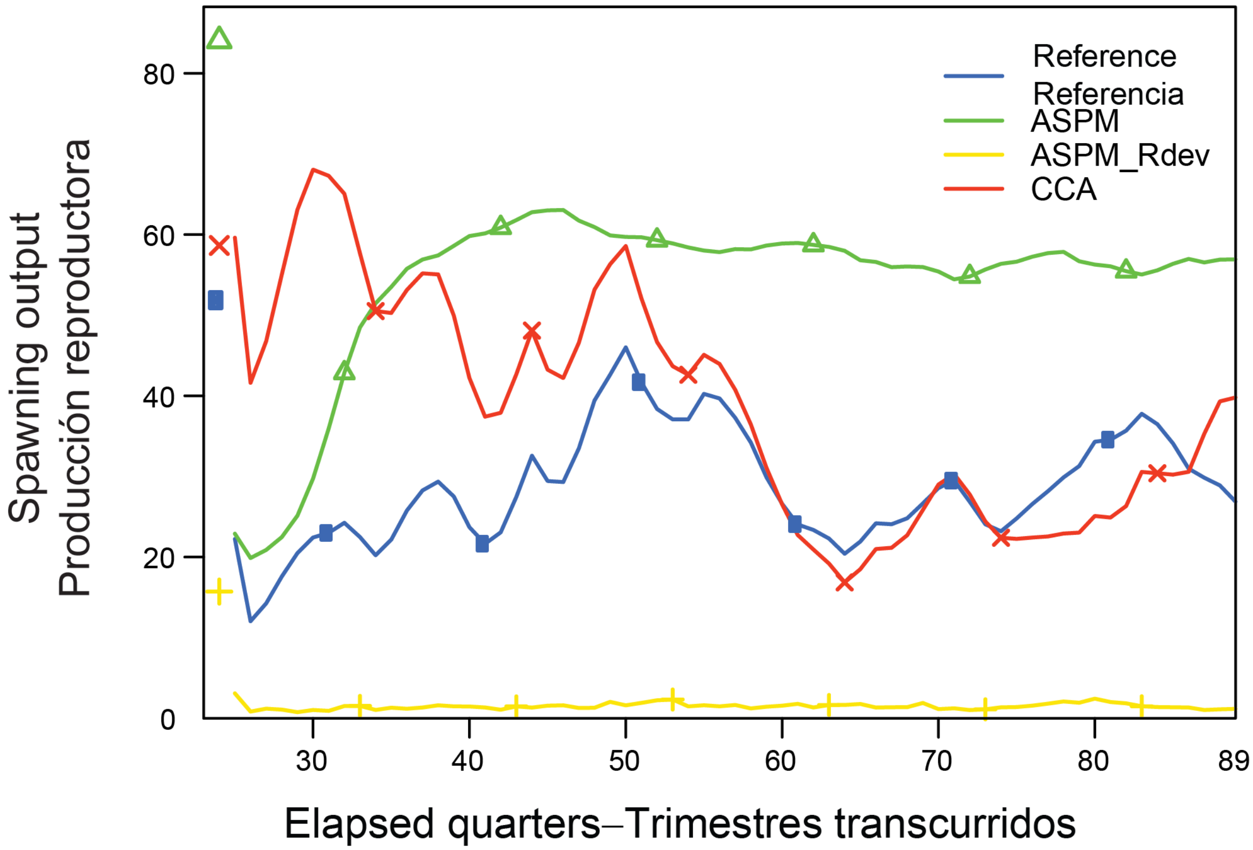

FIGURE 11a. Spawning biomass for the age-structured production model and catch-curve diagnostics for the reference model.

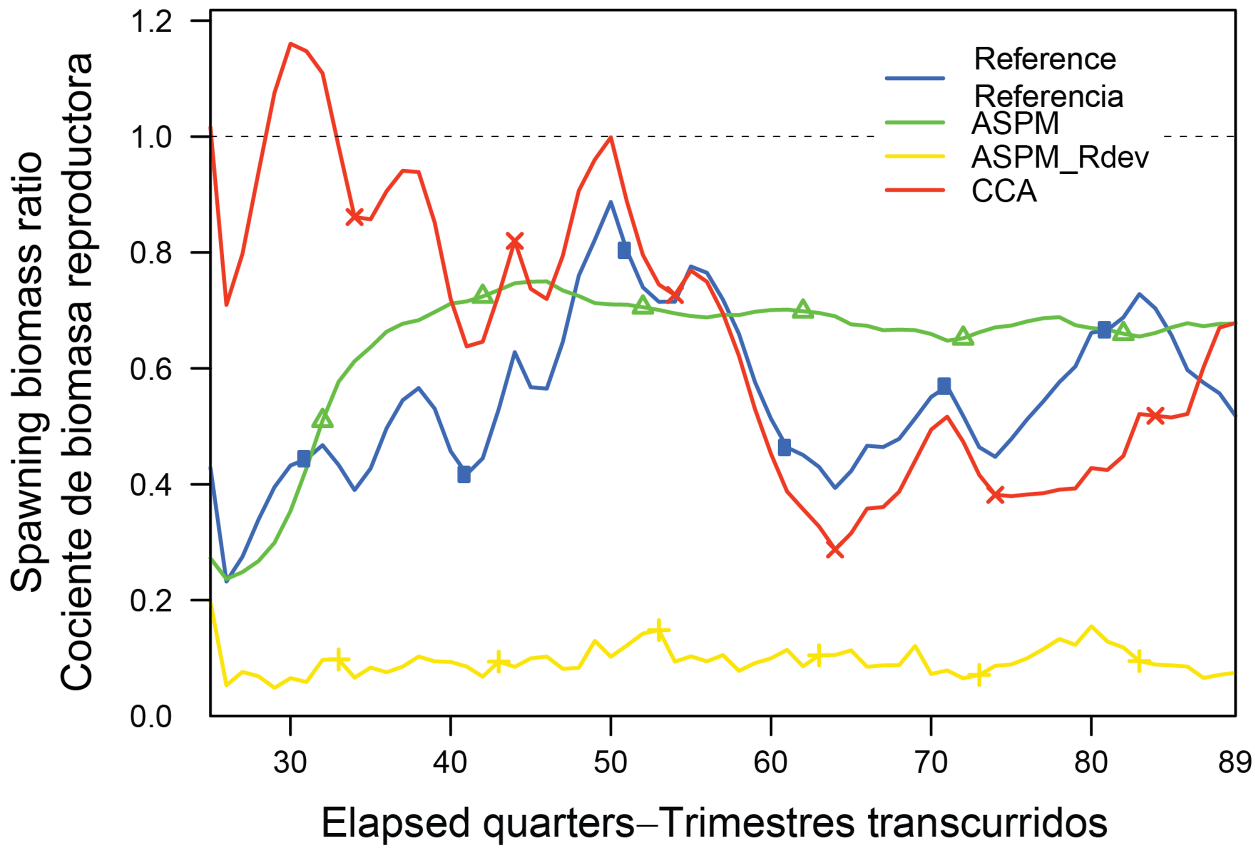

FIGURE 11b. Spawning biomass ratio for the age-structured production model and catch-curve diagnostics for the reference model.

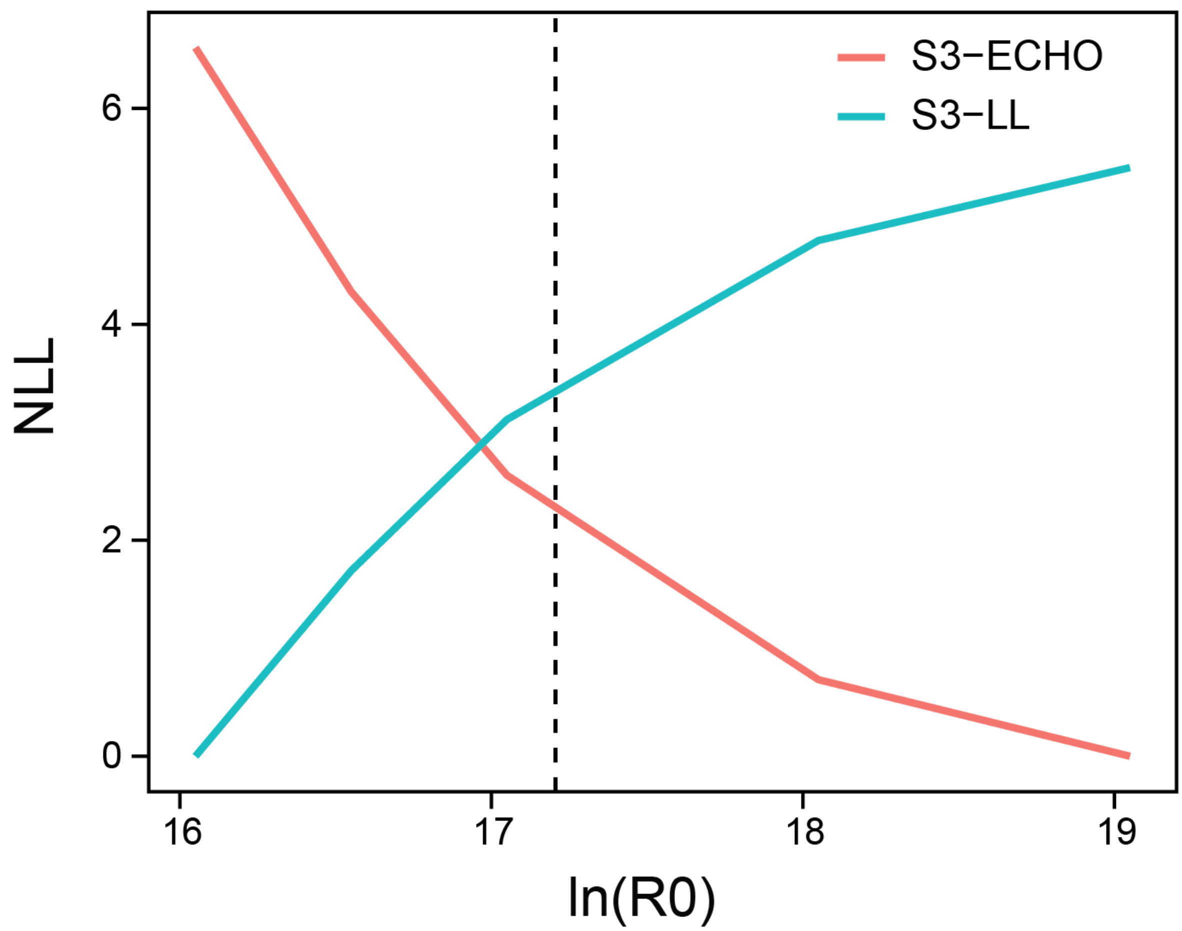

FIGURE 12a. R0 likleihood component profile for the indices of abundance from the reference model.

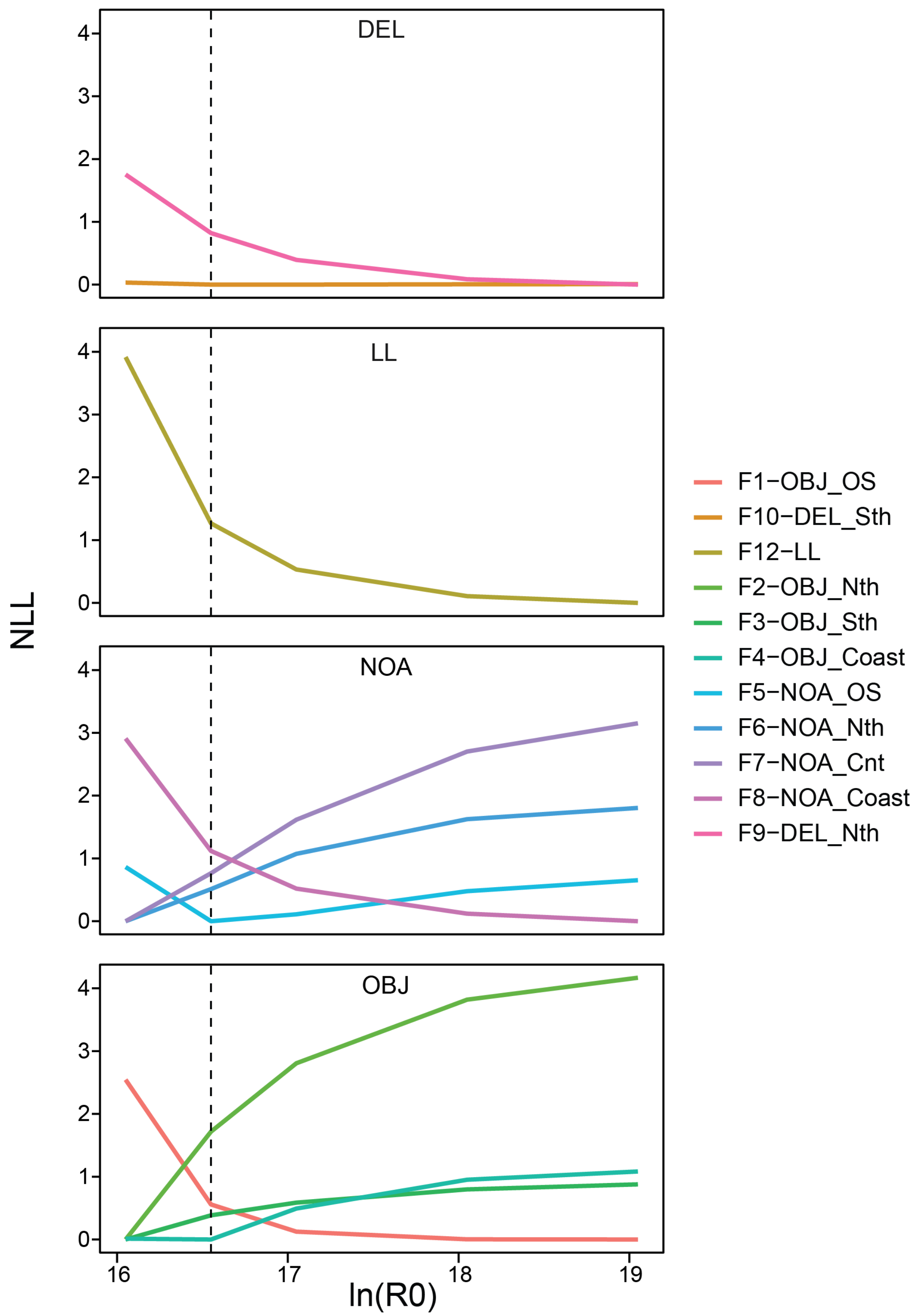

FIGURE 12b. R0 likleihood component profile for the fishery length composition data from the Reference Model.

