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ASSESSMENT METHODS FOR SKIPJACK IN THE EPO: A PROPOSAL RELYING ON RECENT DATA FROM THE IATTC REGIONAL TUNA TAGGING PROGRAM (2019-2022)

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1. SUMMARY

Skipjack tuna is a major component of the EPO tropical tuna fishery, but no reliable assessment is currently available. Stock status indicators suggest that the stock is under increasing fishing pressure. Management is based on arguments that, since skipjack tuna is more productive than bigeye tuna, appropriate management for bigeye will be adequate for skipjack. A reliable stock assessment for skipjack is needed to improve management advice for skipjack. Currently, there is no reliable index of relative abundance (e.g. CPUE) for skipjack tuna in the EPO and recently collected tagging data from the IATTC Regional Tuna Tagging Program (2019-2022) provides the most promise for providing information to conduct an assessment. However, the practicalities of tagging limit the distribution of tag releases and incomplete tag mixing needs to be addressed. We outline an approach based on advection-diffusion modelling of tags and spatio-temporal modelling of abundance that can reduce the impact of incomplete mixing. The workplan proposes to present preliminary results at the 2022 SAC and a benchmark assessment at the 2023 SAC.

2. INTRODUCTION

A major management objective for tunas in the eastern Pacific Ocean (EPO) is to keep stocks at levels capable of producing maximum sustainable yields (MSYs). Management objectives based on MSY or related reference points (*e.g.* fishing mortality that produces MSY (F_{MSY}); spawner-per-recruit proxies) are in use for many species and stocks worldwide. However, these objectives require that reference points and quantities to which they are compared be available. The various reference points require different amounts and types of information, ranging from biological information (*e.g.* natural mortality, growth, and stock-recruitment relationship) and fisheries characteristics (*e.g.* age-specific selectivity), to absolute estimates of biomass and exploitation rates. These absolute estimates generally require a formal stock assessment model. For many species, the information required to estimate these quantities is not available, and alternative approaches are needed. Even more data are required if catch quotas are to be used as the management tool.

Skipjack tuna is a notoriously difficult species to assess. Due to its high and variable productivity and short lifespan (*i.e.* annual recruitment is a large proportion of total biomass), it is difficult to detect the effect of fishing on the population with standard fisheries data and stock assessment methods. This is particularly true for the stock of the EPO, due to the lack of a reliable index of relative abundance and age-composition data, and the limited tagging data that is currently available. The continuous recruitment and rapid growth of skipjack mean that the temporal stratification needed to observe modes in length-frequency data make the current sample sizes inadequate. Previous assessments have had difficulty in estimating the absolute levels of biomass and exploitation rates, due to the possibility of a dome-shaped selectivity curve (Maunder 2002a; Maunder and Harley 2005), which would mean that there is a cryptic biomass of large skipjack that cannot be estimated. The most recent comprehensive assessment of skipjack in the EPO, which was based on an age-structured catch-at-length integrated analysis (Maunder and Harley 2005), was considered preliminary because it is not known whether the catch per day fished for purse-seine fisheries is proportional to abundance. Analysis of historical tagging data is unlikely to improve the skipjack stock assessment (Maunder 2012a) and a fully length-structured model produced unrealistic estimates (Maunder 2012b). In addition to the problems listed above, the levels of age-specific natural mortality are uncertain, if not unknown, and yield-per-recruit (YPR) calculations indicate that the YPR would be maximized by catching the youngest skipjack in the model (Maunder and Harley 2005). Therefore, neither the biomass- nor fishing mortality-based reference points, nor the indicators to which they are compared, are available for skipjack in the EPO.

One of the major problems mentioned above is the uncertainty as to whether the catch per unit of effort (CPUE) of the purse-seine fisheries is reliable index of abundance for skipjack, particularly when the fish are associated with fish-aggregating devices (FADs). Purse-seine CPUE data are particularly problematic, because it is difficult to identify the appropriate unit of effort. In previous assessments, effort was defined as the searching time required to find a school of fish on which to set the purse seine, and this is approximated by number of days fished. Few skipjack are caught in the longline fisheries or dolphin-associated purse-seine fisheries, so these fisheries cannot be used to develop reliable indices of abundance for skipjack. Within a single trip, purse-seine sets on unassociated schools are generally intermingled with floating-object or dolphin-associated sets, complicating the CPUE calculations. A method was used to attribute days fished to set type, but this method is now considered biased and catch per day fished is no longer used (Maunder 2019). Maunder and Hoyle (2007) developed a novel method to generate an index of abundance, using data from the floating-object fisheries. This method used the ratio of skipjack to bigeye in the catch and the “known” abundance of bigeye based on stock assessment results. Unfortunately, the method was of limited usefulness, and more research is needed to improve it. Currently, there is no reliable index of relative abundance for skipjack in the EPO. Therefore, other indicators of stock status, such as the average weight of the fish in the catch, have been used (Maunder 2019).

Since the stock assessments and reference points for skipjack in the EPO are so uncertain, developing alternative methods to assess and manage the species that are robust to these uncertainties would be beneficial. Full management strategy evaluation (MSE) for skipjack would be the most comprehensive method to develop and test alternative assessment methods and management strategies (Maunder 2014; Valero *et al.* 2016; Valero and Aires-da-Silva 2019); however, developing MSE is time-consuming, and has not yet been conducted for skipjack. In addition, higher priority for MSE is given to yellowfin and bigeye tuna, as available data indicate that these species are more susceptible to overfishing than skipjack. Therefore, Maunder and Deriso (2007) investigated some simple indicators of stock status based on relative quantities. Rather than using reference points based on MSY, they compared current values of indicators to the distribution of indicators observed historically. They also developed a simple stock assessment model to generate indicators for biomass, recruitment, and exploitation rate. To evaluate the current values of the indicators in comparison to historical values, they used reference levels based on the 5th and 95th percentiles, as the distributions of the indicators are somewhat asymmetric. The results have been compared with historical assessments based on analysis of tag data, a length-structured stock assessment model, Age-Structured Catch-at-Length Analysis (A-SCALA), and a Spatial Ecosystem and Population Dynamic Model (SEAPODYM) (Maunder 2016).

Here we propose a new method to assess skipjack tuna based on the newly available data obtained from the IATTC multi-year Regional Tuna Tagging Program in the eastern Pacific Ocean (RTTP-EPO 2019-2022, Project E.4.a). The practicalities of tagging prevent random distribution of the tagged fish and therefore time is needed to ensure full mixing of the tagged fish with the rest of the population. The short lifespan of skipjack may even prevent full mixing. Therefore, the spatial structure of the population and the tagged fish needs to be taken into consideration. To overcome incomplete mixing, the approach combines the advection-diffusion methods to analyze tagging data (Sibert *et al.* 1999; Thorson *et al.* 2017) with spatio-temporal modelling of abundance (Thorson *et al.* 2015; Maunder *et al.* 2020).

First, we describe the methods used historically to assess skipjack tuna in the EPO, then we describe the recent tagging data, and finally we present the proposed method.

