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UPDATES TO THE OPERATING MODELS FOR BIGEYE TUNA IN THE WCPO

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Rev01: Section added to the end of the report outlining additional analyses to develop OMs representing a more depleted stock

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Contents

Executive Summary

Under the WCPFC harvest strategy workplan, SC22 is scheduled to agree the operating models for bigeye tuna in the WCPO. An initial grid of operating models was presented to SC21 and was accepted as the basis for initial analyses. However, SC21 recommended that further work be conducted to refine and expand the OM reference set as much as practicable to encompass a wider range of uncertainty. Several areas of uncertainty were identified for further consideration with SC21 noting that it may not be possible to address all of them in the short-term.

We present a reference set of 480 operating models for bigeye tuna that better captures the range of key uncertainties and includes alternative settings for steepness, growth, natural mortality, tag mixing, future recruitment variability and effort creep.

Bigeye tuna OM uncertainty grid (reference set, 480 scenarios).

Axis	**Levels**	**Options**				
		1	**2**	**3**	**4**	**5**
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 ‡	4					
Lmin		22	38	22	30	
Lmax		150	155	160	150	
k		0.118	0.066	0.118	0.09	
Natural mortality ‡	5	0.1	0.125	0.15	0.175	0.2
Movement ‡		estimated internally				
DD catchability		not currently implemented				
Implementation Error						
Effort creep	2	0%	PS 2%, LL 1%			

We consider potential scenarios for robustness and one-off sensitivity analyses include alternative catch histories for the domestic fisheries of Indonesia and Philippines; scenarios for reduced future recruitment and, where possible, alternative movement rates.

We invite SC22 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 testing of candidate MPs for bigeye tuna.
- note that work will continue in the longer-term to further develop the OMs and this can be managed through an agreed monitoring strategy.

1 Introduction

The WCPFC has committed to developing harvest strategies for priority tuna stocks (CMM 2022-03), and, under the harvest strategy workplan, the adoption of a management procedure for bigeye tuna in the WCPO is scheduled for 2026.

Management procedures should be tested prior to implementation to ensure that they are likely to achieve defined management objectives. Operating models (OMs) form the basis of management procedure testing by providing a set of plausible, alternative biological and operational dynamics for the stock and fishery. Uncertainty in biological processes and fishery operations should be sufficiently represented in the set of operating models so that management procedures can be developed and tested for robustness to these uncertainties. Under the WCPFC harvest strategy workplan, SC22 is scheduled to agree the operating models for bigeye tuna in the WCPO.

An initial grid of operating models was presented to the 21st Scientific Committee (SC21). This initial set of OMs was based closely on the modelling approach used for recent stock assessments (Ducharme-Barth et al., 2020; Day et al., 2023) as well as the recommendations of the 2020 yellowfin tuna stock assessment review (Punt et al., 2023). Whilst key sources of uncertainty were included in the grid, the assumed functional relationships betweeen the biological processes of growth, natural mortality and maturity were retained such that overall uncertainty was limited. Consequently, this set of OMs represented a relatively narrow range of outcomes, particularly in terms of stock status.

SC21 supported the use of the initial reference set of 24 OMs for bigeye tuna as the basis for further development, but recommended that further work be conducted to refine and expand the OM reference set as much as practicable. Eight areas of uncertainty were identified for further consideration (Table 1), although it was noted by SC21 that it may not be possible to address all of them in the short-term.

A stock assessment of bigeye tuna in the WCPO is also scheduled for 2026. Work to condition the operating models has, therefore, run concurrently with work to develop the updated stock assessment. The timelines for the two development streams, however, differed quite markedly. The OMs are, ideally, required at an earlier point in time such that subsequent work to develop and test candidate management procedures can be undertaken. As such, it has not been possible for any significant developments to the stock assessment in terms of, for example, spatial structure and fishery groupings to be represented in the OMs. The SC21 recommended that the OMs be based on the 2023 stock assessment spatial structure and fishery definitions, with further investigation of spatial structure to be undertaken in the longer-term.

In this paper we further develop the grid of OMs for WCPO bigeye tuna, following the recommendations of SC21 to the extent possible. We present recommendations for an OM grid and initial consideration of a set of robustness and sensitivity scenarios. We investigate options and recommended settings for modelling stock status into the future and for simulating future catch and effort data. We note that ongoing work will be required to further develop and refine the robustness

Uncertainty	Priority	Timing
Growth	High	Short (preferably by 2026)
Natural mortality	High	Short (preferably by 2026)
Movement dynamics	High	Short (preferably by 2026)
Hyperstability in CPUE	High	Short (preferably by 2026)
Variability in recruitment	High	Short (preferably by 2026)
Spatial structure	High	Long
Uncertainty in domestic catch level	High	Long
Effect of climate change	High	Long

Table 1: List and priorities of uncertainties to be considered in bigeye tuna operating models (Table MI-01 in WCPFC (2025)).

and sensitivity scenarios.

2 OM structure

2.1 Spatial structure and fishery definitions

The proposed OMs retain the same 9-region spatial structure (Figure 1) that has been used for the last two stock assessments of bigeye tuna in the WCPO (Ducharme-Barth et al., 2020; Day et al., 2023) and have largely retained the associated fishery definitions (Table 2). To facilitate analyses for the proposed mixed fishery design (Scott et al., 2023) for which the tropical longline fishery (TLL) extends from 20° north to 10° south, three additional longline fisheries have been defined (fisheries 33 to 35) that allow separation of the longline fisheries in regions 1 and 2 at 20° north. Selection patterns for these fisheries were mirrored to their counterparts north of 20° north to maintain consistency with the stock assessment estimates.

A further change to the fishery definitions was to separate the handline fisheries of Indonesia and Philippines into two distinct components (fisheries 18 and 36, Table 2). These fisheries have different operational characteristics and target different components of the stock. Separating them allows fishery specific selectivity to be more appropriately determined and also isolates the Indonesian handline fishery for which there is considerable uncertainty in catch and effort statistics.

Catches of bigeye tuna in the WCPO by gear type (Figure 2) shows a general decline in overall catch from around 2014 to 2021 (the last year of data represented in the OMs) to around 150,000 tonnes, with relatively stable overall catches continuing in 2022 to 2024. Catches for purse seine and longline fisheries appear to have declined slightly in recent years with catches in domestic fisheries increasing. Catches of bigeye tuna by fishery (Figure 3) show considerable increases in catches, and potential data anomalies, for some fisheries, in particular the domestic fisheries of Indonesia (Z-ID-7) and the handline fisheries of Indonesia and the Philippines (ID-H-7, PH-H-7).

For stock assessments, catches of longline fisheries are typically input to the assessment model as numbers of fish caught, rather than catch by weight. The use of either catch in number or catch in weight has no impact on the historical estimation of stock status but can be problematic when conducting catch-based projections because the total weight of caught fish determined from projections based on catch in numbers will vary depending on the age structure of the population. Therefore to simplify the testing of potential management procedures that may set management on total catch weight, the inputs to the OM were provided as catch by weight rather than catch number (see Annexe C).

2.2 Stepwise model development

The stepwise progression of these changes from the 2023 diagnostic model to the OM structure (Figure 4) shows very small changes in estimates of stock depletion with modifications comprising, step 1: changes to the inputs to accomodate the latest version of MFCL; and step 2: the combined effects of the disaggregation of longline and handline fisheries and the switch to catch in weight for longline fisheries. A further modification, step 3: to fix the recruitment deviates in the terminal 8 quarters (described further in section 3.4) resulted in a more significant change to a less depleted stock.

3 Sources of uncertainty

The main sources of uncertainty considered for the updated OMs presented here are similar to those considered for the initial set presented to SC21. A key difference, however, is the separation of the assumed relationship between the biological processes of growth and natural mortality and the use of externally derived parameters rather than model fitted values.

3.1 Growth

Bigeye growth has been extensively researched but limited by the small number of otolith samples ($n = 1004$) (Farley et al., 2017; Nicol et al., 2011; Day et al., 2023). There is evidence to suggest that growth of bigeye varies spatially, with length-at-age above average in the westernmost (< 140E) and easternmost (> 205E) longitudes of the Pacific Ocean (Farley et al., 2017). Latitudinal variation was also evidenced by the 2011 stock assessment and corroborated with otolith data (Nicol et al., 2011). More recently, Japanese otolith data has revealed faster growing and larger fish in the Northern latitudes of the WPO (Hasegawa et al., 2026).

For the 2023 stock assessment, growth was estimated internally within MFCL using information from conditional length-at-age data, tags and modal progressions apparent in size composition data. This approach applied a single, time- and spatially-invariant, growth model to the population. The software underpinning the MSE framework (masala) can allow for spatial and temporal variability in growth, but currently has no mechanism to track the growth of individual fish as they move between regions. Consequently the OMs presented here continue to employ a range of fixed growth assumptions that do not vary either spatially or temporally.

Four alternative von Bertalanffy growth models have been assumed for the OM grid (Figure 5) that have been informed by recent growth studies for both the tropical (Wakefield et al., 2026) and temperate (Hasegawa et al., 2026) regions, as well as by model fits to recent bigeye stock assesments (Day et al., 2023).

3.2 Natural mortality

The assumed level of natural mortality (M) can be a highly influential parameter when modelling population dynamics, but is also very difficult to estimate. Efforts to derive estimates of M from a meta-analytic analysis of 14 M-estimators (Vincent et al., 2020) yielded average quarterly values of around 0.127.

The 2023 bigeye stock assessment assumed functional relatonships for both maturity and natural mortality that were linked to estimated growth rates. Natuaral mortality at age was estimated assuming a Lorenzen functional form (Lorenzen, 2022; Hamel and Cope, 2022) where M for the oldest age was estimated and an inverse relationship with length assumed for younger ages. Estimates of average M at age ranged between values of 0.115 and 0.145.

The current OM grid employs a similar approach except that, rather than estimate M for the oldest age, age-specific values were derived to achieve a pre-specified overall average natural mortality across all ages of between 0.1 and 0.2. Five different levels of natural mortality (0.1, 0.125, 0.15, 0.175, 0.2) were set for each of the four growth models described above, resulting in twenty alternative growth and natural mortality combinations across the OM grid (Figure 6).

More recent estimates of natural mortality for bigeye tuna in the WCPO determined from analyses of archival tag recapture data (Ducharme-Barth et al., 2026) are broadly comparable to the values assuned for the OM grid presented here. Estimates derived from independent fits that used the PTTP tagging programme recaptures only were close to the upper levels included in the OM grid, whilst estimates derived from RTTP tagging programme recaptures were slightly lower than the levels included in the OM grid.

3.3 Reproductive potential

Recent assessments of bigeye tuna in the WCPO determine the spawning fraction of the population using a reproductive potential ogive rather than a measure of maturity at age. The reproductive potential ogive is constructed as the product of fecundity at length (per kg), proportion female at length and proportion mature at length (Vincent et al., 2020). This length based ogive is converted to age within MFCL conditional on the asssumed growth model.

Vincent et al. (2020) note that the reproductive potential ogive is constructed from relatively sparse data. No new data were available to update current estimates and no alternative ogives for reproductive potential have been included in the OM grid. Given the uncertainty associated with the components of the ogive further investigation of it's inputs would be warranted and should be considered for future versions of the OMs. At this point, the proposed OM grid comprises a single length-based reproductive potential ogive (Figure 7) which translates to four age-specific ogives given the four alternative growth models (Figure 8).

3.4 Recruitment dynamics

Variability in future recruitment is one of the most significant sources of uncertainty affecting the future dynamics of the stock. Uncertainty in recruitment dynamics is incorporated in the OMs through 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 candidate management procedures that drive the stock 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 (Figure 9).

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). Two recruitment variability options (1969:2020 and 2010:2020) continue to be included in the OM grid, although the pattern for increasing recruitment is much less apparent in the current set of OMs (Figures 11 and 12).

3.5 Tag release and recapture data

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

Previous analyses to inform on the most appropriate tag mixing periods to assume have used the spatial distributions of relative recapture rates along with the displacement distances of tag recaptures (i.e. distance from point of release (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.

3.6 Spatial distribution and movement

Stock assessments for tropical tunas in the WCPO typically incorporate spatial structure to try to 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).

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 OMs presented here are based on internally estimated seasonal movement rates that are age and time invariant (Figures 19 and 20a). These movement rates are relatively consistently estimated across the OM grid. Alternative scenarios for movement dynamics (Figure 20b) are available from SEAPODYM models for bigeye tuna (Senina et al., 2023), however, attempts to use these estimates within the OM grid were unsuccessful with models showing poor convergence and estimation failure for key variables.

3.7 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.

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. However, for technical reasons, hyperstability in CPUE is not currently included in the OM grid. The basis of the OMs are catch-conditioned models that do not use fishery specific effort data for extraction fisheries. As such the model provides no fishery specific estimate of catchability to which the biomass dependent exponent of the hyper-stability relationship can be applied. Options for including hyper-stability in the models comprising the OM grid are currently being explored with a view to including it in future iterations of the MSE framework.

3.8 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 over time.

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. Higher levels of effort creep 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., 2024b) but are also selected to bound the uncertainty in potential levels of effort creep.

3.9 Climate change impacts

The development of climate change scenarios and their incorporation into operating models for WCPO stocks has been identified as an important task, but one that may not be possible to address in the short-term. The necessary tools to develop and test alternative climate change scenarios (e.g. masala) are under development and are used extensively for evaluating candidate bigeye management procedures (Scott et al., 2026), but are not yet sufficiently developed to incorporate specific climate change scenarios.

Recent developments in the quantitative modelling of tuna population dynamics using SEAPODYM (Senina et al., 2021, 2026) provide a platform for developing future scenarios for alternative spatial structures, movement rates and recruitment distributions under climate change predictions. In addition, studies of the historical variability of key biological processes and fishery characteristics (Castillo-Jordan et al., 2026; Gislard et al., 2026; McKechnie et al., 2026) can also inform on trends and variability for future scenarios.

4 Bigeye tuna operating models

OMs have been developed based upon the key uncertainties described above and are separated into reference and robustness sets (Rademeyer et al., 2007). The reference set reflects the most plausible hypotheses of stock and fishery dynamics and forms the basis for testing candidate management procedures. The robustness set and sensitivity tests represent more extreme, though still plausible, parameter values and specific scenarios for secondary testing on a smaller subset of preferred MPs.

4.1 Operating model grid

The sources of uncertainty comprising the reference set are outlined in Table 4. These scenarios provide a grid of 480 OMs representing a combination of alternative model fits and projection settings.

Scenarios for the steepness of the stock and recruitment relationship and for tag mixing have been retained from the 2023 stock assessment uncertainty grid. Additional model fits to explore a range of alternative growth and natural mortality scenarios are also included. Scenarios for effort creep and future recruitment variability provide additional uncertainty for the projection period. The operating models generate simulated catch and CPUE for input to the estimation method (Wickens et al., 2026) with CVs of 20% and 10% respectively.

Estimated depletion across the OM grid (Figure 22) follows a similar overall trend to that of the 2023 assessment but shows greater variability particulaly for the most recent years and estimates a less depleted stock. Stock status relative to average depletion across 2012-2015, however, is similar. Terminal depletion (2019-2021) for the 2023 stock assesment was around 3% greater than the 2012-15 average whereas terminal depletion across the OM grid was around 7% greater than the 2012-15 average for corresponding models. Estimates of depletion scaled with the assumed level of natural mortality (Figure 24) with the least depleted stock status associated with the highest values of natural mortality.

4.2 Robustness and sensitivity test scenarios

A number of robustness and sensitivity scenarios are considered, although further work will be required to fully develop and refine these models. Proposed robustness scenarios include more extreme settings for future effort creep; reduced recruitment scenarios, and uncertainty in catches in the domestic and small scale fisheries of Indonesia and the Philippines.

4.2.1 Reduced recruitment

Initial investigation of a reduced recruitment scenario, in which future recrtuitment is persistently lower than that seen in the historical period, considered a 30% reduction in future recruitment levels. Stochastic projections, conducted for status quo effort conditions, in which recruitment deviates for the projection period were modified to give psersistently lower recruitment in all regions of the model show a more depleted stock relative to the base-case scenario (Figure 29). Greater reductions in future recruitment may be considered for MP testing, but could not be further investigated in the time available.

