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Operating Models for Bigeye Tuna in the WCPO

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Contents

Executive Summary

In this paper we develop a grid of operating models (OMs) for WCPO bigeye tuna, designed to capture the most important sources of uncertainty. As a starting point we consider the scenarios identified in recent stock assessments as well as recommendations from a recent review of the 2020 yellowfin stock assessment where they apply to bigeye tuna. We summarise the analyses and conclusions from several recent studies that support the most recent stock assessment. We note that the stock assessment uncertainty grid includes factors that affect the current status and historical trajectory of the stock and investigate a limited set of additional sources of uncertainty associated with future stock dynamics.

The bigeye oprating models presented here have been developed using a combination of modelling approaches that employ MULTIFAN-CL for fitting models to historical observations and a revised framework (working title Tandoori) for projecting into the future. The revised framework implements deterministic and stochastic projections in the same way as MULTIFAN-CL but allows for a much larger and more flexible range of stochastic inputs. Testing of the framework yields identical projection outcomes to those of MULTIFAN-CL for projections conducted with fishery-specific constraints for either catch or effort.

We present a reference set of 24 operating models for bigeye tuna that includes alternative settings for steepness, tag mixing, future recruitment variability and effort creep. We note that additional sources of uncertainty could include alternative spatial structures and movement dynamics, and hyperstability in CPUE. These additional sources of uncertainty can be further investigated and included in future reference or robustness sets, as appropriate.

Bigeye tuna OM uncertainty grid (reference set, 24 model scenarios).

Axis	**Levels**	**Options**		
		0	**1**	**2**
Process Error				
Recruitment variability	**2**	**1962-2020**	**2010-2020**	
Observation Error				
Catch and effort	**1**	**20%**		
Model Error				
Steepness	**3**	**0.8**	**0.65**	**0.95**
Mixing period (qtr)	**2**	**1**	**2**	
Growth	**1**	estimated internally		
Movement	**1**	estimated internally		
DD catchability (k)				
Implementation Error				
Effort creep	**2**	**0%**	**PS 2%, LL 1%**	

Whilst this grid is considered sufficient for testing candidate bigeye MPs, a number of additional sources of uncertainty have been identified that can be included in the robustness set at a later date, but may also be considered for the reference set. In particular, we recommend further investigation of growth and natural mortality assumptions, as well as the development of scenarios for alternative spatial structures and movement dynamics.

We note that the technical approach to modelling alternative FAD closure periods within stock projections is well established through recent analyses. Current MSE modelling assumes the closure specified in CMM 2023-01 will continue into the future. SC may wish to note and discuss the current proposed settings for future work, and seek guidance from the Commission on the settings appropriate for the bigeye tuna MSE.

We invite SC21 to:

- confirm that the reference set of OMs reflects the most important sources of uncertainty and plausible states of nature for WCPO bigeye tuna.
- agree the reference set of OMs as the basis for testing candidate MPs.
- provide guidance on the settings to assume for future FAD closure scenarios.
- note that work will continue in the longer-term to further develop the OMs and that ongoing development of the OMs can be managed through an agreed monitoring strategy.

1 Introduction

The harvest strategy approach provides a framework for taking the best available information about a stock or fishery and applying an evidence and risk-based approach to setting harvest levels. An important benefit of the harvest strategy approach is the explicit consideration of uncertainty when designing, testing and selecting management procedures. Testing candidate management procedures before they are implemented increases the chance that defined management objectives will be achieved.

When testing candidate MPs it is important that appropriate consideration is taken of the various sources of uncertainty that can impact on management performance. Some sources of uncertainty will be more influential than others and not all of them will need to be considered. Ideally, the range of operating models should encompass all plausible states of nature such that the inclusion of new information (when available) should reduce the range of uncertainty and not increase it.

Under the WCPFC harvest strategy workplan, SC21 is scheduled to agree the operating models (OMs) for bigeye tuna in the WCPO.

In this paper we develop a grid of OMs for WCPO bigeye tuna, designed to capture the most important sources of uncertainty. As a starting point we consider the scenarios identified in recent stock assessments (Ducharme-Barth et al., 2020; Day et al., 2023) as well as any recommendations from a recent review of the 2020 yellowfin stock assessment (Punt et al., 2023) that may also apply to bigeye. We note that the stock assessment uncertainty grid includes factors that affect the current status and historical trajectory of the stock and investigate a limited set of additional sources of uncertainty associated with future stock dynamics. We consider previous work on retrospective and hindcast analyses to determine the prediction skill of the proposed operating models. We present recommendations for an initial OM grid and investigate options for simulating future catch and effort data.

1.1 Revised MSE framework

Previous work to evaluate candidate MPs for WCPO tuna stocks has been based on a modelling framework largely built around the stock assessment software MULTIFAN-CL (Scott et al., 2019). Due to a number of limitations of this approach for MSE, a revised framework has been developed that provides greater flexibility, particularly for future modelling assumptions (see appendix D for further details). The revised framework provides a platform for running the evaluations but cannot, in its current form, be used for fitting the models to data. In this respect there is still a reliance on MULTIFAN-CL for 'conditioning' the operating models.

2 Sources of uncertainty

To the extent possible, key sources of uncertainty are taken into consideration during the stock assessment development process, and a grid of assessment models is routinely constructed to try to capture the most influential of these. The 2023 assessment of bigeye tuna in the WCPO comprised a final grid of 54 models with alternative settings for steepness of the stock and recruitment relationship, the time period for tag mixing, and the relative weighting given to the size composition data and the weight frequency data in the assessment (Table 2). Additional sources of uncertainty, such as alternative data weighting approaches, spatial structures and movement dynamics, were also considered during the development of the 2023 assessment, but were not included in the final grid.

We review the main biological and fishery characteristics to determine the most important components to include in the grid of operating models for bigeye tuna.

2.1 Growth, maturity and natural mortality

Despite recent improvements in our understanding of growth rates in bigeye tuna, growth remains an area of uncertainty. The form of the assumed growth curve was a major focus of the 2017 stock assessment (McKechnie et al., 2017) for which updated otolith aging data significantly revised estimates of length at age. Subsequent stock assessments have continued to source additional information on bigeye growth rates and to explore alternative functional forms of the assumed length at age relationship (Ducharme-Barth et al., 2020).

For previous bigeye assessments, growth was estimated externally and used within the assessment as fixed, pre-determined estimates of length at age. Following a recommendation from the review of the yellowfin assessment, growth parameters for the 2023 assessment (Day et al., 2023) have been estimated internally as part of the stock assessment model fit. Fits were facilitated by the inclusion of additional conditional length at age data. Maximum length at age was estimated between 146 to 155 cm across the assessment model grid (Figure 7), consistent with previous analyses. A small range of alternative growth assumptions were investigated (see Appendix C) but were not included in the OM grid as they had minimal impact on estimates of stock status.

Growth, maturity and natural mortality are intrinsically linked. Individuals that grow faster are likely to reach sexual maturity at an earlier age (Charnov and Berrigan, 1991). The 2023 assessment assumed functional relationships for maturity and natural mortality that were linked to estimated growth rates. Natural mortality at age was estimated assuming a Lorenzen functional form (Lorenzen, 2022; Hamel and Cope, 2022), where M for the oldest age class was estimated, and an inverse relationship with length assumed for younger ages. Similarly, maturity at age was determined from length estimates from a maturity at length ogive. As such, variability in maturity and natural mortality (Figure 7) is incorporated into the OM grid given the variability in fitted growth rates.

The range of values assumed for growth, natural mortality and maturity at age in the OM grid are shown in Figure 7 and are determined from model estimates of length at age from individual MULTIFAN-CL fits. We note the relatively narrow range of stock status estimates resulting from these fitted growth models and recommend further work to better determine the full range of uncertainty in these biological processes.

2.2 Recruitment dynamics

Variability in future recruitment is one of the most significant sources of uncertainty represented in the operating models. Uncertainty in recruitment dynamics relates to the functional form of the stock and recruitment relationship (in particular its dynamics at low levels of stock abundance), the spatial and seasonal distribution of recruits amongst model regions, and the overall level of variability in annual recruitments.

Steepness is routinely included in the uncertainty grids for both stock assessments and MSE evaluations. Steepness, which refers to the slope of the stock and recruitment curve (SRR) as it approaches the origin, often has less impact on stock assessment results, but can have substantial impact for MSE analyses when evaluating the performance of management procedures in situations where the stock is reduced to low biomass levels. The assumed value of steepness can impact on the risk of breaching the limit reference point. Given the considerable uncertainty in the true recruitment dynamics at low stock sizes a range of steepness values are typically assumed to represent either low (h=0.65), intermediate (h=0.8), or high stock productivity (h=0.95) at low levels of abundance.

The most recent bigeye stock assessment applied an annual stock and recruitment relationship for all regions of the assessment combined. Recruits were then proportionally allocated across seasons and regions according to a time invariant distribution which is estimated in each model run (Figure 2). The spatial and temporal distribution of recruits is closely linked with the estimated movement dynamics. Any alternative scenarios for recruitment distribution would need to be considered in association with corresponding movement estimates. We note the potential for changes in the seasonal and spatial distribution of recruitment under future climate change scenarios but do not include them in the grid at this stage pending futher work on alternative movement dynamics.