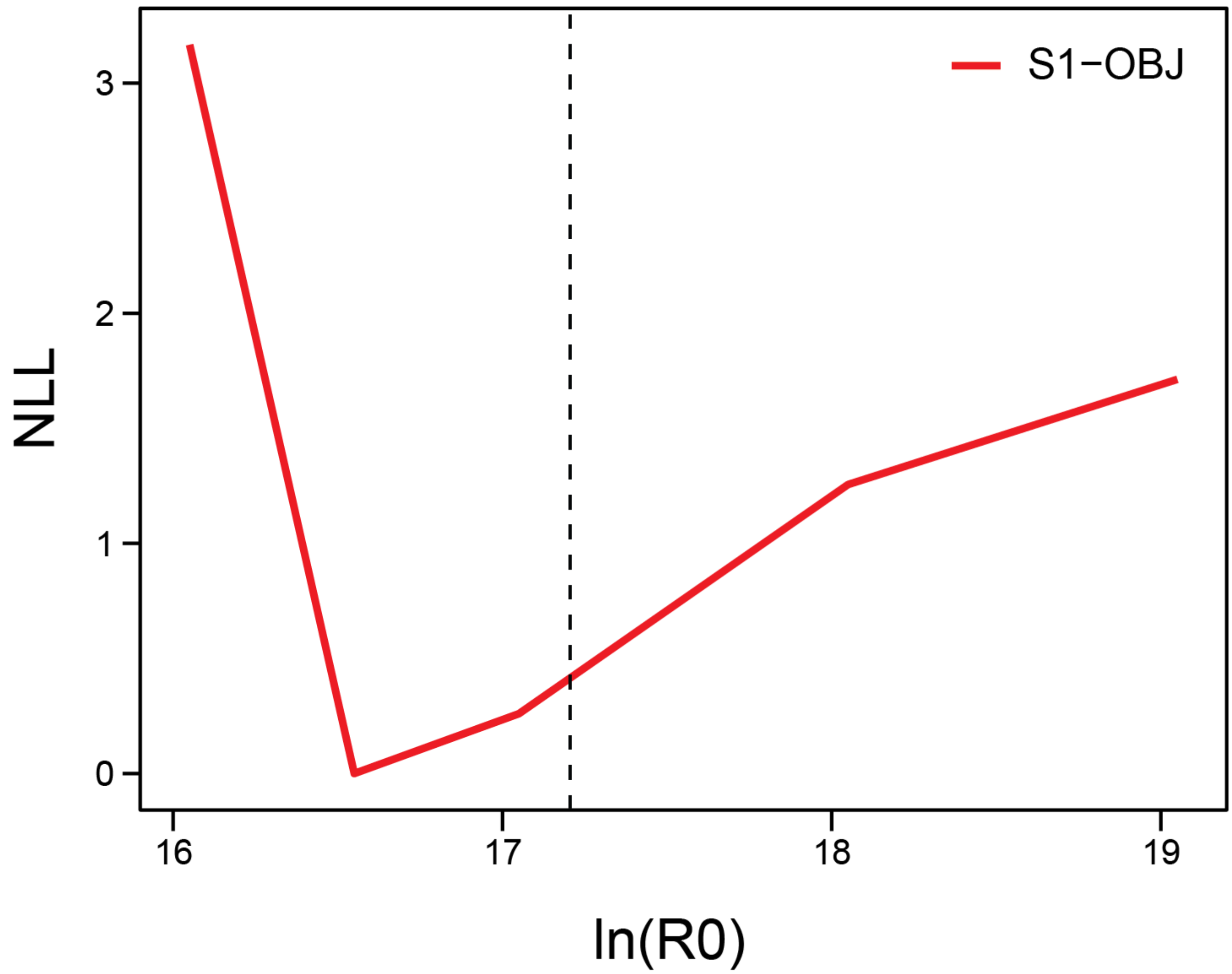

FIGURE 12c. R0 likleihood component profile for the fishery length composition data from the Reference Model.

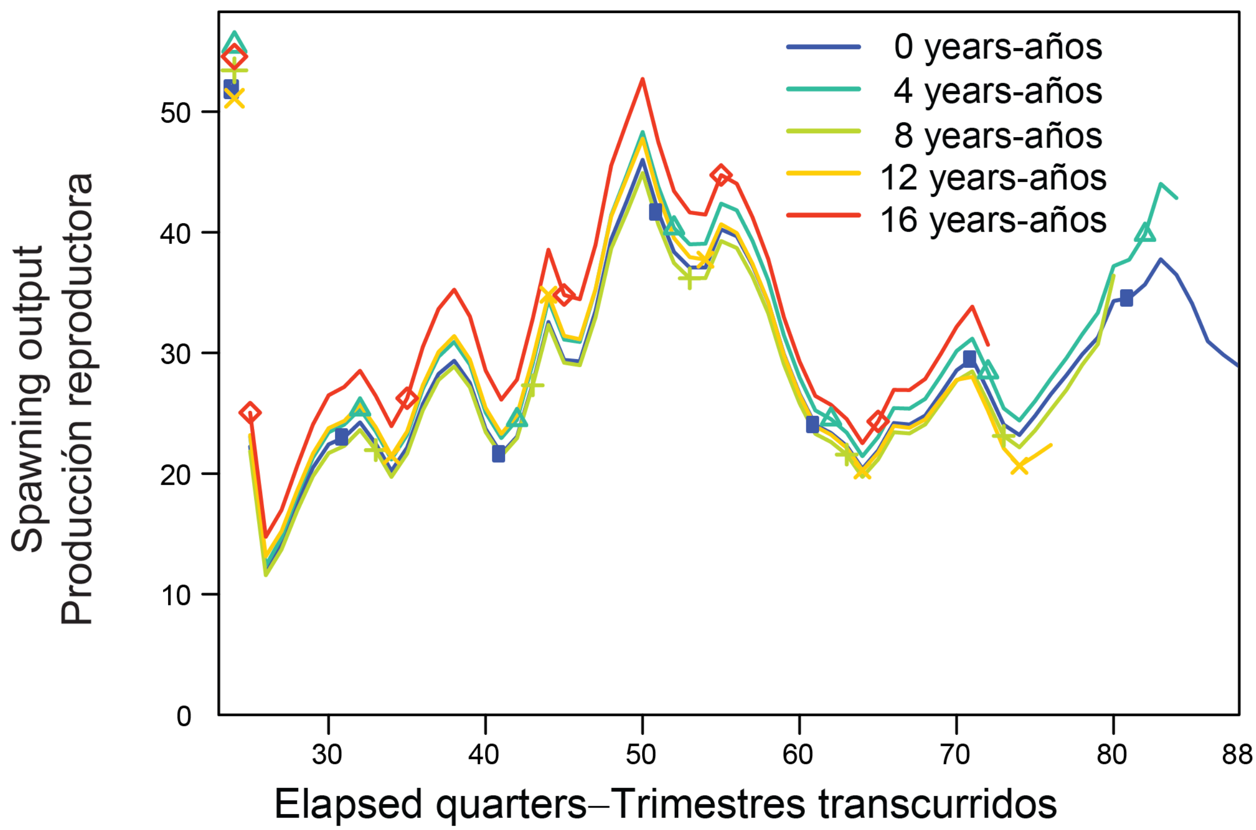

FIGURE 13a. SpawnIng biomass for the Retrospective analysis from the reference model.

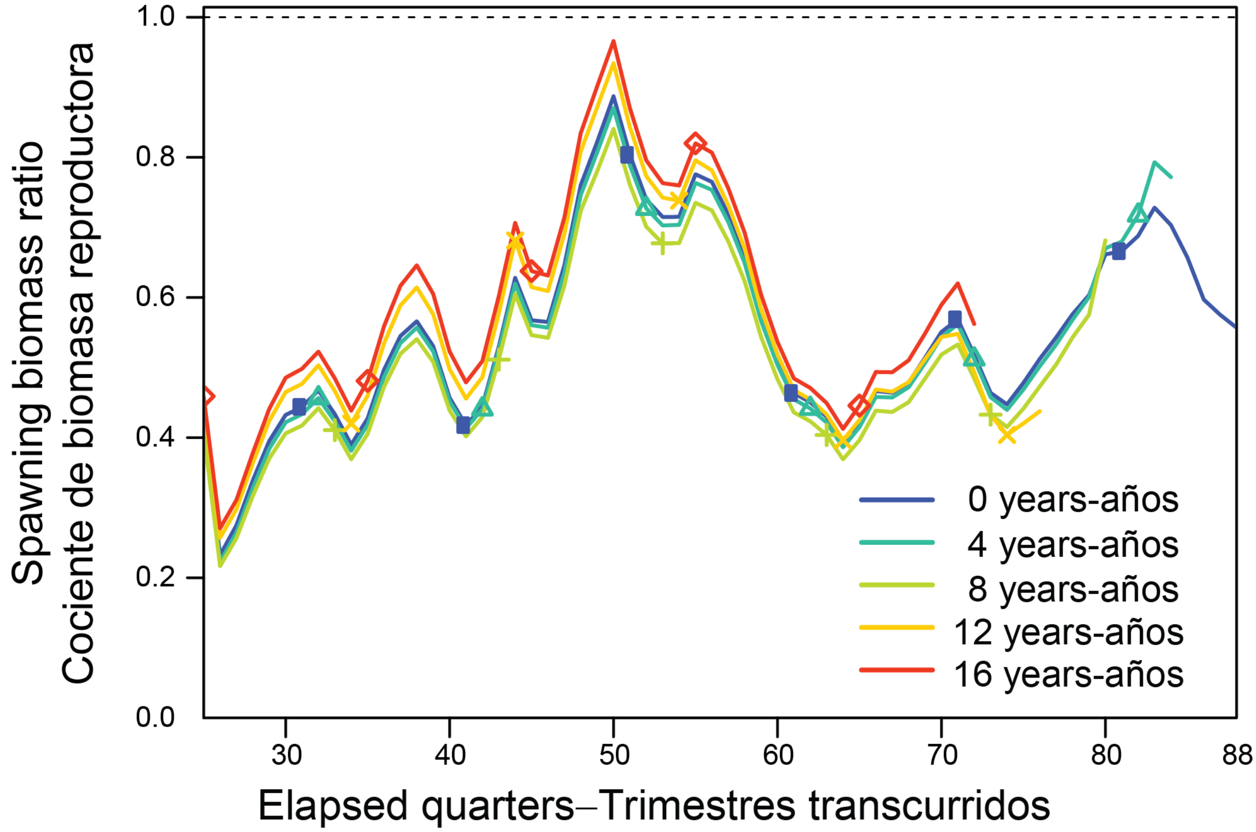

FIGURE 13b. SpawnIng biomass ratio for the Retrospective analysis from the reference model.

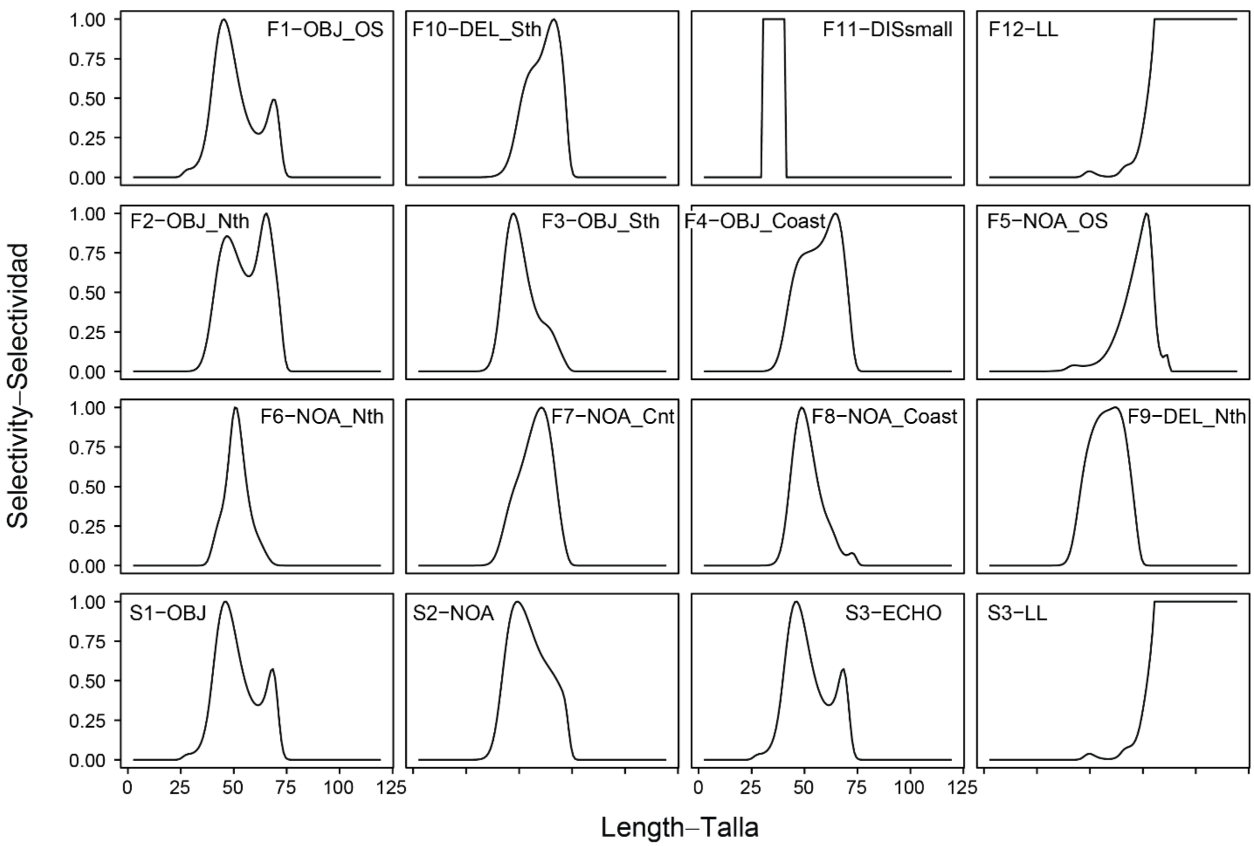

FIGURE 14. Estimated selectivity for the fisheries and “surveys” from the refernce model.

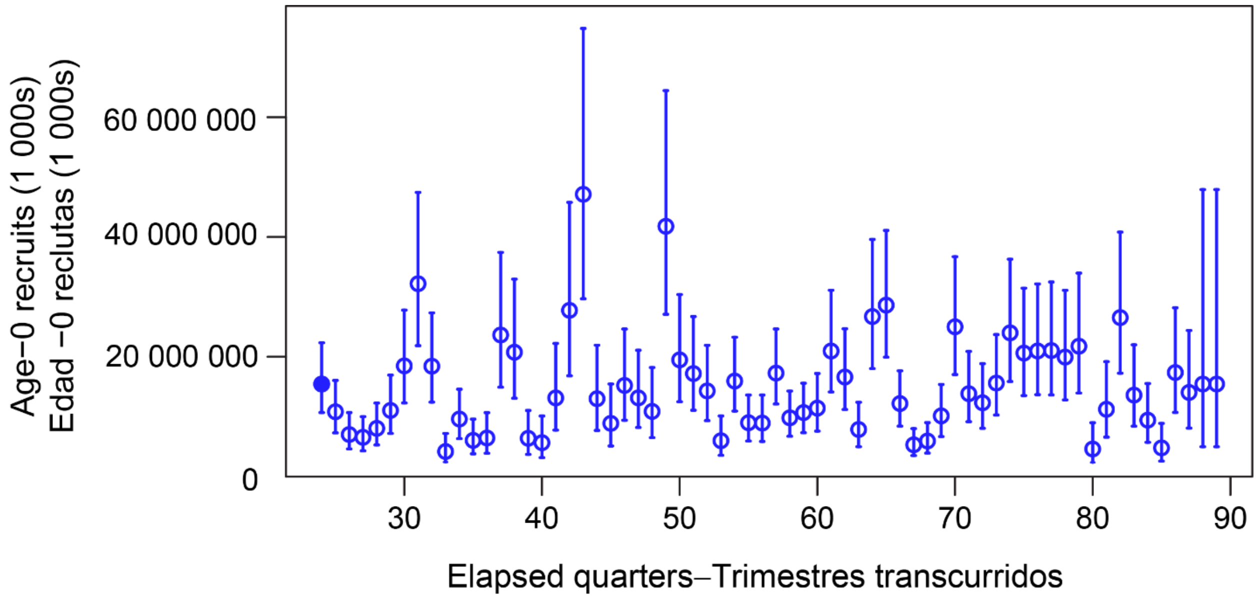

FIGURE 15. Quarterly recruitment and 95% confidence intervals of skipjack tuna estimated by the reference model.

