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EXPLORATORY ASSESSMENT AND STOCK STATUS INDICATORS FOR YELLOWFIN TUNA IN THE EPO

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SUMMARY

Yellowfin tuna is one of the three main tropical tunas harvested in the EPO and sustains a substantial targeted purse seine fishery that predominantly makes sets on yellowfin associated with dolphins. It is also caught in purse seine sets on floating objects and unassociated schools and to a lesser extent in bait boat and longline fisheries. Management of the stock is typically driven by the status of bigeye tuna, but the recent introduction of the Individual Vessel Threshold (IVT) for bigeye tuna has put more focus on the assessments of the other tropical tuna species to provide management advice. The previous benchmark assessment for yellowfin in the EPO was carried out in 2020 and the results were included in a risk analysis. Several uncertainties in the stock assessment remained including the spatial structure and fits to the composition data for the fisheries that are assumed to have asymptotic selectivity. Therefore, substantial research was conducted to improve the assessment. Improvements were made to natural mortality, growth, and how fisheries are modelled. However, uncertainty remains in the stock structure. An exploratory stock assessment was developed using these improvements that focus on data from the core area of the dolphin (DEL) fishery. Sensitivity to the assumption about the stock structure and the presence of large fish were also carried out. Stock status indicators based on DEL fishery and longline CPUE and mean length were evaluated for five areas to investigate the possibility of local depletion. The results indicate that the yellowfin stock and the possible sub-stocks are likely to be near or above the level that corresponds to dynamic MSY and not likely to have exceeded the spawning biomass limit reference point. However, these conclusions are uncertain and dependent on the assumed steepness of the Beverton-Holt stock-recruitment relationship. Further research and data collection, which is outlined in this report, particularly about stock and spatial structure, are needed to produce reliable assessments and management advice in the future.

INTRODUCTION

Yellowfin tuna is one of the three main tropical tunas harvested in the EPO and sustains a substantial targeted purse seine fishery that predominantly makes sets on yellowfin associated with dolphins. It is also caught in purse seine sets on floating objects and unassociated schools and to a lesser extent in bait boat and longline fisheries. Management of the stock is typically driven by the status of bigeye tuna, but the recent introduction of the Individual Vessel Threshold (IVT) for bigeye has put more focus on the assessments of the other tropical tuna species to provide management advice. The previous benchmark assessment for yellowfin in the EPO was carried out in 2020 (SAC-11-07) and the results were included in a risk analysis (SAC-11 INF-J, SAC-11-08). Several uncertainties in the stock assessment remained including the spatial structure and fits to the composition data for the fisheries that are assumed to have asymptotic selectivity. Therefore, substantial research was conducted to improve the assessment.

Research was carried out to better define the population and fishery structure, estimate natural mortality, improve the growth estimates, and better model the selectivity of the fisheries. This research greatly improved the assessment, but uncertainties remain in the assessment.

Here we outline the research conducted and the improvements made to the stock assessment. Then we introduce an exploratory assessment. Next, we present stock status indicators to provide further insights into the status of the stock, particularly in the context of possible stock structure and local depletion. Finally, we outline the research and data collection that is needed to improve the stock assessment and management advice.

RESEARCH

Stock structure

The previous 2020 benchmark assessment (SAC-11-07) and external reviews (YFT-02-Rep, RVDTT-01, RVMTT-01) highlighted uncertainty about the stock-structure of yellowfin in the EPO. Of particular concern was inconsistencies in the large peak in biomass around the early 2000s indicated by indices of abundance from the dolphin associated purse seine fishery and the longline fishery. Since these two fisheries are mainly conducted in different areas, north and south, respectively, this suggests that there may be at least two stocks of yellowfin in the EPO. The 2020 benchmark assessment considered a set of overarching hypotheses concerning stock structure, but due to the practical need for an assessment of the whole EPO, the assessment model was focused on the data for the “core” dolphin associated fishery area with catch included for the whole EPO. The external review concluded that there is evidence of spatial heterogeneity, but there was insufficient information to determine how to define areas for the assessment.

Substantial investigations were conducted into the stock structure of yellowfin in the EPO. Recent analysis of tagging data (Figure 1) indicates that movement of yellowfin is limited (Schaefer and Fuller, 2022) and that isolation by distance may be occurring even within the area of distribution of dolphin associated fisheries, which was previously thought could be modelled as one group (SAC-14-06). This suggests that there may be stock structure relevant for management and local depletion may occur. Also, environmental variation may influence the spatial distribution of yellowfin and how the “stocks” interact (SAC-14-06). The environment also drives variation in recruitment (e.g., Torres-Faurrieta et al., 2016) and possibly causes correlation in recruitment among “stocks”.

Exploratory stock assessments that used a dolphin associated purse seine set index of abundance and associated length composition data of the whole EPO illuminated inconsistencies in the length composition from different parts of the EPO. The index comprised intermediate size fish in the core dolphin associated fishing area (area 4 defined using tree analysis for length composition data, see Fishery definitions below), smaller fish in the northern area (area 5), and larger fish in the southern (areas 1 and 2) and western (area 3) areas (see Figure 6 for the area definitions and Figure 7a for the length compositions). The stock assessment model was unable to reconcile the joint length composition distribution with a regular (e.g., double normal) selectivity curve (Figure 2) indicating that multiple fisheries with different selectivities or different stocks were being combined. Further investigation of historic Japanese longline length composition from the 1960s and 70s (Figure 7b) and current data from the longline observer program of distant water fleets in the same areas supported the hypothesis that larger fish were historically found in the core dolphin associated fishing area, but are now of an intermediate size, while large fish are found historically and currently in the southern and western areas.

It also found that smaller fish were found in the north. This information suggests that local depletion may be occurring in the core area.

Natural mortality

Natural mortality is a notoriously difficult parameter to estimate. Preferably, estimates come from well-designed tagging programs. However, in most cases, natural mortality is taken from different stocks or similar species or from relationships with other parameters (e.g., growth rate (K) or maximum age). Natural mortality can also differ by age and sex. In particular, natural mortality has been shown to have a consistent pattern of declining with size (Lorenzen, 2022). Natural mortality for yellowfin tuna in the EPO is assumed to differ by age and sex. The values used in previous assessments were based on estimates from tagging data in the WCPO and sex ratios from the EPO. The assumption is that natural mortality increases when females mature, and this gives rise to the preponderance of males at large sizes.

The estimates of M for yellowfin in the EPO were updated (see Figure 3) by applying a cohort analysis to EPO tagging data obtained by the recent IATTC tagging program (SAC-14-07) and fitting to sex ratio data from the EPO. Cohort analysis is used because it addresses the impact of non-mixing on fishing mortality. However, it instead makes assumptions about the terminal fishing mortality (i.e., no tagged fish are alive after the last recapture). The natural mortality was parameterized using the Lorenzen function to model the decline in M with age and an increase in female natural mortality related to maturity.

Growth

The assumptions about growth are central to the assessment of tropical tunas in the EPO as only length composition data is available (i.e., no age composition data is available) and it can have a substantial influence on estimates of absolute abundance. The growth of yellowfin tuna in the EPO was updated by fitting the growth cessation model to otolith daily increment data and tag-recapture data (Figure 4). The growth cessation model was used because it generally fits tuna data slightly better than the previously used Richards model and it also reduces the impact of the numerous data from young fish on the estimates of length-at-age of old fish that have few data (Maunder et al., 2018). Reliable information from otolith daily increments is only available up to about age 4 years, so information on older yellowfin comes from a few tagged fish recaptured at a large size, in different areas of the EPO. There are only 6 fish recovered that are above 20 quarters of age. Sex specific growth was also investigated.

Fishery definitions, selectivity and data weighting

In the previous assessment (SAC-11-07) splines were used to represent selectivity to model the irregular (e.g. multi-modal distributions, shoulders, etc.) nature of the length composition for some fisheries. Using splines to model irregular distributions is problematic because data that should be defined as two or more fisheries with different selectivites is being combined into one fishery. If catch allocation among these fisheries changes, the combined selectivity will also change and, without time varying selectivity, the ages of the fish that are removed from the fishery are wrong and the misspecified selectivity might cause the fit to the composition data to bias the stock assessment results.

A new approach was developed to define fisheries and how their length composition data are modelled in the stock assessment. This approach is based on the philosophy that the index of abundance and its composition data, which is standardized using spatio-temporal models to better represent the abundance and reduce any time trend in selectivity, should provide the main source of information on abundance. In contrast, the fisheries should be modelled to remove the catch at the right age and provide limited information on abundance. The approach also assumes that fisheries should exhibit “regular” (i.e., that can be represented by a double normal distribution) length composition distributions. This assumption is influenced by the results from gear selectivity studies that show regular length compositions. Although, to be practical, when the index does not provide reliable information on absolute abundance, the fisheries may need to be relied upon to provide this information.

To implement this philosophy, a framework was developed which involves using regression tree analysis on length composition data to find areas and/or seasons where the length compositions are similar. These are then evaluated to determine if they are "regular" and/or a double normal selectivity can well predict the length composition in the stock assessment. If not, either more work is needed to define the fisheries or the composition data are 1) down weighed or 2) eliminated and the selectivity fixed appropriately. Fisheries that catch a large amount and have good composition data should have time varying selectivity, while those with low catch or poor composition data should have constant selectivity and the composition data down weighted, and those with low catch and poor composition data should have their selectivity's fixed at an appropriate level and their composition data not fit (Figure 5).

The regression tree analysis (Lennert-Cody et al. 2010) was used to define 5 area-based fisheries for the dolphin associated purse seine gear (Figure 6). The northern area (area 5) captures small yellowfin, the core area (area 4) captures medium sized yellowfin, and the southern (areas 1 and 2) and western (area 3) areas capture large yellowfin (Figure 7a).

It was not possible to develop fisheries for some of the unassociated fisheries that had no "regular" length frequency data. These fisheries were bimodal with peaks at small and large fish. This phenomenon is also seen in other oceans. Further investigation showed that individual sets in the same areas were generally all small fish or all large fish. Ideally the catch of these fisheries should be split at the individual set level, and a procedure to implement this split should be investigated, as available length composition data is aggregated at the well level, which may contain multiple sets. In the exploratory model the data (catch and length compositions) were separated by size into a small fish fishery and a large fish fishery, each with their own selectivity, but knife edge at the split size.

Unfortunately, although the new approach worked well for bigeye (SAC-15-02) and skipjack tuna (SAC-15-04), it was problematic for yellowfin, particularly for the core dolphin associated purse seine fishery (area 4, which has the largest catches and effort) and for the index of abundance based on the core area, as the resulting length distributions were still irregular (Figure 8). Spline-based selectivities were needed to adequately represent the composition data when using both asymptotic and dome-shaped assumptions. However, since the model platform Stock Synthesis that was used for the assessment does not allow the position of the knots to be estimated, appropriate selectivities are difficult to determine. Therefore, double normal selectivities were used in the exploratory assessment even though the length composition data was not fit as well as when using splines. Future research is required to develop more stable selectivity curves that have more flexibility than the double normal.

EXPLORATORY ASSESSMENT

Exploratory stock assessment models identified several remaining issues with the EPO yellowfin tuna stock assessment despite the improvements listed above. As previously mentioned in the section on stock structure, an index of relative abundance and its associated length composition data for the whole EPO was found to be inappropriate due to possible stock-structure and local depletion. Therefore, an assessment was conducted for the core area of the dolphin associated purse seine fishery (area 4 in Figure 6). This core area comprises most of the catch of dolphin associated yellowfin in the EPO, but a substantial amount of floating object and unassociated yellowfin catch is caught outside the core area (Figure 9). Another assessment was also conducted using the data from the same core area but included catch from the whole EPO. This second model is similar to the approach used in the 2020 benchmark assessment.

The assessment model is simplified and highly focused on the core dolphin associated purse seine fishery (Table 1). The main pieces of data are the index of abundance and length composition data from the dolphin associated purse seine fishery for the core area based on a spatio-temporal model and the composition data for the core area dolphin associated purse seine fishery. The selectivities are estimated for the index and the core area dolphin associated fishery, while the selectivities of the other fisheries are fixed at approximately the right values (based on previous run of the exploratory models fit to their composition data). This is so the catch is taken out at the approximately correct sizes, but their composition data has no influence on the parameter estimates. It is similar to the approach used to construct an age-structured production model.

Because of the challenges to determine appropriate splines, the double normal distribution is used to represent selectivities. For the asymptotic selectivities, which were used for the index and the dolphin associated purse seine fishery, only the left-hand side of the double normal is used. Similarly, to the index for the whole EPO, as mentioned above in the section on "Fishery definitions, selectivity and data weighting", the double normal neither fit well the length composition data for the index based on core area (Figure 8) nor the length composition of dolphin associated purse seine fishery in the core area.

In the core area, there are very few yellowfin caught at the asymptotic length (172 cm) and it is not clear if the asymptotic length is biased due to including fish in the growth analysis that are from different areas (stocks) or if it is due to some other factor. Therefore, the analyses were repeated where the 1) asymptotic length is estimated in the stock assessment and 2) the asymptotic selectivities are assumed to be dome-shape (Table 2).