Recent assessments of bigeye tuna have indicated a trend for increasing recruitment through time and projections of future stock status have typically included options for both high and low future recruitment levels (Pilling et al., 2024). Although less apparent in the most recent assessment (Figure 3), this pattern remains. Since it is unclear what overall level of recruitment may occur in the future, the two options continue to be considered and are included in the OM grid.

Within the MSE modelling framework, future stochastic recruitment is applied as deviates to the predictions of the stock and recruitment relationship. Deviates are sampled from the historical period. Scenarios represented in the OM grid draw deviates from the recent, more positive, period (2010-2020) and from a longer, less positive, period (1962-2020), giving rise to the alternative future scenarios shown in Figure 6.

The bigeye OMs employ an annualised stock and recruitment relationship. Deviates are applied to each time period (yrqtr) within each future calendar year according to the average seasonal recruitment distribution so as to maintain the regional and seasonal distribution of recruitment into the future.

2.3 Tag release and recapture data

Tag release and recapture data from three tagging programs (RTTP, PTTP, JPTP) were used for the 2023 stock assessment of bigeye tuna. The tag mixing period, the time taken for tagged fish to become fully mixed with the untagged population, can be an important assumption in the model development process. Model estimates are often sensitive to this assumption (Kolody and Hoyle, 2014) and alternative tag mixing periods typically feature in the stock assessment uncertainty grid.

To inform on the most appropriate tag mixing period to assume for the 2023 assessment, the spatial distributions of relative recapture rates along with the displacement distances of tag recaptures (i.e. distance from point of release) were plotted to provide an indication of reasonable mixing period assumptions to apply (Teears et al., 2023). Overall for tag release events with good numbers of recaptures these qualitative analyses supported the use of tag mixing periods of either 1 or 2 quarters, consistent with the assumptions of previous assessments. Scenarios for either 1 or 2 quarter mixing have been included in the OM grid.

2.4 Spatial distribution and movement dynamics

Stock assessments for tropical tunas in the WCPO typically incorporate spatial structure to try account for the impact on the population of spatial heterogeneity in fishing operations (Hampton and Fournier, 2001; Fournier et al., 1997). The assumed spatial structure of the population and fishery is a key consideration for each stock assessment and often changes as new information becomes available and as new modelling approaches are developed (Goethel et al., 2011; Berger et al., 2017).

Genomic analyses of bigeye tuna indicate that a single panmictic stock exists within the WCPO (Natasha et al., 2022). A review of spatial structures and associated biological information for bigeye and yellowfin tuna (Hamer et al., 2023) supported options for moving to simpler spatial stratifications. The review highlighted the advantages of simpler spatial models, noting the associated improvements in stability and efficiency of stock assessments. However, simpler models may limit possibilities for modelling alternative scenarios for biological and fishery processes when, for example, considering the spatial effects of short-term environmental forcing or longer-term climate change scenarios in management strategy evaluations (MSE). It may therefore be preferrable for operating models to have greater spatial complexity than stock assessments and, where possible, to consider a range of alternative spatial structures.

The 2023 bigeye stock assessment incorporates internally estimated seasonal movement rates that are age and time invariant (Figure 4). Alternative movement dynamics of bigeye tuna were considered in the 2023 assessment as a one-off sensitivity analysis, but due to time constraints were only briefly explored. That sensitivity analysis used alternative age-specific and temporally varying SEAPODYM derived movement (Senina et al., 2023). It showed relatively poor model diagnostics and was not explored further. Hamer et al. (2023) suggest that a 6 region model for bigeye tuna may be appropriate, although additional complexity may be required to account for tag mixing assumptions. They note that, for both bigeye and yellowfin tuna, the 9 region spatial structure, as used for the OMs presented here, remains appropriate and may continue to be applied.

The investigation of alternative spatial structures and movement dynamics of tropical tunas is an active area of research. Future iterations of the bigeye tuna OMs will likely be informed by ongoing developments in tagging programmes and model development (OFP, 2025; Davies et al., 2025; Magnusson et al., 2024). At present, the 9-region model forms the basis of the models identified for the OM grid.

2.5 Hyperstability in CPUE

Stock assessments typically assume that catch per unit effort (CPUE) scales in strict proportion with stock abundance. But for schooling species that form aggregations, such as tunas, there is the potential for CPUE to remain high as stock abundance declines. This is known as hyperstability in CPUE (Harley et al., 2001; Gaertner and Dreyfus-Leon, 2004) and, if not properly accounted for, can lead to biased population estimates (Scott et al., 2015). The true extent of hyperstability in CPUE can be very difficult to determine. Instead, management procedures are often tested against a range of hyperstability assumptions to determine if they are robust to it, in the event that it is occurring.

Evaluations of the skipjack management procedure (Scott et al., 2022) considered a range of CPUE hyperstability scenarios, but found the performance of the MP relatively insensitive to them. This is because the MP maintained the biomass of the skipjack stock at relatively constant levels. Without significant changes in stock abundance there was little change in the realised CPUE and little impact of any potential hyperstability.

We note the potential for hyperstability in CPUE for catches of bigeye tuna in purse seine fisheries but consider it is less likely to occur in longline fishing operations. At present, hyperstability in CPUE is not included in the OM grid, but could be incorporated, if desired, specifically for purse seine fisheries.

2.6 Effort creep

A potential source of implementation error is the occurrence of effort creep in commercial fishing operations. Where effort creep is occurring, the efficiency of vessels increases as a result of, for example, technological developments and improvements, such that nominal fishing effort (e.g.days fished) no longer represents a consistent and reliable measure of fishing activity.

Two effort creep scenarios have been included within the OM grid. In the first, effort creep is assumed not to occur. The second assumes a 2% annual increase in effective effort for purse seine fisheries, similar to the levels assumed when testing the skipjack MP, and a 1% annual increase in effective effort for longline fisheries. A higher value of effort creep for longline fisheries of 3% might be considered for robustness testing. These values are informed by recent studies to determine appropriate estimates of effort creep, (Hoyle, 2024; Hamer et al., 2024) but are also selected to bound the uncertainty in potential levels of effort creep.

2.7 Climate change scenarios

The development of climate change scenarios and their incorporation into the operating models for WCPO tuna stocks has been identified as an important task. Recent developments in the quantitative modelling of tuna population dynamics with SEAPODYM (Senina et al., 2021) provide a platform for developing scenarios for alternative spatial structures, movement rates and recruitment distributions under future climate change predicitons.

Initial attempts to investigate climate change impacts through the MSE framework have been limited, in part, by the options available for projections conducted using MULTIFAN-CL. The implementation of time-varying parameters for movement, growth, recruitment, catchability, etc. that would be necessary to investigate the effects on the stock and fishery of a progressively changing environment is not possible using MULTIFAN-CL in its current form. To address these, and other, issues an alternative modelling framework has been developed for running MSE analyses for WCPO tuna stocks. The framework (working title Tandoori) implements deterministic and stochastic projections in the same way as MULTIFAN-CL but allows for a much larger and more flexible range of stochastic inputs. This revised framework will provide a more tractable approach to developing climate change scenarios for MSE. The development of climate change scenarios, however, is non-trivial and is expected to occur over a longer time-frame.

2.8 FAD management measures

A temporary closure of purse seine FAD fishing has been in place since 2009. In 2024 the extent of the FAD closure was reduced to around half of what it had been in recent years. Catches of bigeye tuna in the purse seine fishery are mostly taken in FAD sets and any change in the relative proportion of FAD vs free school fishing is likely to have implications for the quantity of bigeye caught in the purse seine fishery (SPC-OFP, 2014; Hampton and Pilling, 2014).

The separation of FAD and free-school fishing operations for purse seine fisheries in the operating models (Table 1) allows for alternative FAD closure scenarios to be implemented. This can be achieved simply by scaling the effort of one group of fisheries relative to that of others such that the overall purse seine effort remains the same but the split of FAD vs free-school fishing changes

(Scott et al., 2025b). Through this approach alternative FAD closure periods can be evaluated.

We do not propose that the FAD closure period be included in the OM grid. The extent of the FAD closure is not a source of uncertainty but, rather, a factor that can be controlled through management. We therefore propose that any investigation of alternative FAD management measures be undertaken as one-off sensitivity analyses. FAD management measures are further considered in section 6 of this report.

3 Simulated data generation

A critical function of the operating model is the generation of simulated data that represent the information that is routinely collected from the fishery to monitor and assess the status of the stock. Within the evaluation framework these data are used by the management procedure to determine the overall level of depletion that is used as the primary input to the HCR. It is, therefore, particularly important that these simulated data are representative of the type, and quality, of data that are collected in reality.

For the range of candidate management procedures under consideration for bigeye tuna (Wickens et al., 2025) the estimation methods require only catch and effort data as model inputs. There is no requirement to simulate size frequency or tag recapture data. Simulated catch and effort data are generated from model predictions with a time invariant normally distributed observation error (20% c.v.) which is broadly consistent with historical values (Figures 10 and 11).

When generating simulated data with MULTIFAN-CL there was only the option to apply a single coefficient of variation for catch or effort that applied to all fisheries. Under the new OM framework there is greater flexibility to apply fishery specific variability, although for the current grid of OMs only a single option for 20% c.v. across all fisheries has been considered.

