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AN EXPLORATION OF ALTERNATIVE METHODS TO DEAL WITH TIME-VARYING SELECTIVITY IN THE STOCK ASSESSMENT OF YELLOWFIN TUNA IN THE EASTERN PACIFIC OCEAN

Alexandre Aires-da-Silva and Mark Maunder

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1. ABSTRACT

All selectivity curves in the yellowfin tuna (YFT) assessment are assumed to be constant over time. While this stationary assumption seems reasonable for most fisheries in the model, it may be inappropriate for others. This is the case of the floating-object (OBJ) fisheries which show high variability in the YFT length -compositions which result from appearance, disappearance, and reappearance of strong cohorts over time. Misspecified selectivity is not desirable in any stock assessment model since it may cause retrospective patterns and biases in recent recruitments and fishing mortalities which drive management actions.

This paper investigates alternative approaches available in Stock Synthesis 3 which could be used to model time-varying selectivity in the YFT assessment. The methods vary from ignoring time-varying selectivity (the approach currently used) to a full time-varying selectivity process through quarterly changes in selectivity, or wider time-blocks which mark changes in selectivity over time. We chose the floating-object (OBJ) fisheries to illustrate the different methods.

We assume that the current retrospective pattern of recent recruitment estimates in the YFT assessment is mainly driven by a model misfit to the recent OBJ length-frequency data (small fish) caused by misspecified selectivities of the OBJ fisheries. Accordingly, we also assume that by fitting better to these data a full time-varying selectivity model provides the best (“unbiased”) description of the population dynamics. We take this model as reference for comparisons with other models but recognize that other causes for bias and retrospective pattern may exist and that a simulation study to investigate bias needs to be conducted.

A balance is needed between the amount of selectivity process (numbers of parameters) that is needed to reduce bias in the recent recruitments, and the amount of OBJ length-frequency data to be used in the model fit (full time series of data or a few terminal years only). This work indicates that allowing for time-varying selectivity (quarterly deviates) in the 5 terminal years of the assessment only while fitting to the length-frequency data available for this period is a reasonable compromise. An "average" stationary selectivity curve is applied to the early period of the assessment with no need to fit to length-frequency data for the early period. This approach seems to greatly minimize retrospective pattern and improve recent recruitment estimates and fishing mortality rates that are influential in population projection work. Improved estimates of other management quantities are also obtained (Srecent/Smsy and Fmultiplier).

2. INTRODUCTION

The stock assessment model for yellowfin tuna (YFT) in the eastern Pacific Ocean (EPO) assumes one single stock of YFT in the region, with little or no mixing with the stock(s) of the western and central Pacific. Although this model is not spatially structured, an attempt is made to account for spatial structure by considering sixteen fisheries which are spatially-defined based on the following: gear type (purse seine, pole and line, and longline), purse seine set type (sets on schools associated with floating objects, unassociated schools, and dolphin-associated schools), and IATTC length-frequency sampling area or latitude (see Table 2.1 in Aires-da-Silva and Maunder, 2012 for fishery definitions). Since these fisheries catch different sizes of YFT, the model allows for different selectivity curves acting on the YFT stock. Specifically, selectivity curves for 11 out of the 16 fisheries are estimated (one of the remaining is mirrored, i.e., set equal to another fishery that is estimated) while other four are discard fisheries with assumed selectivity curves; see page 10 on Section 4 in Aires-da-Silva and Maunder, 2012, for details).

All selectivity curves in the YFT assessment are assumed to be constant over time. While this stationary assumption seems reasonable for most fisheries in the model, it may be inappropriate for others. This is the case of the floating-object (OBJ) fisheries (F1-4). As shown in Figure 1, the length-frequency data from the OBJ fisheries are highly variable over time. The appearance, disappearance, and subsequent reappearance of strong cohorts in the length-frequency data is a common phenomenon for yellowfin in the EPO. It may indicate spatial movement of cohorts or fishing effort, limitations in the length-frequency sampling, or fluctuations in the catchability and/or selectivity of the fisheries. Bayliff (1971) observed that groups of tagged fish have also disappeared and then reappeared in this fishery, which he attributed to fluctuations in catchability and/or selectivity.

Misspecified selectivity is not desirable in any stock assessment model since it may cause retrospective patterns and biases in recent recruitments and fishing mortalities which drive management actions. A misspecification of selectivity may be related to some of the issues we have encountered with the YFT model: 1) unstable selectivity estimation for OBJ fisheries consisting of high sensitivity to initial parameter values (which have to be fixed to reasonable values for some parameters) and phases in which the parameters are estimated; 2) inability to obtain a positive definite hessian matrix for some changes in model structure (e.g., steepness assumptions); 3) long run times (4-5 hours) which may result from conflicts in the data sets due to model misspecification and are prohibitive for future planned work (spatial modeling, simulation studies, management strategy evaluation). Rather than assuming constant selectivity over time, allowing for time-varying selectivity may be necessary for some fisheries in the YFT assessment model, in particular the OBJ fisheries.

Age- or length- composition provides information about the selectivity of the gear. In contemporary statistical models that apply some version of the separability assumption - i.e., age-specific fishing mortality can be separated into an age component, the selectivity curve, and a time component - the age composition data also influence the estimates of other important model parameters. This differs from the historic methods such as VPA and cohort analysis that implicitly estimate a parameter for each age for each time period (i.e. they have fully time-varying selectivity) and the sum of the catch-at-age for a cohort adjusted by natural mortality is used to estimate recruitment. Making the separability assumption (i.e. age-specific selectivity is constant over time) or some similar assumption about age-specific fishing mortality being somewhat smooth over time, the model is implying that there is information in the age composition data about other parameters in the model. Therefore, an important question in the use of any age- or length- composition data set is whether the data provide useful information about the dynamics of the population or should it just be used to remove the catch at the right age from the population (capturing the right selectivity process)? For the YFT assessment, in particular, the question can be rephrased as : does the length-frequency data for the OBJ fisheries contain information that should be used in the assessment and how to appropriately use it in the model.

Objectives of study

This paper explores alternative approaches available in Stock Synthesis 3 (Methot, 2009) which could be used to model time-varying selectivity in the YFT stock assessment. The methods vary from ignoring time-varying selectivity (the approach currently used in the YFT assessment) to a full time-varying selectivity process through quarterly changes in selectivity, or wider time-blocks which mark changes in selectivity over time. We chose the floating-object (OBJ) fisheries to illustrate the different methods.

3. METHODS

Indices of abundance (CPUE) for OBJ fisheries are not fit in the YFT assessment model. For this reason, allowing for time-varying OBJ selectivity could be done since the extra variability explained by the time-varying process will not interfere with CPUE fitting for the same fisheries. This could help to improve the model fit to the highly variable length-frequency data and better estimate selectivity curves, hence removing catches from the "right" age/length classes. However, the YFT model has a quarterly time step and time-varying selectivity could greatly increase the number of estimated parameters. A balance is needed between how much additional process is required in the model to better capture selectivites and numbers of parameters.

To simplify the current YFT base case model and reduce number of parameters, a reduced YFT Stock Synthesis model was built in which the original four OBJ fisheries (F1-4) were lumped into a single OBJ fishery (F1 in the reduced model). To obtain the YFT length-frequencies for this new lumped fishery, the average length-frequencies across the original four OBJ fisheries were taken (weighted by the total catch of each fishery) (Figure 2).

The following alternative approaches (models types) were explored to treat time-varying selectivity in the YFT assessment:

Model 0	Ignore time-varying selectivity. Estimate a stationary "average" OBJ selectivity curve for the whole historic period of the assessment while fitting to the OBJ length-frequency data. This is the current base case approach with the only difference being that the original four OBJ fisheries and their length-frequency data having been lumped into a single fishery.
Models 1	Assume a full time-varying selectivity process. Estimate the dome-shape (double normal) OBJ selectivity curve in each time-step of the model by allowing for quarterly deviates on its four estimated (base) parameters. Fit to the length-frequency data available for the whole historic period. Grant-Thompson's (GT) method (personal communication): the coefficients of variation (CVs) for the deviates on each parameter first need to be defined and this choice is somehow

	arbitrary. GT method was applied as an attempt to use an objective criterion to define the CVs for the deviates. The method consists of a first run in which high flexibility is given to the deviates by assuming a high CV (a CV of 1 was used). The average CVs of the quarterly deviates on each parameter estimated in this run are then taken (fixed) as the best CV estimates in a second and final time-varying run.
Models 2	Assume a stationary “average” OBJ selectivity curve for the whole historic period of the assessment. Rather than fitting to the OBJ length-frequency data as in method 0, not fit to these data. The base selectivity parameters estimated in the time-varying runs (method 1) are assumed (fixed) in these runs.
Models 3	Allow for quarterly time-varying deviates in the recent period of the assessment only, which is the most influential in the management quantities (e.g., recent fishing mortalities, population projection work). The model is fit only to the length-frequency data of the recent years (the recent 3 years were taken since a 3-year average is used for management quantities, and also the 5 recent years was taken as a longer period). As for the selectivity curve for the early period, an “average” stationary OBJ selectivity is taken, which is that derived from the base parameters estimated from the length-frequency data of the recent years (time-varying deviates).
Models 4	As in models 3, allow for quarterly time-varying deviates in the recent period of the assessment only (5 years). However, more flexibility is allowed in the early period by assuming wider time-blocks of varying selectivity rather than assuming a single curve for the early period. The model is fit to length-frequency data for the whole historic period.

