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A PRELIMINARY STOCK ASSESSMENT OF BIGEYE TUNA IN THE WESTERN AND CENTRAL PACIFIC OCEAN USING STOCK SYNTHESIS; A COMPARISON WITH MULTIFAN-CL

WCPFC-SC4-2008/SA-WP-2

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Abstract

A parallel assessment of the current WCPO bigeye assessment, conducted using MULTIFAN-CL (MFCL), was undertaken using Stock Synthesis (SS) software. The two models incorporated the equivalent data sets (catch, effort, size composition, and tag data) and, where possible, the MFCL assumptions were mimicked in the SS model. Differences in the underlying model structure were noted, where relevant. The SS model yielded comparable trends in region-specific recruitment, biomass, and fishing mortality rates to the MFCL assessment. The length-based selectivity formulation, available in SS but not currently available in MFCL, was also applied in a sensitivity analysis to address a potential conflict between key data sets incorporated in the model. It is recommended that SS be applied to other WCPO assessments in parallel with MFCL.

Introduction

Since the late 1990s, the stock assessment of tuna species in the western and central Pacific Ocean has been undertaken using the MULTIFAN-CL (MFCL). MFCL is software that implements a size-based, age- and spatially-structured population model integrating fisheries catch, effort and size (length and weight) composition data and tag release/recovery data (Fournier et al. 1998; Hampton and Fournier 2001; Kleiber et al. 2003; http://www.multifan-cl.org).

MFCL has many similarities to software developed to undertake assessments of other fish stocks; for example A-SCALA which has been used to undertake stock assessments of tuna species in the eastern Pacific Ocean (Maunder & Watters 2003) and Stock Synthesis (Methot 2005, 2007) which was initially developed for the assessment of ground fish stocks. These three software packages have similar population dynamics equations, observational models, structure for priors, and objective functions. As such, there is potential to use the different sets of software to undertake parallel stock assessments to provide a comparison with the results from the principal assessment software.

Parallel assessments have the benefit of providing a check on the principal assessment, potentially identifying errors in the software code, logic errors in key model assumptions (such as priors and penalties) and errors in the input data sets. In addition, they may provide the opportunity to investigate alternative parameterisations of key variables included within the model. More flexible software platforms may also enable some of the key assumptions of the principal assessment to be examined more thoroughly.

To date, parallel stock assessments have been undertaken for EPO bigeye tuna using A-SCALA and Stock Synthesis 2 (SS2) (Aires-da-Silva & Maunder 2007, Maunder 2007) and for south Pacific albacore using MFCL and SS2 (Hoyle & Langley 2007). In both cases, the population dynamics of the SS2 model was comparable to the results from the principal assessment software platform (A-SCALA and MFCL), although some differences were evident. These differences were largely attributable to differences in the parameterisation of some key variables, in particular selectivity functions.

These two parallel sets of assessments were conducted for a single (homogeneous) region and lacked the complexity of the (six region) spatial structure of the assessments of WCPO yellowfin and bigeye tuna stocks. While SS2 has the capacity to undertake spatially-structured assessments, the software lacked the capacity to incorporate two key sources of data that are included in these assessments: fishery-specific weight frequency data and tag release/recovery data. The latest generation of the Stock Synthesis software (denoted Stock Synthesis V3.00 or SS), developed over the last year by Rick Methot, has included this functionality as well as including a range of other features that enable the assessments to be more closely aligned with stock assessments undertaken using MFCL (including fixed age-specific natural mortality and improvements in the growth parameterisation).

In formulating the scientific services for the WCPFC, the third meeting of the Scientific Committee requested that a stock assessment be undertaken for bigeye tuna in the WCPO for presentation at SC4. The principal stock assessment was conducted using MFCL and the results are documented in Langley et al (2008). In addition, the SC requested that a parallel assessment be undertaken using Stock Synthesis. This report documents the results of the assessment of WCPO bigeye tuna using SS and provides a comparison with the results from the MFCL assessment.

Methods

The SS assessment maintained the equivalent regional structure, fishery definitions (25 fisheries), and quarterly temporal structure (commencing in 1952) to the MFCL model. MFCL assumes a common set of biological parameters for both sexes (including maturity, growth in length, growth in weight, maturity and natural mortality) and these assumptions were transferred to the SS model.

The data sets included in both the SS and MFCL assessments are described in detail in Langley et al. 2008. The model period for SS did not include the last year of the MFCL model (2007) due to the lack of catch data for that year.

In MFCL, the key longline fisheries provide the principal index of region-specific stock abundance. The CPUE data from each of these six fisheries was included in the SS model as a “survey” with the selectivity linked to the common selectivity shared by the six longline fisheries (this differs somewhat from MFCL where a separate selectivity function is estimated for the longline fisheries in regions 1 and 2). Likewise, catchability for the six “surveys” was common among regions. Only CPUE data from quarter 1 (Jan–Mar) were used as the region-specific “survey”. For each region, the trend in the CPUE index from the first quarter is comparable to the CPUE trends in the other three quarters. Including the additional three quarters would have required including a total of 24 (6x4) “surveys” as there is no capacity to include a seasonal catchability coefficient in SS.

Catch and length frequency data were reconfigured to be equivalent to the MFCL data sets, while the resolution of the weight frequency data was reduced (from 200 to 46 weight intervals) to reduce memory usage. A total of 1,865 length- and 1,377 weight frequency distributions are included, stratified by fishery and time interval (quarter).

In MFCL, tag data are grouped by release event (region/quarter), while SS further stratifies tag releases in the input data by age and, where available, sex. As a result, it was necessary to reconfigure the MFCL tag releases by age based on the length-at-release and the bigeye growth function (estimated from MFCL), resulting in an increase in the number of tag release groups from to 23 to 118. MFCL structures the tag releases by age internally during the estimation procedure, dynamically determining the age-at-release from the length-at-release and the estimated growth parameters.

In SS, fishery-specific selectivities were parameterised using logistic (TW CN LL fisheries and AU LL), double logistic (HW HL) and double normal (principal LL fisheries and surveys and all other fisheries) functional forms. The starting values of the individual parameters were set at values to approximate the selectivity of the corresponding fisheries in the MFCL model.

The mean proportion of the total recruitment from each region was estimated as were the time series of overall recruitment deviations. As with MFCL, recruitment deviations can also be estimated at the regional level (regional recruitment deviations). For the SS model, these were estimated for 1952–2004.5 and assumed to be zero for the last 10 quarters of the model.

For regions 3–6, the initial age structure (1952) was determined assuming unexploited conditions, while initial levels of fishing mortality were estimated for regions 1 and 2.

Movement rates were estimated between all adjacent regions. SS parameterises age-specific movement by the estimation of separate movement coefficients for young and old fish and linear interpolation of the movement coefficients between the intervening age classes. For bigeye tuna, young and old fish were defined as the 1–4 and 10+ age classes. Seasonal movement rates were estimated for MFCL and, while this feature is available in SS, it was not implemented in this analysis due to differences in the formulation of the model time interval (to enable the estimation of seasonal recruitments by SS).

The prior on the steepness of the spawning stock-recruitment relationship was set to approximate the prior in the MFCL model.

SS has the functionality to estimate initial tag loss and chronic tag loss for each tag group. For the BET model, there are insufficient data to estimate these parameters and, mirroring the assumptions in the MFCL model, these parameters were fixed at (approximately) zero. Two alternative scenarios were considered for the priors used for the fleet specific tag reporting rates: i) tag reporting rate priors comparable to those used in MFCL with informative priors for key fisheries (tag-high scenario) and ii) uninformative priors for all fleets (tag-low scenario).

The fleets with informative priors are those that returned a significant number of tags and for which there was auxiliary information to suggest reasonable tag return rates (either from tag seeding experiments or qualitative assessment of fisher behaviour). Specifically, these fleets are the Hawaii longline fleet (LL HW 2 & 4), the Australian longline fleet (LL AU 5), the equatorial purse-seine fisheries, and the Philippines and Indonesian domestic fisheries. In MFCL, there is a penalty associated with deviating from the assumed reporting rate. For the fleets with informative priors, the penalty is set at 50 (representing a cv of approximately 0.10), while other fleets have a negligible penalty (1).

The sensitivity of the SS model to the assumed coefficient of variation (cv) on the survey indices was also examined. In the MFCL bigeye assessment, a penalty of 50 was applied to the effort deviations associated with the principal longline fisheries corresponding to a cv of approximately 0.1 (cpue-high scenario). For the SS model, a cv of 0.22 was also investigated (cpue-low) – a value closer to the standard error associated with the GLM CPUE indices.

In addition, SS was applied to investigate the sensitivity of the stock assessment to the assumption of age-based selectivity for the Taiwanese-Chinese longline fisheries in regions 3 and 4. These fisheries catch very large bigeye and the inclusion of the size data from these fisheries has resulted in a persistent lack of fit to the region 3 CPUE indices in the MFCL model (Langley et al. 2008). As an alternative, the selectivity of these fisheries was modelled in SS using length-based selectivity, parameterised using a simple logistic function.

Four separate model runs were conducted in SS:

1. Uninformative tag reporting rate priors, lower weighting (higher cv) on longline CPUE indices (“surveys”) (tag-low, cpue-low);
2. Uninformative tag reporting rate priors, higher weighting (higher cv) on longline CPUE indices (“surveys”) (tag-low, cpue-high);
3. Informative tag reporting rate priors, high weighting (low cv) on longline CPUE indices (“surveys”) (tag-high, cpue-high); and,
4. Uninformative tag reporting rate priors, higher weighting (higher cv) on longline CPUE indices (“surveys”). Selectivity of the TW-CN longline fisheries modelled using length-based selectivity (tw-cn-length-select).

The configuration of the third option (tag-high, cpue-high) most closely approximates the base-case run from the 2008 MFCL bigeye stock assessment.

Results

An initial examination of the adult biomass trajectories from the three SS model options (not including the tw-cn-length-select option) revealed the regional distribution and temporal trends in absolute biomass were very similar to the results from the MFCL base-case assessment (Figure 1). As in the MFCL assessment, adult biomass is concentrated in the two equatorial regions and all regions exhibit a large decline in adult biomass.

However, for region 3 the SS model runs with the lower weighting on the CPUE indices (tag-low, cpue-low) estimated a significantly different biomass trajectory in the early model period (1952–1970) compared to the MFCL base case assessment (Figure 1). Further, the three SS runs considered also estimated a considerably higher level of adult biomass in region 3 in the last decade relative to the MFCL model.

The SS model with uninformative tag reporting rates and a low cv on the CPUE indices (tag-low, cpue-high) was selected for a more detailed comparison of the results from the MFCL model. This model option does not have the informative tag reporting rate priors common with the MFCL model. However, the reporting rates estimated for the “tag-high, cpue-high” model differed considerably from the MFCL model and it was considered that the change in the configuration of the tagging data in the SS model might also be influencing the underlying population dynamics. For that reason, the “tag-low, cpue-high” SS model was selected in preference to “tag-high, cpue-high” for comparative purposes.