4 Bigeye tuna operating models

It is considered best practice to divide the suite of OMs into a reference set and a robustness set (Rademeyer et al., 2007). The reference set is considered to reflect the most plausible hypotheses and forms the primary basis for identifying the 'best' management strategy. The robustness set comprises hypotheses that are considered less likely but still plausible and provides a secondary level of testing that can be applied to a reduced set of preferred MPs.

4.1 OM grid

The key sources of uncertainty to be considered in the OMs and their proposed parameter values are summarised in Table 3. These scenarios provide a grid of 24 OMs representing a combination of model fits and projection settings.

The two data weighting options that were included in the stock assessment grid have been dropped from the OM grid as they had only a relatively small impact on model estimates and contributed little to overall uncertainty in estimates of stock status (Figures 5 and 7). Scenarios for alternative values of steepness and tag mixing have been retained. In addition, scenarios for effort creep and future recruitment variability have been included.

Variability in growth and movement is introduced by the fitted values of individual model runs. A single option for observation error is applied which sets a 20% c.v. on simulated catch and effort.

4.2 Robustness and sensitivity test scenarios

The robustness set provides an opportunity for testing more extreme scenarios on a smaller scale and for testing scenarios that might be difficult to include in the reference set. Whilst no specific models are proposed for the robustness set at this stage, we identify a number of potential scenarios that could be considered.

Catches of bigeye tuna will occur in areas outside the control of the MP. The majority of bigeye tuna are caught in the tropical longline and purse seine fisheries that will be subject to management control either through the skipjack or bigeye MPs (Scott et al., 2023). But a component of the catch will also be taken from fisheries in regions that are outside the control of any current MP.

The development of alternative spatial structures and movement dynamics can require considerable work and is likely to progress over longer time-scales. Including such scenarios, when available, in the robustness set allows for a more progressive approach to developing this area.

A limited set of more extreme settings for factors already included in the reference set can also be included in the robustness set, where considered appropriate. These may include alternative levels of observation error, or more extreme levels of effort creep.

5 Model diagnostics

The six models in the OM grid representing alternative steepness and tag mixing scenarios were fitted using MULTIFAN-CL as part of the 2023 stock assessment. Comprehensive diagnostics for these models are presented in Day et al. (2023). All six models achieved good model diagnostics including positive-definite hessian matrices, indicating satisfactory convergence to a stable solution.

5.1 Goodness of fit

Likelihood profiles for the six model fits of the OM grid (Yao et al., 2024) show relatively good model consistency particularly for the 1 qtr tag mixing models (Figure 8). Under the 2 qtr tag mixing assumption, the different data components of the model start to show greater divergence in model estimates, particularly in the case of the length frequency and weight frequency input data.

5.2 Retrospective analyses

Retrospective analyses for the six model fits of the OM grid (Yao et al., 2024) show little retrospective bias (Figure 9), particularly for the 2 qtr tag mixing models. In all cases Mohn's rho, a measure of retrospective bias, was within guidelines for acceptable tolerance levels proposed by Hurtado-Ferro et al. (2015).

6 Discussion

6.1 FAD closure impacts

In 2024 the extent of the FAD closure reduced from a period of 3 months in EEZs and high seas plus an extra 2 months in the high seas, to a period of 1.5 months in EEZs and the high seas plus an extra 1 month on the high seas. It might be assumed that the current closure period (1.5 + 1) should be taken as the basis for evaluations. Although at this point, it is unclear if there will be further changes to the extent of the FAD closure. Initial evaluations of candidate bigeye MPs (Scott et al., 2025a) have assumed purse seine fishing levels consistent with the reduced (1.5 + 1) FAD closure.

We note that the technical approach to modelling alternative FAD closure periods within stock projections is well established through recent analyses. Current MSE modelling assumes the closure specified in CMM 2023-01 will continue into the future. SC may wish to note and discuss the current proposed settings for future work, and seek guidance from the Commission on the settings appropriate for the bigeye tuna MSE.

6.2 Updating the OM grid through the monitoring stratgy

The proposed grid of OMs comprises 24 models, based on a combination of model and projection settings. It represents a smaller grid than those presented for other WCPO tuna stocks. Whilst this grid is considered sufficient for testing candidate bigeye MPs, a number of additional sources of uncertainty have been identified that can be included in the robustness set at a later date, but may also be considered for the reference set. In some cases further work will be required to develop appropriate scenarios (e.g. for the impacts of climate change or for alternative spatial structures). We note that the OM grid can be modified as new information and modelling approaches become available and that, under an agreed monitoring strategy, the OMs will be regularly reviewed to ensure they remain appropriate.

6.3 Exceptional circumstances

Throughout the evaluation and testing process it must be borne in mind that the identification of a 'best performing' management procedure will be dependent on the range of assumptions over which it has been tested and the extent to which those assumptions reflect the true underlying dynamics of the stock and fishery. The scenarios we have selected are expected to cover the most likely eventualities, but we cannot assume that they cover all eventualities. It is therefore necessary to identify those situations, termed "exceptional circumstances", in which one might need to revisit either the HCR or the overall management procedure.

In general terms, exceptional circumstances include any event that falls outside the range of assumptions over which the management procedure has been tested, but may also include situations where the trajectory of the stock does not respond as expected to management action. For example, if stock status falls outside the expected range, or catches continually exceed some upper threshold.

We do not identify any exceptional circumstances here, but note that the range of OMs selected for the evaluations will be a key consideration when the time comes to identify them. We note that the range of stock status estimates for the proposed OM grid, particularly for the historical period, is relatively narrow and that the wider range of values for the prediction period is largely driven by uncertainty in recruitment. Additional sources of uncertainty have been identified for potential inclusion in the OM grid. These will be further explored, potentially as part of the upcoming stock assessment for bigeye tuna in 2026, and may be included either in future iterations of the OM grid or as one-off sensitivity analyses, as appropriate.

7 Conclusions

We present an initial reference set of 24 operating models for bigeye tuna that includes alternative settings for steepness, tag mixing, future recruitment variability and effort creep. We note that additional sources of uncertainty could include alternative spatial structures and movement dynamics, and hyperstability in CPUE. These additional sources of uncertainty will be further investigated and may be included in either the reference or robustness sets, as appropriate.

We note that the technical approach to modelling alternative FAD closure periods within stock projections is well established through recent analyses. Current MSE modelling assumes the closure specified in CMM 2023-01 will continue into the future. SC may wish to note and discuss the current proposed settings for future work, and seek guidance from the Commission on the settings appropriate for the bigeye tuna MSE.

We invite SC21 to:

- note that the reference set of OMs reflects the most important sources of uncertainty and plausible states of nature for WCPO bigeye tuna.
- agree the reference set of OMs as the basis for initial testing of candidate MPs.
- provide guidance on the settings to assume for future FAD closure scenarios.
- note that work will continue in the longer-term to further develop the OMs and this can be managed through an agreed monitoring strategy.

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A Tables

Table 1: Definition of fisheries for the 2023 bigeye stock assessment in the WCPO.

Fishery No	Fishery	Flag	Region	Sel Group	% catch last 10 yrs	% catch all yrs
F1	LL-ALL-1	ALL	1	1	4.41	7.92
F2	LL-ALL-2	ALL	2	2	4.67	9.17
F3	LL-US-2	US	2	3	3.55	1.75
F4	LL-ALL-3	ALL	3	4	3.00	6.62
F5	LL-OS-3	OS	3	8	3.83	2.34
F6	LL-OS-7	OS	7	9	7.40	6.57
F7	LL-ALL-7	ALL	7	10	1.13	2.26
F8	LL-ALL-8	ALL	8	11	0.42	0.56
F9	LL-ALL-4	AU	4	5	14.88	19.08
F10	LL-AU-5	ALL	5	12	0.30	0.24
F11	LL-ALL-5	ALL	5	7	1.12	1.51
F12	LL-ALL-6	ALL	6	6	2.69	2.07
F13	SA-ALL-3	ALL	3	13	11.59	12.05
F14	SU-ALL-3	ALL	3	16	2.86	1.77
F15	SA-ALL-4	ALL	4	14	17.98	8.08
F16	SU-ALL-4	ALL	4	17	1.08	0.47
F17	Z-PH-7	PH	7	19	1.20	3.33
F18	Z-ID.PH-7	ID.PH	7	20	1.29	0.51
F19	S-JP-1	JP	1	21	0.26	0.47
F20	P-JP-1	JP	1	22	0.96	1.92
F21	PL-ALL-3	ALL	3	23	0.01	0.05
F22	PL-ALL-8	ALL	8	24	0.00	0.01
F23	Z-ID-7	ID	7	25	8.10	3.34
F24	S-ID.PH-7	ID.PH	7	26	0.68	1.06
F25	SA-ALL-8	ALL	8	15	2.13	3.34
F26	SU-ALL-8	ALL	8	18	1.90	0.84
F27	L-AU-9	AU	9	12	0.02	0.04
F28	P-ALL-7	ALL	7	27	1.29	1.83
F29	L-ALL-9	ALL	9	7	0.00	0.02
F30	SA-ALL-7	ALL	7	13	0.03	0.31
F31	SU-ALL-7	ALL	7	16	0.05	0.05
F32	Z-VN-7	VN	7	28	1.20	0.41
Index fisheries						
F33	LL-ALL-1	ALL	1	29		
F34	LL-ALL-2	ALL	2	29		
F35	LL-ALL-3	ALL	3	29		
F36	LL-ALL-4	ALL	4	29		
F37	LL-ALL-5	ALL	5	29		
F38	LL-ALL-6	ALL	6	29		
F39	LL-ALL-7	ALL	7	29		
F40	LL-ALL-8	ALL	8	29		
F41	LL-ALL-9	ALL	9	29		

Table 2: Structural uncertainty grid for the 2023 WCPO bigeye tuna stock assessment.

