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SUMMARY OF MODELING WORK ON EVALUATING BIGEYE TUNA RECRUITMENT SHIFT HYPOTHESES

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CONTENTS

SUMMARY

A recurrent feature of bigeye assessments in the EPO since 2003 (Harley *et al*. 2005; Fonteneau and Ariz 2008; Aires-da-Silva 2017) is a sudden increase in the estimated recruitment starting in the mid-1990s, and resulting in an apparent “two-regime” pattern in recruitment, with estimates after 1993 about double those before that year. This recruitment shift coincides with the very rapid expansion of the purse-seine fishery on fish-aggregating devices (FADs) in the equatorial EPO in the mid-1990s. Although the “two-regime” recruitment pattern mostly disappeared in the 2014 assessment, by down-weighting the composition data (Aires-da-Silva and Maunder 2014), it resurfaced in subsequent assessments. Some of the hypotheses proposed to explain this pattern (Aires-da-Silva *et al*. 2010, Valero *et al*. 2019), ascribe the increase in recruitment to a modelling artifact while others postulate that there is a real increase in recruitment. The rationales, outcomes of research to date, and references for different hypotheses are shown in Table 1. This report summarizes results only for those hypotheses that substantially reduce or eliminate the shift in estimated recruitment (Valero *et al*. 2019); for results for other hypotheses, see Valero *et al*. 2019, and the report of the 2nd Bigeye Assessment Review for further details. Contrary to what was reported previously (Aires-da-Silva and Maunder, 2010; Valero *et al*., 2018), spatial models of EPO bigeye tuna with no movement did not remove the recruitment shift and therefore were not included in this summary. Although including historical catches and starting the model in 1954 instead of 1975 reduced the estimated recruitment shift for the 2018 base model (Valero *et al*., 2019), it did not reduce the shift for the fleets-as-areas model with new area definitions. Alternative models that reduced the

recruitment shift included estimating growth internally, assuming higher natural mortality for juveniles, and dome-shaped selectivities for all fishing gears, and they estimated a wide range of *F* multiplier values. It is important to note that, in their current configuration, none of the models summarized in this report is being considered as a potential new base case for EPO bigeye tuna, so these results should be treated with caution in any management context.

1. MODELING APPROACH

Alternative integrated model runs were conducted with the modeling platform Stock Synthesis (SS). The latest bigeye tuna (BET) base-case assessment model (Xu *et al*. 2018) was run with SS version 3.23b (compiled November 2011) and some of work reported in Valero *et al*. (2019) was conducted using SS 3.23b, but most of the alternative models were implemented in version 3.3.12 (compiled September 2018). A comparison of BET base case model run results using both versions (Valero 2019) was an information paper for the 2nd Bigeye Assessment Review. For this summary document we used a new fleets-as-areas (FAA) model as the basis for alternative runs, in which the areas, as defined in WSBET-02-02, are implicitly modeled as separate fleets in a one-area model (Hurtado-Ferro *et al*. 2014). We compared alternative runs under different assumptions for the FAA model and also for the 2018 base case (BC) model (also an FAA model, but with different areas) (Xu *et al*. 2018) with lambda[1] (λ) = 0.05 ($BC_{\lambda=0.05}$) and λ = 1 ($BC_{\lambda=1}$) for weighting the length-composition data. Table 2 is an overview of main differences in configuration between the 2018 BC model for bigeye and the FAA model. Since the main goals were to evaluate the impact of alternative model configurations on the bigeye assessment, and to determine which configurations reduce the recruitment shift, we set up alternative models under different hypotheses and report key model results, such as comparisons of estimated biomass trajectories and a simple statistic of the magnitude of the recruitment shift (R_{shift}: the ratio of the median age-0 recruitment after 1994 (after the expansion of the FAD fishery) to the median age-0 recruitment before 1994). Alternative model configurations reflected hypotheses or processes that have been shown to substantially reduce or eliminate the estimated regime shift in recruitment (Valero *et al*., 2019), among them the following.

1.1. Higher natural mortality of juvenile bigeye

Aires-da-Silva *et al*. (2010) considered that alternative patterns of higher natural mortality (*M*) for juvenile and adult bigeye that were shown to reduce the recruitment shift were unrealistically high. The Lorenzen *M* curve was proposed during the 2nd Bigeye Assessment Review as an alternative, and model runs were conducted including the expected schedule of sex- and age-specific *M* (Figure 1).

1.2. Alternative growth

Growth in the EPO bigeye assessments has been modeled using a Richards model (WSBET-02-05). The Richards growth model, as parameterized in Stock Synthesis, was fitted to the quarterly estimates of mean length-at-age from Aires da Silva *et al*. (2015); those estimates of the growth parameters were then used as fixed values in the 2018 BC model. In order to evaluate potential issues with using growth estimated externally to the integrated model, Stock Synthesis runs were performed with all growth parameters of the Richards growth curve estimated inside the integrated model, including the parameters describing the variation of length at age.

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[1] Lambda (λ) is a data emphasis factor that is multiplied by the corresponding likelihood component to calculate the overall negative log likelihood to be minimized during estimation. For example, λ=0 for particular data will remove the effect of those data in the estimation, λ=0.05 and λ=1 will use 5% and 100%, respectively, of that data likelihood component during estimation.

1.3. Dome-shaped selectivities for the longline fisheries

The selectivity of the two longline fisheries that provide indices of abundance is assumed to be asymptotic in the 2018 BC model. The rest of the selectivities have flexible curves, allowing for dome-shaped selectivities, in which fish are less selected to the fishing gears as they grow larger. In order to evaluate the effect of asymptotic versus dome-shaped selectivities, Stock Synthesis runs were performed with dome-shaped selectivities for all gears, including longlines.

1.4. Use of historical catches

Stock assessment models for bigeye, including the 2018 BC model, have historically started in 1975, although exploitation had already been occurring since at least the early 1950s. In those models, initial conditions are implemented by estimating initial fishing mortalities, with the intention of using mainly the information from the length-composition data to estimate the initial conditions (as the initial equilibrium catch penalty is turned off in the likelihood, but other data, such as the indices of abundance, will also influence the estimates). There could be issues in the way the initial conditions are estimated, given the low emphasis given to the length-composition data ($\lambda = 0.05$ in the 2018 BC model) and the implied initial equilibrium catch expected by the models (given estimated initial fishing mortalities not fitted to equilibrium catches) to be much greater than the observed historical catches from the fishery prior to 1975. To evaluate the effect of alternative initial conditions on model results, model runs were conducted using time series of historical catches, by fleet, going back to 1954 (Figure 2), assuming virgin conditions at the start of the model and estimating recruitment deviates.

1.5. Spatially-structured models with movement

Aires-da-Silva and Maunder (2010) reported that spatially-disaggregated assessment models with no movement of EPO bigeye removed the recruitment shift. However, Valero *et al*. (2019) found that spatial models with no movement, using a variety of alternative spatial structures, including one close in configuration to the one used by Aires-da-Silva and Maunder (2010), did not remove the recruitment shift. Although some spatial configurations with movement reduced the recruitment shift, there are uncertainties in the movement rates of juvenile bigeye (which seem too high, based on assessment model results), and those for adults are unknown, both in direction and rate. While some combinations of estimated juvenile rates and assumed rates and directions of adult movement reduce the recruitment shift, they result in accumulation of fish to the coastal areas, and lead to either unrealistically large differences in longline catchability between areas, or to lack of model convergence when mirroring catchability among areas. Given these issues, results from spatially-structured models are not summarized here, although they are reported elsewhere (Valero *et al*. 2019, 2019b).