The selectivity functions from the two models (MFCL and “tag-low, cpue-high”) are similar for most fisheries, in particular the principal longline fisheries (Figure 2), although MFCL estimated a separate selectivity for the fisheries in region 1 and 2, while all the principal longline fisheries were constrained to have the same selectivity in SS. The main differences in selectivity occur in some of the fisheries that principally catch smaller bigeye, namely the pole-and-line fishery (PL ALL 3), the Philippines and Indonesian domestic fisheries (PH MISC 3 and ID MISC 3) and the Hawaii hand-line fishery (HW HL 4). In these cases, MFCL estimated high selectivity for the oldest age classes largely due to the observation of a very small number of larger fish in the catch composition. For SS, the parameterisation of the selectivity functions makes it easier to constrain the selectivity of the older age classes. However, the more flexible cubic spline parameterisation of the MFCL selectivity functions makes it easier for the model to fit the bimodality evident in the size composition of the purse-seine and pole-and-line fisheries (Figure 2).

The historical trend in recruitment deviates from the SS and MFCL models were comparable with respect to the magnitude of the deviates and the short- and long-term trends in the recruitment deviates (Figure 3). From the mid 1990s onwards, recruitment deviates from both models revealed recruitment at above average levels, although the recruitment deviates from the SS model were at a higher level than from MFCL. For all regions, there are considerable differences in the regional recruitment deviations between the two models (Figure 4).

The number of age 1 fish estimated to recruit to a region is a function of the overall regional recruitment distribution, the temporal recruitment deviates, and the regional recruitment deviates. For older age classes, this distribution is further influenced by the movement coefficients, as well as the cumulative effects of natural mortality and region specific fishing mortality. Consequently, there are multiple solutions for the model to attain a similar regional distribution and abundance of recruits for a particular time interval.

For example, SS estimates that a substantially higher proportion of the overall recruitment occurs within region 3 compared to the MFCL model (Table 1). In recent years, the overall recruitment level is estimated to be higher than average, particularly for the SS model, although in the SS model this is countered by the negative regional recruitment deviates from 1990 onwards (Figure 4). Conversely, for the MFCL model, the overall recruitment deviates are lower in recent years than for the SS model; however, the regional recruitment deviates for region 3 are strongly positive. The two distinct configurations of the recruitment parameters have a similar net result in determining the absolute number of recruits within region 3; both models predict historical recruitment at low levels followed by a steady increase from the late 1980s to a high level about 2000 (Figure 5). Similarly, temporal trends in recruitment are also comparable between the SS and MFCL models for the other model regions. The only significant divergence is the lower level of recruitment estimated from the SS model for region 4 prior to 1970 (Figure 5).

Over subsequent time steps, the regional recruitment trends are mediated by the movement of fish between regions. For the SS model, high movement rates were estimated for young fish from region 4 to region 3 and region 5 to region 3. The MFCL model also estimated a significant movement of fish from region 4 to region 3 across all age classes (age specific movement coefficients were not estimated). The effects of movement resulted in a convergence of the number of fish at age 10 in region 3 between the two model platforms, particularly prior to 1985 (Figure 6). Conversely, there was further divergence in the numbers of fish by age class 10 within region 4, particularly prior to 1990.

Nevertheless, despite these relatively minor differences, the trends in region specific adult biomass are very similar between the SS (tag-low, cpue-low) and MFCL models (Figure 7). Further, the two models both estimated comparable levels of stock depletion attributable to fishing, with very high fishery impacts occurring in all regions and reductions in adult biomass of at least 90% in the two equatorial regions (Figure 8).

In general, the SS (tag-low, cpue-high) model fitted the CPUE ("survey") indices from each region, although there is a significant lack of fit to the region 3 CPUE indices from 1990 onwards (Figure 9). This lack of fit is also evident in the MFCL model where it is expressed as a period of low effort deviations and has been attributable to the influence of the size data from the TW-CN longline fisheries (see Langley et al. 2008). The influence of these data is evident when the cv of the CPUE indices is increased (tag-low, cpue-low) and the fit to the CPUE indices is further eroded (Figure 10).

For the three SS models, the trends in recent adult biomass in region 3 deviated from the MFCL biomass trajectory during the last decade (Figure 1) and the lack of fit to the CPUE indices was more pronounced than for the MFCL model. This is likely to be due to the lower effective weighting of CPUE data sets in the SS models as the CPUE data are only included as a single quarterly CPUE index, while the MFCL model includes the longline catch and effort data from all four quarters.

Recent age-specific fishing mortality rates (combined across regions) are generally similar between the SS (tag-low, cpue-high) model and the MFCL base-case, although fishing mortality is lower for the MFCL model, particularly for age classes 1–4. For these young age classes, the difference may be partly attributable to differences in the movement parameterisation (age-specific in SS, seasonal in MFCL) between the two model platforms, differences in selectivity functions, and/or the lack of regional recruitment deviations for the last 10 quarters.

For the SS runs with an uninformative prior (tag-low), the estimated reporting rates deviated substantially from the reporting rates estimated from the MFCL model, approaching either zero or complete (100%) reporting of recaptured tags (Figure 12); for example, the reporting rates for the purse-seine associated fisheries reached the upper bound of 100%, while the MFCL estimate was about 65%, closer to the mean of the prior of 45%. Conversely, reporting rates for the Philippines domestic fisheries were considerably lower than estimated by MFCL (Figure 12).

For the SS run with the informative priors on tag reporting, tag reporting rates were more closely aligned to those from the MFCL model, although reporting rates tended to be less variable among fleets from the SS model (Figure 13), remaining closer to the mean of the prior. In particular, for many of the longline fisheries MFCL estimated very low reporting rates, while SS reporting rates were considerably higher (e.g. LL ALL 5, LL ALL 6, LL BMK 3). However, these fisheries have a very small number of tag recoveries and recaptures from these fisheries are unlikely to contribute substantively to the total tag likelihood.

Modelling the selectivity of the Taiwanese-Chinese longline fisheries using a length-based function resulted in a significant improvement in the fit to the CPUE indices from region 3 (Figure 14 compared to Figure 9) and a significant improvement in the objective function value (from 27165.3 to 27835.3). However, there still remained some lack of fit to the region 3 CPUE indices in the last decade (Figure 14).

The estimated selectivity functions for these two fisheries yielded full selectivity of bigeye at about 110 cm (fork length) (Figure 15), compared to full selectivity at age class 18 (equivalent to a mean size of 137 cm) from the age-based selectivity parameterisation (Figure 2). Given the estimated growth of bigeye tuna, the length-based selectivity functions result in the two fisheries selecting a higher proportion of the larger fish from the younger age classes compared to the age based selectivity (Figure 16).

The length-based parameterisation of selectivity for these fisheries results in a considerable change in the underlying population dynamics of the model. For all regions, the trend in adult biomass is comparable between the two SS models; however, the absolute level of adult biomass is consistently higher for the model with length-based selectivity, particularly in the equatorial regions (Figure 17). This is likely to reflect, at least partly, the decline in the estimated selectivity of older age classes (greater than age 20) by the principal longline fisheries (Figure 18).

There is also a substantial difference in the historical pattern of recruitments between the two models. Recruitment from the model with length-based selectivity (tw-cn-length-select) is at least 50% higher than the level of recruitment from the age-based selectivity model (tag-low, cpue-high) during 1952–1985 (Figure 19), while recruitment is comparable between the two models in the latter period (1985 onwards).

The SS model with length-based selectivity also estimates considerably lower (approx. 50%) levels of historical and recent fishing mortality for the older (15+) age classes, although levels of recent fishing mortality for the younger age classes are comparable.

Discussion

The WCPO bigeye stock assessment represents one of the most complex assessments undertaken using Stock Synthesis to date and utilises many of the new features implemented in the latest version of the software. The resulting model runs provide a direct comparison with the principal assessment undertaken with MFCL and illustrates that the two software platforms are capable of producing comparable results, given that the data inputs are similar and key assumptions are mirrored in the two assessments. This is despite of the difference in the treatment of catch (exact in SS, estimated with error in MFCL) and the catch equations (linearized in SS and Baranov in MFCL). The result reaffirms and strengthens the conclusions of Hoyle & Langley (2007) and Aires-da-Silva & Maunder (2007) by extending the comparison to include a model with a complex spatial structure and movement dynamics.

SS and MFCL share many of the same underlying population dynamics equations and for most parameters it is possible to duplicate the key assumptions/parameterisations. However, there are some differences in the configuration of the two models that may result in small differences in the model results. For the current example, a significant difference between MFCL and SS is the structure of the tag release cohorts in the input data set, where it is necessary to assume an age of release for the tags in SS. The alternative configuration of the tag data is only likely to have a significant effect where the model estimates growth parameters that are significantly different from the initial values. However, a more comprehensive analysis of the SS tag diagnostics should be undertaken particularly given the differences in the reporting rate estimates from the two models. Differences also exist in the parameterisation of the movement coefficients between the MFCL and SS model runs, although it is possible to estimate non age dependent movement in SS and, thereby, configure the movement dynamics to be more consistent with MFCL (or conversely estimate age-specific movement in MFCL). These differences may contribute to the observed differences in the estimates of the various recruitment parameters, for example.

Despite these differences, the key results from the two models, particularly with respect to the trends in regional-specific stock abundance, are remarkably similar. The SS model runs confirm the high level of stock depletion of bigeye, particularly in the equatorial regions. However, it is premature to apply the results of SS model to formulate management advice. The SS software is still in the beta phase of release and more definitive testing of the new features should be undertaken (using simulated data sets, for example), particularly the integration of tagging data in the model, as well as more consideration of some of the key assumptions and priors used in the current runs. For this reason, the SS runs have not been applied to determine the key MSY-based management measures (B/B_{MSY}, SB/SB_{MSY}, and F/F_{MSY}) typically reported for the WCPO tuna stock assessments, although these metrics can be readily generated by SS.

Computational performance of the two software platforms has not been fully assessed in this study, although some qualitative observations are available. The SS model included 1,606 active parameters, while the MFCL model included 5,643 parameters. Most of the additional parameters in the MFCL model are the effort deviates associated with each fishery effort observation, although these parameters can be removed with the implementation of the catch conditioned approach (Hampton et al. 2007). Nonetheless, despite the large number of additional parameters, the MFCL model was not appreciably slower to run with both models taking 12–16 hours to achieve a converged fit (9500 2.20 GHz quad-core processor, 4 GB RAM). It is also worth noting that difficulties were encountered achieving convergence for some of the SS runs with highly informative priors on the tag reporting rates.

A comparative strength of SS is the greater flexibility in model structure. Unlike MFCL, SS is capable of incorporating sexual dimorphism in growth (and other biological parameters), including separate growth morphs, and home ground migrations. There is evidence of these life history and behavioural traits amongst many of the tuna and billfish species that are regularly assessed. Further, covariates can be included to estimate temporal variation in key parameters; for example temporal variation in fishery-specific selectivity could be modelled via the inclusion of a covariate that describes the gear configuration such as number of hooks between floats. Conversely, there are many features within MFCL that are currently not available in SS, including seasonal catchability variation, seasonal movement, more flexible selectivity parameterisation, and the estimation of uncertainty using likelihood profile techniques.