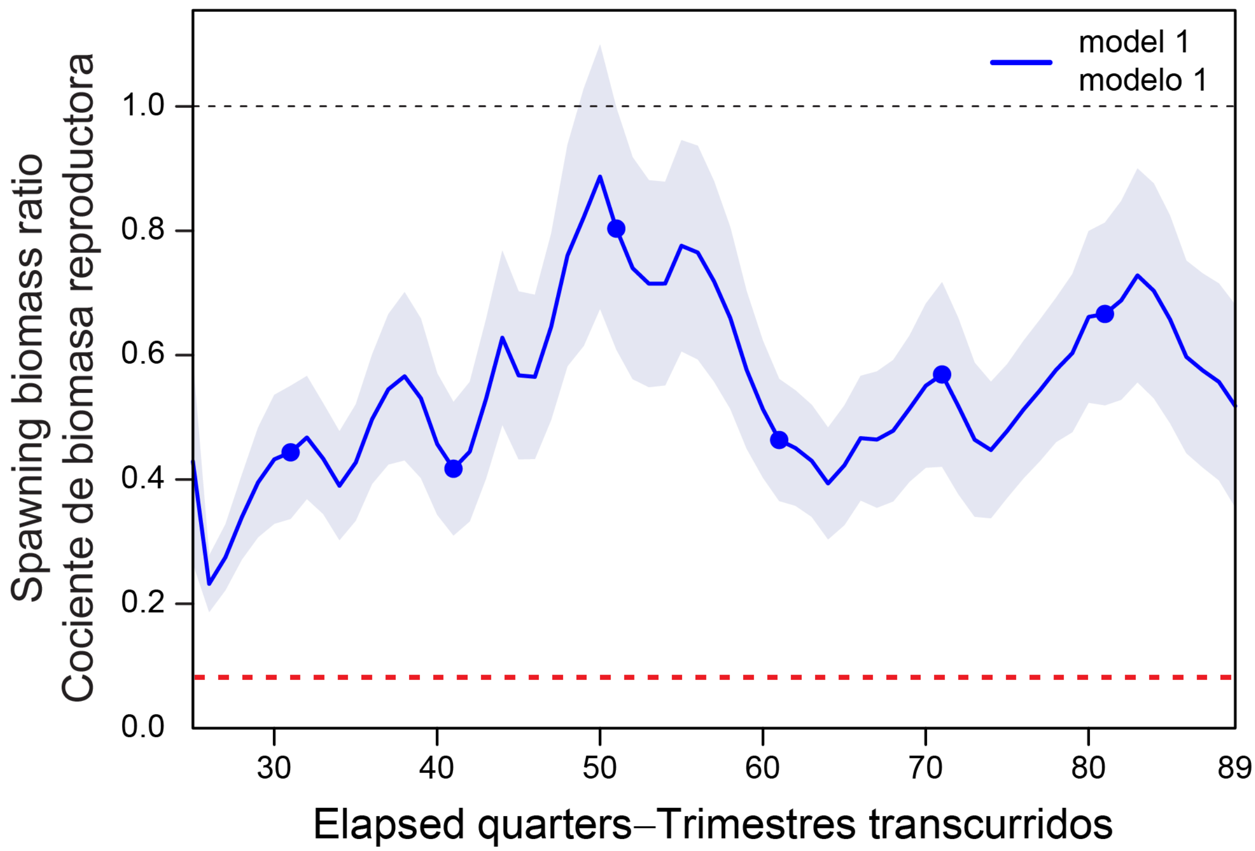

FIGURE 16. Spawning biomass ratio (SBR) for skipkjack tuna in the EPO, 2006-2021 estimated by the reference model. The solid lines represent the maximum likelihood estimates and the shaded area the approximate 95% confidence intervals around those estimates. The red dashed horizontal line (at 0.077) identifies the SBR at S_{LIMIT}.

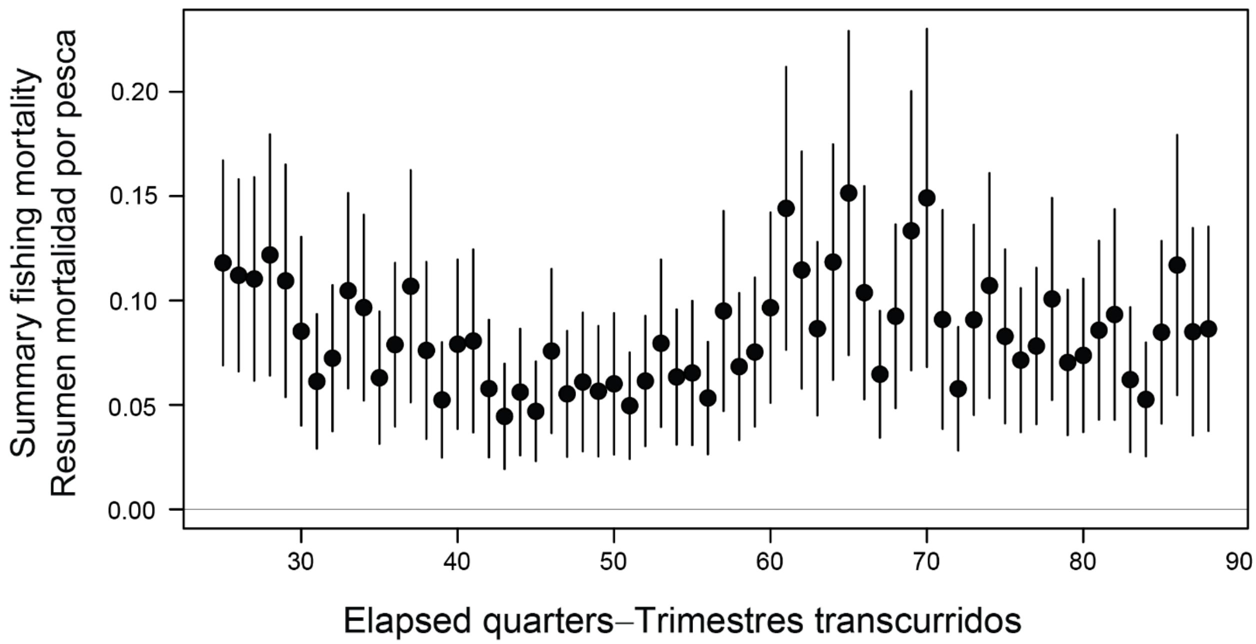

FIGURE 17. Index of quarterly exploitation rate of skipjack tuna in the EPO estimated by the reference model.

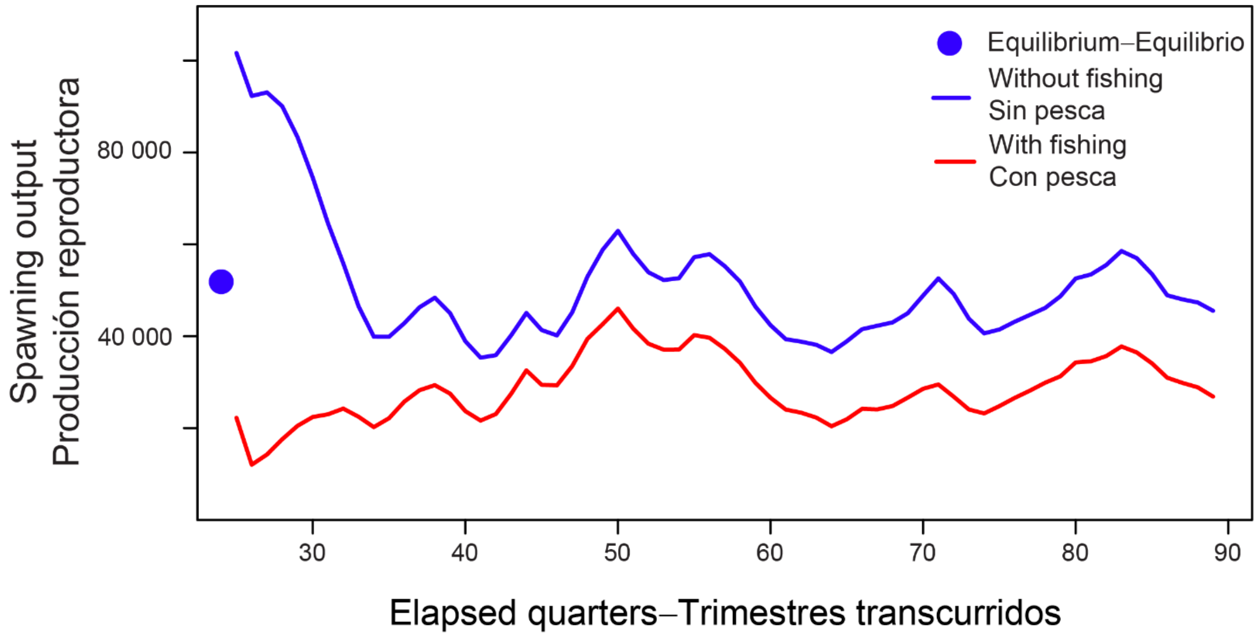

FIGURE 18. Impact of fishing, 2006-2021: trajectory of the spawning biomass (a fecundity index, see text for details) of a simulated population of skipjack tuna that was never exploited (blue line) and that predicted by the reference model (red line).

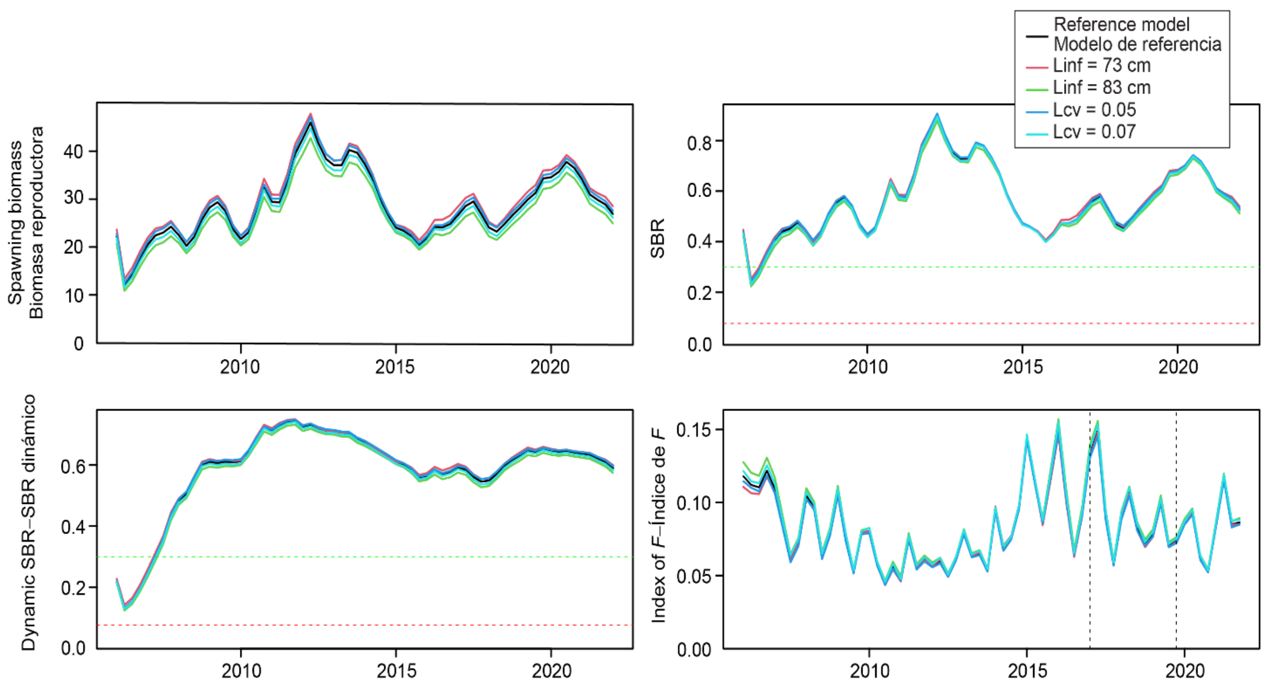

FIGURE 19. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analyses to the asymptotic length and the CV of variation of length at age at the asymptotic length. The green dashed horizontal line is the target biomass reference point (SBR = 0.3) and the red horizontal dashed line is the limit biomass reference point (SBR = 0.077). The two vertical lines represent the status quo period (2017-2019).

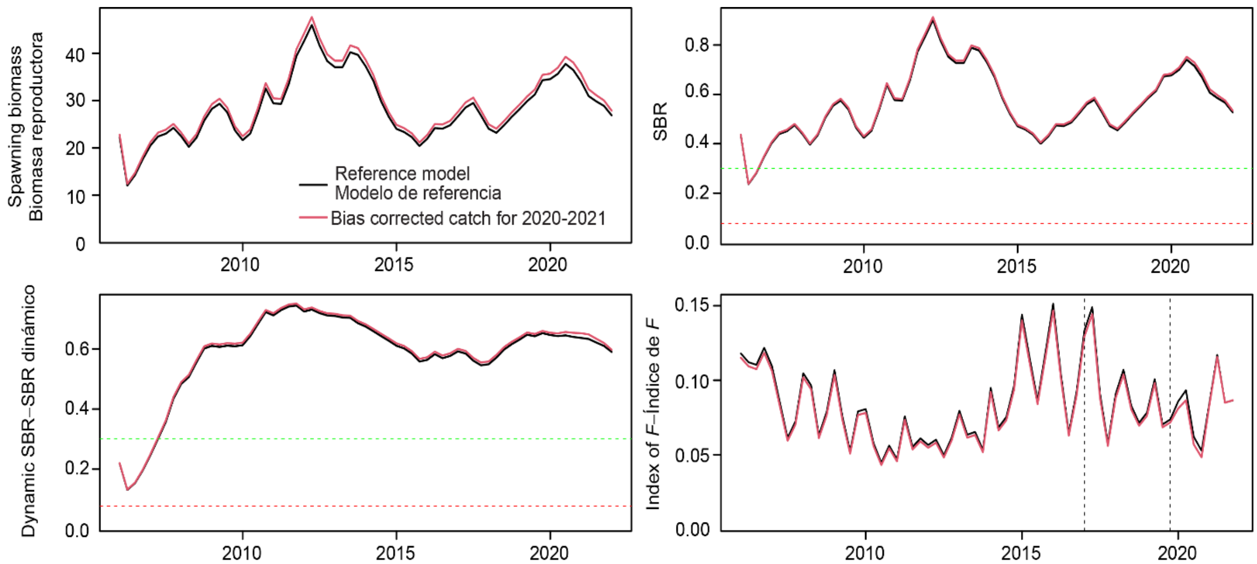

FIGURE 20. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analysis that uses the corrected catches for 2020 and 2021. The green dashed horizontal line is the target biomass reference point (SBR = 0.3) and the red horizontal dashed line is the limit biomass reference point (SBR = 0.077).The two vertical lines represent the status quo period (2017-2019).