4. RESULTS AND DISCUSSION

We assume that the current retrospective pattern of recent recruitment estimates in the YFT assessment is mainly driven by a model misfit to the recent OBJ length-frequency data (small fish) caused by misspecified selectivities of the OBJ fisheries. Accordingly, we also assume that by fitting better to these data a full time-varying selectivity model provides the best (“unbiased”) description of the population dynamics. We take this model as reference for comparisons with other models but recognize that other causes for bias and retrospective pattern may exist and that a simulation study to investigate bias needs to be conducted.

MODEL 0: Fit to OBJ LF, estimate stationary selectivity

Model 0 differs from the YFT base case model in having defined one rather than four OBJ fisheries. The original four OBJ fisheries have been lumped into a single fishery in this reduced model (and all other models ahead), thus fitting to a single time series of OBJ length-frequency data. As in the base case model, a stationary OBJ selectivity is estimated.

The estimated dome-shape (double normal) selectivity curve for the OBJ fishery in model 0 (OBJ-lumped) is very similar to the selectivity curve of F3 (OBJ-SAC3) in the base case model (Figure 3a). This is not surprising since the majority of the OBJ catch takes place in the central area (F3 in the base case) and a weighted average (weighted by the total catch of each fishery) was used to estimate the lumped OBJ size-frequency distributions.

It seems that, on average, model 0 is removing the YFT OBJ catch out of the right modal length distribution (Figure 3b). However, there is residual pattern in the model fit to the OBJ length-frequency data. Specifically, the model underestimates the proportions of the smaller fish (filled circles at lengths less than 60 cm) for most of the historic period, as well as underestimates the proportions of some medium to large fish (100-160 cm), but in the second half of the period only (Figure 3c). This pattern supports that there is a strong time-varying selectivity process in the YFT model that is missed while assuming stationary OBJ selectivity.

In terms of management quantities, most of the quantities were robust to the lumping of the four OBJ fisheries. However, the F multiplier (Fmsy/Fcurrent) slightly increased from the base case estimate of 1.15 to 1.20 in the reduced model 0 (Table 2).

MODELS 1: Fit to all OBJ LF, estimate quarterly time-varying selectivity

In models type 1, a full time-varying selectivity process was allowed by estimating quarterly deviates while fitting to the length-frequency data available for all the historic period.

We found two models which could be considered to develop a full-time varying selectivity approach for YFT. This is probably due to local optima on the likelihood surface. In the first model, the base parameter 2 (P2) which defines the width of the plateau of the double normal curve was estimated at a very low value of -14 (logistic space). As a result, the estimated OBJ selectivity curve descends right after reaching its peak and shows no plateau. Estimating the quarterly deviates around this extremely low base parameter (-14) will make little difference in this absence of a plateau pattern. To avoid numerical issues and convergence problems with the full time-varying approach, we kept the P2 base parameter fixed at -15 and did not estimate deviates on this parameter. Below in this report, we refer to this model 1 configuration as “M1-P2fixed”. The alternative model configuration is obtained by estimating P2 at a later phase and had a relatively large plateau. Therefore, the deviates on the P2 parameter were estimated (“M1-P2est”).

The CVs derived from Grant Thompson’s method (personal communication) used to estimate the quarterly deviates on the selectivity parameters are shown below.

Parameter	M1-P2fixed	M1-P2est
P1 - peak	0.13	0.14
P2 - top	Fixed	1.08
P3 - ascending	0.55	0.51
P4 - descending	1.03	0.41

The shape of the selectivity curves varied greatly for both model types when a quarterly time-varying process was allowed (Figure 4a-d). This is not surprising given the variability observed in the OBJ size-frequency data (Figure 2).

As for model 0, both quarterly time-varying selectivity models seem to be removing the YFT OBJ catch from the right modal length distribution, on average (Figures 4e-f). Not surprisingly, the time-varying selectivity process improved the length-frequency residual pattern. Specifically, the residual pattern became more evenly distributed over time and length when compared to the results of model 0 (Figure 4 g-h). There was great improvement in model fit over the time-invariant model (479 and 469 likelihood units for M1-P2fixed and M1-P2est, respectively). Most of this improvement went to the fit to the length-frequency data (Table 1a). The time-varying model in which P2 was fixed (M1-P2fixed) provided a slightly better likelihood (9 likelihood units better) than that in which P2 was estimated to allow for a plateau (M1-P2est) despite the later having more parameters.

When compared to the YFT base case model (SAC3) and the reduced time-invariant model 0, absolute management quantities (MSY, Bmsy, Smsy) and management quantities relative to virgin conditions (Bmsy/B0, Smsy/B0) were robust to the time-varying selectivity assumption (Table 2a). In contrast, management quantities that depend on recent conditions (Crecent/msy, Brecent/Bmsy, Srecent/Smsy, and the F multiplier) were moderately sensitive to the time-varying assumptions (Table 2a). Srecent/Smsy was at about 0.90 for both time-variant models 1, which is lower than the values estimated in the YFT base case model (1.0) and the reduced time-invariant model 0 (1.07). Likewise, the Fmultipler was estimated to be lower for both time-varying models 1 (1.07 and 1.05), estimates that a lower than the base case and reduced model 1 (1.15 and 1.20). These results indicate that Srecent/Smsy and Fmultiplier, the two management quantities which are used to define current stock status on the "Kobe plot" may be underestimated for the EPO yellowfin tuna assessment if the "right" OBJ selectivity curves are not estimated, particularly in the terminal years of the assessment.

A great disadvantage of the time-varying selectivity models is number of estimated parameters which increased from 201 (model 0) to 644 (M1-P2fixed) and 793 (M1-P2est). We found no problems with both models 1 while inverting the hessian matrix.

MODELS 2: No fit to OBJ LF, stationary selectivity fixed at base selectivity parameters from Models 1

Although the quarterly time-varying selectivity models (M1) provided great improvement in the model fit to the YFT length composition data, their longer run times and high numbers of parameters seem prohibitive for future work (up to approximately 800 parameters). One alternative is to take the results from models 1 as external and use them as fixed selectivity assumptions in a reduced model. In particular, to use the "average" base selectivity parameters of the full time-varying runs as fixed parameters (Figure 5a-b), and not fit to OBJ length-frequency data. The rationale beyond this approach is to just remove catch with the best "average" selectivity curve and not let the length-frequency data influence the other model parameters. The selectivity was taken from the model in which the full time-varying process was allowed, thus providing the best correspondence to the length-frequency data (Models 1).

Although these models were not fit to the OBJ length-frequency data, these data are in the model so that expected values can be compared to observations. There was deterioration on the average fit to the length-frequency data, particularly for medium to large fish in the tail of the distributions (Figure 5c-d). There is also prominent positive residual pattern in the length-frequencies over time, particularly in the second half of the historic period (Figure 5e-f). Total and length data likelihood comparisons with other models cannot be made since these models are not fitting to the length-frequency data. Comparisons can be made across other data components to check for potential conflicts between the the OBJ length-frequency data and other data. No major conflicts were found. When compared to the time-varying models 1, there was an improvement of 19 and 5 likelihood units only in the model fit to the CPUE data for models M2-P2fixed and M2-P2est, when the OBJ length-frequency data was not fitted.

When compared to the YFT base case model (SAC3) and the reduced M0 time-invariant model, absolute management quantities (MSY, Bmsy, Smsy) and management quantities relative to virgin conditions (Bmsy/B0, Smsy/B0) were robust to the time-varying selectivity assumption (Table 2b). In contrast, management quantities that depend on recent conditions (Crecent/msy, Brecent/Bmsy, Srecent/Smsy, and the F multiplier) were moderately sensitive to the time-varying assumptions (Table 2b). Regardless of the of residual pattern in the size-frequency data obtained for models 2, both S/Smsy and the Fmultiplier were closer to those estimated from the time-varying model runs (model1) than the base case and model 0.