3. HISTORICAL METHODS

Several assessment methods have been applied to the stock of skipjack tuna in the EPO, some being more exploratory in nature than others. However, none were considered reliable enough to provide management advice. The following describes these approaches.

3.1.1. Indicators

Since the stock assessments and reference points for skipjack in the EPO are uncertain, developing alternative methods to assess and manage the species that are robust to these uncertainties would be beneficial. Maunder and Deriso (2007) investigated some simple indicators of stock status based on relative quantities. Rather than using reference points based on MSY, they compared current values of indicators to the distribution of indicators observed historically. They also developed a simple stock assessment model to generate indicators for biomass, recruitment, and exploitation rate. To evaluate the current values of the indicators in comparison to historical values, they use reference levels based on the 5th and 95th percentiles, as the distributions of the indicators are somewhat asymmetric. Eight data- and model-based indicators are evaluated: catch, catch-per-day-fished by floating object fisheries, catch-per-day-fished by unassociated fisheries, standardized effort, average weight, relative biomass, relative recruitment, and relative exploitation rate. These indicators are presented for the whole EPO stock, although indicators by sub-areas have also been presented. The purse seine catch per day fished is now considered unreliable due to vessels making multiple set types and the algorithm to separate days fished by set type may be biased. Therefore, indicators based on this data and the model-based indicators are not used.

3.1.2. Analysis of tag-recapture data

The IATTC carried out numerous tagging experiments during the 1950s to the early 1980s, and then resumed a limited amount of tuna tagging again beginning in 2000. These data have not been used in the stock assessments of skipjack tuna except to provide information on growth rates (Bayliff 1988; Maunder 2002b). Maunder (2012c) conducted a preliminary analysis of the tagging data to investigate its information content about exploitation rates. The tag data were analyzed using a tag attrition model comparing observed and predicted tag recoveries. The tag dynamics are modeled using a population dynamics model that is essentially the same as that used in stock assessments. The model differs in that recruitment is tag releases and factors such as tag loss, tagging related mortality, and reporting rate are modeled. Estimates are only available for two sub-regions. The estimates of exploitation rates are highly uncertain.

3.1.3. Length-structured stock assessment model

Maunder (2012b) developed a length-structured model for assessing skipjack tuna. This model differs from the standard age-structured model approach used for assessing yellowfin and bigeye tuna, implemented using Stock Synthesis. The ageing data for skipjack tuna is unreliable, and growth information is based on tagging length-increment data. Growth based on length-increment data is ideally suited for length-structured models, and is problematic for age-structured models. The EPO was divided into six stocks and each stock is analysed separately. The model was fitted to CPUE-based indices of relative abundance and length-composition data.

There is insufficient information in the CPUE and length-composition data to produce reliable estimates of skipjack stock size. In all but one region (off the coast of Ecuador) the estimates of abundance and exploitation rates were unrealistic.

3.1.4. Age-Structured Catch-At-Length Analysis (A-SCALA)

Maunder and Harley (2005) used an age-structured, catch-at-length analysis (A-SCALA) to assess skipjack tuna in the EPO. The analysis method and its technical details are described in IATTC Bulletin, Vol. 22, No. 5 (2003). The assessment was still considered preliminary because 1) it was unknown if catch-per-day-fished for purse-seine fisheries is proportional to abundance, 2) it is possible that there is a population of large skipjack that is invulnerable to the fisheries, 3) the structure of the EPO stock in relation to the western and central Pacific stocks is uncertain.

3.1.5. Spatial Ecosystem and Population Dynamic Model (SEAPODYM)

A Spatial Ecosystem and Population Dynamic Model (SEAPODYM; Senina *et al*. 2008) that fits to a variety of data sources has been applied to skipjack tuna in the Pacific Ocean (see Lehodey *et al*. 2011 for details). The analysis differs from Lehodey *et al.* (2011) in that the analysis: 1) used the latest available Simple Ocean Data Assimilation ocean/sea ice reanalysis (SODA 2.1.6; https://www2.atmos.umd.edu/~ocean/) variables; 2) switched to Multifan-CL (MFCL)-2010 length-at-age estimates; 3) scaled the western and central Pacific Ocean (WCPO) stock to MFCL estimates via fixing recruitment and mortality coefficients; and 4) used asymmetric Gaussian functions for purse-seine selectivities instead of sigmoid selectivities.

The SEAPODYM model is a two-dimensional coupled physical–biological interaction model at the ocean basin scale, and contains environmental and spatial components used to constrain the movement and the recruitment of tuna. The model combines a forage (prey) production model with an age-structured population model of the fishery target (tuna predator) species. All the spatial dynamics are described with an advection–diffusion equation. Oceanographic input data sets for the model are sea-surface temperature (SST), oceanic currents and primary production that can be predicted data from coupled physical–biogeochemical models, as well as satellite-derived data distributions. Recent improvements include rigorous parameter optimization using fisheries data (tagging data, size composition and abundance indices), which are based on methods used for contemporary stock assessment models (Senina *et al*., 2008; Senina *et al*. 2020).

4. TAGGING DATA

Skipjack tuna tagging experiments by IATTC in the eastern Pacific commenced in 1955, and through 1964 a total of 127,709 skipjack were tagged and released throughout the range of the fishery, from northern Mexico to northern Chile, within about 200 miles of the coast and around offshore islands. There were 12,881 tags recovered (10.1%) from those releases. Most of the tagging took place aboard live-bait pole-and-line vessels during charter cruises or opportunistically during regular fishing trips. One charter tagging cruise was conducted each year between 1958 and 1963. A lesser amount of tagging also took place opportunistically aboard purse-seine vessels during regular fishing trips. The objectives of the tagging experiments were to obtain information on movements and population structure, along with estimates of growth and mortality.

During 1979 through 1981 there were several tropical tuna tagging cruises undertaken on chartered live-bait pole-and-line vessels by IATTC where tagging was conducted from Mexico to Ecuador. During those cruises 2,546 skipjack were tagged and released, and 992 tags recovered (39.0%).

During March to May of 2000 and 2002 to 2006 there were six tuna tagging cruises undertaken on a chartered live-bait pole-and-line vessel to the equatorial eastern Pacific targeting bigeye tuna, with lesser numbers of skipjack and yellowfin tunas also tagged. During those cruises 3,425 skipjack were tagged and released with plastic dart tags (PDTs) and 563 tags recovered (16.4%), and 134 skipjack were tagged and released with archival tags (ATs) and 7 tags recovered (5.2%).

In 2019 the IATTC, with financial assistance from the European Union, initiated a Regional Tuna Tagging Program (RTTP) in the eastern Pacific, with an emphasis on skipjack tuna. The principle objective of the RTTP is to focus effort and resources on tagging skipjack, to attempt to provide a direct means for estimating their abundance and exploitation rate, deemed essential to produce a reliable stock assessment. The experimental design of the RTTP included three tagging cruises during 2019 to 2021, of about 3 months each, utilizing a live-bait pole-and-line vessel. The first two tagging cruises during 2019 and 2020 were completed, and the results are described below. The tagging cruise scheduled for 2021 was canceled due to logistical issues and concerns during the COVID-19 pandemic but has been rescheduled to take place in early 2022.