4.2.2 Recruitment distribution

The 2023 bigeye stock assessment applied an annual stock and recruitment relationship for all regions of the assessment combined, with the proportional allocation of recruits amongst seasons and regions for the historical period estimated independently for each time period.

Projections of future stock status conducted using MFCL apply a fixed distribution for future recruitment by season and region based on the average historical distibution of the full time series of the assessment (Figure 14a). This full time period includes recruitment estimates and regional distributions for the initial years of the assessment model that are often poorly estimated, in part because the longline fishery that was predominant in the early years selected for larger fish and was less informative about recruitment strength and distribution. The use of a truncated time-period that excludes the early years and covers a period where the purse seine and other fisheries may offer better information on recruitment (e.g. 1980:2010) provides an alternative recruitment distribution that differs from the full time period and influences estimates of future stock status (Figure 13).

Whilst alternative recruitment distributions can impact on estimates of future stock status, they have not been included in the OM grid presented here. The historical distribution of recruitment can be affected by a number of fundamental modelling assumptions including spatial structure and assumed movement rates as well as fishery specific characteristics. We propose that this area of uncertainty be further investigated in the longer-term alongside issues of stock distribution, spatial structure, movement and the potential impacts of climate change.

4.2.3 Uncertainty in domestic catch levels

One-off sensitivity analyses were conducted to investigate the impact of alternative catch scenarios, in particular for Indonesian domestic fisheries for which recent catch statistics show significant increases and considerable variability in catch by gear type.

To investigate the potential impact, historical catches were increased to be more comparable to the most recent catch estimates. Catches of the Indonesian domestic fishery in region 7 were increased by a factor of 1.5; for the Philippines handline fishery by a factor of 2.5 and for the Indonesian handline fishery by a factor of 5 (Figure 35).

While initial results indicate relatively little impact on estimates of depletion for the stock as a whole (Figure 36) the impact on future stock status from projections and fishery specific impacts within the region, remains to be fully explored.

4.2.4 Effort creep

Two effort creep scenarios have been included in the OM grid reference set. 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. Higher values of effort creep for longline fisheries of 2% and, similar to the skipjack MP evaluations, of 3% for purse seine, might be considered for robustness testing. As noted previously, these values are informed by recent studies, (Hoyle, 2024; Hamer et al., 2024a) but are also selected to bound the uncertainty in potential levels of effort creep.

5 Model diagnostics

Model diagnostics were examined from the 120 OMs that were conditioned on data from the historical period. There was no evidence of model failure across the OM grid. All 120 models ran successfully with 118 models achieving the maximum gradient convergence criteria of $1\text{x}10^{-05}$, and the two remaining models achieving acceptable final maximum gradient values (Figure 30). Contributions to the overall likelihood were remarkably consistent across the OM grid, and estimates of the total populaton scaling parameter were relatively uniformly distributed between values of 16 and 18.5 on the log scale.

All models showed similar patterns for fits to length and weight composition data (Figures 15 and 16) and fits to CPUE for the index fisheries (Figure 17). Standardised residuals for tag recapture fits were also similarly estimated across the OM grid (Figure 18) with a general pattern for initial over-estimation of tag recaptures and subsequent tendency for under-estimation of recaptures at times-at-liberty greater than one year.

5.1 Retrospective analyses

Due to time constraints, retrospective analyses were run for only a subset of models. Figure 32 shows the results of 7-year retrospective analyses conducted on a randomly selected subset of eight models from the OM grid. Whilst all models showed a tendency for retrospective under-estimation of depletion, there was no evidence of significant retrospective bias with Mohn's rho for the worst case (OM3) within acceptable tolerance levels proposed by Hurtado-Ferro et al. (2015).

5.2 Likelihood profiles

Likelihood profiles on terminal biomass were conducted across a subset of the OM grid (Figure 33). Similar to the 2023 stock assessment the profiles identified data conflicts in particular between the weight composition data that fit better at high biomass and the length compositon and tag data that show improved fits at lower biomass.

5.3 Stochastic projections

A simple effort-based, 30-year stochastic projection (Figure 28) provides an indication of the future stock trajectory and range of depletion estimates resulting from the combined sources of uncertainty in the OM grid. This figure is indicative of the range of values and projection outcomes but will differ from those presented in Scott et al. (2026) for which different projection settings have been assumed.

5.4 Impact analyses

Impact of the various gear-types catching bigeye tuna in terms of their reduction of potential spawning biomass are shown for a random subset of the OM grid (Figure 34). Whilst the overall pattern in impact by gear type is relatively consistent, the absolute levels of stock depletion can vary depending on growth, mortality and the estimated fishery specific selection patterns. Lower values of assumed natural mortality (e.g. OM3) suggest higher levels of overall impact with greatest impact due to the purse seine and domestic fisheries. Higher values of natural mortality (e.g. OM101) suggest lower overall impact and reduced impact from fisheries catching smaller individuals.

6 Discussion

6.1 Fishery-specific selection patterns

The range of scenarios for growth and natural mortality result in a very wide range of potential fishery-specific selection patterns, most notably for longline fisheries (Figure 26). Purse seine, pole and line and domestic fisheries that typically select the smaller size classes show more consistent selectivity-at-age across the grid. Estimated longline selection patterns range from sigmoid, flat topped patterns that select for the oldest ages, to strongly dome-shaped patterns that potentially allow for substantial cryptic biomass in the population. We note that the 2023 stock assessment also estimated strongly dome-shaped selection patterns for longline fisheries.

This range of selection patterns gives rise to highly variable estimates of MSY and F/FMSY (Figure 31). Methods for calculating MSY under the revised MSE framework are ongoing. Results for MSY based performance indicators for the projection period are not currently available but will be presented for future MP evaluations.

6.2 Further work

The proposed OM grid comprises 480 models, based on a combination of model and projection settings. It incorporates many of the most influential sources of uncertainty, most notably in alternative assumptions for growth and natural mortality. Additional sources of uncertainty, beyond the 480 models of the reference set, have been identified that should be considered for future inclusion in the OM grid. These include alternative spatial structures and movement dynamics; recruitment distribution; assumptions on population biology including reproductive potential, and climate change scenarios. In some cases further work will be required to develop appropriate scenarios, in particular for climate change and spatial distribution. 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 should 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. We do not identify any exceptional circumstances here, but note that the range of OMs selected for the evaluations will be a key consideration for them.

Consideration of exceptional circumstances has previously considered them to *"include any event that falls outside the range of assumptions over which the management procedure has been tested"*, however, recent experience in other tuna RFMOs suggests this text may be prone to an overly strict interpretation. Instead it is suggested that for exceptional circumstances to be triggered, circumstances should be *"substantially different from those simulated in the MSE"*. We note that the declaration of exceptional circumstances does not necessarily mean that the MP should be abandoned. To date, the CCSBT has identified four instances of exceptional circumstances but has in each case been able to apply the MP to set catch limits.

7 Conclusions

We present a reference set of 480 operating models for bigeye tuna that includes alternative settings for steepness, growth, natural mortality, tag mixing, future recruitment variability and effort creep.

We consider scenarios for robustness and one-off sensitivity analyses include alternative catch histories for the domestic fisheries of Indonesia and Philippines; scenarios for reduced future recruitment and, where possible, alternative movement rates. Work to further develop these scenarios will be undertaken.

We invite SC22 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 testing of candidate MPs for bigeye tuna.
- 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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Declaration of generative AI and AI-assisted technologies in the SC paper preparation process

No AI technologies were used in the preparation of this paper.

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A Tables

Table 2: Definition of fisheries for the bigeye tuna operating models.

Fishery No	Fishery	Flag	Region	Sel Group	% catch last 10 yrs	% catch all yrs
F1	LL-ALL-1	ALL	1	1	3.68	9.54
F2	LL-ALL-2	ALL	2	2	1.24	6.27
F3	LL-US-2	US	2	3	1.83	0.63
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	HL-PH-7	PH	7	20	0.52	0.02
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
F33	LL-ALL-1	ALL	1	1	0.59	1.33
F34	LL-ALL-2	ALL	2	2	4.31	8.56
F35	LL-US-2	US	2	3	1.46	0.44
F36	HL-ID-7	ID	7	20	0.75	0.16
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 3: 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 4: Bigeye tuna OM uncertainty grid (reference set, 480 scenarios). ‡ denotes those scenarios for which a dedicated fit of MULTIFAN-CL is required. (DD refers to density dependent catchability)

Axis	**Levels**	**Options**				
		1	**2**	**3**	**4**	**5**
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 ‡	4					
Lmin		22	38	22	30	
Lmax		150	155	160	150	
k		0.118	0.066	0.118	0.09	
Natural mortality ‡	5	0.1	0.125	0.15	0.175	0.2
Movement ‡		estimated internally				
DD catchability		not currently implemented				
Implementation Error						
Effort creep	2	0%	PS 2%, LL 1%			

B Figures

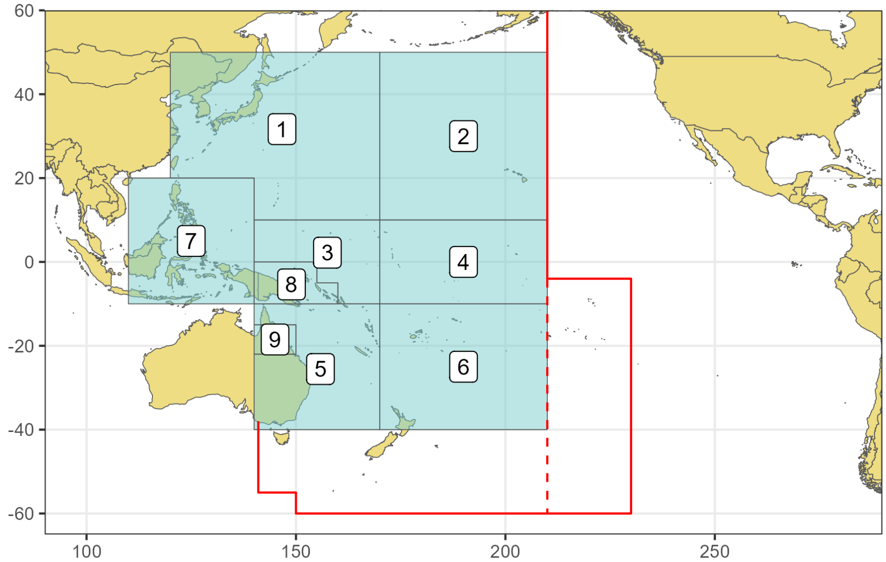


Figure 1: Spatial structure of the bigeye MSE modelling framework showing the extent of the WCPFC convention area, including the overlap, (red) and the 9 region spatial structure of the bigeye tuna operating models (blue).

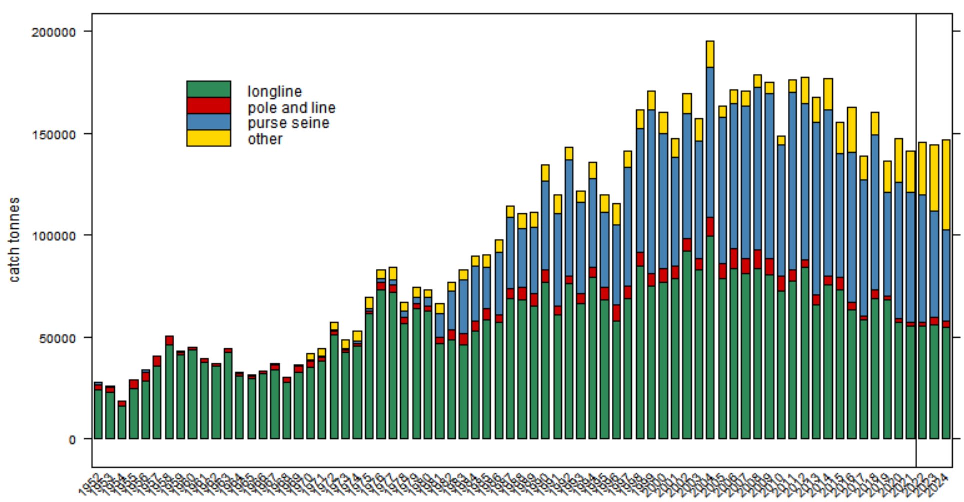


Figure 2: Catches of bigeye tuna in the WCPO by gear group. OMs include catches to 2021, shown by the vertical black line

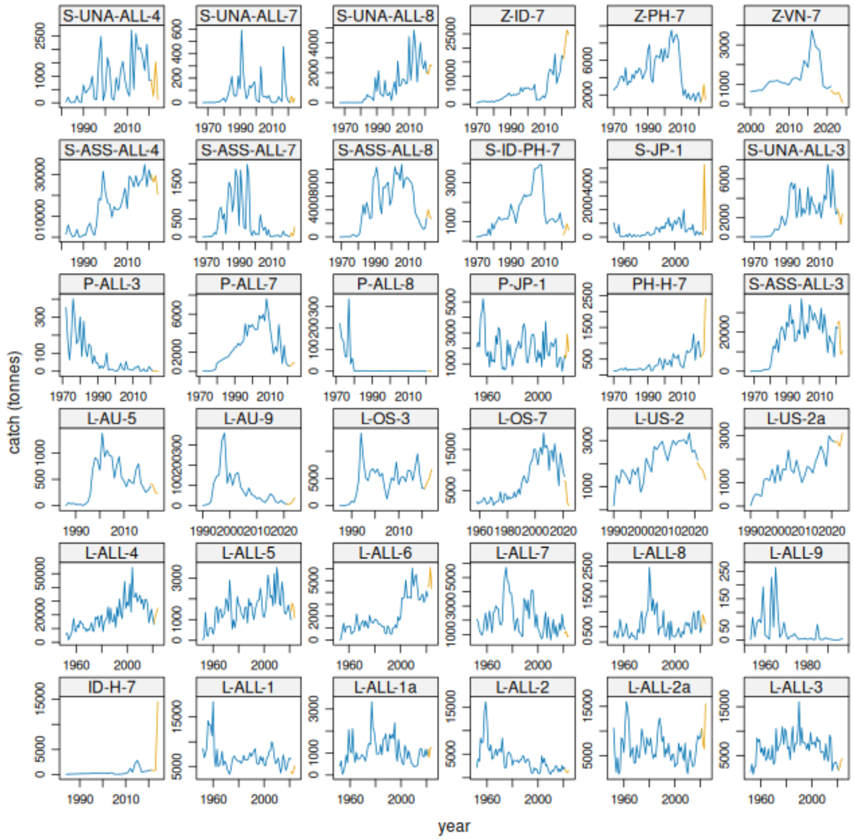


Figure 3: Annual catch (tonnes) for the 36 extraction fisheries defined for the bigeye tuna operating models for the period 1952 to 2021 (blue) as used for the 2023 assessment and BET OMs, and recent catches for 2022 to 2024 (yellow).

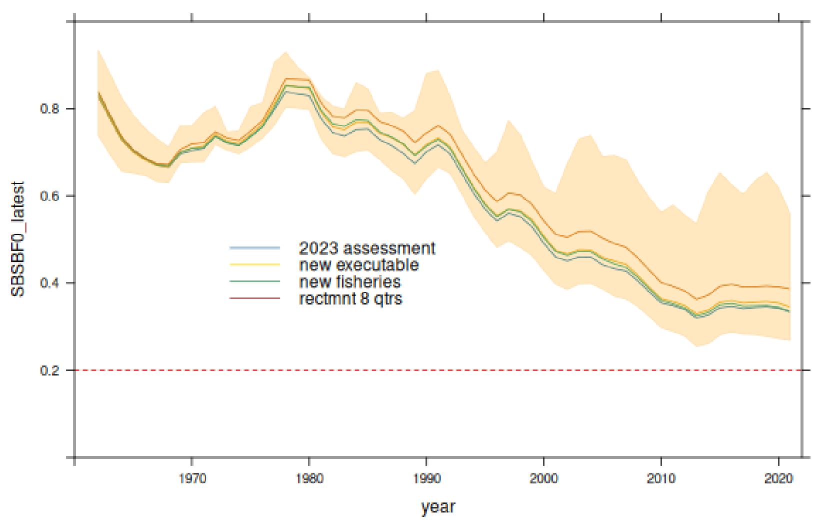


Figure 4: Depletion (SBSBF0latest) for the stepwise progression of the OM inputs from the 2023 stock assessment. Shaded area shows the range of depletion estimates from the full OM grid.