Axis	Levels	Option 1	Option 2	Option 3
Steepness	3	0.65	0.8	0.95
Tag mixing (# quarters)	2	1	2	
Size data weighting divisor	3	10	20	40
Age data weighting	3	0.5	0.75	1

Table 3: Bigeye tuna OM uncertainty grid (reference set, 24 model scenarios).

Axis	**Levels**	**Options**		
		0	**1**	**2**
Process Error				
Recruitment variability	**2**	**1962-2020**	**2010-2020**	
Observation Error				
Catch and effort	**1**	**20%**		
Model Error				
Steepness	**3**	**0.8**	**0.65**	**0.95**
Mixing period (qtr)	**2**	**1**	**2**	
Growth	**1**	estimated internally		
Movement	**1**	estimated internally		
DD catchability (k)				
Implementation Error				
Effort creep	**2**	**0%**	**PS 2%, LL 1%**	

B Figures

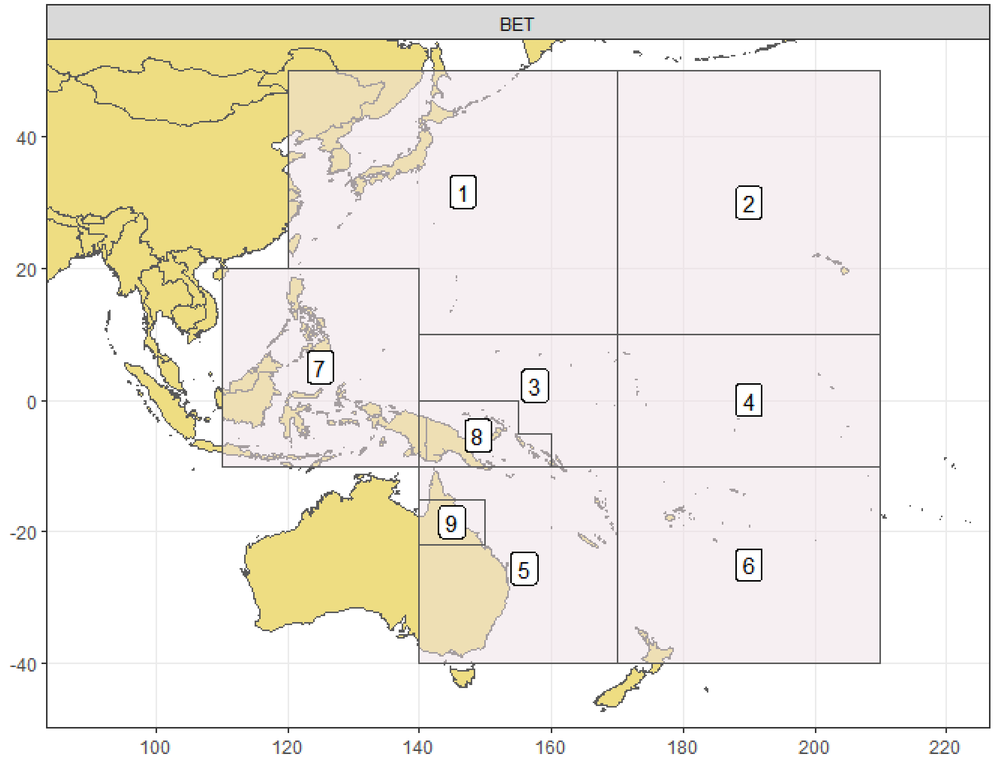


Figure 1: Spatial structure of the bigeye modelling framework.

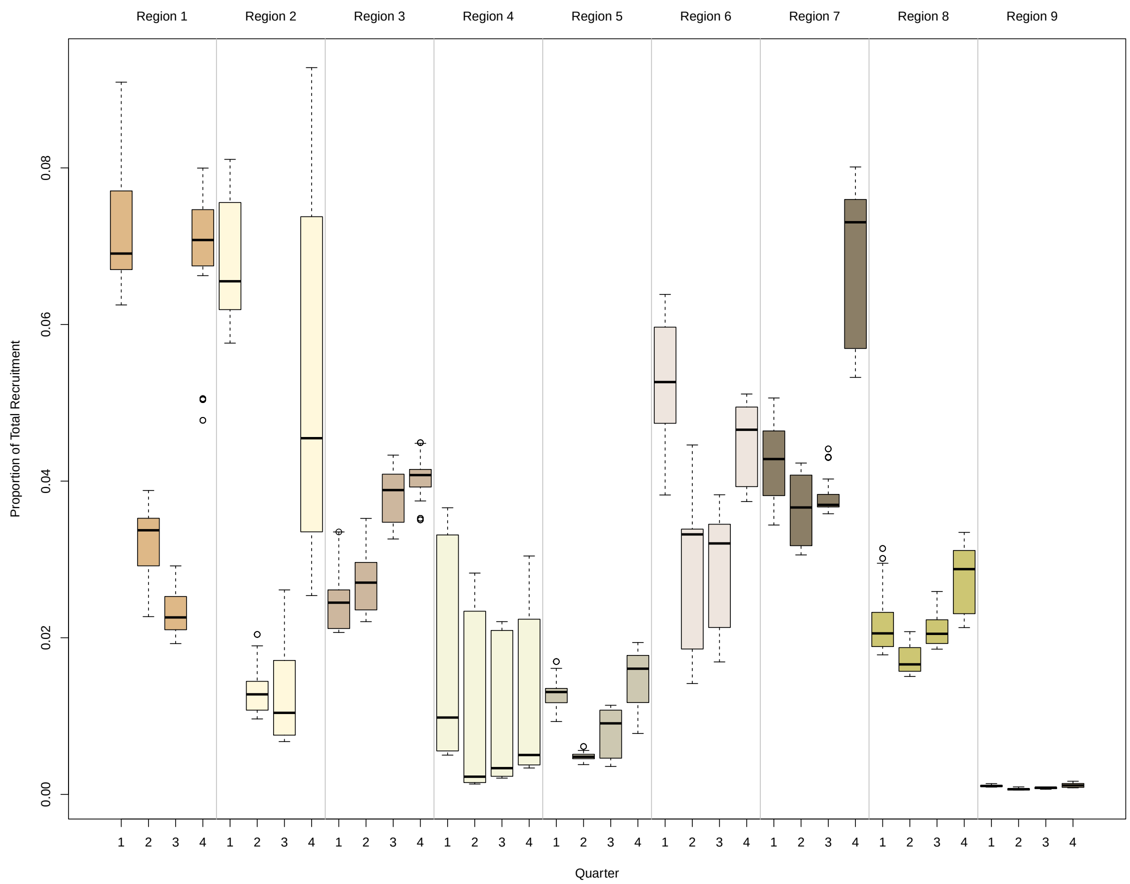


Figure 2: Regional and seasonal distribution of recruitments across the 54 models of the stock assessment grid.