Three tag recovery specialists (TRSs) are working full time, within the RTTP structure, at major purse-seine vessel unloading ports in Mexico and Ecuador, which is essential for collecting high-confidence tag recapture data. The responsibility of the TRSs is to collect high-confidence tag recapture information at the time vessels are unloading, which includes verifying vessel names and well numbers at the time tagged tunas are found to verify date and location of capture, and taking length measurements of recovered tunas with tags still attached.

For the 2019 and 2020 tagging cruises, the numbers of releases and returns of skipjack with PDTs and ATs, by times at liberty are shown in Tables 1 and 2, respectively. Table 1 also includes the proportion of PDT returns which are high confidence, where a TRS was able to confirm the validity of the return information. The low percentage of high confidence PDT returns following the 2020 tagging cruise is mostly because the TRSs did not have access to the piers or vessels during unloading from March 2020 until September 2020 due to COVID-19 restrictions. Access continues to be restricted to some facilities and aboard certain vessels. Lengths of fish released with PDTs and ATs are shown in Figures 1 and 2, respectively. The proportion of skipjack with their PDTs returned by months at liberty are shown in Figure 3. The linear displacements of skipjack released with PDTs and ATs, determined from release and recapture positions, are shown in Figure 4. A speed filter was utilized to reduce the number of unrealistic recapture dates and positions exasperated by tag reporting errors. The filter is based on recapture dates and locations of both AT and high confidence PDT returns. Mean daily speeds are calculated for each high confidence return and the 95th quantile derived for each time at liberty grouping, which is then compared to the mean daily speeds of all low confidence returns by the corresponding times at liberty. A total of 159 (10.5%) tag returns from skipjack with mean daily speeds exceeding the threshold of the speed filter for a given time at liberty grouping were excluded. After 30 days at liberty, 95 percent of the recaptured skipjack were within 1,604 nm of their release positions, and 86.6 percent were recaptured within 1,000 nm of their release positions. The greatest linear displacement for a skipjack was 1,643 nm. It was recaptured by a purse-seine vessel during a set on a FAD at about 1°30’ N and 94°26’ W after 193 days at liberty.

Tag seeding experiments conducted by IATTC observers aboard purse-seine vessels operating in the eastern Pacific to estimate reporting rates began in 2019 as an essential component of the RTTP. Accurate information on reporting rates, estimated from tag seeding experiments, is required for estimating fishing mortality rates, and tag return information error rates. From March 2019 to November 2020, 32 tag seeding kits (consisting of seeding tags, applicators, instructions, and data forms) for a total of 960 tags have been given to observers to conduct tag seeding experiments with tunas placed in the wells of purse-seine vessels during the brailing and loading process. Two tag types, 15 of each, PDT and plastic intra-muscular (PIMA) tags were used in 3 tagging configurations, during each experiment aboard a purse-seine vessel. The PIMA tags were used in the seeding experiments to evaluate their retention rates relative to the PDTs. Ten fish were tagged with a single PDT, another 10 fish were tagged with a single PIMA, and 5 fish were double tagged with one PIMA and one PDT. Thirty-two tag seeding kits have been given to observers and 32 completed tag seeding data forms have been received from those observers at IATTC field offices during debriefing following completion of their trips. Of the 792 total tags which have been seeded, 644 tags (81.3%) have been returned by finders and 482 (74.8%) of returned tags were reported as high confidence. 88.7% of the seeded tags were recovered by unloaders at the time purse-seine vessels wells were being unloaded.

5. ABUNDANCE ESTIMATION

Tagging data is key to the development of spatially structured stock assessment models. Unfortunately, the practicalities of tagging fish inhibit the implementation of tagging designs, and the tagged fish do not completely mix instantaneously with the population. As a convenient fix, the initial recoveries are often “ignored” for a given period to “ensure” complete mixing. However, this is not optimal and alternative approaches should be investigated to deal with tag mixing, particularly for short lived or slow mixing stocks. Here we describe an attempt to account for mixing based on spatio-temporal models. The tagged population is modelled over time as an advection-diffusion process (e.g. Sibert *et al*. 1999). The total population is modelled using a spatio-temporal generalized linear mixed model (GLMM, e.g. Thorson *et al*. 2015). The predicted recoveries are then compared to the observed recoveries based on the exploitation rates using a likelihood function where the spatially specific exploitation rates are equal to the catch divided by the predicted total abundance. We are essentially combing the approach to model movement described by Thorson *et al*. (2017) with the spatio-temporal model of population density described by Thorson *et al*. (2015).

The following gives an illustration of the general approach and then we describe possible modifications. The tagged population, *T*, is modelled based on latitude, longitude, and time as the survivors from all locations that move into or stay within the specific location combined with releases in that location at that time.

$$T_{i,j,t+1} = r_{i,j,t} + \sum_{i',j'} \psi_{i',j' \rightarrow i,j} \varphi_{i',j',t} T_{i',j',t}$$

Where $T_{i,j,t}$ and $r_{i,j,t}$ are the number of tagged individuals and releases in location *l(i,j)* at time *t*, respectively, $\psi_{i',j' \rightarrow i,j}$ is the proportion of the individuals (after survival) that transition from location *l*(i',j') to location *l*(i,j) and can be parameterized using advection and diffusion with parameters **u**, **v**, and **D**, and $\varphi_{i,j,t}$ is survival in location *l*(i,j) at time *t*.

The survival, φ, can be separated into natural mortality, *M*, and exploitation rate, *f*,

$$\varphi_{i,j,t} = (1 - f_{i,j,t})e^{-M}$$

The exploitation rate is calculated as the catch, *C*, divided by the estimated abundance, *N*,

$$f_{i,j,t} = \frac{C_{i,j,t}}{N_{i,j,t}}$$

Where the catch in numbers is calculated from the catch in weight ($C^*_{i,j,t}$) divided by the average weight by each location and time.

$$C_{i,j,t} = \frac{C^*_{i,j,t}}{\sum_s p_{i,j,t,s} w_s}$$

Where $p_{i,j,t,s}$is the proportion of fish of size *s* in location *l(I,j)* at time *t* and w_s is the weight at size *s*.

The estimated abundance is modelled using a spatio-temporal generalized log-linear mixed model (GLMM)

$$log(N_{i,j,t}) = \alpha_t + \gamma_{i,j} + \theta_{i,j,t}$$

Where α_t represents a temporal main effect, $\gamma_{i,j}$ represents the spatial component, and $\theta_{i,j,t}$ represents the spatio-temporal interaction term.

The spatial variation, $\gamma_{i,j}$ can be modelled using a Gaussian Random Field (GRF) with a Matérn correlation function and the spatio-temporal component can be modelled by combining the GRF for spatial variation with a first-order autoregressive model for temporal variation following Thorson *et al*. (2015).