2. SUMMARY OF RESULTS

Results of alternative models are summarized, first by describing relevant model estimates (growth, selectivities), and then by comparing time series of estimated population quantities of interest (spawning biomass (SSB), spawning biomass ratio (SBR), recruitment (R), R_{shift} and F multiplier). Alternative runs are summarized under different assumptions for the FAA model with the new area definitions (Minte-Vera *et al*. 2019 WSBET-02-05), and also for the 2018 BC model (also an FAA model, but with different areas) (Xu *et al*. 2018) with $\lambda = 0.05$ ($BC_{\lambda=0.05}$) and $\lambda = 1$ ($BC_{\lambda=1}$) for the length-composition data.

Estimating growth inside the integrated model results in lower estimates of the average size of the oldest fish (L_{Amax}= 173 cm) and faster growth ($K = 0.15$) than the external estimates of growth (L_{Amax} = 196 cm; $K = 0.11$) (Table 3, Figure 3). Estimated dome-shaped selectivities for all gears are shown in Figure 4.

Although general estimated biomass trends are similar for all models summarized here (Figures 5 and 6), the scale differs among models by as much as a factor of 5 in spawning biomass (Figure 5) when estimating dome-shaped selectivities in the FAA model (FAA_DomeLL). Time series of estimated spawning biomass are similar for the FAA model, the FAA model with Lorenzen natural mortality schedules (FAA_*M*), the FAA model with historical catches (FAA_HistC), and the 2018 $BC_{\lambda=1}$ model (Figure 5). Estimating growth in the FAA model (FAA_Growth) produced higher estimates of the SSB time series, similar to those estimated by the 2018 $BC_{\lambda=0.05}$ model (Figure 5).

Different models estimated varying levels of virgin spawning biomass (Figure 5, colored triangles) resulting in differences between estimated time series of the spawning biomass ratio (SBR)(Figure 6). The SBR was lower for the fleets-as-areas and the historical catch models at levels similar to those estimated by the 2018 $BC_{\lambda=1}$ model (Figure 6). The 2018 $BC_{\lambda=0.05}$ model estimates intermediate SBR from the rest of the model runs, higher than the FAA_*M* and lower than both the FAA_Growth or FAA_DomeLL selectivities (Figure 6).

Time series of estimated relative recruitment were similar between models (Figure 7), except for the FAA_Growth, FAA_DomeLL, and FAA_*M* models (Figure 8). The FAA model has an R_{shift} (2.28) higher than the 2018 $BC_{\lambda=1}$ model (R_{shift} = 2.03) and similar to the R_{shift} (2.28) of the historical catch model (Table 3). Among FAA models, only the FAA_Growth, FAA_DomeLL, and FAA_*M* models have smaller R_{shift} than those of the 2018 $BC_{\lambda=1}$ model (Table 3).

Alternative models produce a large range of *F* multiplier values, ranging from 0.52 for the FAA model to 1.79 for the FAA_DomeLL model (Table 4).

3. CONCLUSIONS

Contrary to what was reported previously (Aires-da-Silva and Maunder, 2010; Valero *et al*., 2018), spatial models of EPO bigeye tuna with no movement did not remove the recruitment shift and therefore were not included in this summary. Although including historical catches and starting the model in 1954 instead of 1975 reduced the recruitment shift for the 2018 base model (Valero *et al*., 2019), it did not have a reduction of the shift for the FAA model. There are several differences between the 2018 BC and the FAA approach that could have an impact on this result (Table 2). Further investigations into the initial conditions of the model may be warranted, as recommended by the 2nd Bigeye Review Panel.

Estimating growth reduces the recruitment shift; it also estimates faster growth (*K*), smaller lengths for the older fish and slightly larger CVs of growth. This results in a time series of larger estimated biomass and healthier stock status than the 2018 BC model (irrespective of the λ used, Figure 6). Estimating only L_{Amax} within the BC model, or even fixing it at 183 cm also decrease the shift in recruitment (Minte-Vera et al 2017).Additional work on individual growth was conducted and reported by Valero *et al*. (2019), including the use of conditional-age-at-length data from otolith data, historical length-composition data and alternative data weighting. In all cases, estimating growth internally in the model resulted in lower L_{Amax} estimates, faster growth *K* and larger CVs of growth (Valero *et al*., 2019) than those estimated externally based on otolith and tagging data. Further investigations on how best to include growth processes in the assessment are needed, including alternative growth parameterizations such as the growth cessation model (Maunder *et al*., 2018).

Aires-da-Silva *et al*. (2010) reported that some assumed patterns of higher *M* for juvenile and adult bigeye reduced the recruitment shift; however, they also considered those rates to be unrealistically high, given the life history of bigeye tuna. The Lorenzen *M* curve proposed to be used for bigeye tuna during the 2nd Bigeye Assessment Review has a physiological rationale (Lorenzen 2000); however, there is still uncertainty about its appropriateness for bigeye, particularly the scaling of the overall mortality schedule. The FAA model that uses the Lorenzen *M* schedule has the smallest recruitment shift (Table 3).

Using dome-shaped selectivities for all gears also reduced the recruitment shift (Table 3) and produced the most optimistic stock status, with larger SSB series (Figure 5) and healthier stock status (Figure 6). Caution should be used when considering models with all selectivities assumed to be dome-shaped, given that those models predict that a potentially substantial fraction of the stock is essentially not available to any gear and therefore invisible to the model, creating what is often called “cryptic” biomass.

The range of *F* multiplier values estimated by alternative models is wide, ranging from 0.52 for the FAA model to 1.79 for the FAA_DomeLL model (Table 4). It is important to note that, in their current configuration, none of the models summarized in this report are being considered as a potential new base case for EPO bigeye tuna, so these results should be treated with caution in any management context. Furthermore, some of the processes summarized here and others reported elsewhere (report of the 2nd Bigeye Assessment Review; Valero *et al*. 2019, 2019b) may not be independent, could be simultaneously mis-specified, and may need to be considered in combination when moving forward with future model development and selection.

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TABLE 1. Summary of hypotheses that have been proposed as potential causes of the apparent recruitment shift for bigeye tuna. For more details see Valero *et al*. (2019) and Valero *et al*. (2019b). See also Aires-da-Silva *et al.* (2010) for additional description of hypotheses reviewed during the 2nd Bigeye Assessment Review.