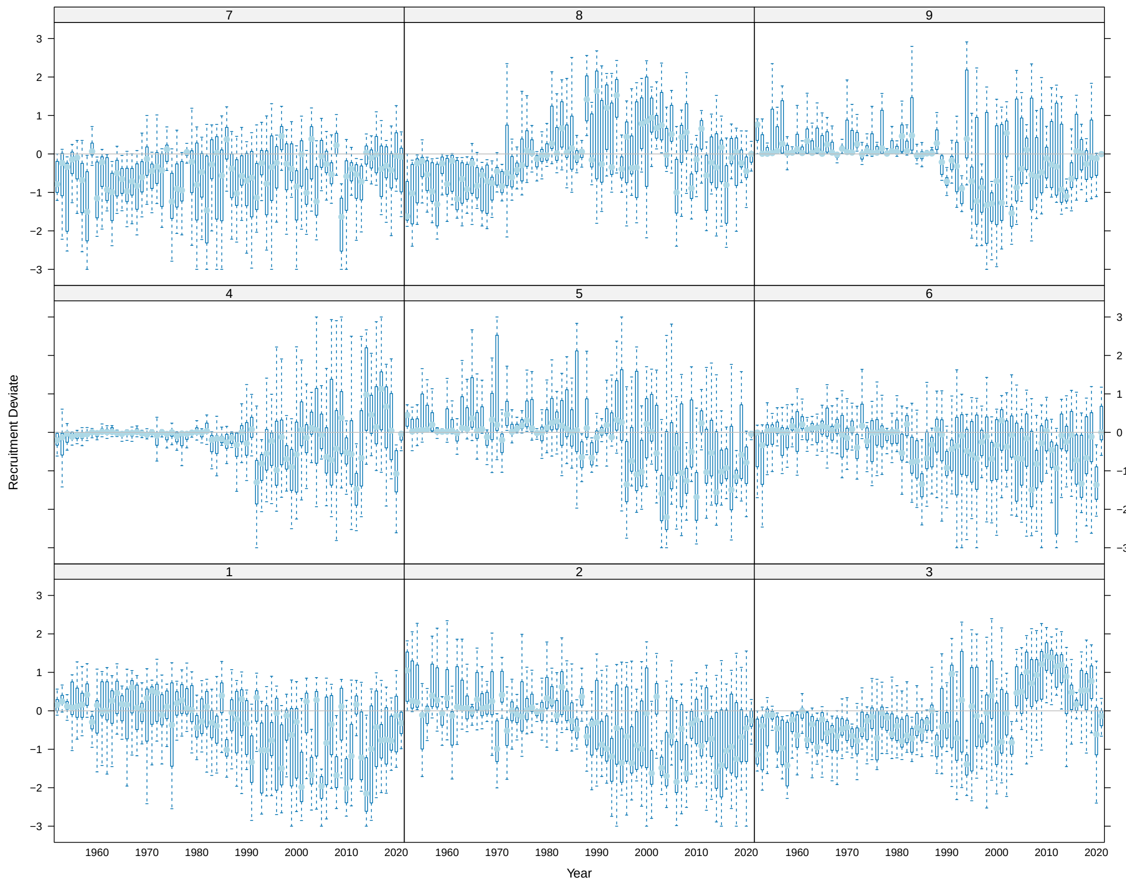
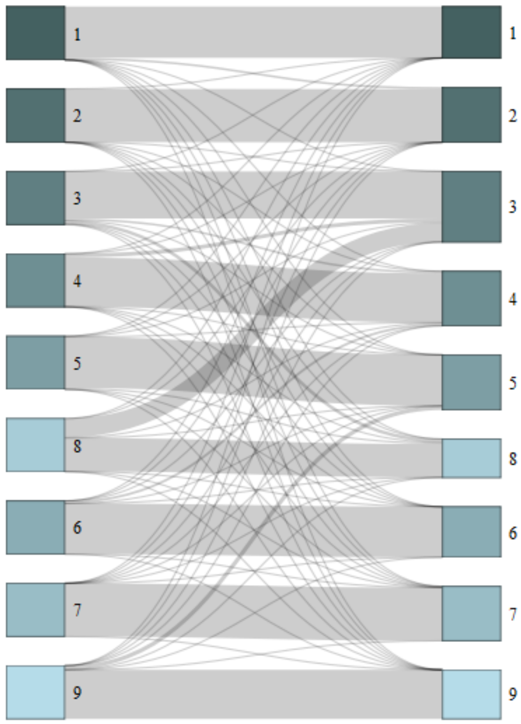
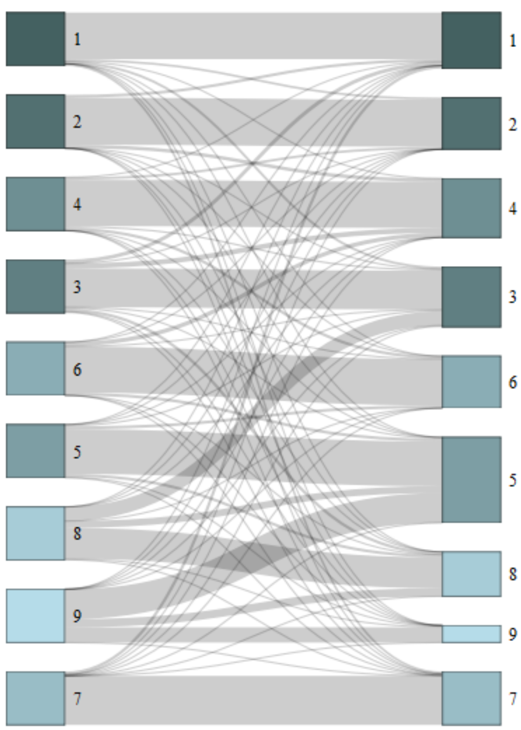


Figure 3: Recruitment deviations from the stock and recruitment relationship, by region, for the 54 models of the stock assessment grid.



(a) MFCL



(b) SEAPODYM

Figure 4: Comparison of estimated movement rates (age 5 yrs, season 1) for WCPO bigeye tuna from MFCL and SEAPODYM.

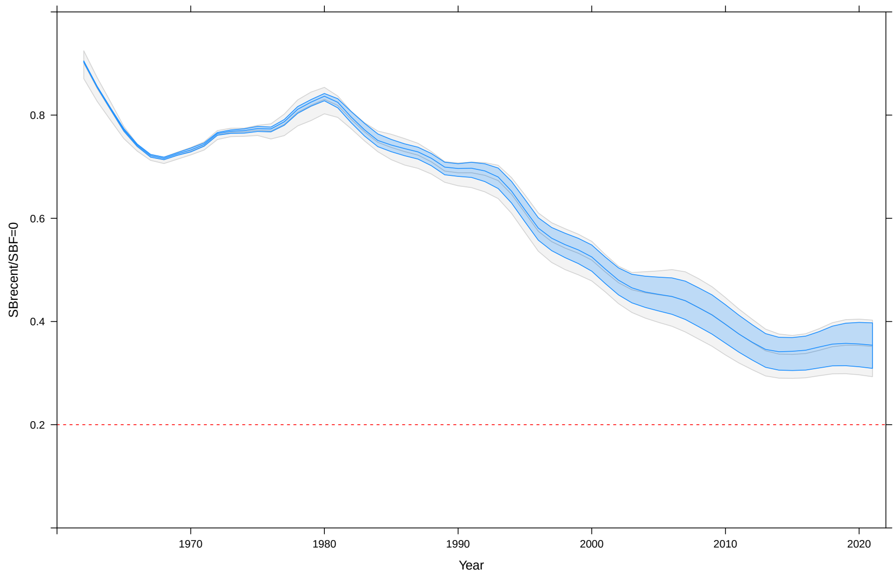


Figure 5: Estimated depletion ($SB_{recent}/SB_{F=0}$) across the 54 models of the stock assessment (grey) and the 6 fitted models of the OM grid (blue).

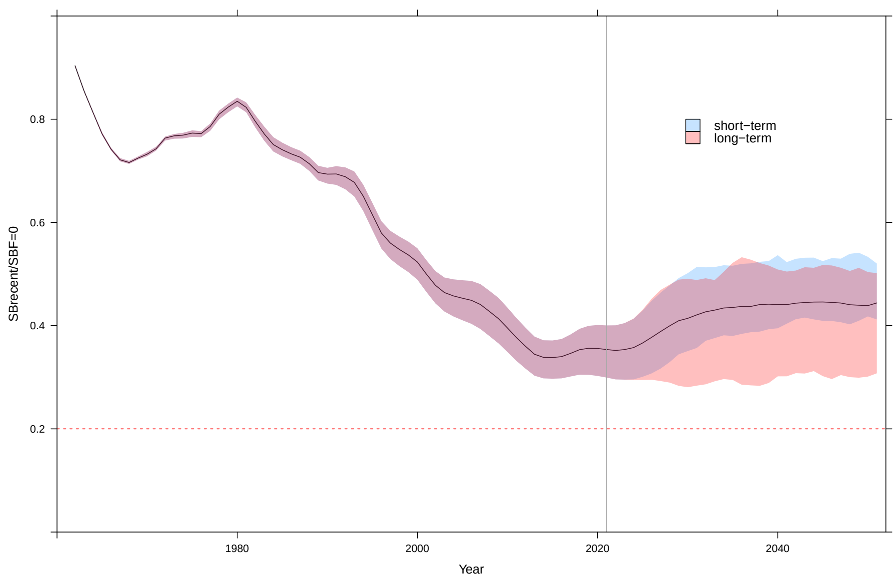


Figure 6: Historical and projected depletion ($SB_{recent}/SB_{F=0}$) across the full OM grid under the short-term (blue) and long-term (red) recruitment assumptions.