The predicted recoveries are simply the predicted number of tags (adjusted for natural mortality if appropriate) times the exploitation rate

$$\hat{R}_{i,j,t} = f_{i,j,t} T_{i,j,t}$$

The parameters are estimated by maximizing a likelihood (e.g. based on the Poisson probability distribution) that is a function of the observed (*R*) and predicted ($\hat{R}$) recoveries by time and location. The likelihood is maximized while integrating across the random effects representing the spatial ($\boldsymbol{\gamma}$) and spatio-temporal ($\boldsymbol{\theta}$) variation. This integration could be conducted using methods such as Laplace approximation as implemented in TMB (Kristensen *et al*. 2016) or Bayesian analysis using MCMC (Hilborn and Mangel 1997). The estimated fixed effects include the advection-diffusion parameters (e.g. ***u,v,D***), natural mortality (*M*), the temporal main effects ($\boldsymbol{\alpha}$), and the parameters representing the correlation structure of the spatial effects and the first-order autoregressive model for the spatio-temporal effects ($\boldsymbol{\sigma}$).

$$L(\boldsymbol{\alpha}, \boldsymbol{\sigma}, \boldsymbol{u}, \boldsymbol{v}, \boldsymbol{D}, M | \boldsymbol{R}, \boldsymbol{r}, \boldsymbol{C}) = \sum_{i,j,t} \tau\left(R_{i,j,t}, \hat{R}_{i,j,t}\right)$$

Where τ is a function representing the appropriate likelihood.

The implementation is a tradeoff between numerical precision and computational practicality (e.g. computational time, memory requirements) and involves dividing the spatial domain into triangles that assume homogenous processes and population density (Thorson *et al*. 2017). Movement is modelled among these triangles. The approaches used by Thorson *et al*. (2017) to improve computational efficiency (e.g. Euler approximation for movement, stochastic partial differential equation (SPDE) approximation for Gaussian random fields) can be applied.

5.1. Modifications

The above description only provides the basic idea behind the approach and several modifications could be applied to improve the estimates.

Movement

Movement, ψ, represents both random (diffusive, parameterized by **D**) and directive (advective, parameterized by **u** and **v**) components and can be calculated from the instantaneous rate of movement (Thorson *et al*. 2017). This allows parametrization of the instantaneous rate of movement among neighboring cells rather than among all cells (Thorson *et al.* 2017) reducing the number of parameters. The movement rates could be further constrained by using large areas or time blocks where movement rates are considered homogeneous (e.g. Sibert *et al.* 1999) or using a spatio-temporal model to share information among locations and time, smoothing the parameter values.

The movement matrix can be modified to reflect behavior at boundaries (e.g. Sibert *et al.* 1999). Boundaries can be reflective (e.g., continental coastlines or islands) or absorptive (e.g., the IATTC management boundary at 150°W)

Exploitation rate

Many stock assessment models use instantaneous fishing mortality rather than exploitation rate to allow natural and fishing mortality to operate simultaneously. However, this would require solving the catch equation iteratively or estimating the fishing mortality at each location and time and fitting to the catch data, greatly increasing the computational demands. The fishing mortality parameters could be constrained by using a spatio-temporal model to share information among locations and time, smoothing the parameter values. Alternatively, Pope's approximation could be used where catch (recaptures) is removed in the middle of the time period. If the time periods are small enough so the fishing mortality is low, which they might be for the skipjack application if it is based on a monthly time step, Pope's approximation should be adequate.

Abundance

Covariates, such as those that represent skipjack habitat, could be added to improve the abundance prediction, particularly in cells with limited or no data (i.e. the true movement rates do not move fish from the release areas to all locations even though the densities of skipjack in those locations are not minimal).

$$log(N_{i,j,t}) = \alpha_t + \gamma_{i,j} + \theta_{i,j,t} + \sum_k \beta_k x_{i,j,t}$$

Where β_k represent the impact of covariate *k* with value $x_{i,j,t}$ on the abundance at location *l(I,j)* and time *t*. The coefficient of the covariates ($\boldsymbol{\beta}$) are estimated simultaneously with the other fixed effects of the model.

Abundance could be modeled with a spatial population dynamics model that implicitly (Cao *et al*. 2020) or explicitly (e.g. Thorson *et al*. 2017) includes movement. For example, the abundance could be modelled based on the survival and movement estimated from the tagging model.

$$N_{i,j,t+1} = R_{i,j,t} + \sum_{i',j'} \psi_{i',j' \to i,j} \varphi_{i',j',t} N_{i',j',t},$$

In this case the additional parameters would be the recruitment, $R_{i,j,t}$, and the initial numbers, $N_{i,j,t=0}$. Both recruitment and the initial numbers could be modelled using a spatio-temporal model.

The population dynamics modelling could be done in a fully integrated approach (Maunder and Punt, 2013; Punt *et al*., 2013) as described below.

Catch in numbers

The catch in numbers is calculated from the catch in weight divided by the average weight in each location *l(I,j)* at time *t*. The average weight is simply the sum of the product of the proportion at each size and the weight for that size. The proportion at size comes from the size composition sampling of the catch. However, the size composition sampling is limited and low sample size may cause some locations to have biased composition data or no composition data at all. Therefore, spatio-temporal modelling of the composition data may provide better average weights.

Size-specific processes

Several population or fishery processes could be size specific or vary over time (e.g. natural mortality, movement, or selectivity). Estimation of parameters representing size-specific processes would require modeling the size structure of the population and the tagged individuals. Size structured spatio-temporal models have already been developed and implemented (e.g. Kai *et al*., 2017; Maunder *et al*., 2020) and could easily be adapted to this approach. The model of tagged individuals could be extended to model the size structure, but would require the inclusion of a growth transition matrix and estimation of the growth parameters (see Maunder 2002b). The size-specific processes could be modelled as functional forms or random effects could be used to share information among adjacent sizes.

Temporal variability in processes

Temporal variation in the population and fishing processes could be modelled. Temporal variation is already included in the fishing mortality, but could also be included in the size-specific fishing mortality (selectivity). The time varying processes could be modelled using covariates or random effects could be used to share information among adjacent time periods.

Additional data

Additional data, such as effort to inform the exploitation rates or size composition of the catch to inform size-specific fishing mortality, could be included in the model. However, as more data and processes get added the model becomes closer to a fully integrated stock assessment as described below. There will be a tradeoff between information content, model realism, information needs, and computational demands.

Archival tags

Inclusion of archival tag data to inform the advection-diffusion parameters should greatly improve the precision of the estimates of the movement parameters. Archival tag data has a fine spatial and temporal scale and may allow estimation of advection and diffusion parameters that vary over space and time and with environmental covariates. The data from archival tags may have to be aggregated at temporal and spatial scales (e.g. use the most frequent location within the time period [e.g. month]) that make the analysis practical. Spatio-temporal modelling of the movement parameters should be considered.

Other

The model would also need to consider tagging related mortality (immediate and long-term), tag loss (immediate and long-term), and tag reporting rates. These are summarized for skipjack tuna in Maunder (2012c) and in the section of tagging data above for the recent information.

A variety of likelihood functions could be used to fit the data. Given that many individuals are tagged in a single tagging event in the same location, there may be pseudoreplication and this should be taken into consideration. However, the spatio-temporal focus of the analysis may deal with much of the apparent pseudoreplication.