All the assessment models estimated similar trends in abundance, however the absolute abundance and depletion levels differed among the three model assumption scenarios (Figure 10). In general, the EPO model estimates were like the core area results. As expected, the models that estimated the asymptotic length were more optimistic than the models that kept it fixed at the value from the growth analysis (Figure 10). The models that assumed a dome shape selectivity for the index and DEL fishery estimated an unrealistically high biomass level and a low level of depletion, particularly when based on the dynamic definition of unfished biomass that takes the time series of recruitment into consideration (Figure 10). The most pessimistic of the models that assume recruitment is independent of stock size (steepness of the stock-recruitment relationship h = 1.0) estimates the dynamic depletion at 22% in 2024, which is above the SMSY/S0 = 16% (Table 3). The stock is more depleted when based on equilibrium unexploited biomass (Figure 11) since there is a regime shift to a lower level of recruitment in the past 20 years. The model with steepness of the Beverton-Holt stock-recruitment relationship fixed at h = 0.8 has the current dynamic depletion at 16%, which is below the corresponding SMSY/S0 level of 31%. This sensitivity was weighted in the 2020 Benchmark risk analysis as having about half the weight (46%) of the models with steepness of h=1. There is much less than a 10% probability that the limit reference point has been exceeded for all scenarios with steepness equal to 1 (less than 0.1%) (Table 3, Figure 12).

STOCK STATUS INDICATORS

Given that the exploratory assessment focused on the core dolphin associated purse-seine fishery and that the limited movement indicated by the tagging data suggest isolation by distance and possible local depletion, there is concern that stock status may differ spatially and the exploratory assessment may not account for stock status outside the core area. This is particularly concerning for the area between the equator and 5°N where there is substantial effort from the floating object purse seine (OBJ) fishery (areas 1 and 2, where for area 2 the catch is high only in recent years). Therefore, stock status indicators based on the dolphin associated purse seine (DEL) fishery and the longline fishery were generated for the areas defined for the DEL fisheries (Figure 6). The indicators included nominal CPUE and mean length.

Initially, it was thought that the southern and western areas appeared to be less exploited because the DEL fishery captures larger yellowfin indicating that the stock may not be as heavily exploited as the core area. However, after further consideration, the OBJ fishery still could be having an impact given that the size of fish caught in the OBJ fishery has limited overlap with the size of the fish in the DEL fishery, and therefore may not impact the size of fish entering the DEL fishery. And, since the DEL fishery catch is small in these areas, the average size may be expected to remain large. Therefore, CPUE might be a better indicator in these areas.

Indicators based on nominal CPUE and mean length for the DEL and longline fisheries for the 5 spatially defined DEL fisheries (Figure 6) were created. Loess smoothers were applied to the values because they were highly variable for some areas due to limited data. The DEL nominal CPUE showed a large peak in CPUE in 2001 in all areas (Figure 13). Areas 1, 3, 4, and 5 showed similar trends with a substantial shift in CPUE after the peak, with area 1 showing larger variations before the peak (Figure 13). Area 2 showed less of a decline. For nominal longline CPUE limited to areas where the DEL fishery operates, only area 2 shows a large peak in 2000 (Figure 14). However, this area shows large fluctuations. All other areas show a reduction in CPUE after 2000. Area 4 shows the least reduction. The picture is somewhat different if the longline CPUE is not restricted to the area where the DEL fishery operates (Figure 15). Area 1 has a peak in 2000 and area 2 has a peak in 2001. All areas except area 2 have a decline in CPUE after 2000. Area 2 has a decline in CPUE after 2009. Area 4 has the least decline. In summary, the DEL CPUE does not indicate any evidence of larger declines in abundance in the other areas compared to the core area that is assessed in the exploratory model (area 4). However, the longline CPUE indicates all the other areas may have a larger decline. The amount of data for area 4 is limited, however, so the comparisons for longline CPUE are uncertain.

Mean length is much less sensitive to exploitation than CPUE so it is more difficult to interpret evidence of higher depletion rates. This is particularly true for a relatively short-lived species like yellowfin with highly variable recruitment. The differences in mean length from the 5 areas in the DEL fishery are consistent over time (Figure 16). However, there is substantial temporal variability. Interestingly, there are changes in mean length after the CPUE peak in 2000, but the direction of the change differs among areas. The mean length increases in the southern areas 1 and 2 but decreases in the other areas. It is very difficult to detect any trends that might indicate higher depletion than the core area, except perhaps the decline in area 2 after 2000. The longline mean length does not appear to show any patterns or trends except that in about 2000 the mean length in the core area increased (Figure 17).

The longline mean length is quite different from the DEL mean length in both magnitude (higher) and relative size among areas. Area 1 has the highest mean length in both, but area 4 is lower than the others (except area 5) for DEL. These comparisons are uncertain due to the restricted area fished by the longline fishery in area 4.

CONCLUSION

There is still substantial structural uncertainty in the stock assessment for yellowfin tuna in the EPO. Much of this uncertainty derives from lack of information on the stock structure and growth, and no direct information on absolute abundance. Exploratory stock assessments indicate that the stock is around the levels corresponding to MSY and above the level relative to the limit reference point. However, these conclusions are uncertain and dependent on the assumed steepness of the Beverton-Holt stock-recruitment relationship. Further analyses that address stock and spatial structure are required to determine the stock status.

In general, there is no strong evidence from the indicators that the other areas are experiencing higher depletion than the core area. In particular, the CPUE from the DEL fishery shows similar trends except the southern inshore area (area 2) which shows less of a decline. The longline CPUE shows some evidence, but the data is sparce from the core area, so any conclusions are uncertain. There are some discrepancies between the DEL and longline length frequencies, but this is also likely due to the limited length frequency information from the longline data in the areas where it overlaps with the DEL fishery. An immediate concern is the impact of the OBJ fishery, which may not be noticeable in the mean length of the DEL fishery due to limited overlap in the lengths that are caught. However, there does not appear to be a signal in the DEL CPUE data indicating substantial impact of the OBJ fishery.

FUTURE RESEARCH

There are several issues that remain in the EPO yellowfin tuna assessment and research is needed to improve the assessment and management advice. The following areas of research are considered priorities.

Short term:

Develop cluster analyses methods that are based on irregular but contiguous areas. The main approach currently used to define fisheries, which can also be used to inform stock structure, is based on a regression tree method that uses latitude and longitude splits. Spatial structure can be caused by a number of factors, and these may not be directly related to latitude and longitude. Some of the issues in defining fisheries and representing the length composition using double normal selectivities and defining stock structure may be due to diagonal or other irregular spatial structure.

Develop flexible well behaved asymptotic selectivity curves. Using the left-hand side of the double normal or a logistic curve to represent asymptotic selectivity appears to be too inflexible to adequately represent the length composition data. Splines tend to be too flexible and produce irregular shapes. It is also not possible to estimate the knot where the asymptotic selectivity occurs in the splines implemented in Stock Synthesis. A more regular, but still flexible, asymptotic selectivity curve that allows the point where it becomes asymptotic to be estimated is needed.

Create a longline CPUE- based index of relative abundance using data from all the distant water fleets. Currently the index of abundance is based only on Japanese vessels. The Japanese fleet has been reducing its effort and spatial coverage and has made the index highly uncertainty. Data from fleets of other nations could be included in the analysis. This may require accounting for differences in catchability and selectivity among the fleets. The analysis can only be efficiently developed if the member countries provide the required data to the IATTC staff on a permanent basis.

Investigate the index derived from the CPUE of the dolphin associated fishery. The length compositions associated with the index of abundance present irregularities despite the standardization using spatio-temporal models, and the restriction to the core area. There are concerns that the index could be indicative of the dolphin-tuna association rather than strictly the abundance of yellowfin tuna, and that it may not be linearly related to abundance. An investigation of potential covariates related to catchability (e.g. the species of dolphin) and abundance (e.g. environmental factors) is needed to better understand the index.

Further develop models to characterize the stock/spatial structure. Further evaluation is needed to define alternative stock structures for the assessment. These alternatives will form the basis for both the risk analysis and the management strategy evaluation of the yellowfin tuna in the EPO.

Improve the spatio-temporal analysis for tagging data and apply it to yellowfin tuna. A new spatio-temporal analysis of tag data has been developed to deal with non-mixing and applied to skipjack (SAC-15-04). This model provides estimates of absolute abundance and could be applied to yellowfin. Currently, a substantial amount of information on absolute abundance for the yellowfin assessment comes from the length composition data which is problematic since it is highly dependent on the asymptotic length of the growth curve and assumptions about selectivity. Several improvements of the spatial temporal model could be made including explicitly modelling the exploitation rate and including length structure.

Medium term:

Collect more data to inform the growth curve. The asymptotic length of the growth curve is informed by only a few tag recaptures of large yellowfin. These yellowfin are larger than generally seen in the core DEL fishery and it is unclear if they are from the same stock or if they indicate that the stock is highly depleted, the DEL fishery has dome shape selectivity, or large yellowfin move out of the core area. Given that the fit to the composition data can have a large influence on the estimates of absolute abundance, better information about the asymptotic length is needed. Given the issues with aging large yellowfin from daily increments and controversy over annual aging (OTM-28), collecting more tagging data of large yellowfin in the core area is a priority.

Collect more tagging data. The current tagging data for yellowfin tuna is limited and therefore the estimates of abundance from the spatio-temporal tagging analysis are likely to be uncertain. In addition, the analysis requires reliable estimates of reporting rates, tag related mortality, and tag loss. The estimates of natural mortality were also obtained from tagging data. An improved comprehensive tagging program would greatly improve the assessment and would also help with better defining stock-structure.

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TABLE 1. Summary of the main assumptions of the exploratory models.
TABLA 1. Resumen de los principales supuestos de los modelos exploratorios.

Process	Component	Assumption
Fishery definitions		33 fisheries defined according to gear and area of operation (Appendix 1). Core model has 2 OBJ, 1 NOA, 1 DEL, 2 LL, 1 sorted OBJ discard, 1 BB fishery EPO model has 7 OBJ, 5 NOA, 5 DEL, 10 LL fisheries, 1 sorted OBJ discard, 1 BB fishery
Selectivity	Index	Asymptotic modelled using a double normal In dome-shape model, assumed double normal with dome-shape
	DEL core fishery	Time-blocks Asymptotic modelled using a double normal in the last block In dome-shape model, assumed double normal with dome-shape
	Other fisheries	Fixed using a double normal
Growth	Mean length-at-age	Estimated using the growth cessation model fit to otolith daily increment data and tag-recapture data, see Figure 4 In asympt_Linf model, the Linf parameters isestimated within the assessment
	Variation of length-at-age	The standard deviation (SD) of the length-at-age is a linear function of length (SD for age zero fish is estimated and is assumed equal to 7.64 for age 29 quarters).
Natural mortality		Age and sex structured. Estimated using a cohort analysis fit to tagging and sex ratio data. See Figure 3.
Recruitment	Stock-recruitment relationship	Recruitment is independent of stock size (*i.e.,* the steepness of the stock-recruitment relationship is h = 1) and is estimated for each quarter.
	Variation	Quarterly recruitment is assumed to vary around the average level by a lognormal distribution with a standard deviation of 1. 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.
Index of abundance		The DEL based index is proportional to abundance

TABLE 2. Exploratory stock assessments models.
TABLA 2. Modelos de evaluación exploratoria.

Model	Catch	Index and DEL fishery selectivity	Asymptotic length	Steepness (h)
Core Asymp	Core	Asymptotic	Fixed	1.0
Core Asymp h 0.8	Core	Asymptotic	Fixed	0.8
Core Asymp Linf	Core	Asymptotic	Estimated	1.0
Core Dome	Core	Dome	Fixed	1.0
EPO Asymp	EPO	Asymptotic	Fixed	1.0
EPO Asymp Linf	EPO	Asymptotic	Estimated	1.0
EPO Dome	EPO	Dome	Fixed	1.0

TABLE 3. Estimates of some reference quantities obtained by the exploratory stock assessments models for yellowfin tuna in the EPO, 2024: S_{MSY}/S_0 is the equilibrium spawning biomass corresponding to the maximum sustainable yield relative to the virgin spawning biomass (S_0), $S_{current}/dS_0$ is the spawning biomass at the beginning of 2024 relative to the spawning biomass with no fishing (dynamic S_0), h is steepness value of the stock-recruitment function, Linf refers to a model that estimates the growth asymptotic length parameters. ($P(S_{current}/S_0 < 0.077)$ is the probability of exceeding the limit reference point. The Core_Asymp h 0.8 failed to estimate a positive-definite Hessian matrix.

TABLA 3. Estimaciones de algunas cantidades de referencia obtenidas por los modelos de evaluación exploratoria para el atún aleta amarilla en el OPO, 2024: S_{RMS}/S_0 es la biomasa reproductora en equilibrio correspondiente al rendimiento máximo sostenible relativa a la biomasa reproductora virgen (S_0), S_{actual}/dS_0 es la biomasa reproductora a principios de 2024 relativa a la biomasa reproductiva sin pesca (S_0 dinamico), h es el valor de la inclinación de la función población-reclutamiento, Linf se refiere a un modelo que estima los parámetros de crecimiento de la talla asintótica. (Ver el Anexo 2 para la definición de las cantidades presentadas). $P(S_{actual}/S_0 < 0.077)$ es la probabilidad de exceder el punto de referencia limite. El modelo Core_Asymp h 0.8 no obtubo una matriz Hessiana positiva definida.