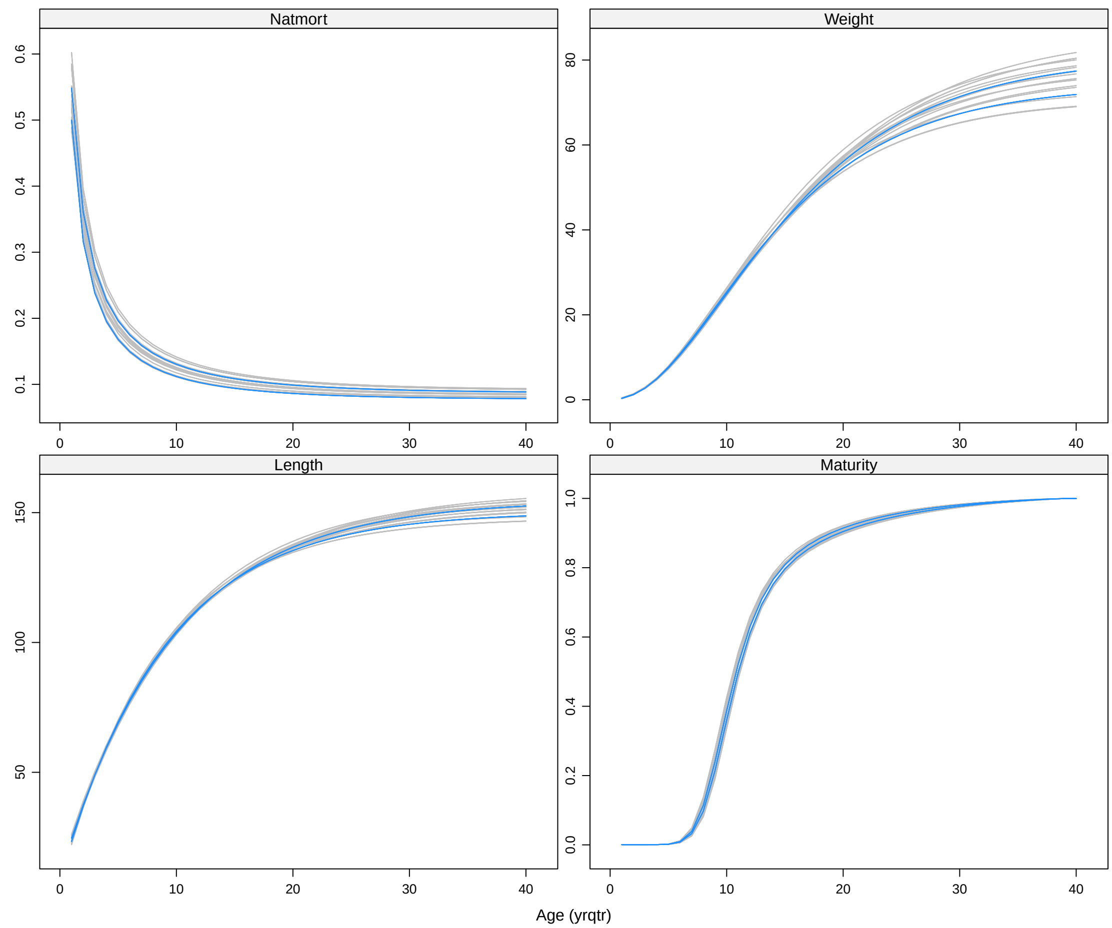


Figure 7: Estimated values of growth, maturity, natural mortality and weight at age across the 54 models of the stock assessment (grey) and the 6 fitted models of the OM grid (blue).

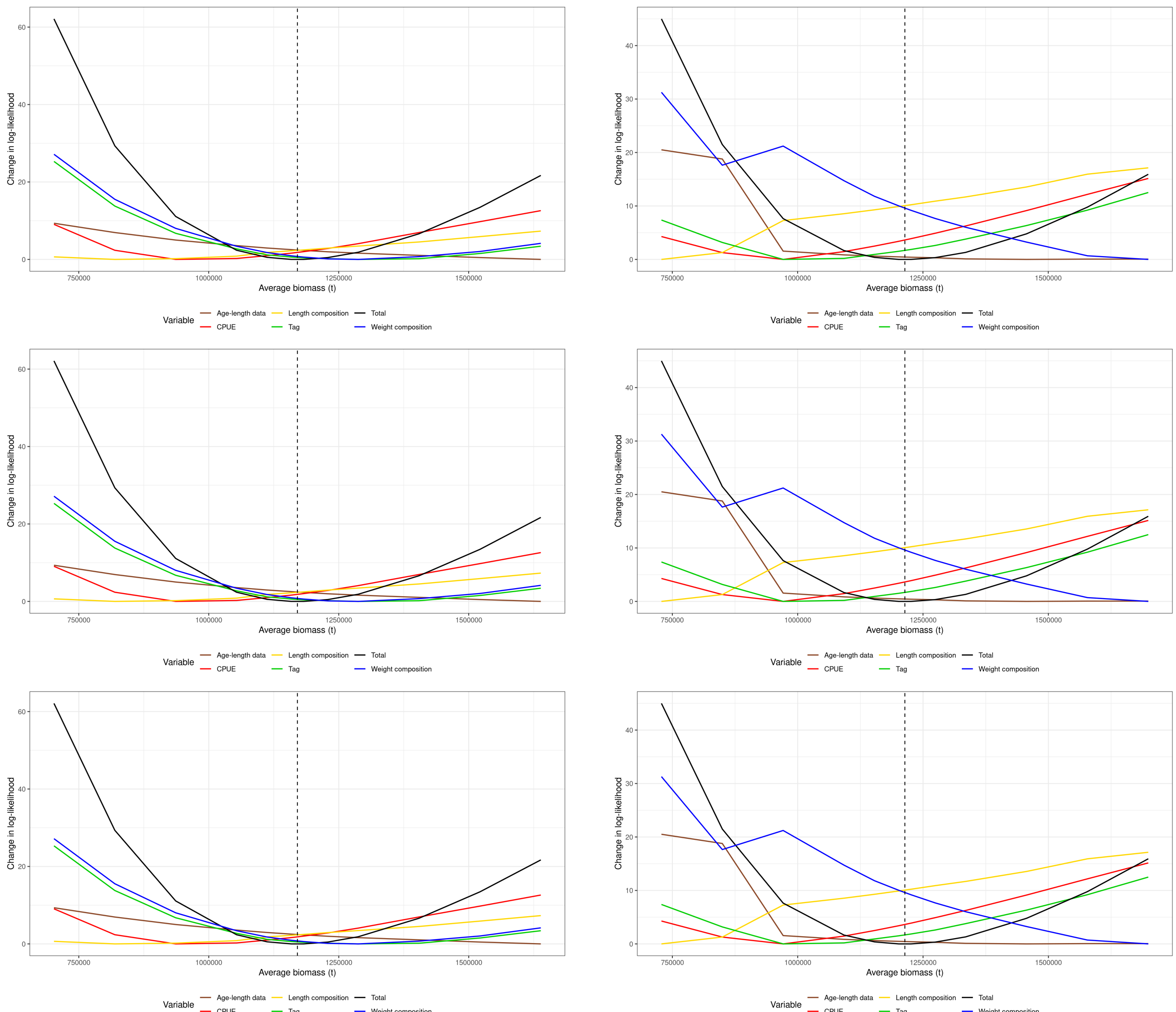


Figure 8: Likelihood profiles of total biomass. Showing the total likelihood (black), CPUE (red), weight frequency (blue), length frequency (yellow), tag data (green), and conditional age length data (brown). Models assuming a 1 qtr tag mixing period are shown in the left column, 2 qtr tag mixing in the right column, with values of steepness increasing from top to bottom (0.65, 0.8, 0.95).