6. STOCK STATUS AND REFERENCE POINT EVALUATION

The ultimate goal of stock assessment is to provide management advice such as stock status and the evaluation of reference points. The proposed approach to model the skipjack tagging data produces an estimate of abundance. However, on its own, an estimate of abundance does not provide useful management advice. The approach also estimates exploitation rate and natural mortality. Continuation of the tagging program would produce a time series of biomass and exploitation rate estimates. There are several approaches that could use the results from the tagging analysis to provide management advice and they are described below.

Yield per recruit analysis

The stock status can be evaluated by comparing fishing mortality (or exploitation rate) estimates with optimal fishing mortality. For example, the fishing mortality can be compared with the fishing mortality that produces the maximum yield from a single cohort based on yield-per-recruit analysis (YPR). YPR analysis requires estimates of natural mortality, which are obtained from the tagging analysis, growth, which can be estimated from the recent tagging data and are available from previous studies (Maunder 2002b notes that the growth is estimated based on length not age), and age-specific selectivity. Assumptions need to be made about the selectivity (e.g. knife edged selectivity) or the tagging analysis could be conducted taking size into consideration to estimate size-specific selectivity. The fishing mortality compared with the optimal values could be estimated by taking the spatially specific fishing mortality rates and weighting it by the corresponding estimates of abundance or the exploitation rate calculated simply as the total catch divided by the estimate of total abundance. The YPR analysis may have to be based on a length-structured model.

YPR analysis does not take into consideration the stock-recruitment relationship. The YPR analysis can be transformed into a MSY type calculation by simply adding a stock-recruitment relationship. However, the stock-recruitment relationship is unknown for skipjack and would have to be assumed. Spawner-per-recruit (SPR) analysis could be used, but the reference points used in SPR are inherently based on assumptions about the stock-recruitment relationship.

Biomass and exploitation rate trends

Continuation of the tagging program will provide a time series of biomass and exploitation rate estimates. This time series could then be used to monitor the trend in the population size or exploitation rates. The time series itself could not be used to define a target (e.g. B_{MSY}) and simple and somewhat arbitrary rules such as keeping the biomass at the same level or increase the biomass by X% in Y years would have to be used. MSE could be used to evaluate the rules based on management objectives. Information from the tagging analysis could be used to improve the operating models used in the MSE.

Full stock assessment

Age (Maunder and Punt 2013) or length (Punt *et al*. 2013) based stock assessment are the gold standard for providing fishery management advice. Previous stock assessments for EPO skipjack have been unsuccessful because they have been based on indices of abundance that are considered unreliable and absolute biomass estimates were uncertain (Maunder 2016). Information about natural mortality and absolute biomass from the tagging study would greatly improve the stock assessments. The estimates could be used in the stock assessment (possibly calculated in length classes) or the tagging data integrated directly into the stock assessment (Maunder 1998, 2001; Hampton and Fournier 2001; Goethel *et al*. 2011). The stock assessment could then be used to evaluate stock status and the EPO tropical tuna harvest control rule following the approach used for bigeye and yellowfin tuna.

Both age (e.g. Maunder and Harley, 2005) and size (Maunder, 2012b) based stock assessment models have been used to assess the EPO skipjack stock. However, aging of skipjack is problematic and size-based methods may be more appropriate since growth data is based on growth increments rather than aging (i.e. it is length based) and the tagging data is more appropriately analyzed using length based methods.

Given the non-mixing issues with the tagging data and the need to model the spatial structure, integrating the tagging data into the stock assessment model is much more computationally intensive than previous analysis. Thorson *et al*. (2017) applied a surplus production model with movement using fine spatial scale, but did not include tagging data. This approach could be extended to a length-based model with the inclusion of tagging data. Multi-area length-based models with tagging data currently exist, but the spatial scale is typically more coarse (Punt *et al*. 2013; McGarvey *et al*. 2010). The approach would differ somewhat to the approach described above since the spatio-temporal model would be replaced by a population dynamics model, the tagged and untagged components of the population would be model using similar models, and the models would be length structured. The resulting stock assessment model would be much more computationally demanding. Previously encountered dome shape selectivity (Maunder and Harley, 2005) may still be an issue in the assessment, but estimation using the tagging data should be investigated.

7. WORKPLAN AND TIMELINE

An initial exploratory model will be presented at the 2022 SAC. The final model will be presented at the 2023 SAC. The final model will likely be based on simplifying assumptions due to computational limitations and time restrictions. For example, the abundance estimates will be based on a spatio-temporal model and using a population dynamics model will be investigated in following years. Therefore, management advice will initially be most likely based on yield per recruit calculations.

Data from the 2022 tagging cruise will not be available until early 2023 and it is not clear if this data can be included in the analyses presented at the 2023 SAC. A benchmark assessment potentially could be produced in 2024 to correspond to the current management cycle if it is 2022-2024.

8. DISCUSSION

Skipjack tuna in the EPO have not been reliably assessed and the use of conventional tagging data is the most promising short-term option to obtain an adequate assessment. However, the practicalities of tagging skipjack, which require the use of pole and line vessels, severely restrict the tagging opportunities reducing the spatial distribution of tags. Therefore, any analysis must deal with tag mixing.

The proposed model combines two computationally intensive approaches, an advection-diffusion model for tag movement (Sibert *et al*., 1999; Thorson *et al*., 2017) and a spatio-temporal model for abundance estimation (Thorson *et al*. 2015). There will be a tradeoff between information content, model realism, information needs, and computational demands. Initial analyses will need to be based on the simplest models, as described above, and more complexity added in a stepwise manner to determine the limits of the computational resources. Movement rates may need to be further simplified (e.g. shared among large areas and time blocks) to reduce the number of parameters. However, Sibert *et al*. (1999) showed that skipjack movement is highly variable at seasonal and interannual time frames.

The approach can be tested on simulated data from SPM of Mormede *et al*. (2013), which is being used to test several different approaches to analyze data from spatially structured populations. A simulated data set is being developed based on Indian Ocean yellowfin tuna, which will have similar characteristics to the EPO skipjack tuna population and tagging data (Dunn *et al*. 2020).

The model would need to consider tagging related mortality, tag loss, and tag reporting rates. These are summarized for skipjack tuna in Maunder (2012c) and above in the tagging data section for the recent data. Estimates for these quantities are available, but they are mostly from historical studies or may be unreliable.

Tag Shedding

Bayliff and Mobrand (1972) estimated tag shedding for yellowfin tuna from double-tagging experiments. Maunder *et al*. (2007) estimated immediate and continuous tag shedding for skipjack, yellowfin, and bigeye tuna combined, but tag shedding may have been influenced by poorly-trained taggers. Hampton (2000) used combined instantaneous tag shedding and instantaneous non-reporting of tags for the three species of tunas, and continuous tag shedding based on Hampton (1997). Some double tagging was conducted in the EPO during 2000, with a shedding rate of about 13%, but the rate depended a lot on the experience of the tagger. Double tagging experiments could be conducted in the 2022 tagging cruise if needed.