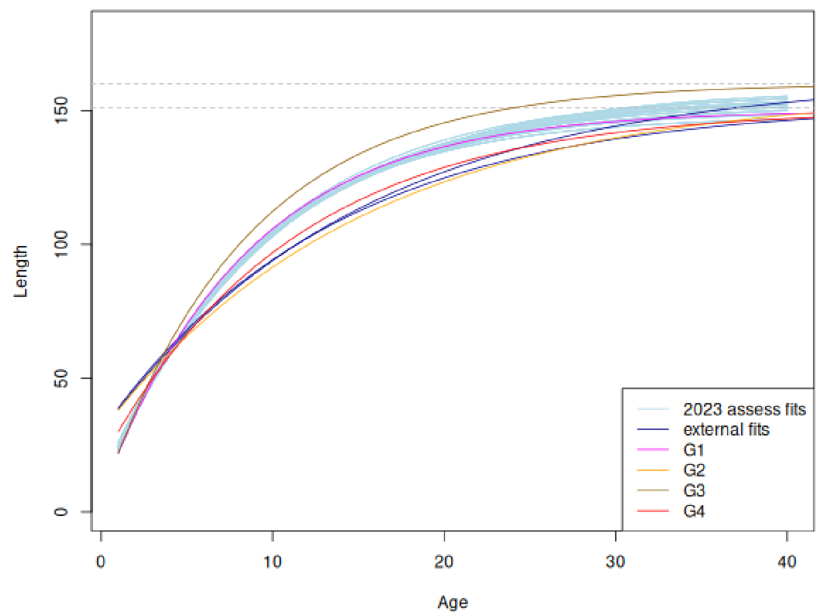


Figure 5: Length at age for bigeye tuna as determined from various sources including the 2023 stock assessment estimates and two individual von Bertalanffy model fits to age at length observations, and the four growth models assumed for the operating model grid.

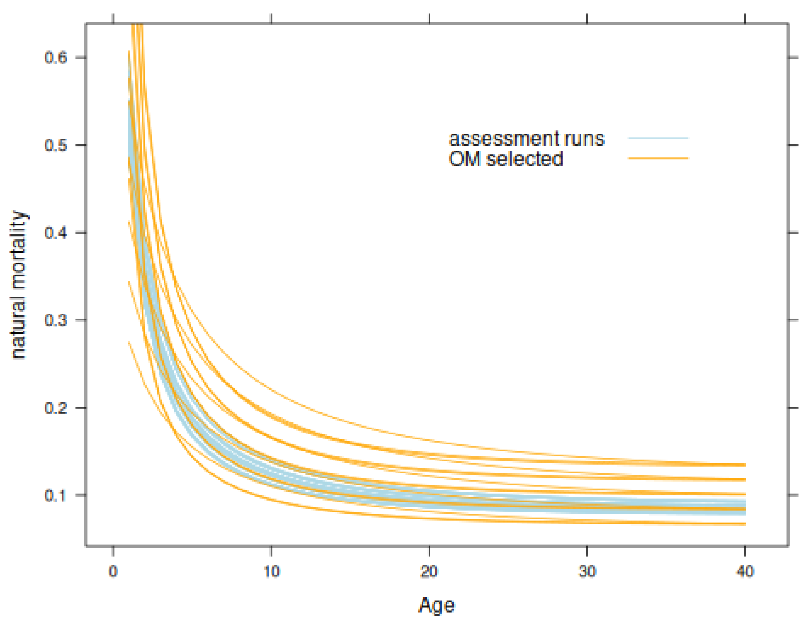


Figure 6: Natural mortality based on the assumed Lorenzen relationship across the operating model grid. Twenty natural mortality curves are shown for the five levels of assumed natural mortality (0.1, 0.125, 0.15, 0.175, 0.2) for each of the four growth models. The estimated natural mortality from the 2023 stock assessment is also shown.

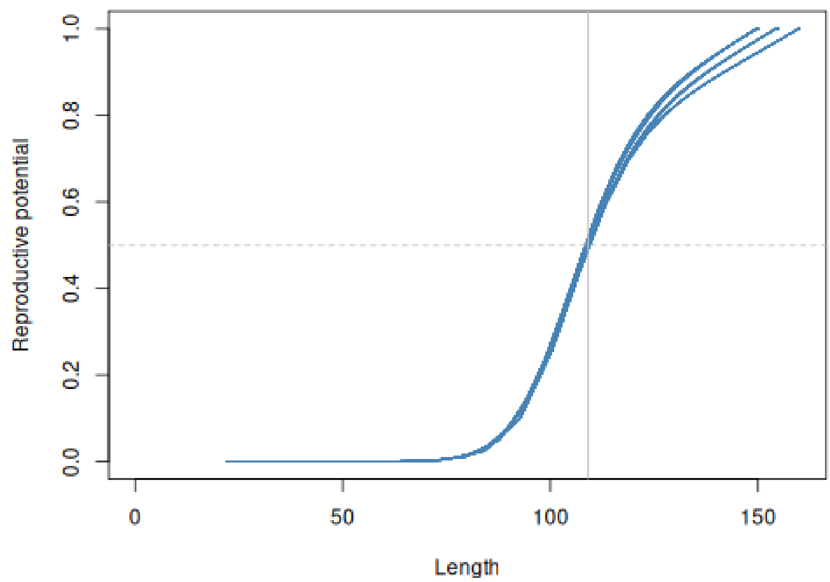


Figure 7: Reproductive potential at length following MFCL re-scaling for Lmax. 50% reproductive potential occurs around 110 cm (vertical line).

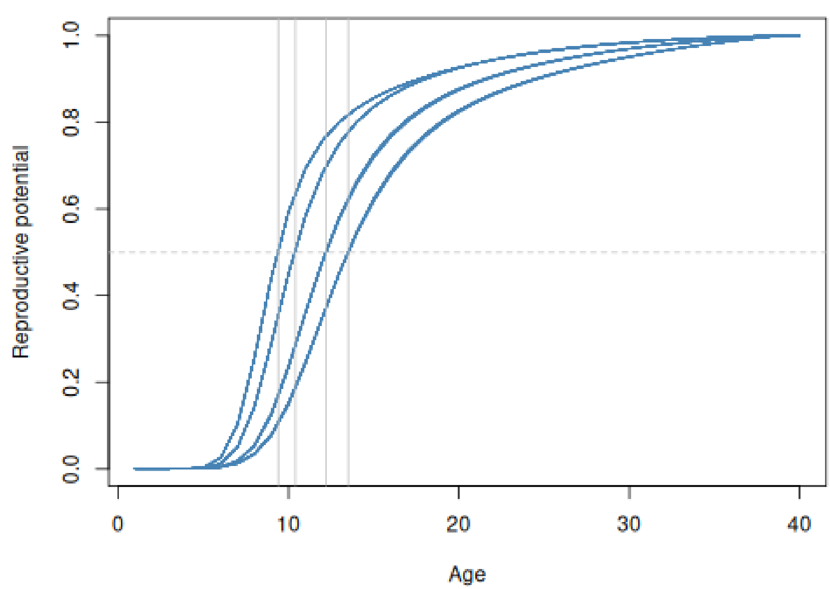


Figure 8: Reproductive potential at age. 50% reproductive potential occurs at approximately age 9.5, 10.5, 12 or 13.5 depending on assumed growth curve (vertical lines).

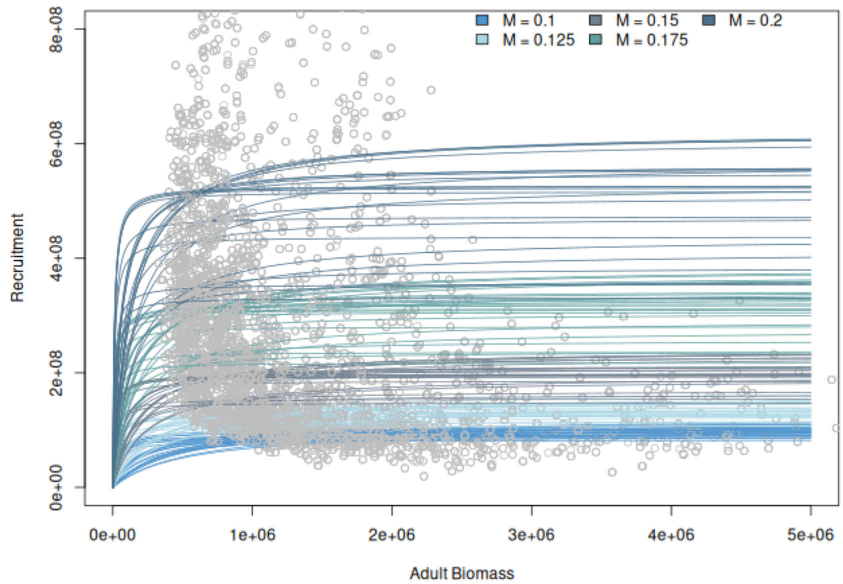


Figure 9: Fitted stock-recruitment relationship for each model in the OM grid. Colours show model fits for the five assumed values of natural mortality and illustrates the progressive population scaling with increasing values of M.

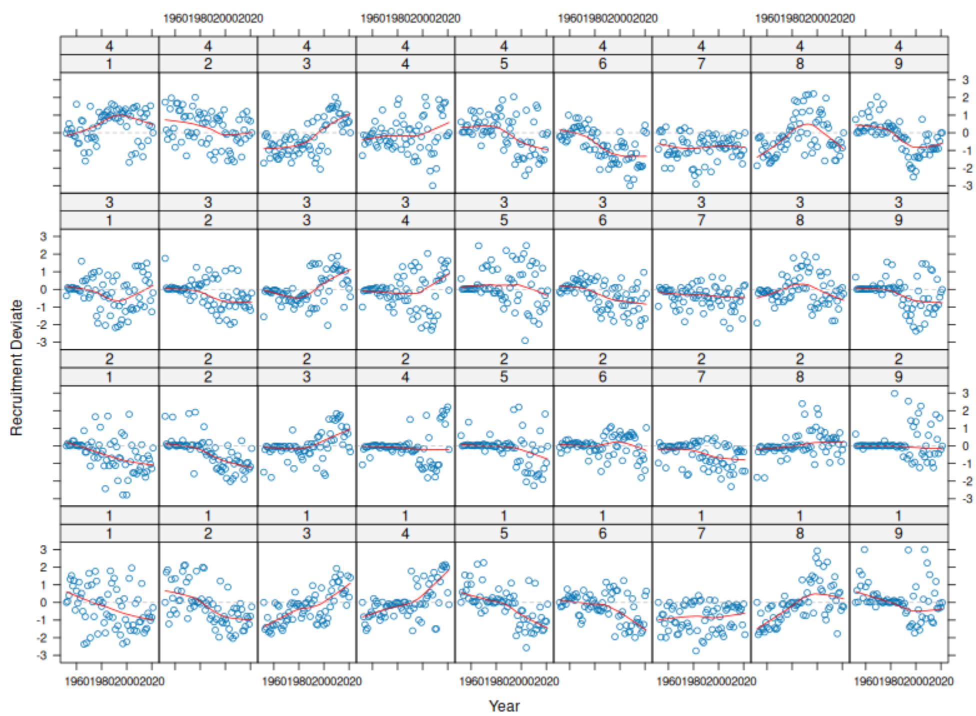


Figure 10: Recruitment deviates by season and region for one OM.

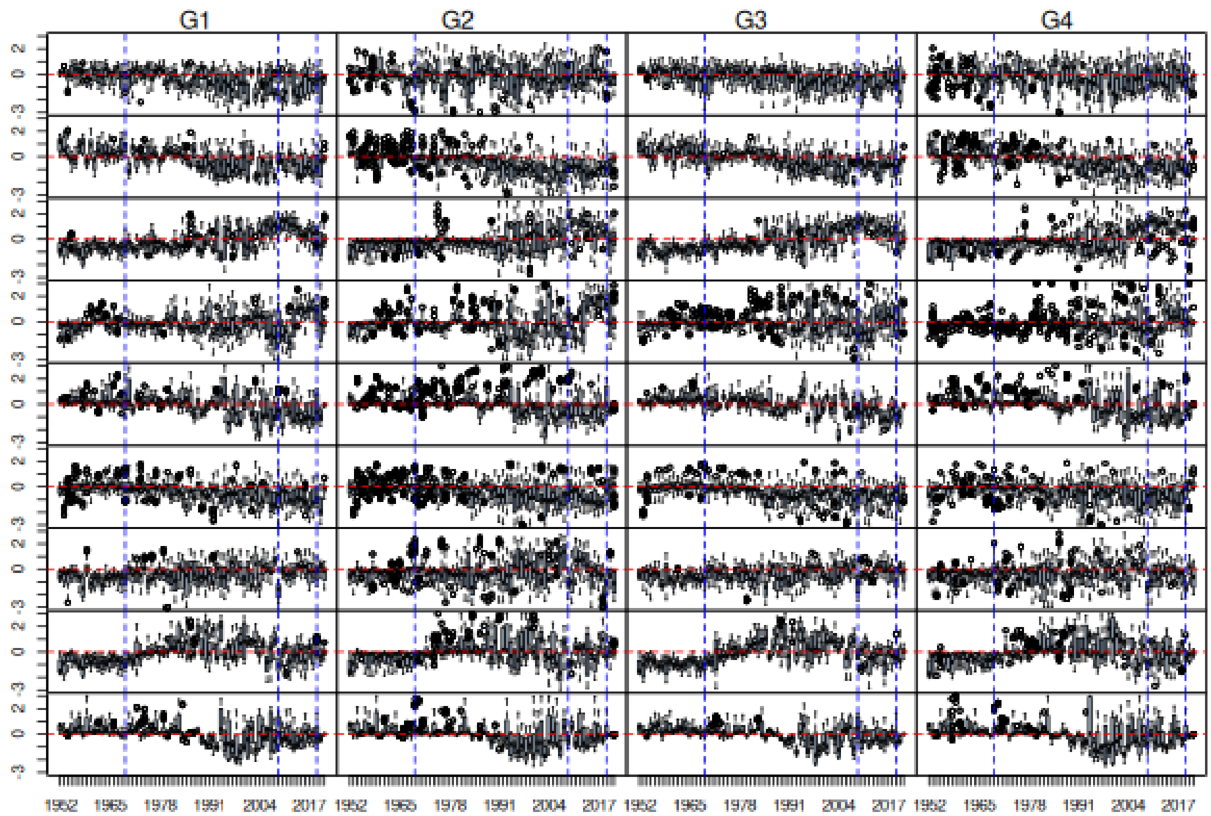


Figure 11: Recruitment deviates by region for each of the four growth models in the OM grid. Vertical dashed lines show the long- (1969:2020) and short-term (2010:2020) ranges assumed for recruitment variability.