Model	S_{MSY}/S_0	$S_{current}/dS_0$	$S_{current}/S_0$	$P(S_{current}/S_0 < 0.077)$
Core_Asymp	0.16	0.22	0.14	0
Core_Asymp h 0.8	0.31	0.16	0.10	NA
Core_Asymp_Linf	0.11	0.33	0.20	0
Core_Dome	0.10	0.80	0.43	0
EPO_Asymp	0.19	0.25	0.19	0
EPO_Asymp_Linf	0.14	0.35	0.25	0
EPO_Dome	0.11	0.91	0.52	0

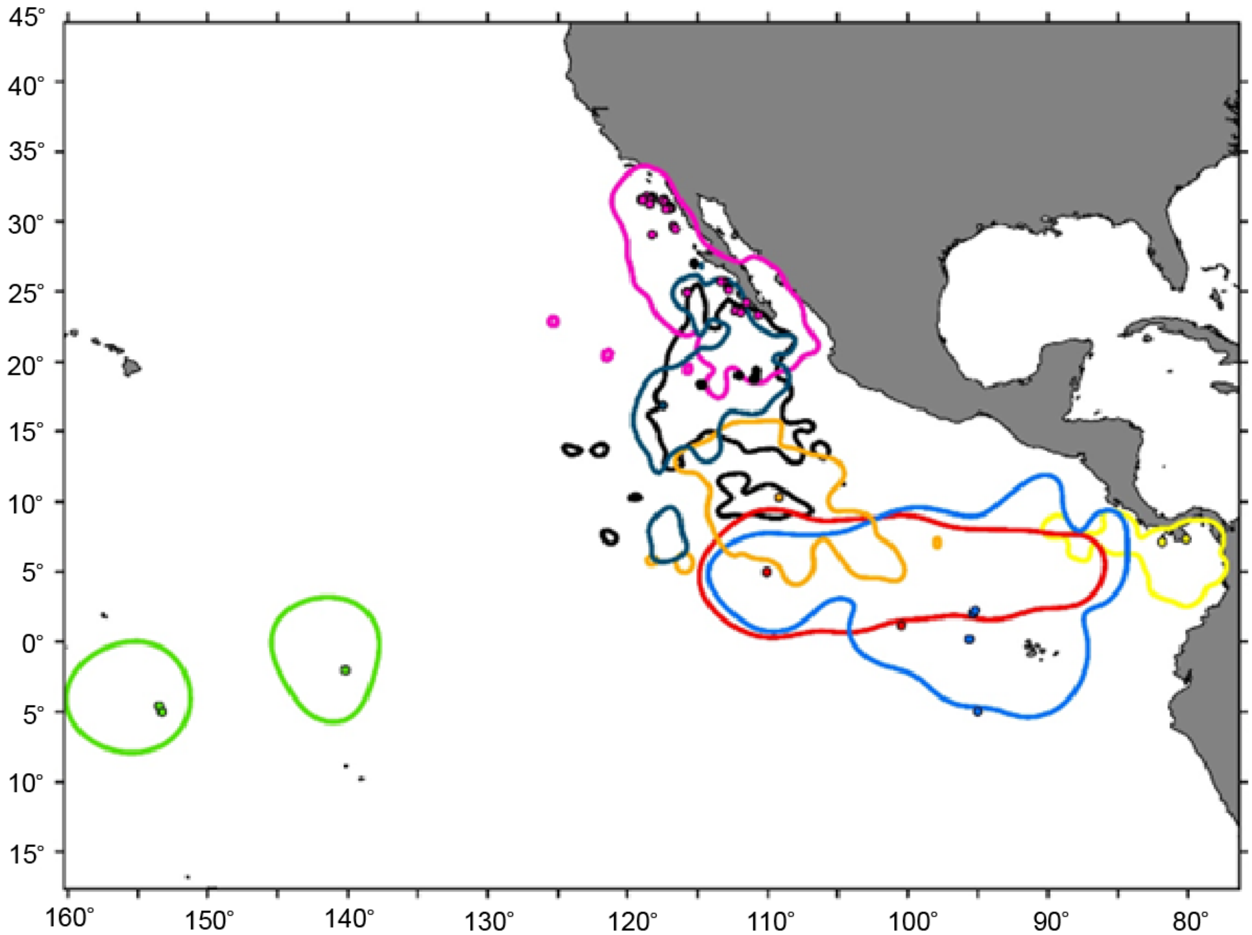

FIGURE 1. 95% contours of the displacement distribution of archival tags depicting the limited movement of yellowfin tuna. Colors indicate the release locations (dots). Each contour represents a group of fish ranging from 5 fish in the Central Pacific Ocean (green) to 126 off Baja California (pink). See Schaefer and Fuller (2022) for more details.

FIGURA 1. Contornos del 95% de la distribución del desplazamiento de las marcas archivadoras que muestran el desplazamiento limitado del atún aleta amarilla. Los colores indican los lugares de liberación (puntos). Cada contorno representa un grupo de peces que va desde 5 peces en el Océano Pacífico central (verde) hasta 126 frente a Baja California (rosa). Ver Schaefer y Fuller (2022) para más detalles.

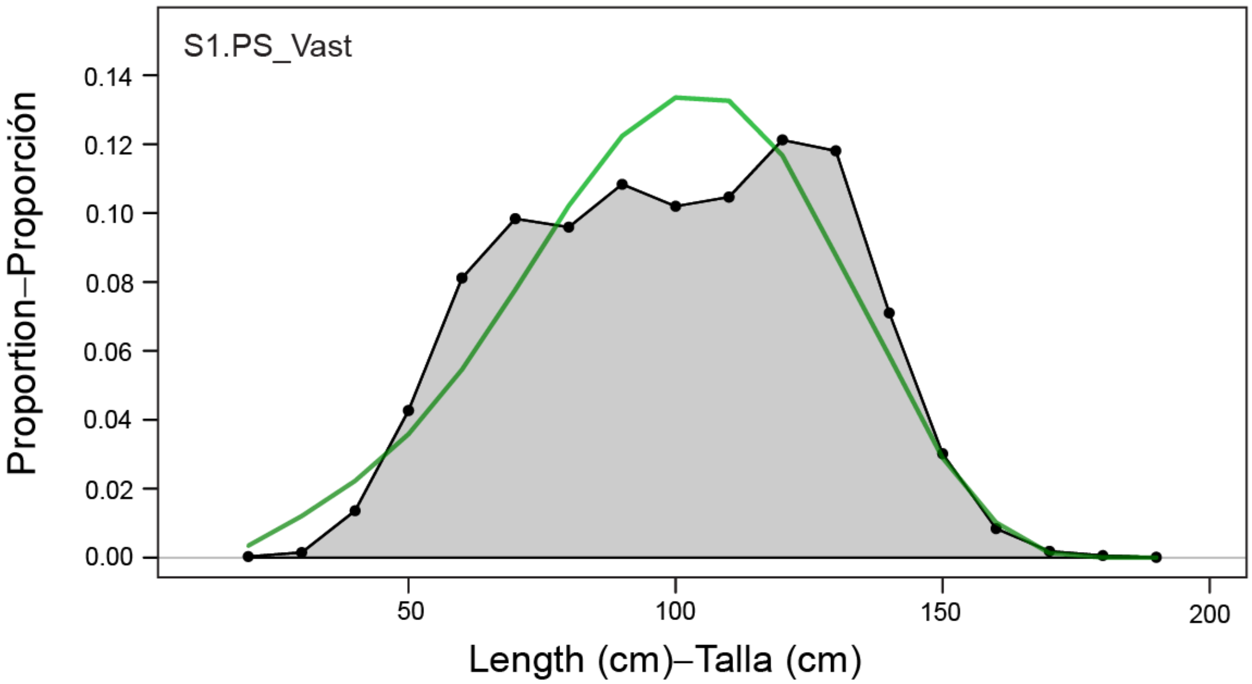

FIGURE 2. Illustration of how the stock assessment model (line) is unable to fit the DEL index of abundance composition data for the whole EPO (shaded area) obtained by standardizing the fishery length composition data using spatio-temporal models.

FIGURA 2. Ilustración de cómo el modelo de evaluación (línea) es incapaz de ajustar los datos de composición por talla del índice de abundancia DEL para el OPO entero (área sombreada) obtenidos mediante la estandarización de los datos de composición por talla de la pesquería usando modelos espaciotemporales.

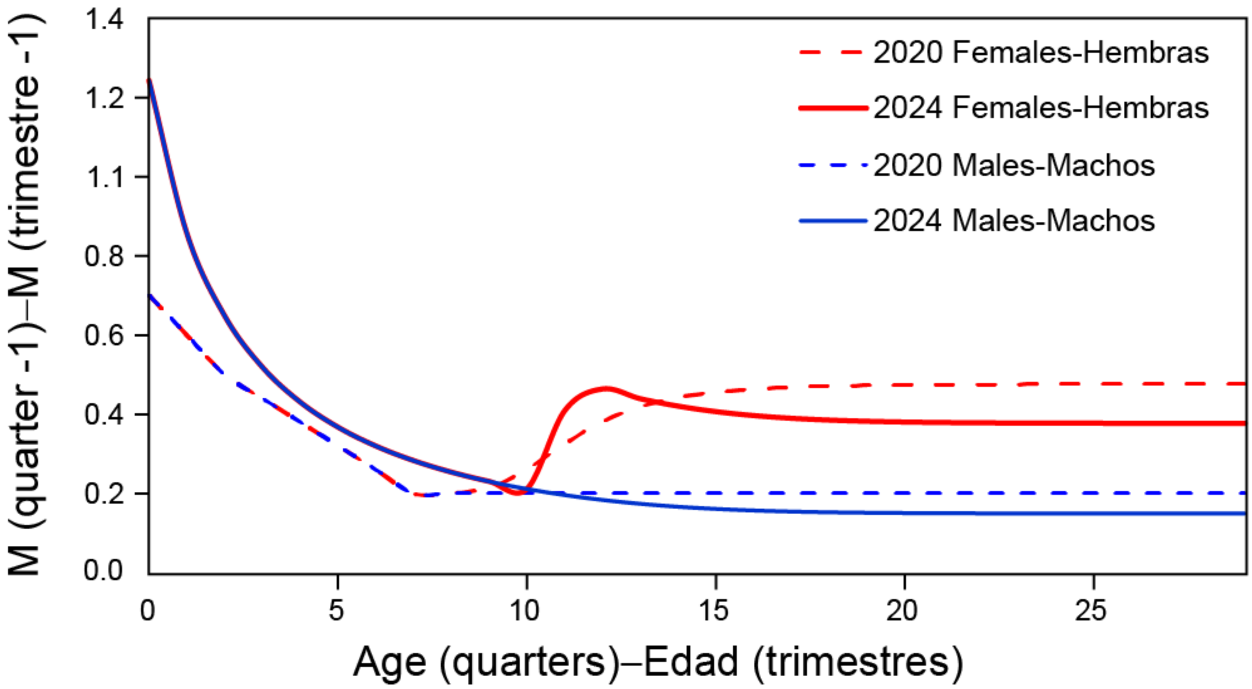

FIGURE 3. Comparison of the 2024 estimates of natural mortality with those used in the 2020 benchmark assessment for males and females.

FIGURA 3. Comparación de las estimaciones de mortalidad natural de 2024 con las utilizadas en la evaluación de referencia de 2020 para machos y hembras.

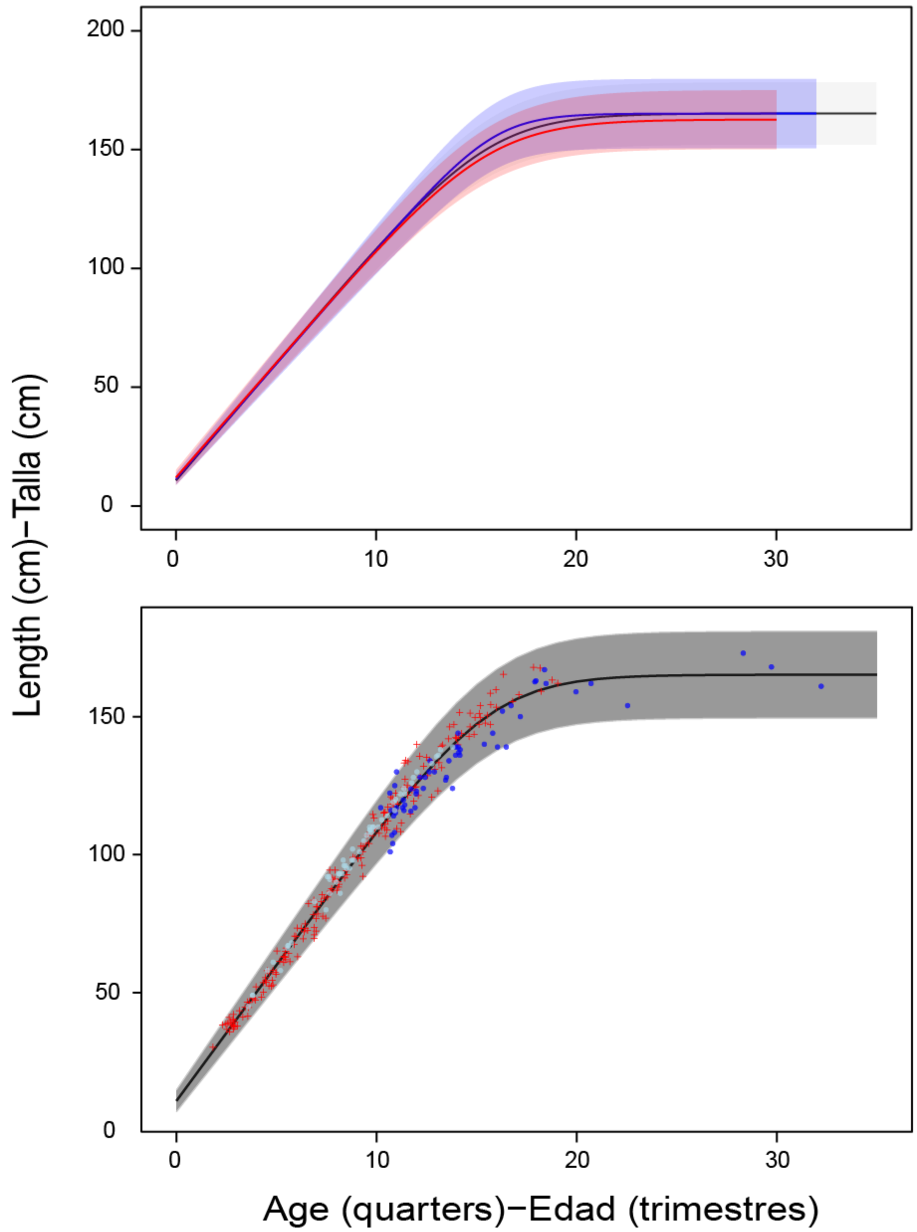

FIGURE 4a. New estimates of growth. Top: estimates for males (blue), females (red), and both (gray). Bottom estimates used in the assessment model. Data fit are otolith data (red crosses) from Wild (1986) and tagging data (releases in light blue, recoveries in dark blue). Tagging data only for older individuals were used (estimated age at recovery larger than 10 quarters).