HYPOTHESIS	**SUMMARY**
Spatial mismatch	
Rationale	Under this hypothesis, the two-regime pattern is the result of a spatial misspecification in the stock assessment model; in other words, an artefact of the model, caused by the assumption that bigeye in the EPO form a single homogeneous stock. Therefore the increase in purse-seine catch does not appear to reduce the longline CPUE, and hence the index of relative abundance, since the longline CPUE index measures abundance over a wider, or different, area than where the increased purse-seine catch occurred.
Outcome	Spatial models of the EPO with no movement do not remove the recruitment shift[1]. This is in contrast with what was found by Aires-da-Silva and Maunder (2010) and Valero *et al*. (2018). Updating Aires-da-Silva and Maunder (2010) work with current data does not resolve the recruitment shift [2]. Valero *et al*. (2018) thought to have removed the recruitment shift based on SS runs for the only EPO sub-area (Central) with data available at the time, however subsequent work with alternative partitions of the EPO identified that the recruitment shift is still present in the offshore equatorial area. Spatial models with movement both for the EPO (4-area models)[3] and CEPO[4] (6-area models including adjacent assessment model boxes from the central Pacific Ocean) showed that movement at 16% per quarter seems too high, even if just for juveniles. Including hypothetical E-W diffusion of adults removed the recruitment shift; however movement rates or general movement patterns for adult bigeye are unknown (further investigations are needed) and results are highly sensitive to assumed movement patterns and rates. CEPO models had convergence issues and did not remove the recruitment shift.
References	[1] Section 3.1.1, Valero *et al*. (2019). 4-area models of the EPO and 4 separate 1 area models (A1, A2, A3, A4) for the "Default" spatial structure from Minte-Vera *et al*. 2019). Runs with 3 additional partitions of the EPO. [2] Section 3.1.1, Valero *et al*. (2019), "Alternative 3" model runs. [3] Section 3.1.1, Valero *et al*. (2019). 4-area models of the EPO with alternative movement scenarios. [4] Valero *et al*. (2019b). CEPO 6-area models including adjacent assessment model boxes from the central Pacific Ocean
Growth issues	
Rationale	Growth in the EPO bigeye assessments has been fixed at an externally estimated Richards growth model (WSBET-02-07). The 2018 bigeye stock assessment starts in 1975, estimating an initial fishing mortality not constrained by equilibrium catches and informed by the length-composition data, which is down-weighted in the assessment. The value at which the length of older fish (L_{Amax}) is fixed, coupled with the assumption of asymptotic selectivity in the longline fishery, will influence the initial depletion level; therefore, if L_{Amax} is mis-specified it could impact the robustness of the model. In addition, the Richards growth model may not be the most appropriate for bigeye growth, particularly for the few large-size tagged bigeye recovered (WSBET-02-07). The Growth Cessation Model developed by Maunder *et al*. (2018) fits better to the data.
Outcome	Estimating growth reduces the recruitment shift[1] markedly; it also estimates faster growth K, smaller lengths for the older fish (L_{Amax}) and larger CVs of variation of length-at-age and results in larger estimated time series of biomass and healthier stock status than the base case[2]. Assuming a smaller L_{Amax} (183 cm, versus 196 cm in the base case) reduces the recruitment shift and moves the estimated integrated model trajectory of spawning biomass to within the envelope of uncertainty of as ASPMdev model (age-structured production model with recruitment deviations estimated)[3].

References	[1] Model runs for the area A1 of the "Default" spatial structure and for the 2018 base-case bigeye assessment. [2] Section 3.1.2, Valero *et al*. (2019) [3]Minte-Vera *et al.* 2017.
Length-weight (L-W) relationship issues	
Rationale	The L-W relationship used in the assessment was collected more than 50 years ago (Nakamura and Uchiyama, 1964) and even though collected only from longline, it is currently applied to purse-seine catches as well in the assessment and in the preparation of data for the assessment.
Outcome	Using a newly-estimated purse seine-only L-W relationship varies at most 6% from the longline L-W relationship[1]. At least with the data available so far this is not enough to remove the recruitment shift[2]. Using the weight-composition data (early-1980s to late 1990s) in the model intensifies the recruitment shift (Minte-Vera *et al*., 2017); these data does not seem compatible with the length-composition data and are not used in the base case model.
References	[1] Section 3.1.3, Valero *et al*. (2019) [2] Model runs for the area A1 of the "Default" spatial structure and for the 2018 base-case bigeye assessment.
Model time span	
Rationale	Current stock assessment model starts in 1975, when exploitation had already been ongoing for at least two decades[1]. The model calculates equilibrium initial conditions, estimating initial fishing mortality but not fitting to equilibrium catch, it therefore relies on other data such as the index of abundance, but particularly also the length-composition data (which are greatly down weighted), whose interpretation depend on the asymptotic assumption of the longline fishery and the assumed growth. There is the potential for mis-specified initial depletion if growth and/or selectivity are mis-specified, which could lead to the recruitment shift.
Outcome	Historical models starting in 1954 rather than 1975 reduce the recruitment shift, although not to the degree that estimating growth does. Historical models also produced estimated trends similar to shorter base-case models, although with larger biomass series and healthier stock status.
References	[1] See Section 3.1.4, Valero et al. (2019) and request 1 from Day 1 of the report of the 2nd Bigeye Assessment Review.
Selectivity issues	
Rationale	The base-case model uses a length-based selectivity, which is asymptotic for the longline fisheries and has implications for the ability to estimate initial conditions properly, given that the model starts after exploitation started. There may be some degree of dome-shaped selectivity if larger/older bigeye tuna are less vulnerable to the longline fisheries, by going deeper in the water column as they age/grow, for example. Perhaps an age-based selectivity could perform better.
Outcome	Using dome-shaped selectivities for all gears also reduced the recruitment shift, and produced similar results as runs with estimated growth, with larger biomass series and healthier stock status. Using blocks in longline selectivity around the increase in FAD catch, or longline age-based selectivity, did not reduce the regime change.
References	Section 3.1.5., Valero *et al*. (2019). Runs were conducted allowing for dome-shaped length-based selectivity for the longline fishery for area A1 of the "Default" bigeye spatial structure.
Catchability issues	
Rationale	Either longline catchability changed in the mid-1990s due to the expansion of FAD fisheries, or there may be hyperdepletion or hyperstability in catchability if the longline index is not proportional to biomass. These potential issues were not evaluated in the assessment, but can affect the way the model interprets changes in the longline index of abundance.

Outcome	Using time blocks for catchability and selectivity in the mid-1990s for the longline fisheries did not produced markedly different results from the base case. Estimating non-proportionality in catchability does not reduce the recruitment shift.
References	Section 3.1.6, Valero *et al*. (2019). Runs implemented for A1 of the “Default” spatial structure
Longline Index issues	
Rationale	The only index of abundance the base-case assessment has been fitted to it is the Japanese CPUE longline index. However there are other longline fleets that fish for bigeye, and recent work has resulted in alternative uses of data and standardization approaches.
Outcome	The alternative indices for abundance using different standardizations or data are remarkably similar and they did not produce markedly different SS model results or reductions in the regime change. In addition to the block in q, a block in longline selectivities (inflection and 95% width of the logistic curve) was also included for the three alternative indices of abundance but did not result in meaningful changes in overall model results (neither biomass trends, q values, selectivities nor recruitment shifts) from the base case.
References	Section 3.1.7, Valero *et al*. (2019). Runs implemented for the A1 of the “Default” spatial structure
Environmental or ecosystem regime shift	
Rationale	Most of the hypotheses evaluated during the first and second review of the bigeye assessment assumed that the estimated regime change in recruitment is due at least in part to one or a combination of hypotheses leading to misspecification of the model, rather than being caused by actual environmental or ecosystem changes. However, there may be an actual regime change whose cause has not yet been identified.
Outcome	There is no evidence so far that the change in recruitment may be environmentally driven. However, there are physical changes in the pelagic EPO such as Oxygen Minimum Zone expansion and shoaling, primary production is decreasing, ocean temperatures are rising and food web changes: the average cell size of plankton organisms has decreased; prey community has changed (see Olson, 2013 SAC-04-08). Similar recruitment patterns to bigeye are not observed in yellowfin tuna recruitment time series in the EPO. However, a similar pattern is seen for bigeye tuna recruitment in some areas of the WCPO ([1],[2]). Indicators for skipjack tuna in the EPO show changes after the mid-1990s[3]. The skipjack model for the western and central Pacific Ocean estimates an increase of recruitment in the early 1980s[4], coincidental with increased purse seine catches in the WCPO. There are changes in yellowfin diet that could be inferred as originating from ecosystem change, but the information for bigeye is limited. There is also some evidence of tuna eating juvenile tunas, which hypothetically could result in higher recruitment as the tuna populations are fished down, but the consumption rates seem low.
References	[1] Harley *et al.* (2009) [2] McKechnie *et al*. (2017) [3] Maunder (2018) [4] Mathew Vincent, SPC, personal communication
Ricker stock recruitment	
Rationale	The estimated increase in recruitment with concurrent decreasing estimates of biomass could potentially be explained by cannibalism.
Outcome	This hypothesis has not been evaluated.
References	Suggested during the second review but not evaluated (see ecosystem effects above).
FAD early catch underestimation	
Rationale	If purse seine catches were underestimated before the mid-1990s this could affect the relative magnitude of the estimation of the recruitment regime shift. Aires-da-Silva *et al*. (2010) reported that increased floating-object catches during the early period did not eliminate the recruitment pattern. The purported underestimation was proposed by Fonteneau and Ariz (2008) by applying species composition ratios estimated after the 2000s to pre-1994 catches.