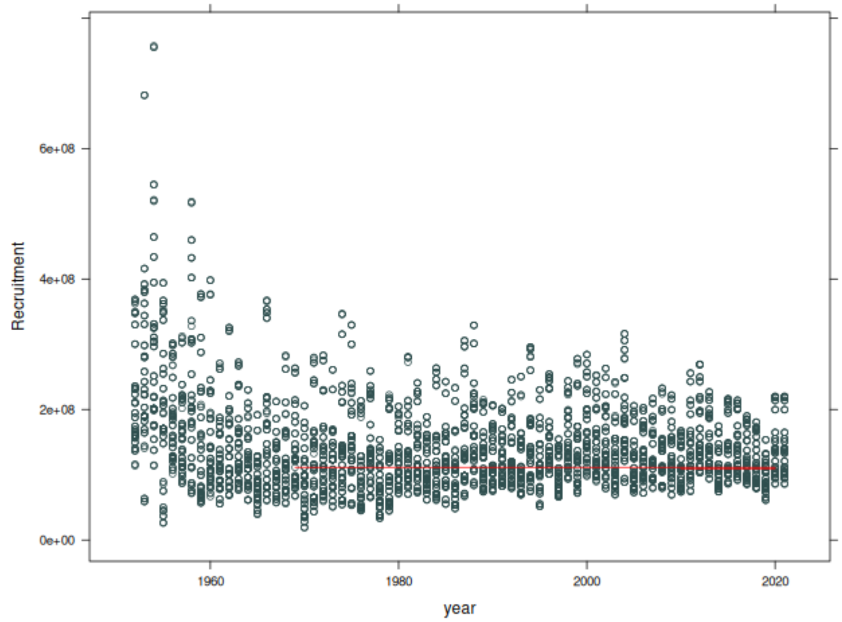


Figure 12: Annual recruitment estimates across the OM grid. Red lines show average annual recruitment for the long-term (1969:2010) and short-term (2010:2020).

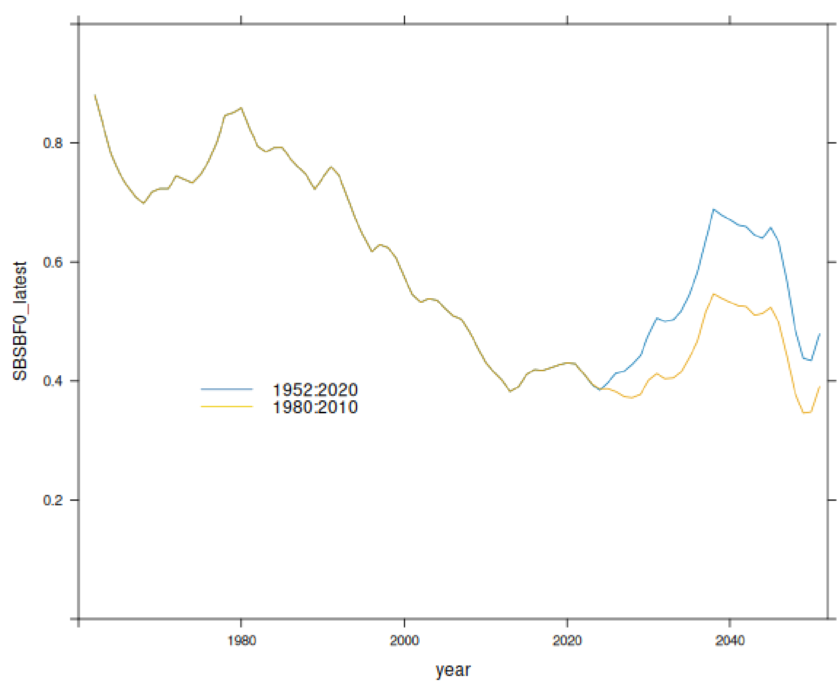
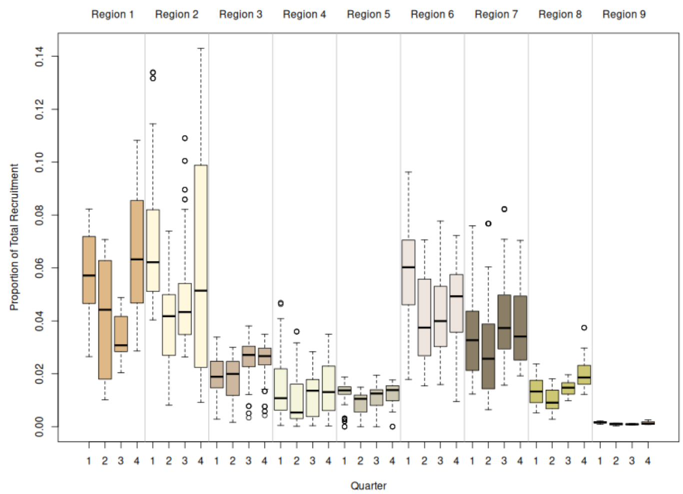
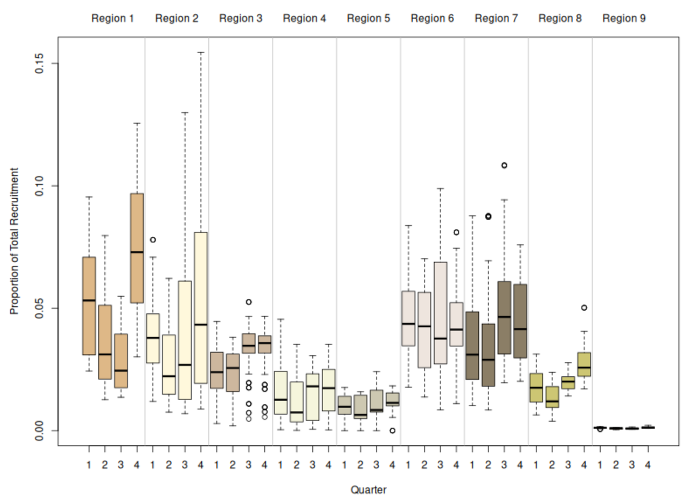


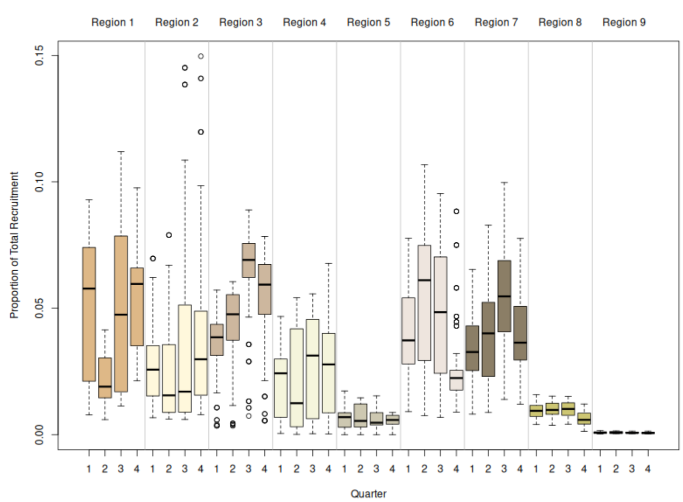
Figure 13: Projected depletion (SBSBF0latest), for a single 30-year projection, under alternative assumptions for the season and regional distribution of recruitment.



(a) 1952-2020



(b) 1969-2020



(c) 1980-2010

Figure 14: Alternative seasonal and regional distributions of recruitment for the whole time series (1952:2020), and for long-term (1969 to 2020) and short-term (2010 to 2020) time periods.

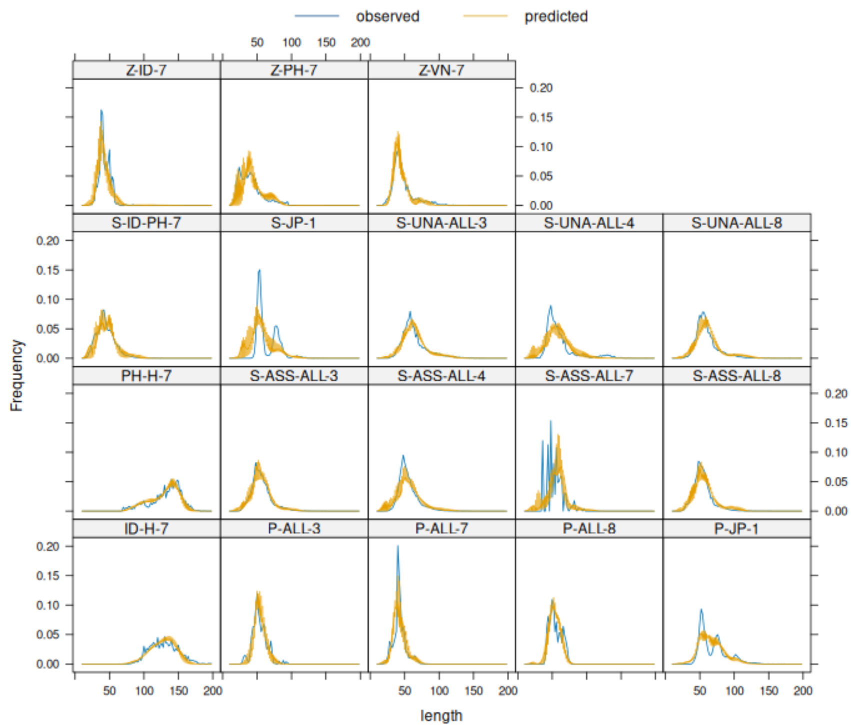


Figure 15: Observed and predicted length composition data for fishery groupings for which length composition data are available, for the 120 models in the OM grid.

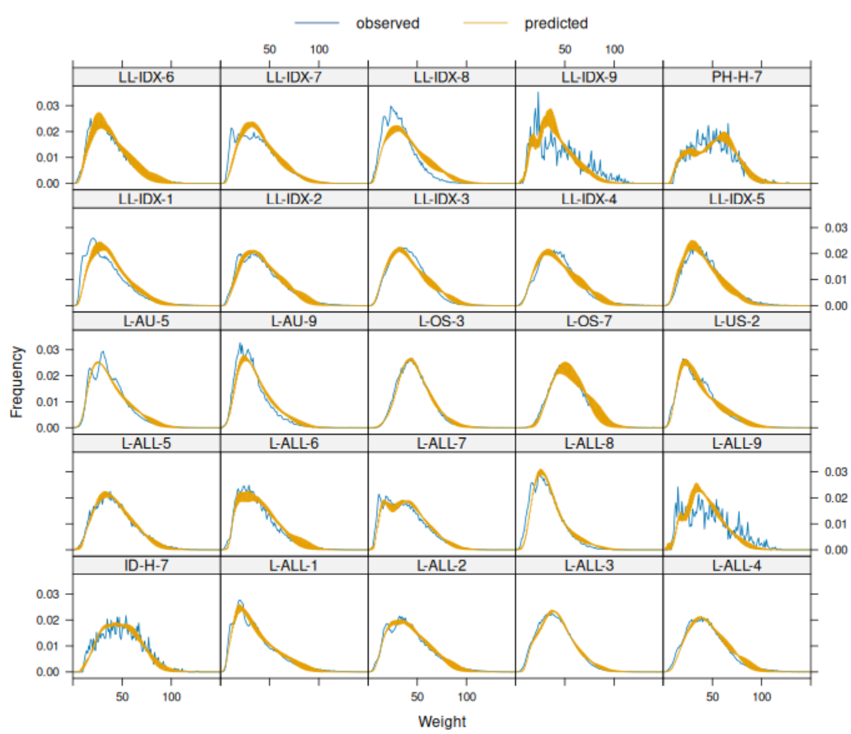


Figure 16: Observed and predicted weight composition data for fishery groupings for which weight composition data are available, for the 120 models in the OM grid.

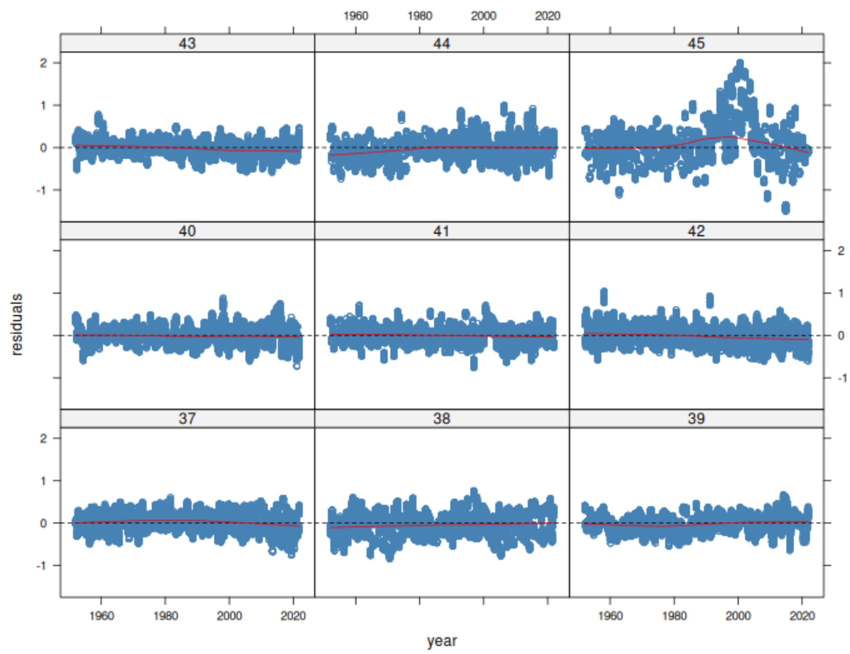


Figure 17: CPUE residuals for the index fisheries across the OM grid (120 models).

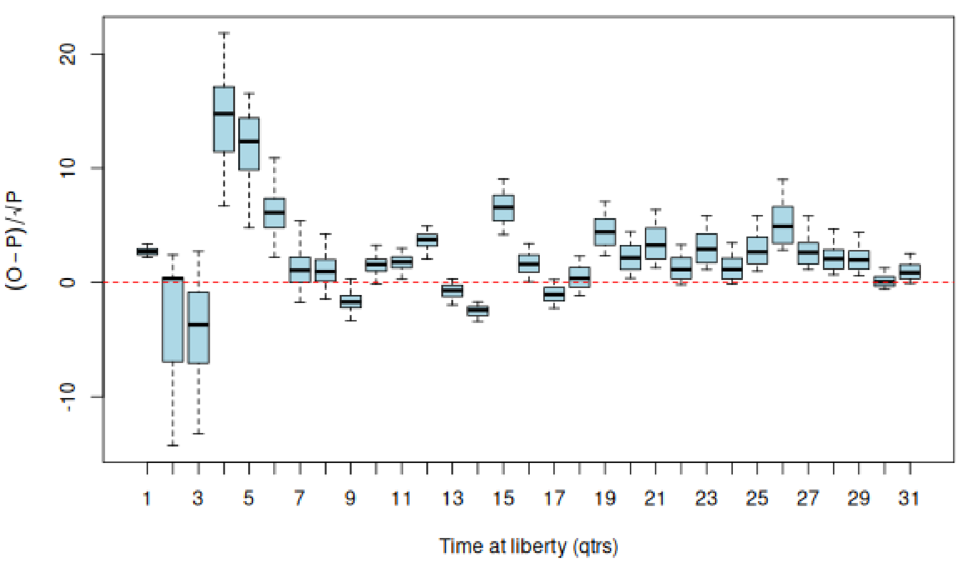


Figure 18: Standardised residuals for tag recapture estimates with time at liberty across the OM grid (120 models).