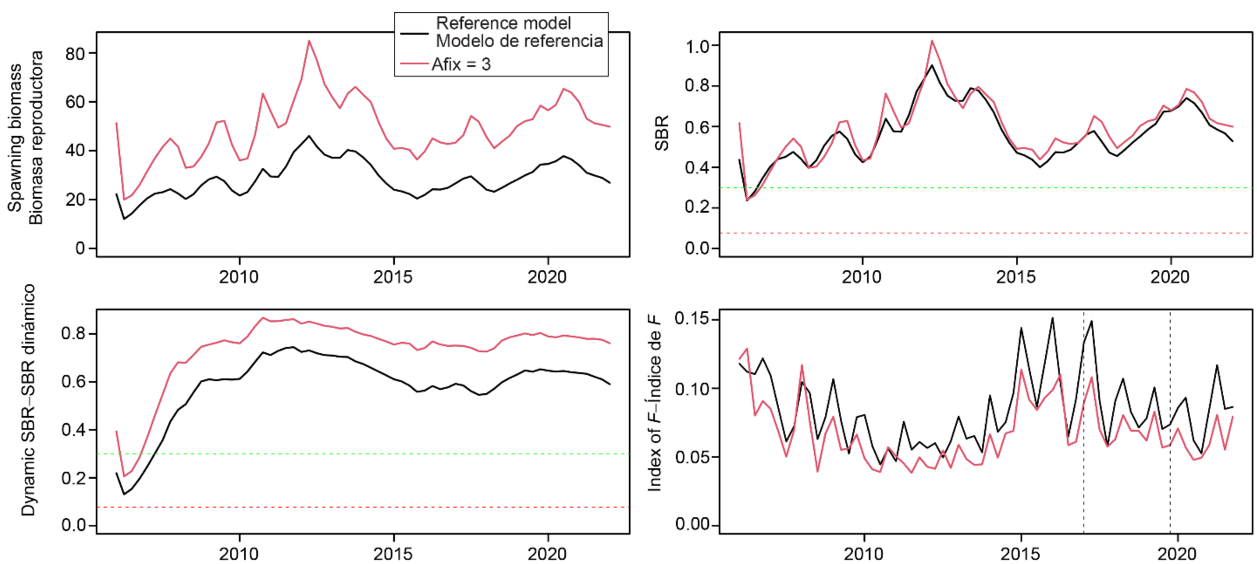

FIGURE 21. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analysis that assumes the age of a 37 cm fish is 3 quarters. The green dashed horizontal line is the target biomass reference point (SBR = 0.3) and the red horizontal dashed line is the limit biomass reference point (SBR = 0.077). The two vertical lines represent the status quo period (2017-2019).

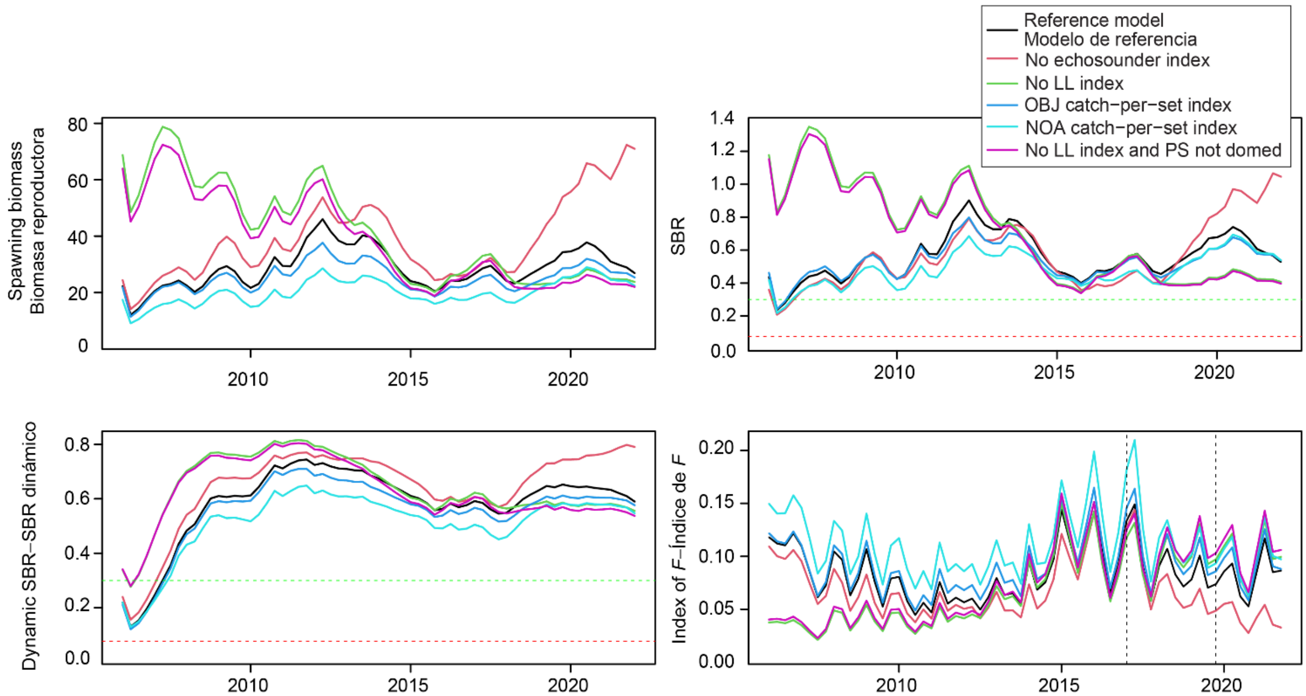

FIGURE 22. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analyses that include or exclude indicies of abundance. The green dashed horizontal line is the target biomass reference point (SBR = 0.3) and the red horizontal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

FIGURE 23. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analyses that assume asymptotic selectivity for a different fishery. The green dashed horizontal line is the target biomass reference point (SBR = 0.3) and the red horizontal dashed line is the limit biomass reference point (SBR = 0.077).The two vertical lines represent the status quo period (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 only model the stock east of -120 ° W. The green dashed horizontal line is the target biomass reference point (SBR = 0.3) and the red horizontal dashed line is the limit biomass reference point (SBR = 0.077).The two vertical lines represent the status quo period (2017-2019).

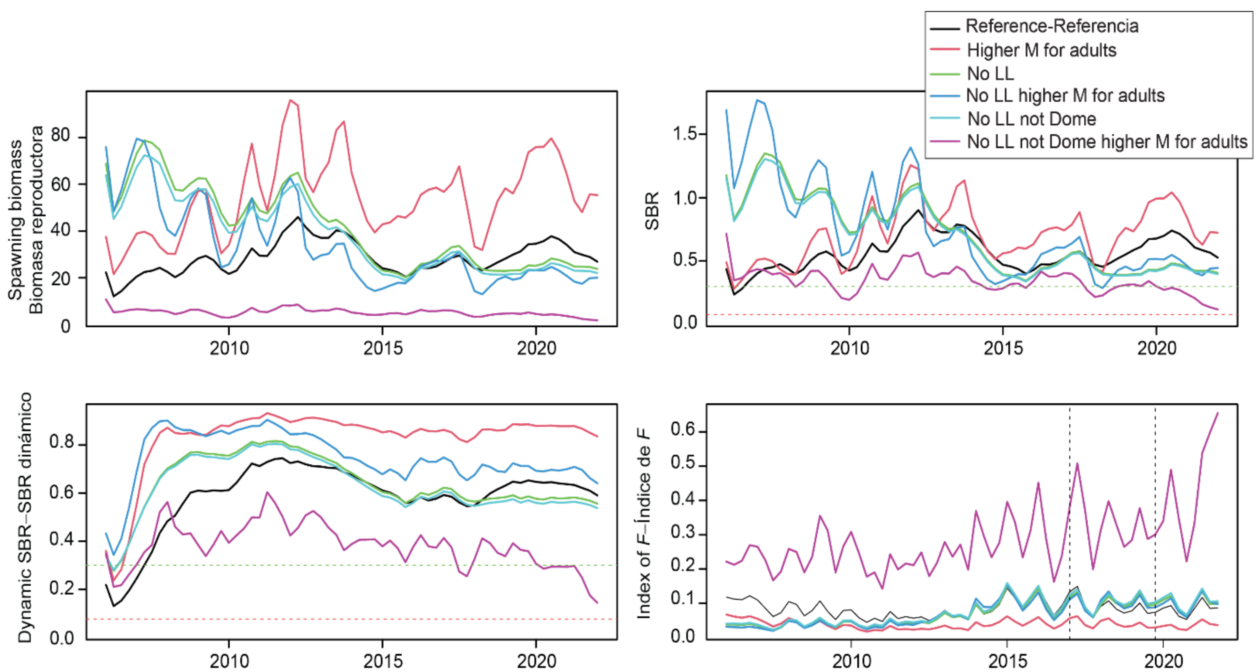

FIGURE 25. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analyses that have higher natural mortality for adults. The green dashed horizontal line is the target biomass reference point (SBR = 0.3) and the red horizontal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

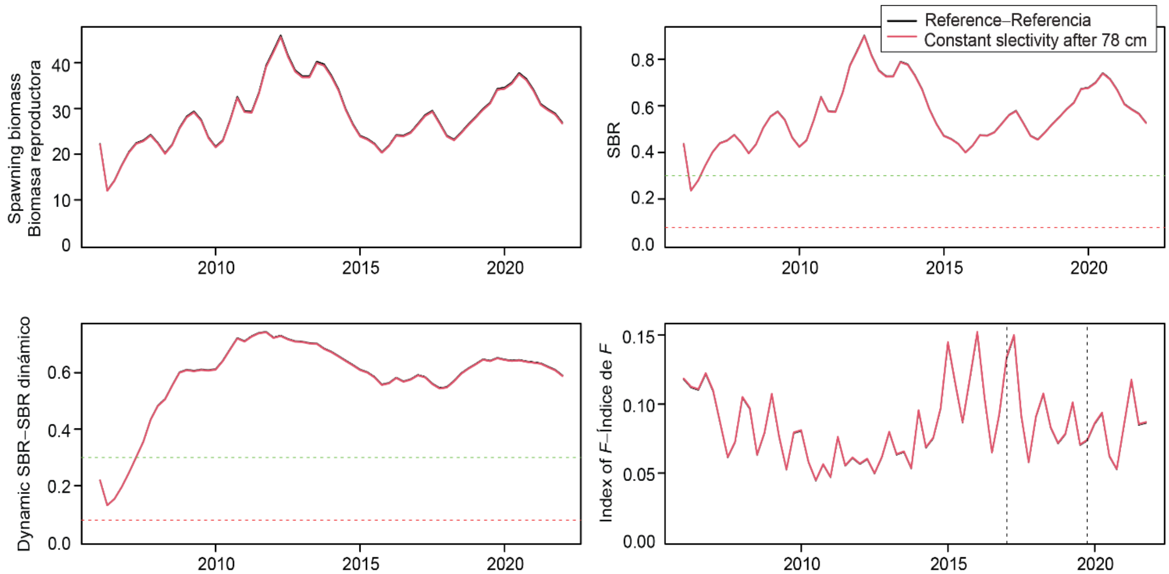

FIGURE 26. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analysis that makes the offshore NOAS fishery (F5) have constant selectivity after the asymptotic length (78 cm). The green dashed horizontal line is the target biomass reference point (SBR = 0.3) and the red horizontal dashed line is the limit biomass reference point (SBR = 0.077). The two vertical lines represent the status quo period (2017-2019).

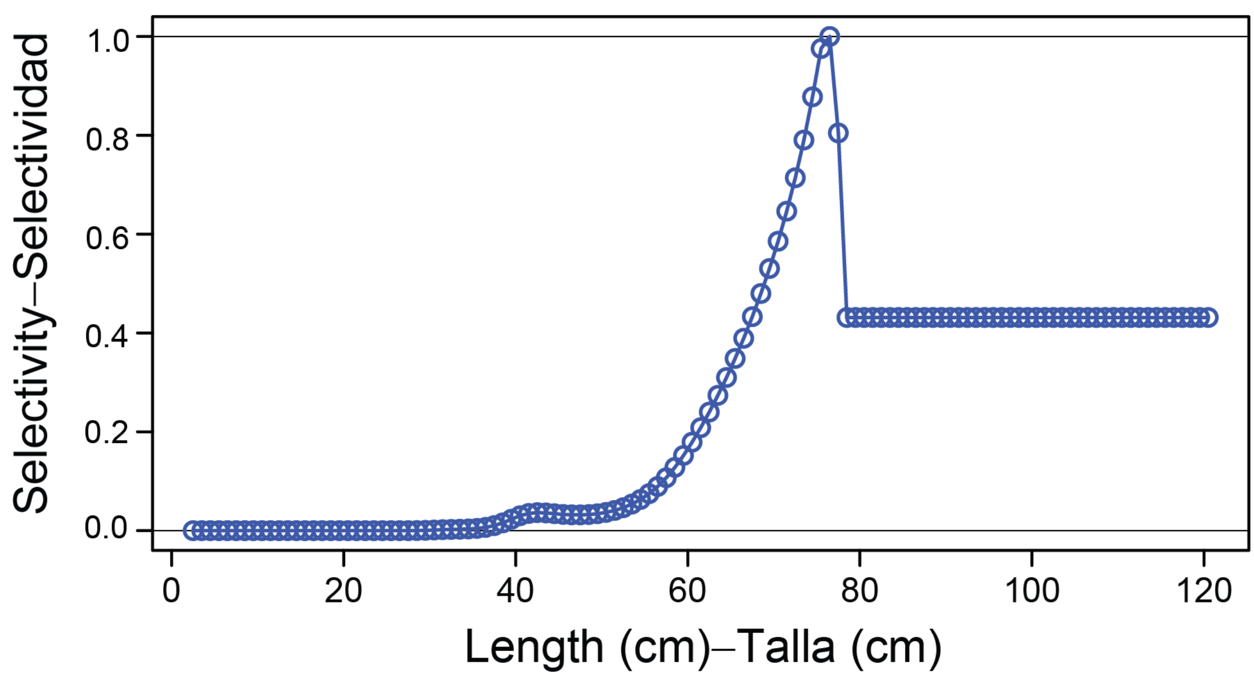

FIGURE 27. Selectivity estimated for the offshore NOAS fishery (F5) when forced to have constant selectivity after the asymptotic length (78 cm).