SS also has the ability to estimate fishery selectivity as a length-based process, rather than selectivity being a function of age. This may be useful when a cohort is not fully vulnerable to the fishery, such as young fish recruiting to a fishery based on attaining a minimum size or when other behavioural characteristics are size dependent rather than age dependent. The MFCL bigeye assessment has difficulty in accounting for the catches of very large bigeye tuna by the Taiwanese-Chinese longline fleet in recent years when fishing mortality on juvenile bigeye has been very high. The model attempts to account for the longline catch by estimating very high recruitment (particularly in region 3) over the last decade, thereby, ensuring sufficient fish survive the initial fishing mortality to recruit to the component of the population vulnerable to the TW-CN longline fishery.

These effects are dissipated when the fishery is assumed to have length-based selectivity enabling fish to be taken at a younger age (the larger fish of younger age classes). This change to the structural assumptions of the model has a significant impact on the population dynamics of the model and, potentially, some of the key model conclusions. The appropriateness of these alternative assumptions requires thorough consideration, potentially augmented by length-age sampling from the fishery. Nevertheless, it serves to highlight the importance of considering and testing some of the key structural assumptions of the current MFCL model and value of using SS as an alternative platform to conduct further parallel assessments.

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Table 1. Overall regional recruitment distributions estimated from the SS (tag-low, cpue-high) and MFCL base case models.

Region	SS	MFCL
1	6.8%	3.5%
2	7.9%	9.6%
3	66.2%	35.5%
4	17.5%	45.3%
5	1.1%	3.5%
6	0.6%	2.6%

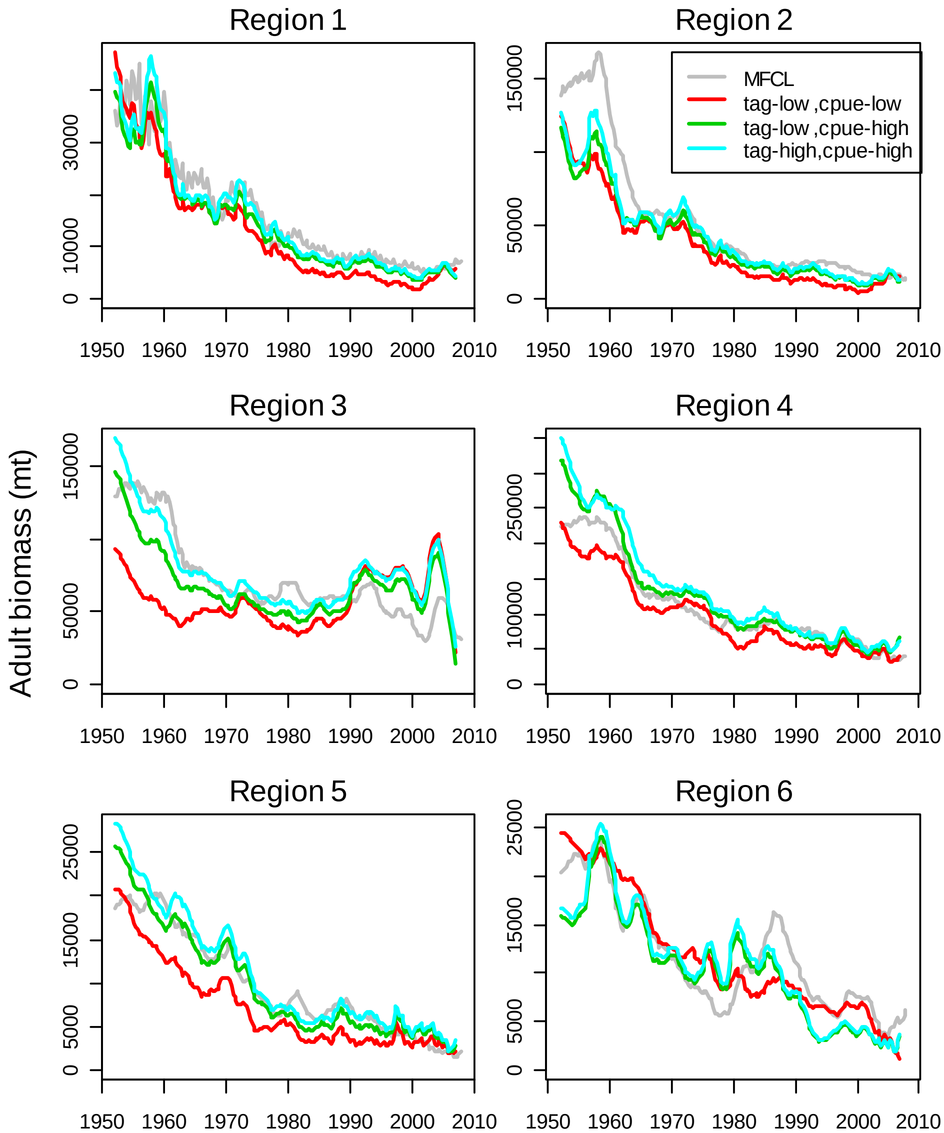

Figure 1. Trends in bigeye adult biomass (mt) by region for three SS model options and the 2008 MFCL base case assessment.

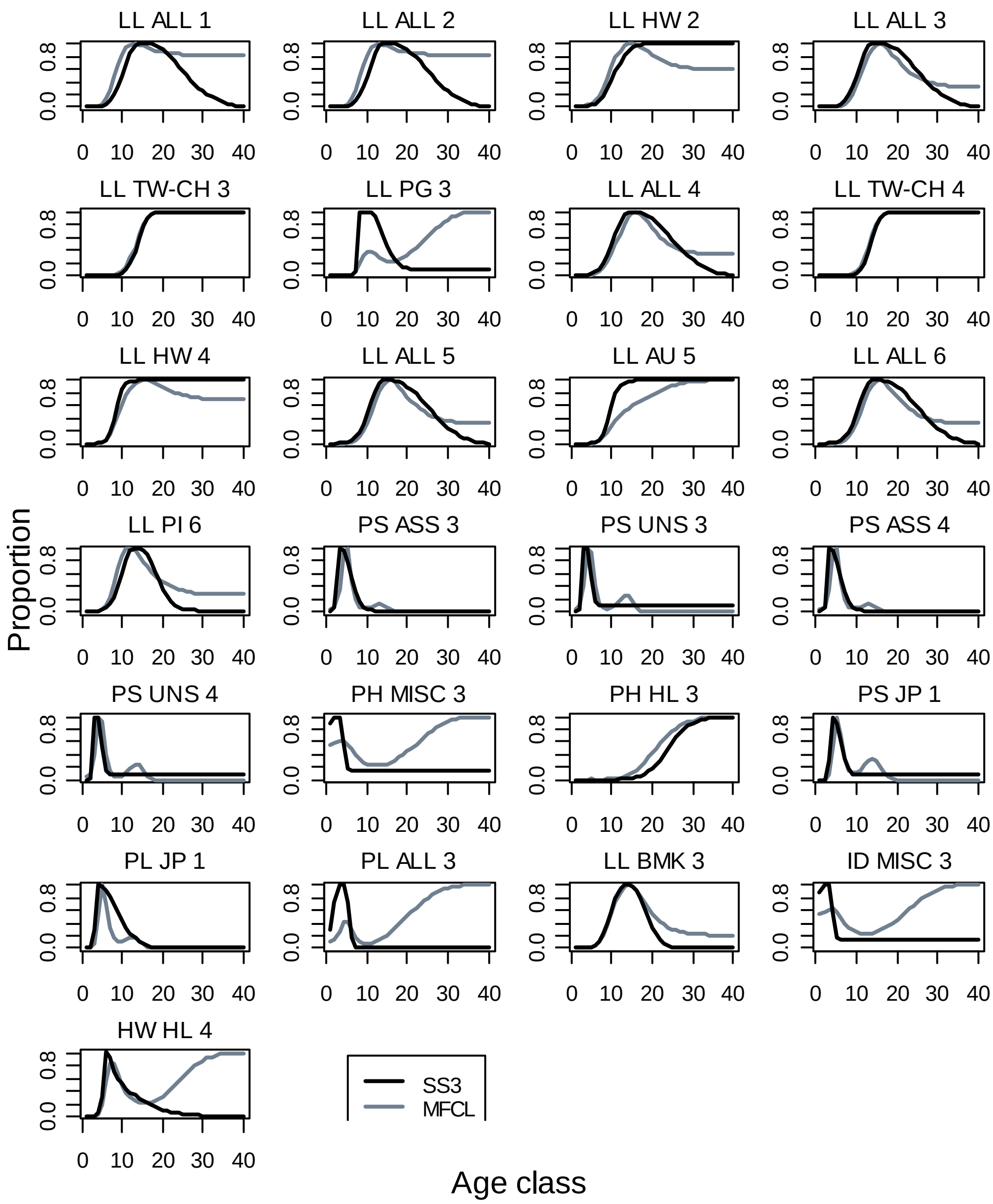

Figure 2. A comparison of the age specific selectivity functions from the SS (tag-low, cpue-high) and MFCL bigeye tuna models.

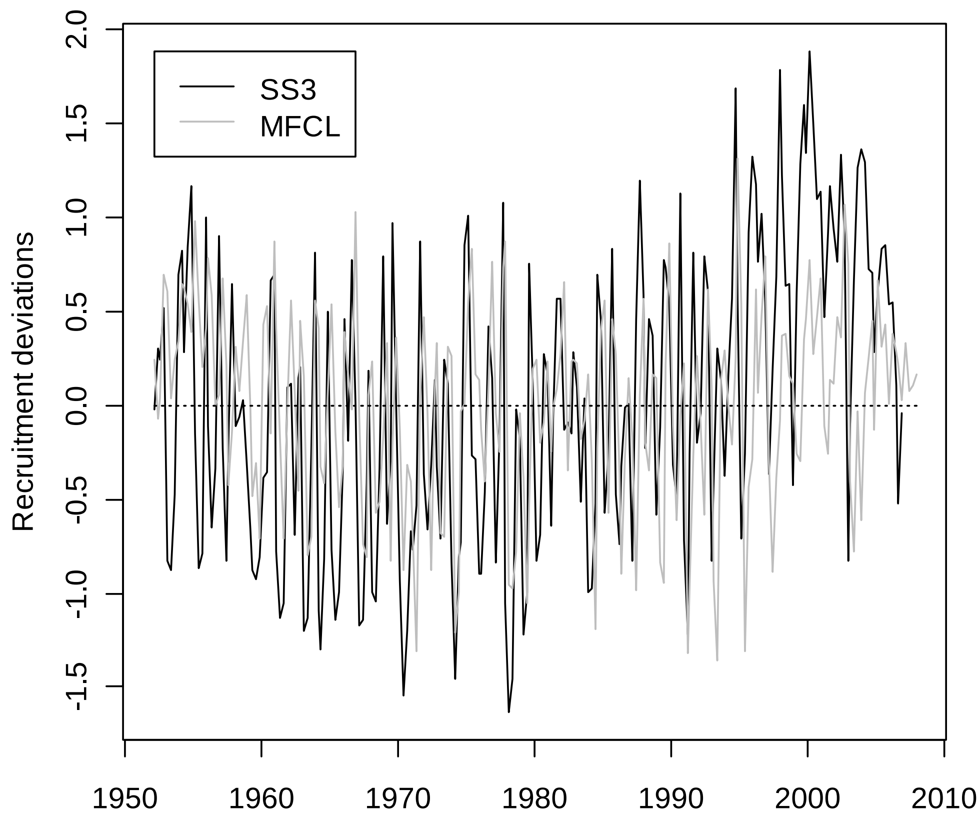

Figure 3. Overall temporal recruitment deviations from the SS (tag-low, cpue-high) and MFCL bigeye tuna models.