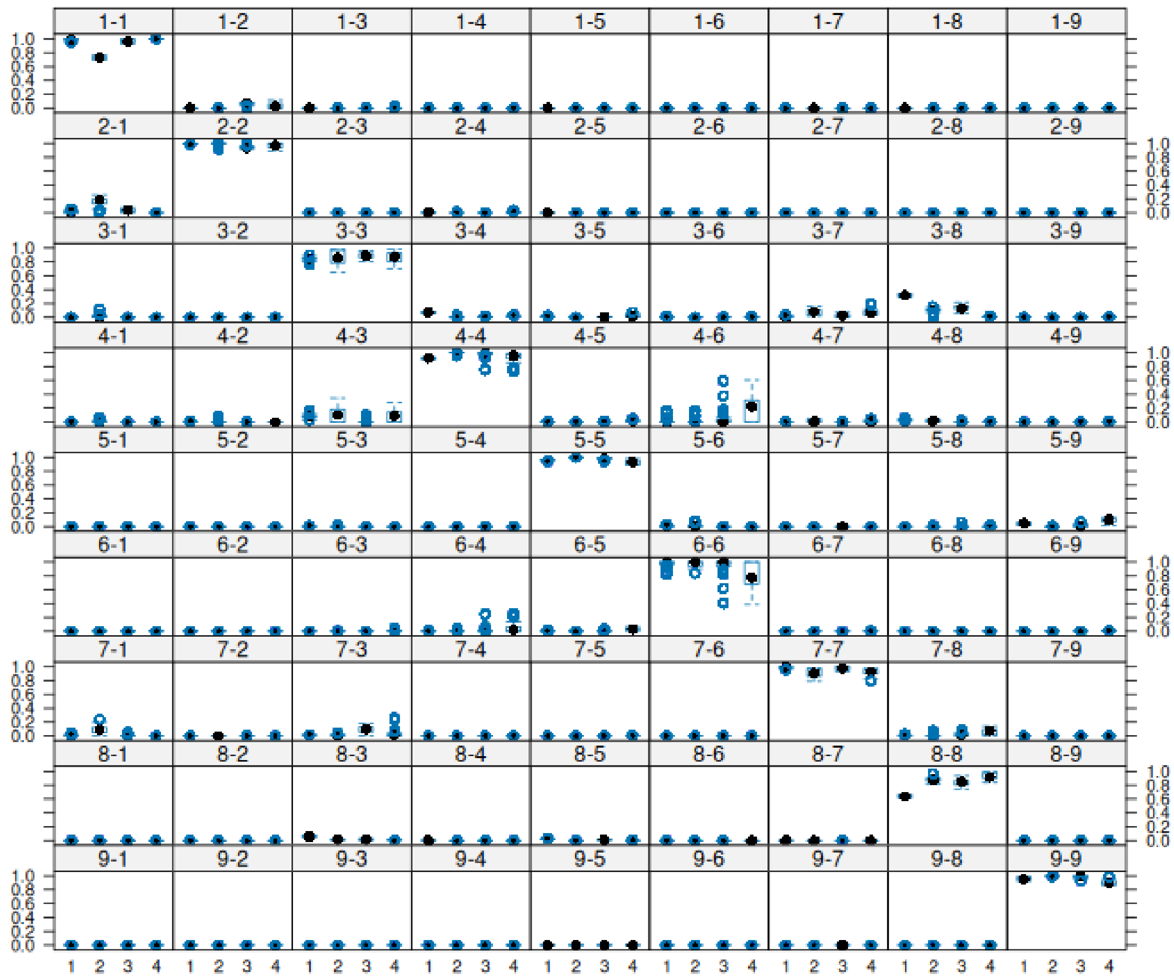
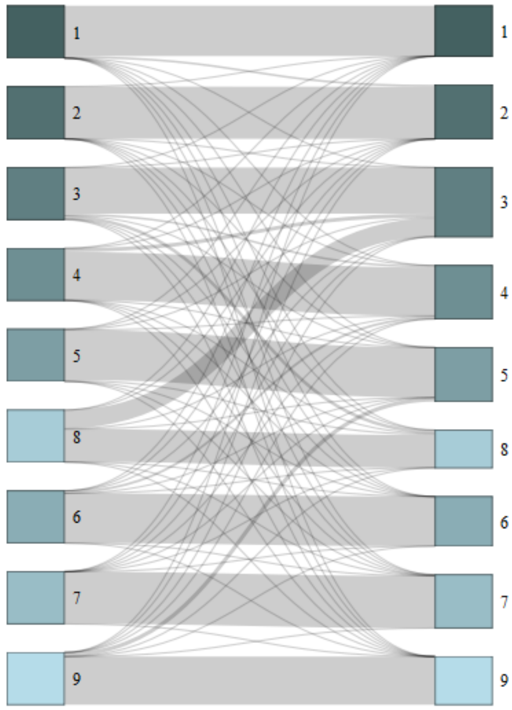
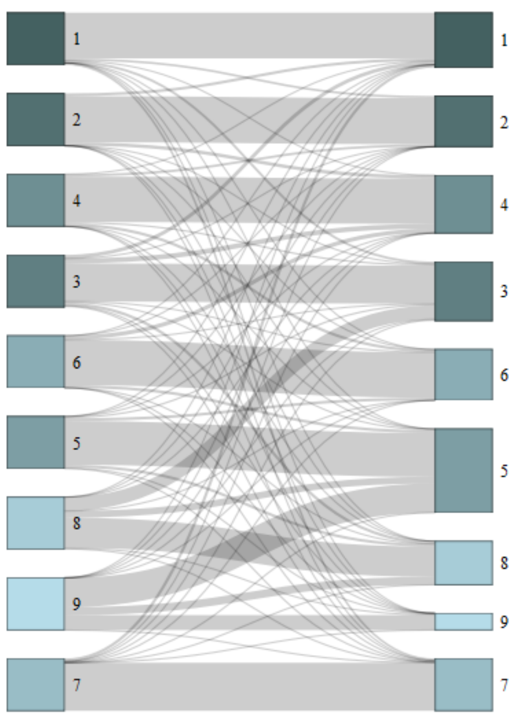


Figure 19: Quarterly movement rates by region (from rows, to columns) across the OM grid (120 models).



(a) MFCL



(b) SEAPODYM

Figure 20: Comparison of estimated movement rates for WCPO bigeye tuna from MFCL and SEAPODYM.

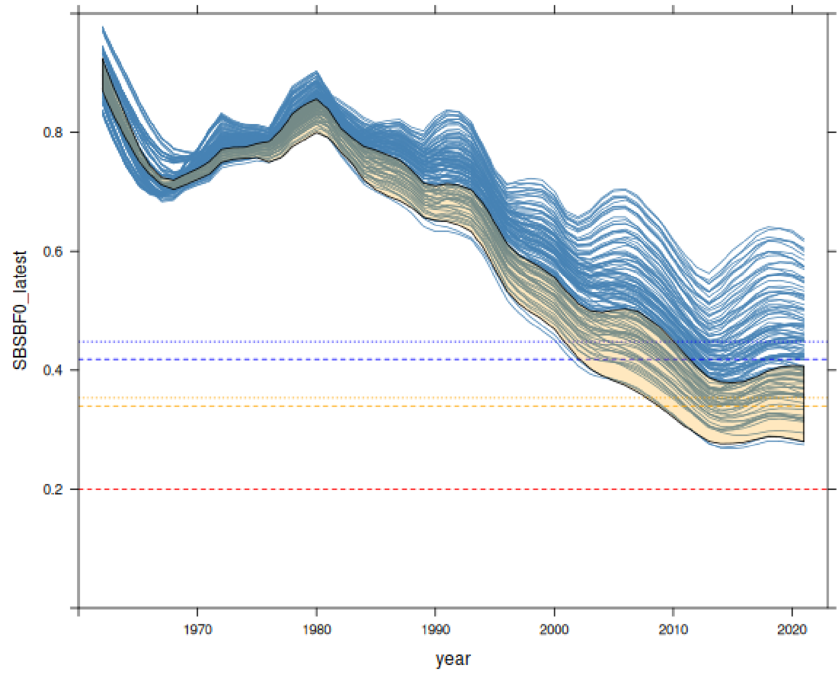


Figure 21: Estimated depletion (SB/SBF0) across the OM grid (blue lines) and the range of estimated depletion from the 2023 stock assessment (yellow shading). Horizontal dashed lines show the LRP (red) and the average of 2012 to 2015 depletion for the OM grid (blue) and 2023 stock assessment runs (yellow). Dotted lines show the average terminal (2019:2021) depletion for the 2023 assessment (yellow) and OM grid (blue).

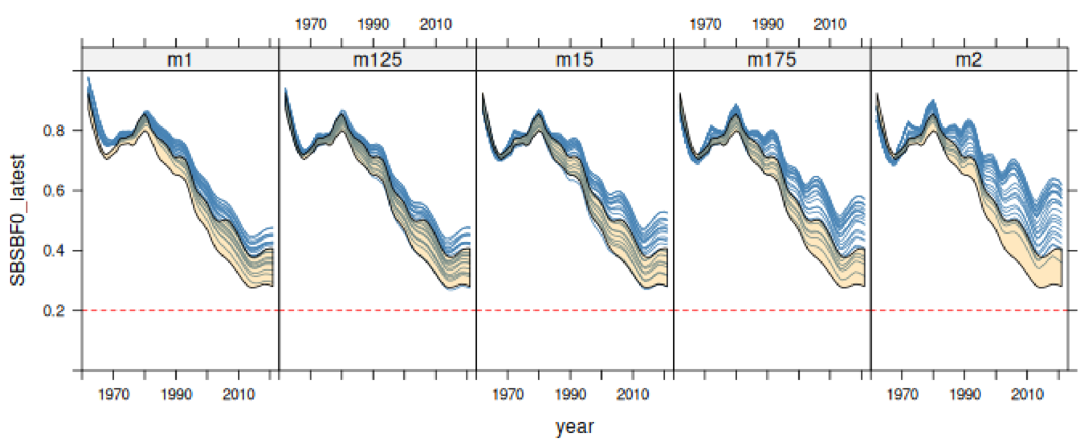


Figure 22: Estimated depletion (SB/SBF0) across the OM grid for each level of natural mortality (blue lines) and the range of estimated depletion from the 2023 stock assessment (yellow shading). Horizontal dotted lines show the LRP (red).

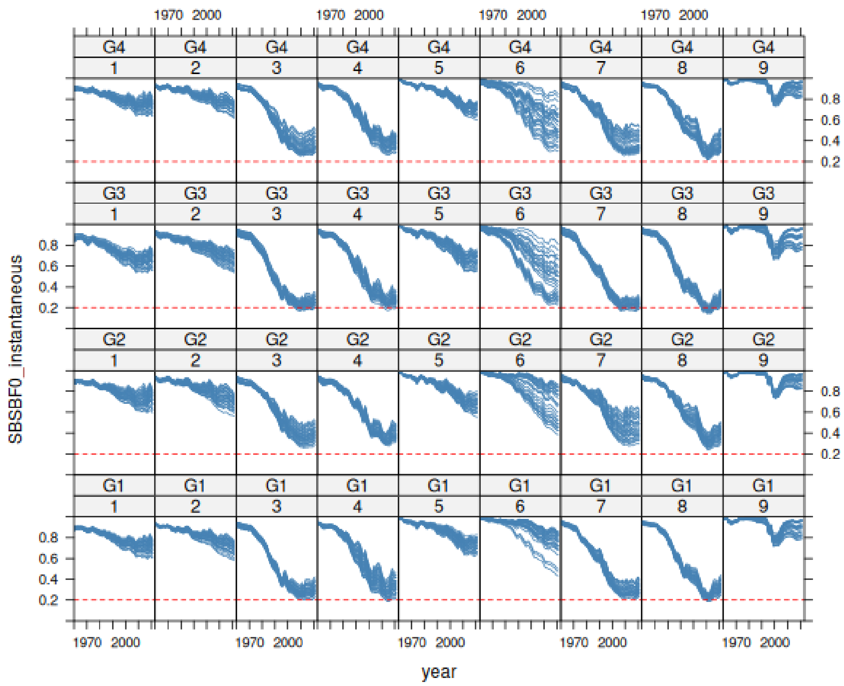


Figure 23: Estimated depletion (SB/SBF0) in each of the nine model regions, across the OM grid (120 models) for each of the four growth models.

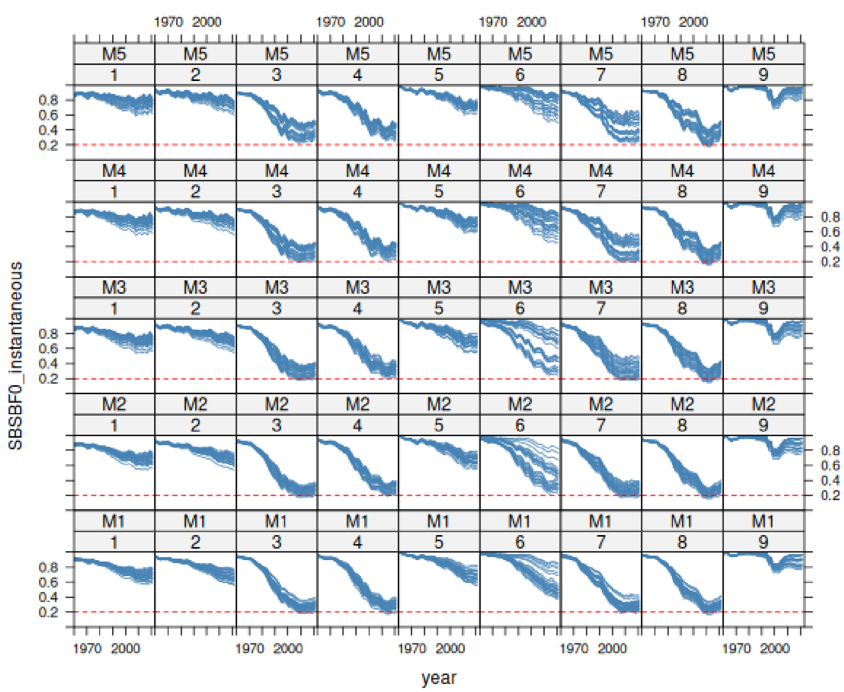


Figure 24: Estimated depletion (SB/SBF0) in each of the nine model regions, across the OM grid (120 models) for each of the five assumed values for natural mortality.

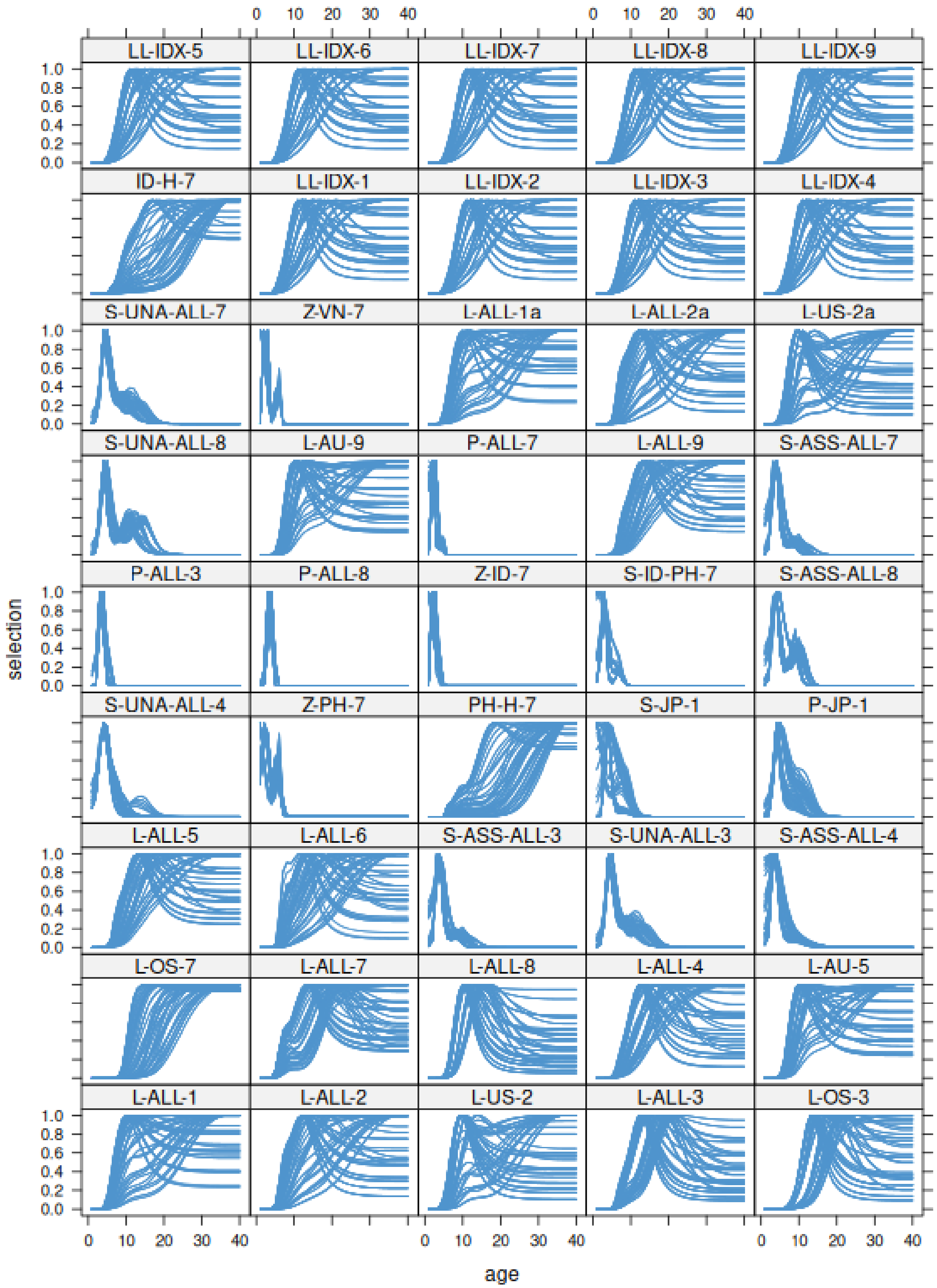


Figure 25: Estimated selection for the 36 extraction fisheries and 9 index fisheries across the OM grid of 120 models.