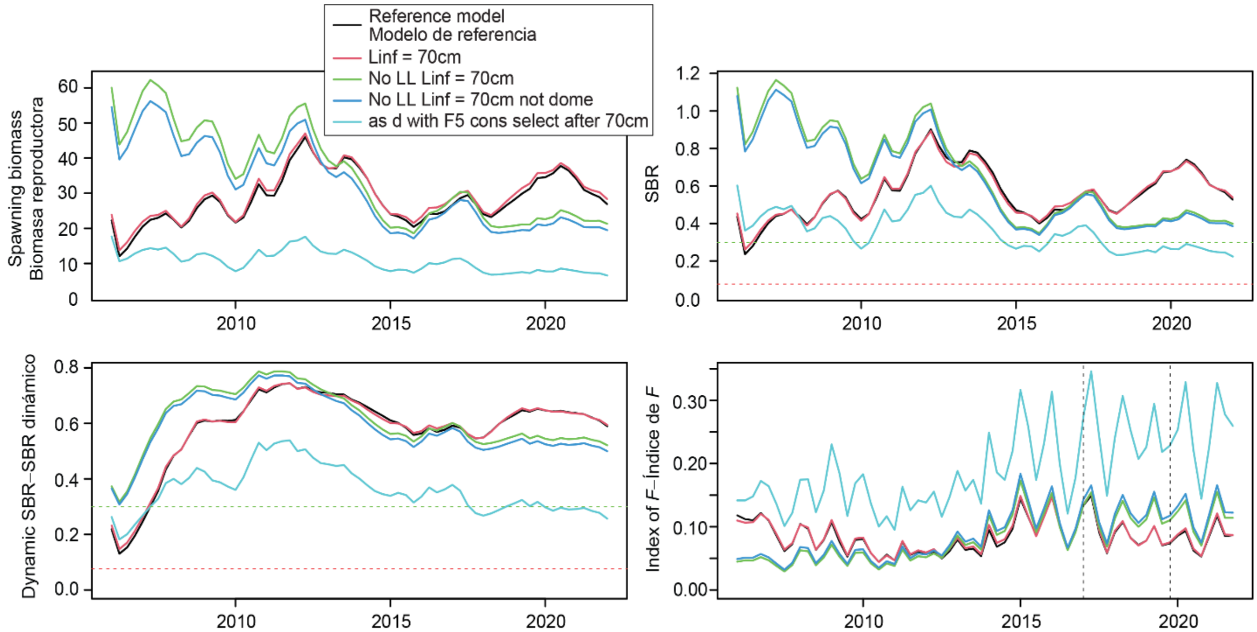

FIGURE 28. Spawning biomass, spawning biomass ratio, dynamic spawning biomass ratio, and an index of quarterly exploitation rate for the sensitivity analyses that investigate lowering the aasymptotic length and not forcing the purse seine selectivity to be dome shaped, removing the longline data, and forcing the offshare NOA fishery (F5) to be asymptotic. The green dashed horizontal line is the target biomass reference point (SBR = 0.3) and the red horizontal dashed line is the limit biomass reference point (SBR = 0.077). The two vertical lines represent the status quo period (2017-2019).

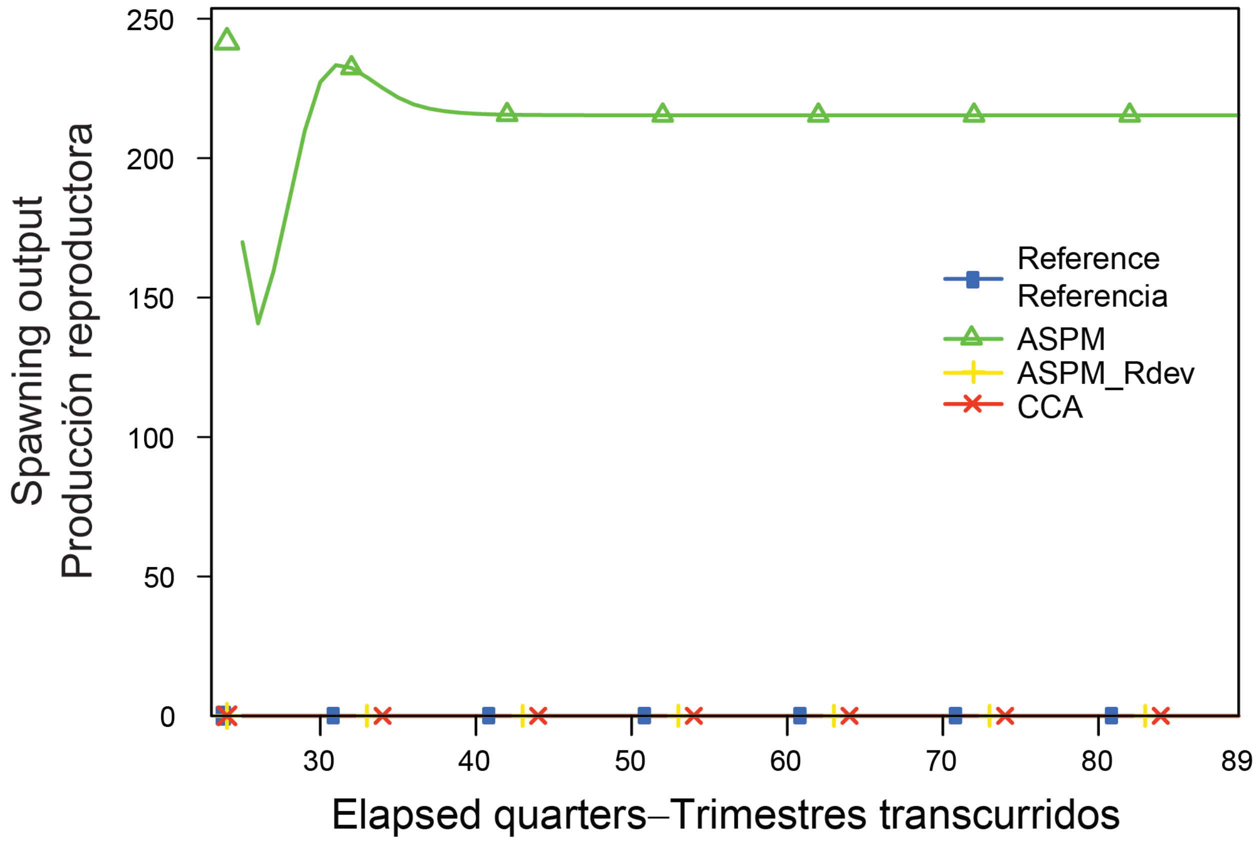

FIGURE 29a. Spwaning biomass for the ASPM and and catch-curve diagnostics for the sensitivity analyses that only models the stock east of -120° W.

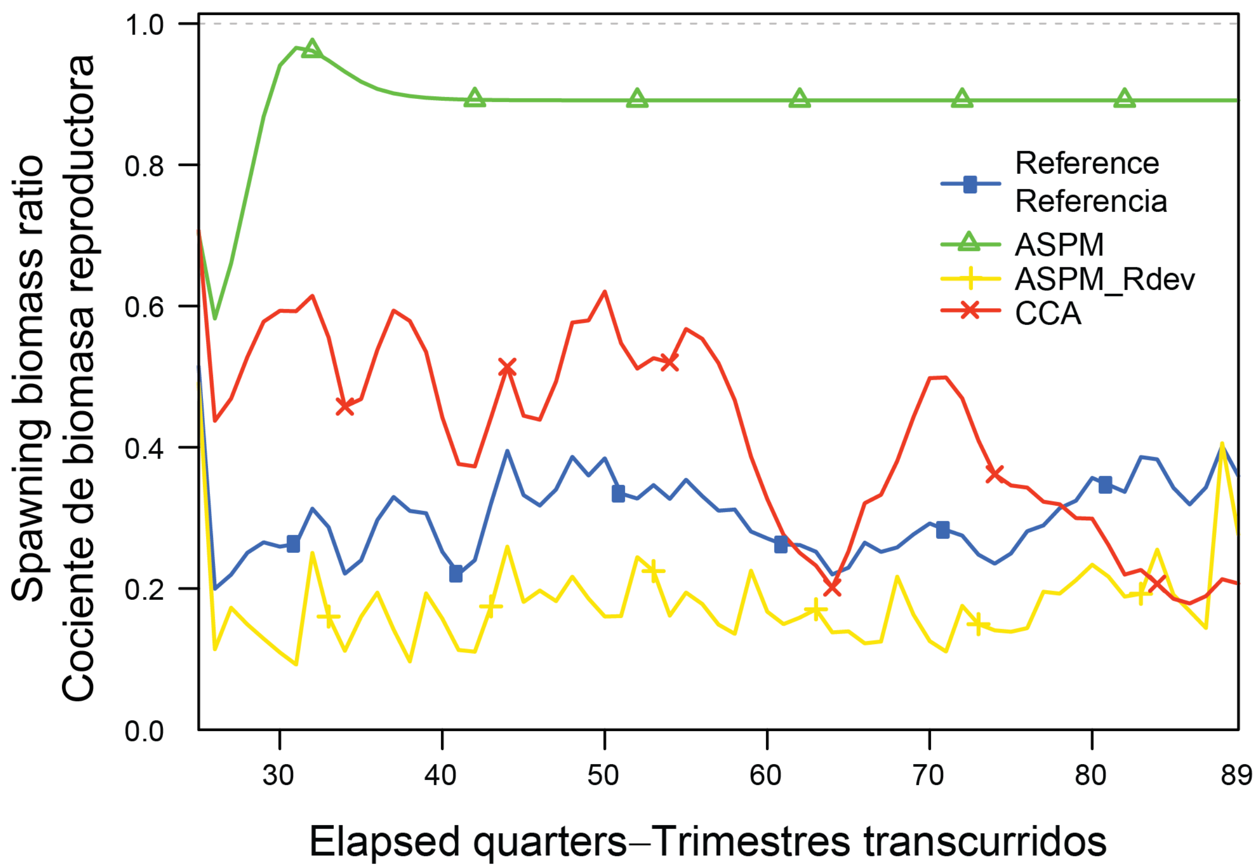

FIGURE 29b. Spwaning biomass ratio for the ASPM and and catch-curve diagnostics for the sensitivity analyses that only models the stock east of -120° W.

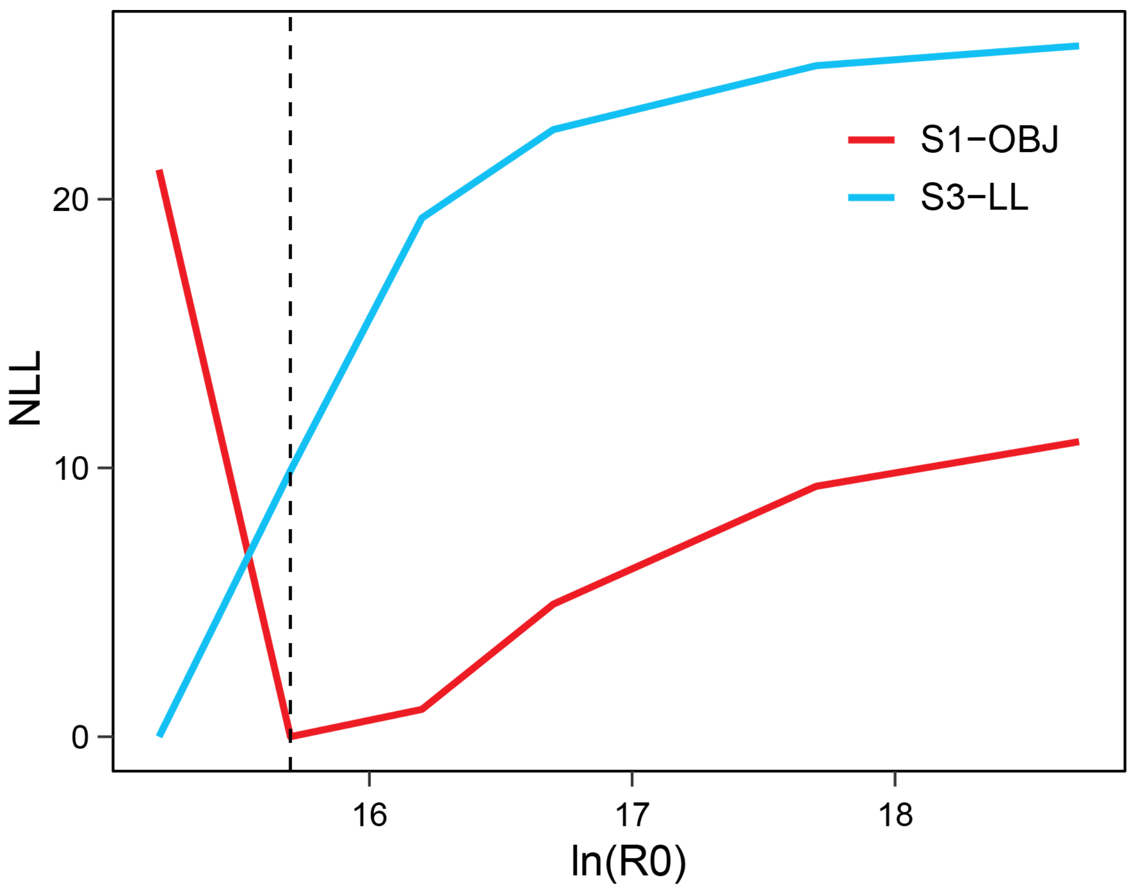

FIGURE 30a. R0 likelihood profile for indicies of abundance from the sensitivity analyses that only models the stock east of -120° W.

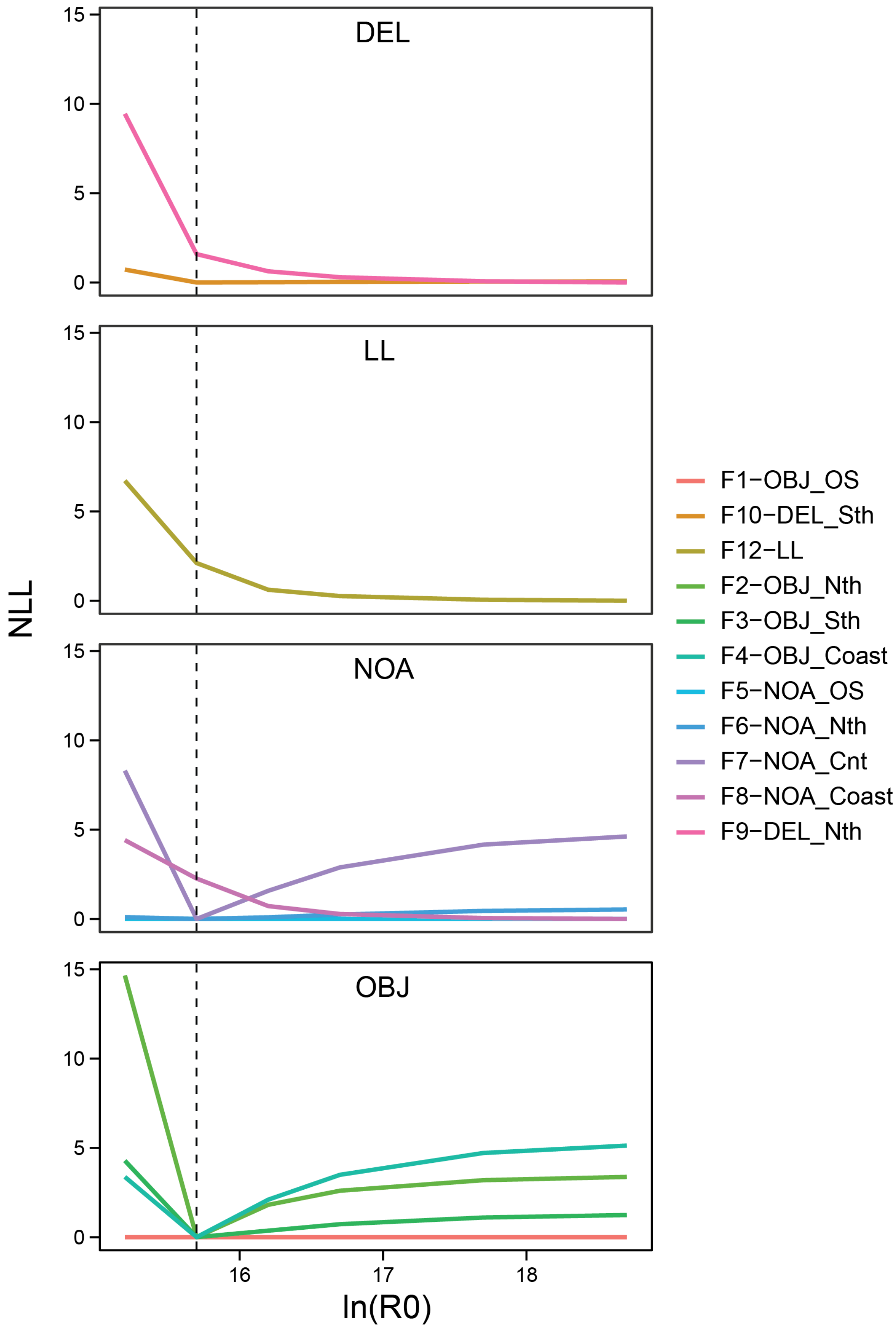

FIGURE 30b. R0 likelihood component profile for the fishery length composition data from the sensitivity analyses that only models the stock east of -120° W.