FIGURA 4a. Nuevas estimaciones de crecimiento. Arriba: estimaciones para machos (azul), hembras (rojo) y ambos (gris). Abajo: estimaciones utilizadas en el modelo de evaluación. Los datos ajustados son datos de otolitos (cruces rojas) de Wild (1986) y datos de marcado (liberaciones en azul claro, recuperaciones en azul oscuro). Solo se utilizaron datos de marcado de individuos más viejos (edad estimada en el momento de recuperación superior a 10 trimestres).

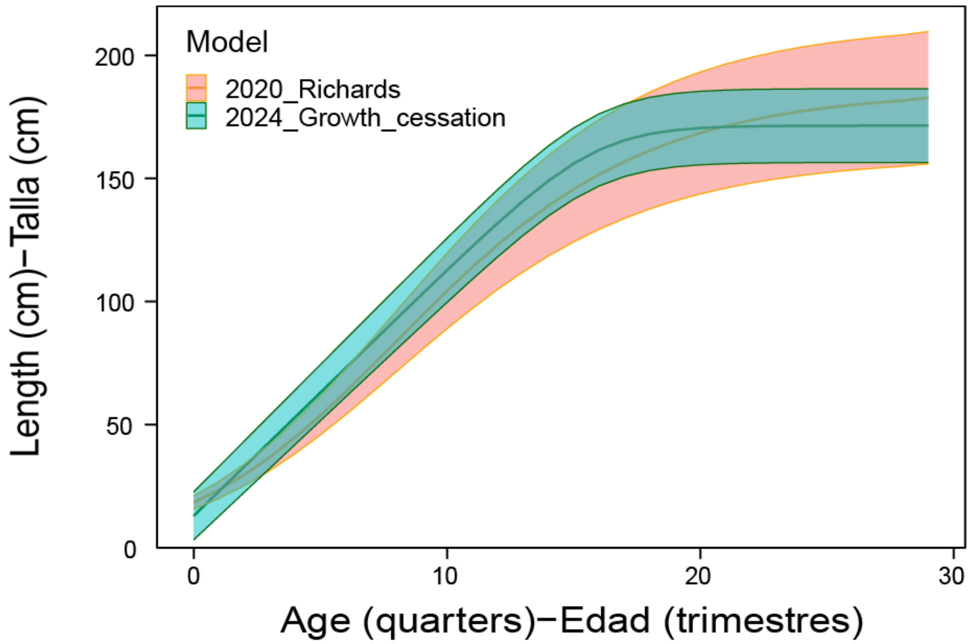

FIGURE 4b. Comparison of growth function used in the 2020 Benchmark assessment and the 2024 growth model used in the current analyses.
FIGURA 4b. Comparación de la función de crecimiento utilizada en la evaluación de referencia de 2020 y el modelo de crecimiento de 2024 utilizado en los análisis actuales.

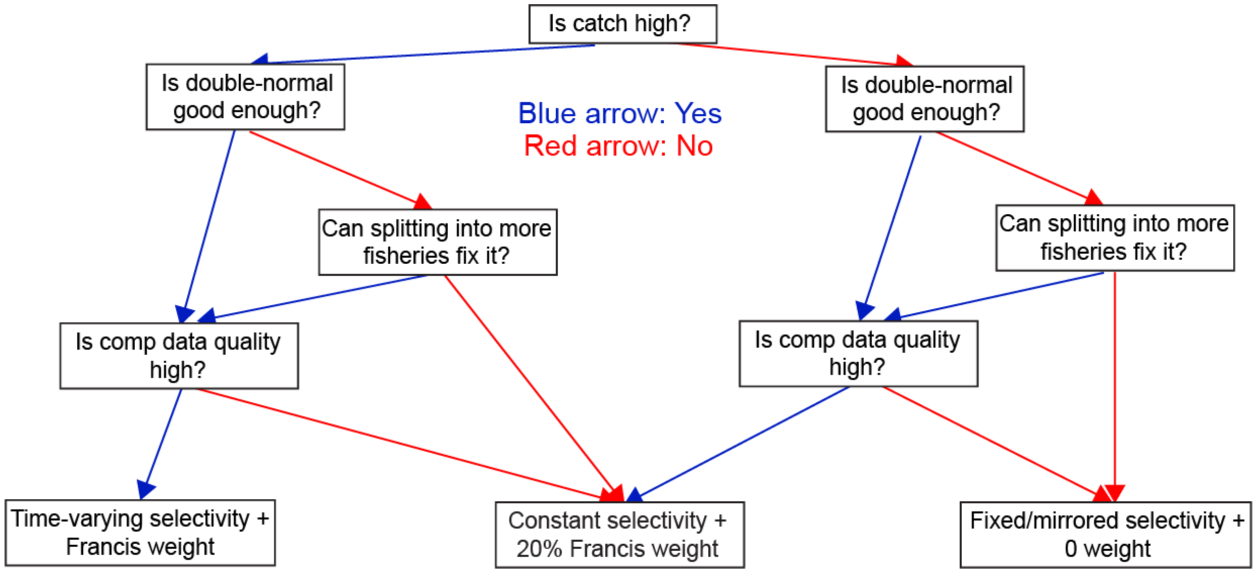

FIGURE 5. The decision tree used to define the selectivity form and temporal variation, and composition data weighting.

FIGURA 5. Árbol de decisión utilizado para definir la forma de la selectividad y la variación temporal, así como la ponderación de los datos de composición.

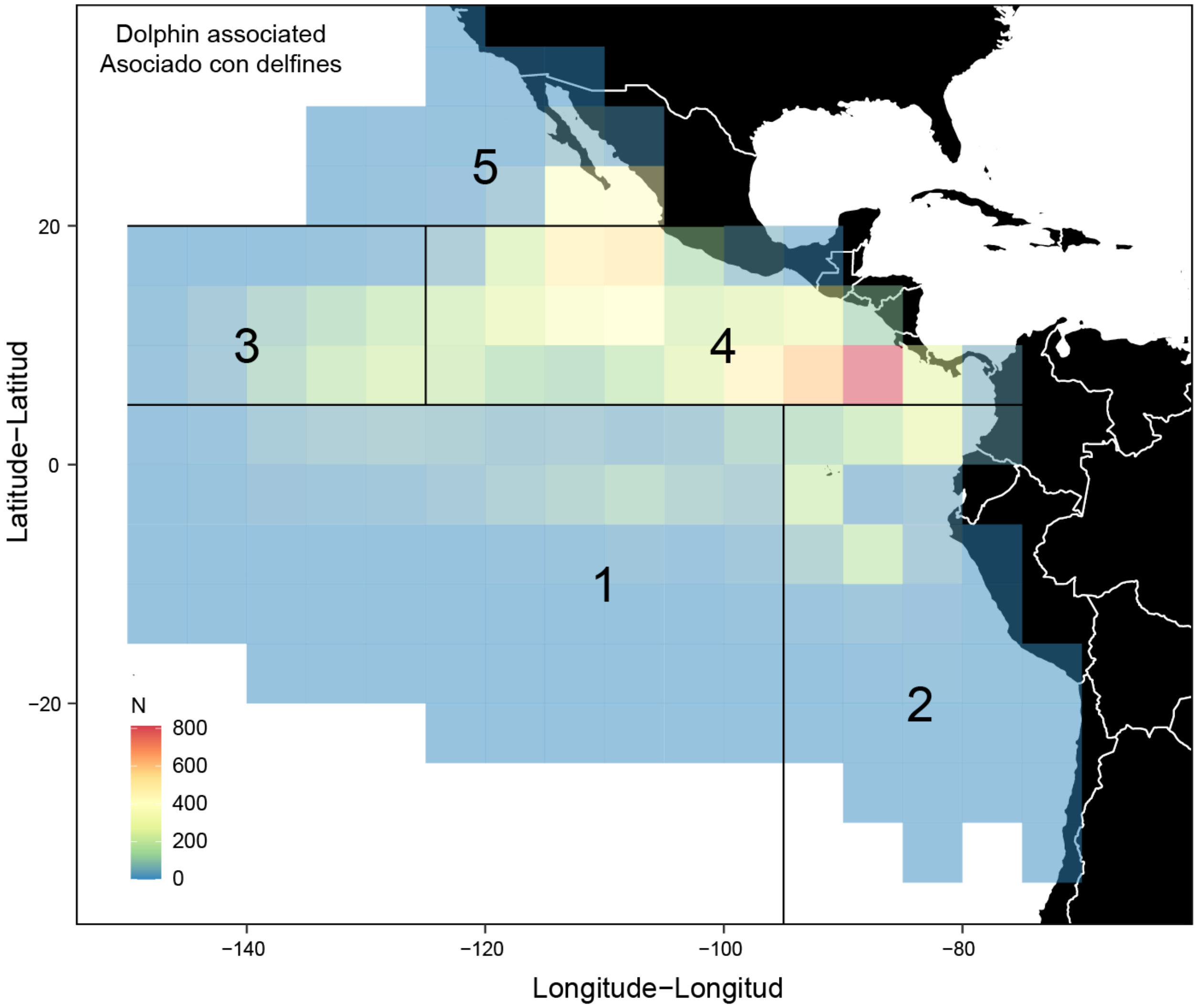

FIGURE 6. The areas defined for the dolphin associated purse seine fisheries using tree analysis of length composition data. The variability explained was 22.27%. The colors show the annual average number (N) of purse-seine set associated with dolphins in 2000-2023.

FIGURA 6. Las áreas definidas para la pesquería cerquera asociada a delfines usando análisis de árbol de datos de composición por talla. La variabilidad explicada fue 22.27%. Los colores indican el número promedio anual de lances cerqueros asociados a delfines en 2000-2023.

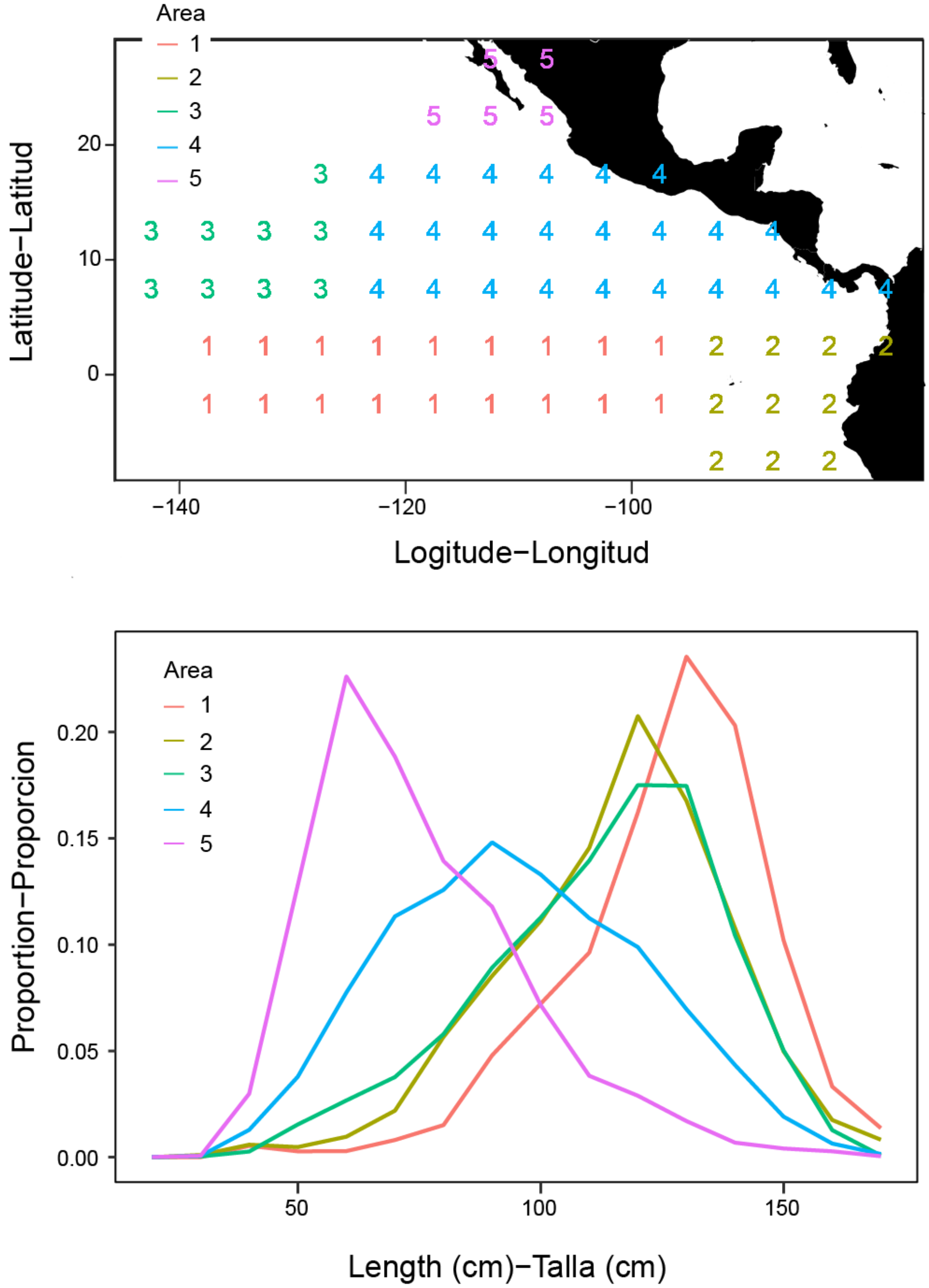

FIGURE 7a. Average length compositions for the 5 areas dolphin associated fisheries (top panel) determined by the cluster analysis, which explained 22.27% of the length composition variability. The data used was from 2000 to 2023.