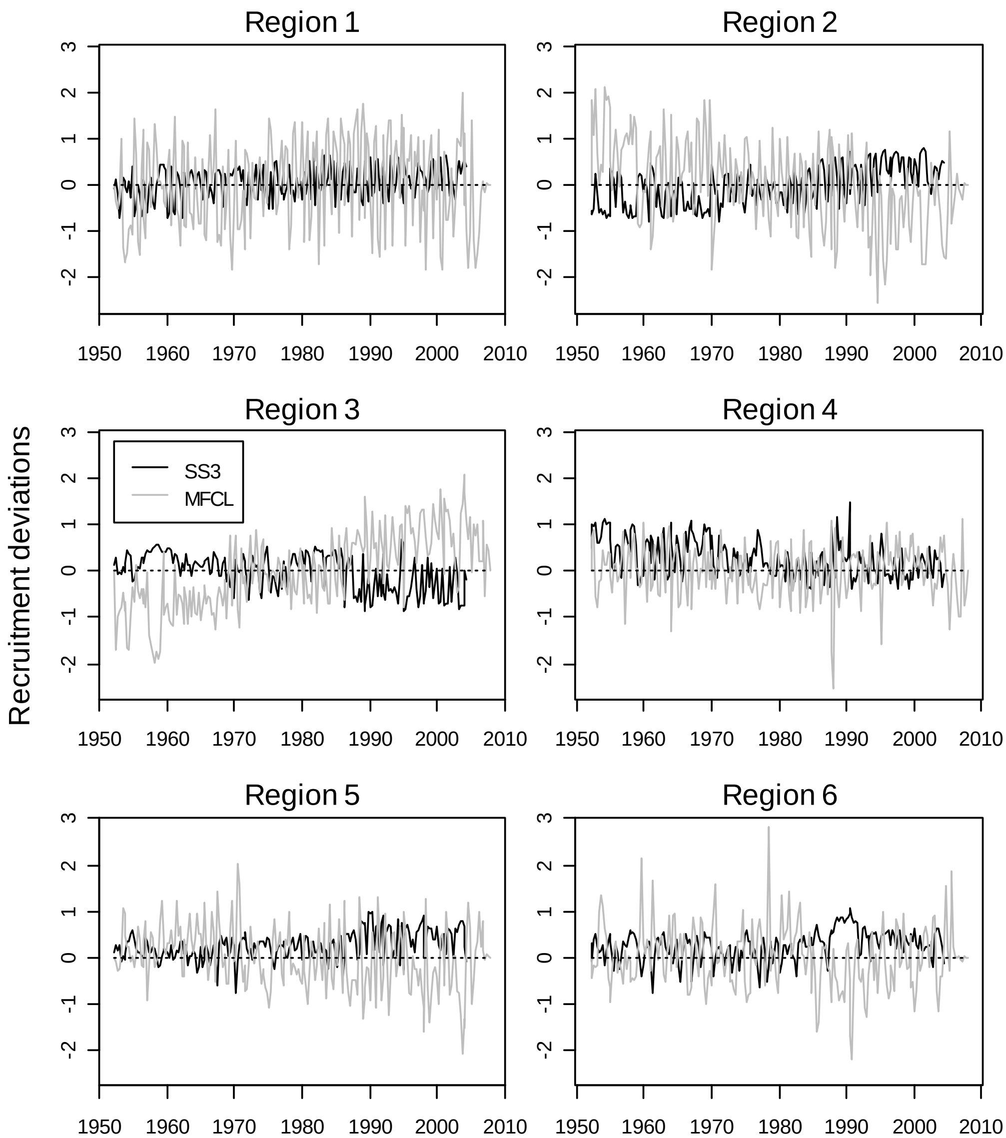

Figure 4. The time series of regional recruitment deviates from the SS (tag-low, cpue-high) and MFCL bigeye tuna models. For SS, the last 14 quarterly recruitment deviates were not estimated.

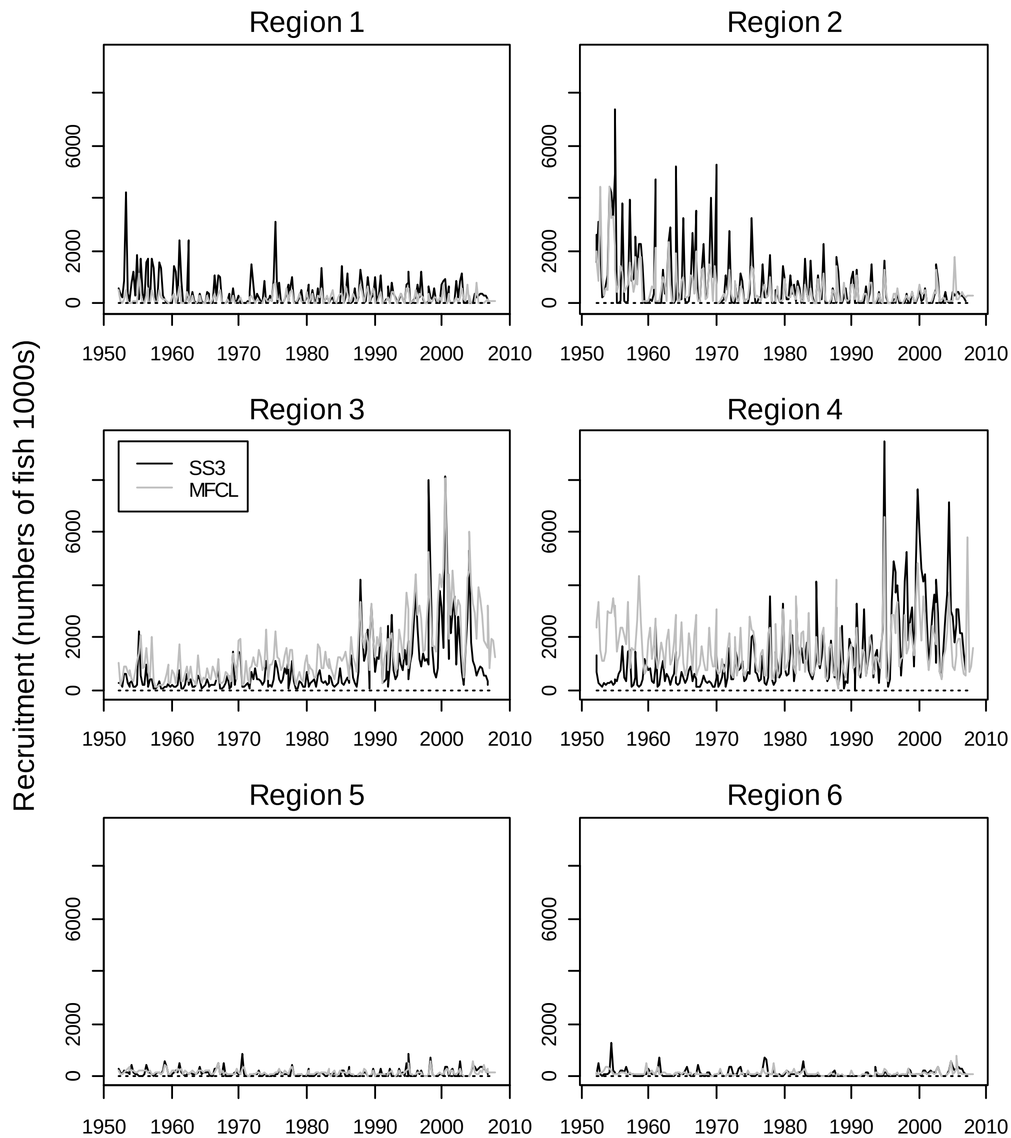

Figure 5. The time series of the number of age 1 fish by region from the SS (tag-low, cpue-high) and MFCL bigeye tuna models.

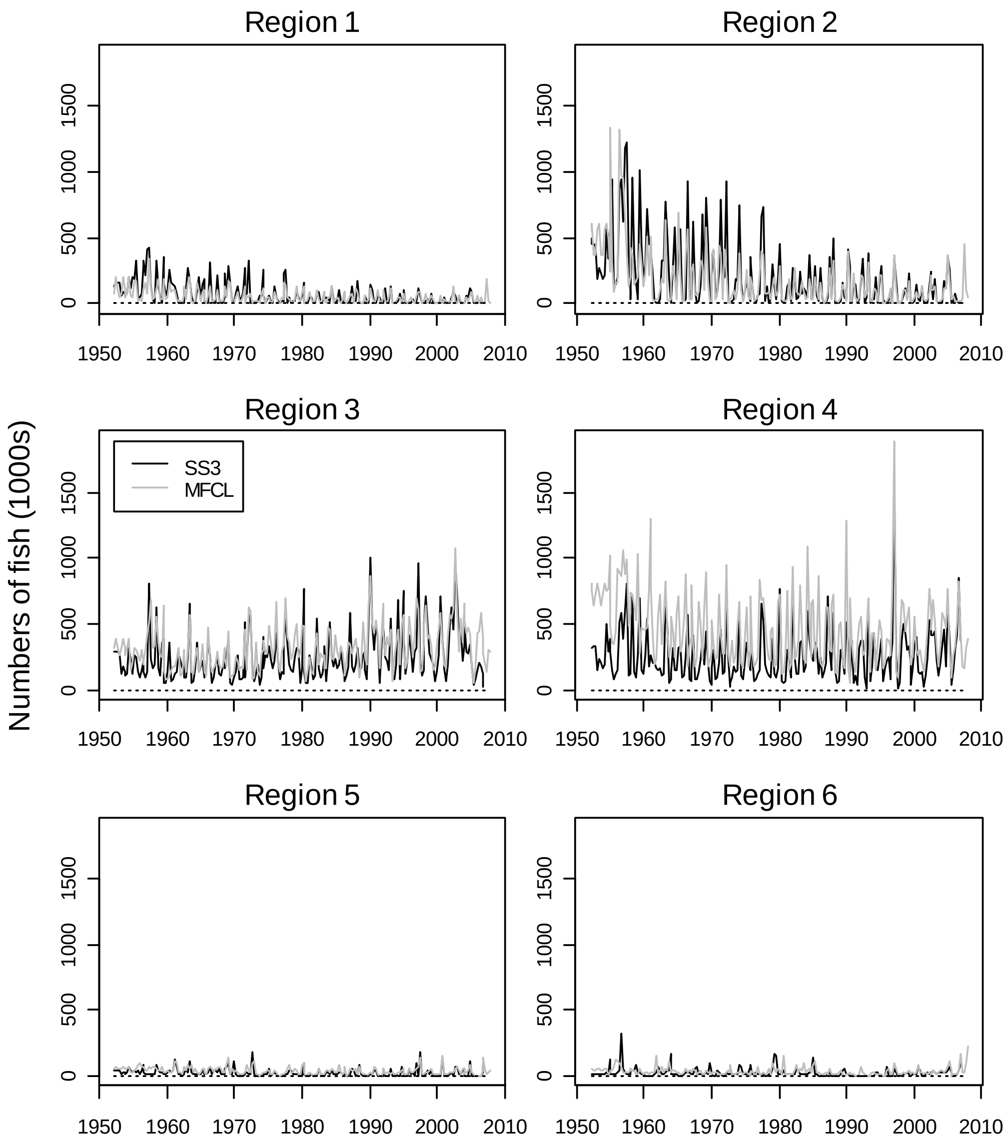

Figure 6. The time series of the number of age 10 fish by region from the SS (tag-low, cpue-high) and MFCL bigeye tuna models.