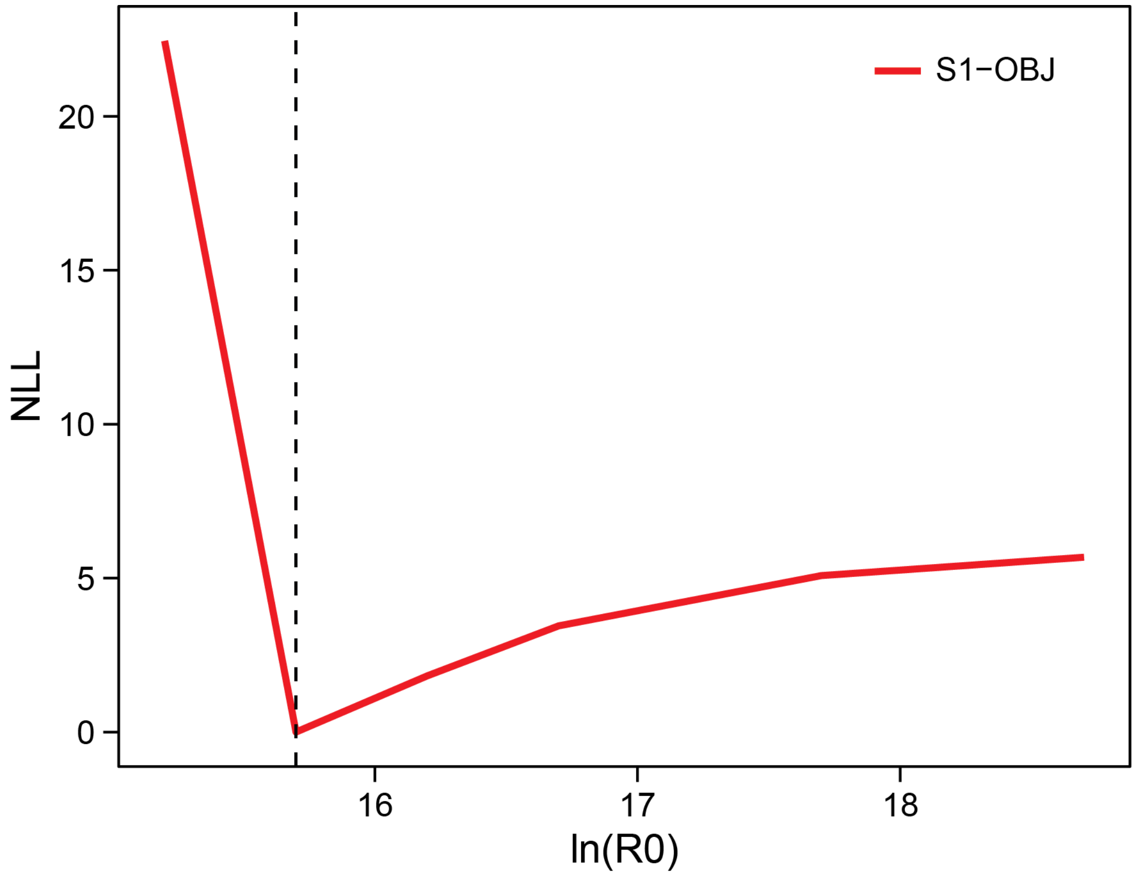

FIGURE 30c. R0 likelihood component profile for the survey length composition from the sensitivity analyses that only models the stock east of -120° W.

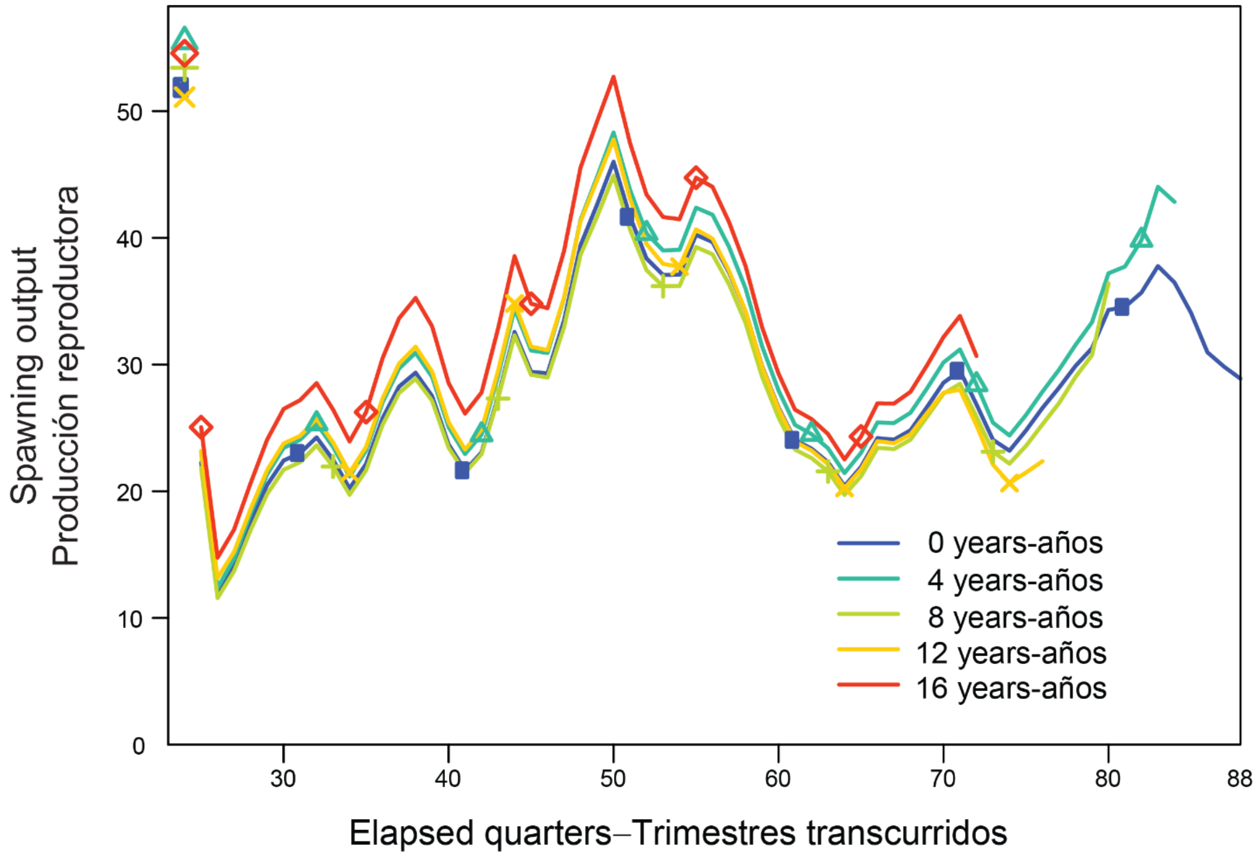

FIGURE 31. Retrospective analsysis for the sensitivity analyses that only models the stock east of -120° W.

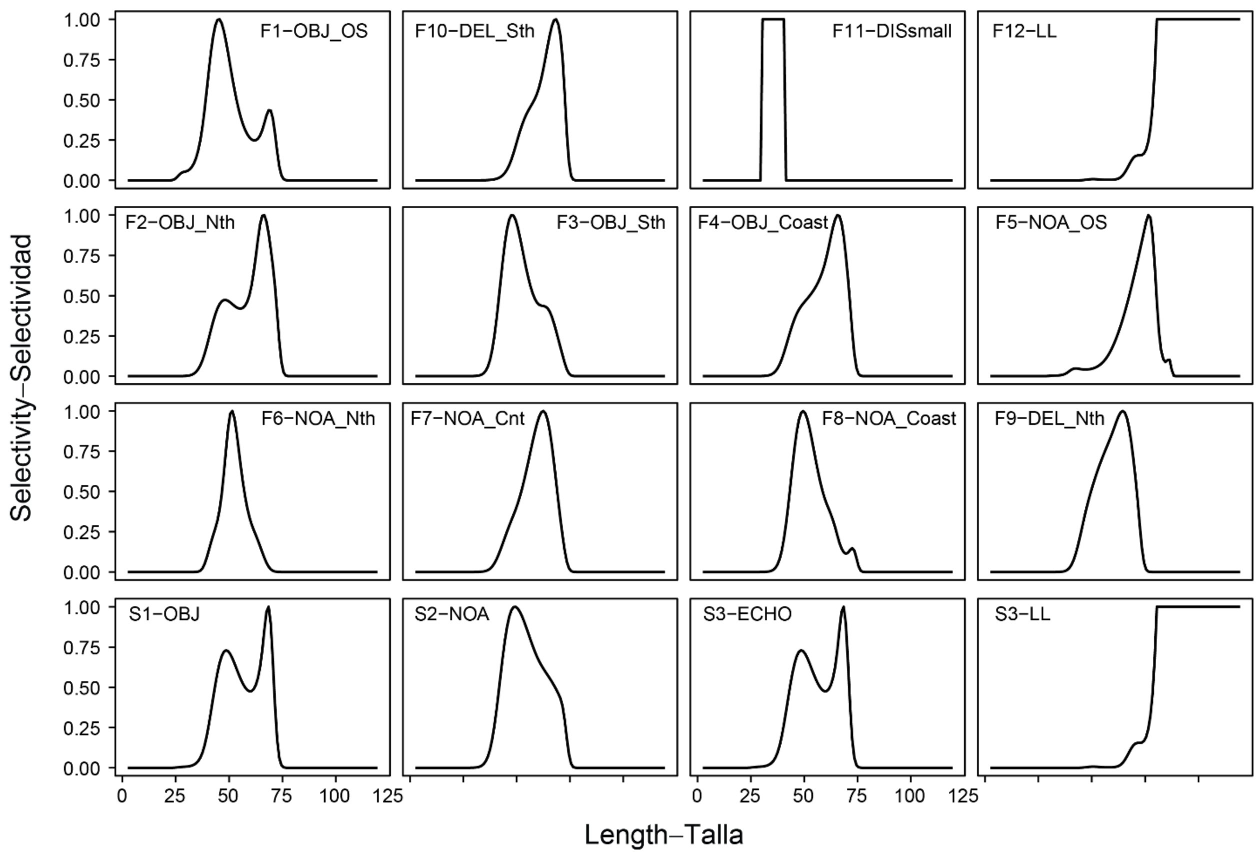

FIGURE 32. Estimated selectivity curves for the sensitivity analyses that only models the stock east of -120° W.

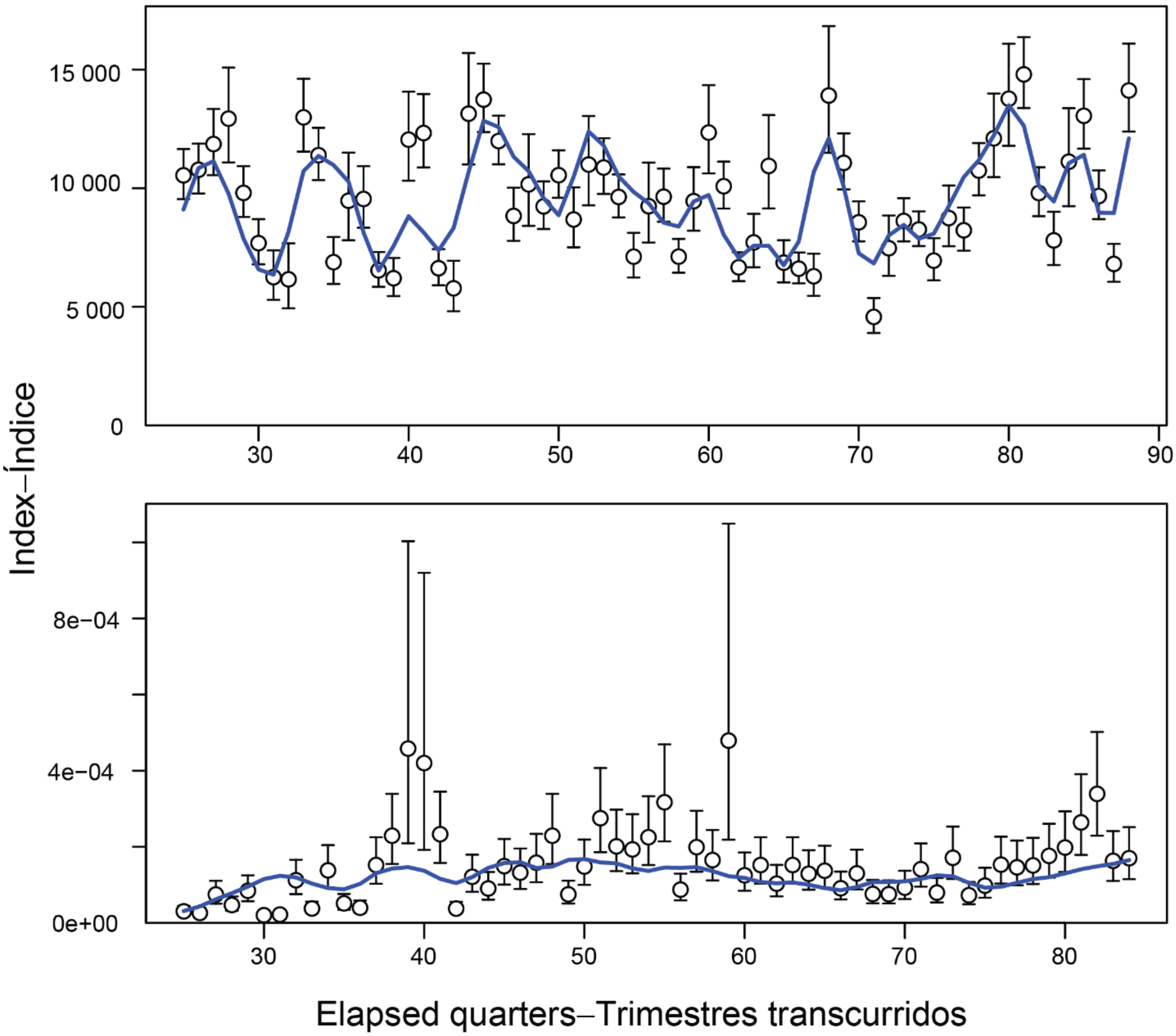

FIGURE 33. Fit to the OBJ catch-per-set (top) and longline (bottom) indices of abundance for the sensitivity analyses that only models the stock east of -120° W.