FIGURA 7a. Composición por talla promedio para las cinco áreas de las pesquerías asociadas a delfines (panel superior) determinadas por el análisis de conglomerados, que explicó el 22.27% de la variabilidad de la composición por talla. Los datos utilizados fueron de 2000 a 2023.

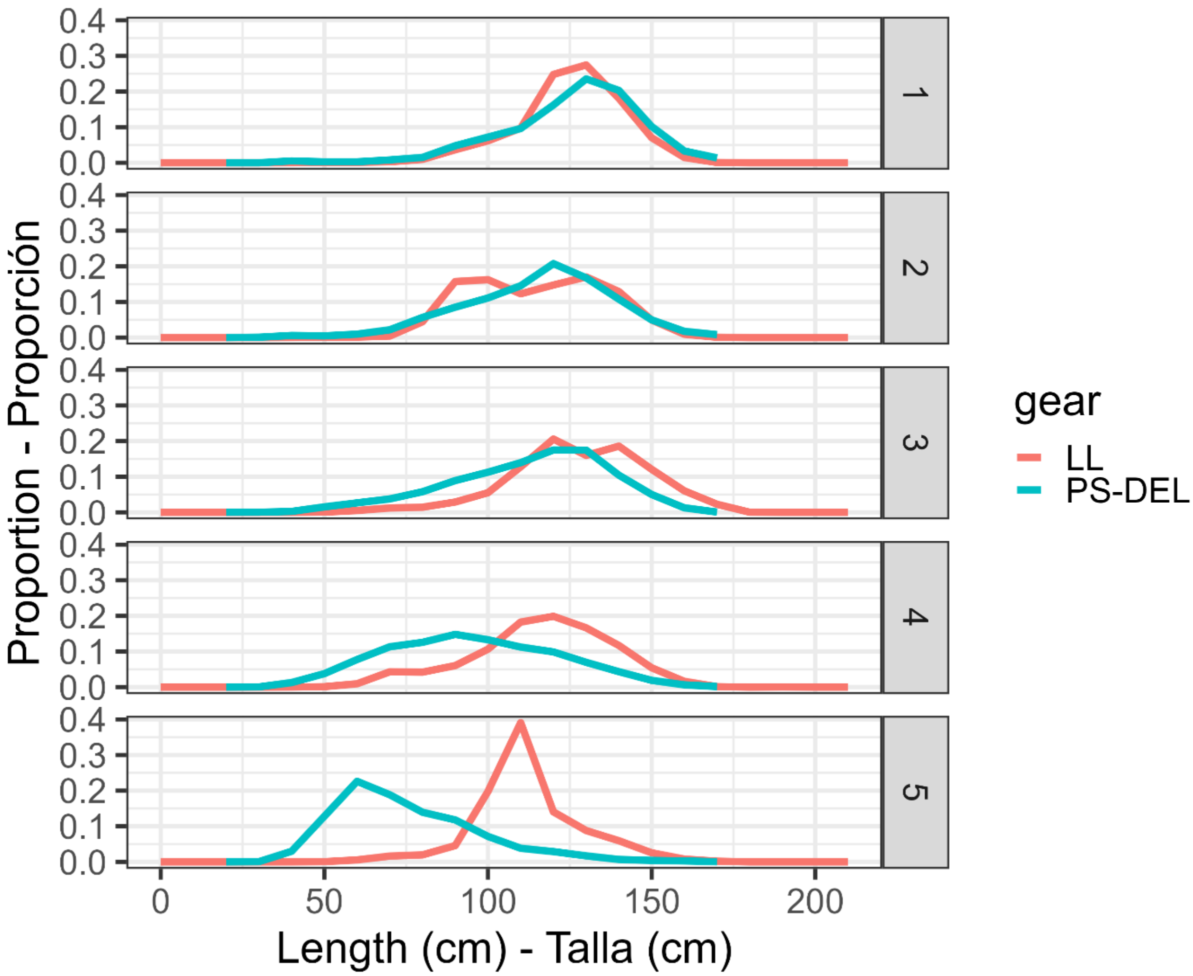

FIGURE 7b. Comparison of the average length compositions for the 5 areas dolphin associated fisheries for 2000-2023 (top panel Figure 7a) determined by the cluster analysis and the average length compositions for the same areas from the Japanese fleets for years 1967 to 1978, when the fleet had its operations fully expanded in the EPO.

FIGURA 7b. Comparación de las composiciones por talla promedio para las cinco áreas de las pesquerías asociadas a delfines (panel superior Figura 7a) determinadas por el análisis de conglomerados y las composiciones por talla promedio para las mismas áreas de las flotas japonesas para los años 1967 a 1978, cuando la flota tenía sus operaciones plenamente expandidas en el OPO.

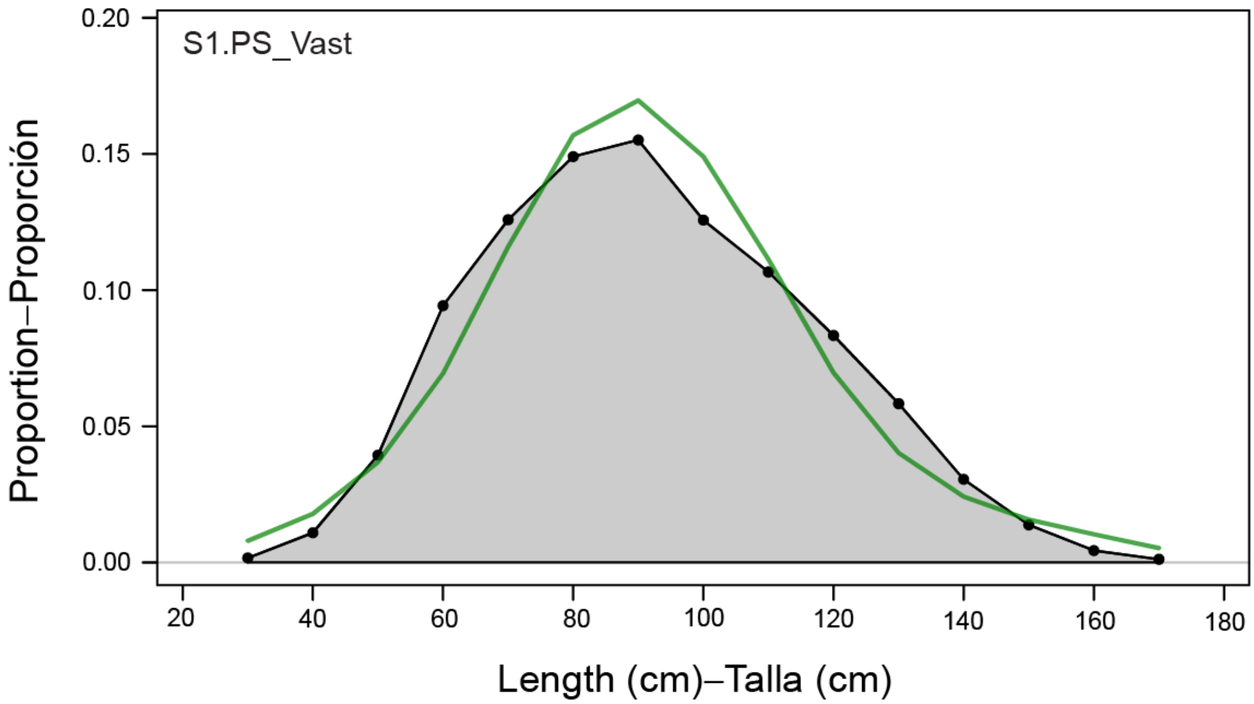

FIGURE 8. Average length and the stock assessment model fit (line) to the dolphin associated purse-seine-based index of abundance composition data (shaded area) based on the core area (area 4) with an asymptotic selectivity (Core Asymp model).

FIGURA 8. Talla promedio y el modelo de evaluación ajustado (línea) a los datos de composición del índice de abundancia basado en la pesquería cerquera asociada a delfines (área sombreada) basado en el área núcleo (Área 4) con una selectividad asintótica (modelo Core Asymp).

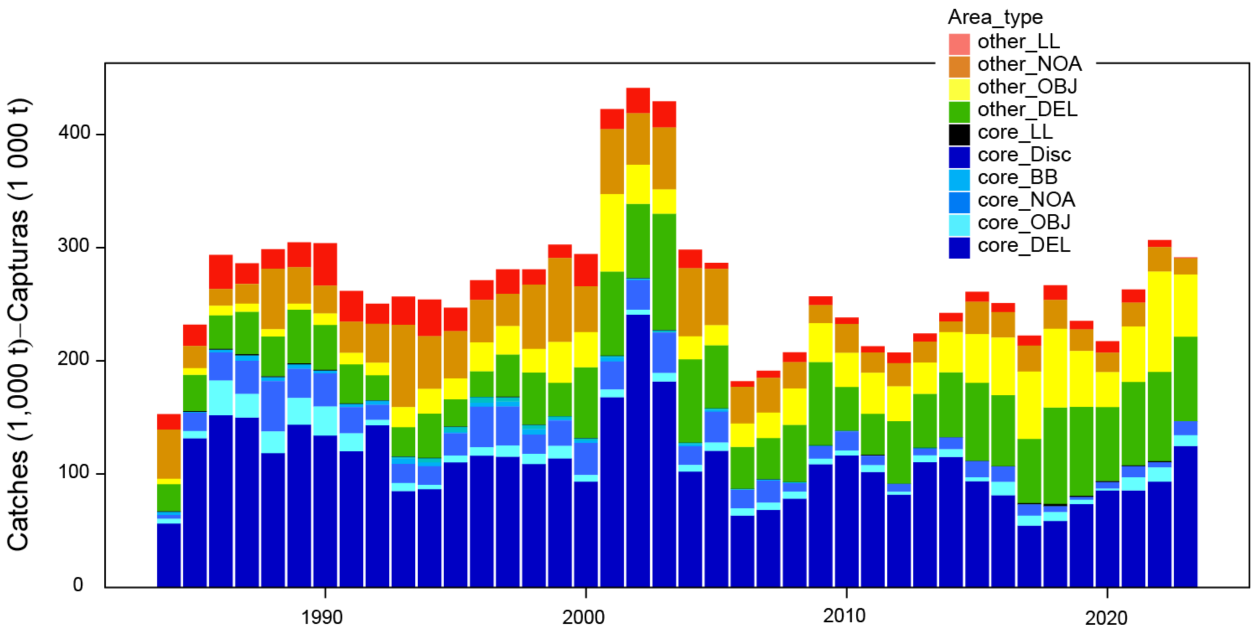

FIGURE 9a. Annual catch used in the model by method and indication of whether it is from the core area or outside the core area.

FIGURA 9a. Captura anual utilizada en el modelo por método e indicación de si procede del área núcleo o de fuera del área núcleo.