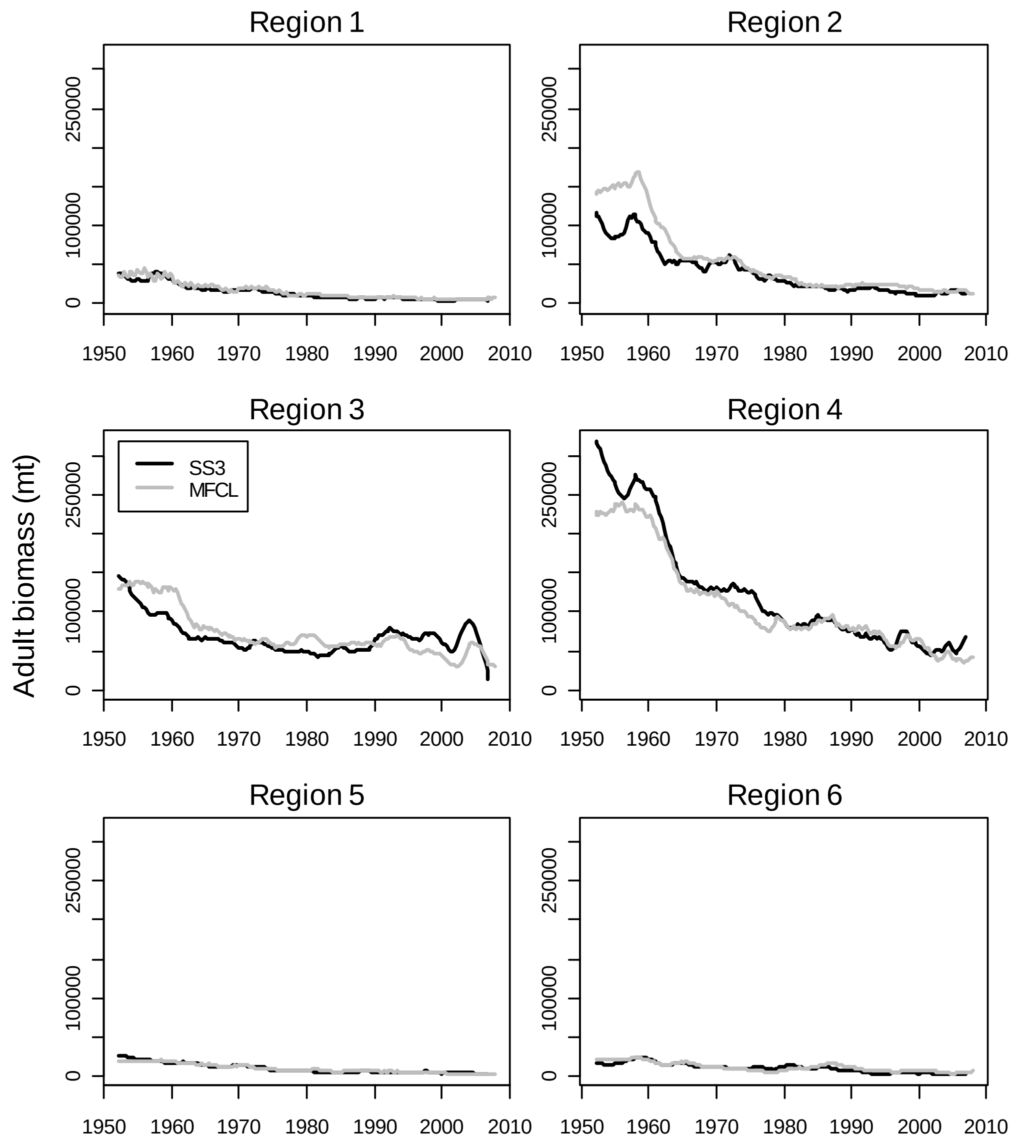

Figure 7. The time series of adult biomass (mt) by region from the SS (tag-low, cpue-high) and MFCL bigeye tuna models.

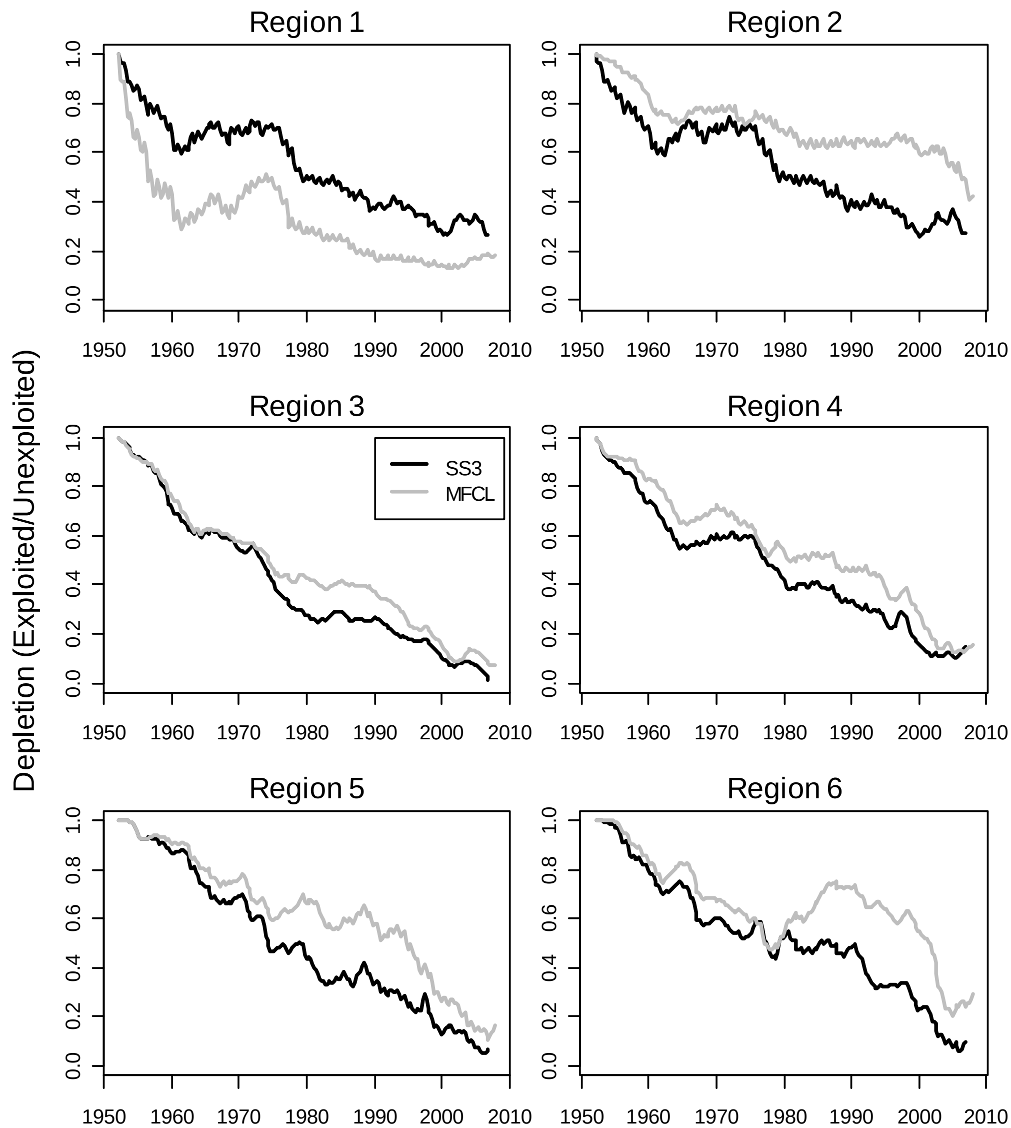

Figure 8. A comparison of the depletion (exploited/unexploited) of the regional adult biomass from the SS (tag-low, cpue-high) and MFCL bigeye tuna models.

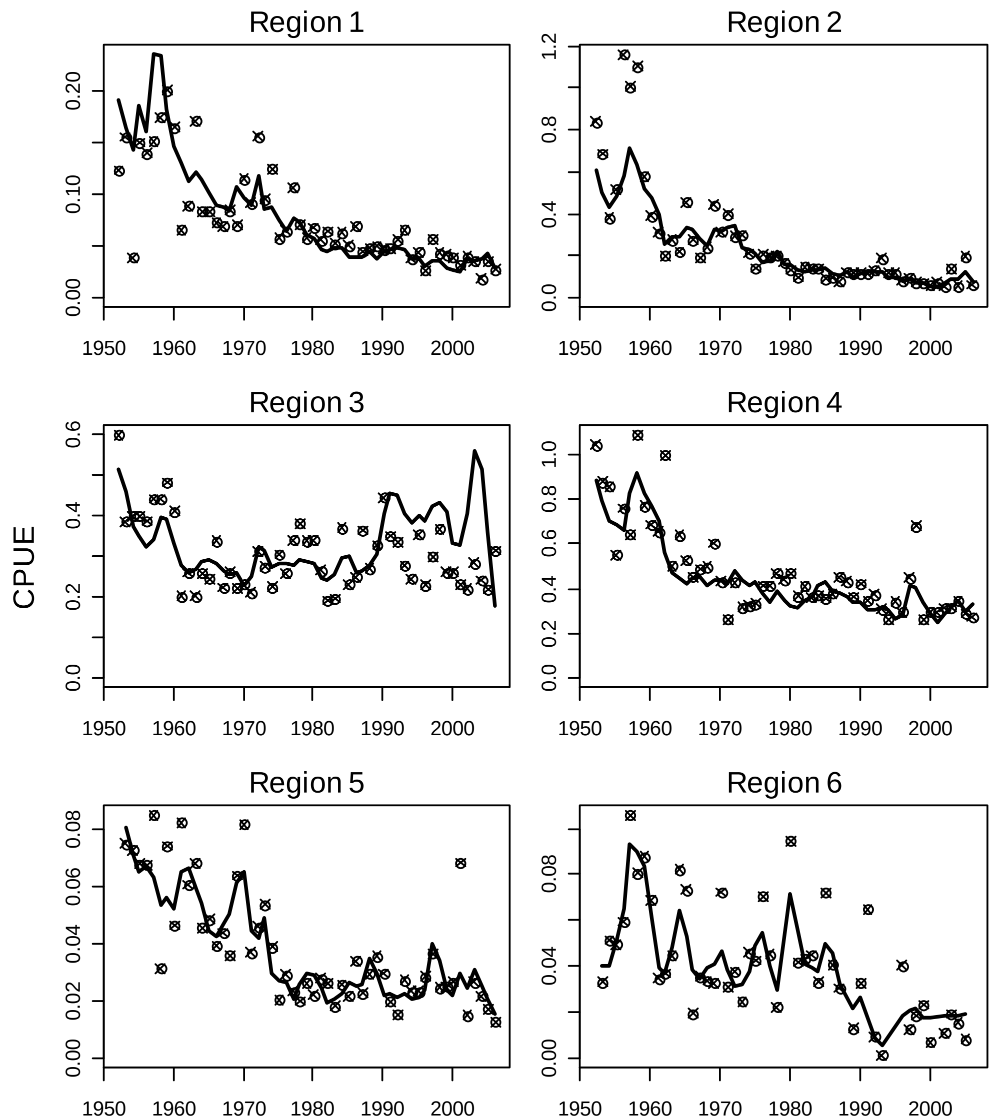

Figure 9. The fit to CPUE ("survey") data (points, observations; line, expected) from the SS (tag-low, cpue-high) WCPO bigeye model.