Models 3: Fit to OBJ LF from terminal years only, full time-varying selectivity in terminal years only, stationary selectivity in early period,

One argument to consider may be that the management quantities are mainly driven by the recent mix of selectivites operating in the fishery. Selectivity misspecification in the terminal years may lead to retrospective biases in recent recruitments which could bias population projection work and related management quantities (catch limits and recent depletion levels). Most importantly in the case of YFT, it may bias estimates for the recent fishing mortalities and the corresponding Fmultiplier (Fmsy/Fcurrent) which drives management in the EPO. It seems reasonable to argue that as long as a reasonable "average" selectivity curve is taken for the early historic period, it is most important to get selectivity "right" in the terminal period of the assessment. Therefore, a time-varying approach (with quarterly deviates) applied to the terminal years only could be an option. Based on the full time-varying runs (M1-P2fixed and M1-P2est; see Models 1 above), we applied this methodology by allowing time-varying selectivity in the last 3 years (a 3-year average is considered for the Fmultiplier calculations) and a longer period of 5 years. The model is fit only to the length-frequencies in these terminal years. The early "average" selectivity is that resulting from the base selectivity parameters estimated while fitting to these recent data.

Only the runs based on the time-varying model in which P2 was fixed (M3-P2fix) converged. Likelihood comparisons between the two type-3 model fits to the length-frequency data for the most recent 3 and 5 years (M3-P2fix-3yr and M3-P2fix-5yr, respectively) should not be made since the size-composition data used in the model fit are different. Same for comparisons with other model types presented above. The selectivity curves estimated for each model type are shown on Figures 6a-d. The average model fit to the length-frequency data seems reasonable (Figures 6e-f). The residual pattern is not prominent over the terminal period of length-frequency data used in the model fit (Figure 6g-h).

Allowing for time-varying selectivity only in the last 3 years of the assessment resulted in management quantities which are very similar to those obtained from the current base case and the time-invariant Model 0. Most noticeable, Fmultiplier is at 1.14 and 1.15 for M3-P2fix-3yr and the base case, respectively (Table 2c). Extending the time-varying selectivites to 5 terminal years resulted in management quantities that are closer to those derived from the full time-variant selectivity approach (Model 1). In particular, Srecent/Smsy is at 0.86 and 0.90 for M3-P2fix-5yr and M1-P2fix, respectively, while the Fmultiplier is at 1.03 and 1.07 for M3-P2fix-5yr and M1-P2fix, respectively (Table 2c). These results suggest that better estimates of the management quantities may be obtained without the need to allow for a full time-varying selectivity process. Rather, this flexibility may only be needed for the terminal period of the assessment as long a reasonable "average" selectivity curve is used for the early period. Such approach would also allow for a reduced number of parameters which is desired. There may be a tradeoff in the number of terminal years of length-frequency data needed to be included in the model fit. A certain number of years may be needed to estimate a standard deviation, so that the precision of the standard deviation for the deviate penalty might be low if a lesser number of years is used. From our exploratory analysis, a 5-year terminal period seems reasonable to apply this approach in the YFT tuna assessment.

Models 4: Estimate full time-varying selectivity in terminal years only, estimate time-blocks of selectivity in early period, fit to OBJ LF data from terminal years only

Finally, another alternative type of model would be to allow more flexibility in the OBJ selectivity within the early period of the assessment without the need to assume a full time-varying process (quarterly deviates). This is done by taking a few wider selectivity time-blocks within the early period. The terminal period is treated in the same way as in models 3 (quarterly deviates). The model fits to all OBJ length-frequency data since selectivity parameters for the early time-blocks are estimated in addition to the terminal time-varying selectivites. To illustrate the approach, a model type 4 was build based on Model3-

P2fixed-5yrs described above. A total a 5 time-blocks were defined in the early period based on visual inspection of the selectivity estimates from the full time-varying runs (Figures 4c-d).

Assuming a few time-blocks of time-varying selectivity provided more flexibility in the OBJ selectivity operating in the early period without the need for a full time-varying process (Figure 7a,b). As expected, the quality of the model fit is intermediate between the stationary selectivity model (Model 0) and the full-time varying model (Model 1-P2fixed) (Table 1d). The average model fit to the OBJ length-frequencies and residual pattern is also satisfactory (Figures 7c,d).

A critical question to be addressed about the use of this approach is if there is any gain in terms of the management quantity estimates from additional selectivity process (time-blocks) in the model. Srecent/Smsy and the Fmultiplier are only slightly closer to the same estimates provided by the full time-varying models, than those obtained from Model3-P2fixed-5yrs fitting only to the 5 terminal years of length-data in a fully time-varying fashion. To conclude - Model type 3 seems to provide a reasonable approximation on the YFT management quantities without the need for additional selectivity process in the model.

Impact of recent recruitment estimates on population projections

The time series of YFT recruitments and biomasses estimated from the different time-varying selectivity methods explored in this paper are shown on Figure 8. The scale of the assessment (defined by R0) was not affected by the use of different methods. Although recruitment trends are very similar for most of the historic period among models, recent recruitment estimates are greatly affected by different treatments of selectivity (Figure 8a). These differences are explained by better fit to the OBJ length-frequency data leading to improved (lower) recent recruitment estimates, while allowing for time-varying selectivity (Figure 9).

A major concern related to the misspecification of selectivity is retrospective pattern and biased estimates of the recent recruitments which are propagated into population projection work. In fact, such pattern has been identified in the YFT assessment (and also for bigeye tuna), and this seems to result in overly optimistic population projections, particularly in the short- to medium-term. A sensitivity analysis excluding the size-frequency data for the OBJ fishery from the assessment lowered the most recent recruitment and biomass estimates. It also removed the retrospective pattern of recent recruitment and biomass being estimated higher (see Maunder and Aires-da-Silva on review of sensitivities at this workshop).

We analyzed the impact of misspecified selectivity on recent YFT recruitment estimates and spawning biomass projections. This analysis is solely used to highlight the influence of the differences in recruitment on projections and therefore uses the same values for the other model parameters from the current YFT base case model. It does not illustrate the difference in forecasts based on the different selectivity assumptions because the non-recruitment parameters are not from the model with the respective selectivity assumption. We ran population forecasts while taking the time series of historic recruitment anomalies (deviates) estimated from the time-varying selectivity models explored in this paper: full quarterly time-varying (deviates) model (Model 1); quarterly time-varying models for last 3 and 5 years only (Models 3); and 5 historic time-blocks of selectivity in addition to the quarterly time-varying selectivity for last 5 years (Model 4). The main question to be answered from this analysis being how much time-varying selectivity process is needed in the model to obtain “good” estimates for the recent recruitments and population projections. For comparisons, we take the recruitment estimates from the full time-varying model approach (Model 1) as the best estimates among methods and reference.

The recent recruitment estimates provided by the current YFT base case model which assumes stationary selectivity are positively biased (Figure 10a). When these estimates are used for population forecasting, they result in a rapid and overly optimistic population rebuilding trend in the short-term (Figure 10b).

One model allowed for quarterly time-varying selectivity (deviates) in the last 3 years of the assessment (M3-P2fix_3yrs). Not surprisingly, the recruitment estimates obtained for these last 3 years are very close to those from the full time-varying model 1 (Figure 10a). However, using 3 years only for the terminal time-varying period seems short as earlier recruitment estimates are positively biased resulting in a similar rapid rebuilding trend as seen for the base case model (Figure 10b).

A longer (5-year) terminal period of time-varying selectivity resulted in recent recruitment estimates that are very similar to those produced by the full time-varying model 1 (Figure 10a). This is also valid for the adjacent years before the 5-year terminal period. The later result indicates that a longer time-varying terminal period may also be needed to better estimate the base selectivity parameters from which terminal deviates are based upon, and used to define the stationary selectivity curve applied to the early period. A 5-year terminal period of time-varying selectivity seems reasonable for YFT. In fact, the overly-optimistic rebuilding pattern is minimized with this approach providing population rebuilding trends that are very similar to those obtained from the full time-varying model (Figure 10b).

Model 4 allowing for selectivity time-blocks in the early period resulted in lower spawning biomass levels than all other runs (Figure 10b). This is due to slightly lower recruitments estimated in the early historic period (Figure 8a). The relative trend in SBR is similar to the full time varying selectivity model indicating that this model more accurately estimates recent recruitments.