Outcome	Runs performed during the BET review showed that added discards in the early period (prior to 1993) when no discards were assumed, had to be 10 times those in the first 5 years discards are available to remove the regime shift, consistent with the results of Aires-da-Silva *et al*. (2010).
References	
FAD recent catch overestimation	
Rationale	If purse seine catches were overestimated after the mid-1990s this could affect the relative magnitude of the estimation of the recruitment regime shift. This could have happened if data collected by the port-sampling program, which have been used to estimate catch species and size composition since 2000, were biased.
Outcome	In order to remove the regime change, recent FAD catches would have to be reduced by 75%.
References	
Higher natural mortality rates	
Rationale	Higher natural mortality of small juveniles will essentially imply that the increased catches of FAD do not have such an impact on the dynamics of BET since fish of those sizes would have died due to natural causes anyways. The Lorenzen natural mortality curve has been used for other species, including tunas such as bigeye in the Atlantic.
Outcome	Aires-da-Silva *et al*. (2010) considered that alternative patterns of higher natural mortality for juvenile and adult BET that were shown to reduce the regime change were unrealistically high. The Lorenzen natural mortality curve was proposed during the review as an alternative and runs that include them reduce greatly the regime shift. Using Lorenzen M while estimating growth removes the regime shift completely and allows for estimation of steepness. It is still unclear if the higher M for juvenile BET is realistic or too high or if the estimates of steepness are realistic.
References	Runs were conducted with the 2018 bigeye base-case model.
Density-dependent growth	
Rationale	Density-dependent growth could explain the recruitment pattern as well. Bigeye growth rates could increase in areas of high exploitation. Faster growth rates would imply greater proportions of larger fish, which, without density dependent growth, the model might explain by increased recruitment. However there is no evidence to support this hypothesis.
Outcome	Computational issues prevented these being evaluated during the review.
Changes in migratory patterns	
Rationale	If availability of larger fish greatly increased due to immigration of adult bigeye to the fishing grounds, the model could try to explain higher observed proportions of large fish by increasing recruitment. Emigration of juvenile fish could have the same effect, since the juveniles would be vulnerable to purse seine but not to longline. However there is no evidence to support this hypothesis.
Outcome	This hypothesis has not been completely evaluated, although some relevant runs were implemented with alternative movement patterns and rates of bigeye of different ages.
References	See Valero *et al*. (2019) and Valero *et al*. (2019b)

TABLE 2. Configurations of the 2018 base-case (BC) and areas-as-fleets (AAF) models for bigeye.

	2018 BC[1]	**AAF**[2]
SS Version	3.23b	3.30.12
Years and time step	Years (1975-2018) as Quarters (1-172) approach	
Ages	Max age 40 quarters (10 years)	
Sexes	2-sex model	
Length bins (data)	2 cm	10 cm
Length bins (population)	2 cm	2 cm
Area configuration	Defined in SAC 07-05a	Defined in WSBET-02-02
Fleets	27	20
Indices of abundance (LL)	2	5
Fleets with length compositions	15	13
Northern area (Hawaii) included?	Yes	No
λ Length comps	0.05	1
Includes discards?	Yes	No
Includes LL training vessel data?	Yes	No

[1] Xu *et al*. (2018); [2]This report.

TABLE 3. Likelihood values by data type for alternative bigeye tuna models in the EPO, along with growth specification and R_{shift} (the ratio of the median age-0 recruitment after 1994 (after the expansion of the FAD fishery) to the median age-0 recruitment before 1994).

	2018_Base	2018_Base_λ1	FAA	FAA_*M*	FAA_Growth	FAA_DomeLL	FAA_HistC
TOTAL_like	126.13	2363.12	4631.96	4661.02	4381.38	4207.93	4599.07
Survey_like	-400.84	-346.51	43.84	20.63	-34.63	-68.81	41.23
Length_comp_like	580.15	2725.02	4579.41	4659.54	4405.09	4289.90	4578.82
Recruitment_like	-53.19	-15.48	0.210541	-23.80	2.17	-21.80	-21.38
L_{Amin}	29.23	29.23	29.23	29.23	29.97	29.23	29.23
L_{Amax}	196.34	196.34	196.34	196.34	172.66	196.34	196.34
VonBert_*K*	0.11	0.11	0.11	0.11	0.15	0.11	0.11
Richards_par	0.23	0.23	0.23	0.23	-0.14	0.23	0.23
CV_young	1.83	1.83	1.83	1.83	1.66	1.83	1.83
CV_old	8.88	8.88	8.88	8.88	10.76	8.88	8.88
CV_young	0.06	0.06	0.06	0.06	0.06	0.06	0.06
CV_old	0.05	0.05	0.05	0.05	0.06	0.05	0.05
R_{shift}	1.47	2.03	2.28	1.35	1.69	1.35	2.28

TABLE 4. Estimates of the *MSY* (maximum sustainable yield) and its associated quantities for bigeye tuna for alternative models in the EPO. All analyses are based on average fishing mortality during 2015-2017. B_{recent} and B_{MSY} are defined as the biomass of fish 3+ quarters old (in metric tons) at the beginning of 2018 and at *MSY*, respectively. S_{recent} and S_{MSY} are in metric tons. C_{recent} is the estimated total catch in 2017. The *F* multiplier indicates how many times effort would have to be effectively increased to achieve the MSY in relation to the average fishing mortality of the last three years.

	2018_Base	2018_Base_λ1	FAA	FAA_*M*	FAA_Growth	FAA_DomeLL	FAA_HistC
MSY	95491	96048	91975	105948	91028	115648	114366
B_{MSY}	371078	350516	328816	203607	340178	501351	308234
S_{MSY}	93329	86212	80035	22815	72754	127952	63772
B_{MSY}/B_0	0.26	0.29	0.31	0.25	0.28	0.25	0.32
S_{MSY}/S_0	0.21	0.24	0.25	0.1	0.22	0.2	0.22
C_{recent}/MSY	1.15	1.06	1.04	0.9	1.05	0.82	0.83
B_{recent}/B_{MSY}	0.91	0.7	0.79	1.95	1.88	2.23	0.79
S_{recent}/S_{MSY}	1.02	0.46	0.53	2.19	1.54	1.98	0.68
F multiplier	0.87	0.57	0.52	1.45	1.19	1.79	0.82