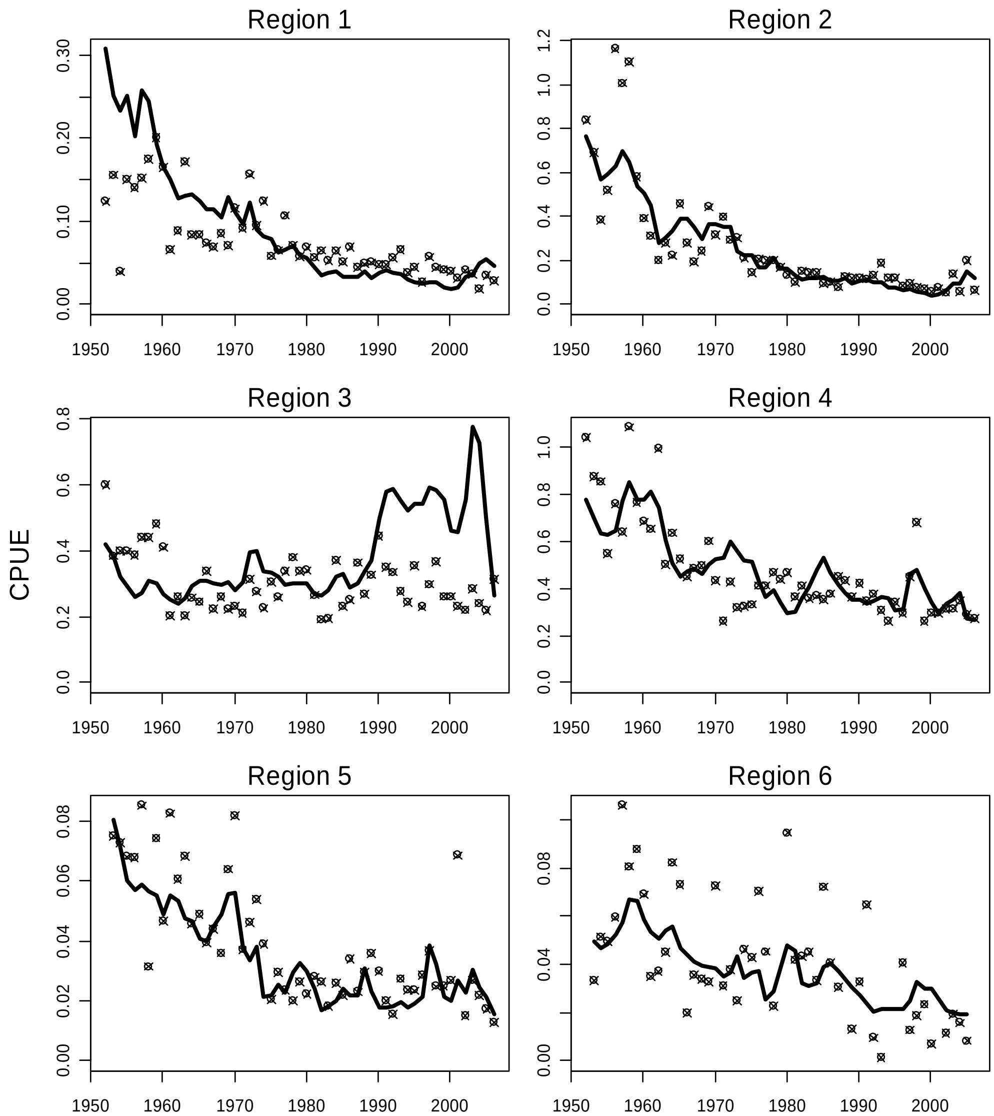

Figure 10. The fit to CPUE ("survey") data (points, observations; line, expected) from the SS (tag-low, cpue-low) WCPO bigeye model.

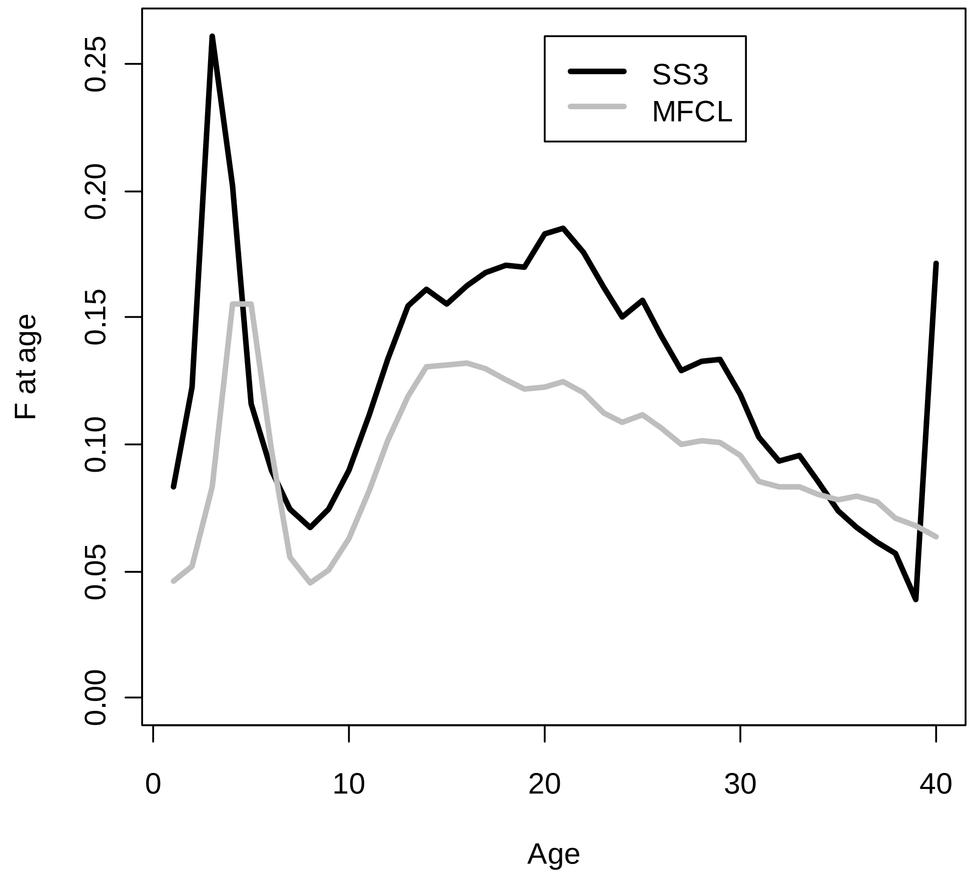

Figure 11. A comparison of the recent (2003-2006 average) fishing mortality at age from the SS (tag-low, cpue-high) and MFCL bigeye tuna models.

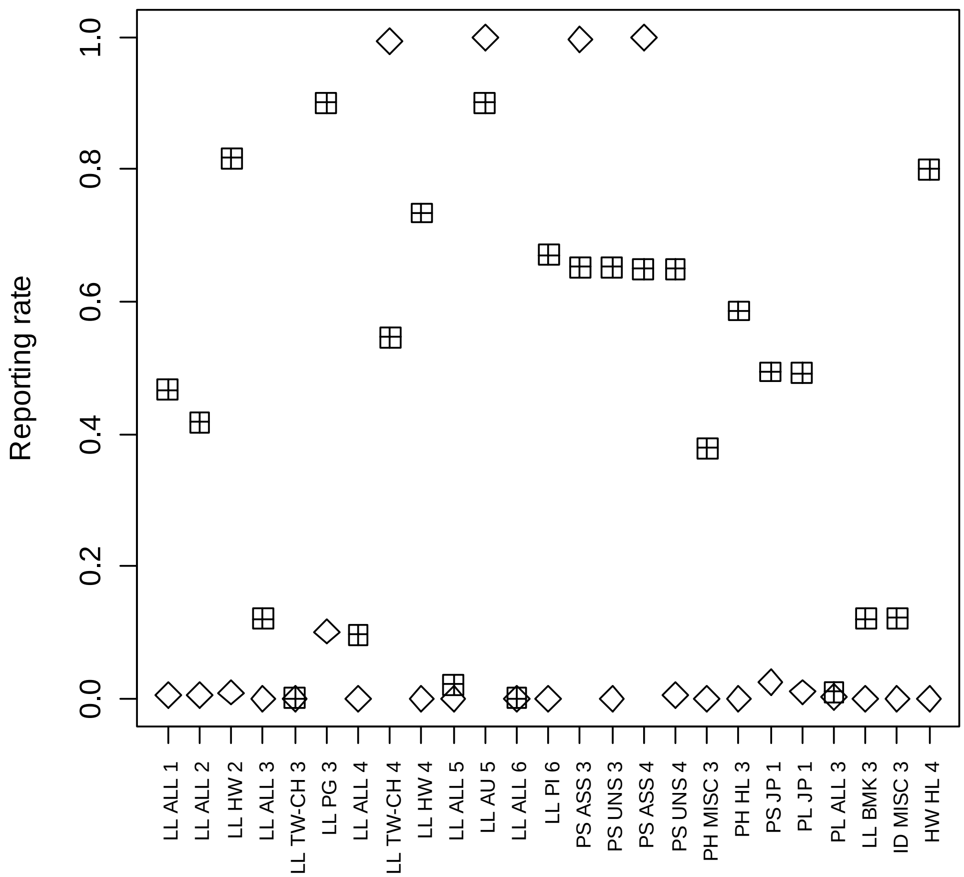

Figure 12. A comparison of the fleet specific tag reporting rates from the SS (tag-low, cpue-high) (diamonds) and MFCL (squares) bigeye tuna models.