Tagging-related mortality

Hampton (1997) assumed tagging-related mortality was insignificant. Hoyle *et al*. (2015) found that recovery rates differed substantially among taggers, suggesting that tagger-related differences in the tagging and release processes can translate into substantial variability in survival rates. It is possible that tagging related mortality either due to injury while tagging due to skipjacks frantic behavior in the tagging cradles or predation when released could be substantial in some tagging locations.

Reporting rate

We believe the reporting rate for the tagging data on purse seiners to be used in our analyses to be relatively high due to the use of tag recovery specialists (see the section of the tagging data above). However, reporting rates can vary by fleet and through time, and they can have a large impact on results. Data presented in Bayliff (1971) indicate that the reporting rate was around 91%, but this estimate is based on limited data. Maunder *et al*. (2007) estimated reporting rates of 50% to 70% for skipjack tuna from tag-seeding experiments, with reporting rate decreasing with size. Hoyle (2011) found low reporting rates of around 50%.

Another source of data for a skipjack assessment is abundance at echosounder buoys. This information could be used to produce an index of relative abundance (Santiago *et al*. 2019). However, the time series would be short given that the data is only available on a voluntary basis for part of the fleet since 2010. Also, due to the large fluctuations in skipjack abundance, the index would unlikely to be able to estimate absolute abundance without reliable estimates of recruitment (e.g. from length-composition data).

However, the index could be used as an indicator or as auxiliary information for tagging-based assessment for years following the tagging studies.

Close-Kin Mark-Recapture (CKMR; Bravington *et al*. 2016) should also be considered for assessing skipjack tuna. CKMR would allow "tagging" from fish caught on purse seine vessels and would reduce the issues with tag mixing. However, the large abundance of skipjack may make the approach economically impractical. Information about CKMR and its applicability to IATTC managed stocks is presented in Maunder *et al*. (2021).

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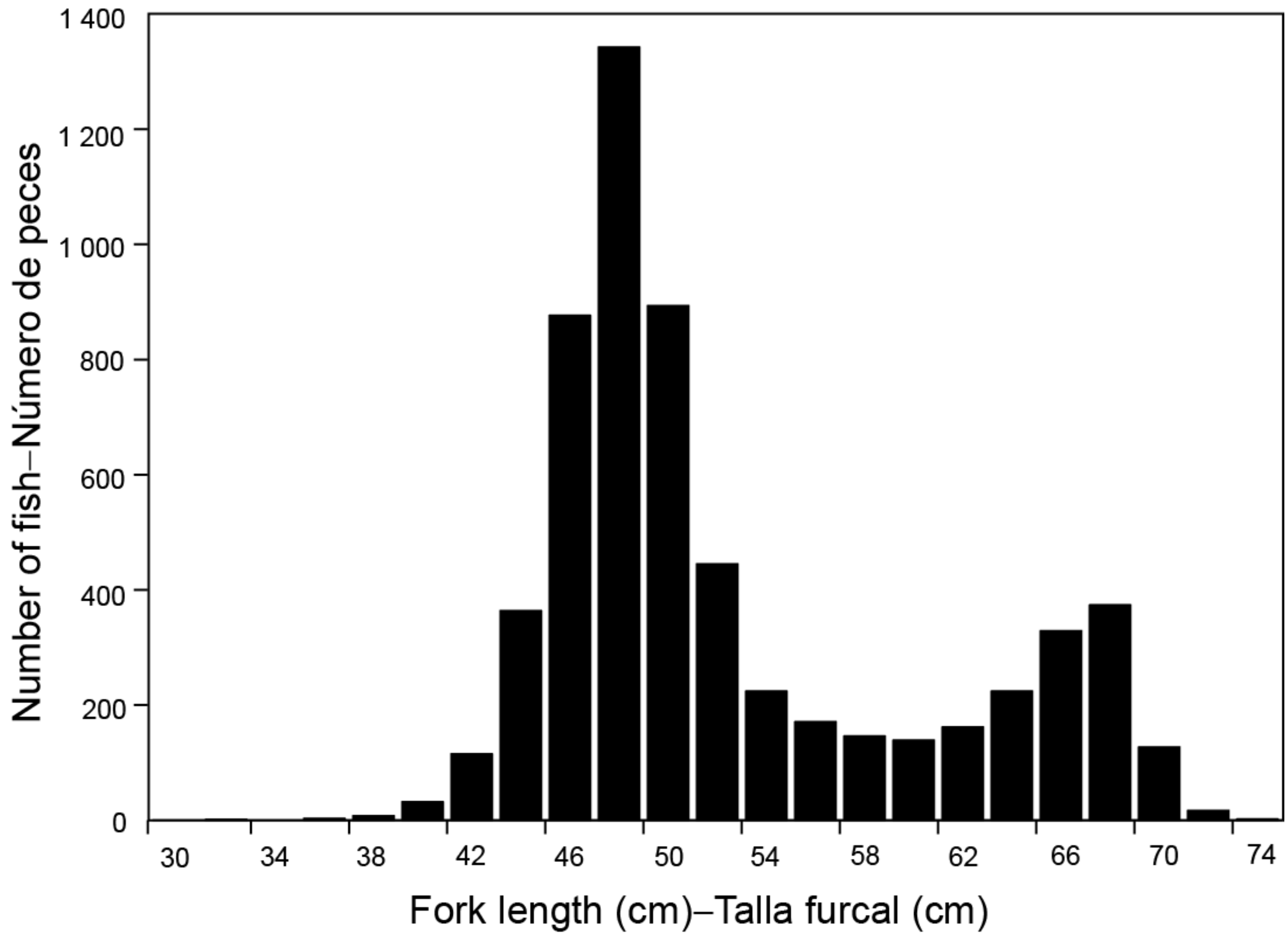

FIGURE 1. Length frequency distribution of 5,998 skipjack tuna tagged and released with plastic dart tags during 2019 and 2020 under the IATTC Regional Tuna Tagging Program (RTTP) in the EPO.

FIGURA 1. Distribución de la frecuencia de talla de 5,998 atunes barrilete marcados y liberados con marcas de dardo plásticas durante 2019 y 2020 bajo el Programa Regional de Marcado de Atunes de la CIAT en el OPO.