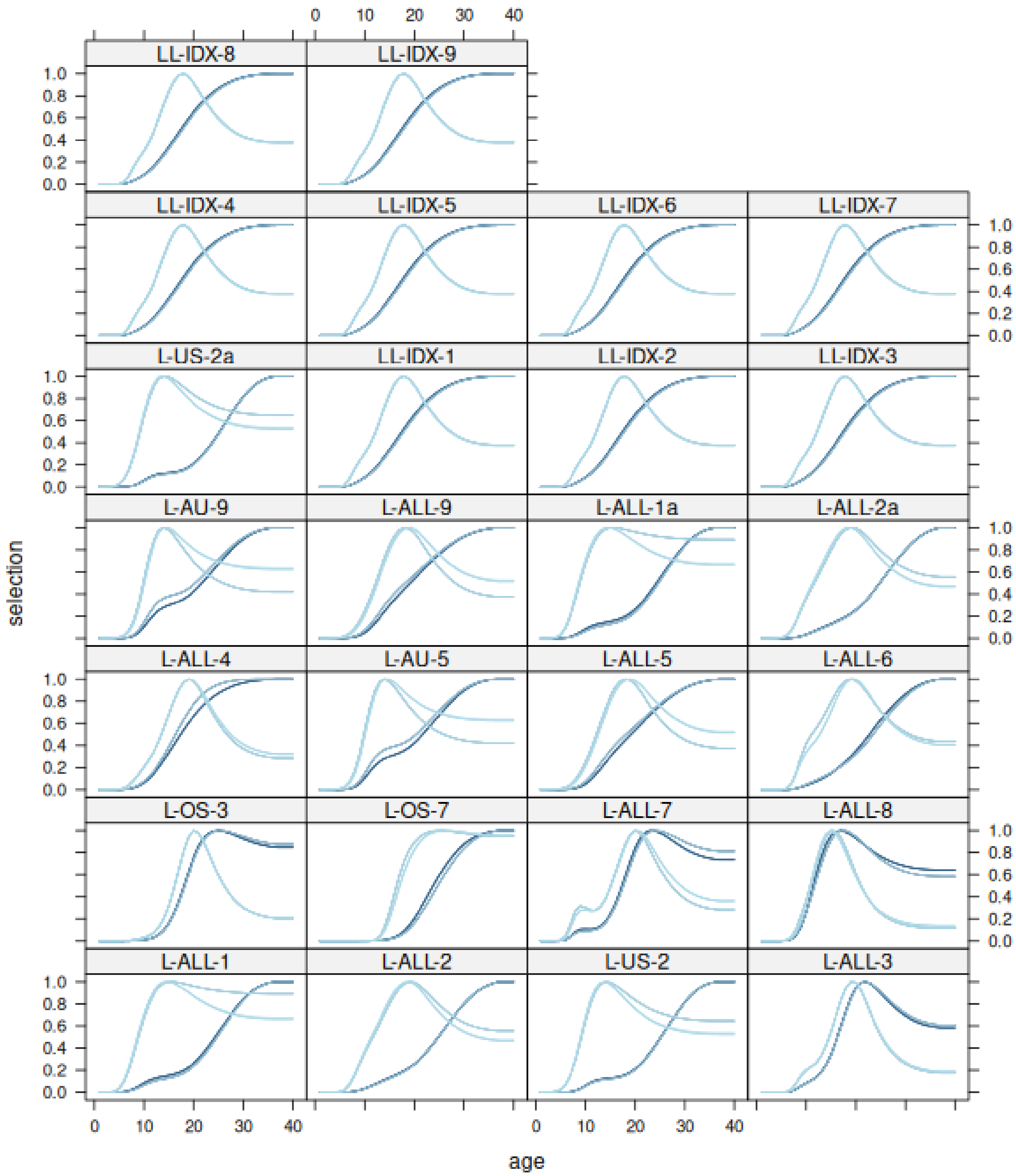


Figure 26: Subset of selection patterns to illustrate the impact of natural mortality. Estimated selection for longline fisheries for growth model 2 and two levels of natural mortality (0.1 darkblue and 0.2 lightblue). Each growth-M combination shows six estimated selection patterns for each of the steepness-tag mixing combinations.

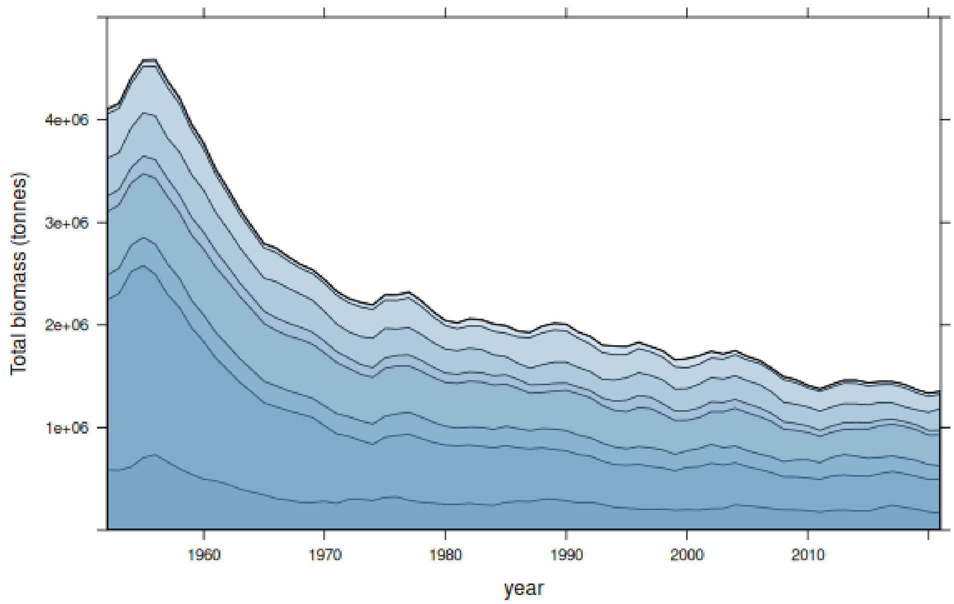


Figure 27: Cumulative total biomass by area (regions 1, bottom to 9, top) averaged across OM grid, for the period 1952 to 2021.

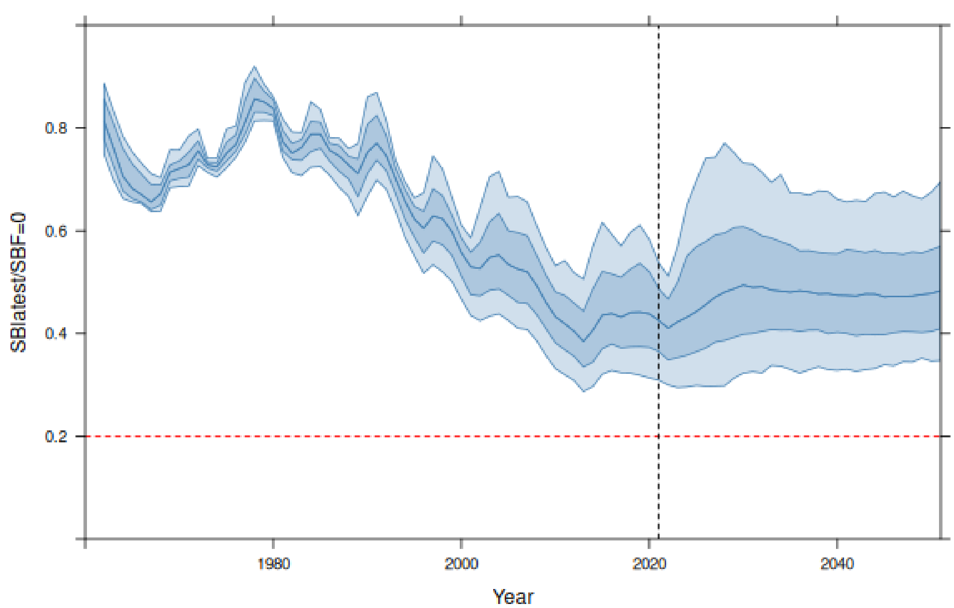


Figure 28: Distribution of depletion (SBSBF0 latest) estimates for thirty-year, effort-based, stochastic projections conducted across the OM grid (120 fitted models only). The median, 60% ile and 90% ile ranges are shown.

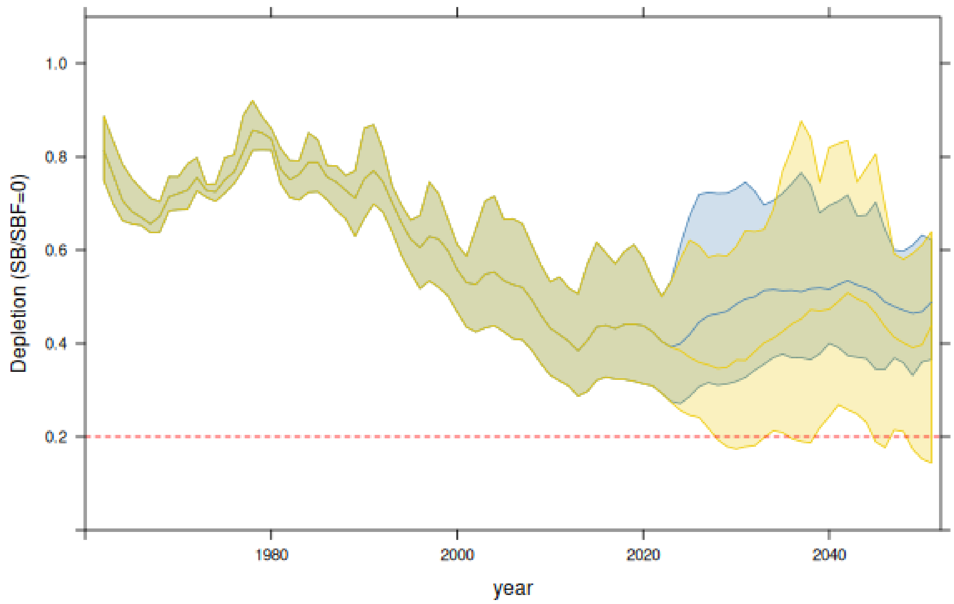


Figure 29: Distribution of depletion (SBSBF0 latest) estimates for thirty-year, effort-based, stochastic projections conducted across the OM grid (120 fitted models, blue) and a low recruitment scenario for which future recruitment is reduced by 30% . The median and 90% ile ranges are shown.

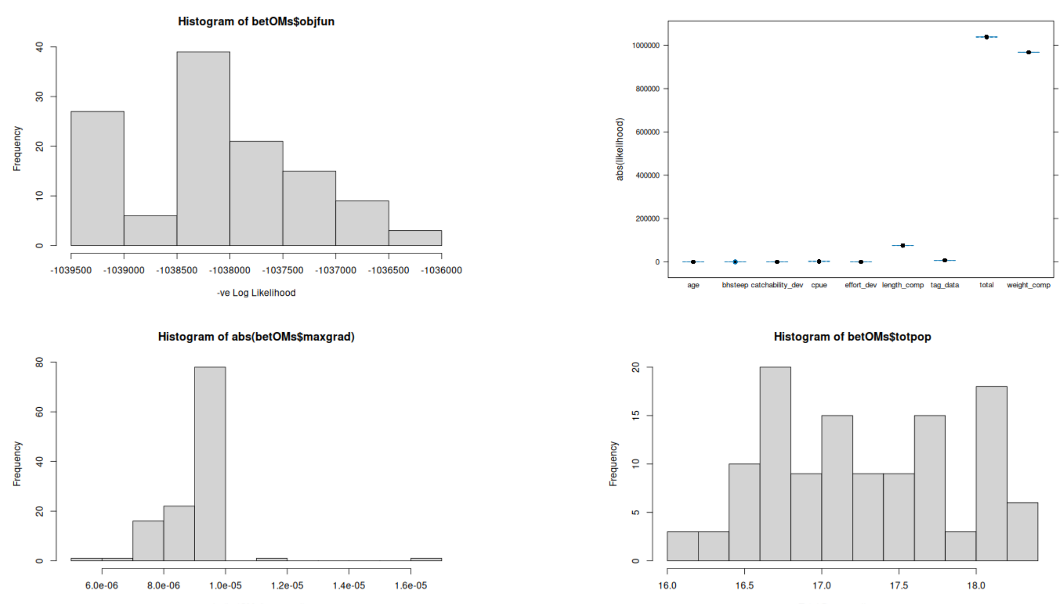


Figure 30: Total negative log likelihood, likelihood contributions, maximum gradient and total population scaling parameter for the 120 models of the OM grid.

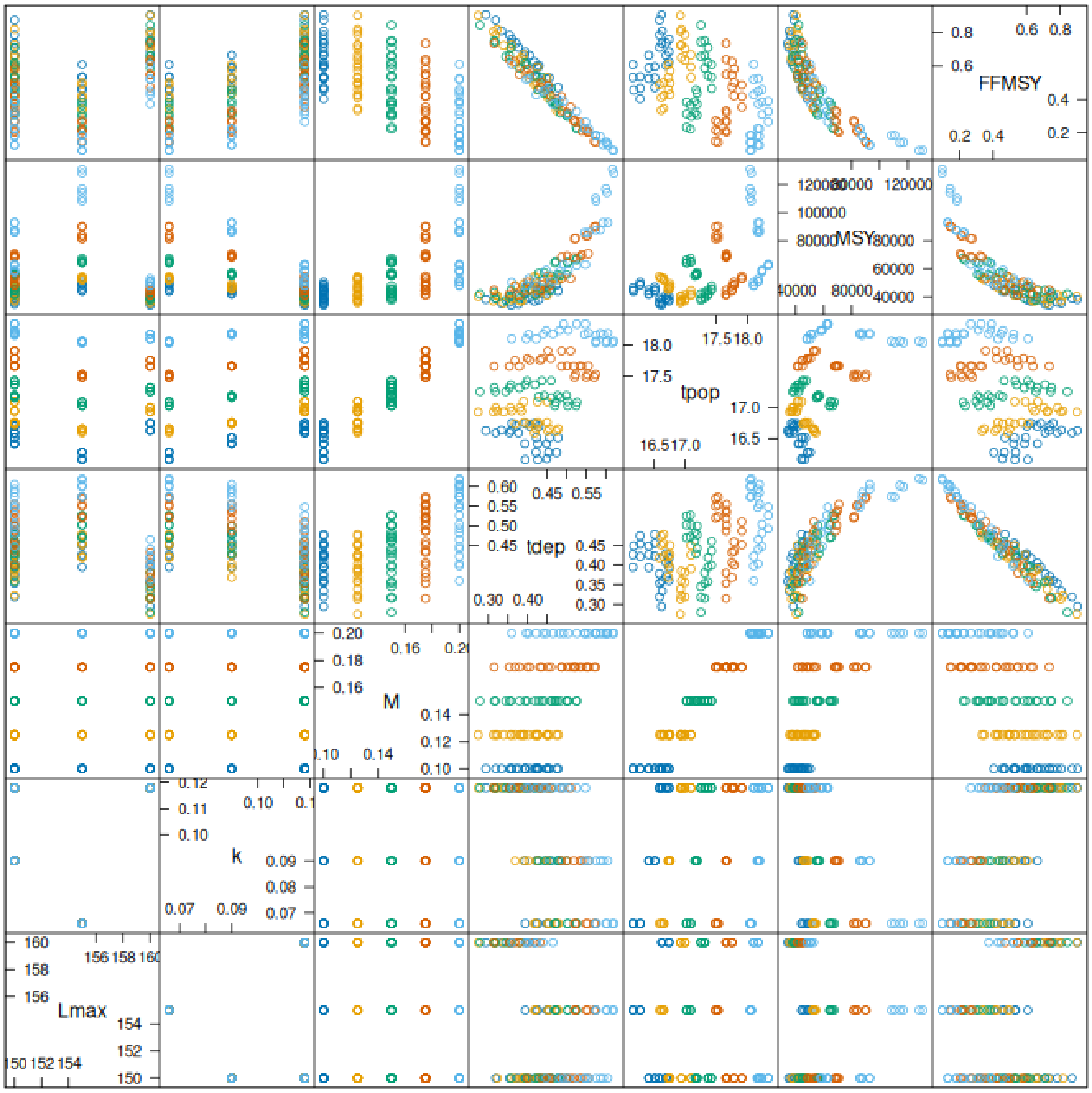


Figure 31: Scatter plot matrix for key factors and model estimates of the bigeye OM grid, showing the influence of growth and natural mortality on model estimates of depletion in the terminal year (tdep, SB/SBF0), MSY and F/FMSY and the total population scaling parameter (tpop). Colours correspond to the different levels of natural mortality.