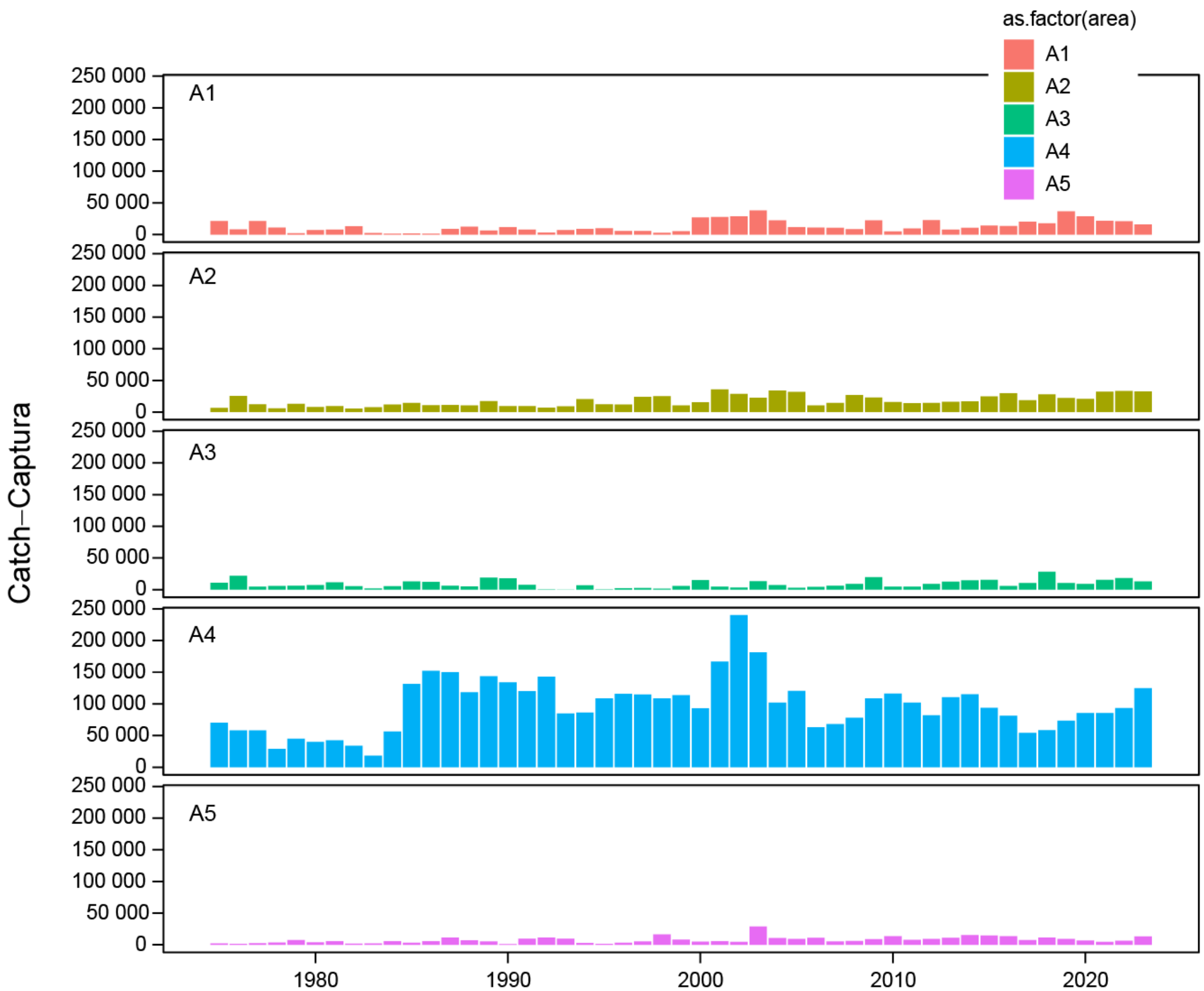

FIGURE 9b. Annual catch (t) of purse-seine fishery on sets associated with dolphin by areas defined in Figure 6.

FIGURA 9b. Captura anual (t) de la pesquería cerquera en lances asociados a delfines por áreas definidas en la Figura 6.

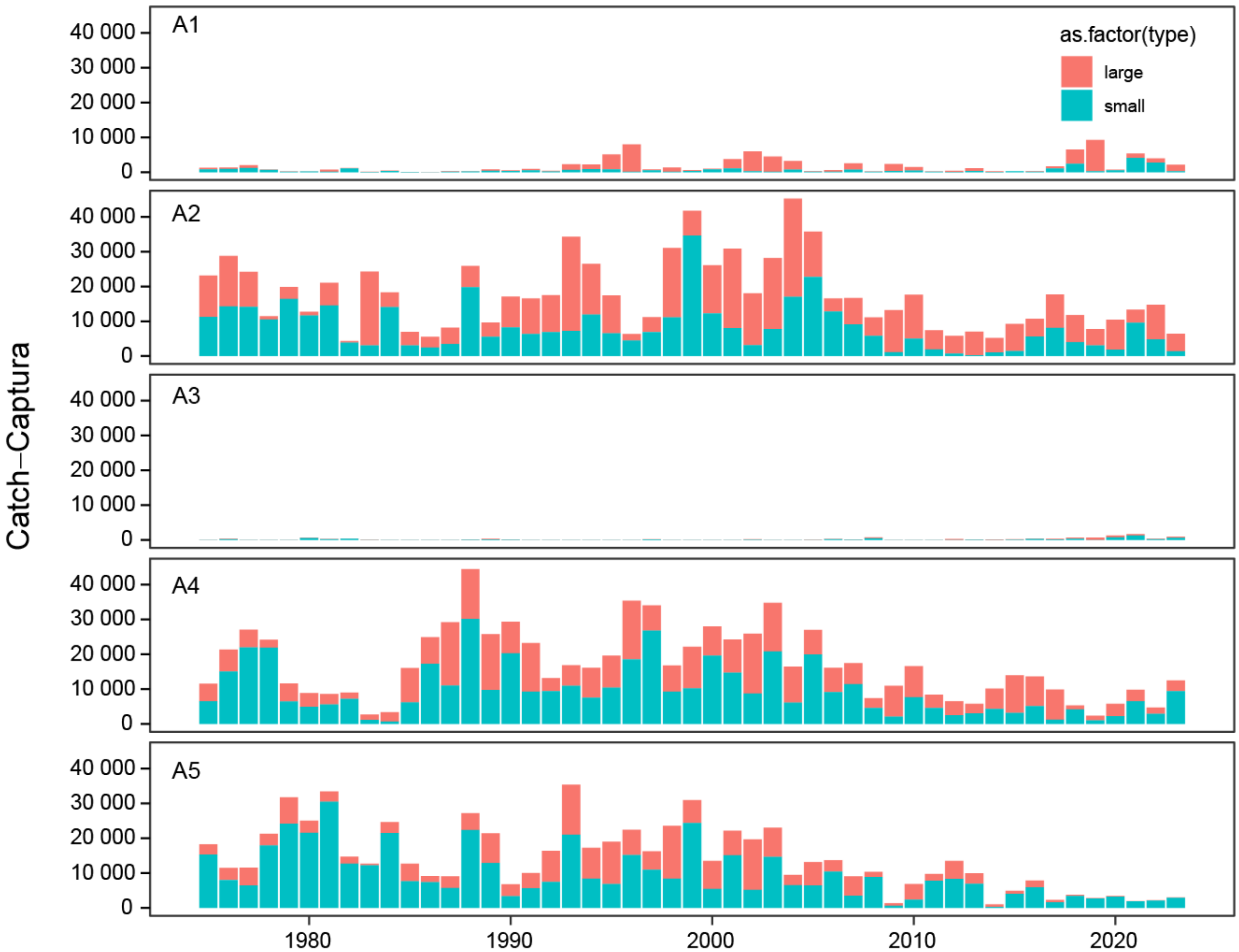

FIGURE 9c. Annual catch (t) by unassociated sets by areas defined in Figure 6 and by size category.
FIGURA 9c. Captura anual (t) por lances no asociados por áreas definidas en la Figura 6 y por categoría de talla.

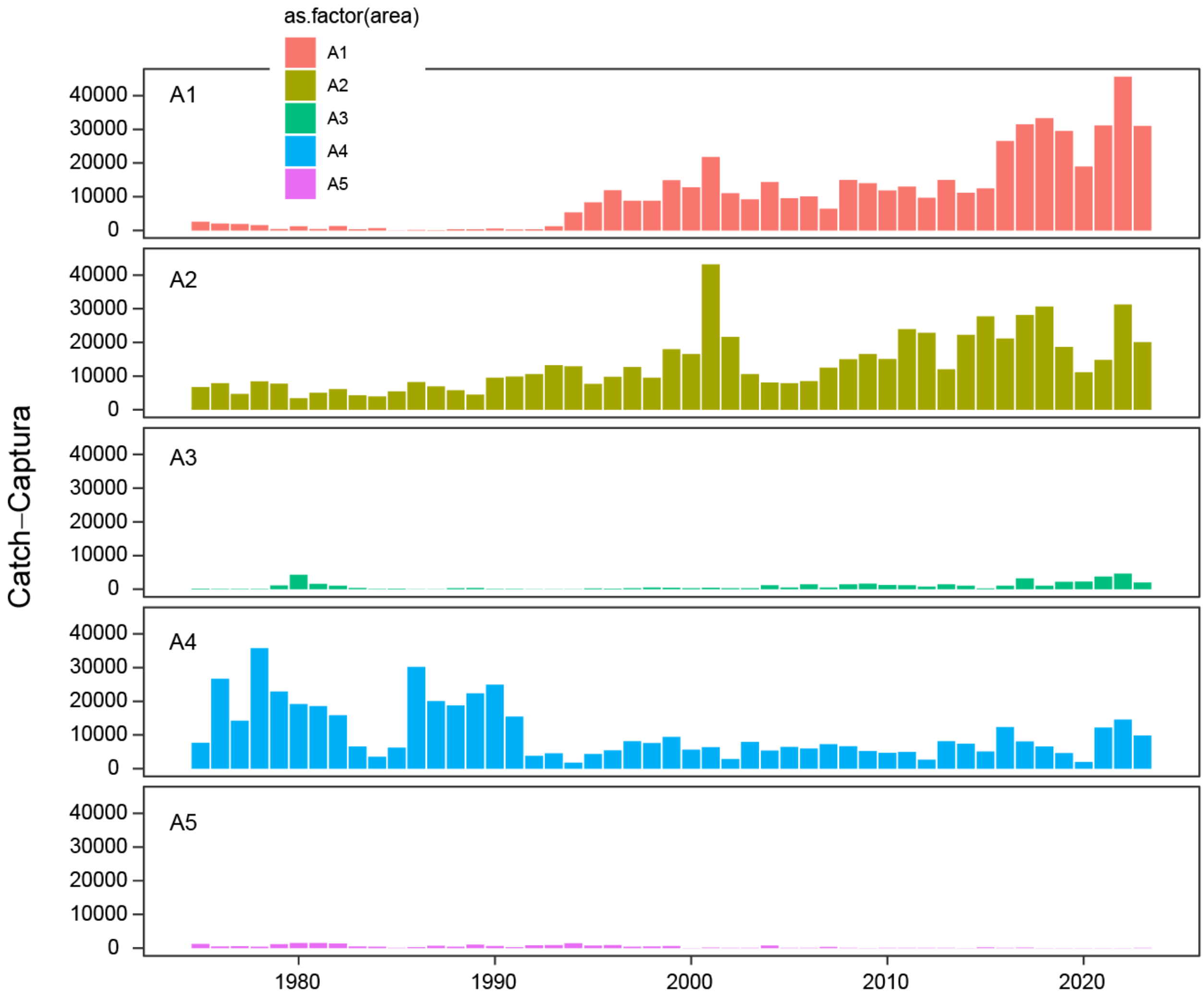

FIGURE 9d. Annual catch (t) by the purse seine fishery on floating-object sets by areas defined in Figure 6.
FIGURA 9d. Captura anual (t) de la pesquería cerquera sobre objetos flotantes por áreas definidas en la Figura 6.

FIGURE 9e. Annual catch (in number of fish) by longliners by areas defined in Figure 6.
FIGURA 9e. Captura anual (en número de peces) por palangreros por áreas definidas en la Figura 6.

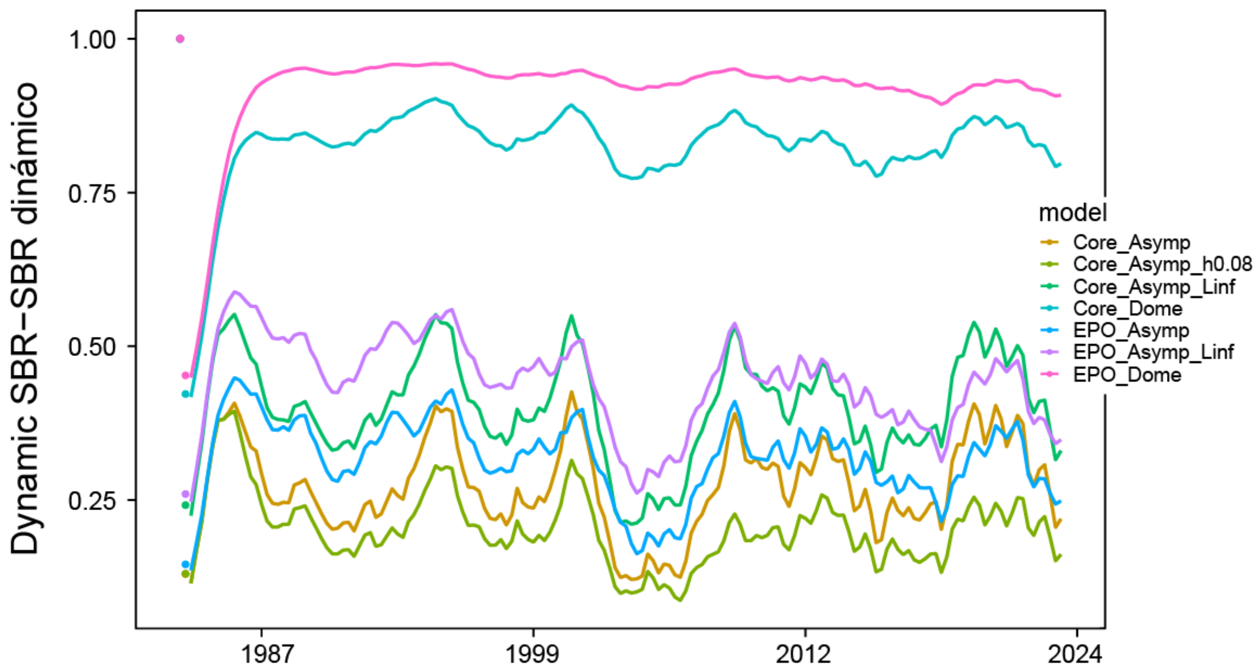

FIGURE 10. Estimated dynamic SBR (spawning stock biomass as a ratio of the spawning stock biomass associated with no fishing)) calculated using the time series of estimated recruitment.

FIGURA 10. SBR dinámico estimado (biomasa de la población reproductora como cociente de la biomasa de la población reproductora asociada a la ausencia de pesca), calculado mediante la serie de tiempo del reclutamiento estimado.