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Table 1. Likelihoods by data component for each model run.

a) MODELS 0 and 1

	Model 0	MODEL 1 CONFIGURATION	
		M1-P2fixed	M1-P2est
Fit to OBJ LF	Yes, all period	Yes, all period	Yes, all period
Base sel params	Estimated	Estimated	Estimated
Devs	No	Yes, all qrts	Yes, all qrts
LIKELIHOOD COMPONENT			
TOTAL	7636.06	7156.94	7166.44
Catch	0.0053679	0.005368	0.00536794
Survey	-143.156	-157.596	-159.758
Length_comp	7784.19	7199.92	7215.39
Recruitment	-4.98712	-6.02737	-6.11765
Parm_softbounds	0.00778615	0.00638726	0.00607614
Parm_devs	0	120.63	116.919

b) MODELS 2

	MODEL 2 CONFIGURATION	
	M2-P2fixed	M2-P2est
Fit to OBJ LF	No	No
Base sel params	Fixed to base M1a	Fixed to base M1b
Devs	No	No
LIKELIHOOD COMPONENT		
TOTAL	5956.61	5953.90
Catch	0.01	0.01
Survey	-162.30	-162.55
Length_comp	6129.17	6126.71
Recruitment	-10.28	-10.28
Parm_softbounds	0.00	0.00
Parm_devs	0.01	0.01

c) MODELS 3

	MODEL 3 CONFIGURATION	
	M3-P2fixed-3yrs	M3-P2fixed-5yrs
Fit to OBJ LF	Yes, last 3 yrs	Yes, last 5 yrs
Base sel params	Estimated	Estimated
Devs	Yes, last 3 yrs	Yes, last 5 yrs
LIKELIHOOD COMPONENT		
TOTAL	6112.23	6218.83
Catch	0.01	0.01
Survey	-158.65	-161.58
Length_comp	6277.55	6373.07
Recruitment	-9.60	-9.63
Parm_priors	0.00	0.00
Parm_softbounds	0.01	0.01
Parm_devs	2.92	16.95

d) MODELS 4

	M4-5 tblocks
Fit to OBJ LF	Yes, last 5 yrs
Base sel params	Estimated
Devs	Yes, last 5 yrs
Time blocks early period	5 time blocks
LIKELIHOOD COMPONENT	
TOTAL	7446.08
Catch	0.00536796
Survey	-149.409
Length_comp	7587.71
Recruitment	-8.12982
Parm_priors	0.00E+00
Parm_softbounds	0.00649136
Parm_devs	15.894

Table 2. Management quantities obtained for each model run.

a) MODELS 0 and 1

		Model 0	MODEL 1 CONFIGURATION	
	SAC3		M1-P2fixed	M1-P2est
Fit to OBJ LF	Yes	Yes, all period	Yes, all period	Yes, all period
Base sel params	Estimated	Estimated	Estimated	Estimated
Devs	No	No	Yes, all qrts	Yes, all qrts
MANAG QUANT				
msy	262,642	262,852	255,597	260,027
Bmsy	356,682	348,836	353,123	348,560
Smsy	3,334	3,208	3,304	3,203
Bmsy/Bzero	0.31	0.31	0.31	0.30
Smsy/Szero	0.26	0.25	0.25	0.25
Crecent/msy	0.79	0.78	0.81	0.79
Brecent/Bmsy	1.00	1.04	0.87	0.91
Srecent/Smsy	1.00	1.07	0.90	0.91
Fmultiplier	1.15	1.20	1.07	1.05

b) MODELS 2

	MODEL 2 CONFIGURATION	
	M2-P2fixed	M2-P2est
Fit to OBJ LF	No	No
Base sel params	Fixed to base M1	Fixed to base M1
Devs	No	No
MANAG QUANT		
msy	258,022	257,813
Bmsy	354,793	351,689
Smsy	3,341	3,279
Bmsy/Bzero	0.31	0.31
Smsy/Szero	0.26	0.26
Crecent/msy	0.8	0.8
Brecent/Bmsy	0.8	0.8
Srecent/Smsy	0.82	0.82
Fmultiplier	1.02	1.02

c) MODELS 3

	MODEL 3 CONFIGURATION	
	M3-P2fixed-3yrs	M3-P2fixed-5yrs
Fit to OBJ LF	Yes, last 3 yrs	Yes, last 5 yrs
Base sel params	Estimated	Estimated
Devs	Yes, last 3 yrs	Yes, last 5 yrs
MANAG QUANT		
msy	261,728	257,126
Bmsy	350,789	351,377
Smsy	3,278	3,273
Bmsy/Bzero	0.32	0.31
Smsy/Szero	0.26	0.25
Crecent/msy	0.79	0.8
Brecent/Bmsy	0.99	0.84
Srecent/Smsy	0.99	0.86
Fmultiplier	1.14	1.03

d) MODELS 4

	M4-5 tblocks
Fit to OBJ LF	Yes, last 5 yrs
Base sel params	Estimated
Devs	Yes, last 5 yrs
Time blocks early period	5 time blocks
MANAG QUANT	
msy	253,903
Bmsy	345,549
Smsy	3,191
Bmsy/Bzero	0.3
Smsy/Szero	0.25
Crecent/msy	0.81
Brecent/Bmsy	0.89
Srecent/Smsy	0.91
Fmultiplier	1.09

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FLOATING OBJECT FISHERIES (OBJ)

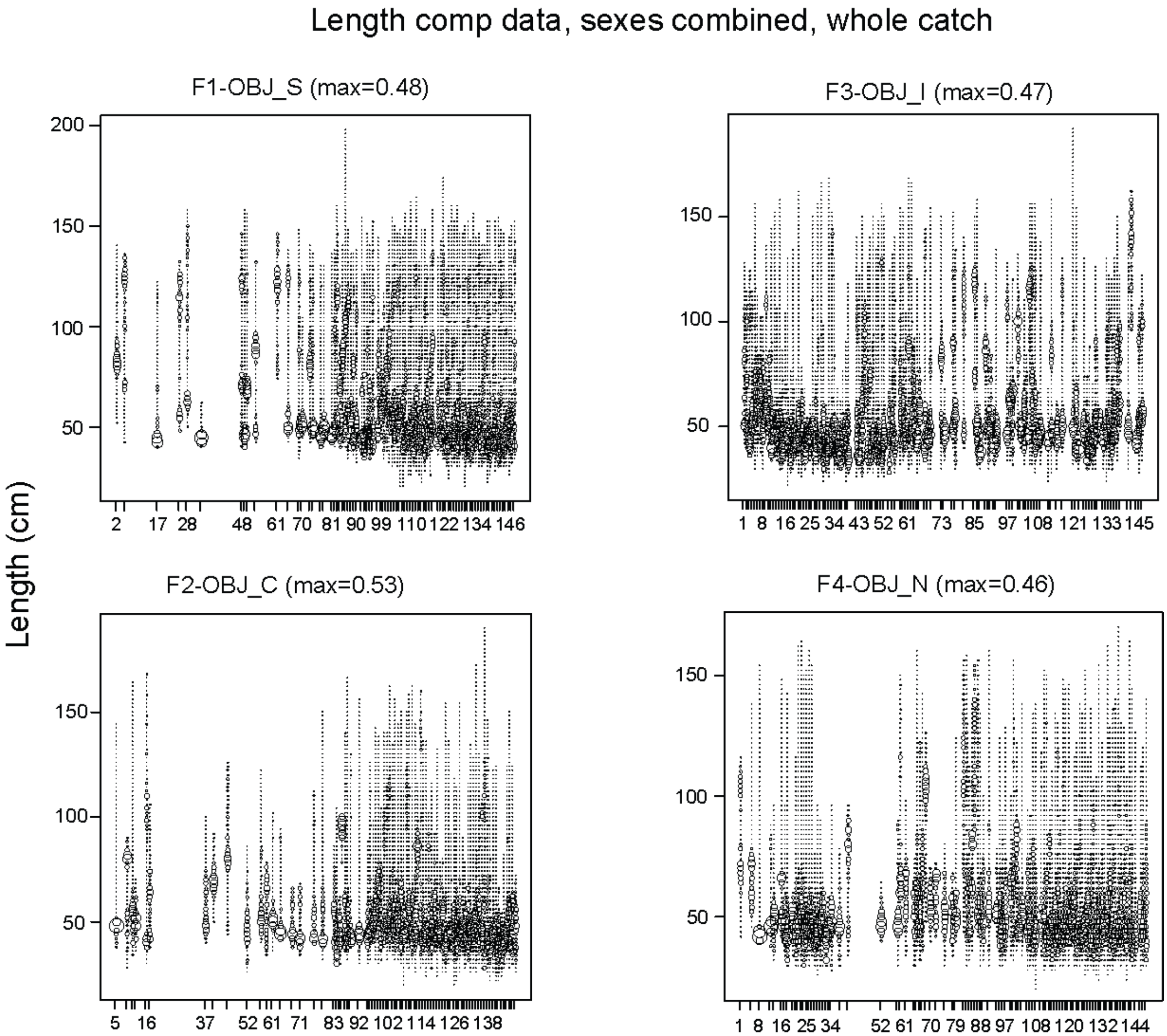

Figure 1. Observed length-frequencies of the quarterly catches of YFT taken by the floating-object (OBJ) fisheries (F1-4), as defined in the base case model (Aires-da-Silva and Maunder, 2012). The areas of the circles are proportional to the catches.