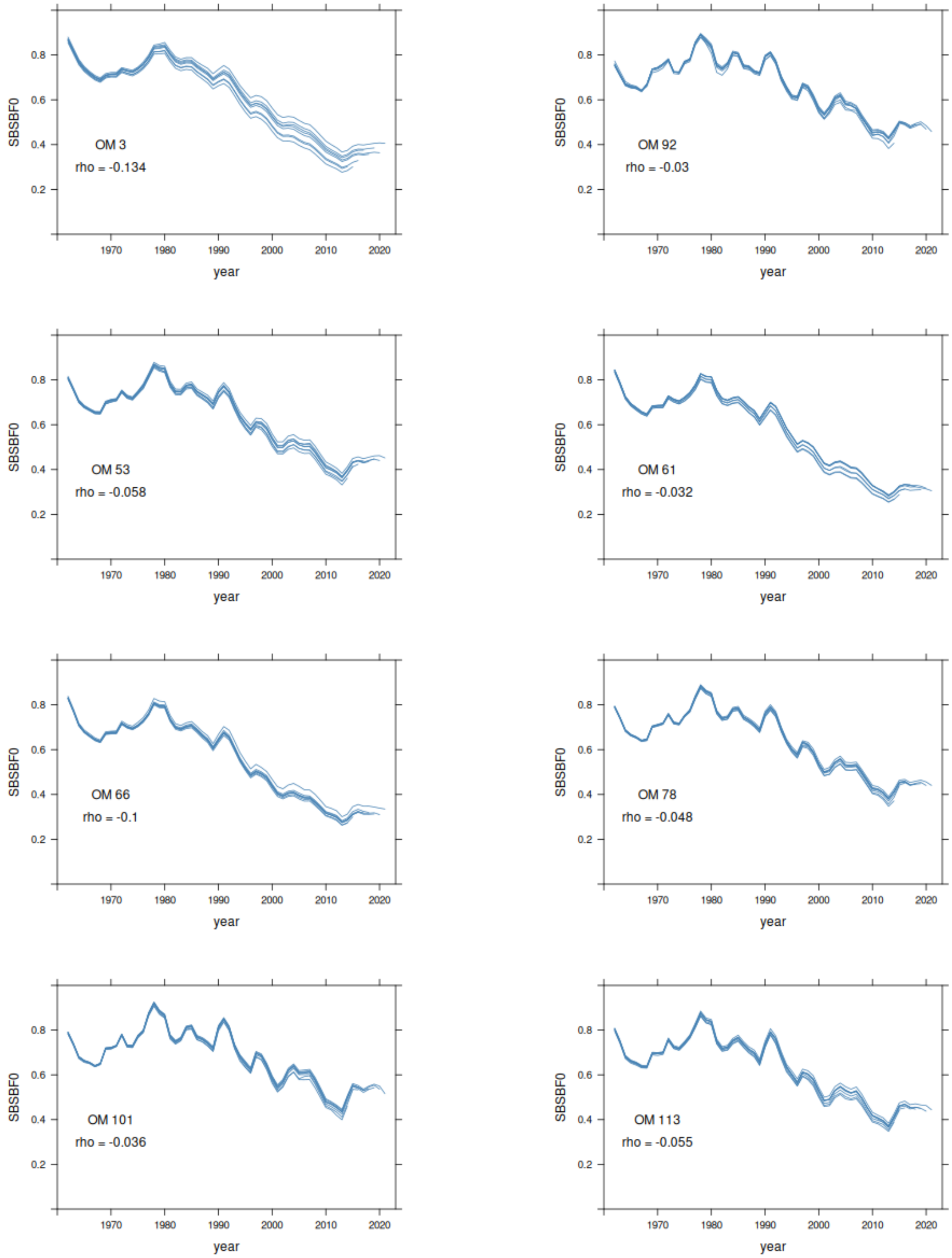
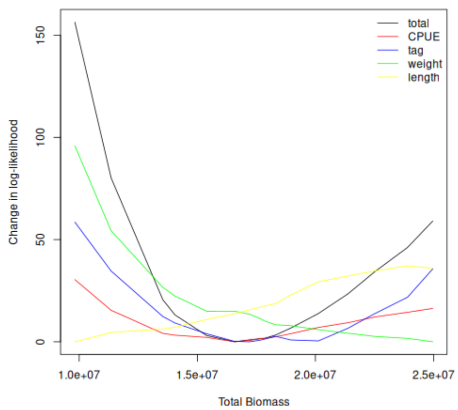
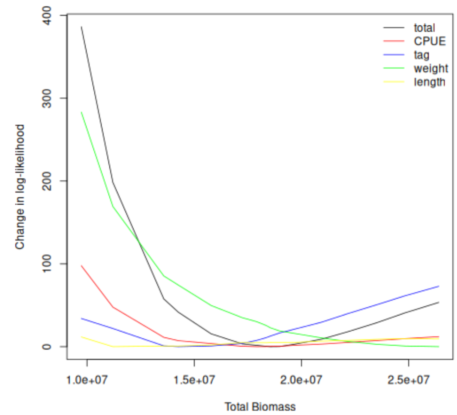


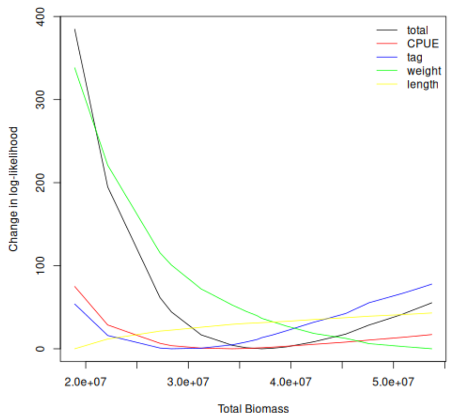
Figure 32: Retrospective fits showing estimated SB/SBF=0 (instantaneous) for model runs with terminal years from 2021 to 2014 (7 peels) for a subset of the OM grid.



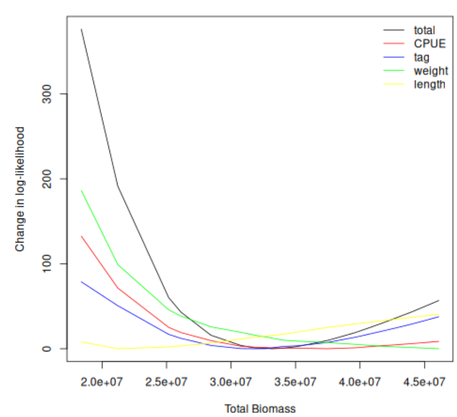
(a) OM3



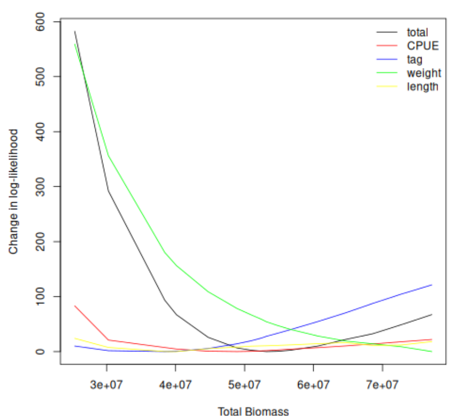
(b) OM48



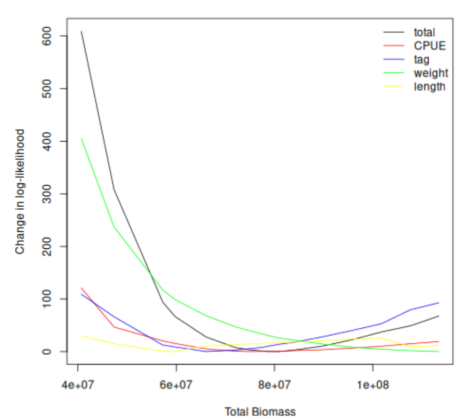
(c) OM53



(d) OM61

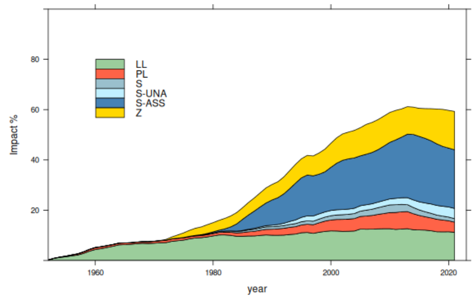


(e) OM78

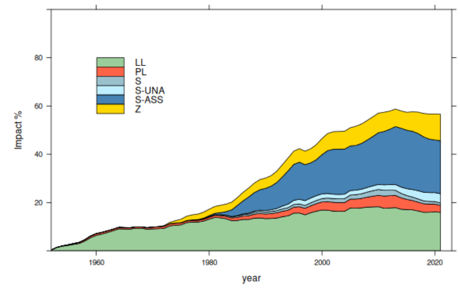


(f) OM113

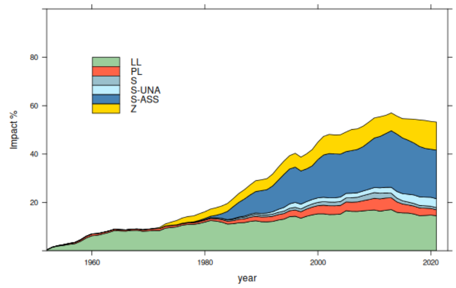
Figure 33: Likelihood profiles for a subset of model runs.



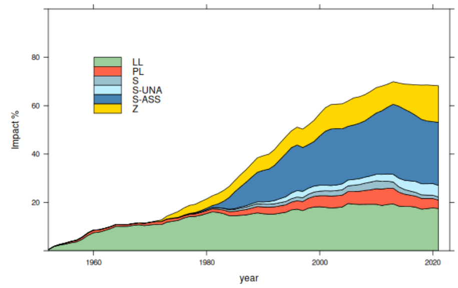
(a) OM3



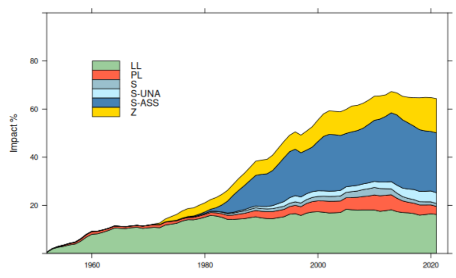
(b) OM48



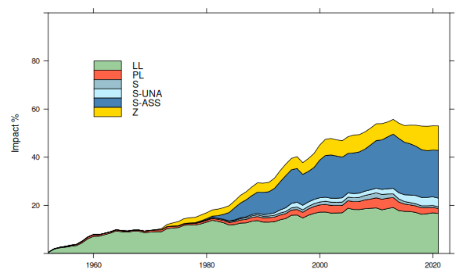
(c) OM53



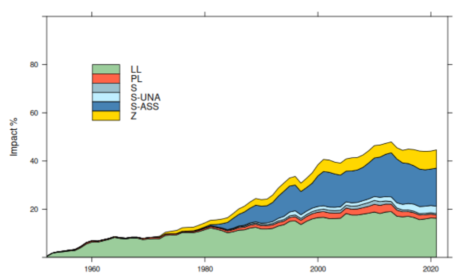
(d) OM61



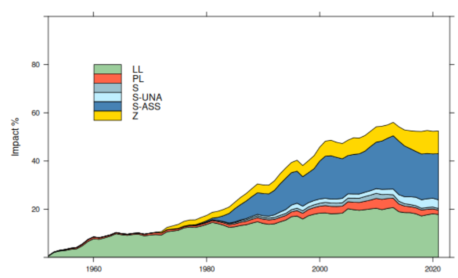
(e) OM66



(f) OM78



(g) OM101



(h) OM113

Figure 34: Impact plots, all regions combined, for fishery groups (longline; pole and line; purse seine; purse seine unassociated; purse sein associated and small scale domestic fisheries) for a subset of the OM grid.

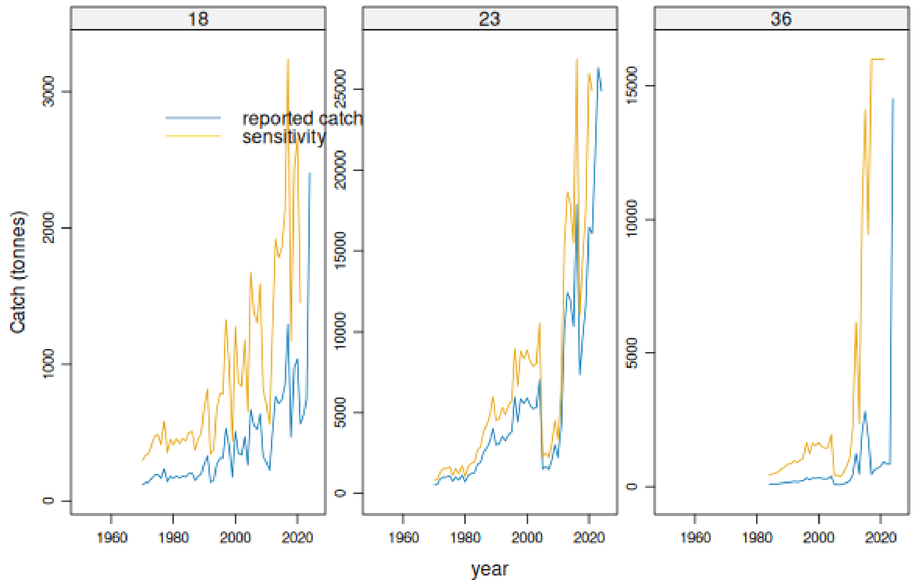


Figure 35: Reported and inflated sensitivity catches for the Indonesian domestic fishery (23), the Philippines handline fishery (18) and the Indonesian handline fishery (36).