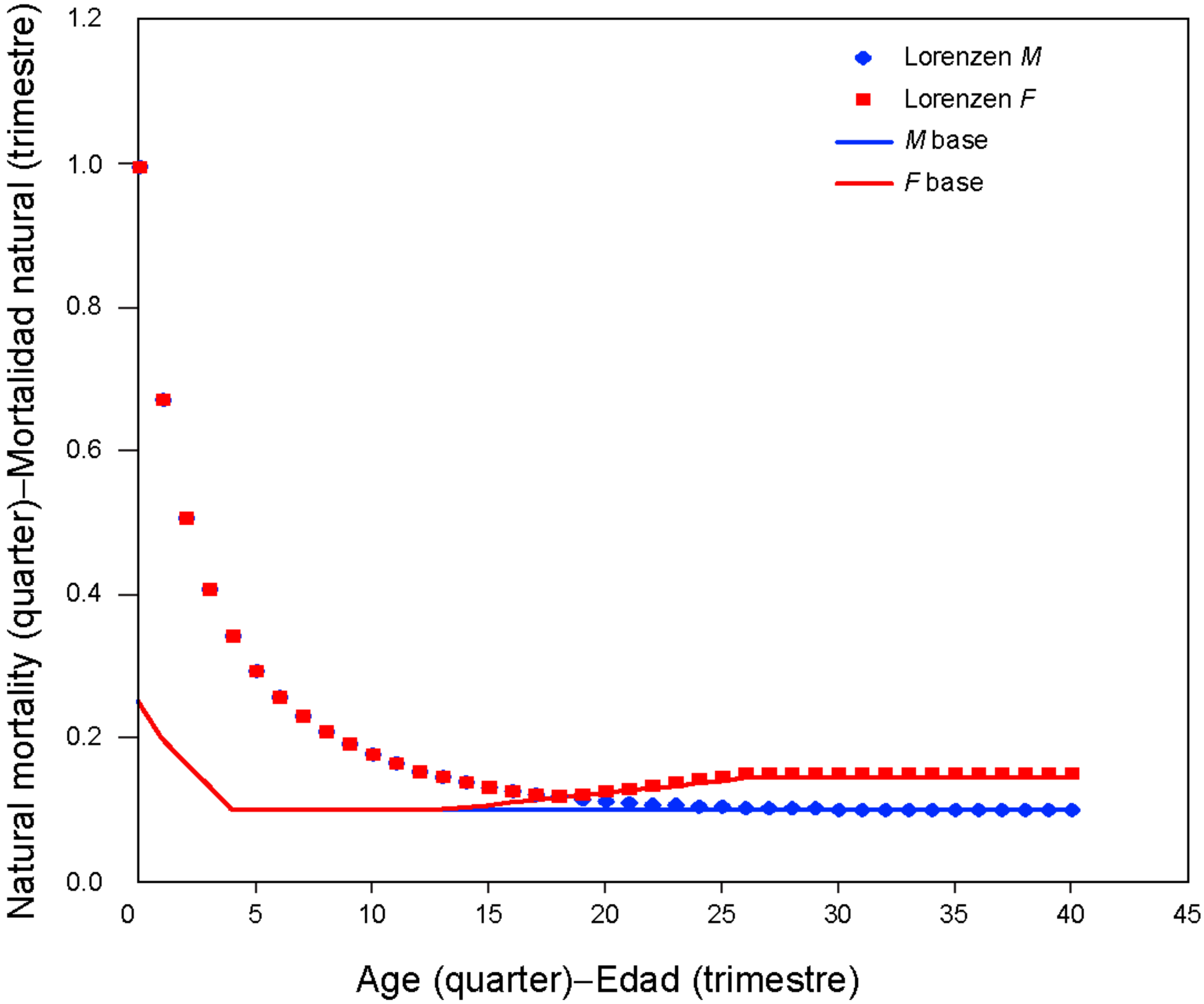

FIGURE 1. *M*-at-age pattern in bigeye tuna: *M* patterns assumed in the current assessment model for males (*M* base) and females (*F* base); and Lorenzen *M* curves.

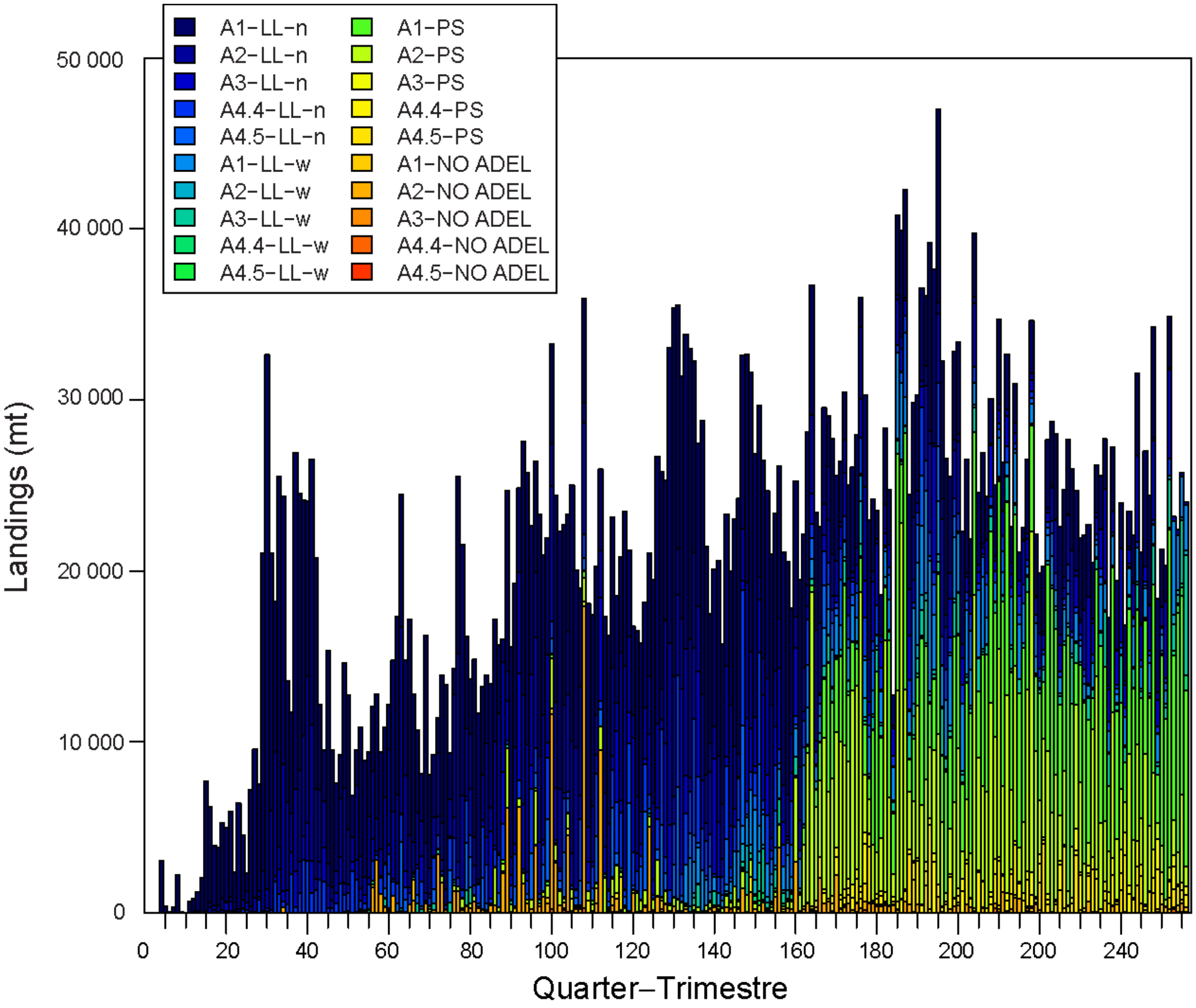

FIGURE 2. Time series of historical EPO bigeye tuna catches for all fleets by quarter implemented in the fleets-as-areas model from 1954 (quarter 0) to the last quarter of 2017 (quarter 256). For reference, non-historical models for EPO bigeye tuna start in 1974 (quarter 85).