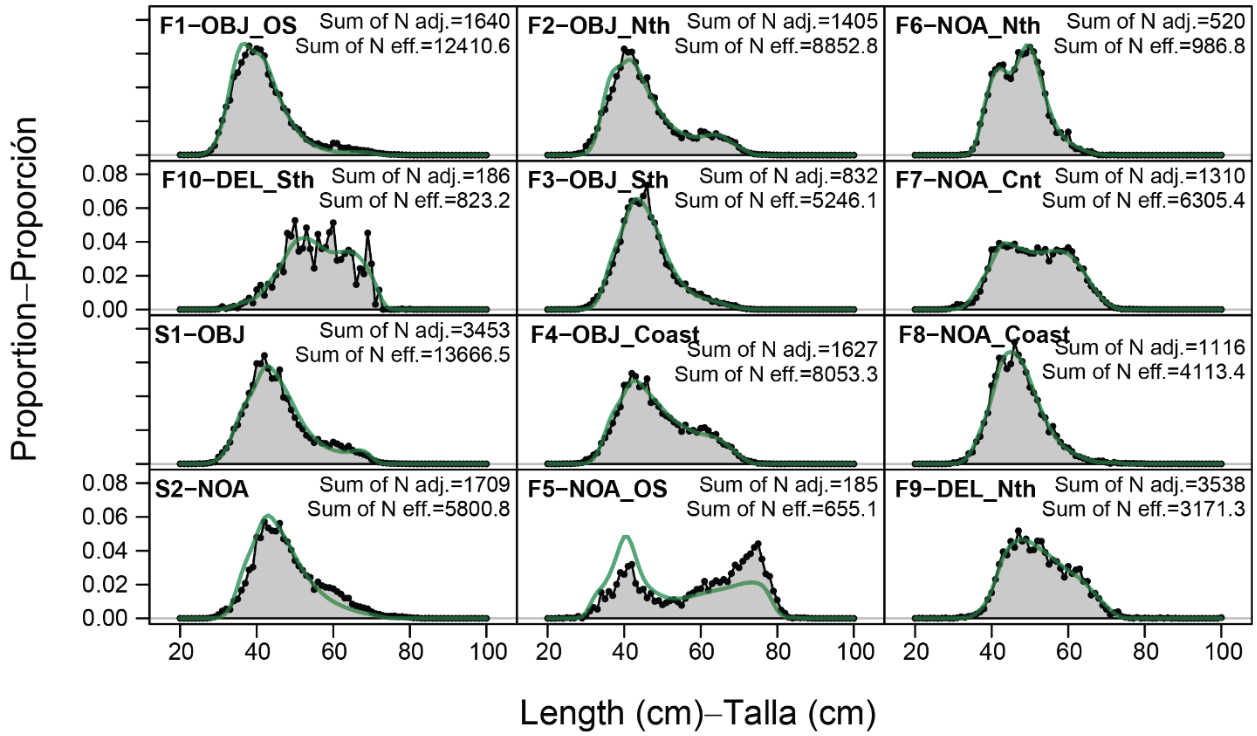

FIGURE 34a. Weighted average observed (shaded area) and predicted (line) length composition data, by purse seine fishery and "survey" for the analyses that only models the stock east of -120° W. The length composition data for F1 and F5 are not fit in the model.

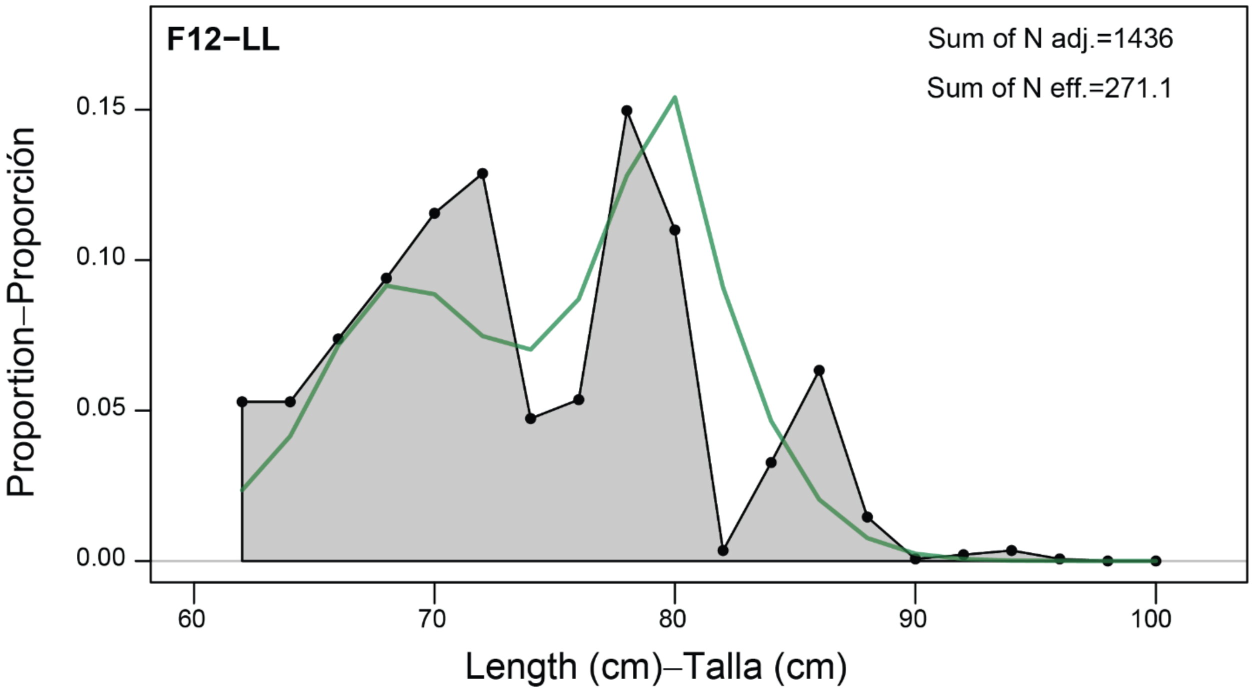

FIGURE 34b. Weighted average observed (shaded area) and predicted (line) length composition data, by longline fishery for the analyses that only models the stock east of -120° W.

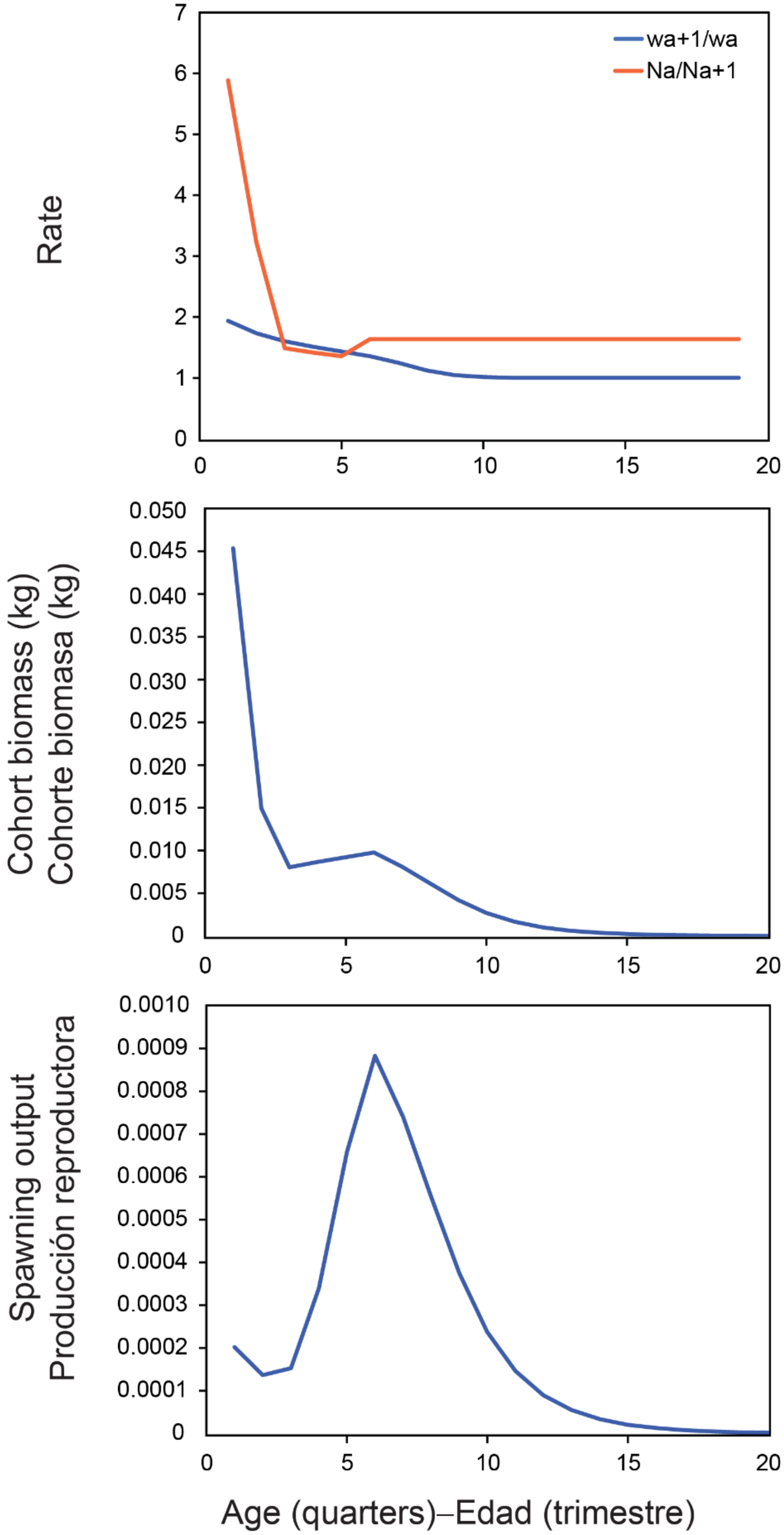

FIGURE 35. Tradeoff between growth and martality rates at age (top), biomass of the cohort of age (middle) and spawning output of a cohort (bottom) at age.

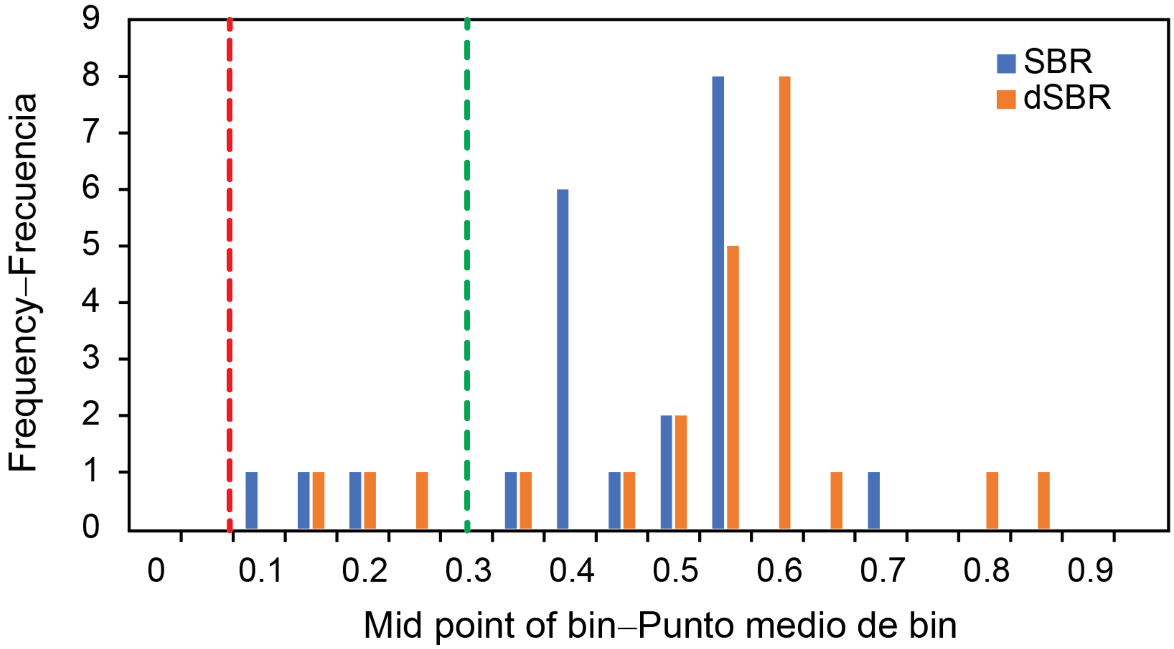

FIGURE 36. Frequency distribution of the estimates of SBR and dSBR. The vertical lines are the limit reference point (0.077) and the proxy target refrence point (0.30).

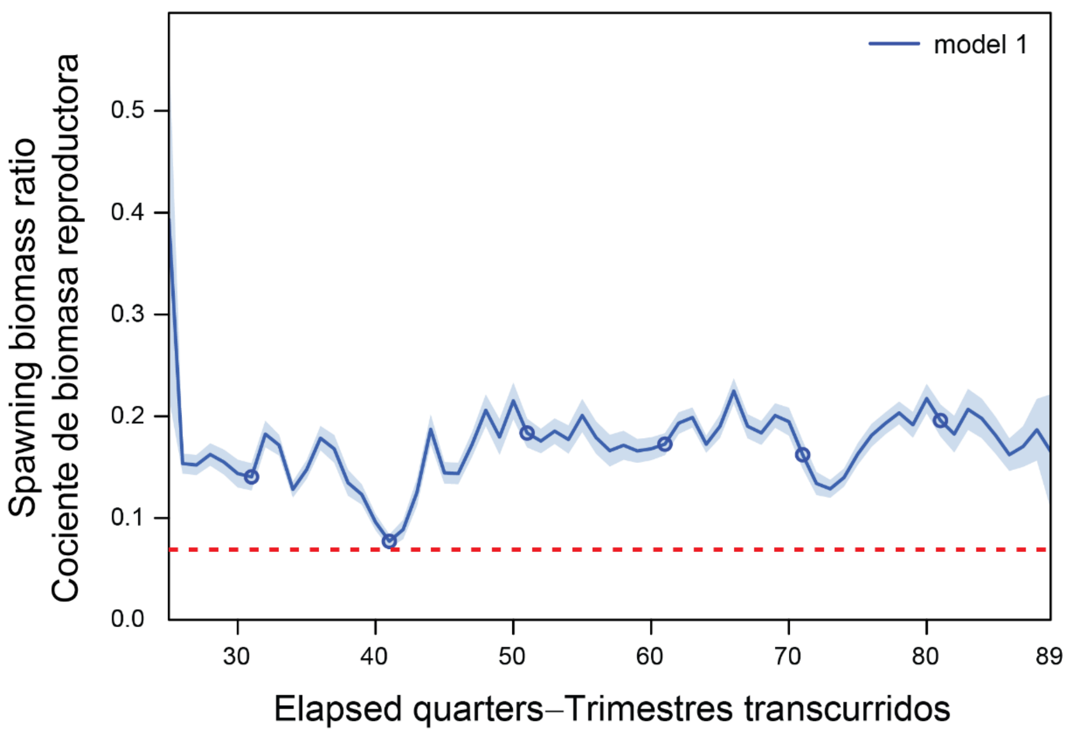

FIGURE 37. Estimate of spawning biomass ratio and 95% confidence intervals from the sensitivity where the NOA offshore fishery (F5) has asymptotic selectivity. The red dashed horizontal line (at 0.077) identifies the SBR at S_{LIMIT}.