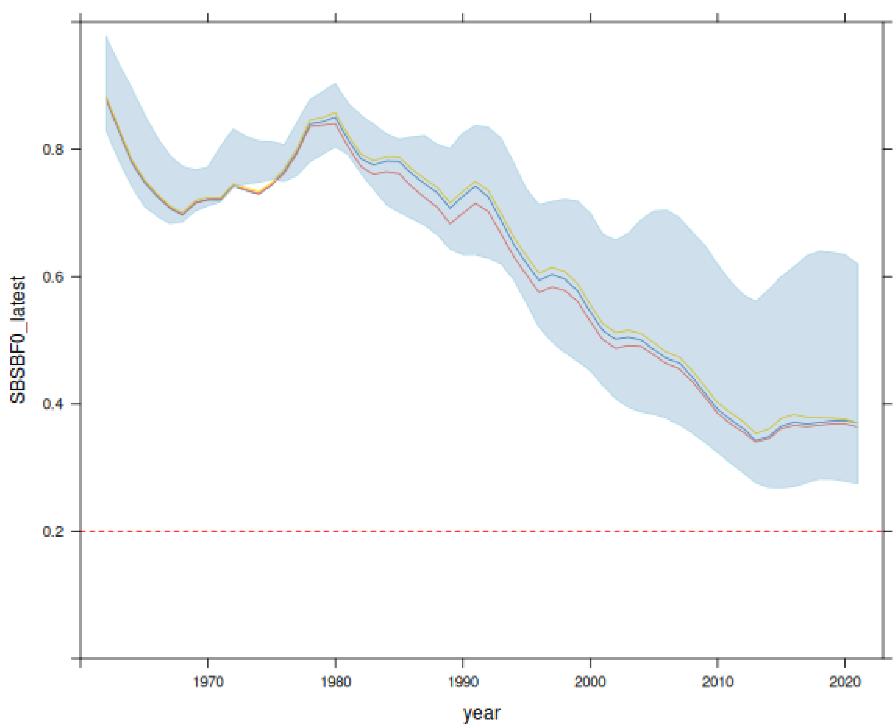


Figure 36: Estimated depletion (all regions combined) for individual sensitivity runs, conducted on a single OM, for alternative catch histories in region 7. Shaded area shows the range of depletion for the historical period acroos the full OM grid.

C Catch number to catch weight conversion

Catches for longline fisheries are often input to the stock assessment model as numbers of fish caught. Catches in number were converted to catch in weight using the available, fishery specific, length and weight frequency data. Where weight frequency data were available catches were determined from the sum of the weight frequency after raising by the number caught. Where only length frequency data were available, a length-weight relationship was applied and the same procedure followed. Where neither length nor weight frequency data were available values were interpolated from fishery-specific regressions of catch weight to catch number (Figure 37). The reesulting catch weight inputs corresponded well with estimated catch weight determined from the 2023 stock assessment (Figure 38).

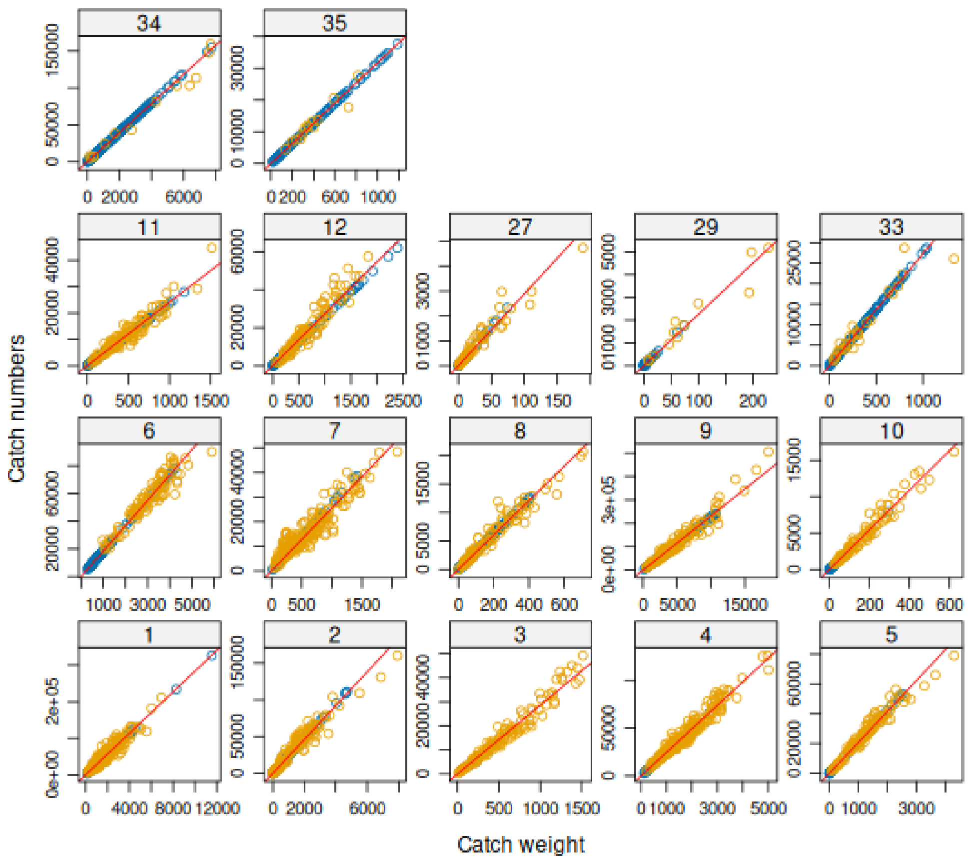


Figure 37: Linear regression of catch in number to catch in weight used to modify the input .frq file for the OM grid showing observed (yellow) and interpolated (blue) values for each fishery.

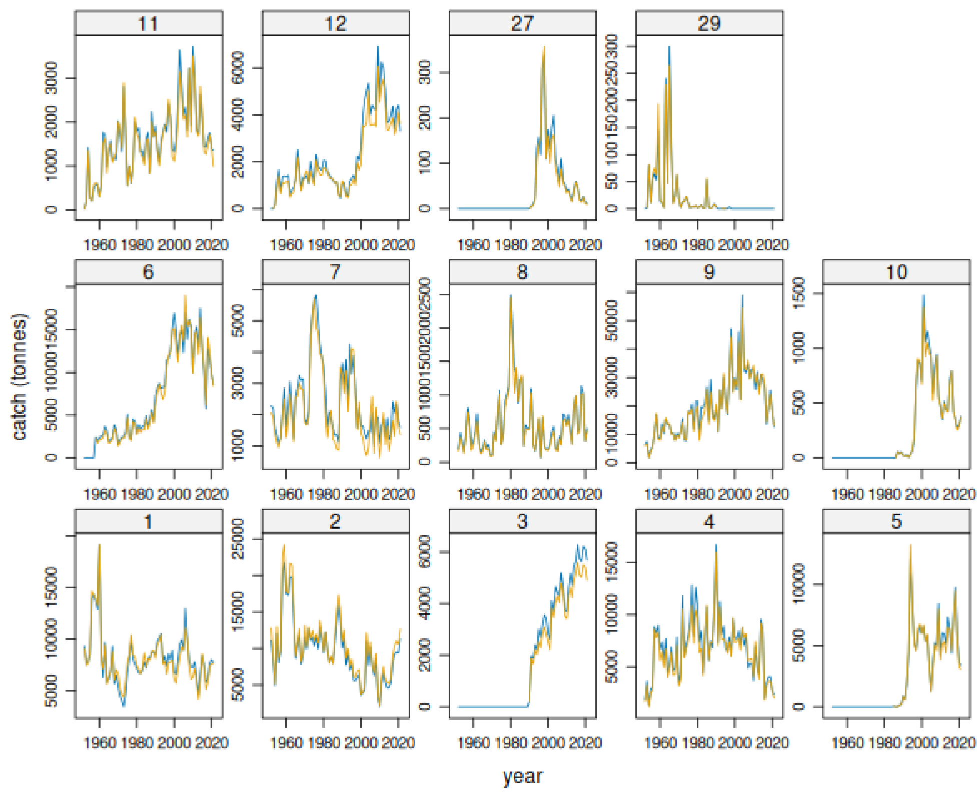


Figure 38: Check of modified .frq input file catch weight for longline fisheries against catch in weight values determined from the 2023 assessment.

D Investigation of additional OMs

The OMs presented in the main paper were developed from a range of alternative settings for growth, natural mortality, steepness of the SRR (stock-recruit relationship) and the period of tag mixing. Model runs across this grid showed a wide range of terminal depletion values (median 0.44, range 0.27-0.62) that overlapped that of the 2023 stock assessment. However, the extent of the overlap was greater at the upper range of stock status estimates than at the lower range. In the light of results recently available for this year's stock assessment of bigeye tuna, which presents a more pessimistic outcome for terminal depletion, a number of additional runs have been investigated to explore options for developing OMs that represent a more depleted stock. Whilst we do not wish to 'chase' the stock assessment, we do want to ensure that the OMs cover a range of plausible stock status scenarios.

Since the original set of OMs showed both total biomass and depletion scaling with increasing values of natural mortality, two lower values of natural mortality were included in the grid. Similarly, an additional option for 3 quarter tag mixing was also included. A further set of OMs was explored in which the overdisperson parameter for the distribution of expected tag recaptures (tau) was increased from the default setting of 1 to 2.

The model runs are outlined in Table 5, below, showing the grid levels and options for the the initial grid (described above), a second grid exploring additional natural mortality and tag mixing settings and a third employing alternative tau settings that was run for a subset of natural mortality values.

Table 5: Additional uncertainty runs.

Axis		Levels		Options						
	Initial	M+tmix	tau							
Growth	4			G1	G2	G3	G4			
Natural Mortality	5					0.1	0.125	0.15	0.175	0.2
Steepness	3			0.65	0.8	0.95				
Tag mixing (qtrs)	2			1	2	3				
Tau	-			1						
Growth		4		G1	G2	G3	G4			
Natural Mortality		7		0.05	0.075	0.1	0.125	0.15	0.175	0.2
Steepness		3		0.65	0.8	0.95				
Tag mixing (qtrs)		3		1	2	3				
Tau		-		1						
Growth			4	G1	G2	G3	G4			
Natural Mortality			3			0.1	0.125	0.15		
Steepness			3	0.65	0.8	0.95				
Tag mixing (qtrs)			3	1	2	3				
Tau			1		2					

The additional runs focussed on alternative settings for natural mortality and tag related model parameters. Alternative settings for other model components were also investigated as one-off runs from OM1 (Figure 39) but did not move the model estimates in the desired direction and, therefore, were not investigated further. Increased weighting of the length frequency data resulted in unchanged estimates of terminal depletion. Similarly, reducing the value of natural mortality below 0.1 resulted in more positive stock status outcomes (Figure 40).

Estimates of depletion from the two additional grids are shown in Figure 42. Whilst the increase in the tag mixing period and the higher tau value have both resulted in reduced estimates of terminal depletion (i.e. a more depleted stock), the lowest estimate remains at around 0.2. Median terminal depletion for the tau2 grid is 0.341 (max 0.488, min 0.196).

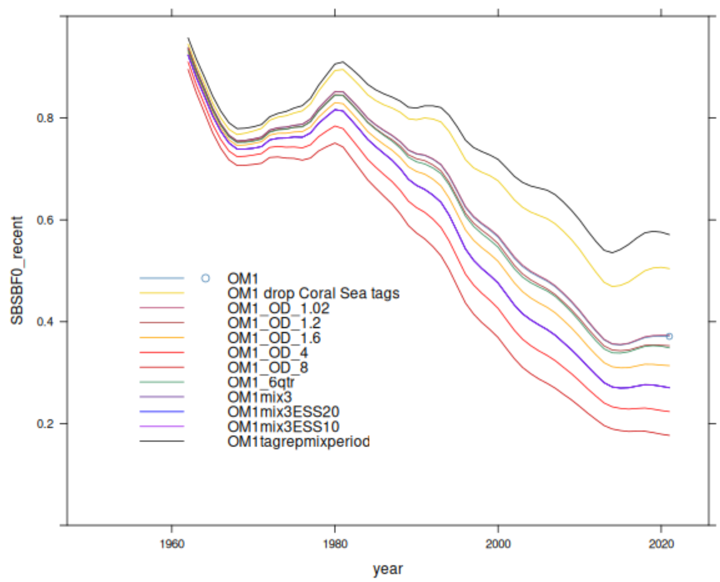


Figure 39: Depletion (SBSBF0recent) for sensitivity analyses conducted for OM1 investigating alternative data weighting settings for tag and length composition data.

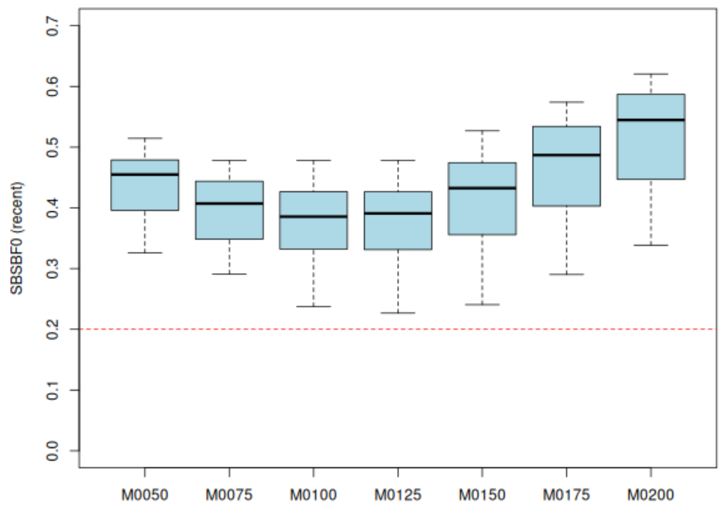


Figure 40: Terminal depletion (SBSBF0recent) for the M+tmix grid by natural mortality value.

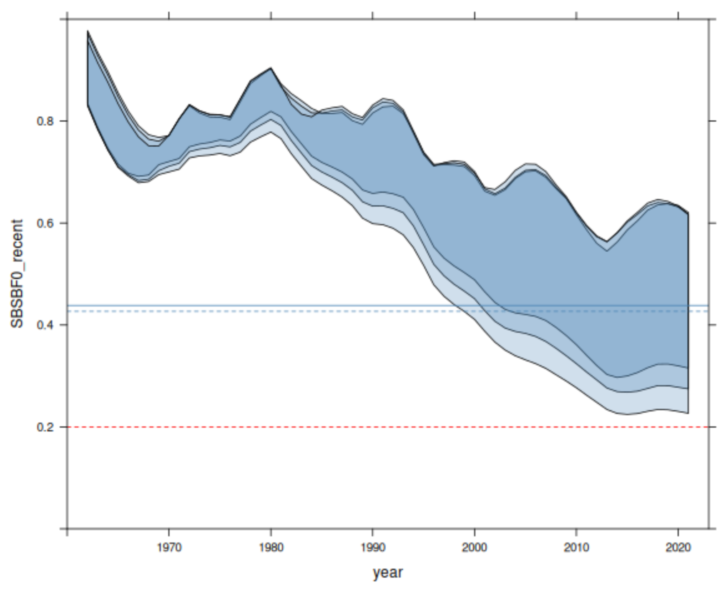


Figure 41: Depletion (SBSBF0recent) for the M+tmix grid by tag mixing period.

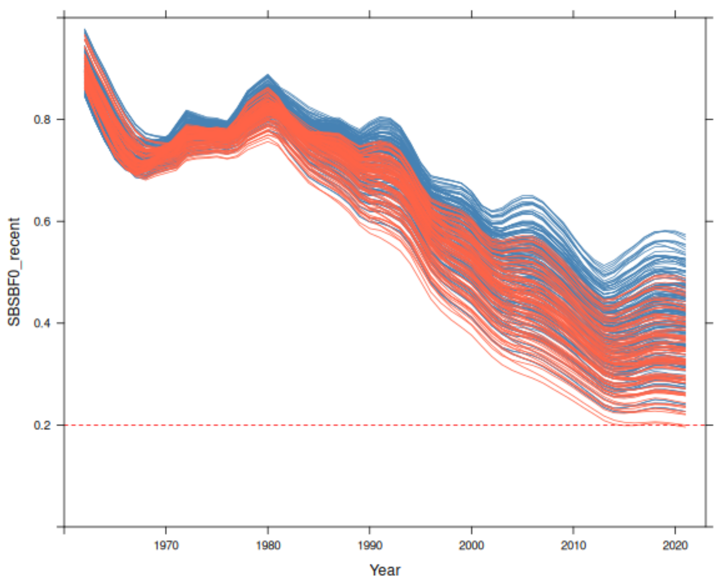


Figure 42: Depletion (SBSBF0recent) for the tau2 grid (red) and the M+tmix grid for M values of 0.1, 0.125 and 0.15 only (blue).