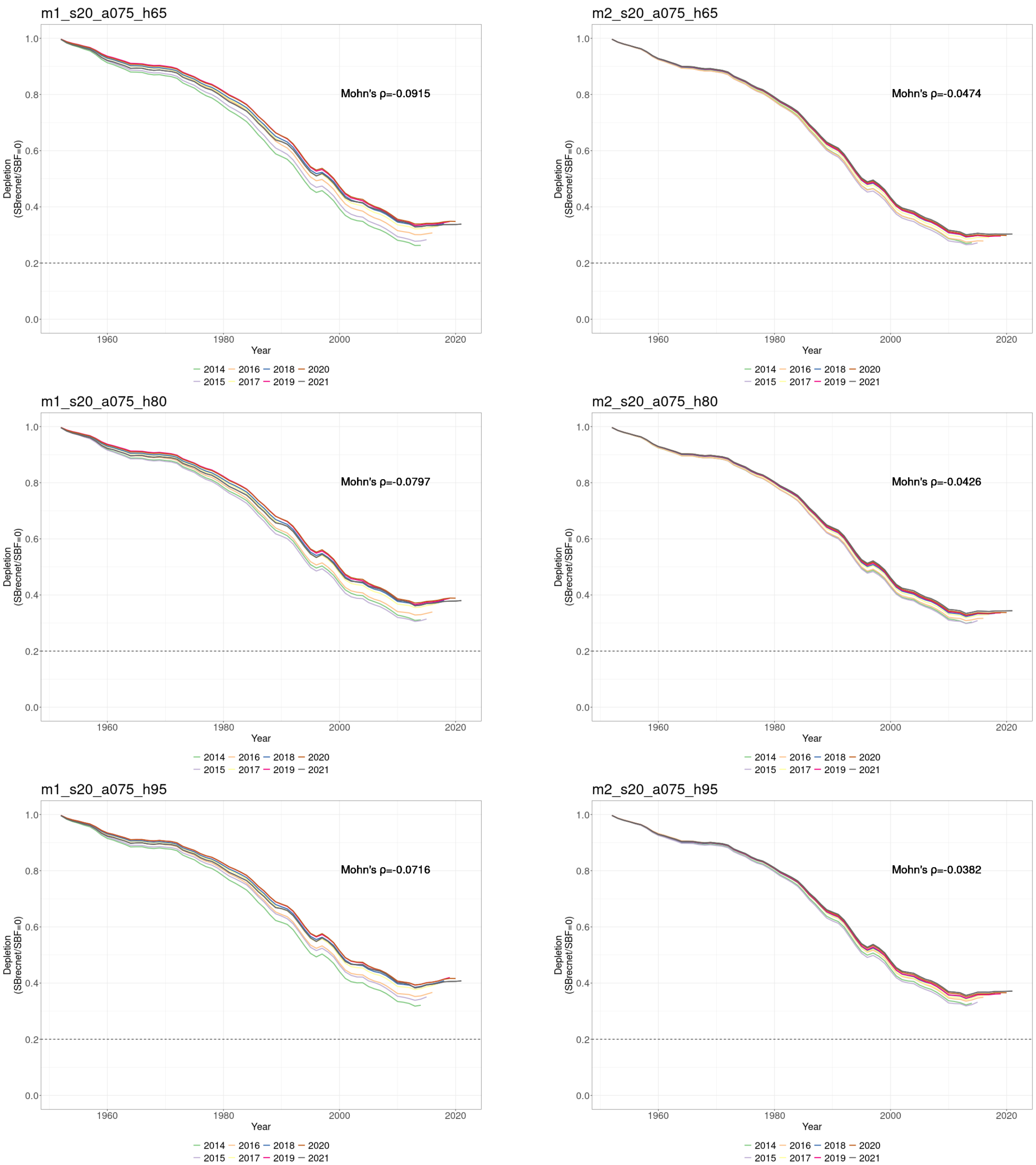


Figure 9: Results of retrospective analyses showing estimated depletion for 8 data peels 2014-2021. Models assuming a 1 qtr tag mixing period are shown in the left column, 2 qtr tag mixing in the right column, with values of steepness increasing from top to bottom (0.65, 0.8, 0.95).

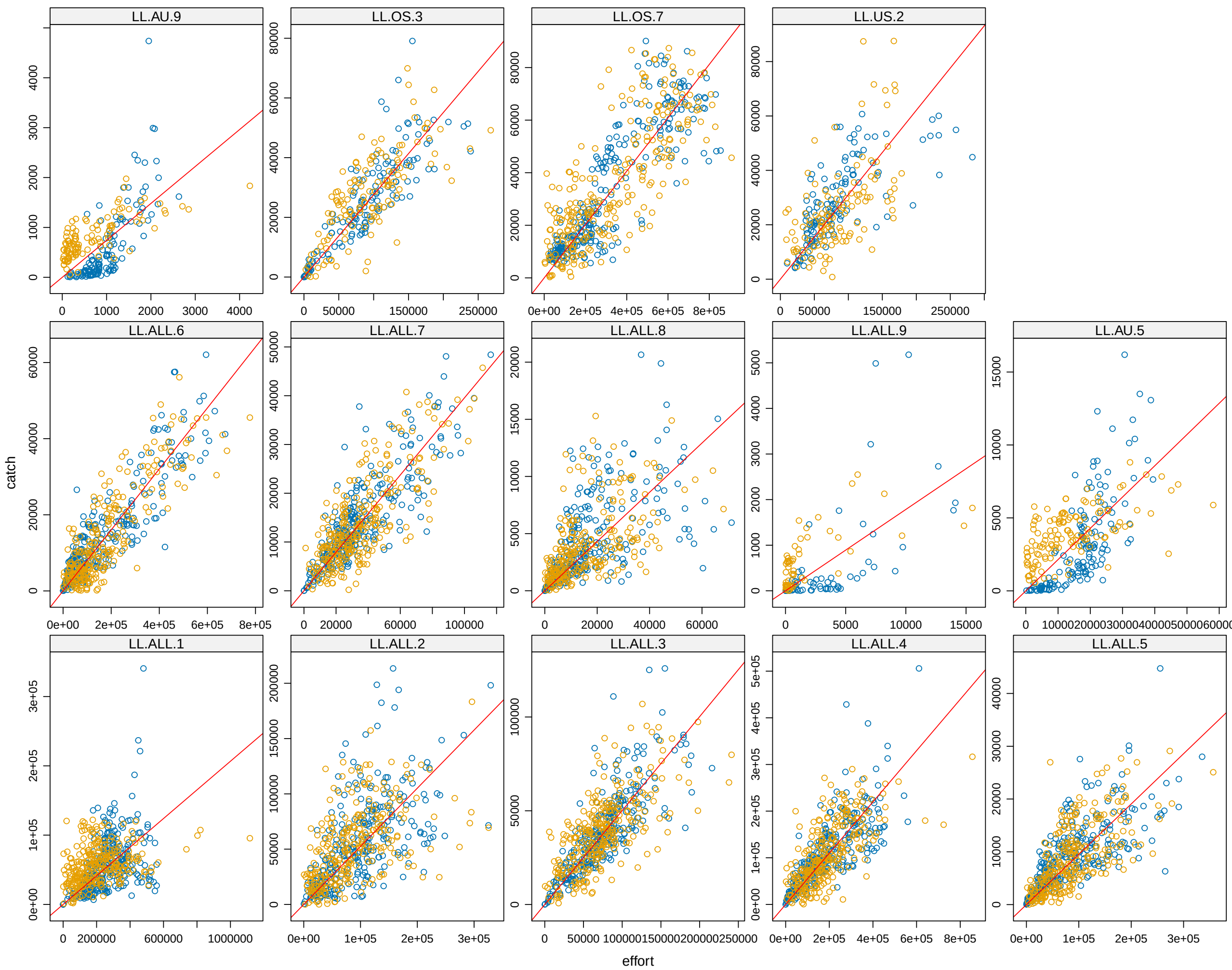


Figure 10: Simulated catch and effort data for longline fisheries assuming a 20% c.v. in both catch and effort.

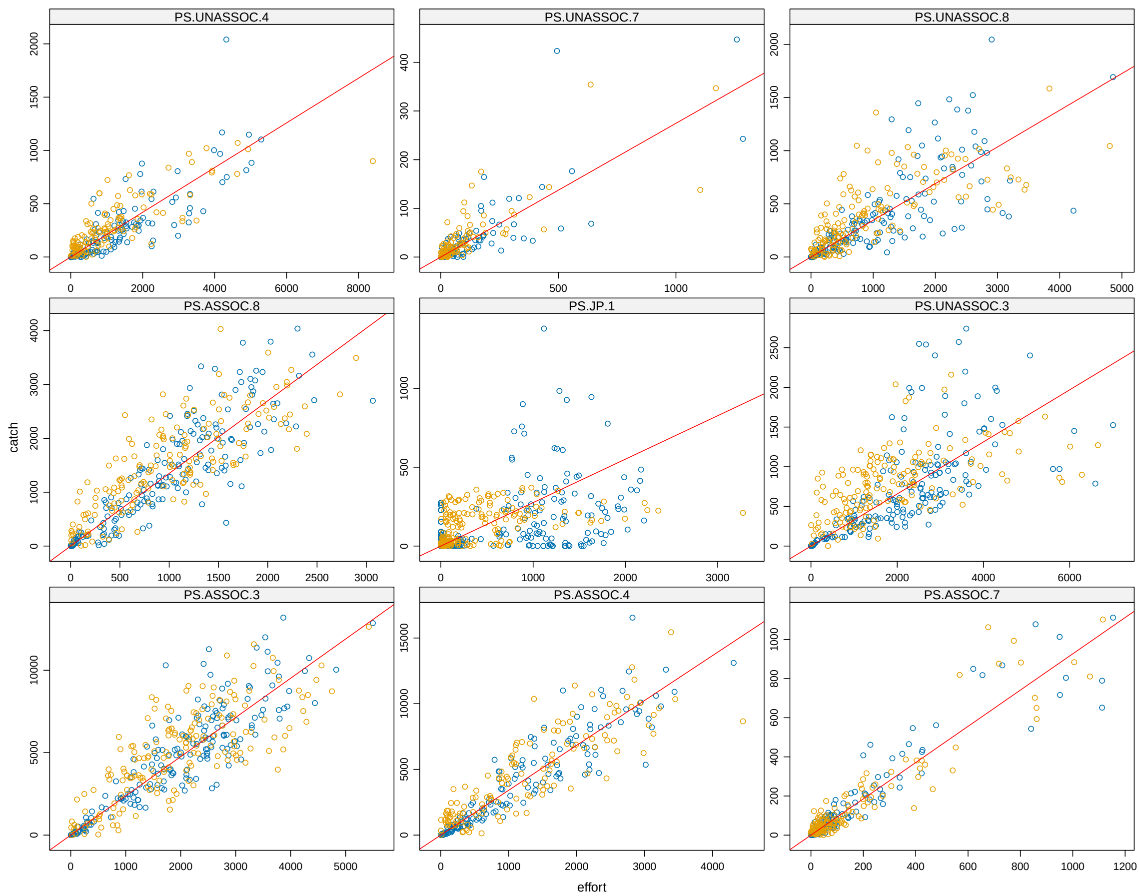


Figure 11: Simulated catch and effort data for purse seine fisheries assuming a 20% c.v. in both catch and effort.

C Alternative growth fits

Uncertainty in growth is introduced into the OM grid through length at age estimates that are individually fit for each of the 6 model fits that represent uncertainty in the historical period. The fitted growth models are relatively consistent across these 6 model fits (and also across the stock assessment grid of 54 models) and result in a relatively narrow range of depletion estimates throughout the historical period (Figure 5).