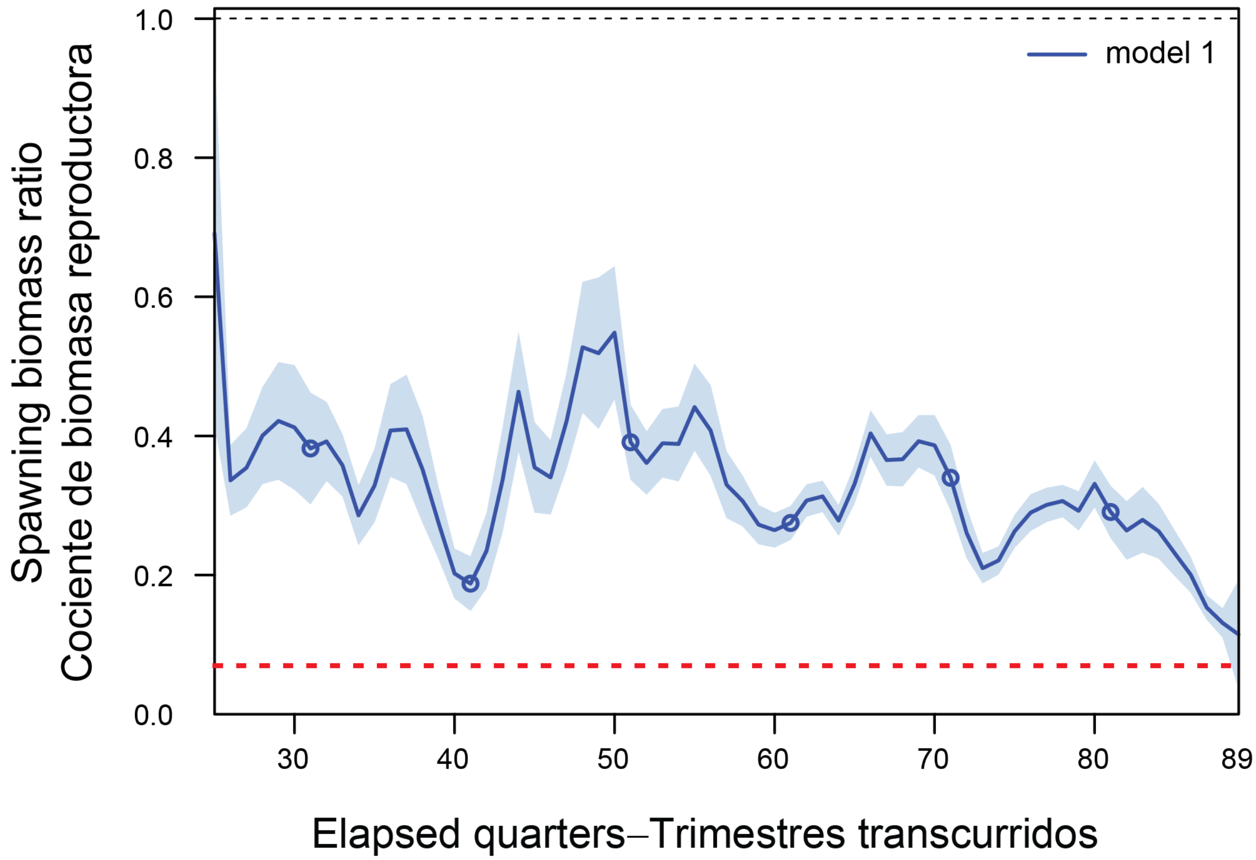

FIGURE 38. Estimate of spawning biomass ratio and 95% confidence intervals from the sensitivity that does not sue the longline data, the purse seine selectivity is not forced to be dome shaped, and the natural mortality is higher for fish greater than 65 cm. The red dashed horizontal line (at 0.077) identifies the SBR at S_{LIMIT}.

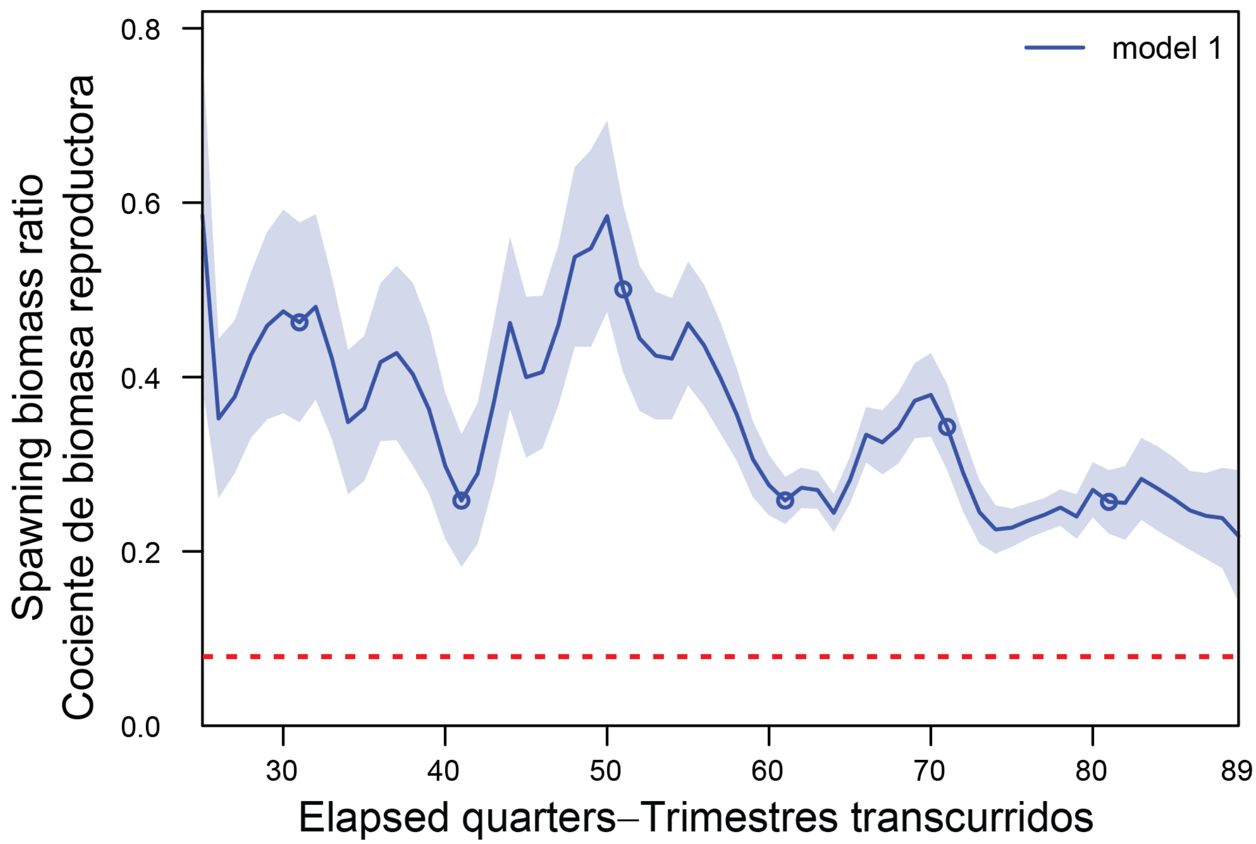

FIGURE 39. Estimate of spawning biomass ratio and 95% confidence intervals from the sensitivity that does not sue the longline data, the purse seine selectivity is not forced to be dome shaped, the asymptotic length is fixed at 70 cm and the offshore NOA fishery (F5) has asymptotic selectivity. The red dashed horizontal line (at 0.077) identifies the SBR at S_{LIMIT}.

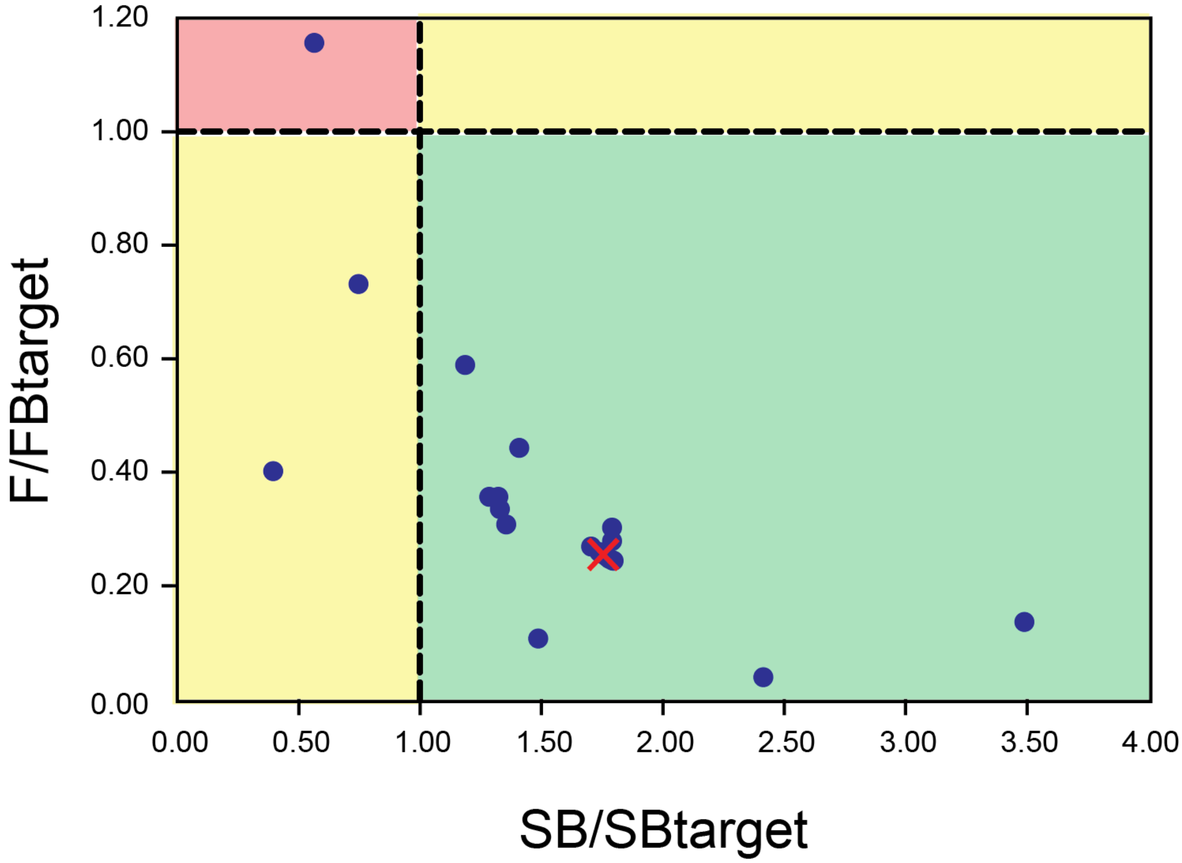

FIGURE 40. Kobe plot showing the stock status estimates from all the models.

TABLE 1. Fisheries defined for the stock assessment of skipjack tuna in the EPO in 2021. **Gear**: PS: purse seine; LL: longline; **PS set type**: OBJ: floating object; NOA: unassociated; DEL: dolphin; **Area**: see Figure 1;

Fishery/survey	Gear	Set type	Area	Units
F1	Purse seine	OBJ	Offshore	Weight
F2	Purse seine	OBJ	North	Weight
F3	Purse seine	OBJ	South	Weight
F4	Purse seine	OBJ	Coastal	Weight
F5	Purse seine	NOA	Offshore	Weight
F6	Purse seine	NOA	North	Weight
F7	Purse seine	NOA	Central	Weight
F8	Purse seine	NOA	Coastal	Weight
F9	Purse seine	DEL	North	Weight
F10	Purse seine	DEL	South	Weight
F11	Purse seine discards	All	EPO	Weight
F12	Longline	NA	EPO	Weight
S1	Purse seine	OBJ	EPO	Weight
S2	Purse seine	NOA	EPO	Weight
S3	Echosounder buoy	NA	EPO	Weight
S4	Longline	NA	EPO	Numbers

TABLE 2. Ranges of S_{MSY}/S_0 estimated in the bigeye (SAC-11-06 table 7) and yellowfin (SAC-11-07 table 8) stock assessments.

Steepness (*h*)	Bigeye	Yellowfin
1.0	0.20 – 0.24	0.23 – 0.32
0.9	0.25 – 0.27	0.28 – 0.35
0.8	0.28 – 0.30	0.32 – 0.37
0.7	0.31 – 0.32	0.35 – 0.40

TABLE 3. Estimates of spawning biomass, spawning biomass ration (SBR), dymanic spawning biomass ration (dSBR), average recruitment over the model time period (except the 4th quarter of 2021) as a ratio of the estimated virgin recruitment for all of the models, average exploitation rate in 2020 as a ratio of the status quo, average exploitation rate in 2021 as a ratio of the status quo, and current fishing mortality as a ratio of the fishing mortality corresponding to Btarget = 0.3B0. Rave/R0 is a check to make sure the SBR based on B0 is not biased due to the bias correction for recruitent residuals (this will affect the plots of SBR that are plotted with confidence intervals). The dSBR is adjsuted by the ratio Rave/R0. The red highlighting and text indicates where SBR or dSBR are below the proxy target refernec point (0.3) and when the status quo fising mortality (average of 2017-2019) has been exceeded.

Model code	Model	SB	SBR	dSBR	Rav/R0	F2020/Fsq	F2021/Fsq	Fcur/ Fbtarget
	Reference model	26871	0.53	0.59	0.98	0.80	1.01	0.25
a	Linf = 73 cm	28475	0.54	0.60	0.99	0.81	1.02	0.24
b	Linf = 83 cm	24899	0.51	0.57	0.98	0.79	1.00	0.27
c	Lcv = 0.05	27560	0.53	0.60	0.97	0.80	1.02	0.25
d	Lcv = 0.07	26086	0.52	0.58	0.99	0.79	1.01	0.26
e	Bias corrected catch for 2020-2021	27861	0.53	0.60	0.98	0.76	1.03	0.25
f	No echosounder index	70976	1.05	0.79	1.04	0.59	0.55	0.14
g	No longline index	23746	0.41	0.56	0.99	0.92	1.06	0.31
h	OBJ catch-per-set index	25339	0.54	0.58	0.98	0.81	0.95	0.28
i	NOA catch-per-set index	22421	0.54	0.55	0.98	0.76	0.90	0.30
j	NOA asymptotic selectivity	3688	0.17	0.18	0.98	0.93	1.00	1.16
k	OBJ asymptotic selectivity	14786	0.42	0.44	0.96	0.77	0.88	0.44
l	East of -120	7960	0.36	0.36	1.01	0.93	0.97	0.59
m1	Higher M for adults	55346	0.72	0.84	0.99	0.72	1.01	0.04
m2	No LL higher M for adults	20029	0.45	0.64	1.00	0.88	1.09	0.11
m3 no M	No LL not Dome	21993	0.40	0.54	0.99	0.92	1.07	0.36
m3 M	No LL not Dome higher M for adults	1772	0.12	0.14	0.97	1.05	1.59	0.40
n	Constant slectivity after 78 cm	26674	0.53	0.59	0.98	0.80	1.01	0.26
o1	Linf = 70cm	28334	0.54	0.59	0.99	0.81	1.02	0.24
o2	No longline Linf = 70cm	21296	0.40	0.52	0.99	0.92	1.06	0.33
o3	No longline Linf = 70cm not dome	19489	0.39	0.50	0.99	0.92	1.07	0.36
o4	as h3 with F5 cons select after 70cm	6572	0.22	0.26	0.97	0.95	1.10	0.73