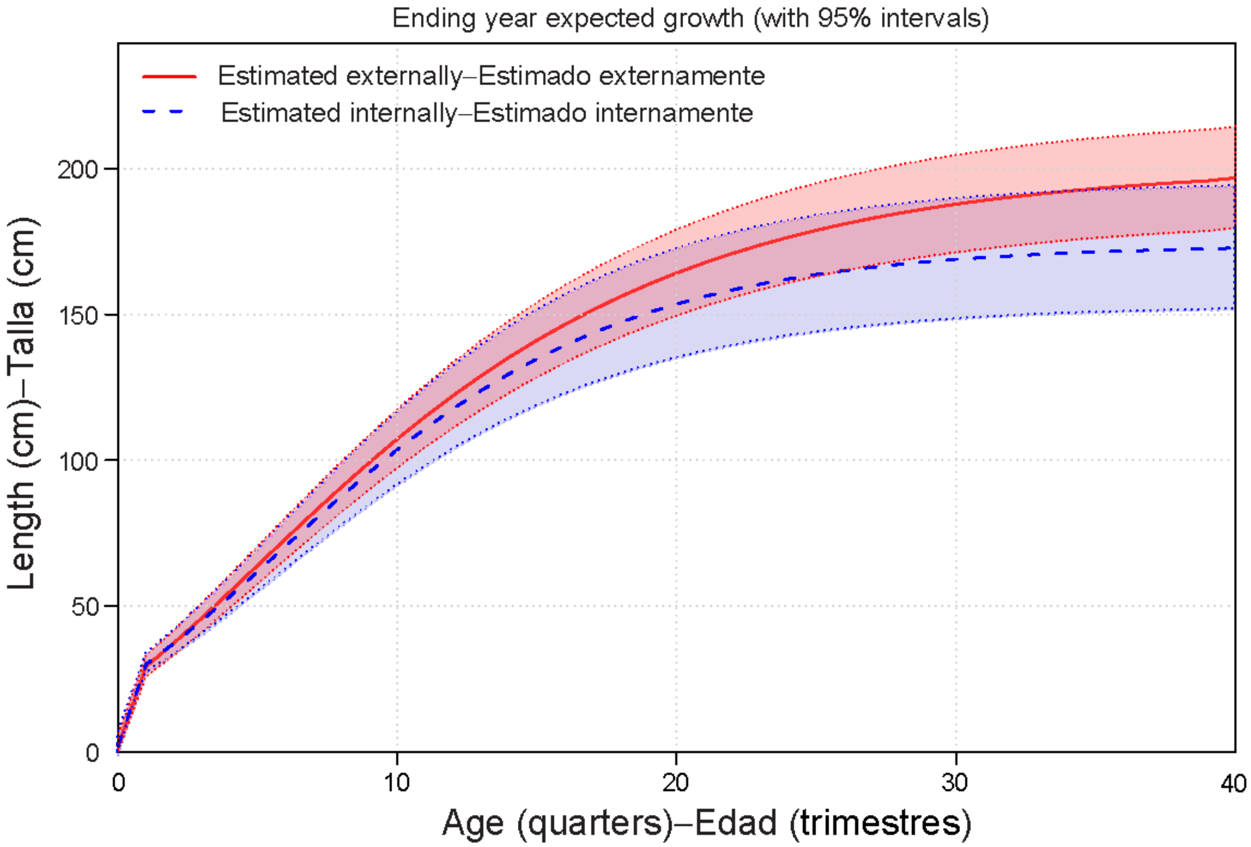

FIGURE 3. Individual growth for EPO bigeye tuna estimated externally (red lines) or internally (blue dashed lines) in the Stock Synthesis model runs.

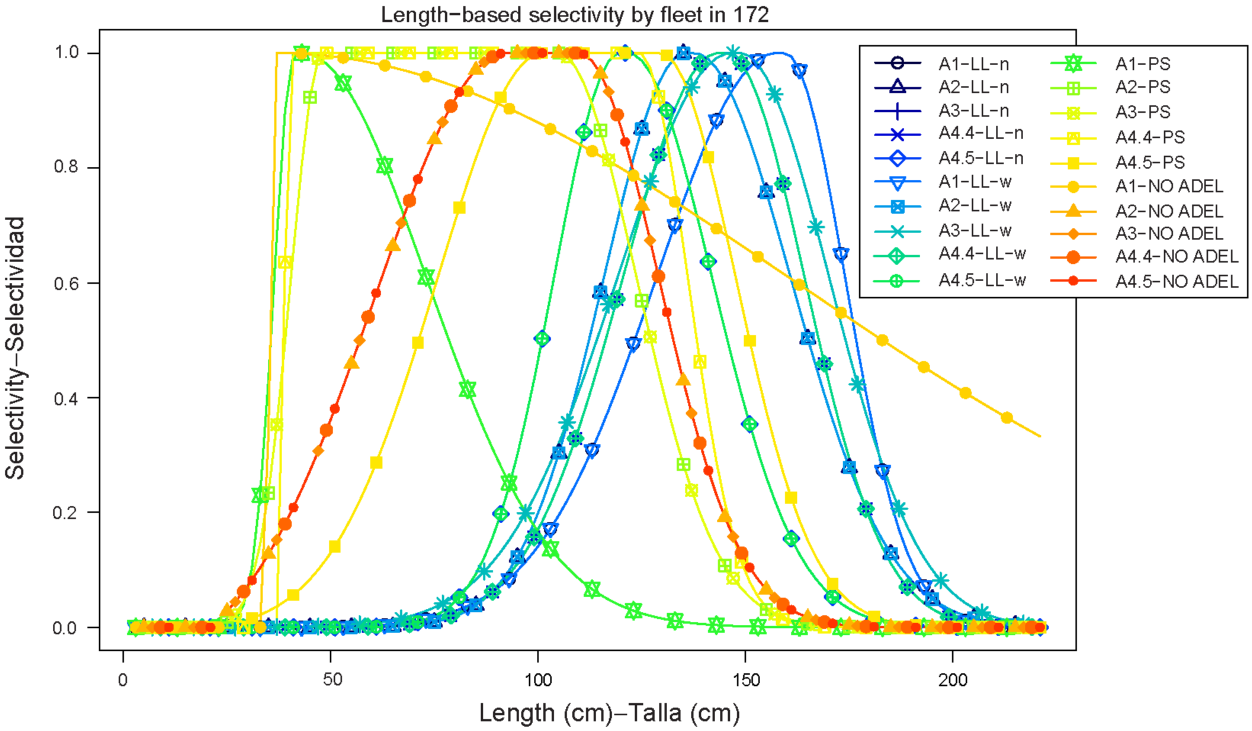

FIGURE 4. Estimated selectivities for all gears for the fleets-as-areas model estimating dome-shape selectivities.