Noting that growth of bigeye tuna continues to be a source of uncertainty and may be under-represented in the fitted estimates comprising the OM grid, additional MULTIFAN-CL fits were conducted using fixed growth parameters. For each of the 6 model fits in the grid two additional models were run where the L1 (length of the youngest age class) and L2 (length of the oldest age class) growth parameters were fixed at either the highest or lowest esimated values from the stock assessment runs, with k continuing to be freely estimated. This resulted in an additional 12 model fits where growth parameters were fixed at their extreme values.

The results, as perhaps expected, show little change in the range of depletion estimates from either the stock assessment grid or the OM grid (Figure 12). Whilst it is possible to fix growth parameters at more extreme values, this has not been done here as the choice of alternative values becomes somewhat arbitrary. We recommend instead that a more considered approach be taken for characterising uncertainty in bigeye growth. However, there is little new information on which to base alternative assumptions. The most recent information on bigeye growth (Farley et al., 2020) provided length at age estimates that were consistent with recent assessments (Ducharme-Barth et al., 2020) and found little difference between length at age estimates derived from von-Bertalanffy and Richards growth models.

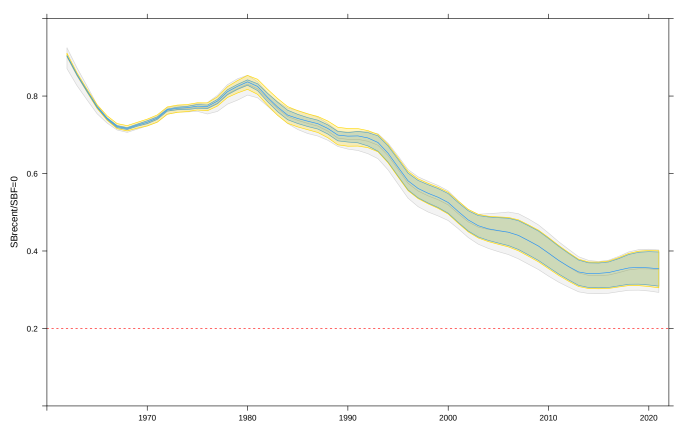


Figure 12: Comparison of estimated depletion from alternative growth model fits showing the range of depletion estimates across the full stock assessment model grid (grey), the reduced 6 model OM grid (blue) and an extended 18 model OM grid with alternative growth (yellow).

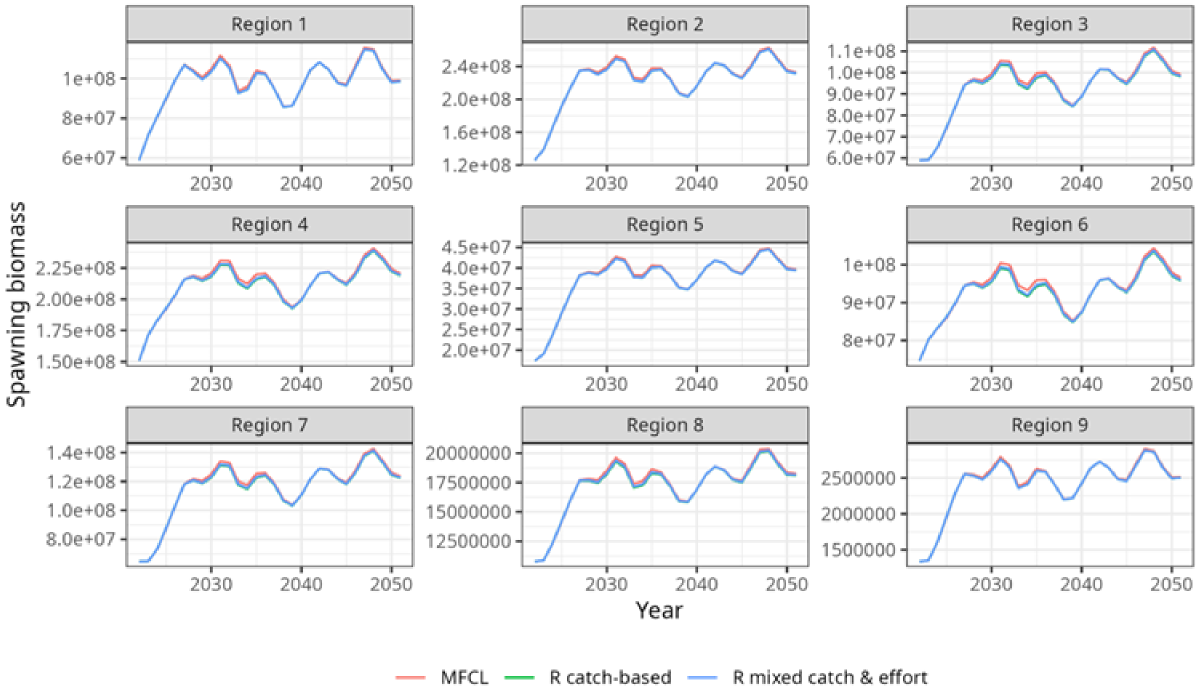
D OM framework updates

The development of climate change scenarios, and their incorporation into operating models when testing candidate MPs for WCPO tunas, has been identified as an important task. These include, for example, the development of scenarios to investigate the potential impacts of warm pool expansion in the WCPO and changing frequency of ENSO events. This task is non-trivial and is expected to occur over a longer time-frame. Analyses to investigate such issues have been restricted to the range of options available for projections conducted using MULTIFAN-CL. The implementation of time-varying parameters for movement, growth, recruitment, etc. that would be necessary to investigate the effects on the stock and fishery of a progressively changing environment is not possible using MULTIFAN-CL in its current form.

To address these, and other, issues an alternative modelling framework has been developed for running MSE analyses for WCPO tuna stocks. The framework (working title Tandoori) implements deterministic and stochastic projections in the same way as MULTIFAN-CL but allows for a much larger and more flexible range of stochastic inputs.

The framework is developed in C++ and R. It uses the CppAD library for automatic differentiation and LBFGSpp header-only library for the bounded BFGS solver. The project is hosted on the PacificCommunity github repository.

Testing of the framework yields identical projection outcomes to MULTIFAN-CL for projections conducted with either catch or effort fishery constraints (Figure 13). The framework is in a development phase, but is sufficiently progressed to allow it to be used for the bigeye tuna MP evaluations presented in MI-WP-07.



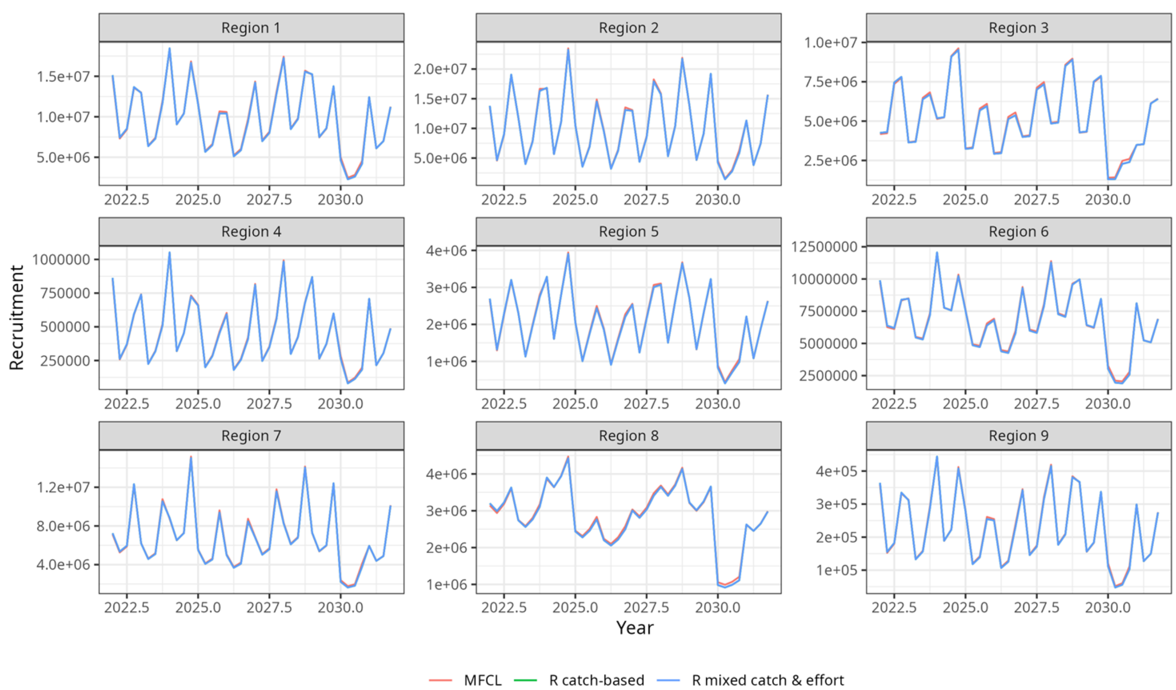


Figure 13: Comparison of spawning biomass and recruitment estimates from projections conducted using MULTIFAN-CL and the new OM framework.