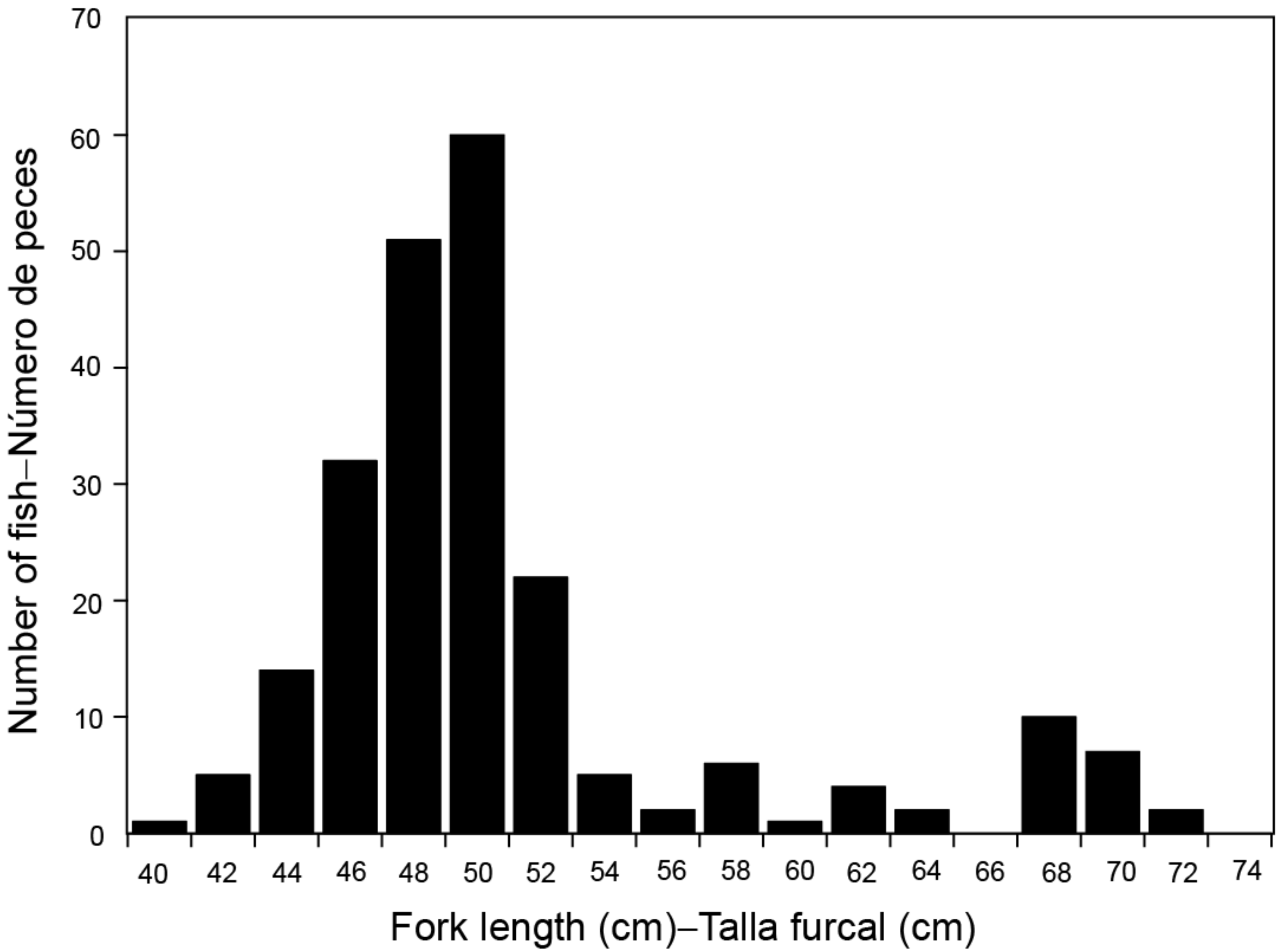

FIGURE 2. Length frequency distribution of 224 skipjack tuna tagged and released with archival tags during 2019 and 2020 under the IATTC Regional Tuna Tagging Program (RTTP) in the EPO.

FIGURA 2. Distribución de la frecuencia de talla de 224 atunes barrilete marcados y liberados con marcas archivadoras durante 2019 y 2020 bajo el Programa Regional de Marcado de Atunes (PRMA) de la CIAT en el OPO.

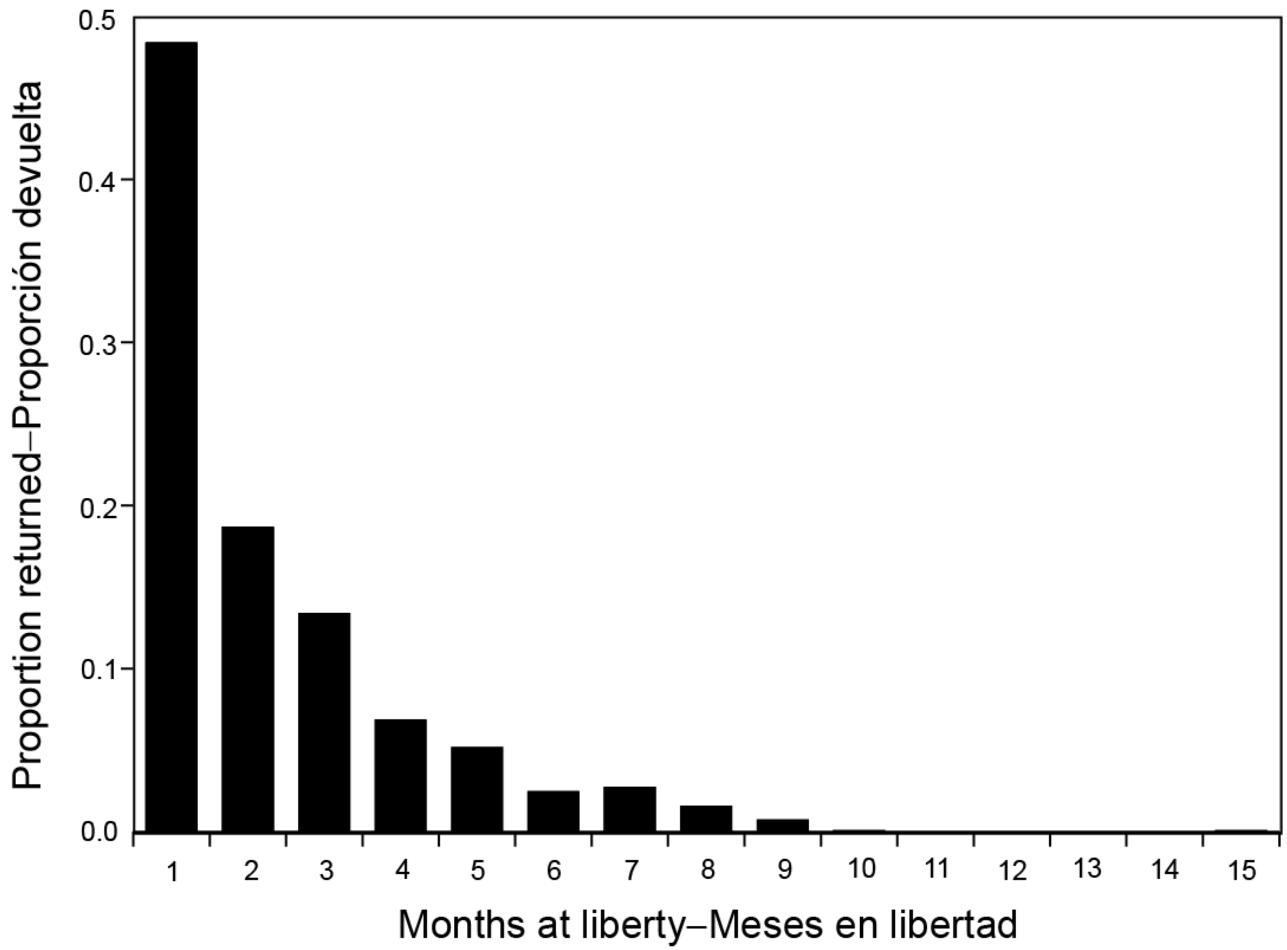

FIGURE 3. Proportion of skipjack tuna tags returned (*n* = 1,389) by months at liberty. Only the tag returns from fish, whose recapture information fell within the speed filter threshold are included. Fish were tagged under the IATTC Regional Tuna Tagging Program (RTTP) in the EPO (1999-2020).