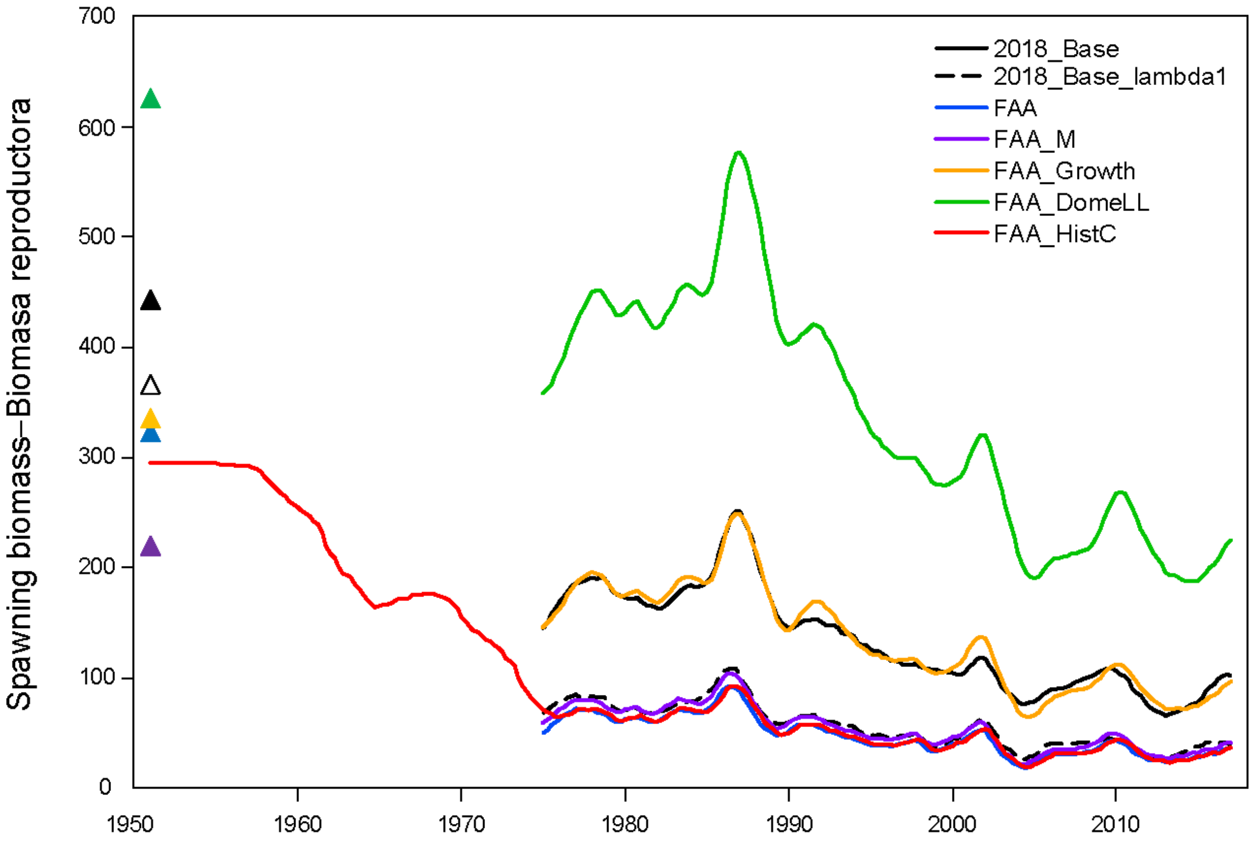

FIGURE 5. Time series of spawning biomass of bigeye tuna in the EPO estimated by the following alternative models: 2018 base case model with λ = 0.05 (2018_Base) and λ =1 (2018_Base_λ1) for the length composition data, fleet-as-areas (FAA), fleets-as-areas with Lorenzen natural mortality schedules (FAA_*M*), estimating growth in the fleet-as-areas model (FAA_Growth), estimating dome-shaped selectivities in the fleet-as-areas model (FAA_DomeLL) and fleet-as-areas with historical catches (FAA_HistC). The colored triangles represent estimates of virgin spawning biomass.

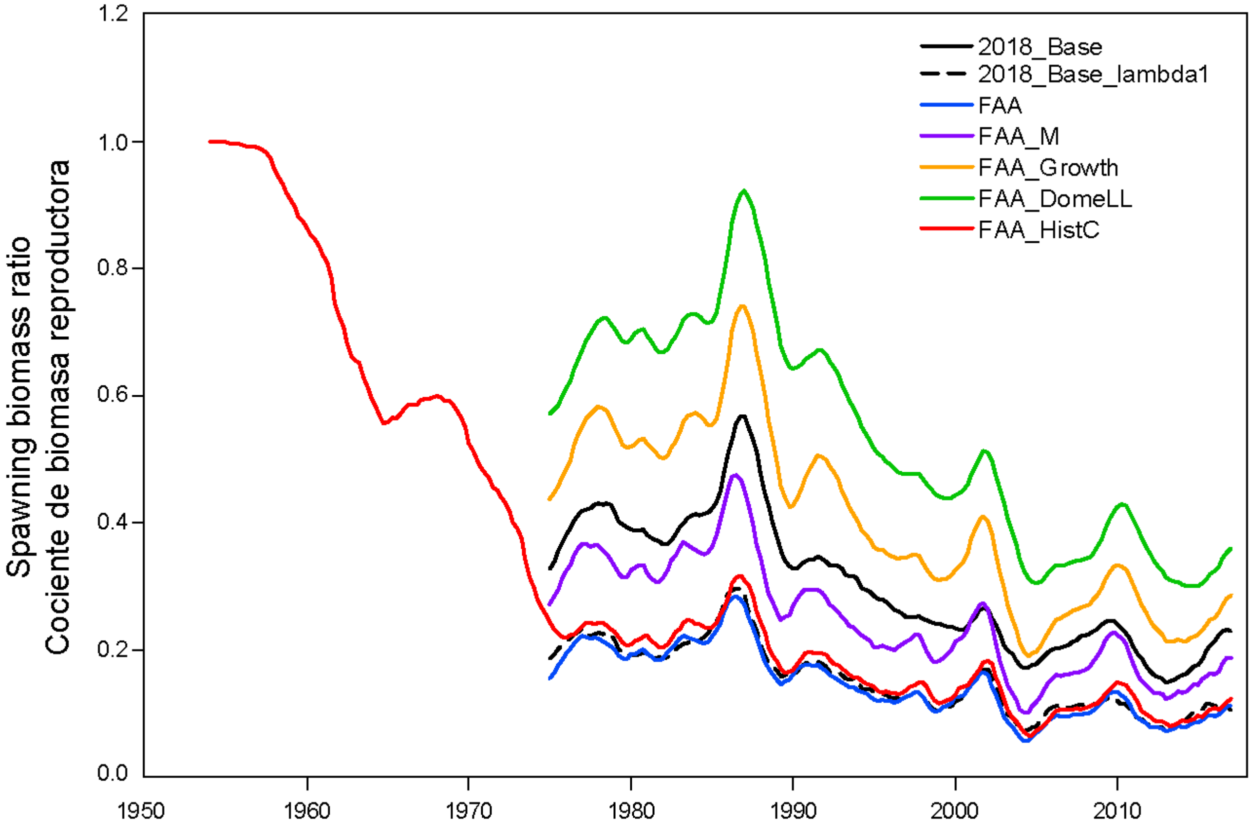

FIGURE 6. Time series of spawning biomass ratio (the ratio of current spawning biomass to virgin spawning biomass) of bigeye tuna in the EPO estimated by the following alternative models: 2018 base case model with λ = 0.05 (2018_Base) and λ =1 (2018_Base_λ1) for the length composition data, fleet-as-areas (FAA), fleets-as-areas with Lorenzen natural mortality schedules (FAA_*M*), estimating growth in the fleet-as-areas model (FAA_Growth), estimating dome-shaped selectivities in the fleet-as-areas model (FAA_DomeLL) and fleet-as-areas with historical catches (FAA_HistC).