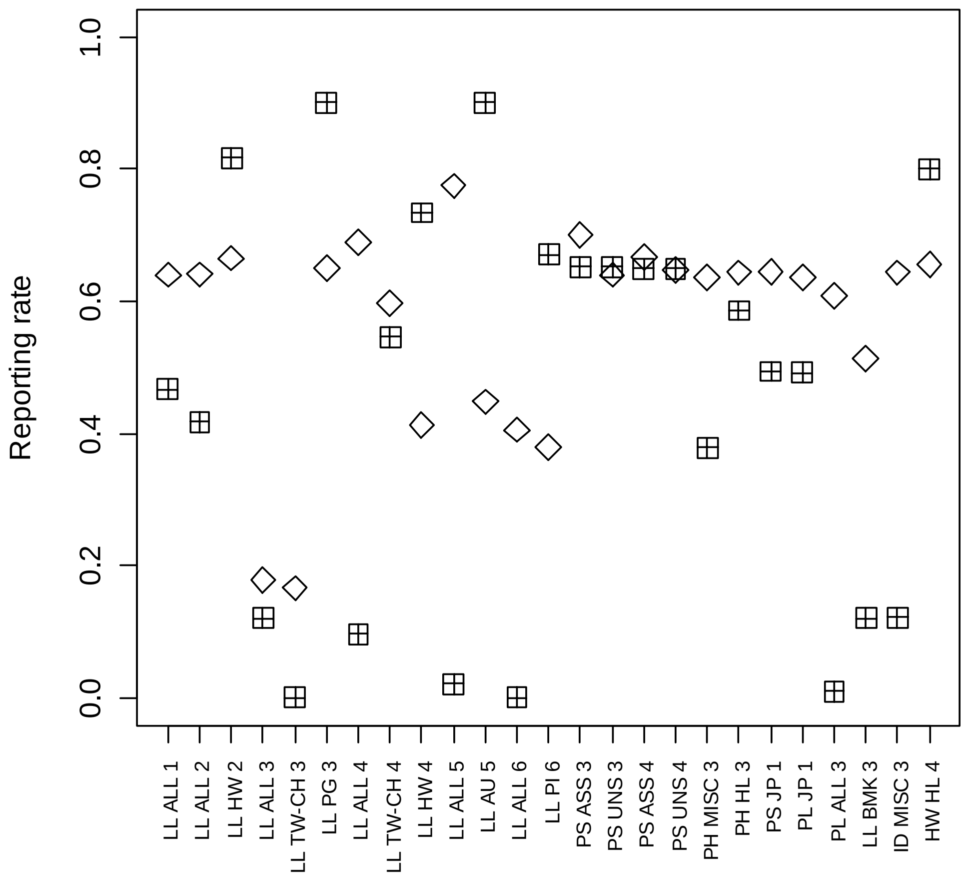

Figure 13. A comparison of the fleet specific tag reporting rates from the SS (tag-high, cpue-high) (diamonds) and MFCL (squares) bigeye tuna models.

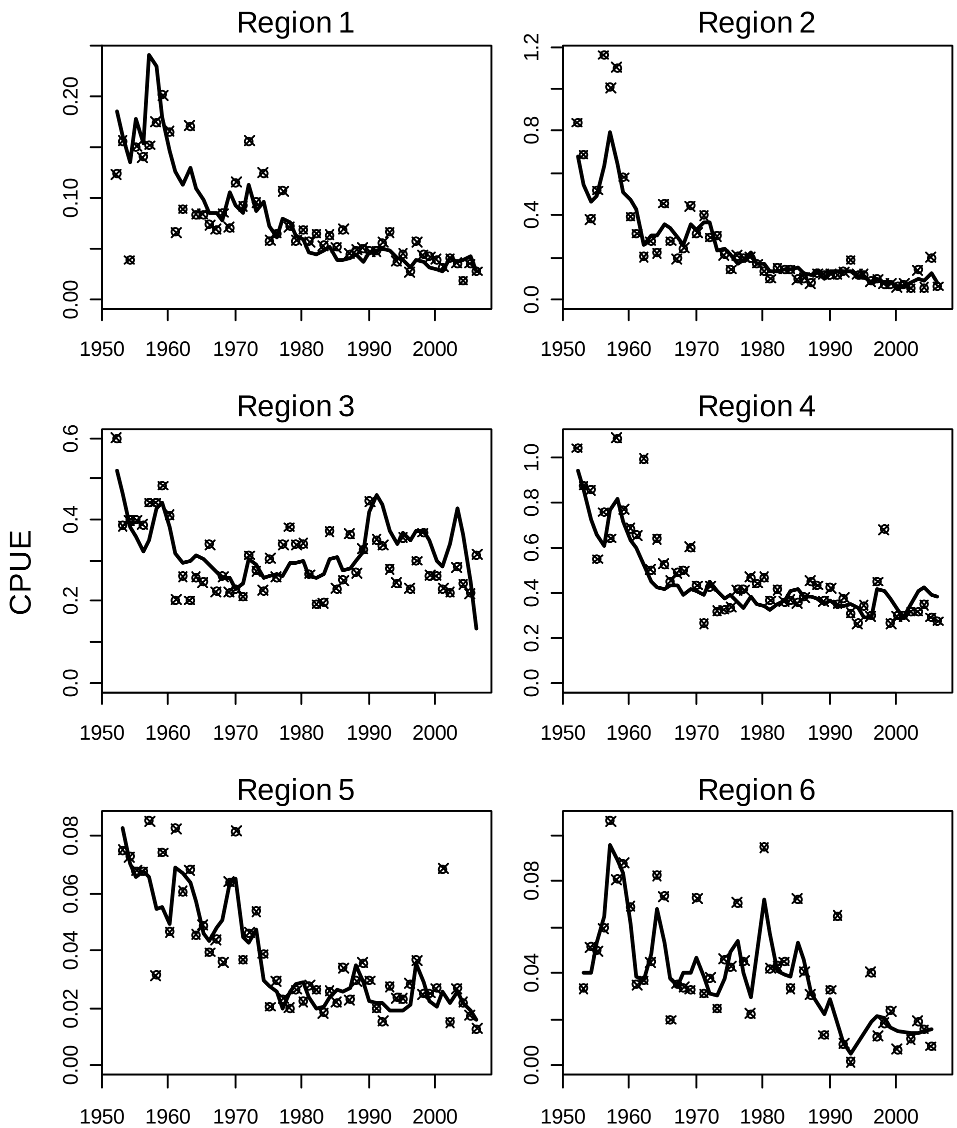

Figure 14. The fit to CPUE ("survey") data (points, observations; line, expected) from the SS (tag-low, cpue-high) WCPO bigeye model with length based selectivity for the TW-CN longline fisheries (tw-cn-length-select).

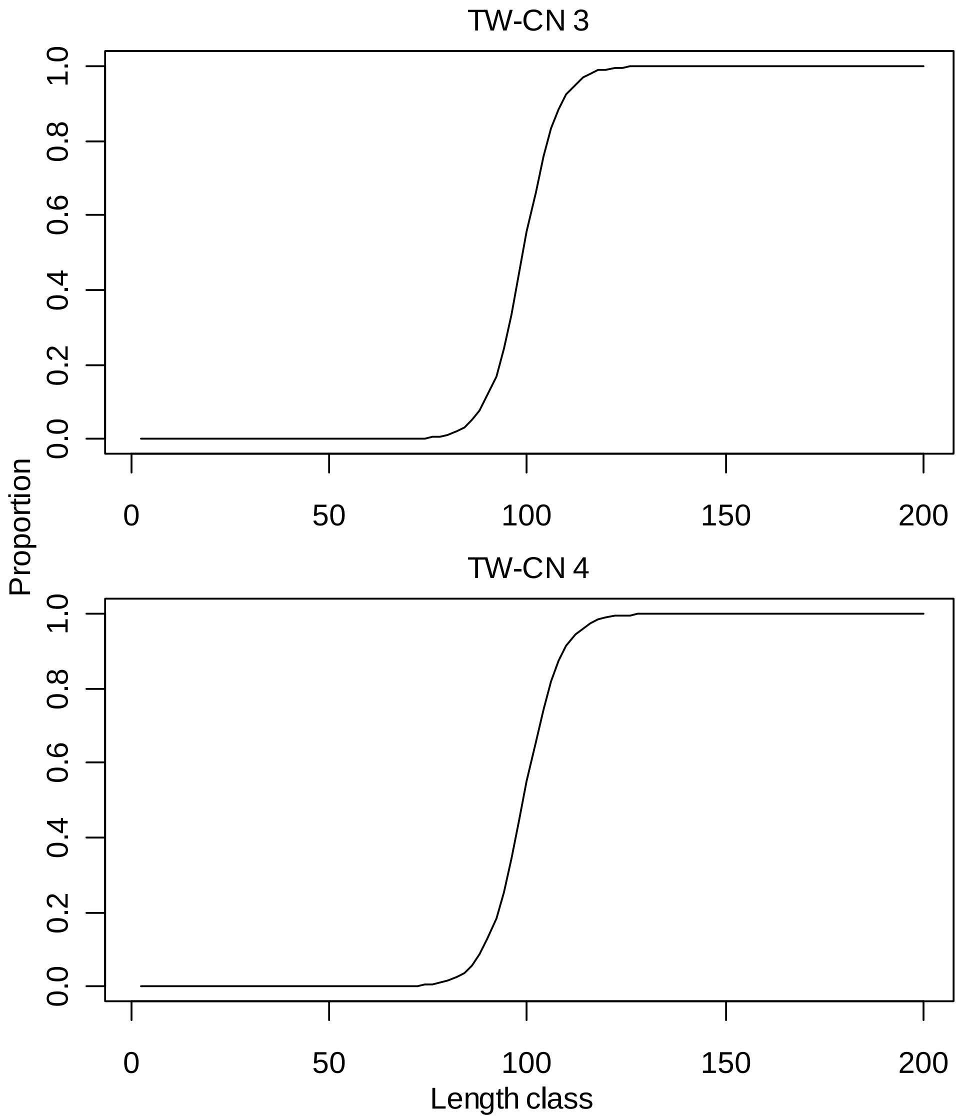

Figure 15. Estimated logistic length-based selectivity functions for the Taiwanese-Chinese longline fisheries in regions 3 and 4 from the tw-cn-length-select SS model.