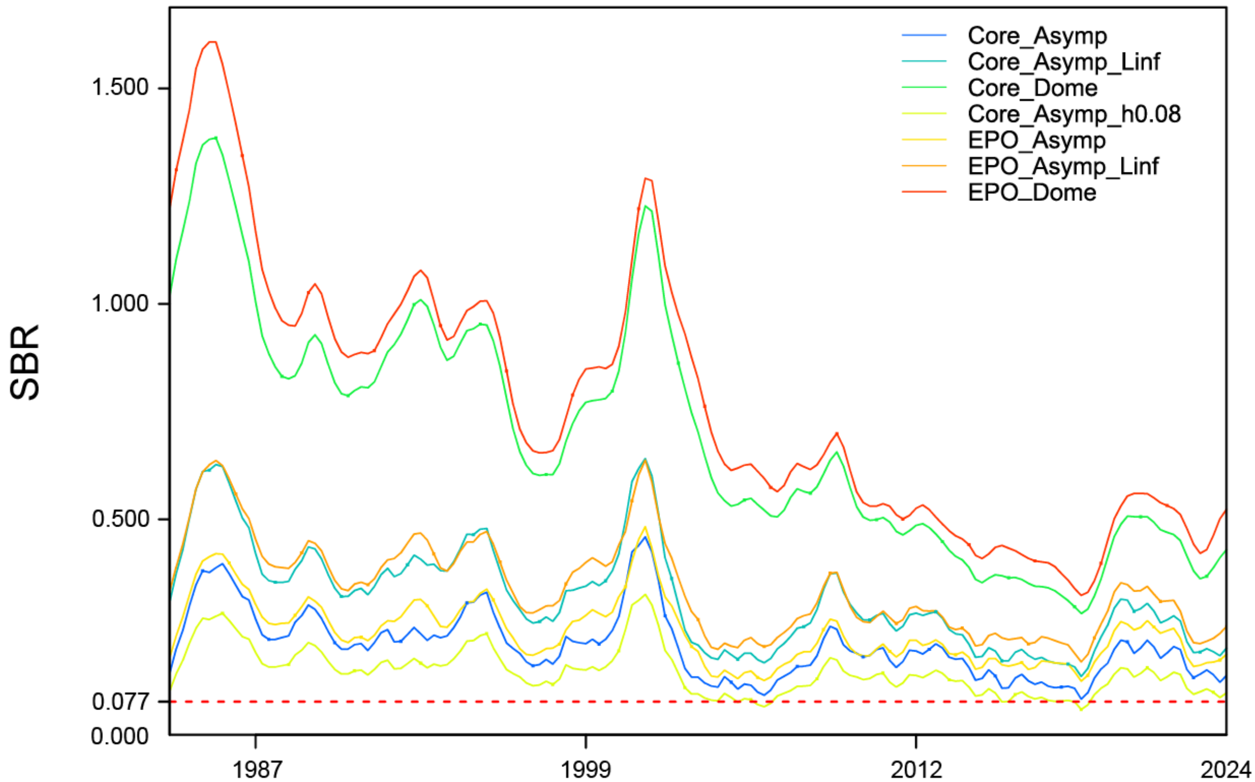

FIGURE 11. Comparison of estimated spawning biomass ratio (SBR) of yellowfin tuna between 1984 and 2023. SBR is the ratio of the spawning output of the current stock to that of the equilibrium unfished stock. The red dashed line is the SBR corresponding to the limit reference point.

FIGURA 11. Comparación del cociente de biomasa reproductora (SBR) estimado del atún aleta amarilla entre 1984 y 2023. El SBR es el cociente de la producción reproductora de la población actual con respecto a la de la población en equilibrio en ausencia de pesca. La línea roja discontinua es el SBR correspondiente al punto de referencia límite.

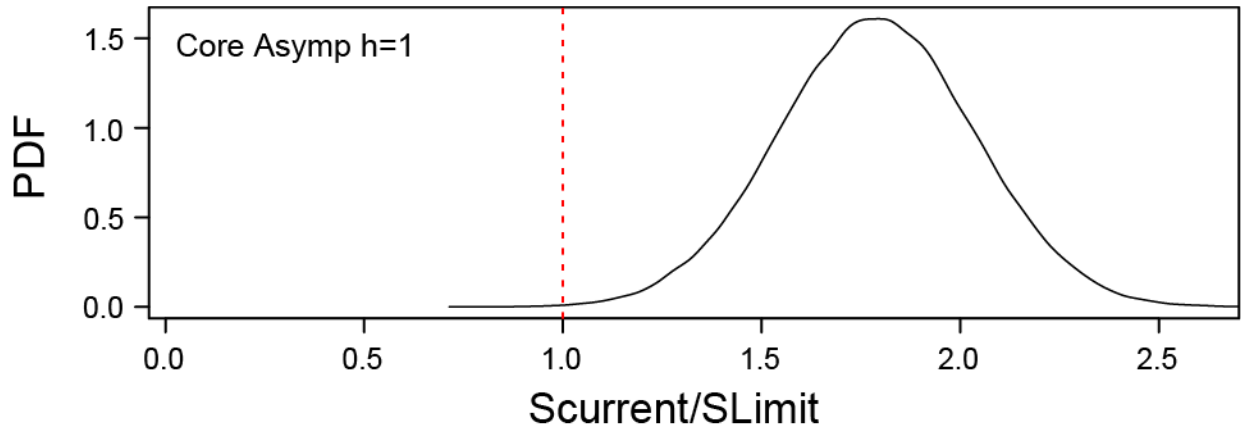

FIGURE 12. The probability density functions (PDF) for the most recent estimates of spawning biomass (S) (first quarter of 2024) relative to their limit reference points (*Slimit*) assuming a normal distribution. The area to the left of the dashed line is the probability of breaching the limit reference point P(S2024/SLimit ≤ 1) for the core area model with steepness h=1. The proportion of the area to the left of the reference point is 0.007.

FIGURA 12. Funciones de densidad de probabilidad (PDF, por sus siglas en inglés) para las estimaciones más recientes de biomasa reproductora (S) (primer trimestre de 2024) en relación con sus puntos de referencia límite ($S_{límite}$) suponiendo una distribución normal. El área a la izquierda de la línea discontinua es la probabilidad de rebasar el punto de referencia límite P(S2024/SLímite≤1) para el modelo del área núcleo con inclinación h=1. La proporción del área a la izquierda del punto de referencia es0.007.

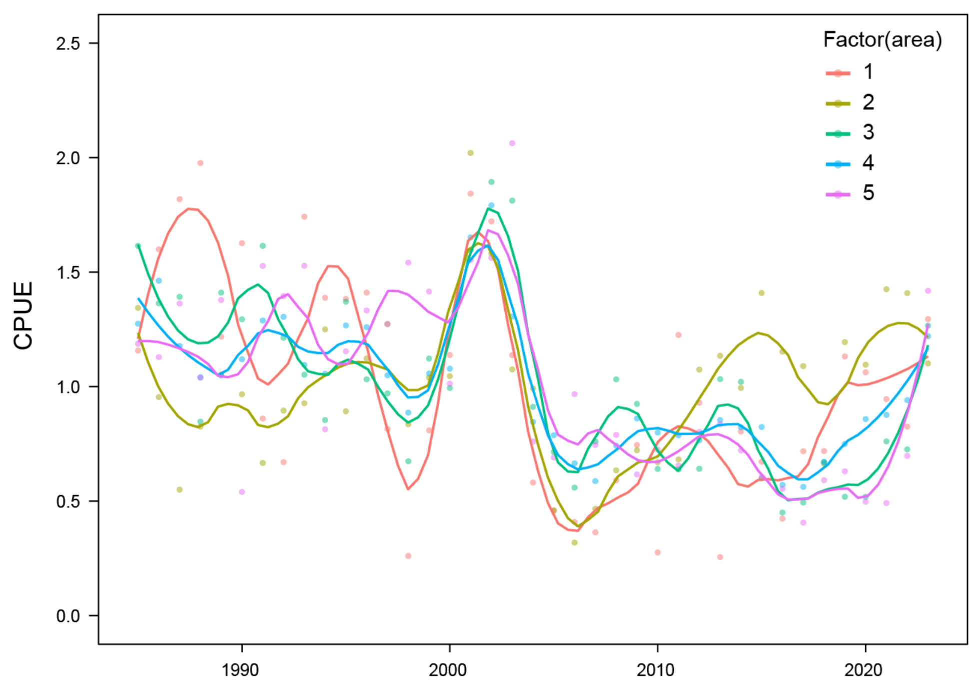

FIGURE 13. Nominal CPUE for the DEL fishery. Areas are defined in Figure 6.

FIGURA 13. CPUE nominal para la pesquería DEL. Las áreas se definen en la Figura 6.

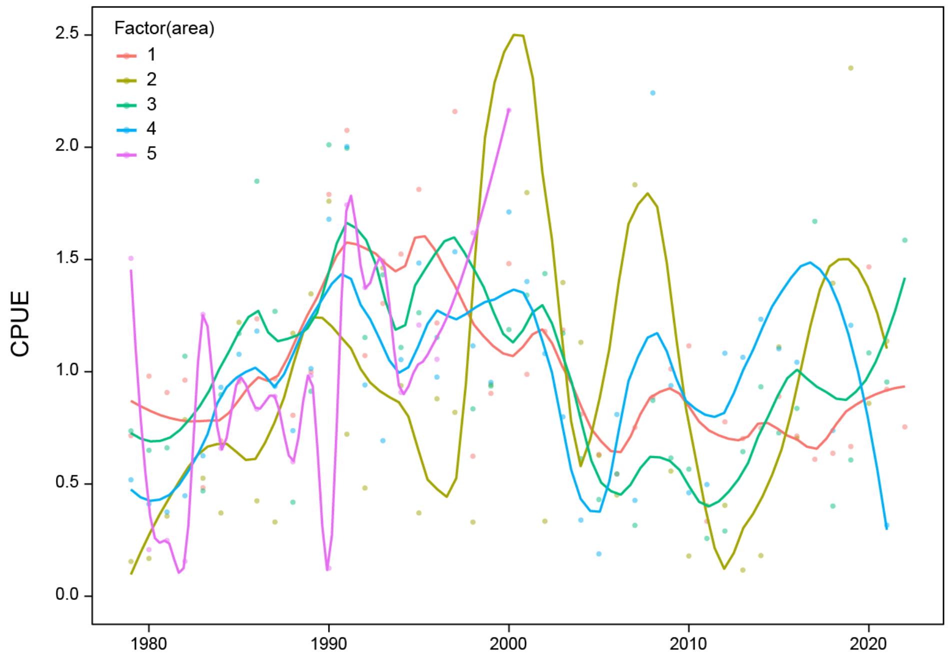

FIGURE 14. Nominal CPUE for the Japanese longline fishery. Areas are defined in Figure 1. Data is restricted to where the DEL fishery operates.

FIGURA 14. CPUE nominal de la pesquería palangrera de Japón. Las áreas se definen en la Figura 1. Los datos se limitan a los lugares donde opera la pesquería DEL.

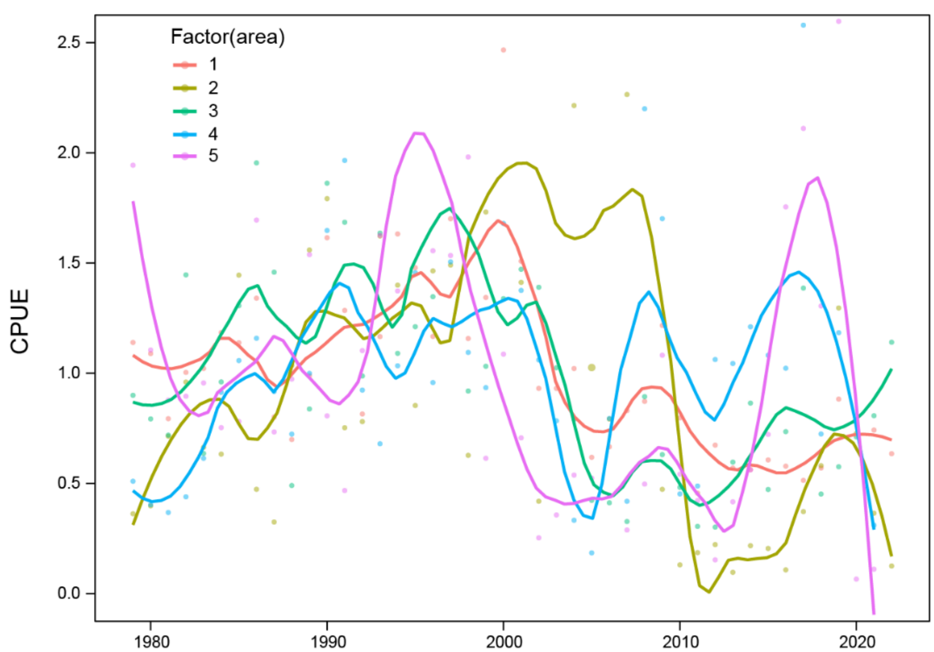

FIGURE 15. Nominal CPUE for the Japanese longline fishery. Areas are defined in Figure 6. Data is not restricted to where the DEL fishery operates.

FIGURA 15. CPUE nominal de la pesquería palangrera de Japón. Las áreas se definen en la Figura 6. Los datos no se limitan a los lugares donde opera la pesquería DEL.