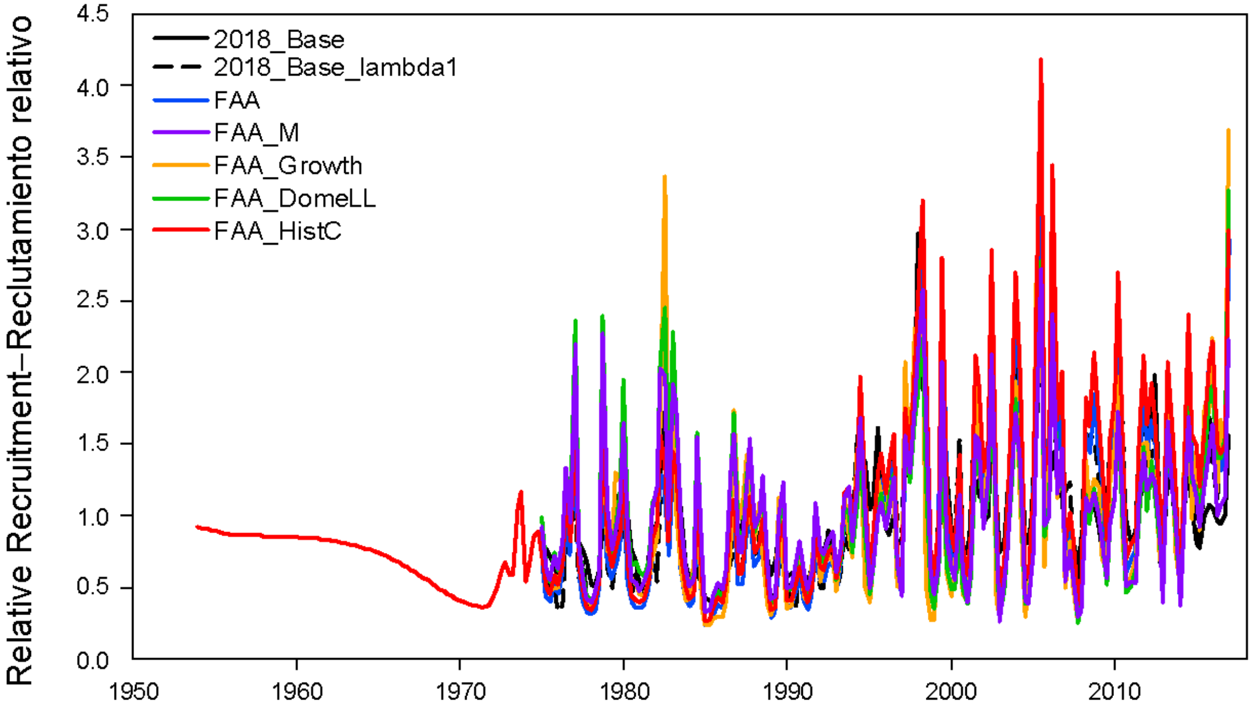

FIGURE 7. Time series of relative recruitment (divided by the average of each series) of bigeye tuna in the EPO estimated by the following alternative models: 2018 base case model with λ = 0.05 (2018_Base) and λ =1 (2018_Base_λ1) for the length composition data, fleet-as-areas (FAA), fleets-as-areas with Lorenzen natural mortality schedules (FAA_*M*), estimating growth in the fleet-as-areas model (FAA_Growth), estimating dome-shaped selectivities in the fleet-as-areas model (FAA_DomeLL) and fleet-as-areas with historical catches (FAA_HistC).

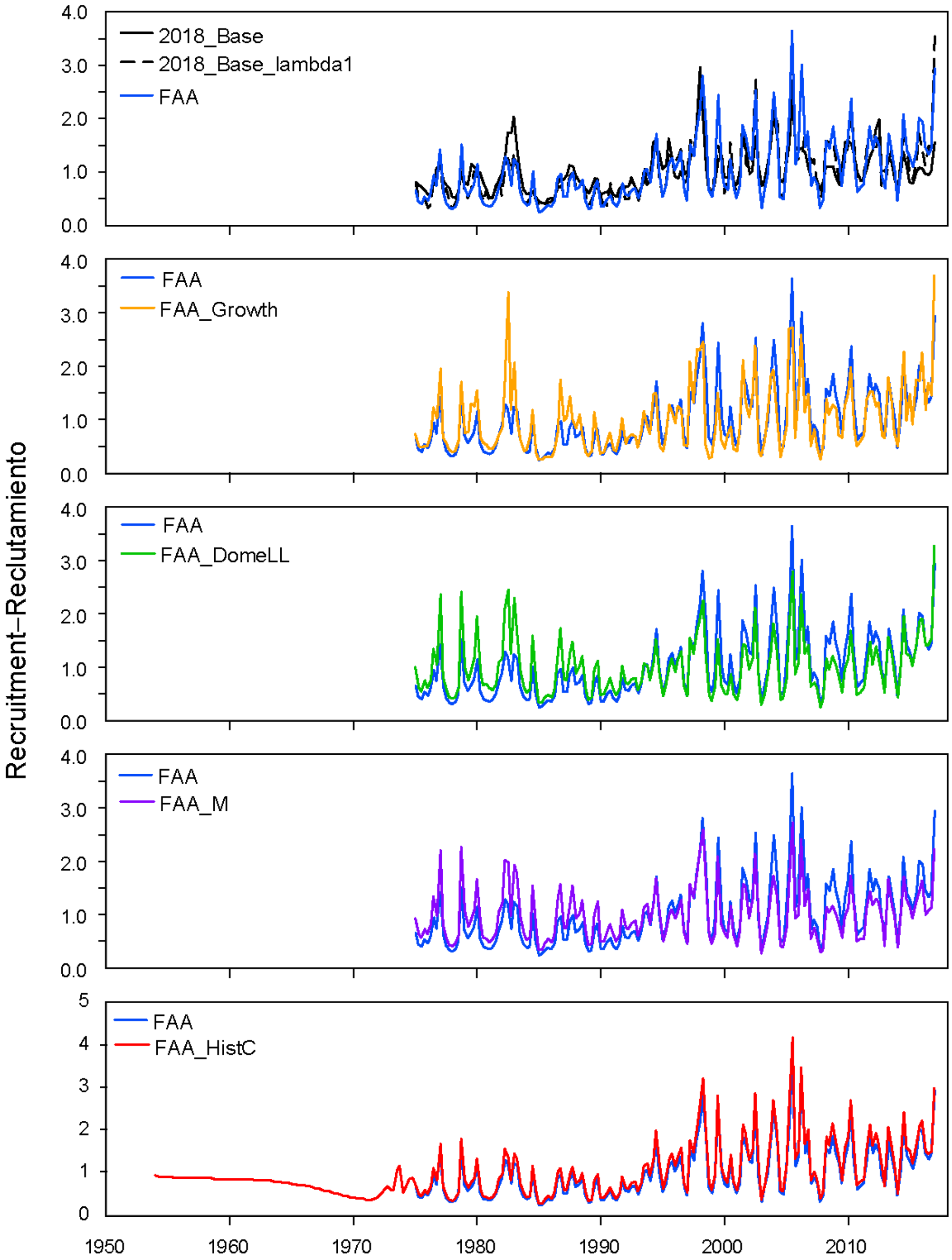

FIGURE 8. Time series of relative recruitment (divided by the average of each series) of bigeye tuna in the EPO estimated by the following alternative models: 2018 base case model with λ = 0.05 (2018_Base) and λ =1 (2018_Base_λ1) for the length composition data, fleet-as-areas (FAA), fleets-as-areas with Lorenzen natural mortality schedules (FAA_*M*), estimating growth in the fleet-as-areas model (FAA_Growth), estimating dome-shaped selectivities in the fleet-as-areas model (FAA_DomeLL) and fleet-as-areas with historical catches (FAA_HistC).