FIGURA 3. Proporción de marcas de atún barrilete devueltas (*n* = 1,389) por meses en libertad. Solo se incluyeron las devoluciones de marcas de peces cuya información caía dentro del umbral del filtro de velocidad. Los peces fueron marcados bajo el Programa Regional de Marcado de Atunes (PRMA) de la CIAT en el OPO (1999-2020).

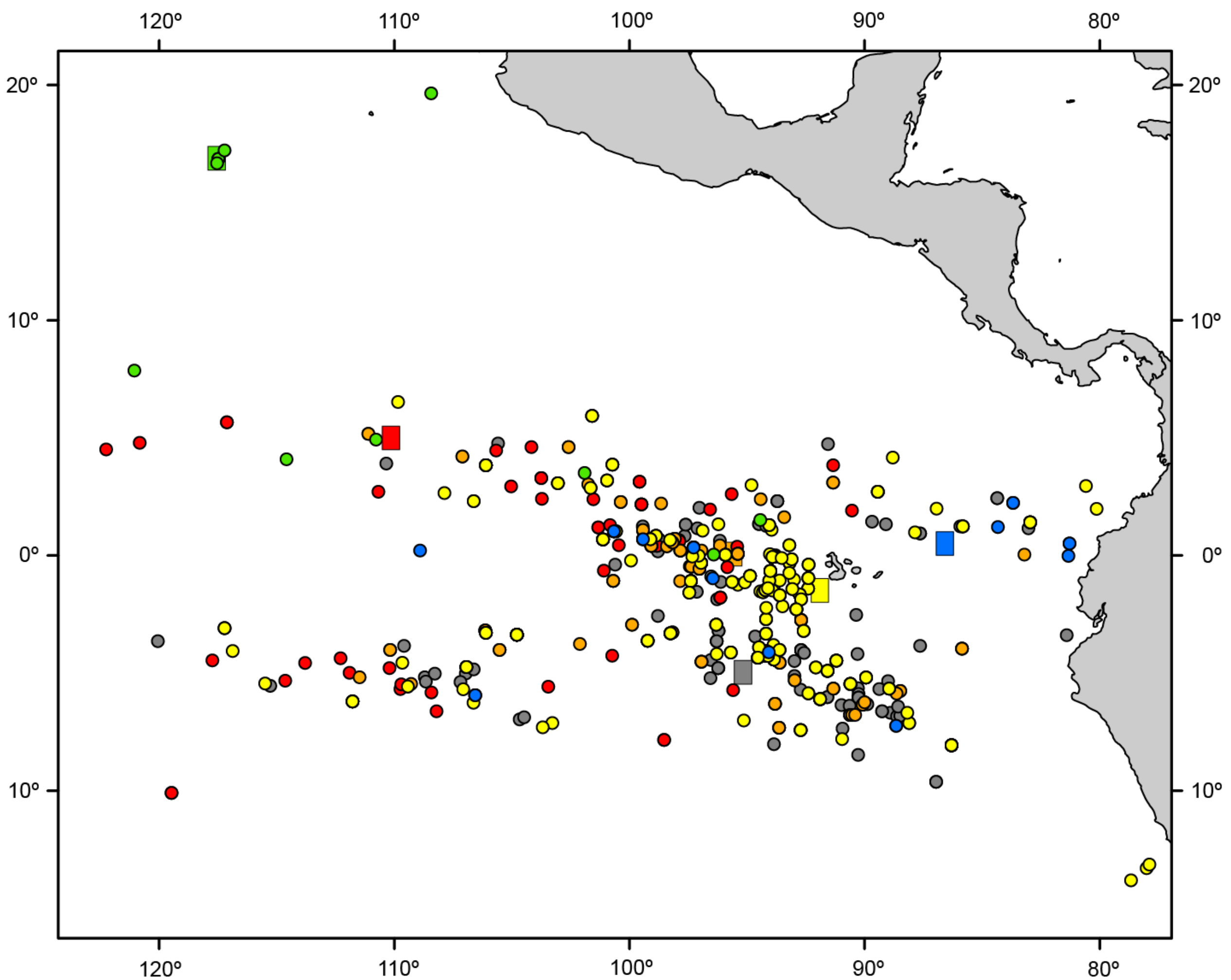

FIGURE 4. Skipjack tuna linear displacements (*n* = 700) for fish at liberty greater than 30 d shown as dots, color coded for six distinct release locations, shown as squares. Fish were tagged under the IATTC Regional Tuna Tagging Program (RTTP) in the EPO (1999-2020).

FIGURA 4. Los desplazamientos lineales del atún barrilete (*n* = 700) para peces en libertad mayor a 30 d se muestran como puntos, codificados por colores para seis lugares distintos de liberación, se muestran como cuadrados. Los peces fueron marcados bajo el Programa Regional de Marcado de Atunes (PRMA) de la CIAT en el OPO (1999-2020).

TABLE 1. Releases and returns of plastic dart tags, by year of release and days at liberty. Percent of total tag returns which were validated by tag recovery specialists as high confidence are provided. Fish were tagged under the IATTC Regional Tuna Tagging Program (RTTP) in the EPO (1999-2020).

TABLA 1. Liberaciones y devoluciones de marcas de dardo plásticas por año de liberación y días en libertad. Se proporciona el porcentaje del total de devoluciones de marcas que fueron validadas por especialistas en recuperación de marcas como de alta confianza. Los peces fueron marcados bajo el Programa Regional de Marcado de Atunes (PRMA) de la CIAT en el OPO (1999-2020).

		Returned						
Year	**Released**	**<30**	**30-89**	**90-179**	**180 – 365**	**>365**	**Total (%)**	**Percent High Confidence (*n*)**
2019	177	6	19	5	2	1	35 (19.8)	60.0 (21)
2020	5854	730	466	210	71		1,569 (26.8)	18.3 (287)
All	6031	736	485	215	73	1	1,604 (26.6)	19.2 (308)

TABLE 2. Releases and returns of archival tags, by year of release and days at liberty. Fish were tagged under the IATTC Regional Tuna Tagging Program (RTTP) in the EPO (1999-2020).

TABLA 2. Liberaciones y devoluciones de marcas archivadoras por año de liberación y días en libertad. Los peces fueron marcados bajo el Programa Regional de Marcado de Atunes (PRMA) de la CIAT en el OPO (1999-2020).

		Returned					
Year	**Released**	**<30**	**30-89**	**90-179**	**180 – 365**	**>365**	**Total (%)**
2019	43	3	0	0	2	0	5 (11.6)
2020	185	10	13	9	3	NA	35 (18.9)
All	228	13	13	9	5	0	40 (17.5)