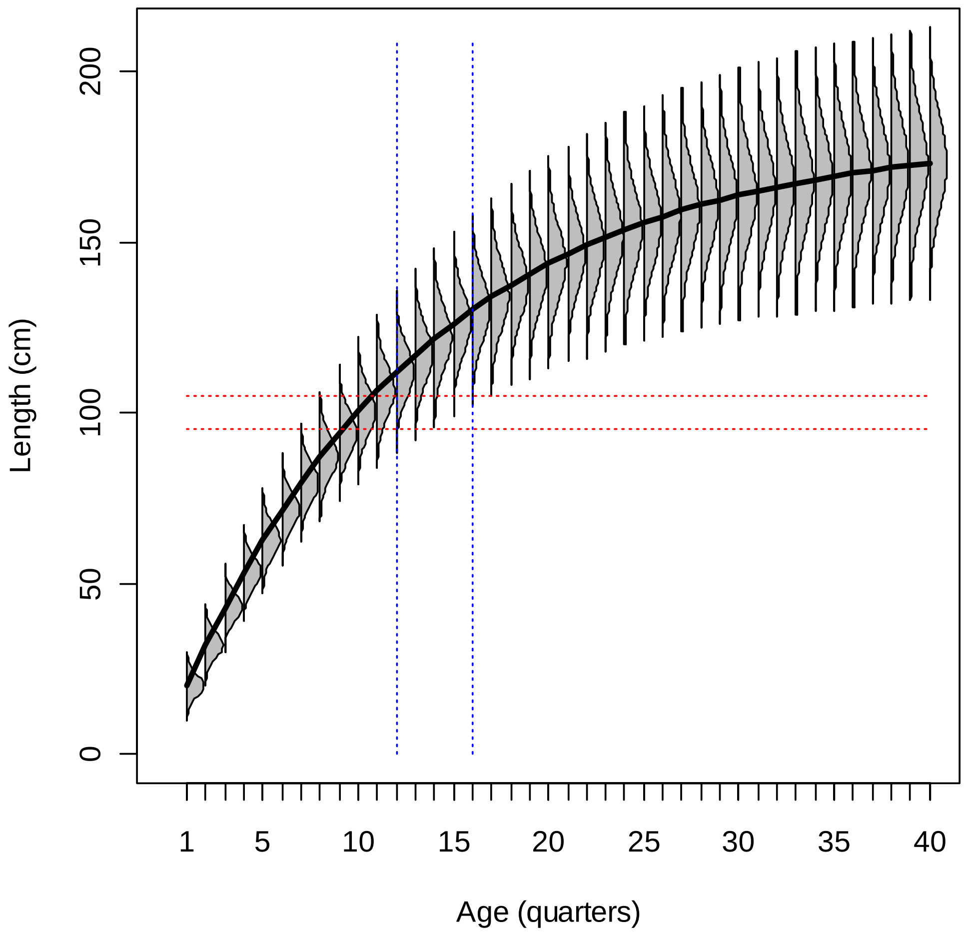

Figure 16. Estimated growth of bigeye derived from the assessment model. The black line represents the estimated length (FL, cm) at age and the grey area represents the estimated distribution of length at age. The red dashed lines represent the length of 25% and 75% selection by the TW-CN longline fisheries from the tw-cn-length-select SS model. The blue dashed lines represent the age of 25% and 75% selection by the TW-CN longline fisheries from the (tag-low, cpue-high SS model.

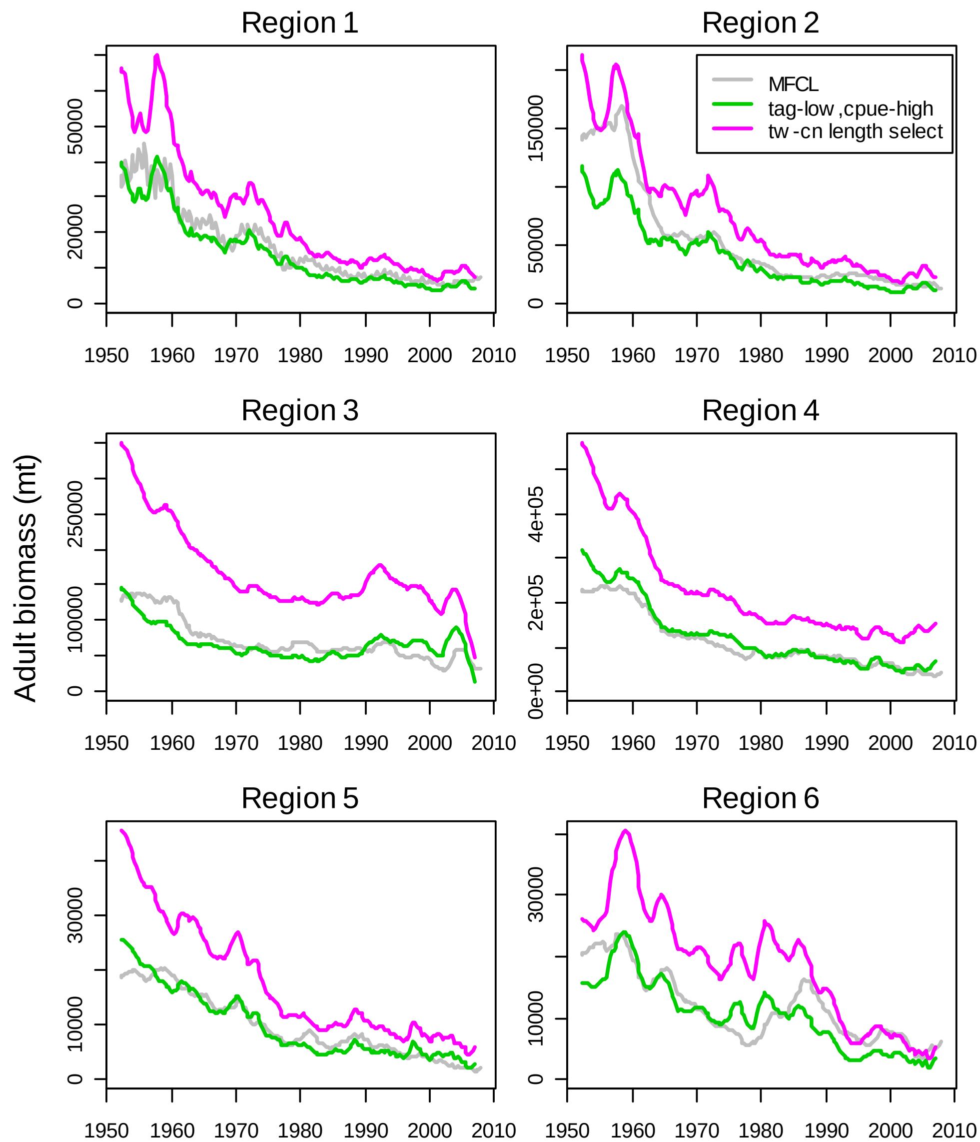

Figure 17. Trends in bigeye adult biomass (mt) by region for the SS models with length- or age-based selectivity for the TW-CN longline fisheries and the 2008 MFCL base case assessment.

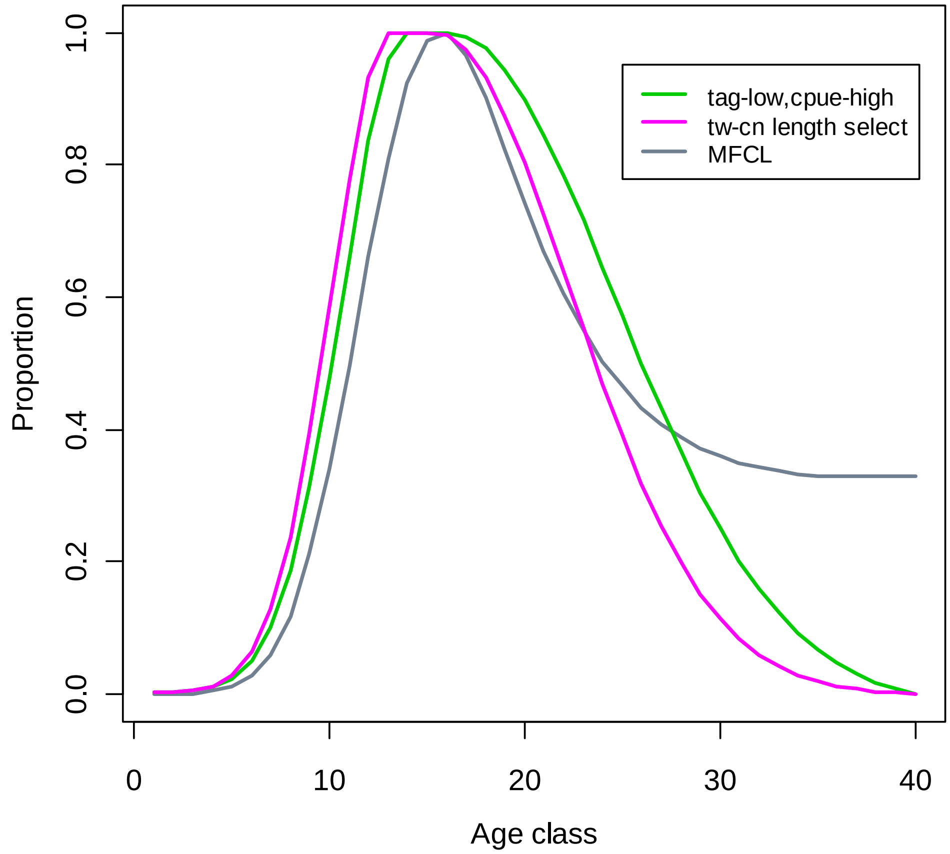

Figure 18. Age-specific selectivity of the principal longline fisheries from the MFCL model and the SS models with length- or age-based selectivity for the TW-CN longline fisheries.

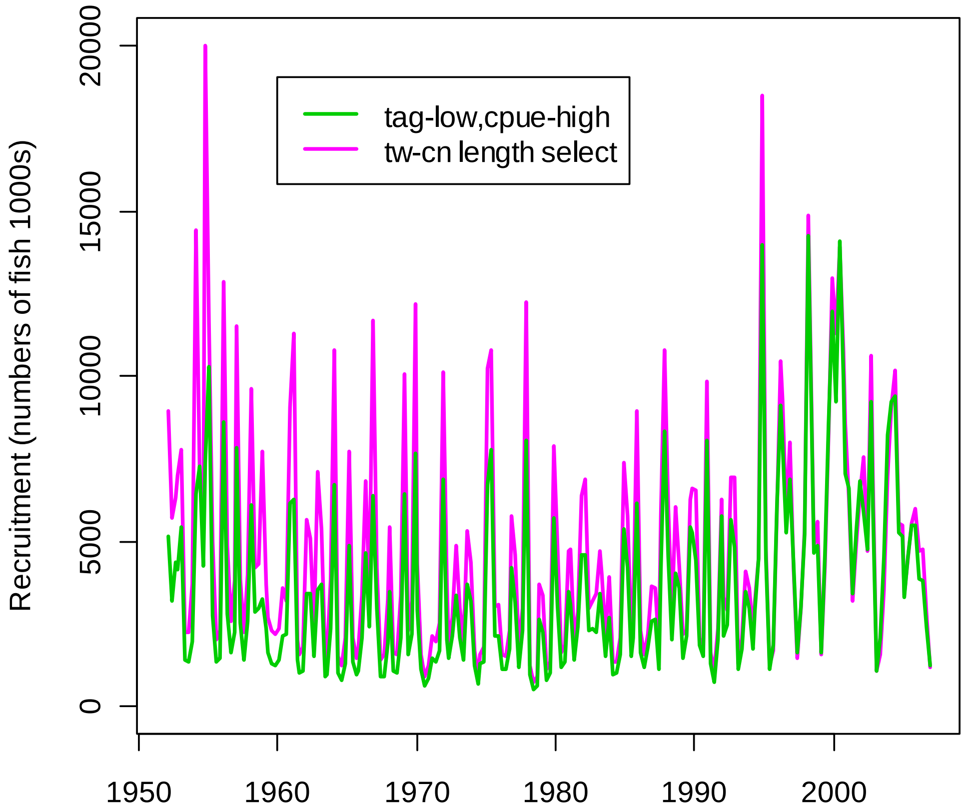

Figure 19. Temporal trend in total recruitment from the SS models with length- or age-based selectivity for the TW-CN longline fisheries.