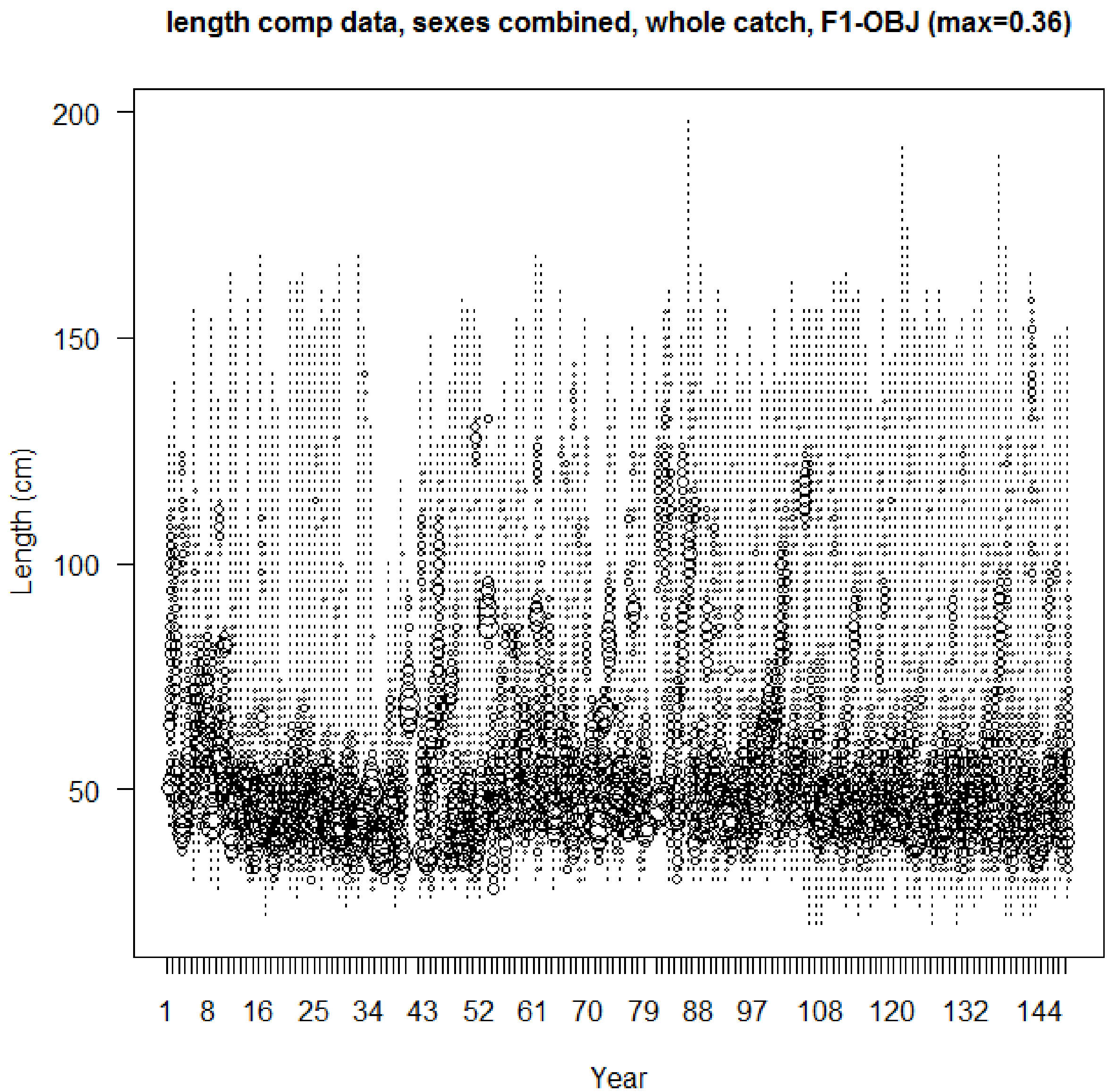

Figure 2. Observed length-frequencies of the quarterly catches of YFT taken by the lumped floating-object (OBJ) fishery (F1), as defined in the reduced model constructed for this paper. The areas of the circles are proportional to the catches.

MODEL 0: Fit to OBJ LF, estimate stationary selectivity

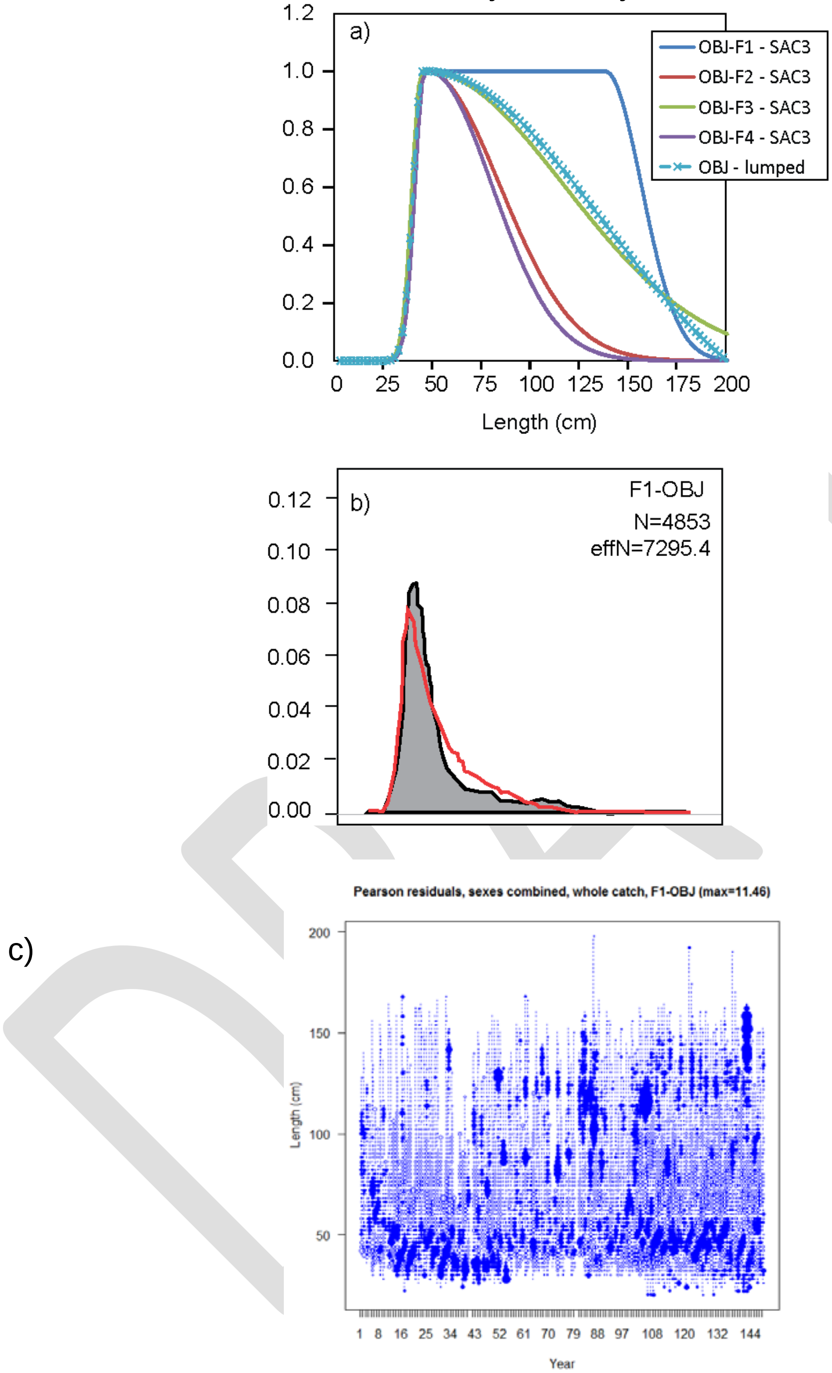

Figure 3. Results from Model 0: a) Selectivity curves estimated for the OBJ fisheries (F1-4) by YFT base case model, and for the lumped OBJ fishery assumed in model 0 (OBJ-lumped); b) Average observed (shaded area) and predicted (curves) length-frequency distributions of the YFT catches taken by the OBJ fishery in model 0; c) Pearson residual plots for the model fits to the length-frequency distributions for the OBJ fishery in model 0. The filled and open circles represent observations that are higher and lower, respectively, than the model predictions.