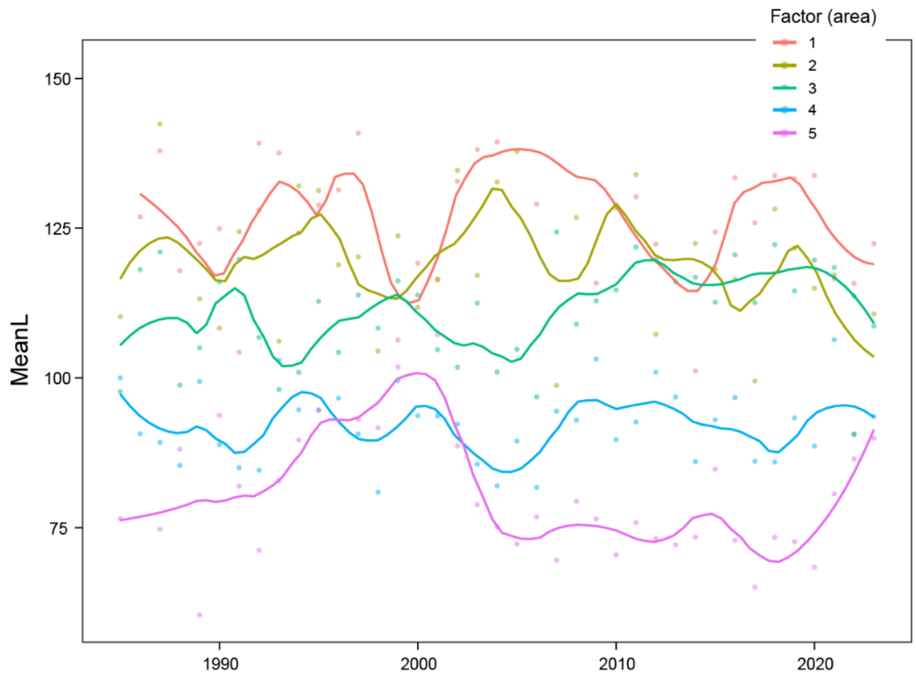

FIGURE 16. Mean length for the DEL fishery. Areas are defined in Figure 6.
FIGURA 16. Talla promedio de la pesquería DEL. Las áreas se definen en la Figura 6.

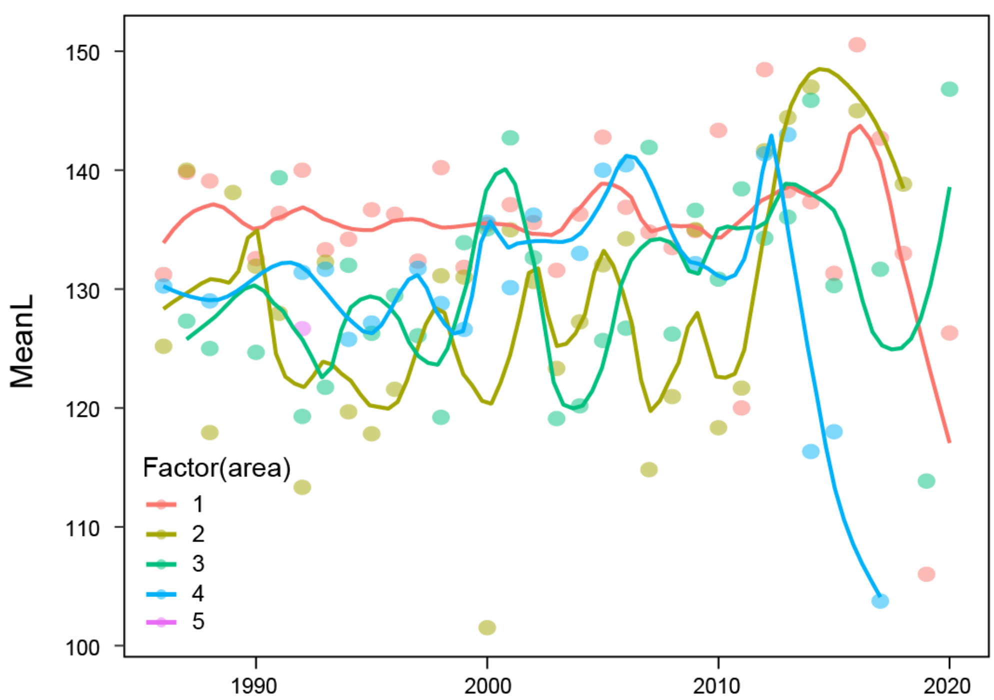

FIGURE 17. Mean length for the Japanese longline fishery. Areas are defined in Figure 6. Data is restricted to areas where the DEL fishery operates.
FIGURA 17. Talla promedio de la pesquería palangrera de Japón. Las áreas se definen en la Figura 6. Los datos se limitan a las áreas en las que opera la pesquería DEL.

APPENDIX 1. Fishery definitions

The fisheries (Table A1.1) defined in the exploratory models were based on gear (longline, purse-seine, baitboat), set type (for purse-seine) and tree analysis of length composition data (for purse-seine). Some areas for OBJ and NOA were further split to produce areas corresponding to the DEL area 4, which corresponds to the core area model. The NOA fisheries were also split in large and small fish at 80 cm, so that their length distributions were regular and unimodal. For longlines, the fisheries were defined in space as in the same areas than DEL, which were slightly different than those defined using tree analysis for length composition data. The areas are shown in Figure A1.1

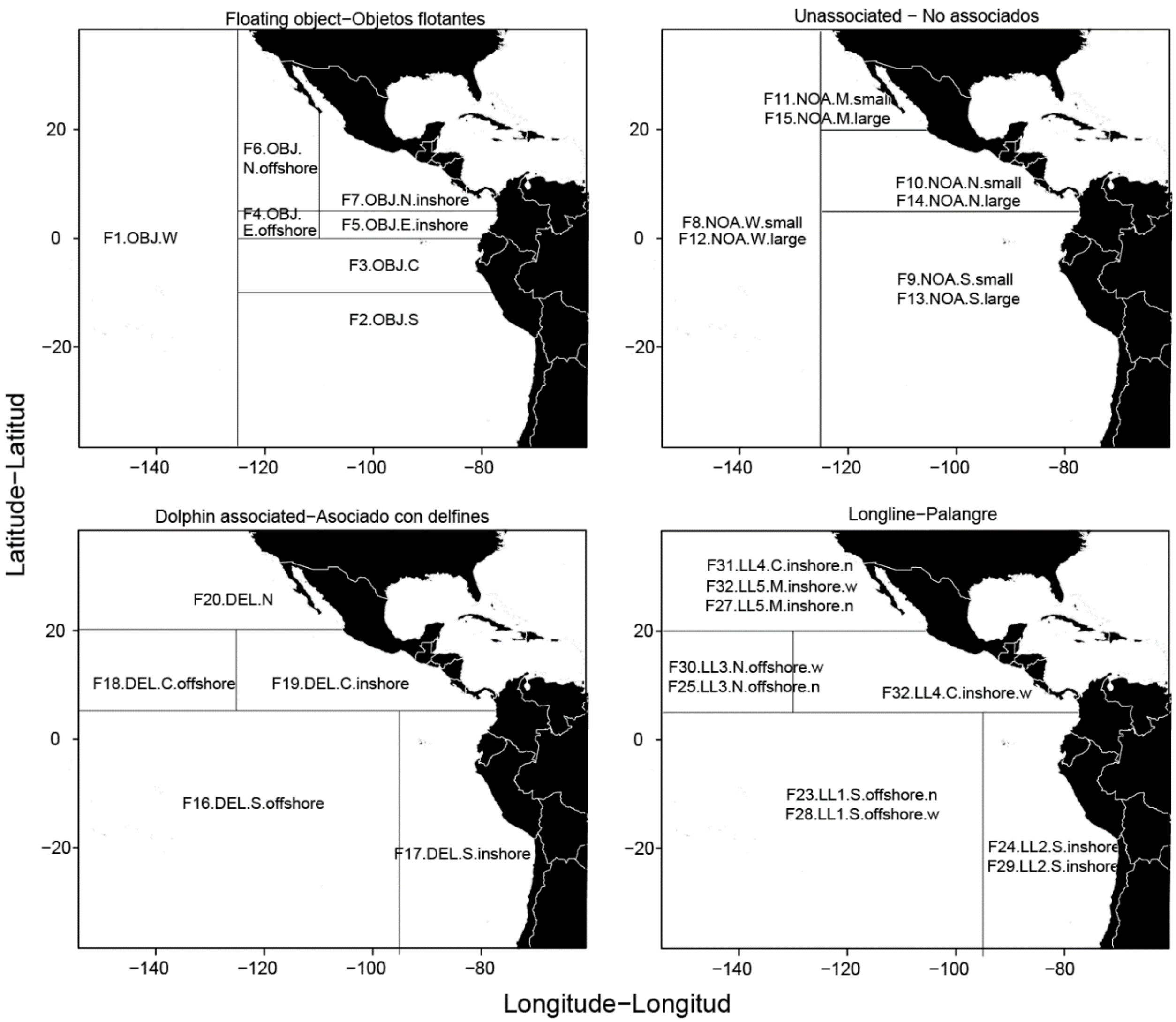

FIGURE A1.1. Areas corresponding to the fishery definitions (Table A1.1) used in the exploratory stock assessment models of yellowfin tuna in the EPO in 2024.

FIGURA A1.1. Áreas correspondientes a las definiciones de las pesquerías (Tabla A1.1) usadas en los modelos exploratorios de evaluación de la población de aleta amarilla en el OPO en 2024.

TABLE A1.1 Fisheries defined for the exploratory stock assessment models of yellowfin tuna in the EPO in 2024. Gear: PS: purse seine; LP: pole and line; LL: longline; PS set type: OBJ: floating object; NOA: unassociated; DEL: dolphin; Area: see Figure A1.1.
TABLA A1.1 Pesquerías definidas para los modelos exploratorios de evaluación de la población de atún aleta amarilla en el OPO en 2024. Arte: PS: red de cerco; LP: caña y anzuelo; LL: palangre; Tipo de lance PS: OBJ: objeto flotante; NOA: no asociado; DEL: delfín; Área: ver Figura A1.1.

#	Fleet type	Fleet name	Gear	Set type	Area	Catch data	Unit	Data used Core models	Data used EPO models
1	Fishery	F1.OBJ.W	PS	OBJ	W	Retained catch + discards (inefficiency)	tons	none	catch
2	Fishery	F2.OBJ.S	PS	OBJ	S	"	tons	none	catch
3	Fishery	F3.OBJ.C	PS	OBJ	C	"	tons	none	catch
4	Fishery	F4.OBJ.E.offshore	PS	OBJ	E offshore	"	tons	none	catch
5	Fishery	F5.OBJ.E.inshore	PS	OBJ	E inshore	"	tons	none	catch
6	Fishery	F6.OBJ.N.offshore	PS	OBJ	N offshore	"	tons	catch	catch
7	Fishery	F7.OBJ.N.inshore	PS	OBJ	N inshore	"	tons	catch	catch
8	Fishery	F8.NOA.W.small	PS	NOA	W	Retained catch + all discards	tons	none	catch
9	Fishery	F9.NOA.S.small	PS	NOA	S	"	tons	none	catch
10	Fishery	F10.NOA.C.small	PS	NOA	C	"	tons	catch	catch
11	Fishery	F11.NOA.N.small	PS	NOA	N	"	tons	none	catch
12	Fishery	F12.NOA.W.large	PS	NOA	W	"	tons	none	catch
13	Fishery	F13.NOA.S.large	PS	NOA	S	"	tons	none	catch
14	Fishery	F14.NOA.C.large	PS	NOA	C	"	tons	catch	catch
15	Fishery	F15.NOA.N.large	PS	NOA	N	"	tons	none	catch
16	Fishery	F16.DEL.S.offshore	PS	DEL	S offshore	"	tons	none	catch
17	Fishery	F17.DEL.S.inshore	PS	DEL	S inshore	"	tons	none	catch
18	Fishery	F18.DEL.C.offshore	PS	DEL	C offshore	"	tons	none	catch

19	Fishery	F19.DEL.C.inshore	PS	DEL	C inshore	"	tons	catch, length composition	catch, length composition
20	Fishery	F20.DEL.N	PS	DEL	N	"	tons	none	catch
21	Fishery	F21.Disc_OBJ	PS	OBJ	EPO	Discards (size-sorting)	tons	none	catch
22	Fishery	F22.BB	BB	-	EPO	Retained catch	tons	none	catch
23	Fishery	F23.LL1.S.offshore.n	LL	-	S offshore	Retained catch	1,000	none	catch
24	Fishery	F24.LL2.S.inshore.n	LL	-	S offshore	"	1,000	none	catch
25	Fishery	F25.LL3.C.offshore.n	LL	-	C offshore	"	1,000	none	catch
26	Fishery	F26.LL4.C.inshore.n	LL	-	C inshore	"	1,000	none	catch
27	Fishery	F27.LL5.N.inshore.n	LL	-	N inshore	"	1,000	none	catch
28	Fishery	F28.LL1.S.offshore.w	LL	-	S offshore	"	tons	none	catch
29	Fishery	F29.LL2.S.inshore.w	LL	-	S offshore	"	tons	none	catch
30	Fishery	F30.LL3.C.offshore.w	LL	-	C offshore	"	tons	none	catch
31	Fishery	F31.LL4.C.inshore.w	LL	-	C inshore	"	tons	none	catch
32	Fishery	F32.LL5.N.inshore.w	LL	-	N inshore	"	tons	none	catch
33	Survey	S1.PS_VAST	PS	-	C	-	tons	index, standardized length compositions	index, standardized length compositions
34	Survey	S2.LL_VAST	LL	-	S	-	1,000	-	-
35	Survey	S3.PS_Echo.east	PS	-	C east of 130°W	-	tons	-	-
36	Survey	S4.PS_Echo.west	PS	-	C west of 130°W	-	tons	-	-