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MODELS 1: Fit to all OBJ LF, estimate quarterly time-varying selectivity

M1-P2fixed M1-P2est

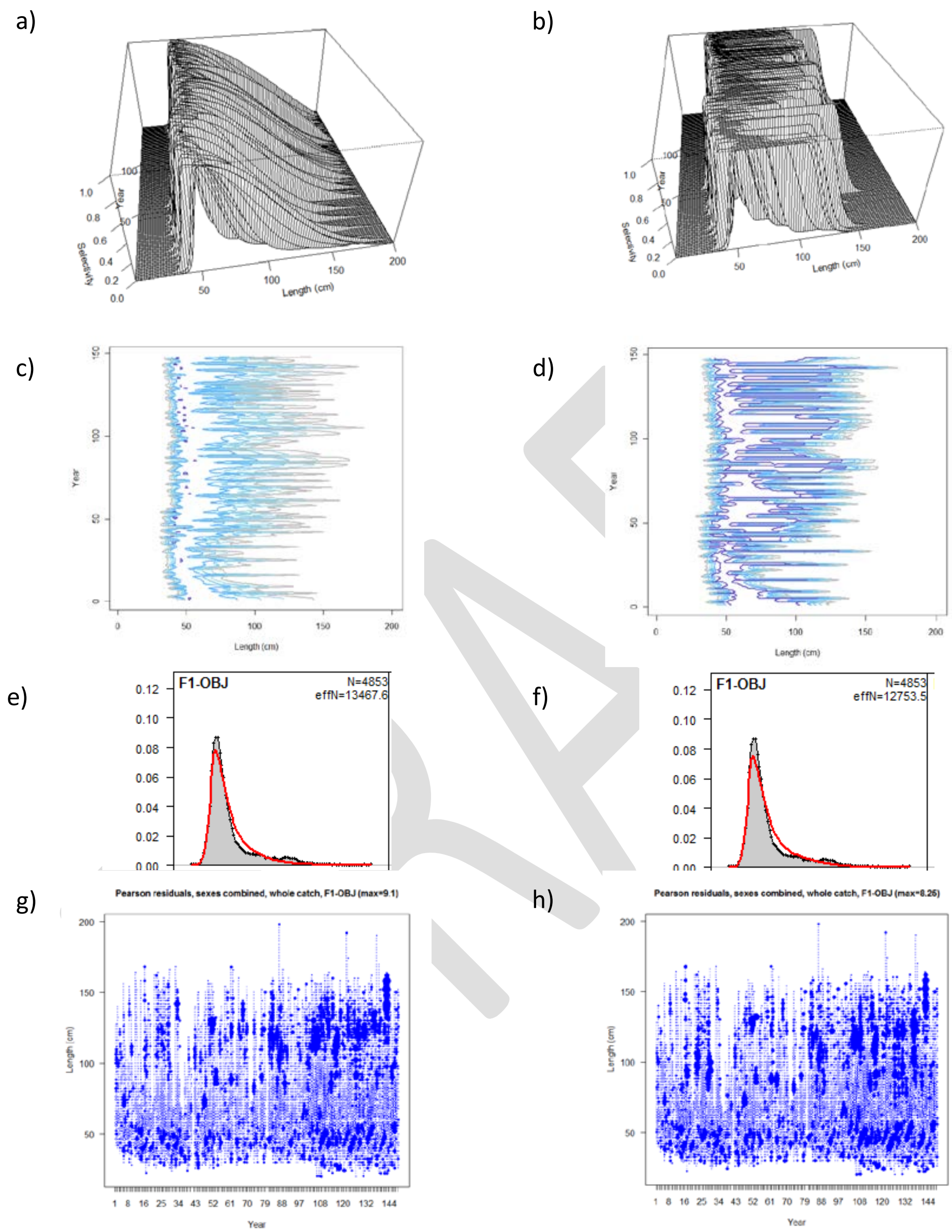


Figure 4. Results from Models 1: M1-P2fixed (left) and M1-P2est (right). a and b) Quarterly time-varying OBJ selectivity curves; c and d) selectivity isoclines for 0.2, 0.4, 0.6, 0.8 and 1.0; e-f) Average observed (shaded area) and predicted (curves) length-frequency distributions of the YFT catches taken by the OBJ fishery; g and h) Pearson residual plots for the model fits to the length-frequency distributions for the OBJ fishery. The filled and open circles represent observations that are higher and lower, respectively, than the model predictions.

MODELS 2: Fit to all OBJ LF, estimate quarterly time-varying selectivity

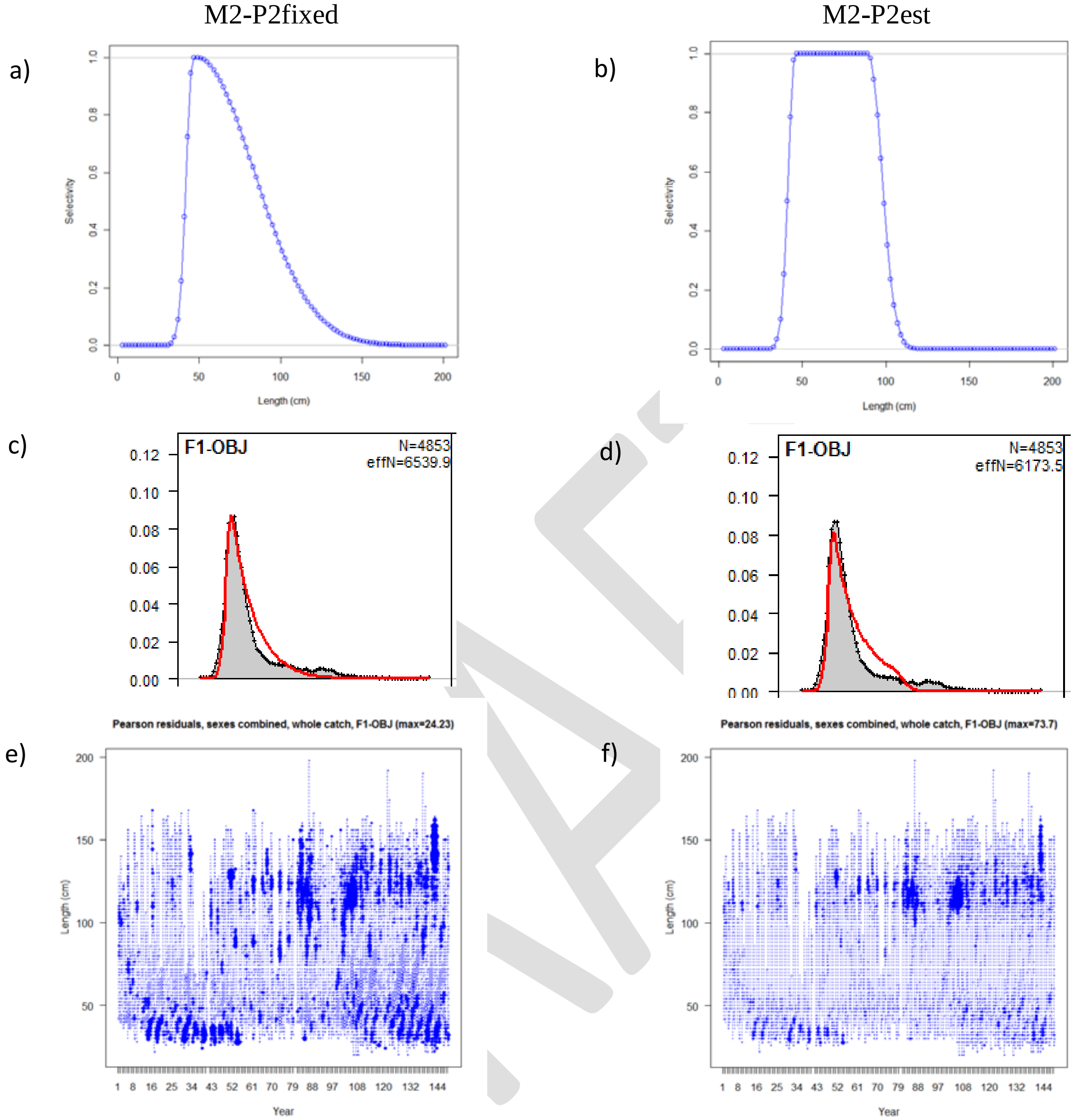


Figure 5. Results from Models 2: M2-P2fixed (left) and M2-P2est (right). a and b) Quarterly time-varying OBJ selectivity curves; c and d) average observed (shaded area) and predicted (curves) length-frequency distributions of the YFT catches taken by the OBJ fishery; e and f) Pearson residual plots for the model fits to the length-frequency distributions for the OBJ fishery. The filled and open circles represent observations that are higher and lower, respectively, than the model predictions.

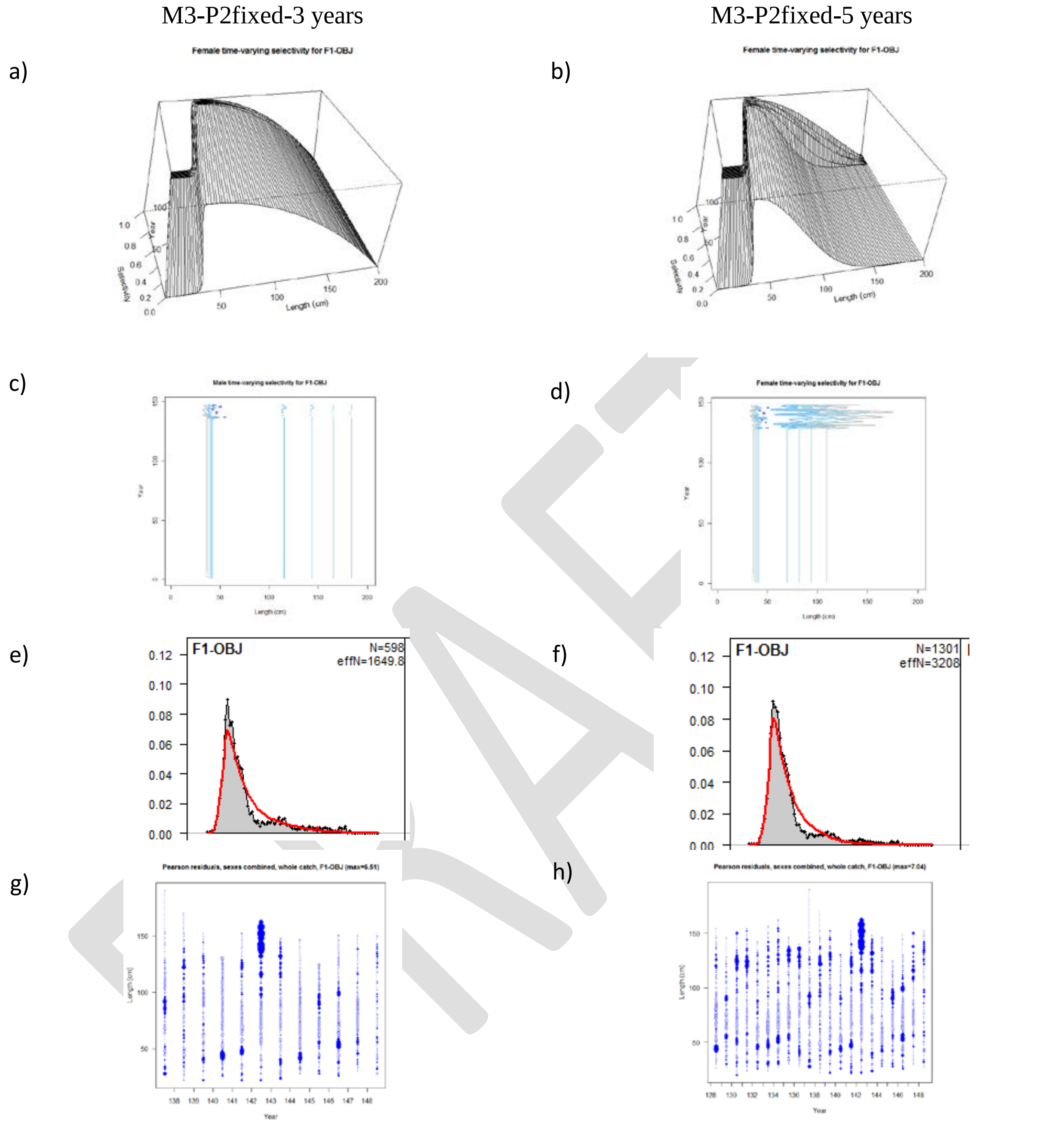


Figure 6. Results from Models 3: M3-P2fixed-3years (left) and M3-P2fixed-5years (right). a and b) Quarterly time-varying OBJ selectivity curves; c and d) selectivity isoclines for 0.2, 0.4, 0.6, 0.8 and 1.0; e-f) average observed (shaded area) and predicted (curves) length-frequency distributions of the YFT catches taken by the OBJ fishery; g and h) Pearson residual plots for the model fits to the length-frequency distributions for the OBJ fishery. The filled and open circles represent observations that are higher and lower, respectively, than the model predictions.

M4-P2fixed-5 years

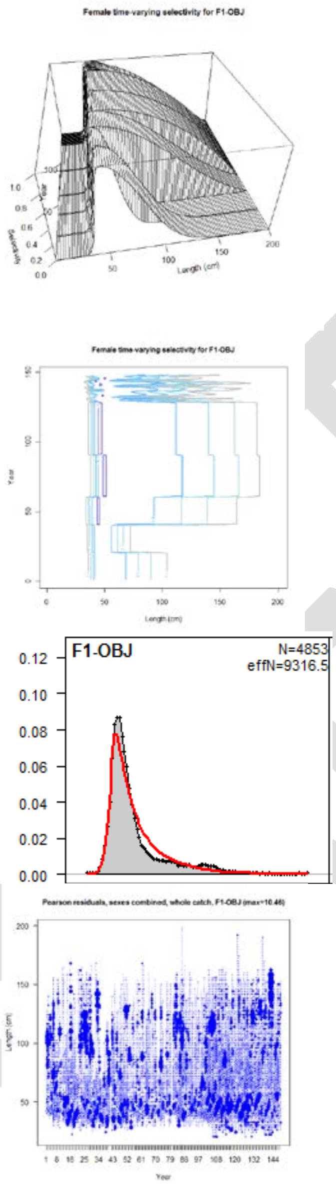


Figure 7. Results from Model 4: a) Quarterly time-varying OBJ selectivity curves; b) selectivity isoclines for 0.2, 0.4, 0.6, 0.8 and 1.0; c) average observed (shaded area) and predicted (curves) length-frequency distributions of the YFT catches taken by the OBJ fishery; d) Pearson residual plots for the model fits to the length-frequency distributions for the OBJ fishery. The filled and open circles represent observations that are higher and lower, respectively, than the model predictions.

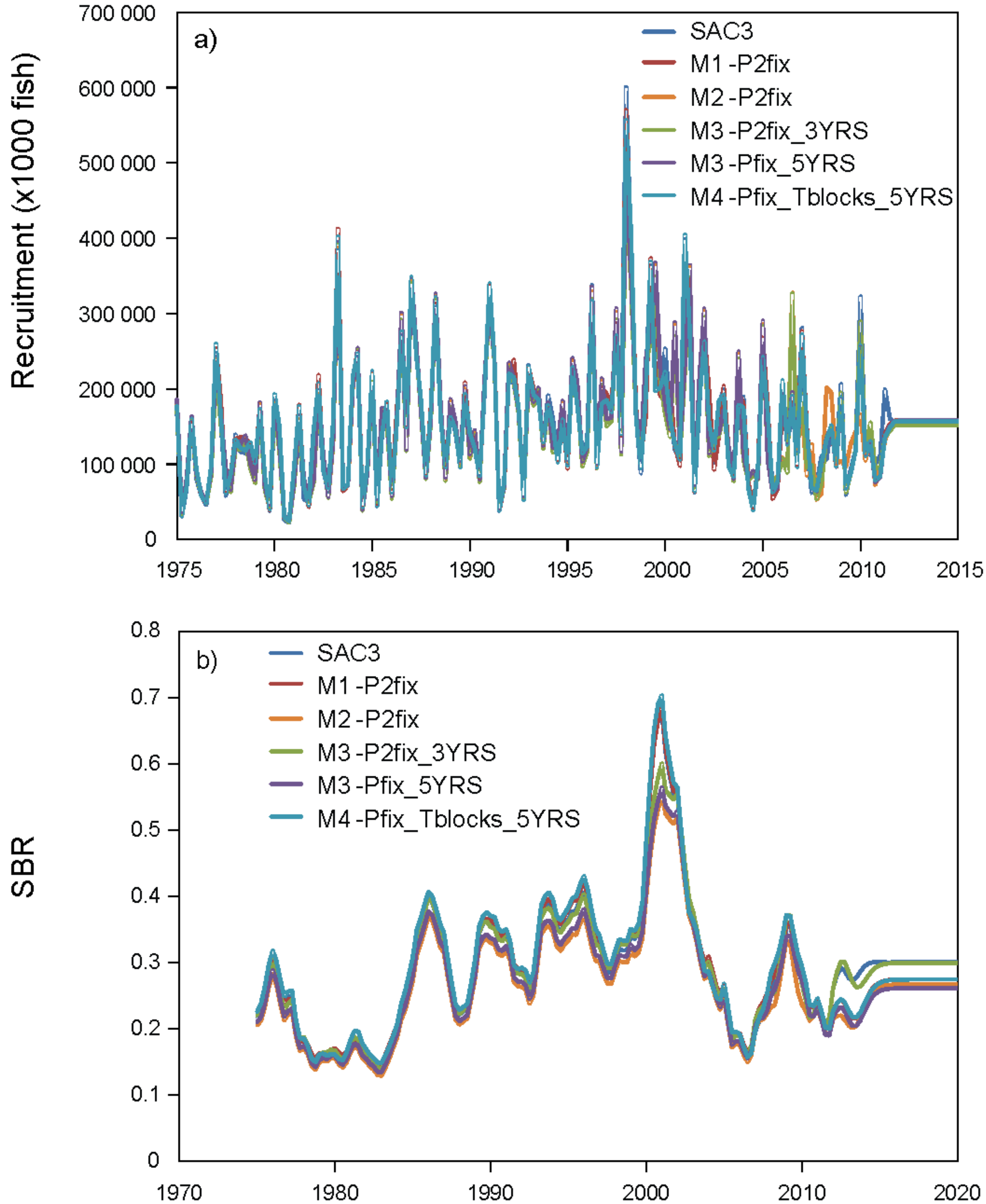


Figure 8. Time series of YFT recruitments (top) and the spawning biomass ratio (SBR, bottom) obtained for different time-varying modeling approaches explored in this paper.

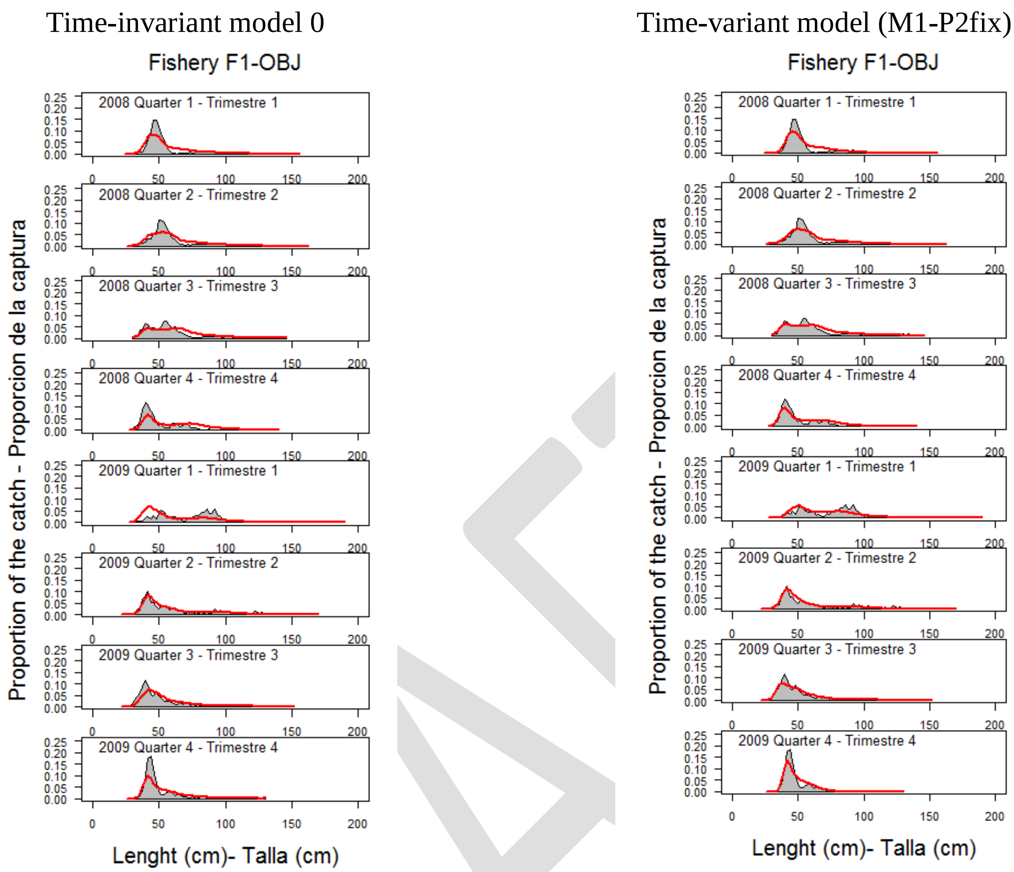
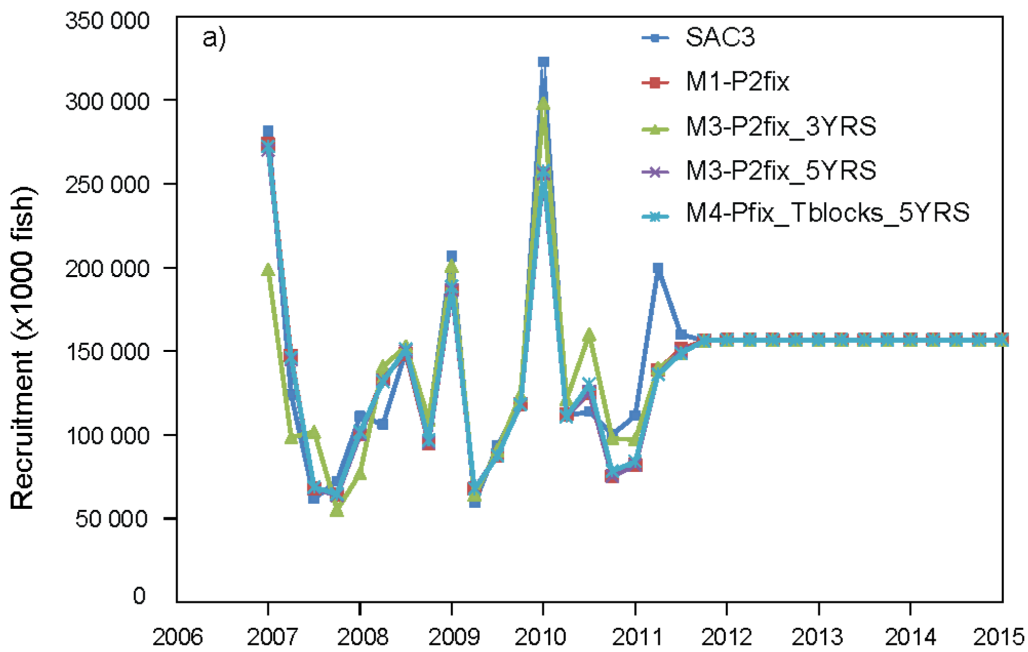


Figure 9. Observed (shaded area) and predicted (curves) length-frequencies of recent catch of YFT by the OBJ fisheries. Left – time-invariant selectivity model 0 ; right – time-varying selectivity model M1-P2fix.



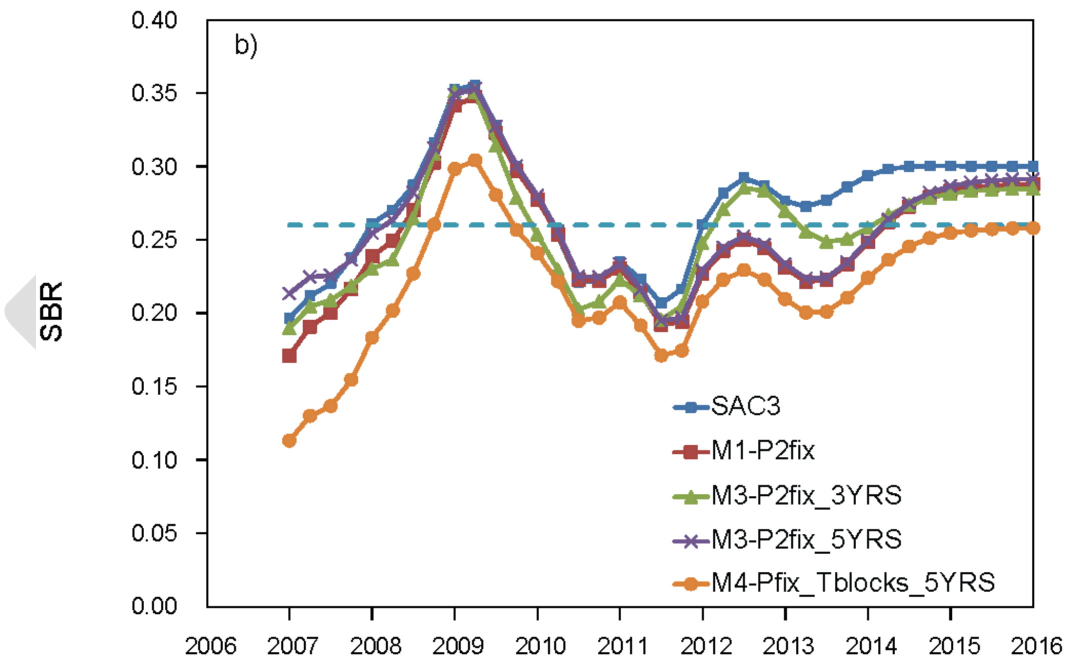


Figure 10. a) Recent recruitment estimates obtained from the YFT base case and the time-varying selectivity models explored in this paper. b) recent and future spawning biomass ratio (SBR) under the YFT base case model (SAC3) and the recruitment time series estimated from the time-varying selectivity models. The horizontal dashed marks Smsy/S0.