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Additional analyses to support the 2016 stock assessment of skipjack tuna in the western and central Pacific Ocean

Additional analyses to support WCPFC-SC12-2016/SA-WP-04

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Executive Summary

This paper presents sensitivity model runs additional to those conducted during the stock assessment of skipjack tuna in the western and central Pacific Ocean that was presented to the 12th scientific committee of the Western and Central Pacific Fisheries Commission (SC12; SA-WP-04). These additional analyses were undertaken in response to suggestions for further analyses made by some CCMs. The sensitivity models included runs with; alternative formulations of the relationship between natural mortality and age, an alternative maturation schedule, further investigation of likelihood profiles by individual data component and a preliminary investigation of a different spatial structure for the stock assessment.

In all cases the sensitivity models produced model results and management recommendations consistent with those presented at SC12 and model quantities were well within the envelope of parameter estimates resulting from the one-off sensitivities and structural uncertainty grid of the original stock assessment. As predicted during the stock assessment, the likelihood profile analysis confirmed the effects of the different data components that had previously been observed during sensitivity analyses, namely that tagging data support a higher total population scaling parameter,

and size composition and CPUE data support a lower value for this parameter.

These additional analyses provide further information on the robustness of the 2016 skipjack stock assessment results, and we encourage the commission to consider this additional work when interpreting the recommendations of the SC12 report.

1 Introduction

A stock assessment of skipjack tuna in the western and central Pacific Ocean (WCPO) was undertaken in 2016 (McKechnie et al., 2016a) and was presented to the 12th scientific committee (SC12) of the Western and Central Pacific Fisheries Commission (WCPFC). This assessment was accepted by the committee although there was a divergence in recommendations made by two groups of CCMs. The minority view were influenced by perceived shortcomings in the stock assessment and made suggestions for further analyses to address their concerns. This report presents the results of additional analyses suggested by those parties, subsequent to SC12, that can be used to inform the 13th regular session of the commission.

Some of the concerns related to a perceived mismatch between model predictions and the catch rates of a small coastal fishery in the northern area of the skipjack geographical range. Many recommendations therefore related to alternatives that might improve the modelling of population dynamics in northern regions. The proposed mechanism to achieve this is an alternative regional structure for the assessment which aims to investigate movement over a slightly finer spatial scale.

While the 2016 reference case model output is consistent with the data inputs used - there are no significant trends in CPUE indices for pole-and-line fisheries in northern regions, it was intended that the suggested alternative spatial structure also be investigated (if time permitted) to confirm, or otherwise, the robustness of the stock assessment (Pilling and Brouwer, 2016). Unfortunately, necessary CPUE indices were not provided in time to meet the modelling deadlines for SC12. This report presents the development of the alternative spatial structure model that has been achieved in the short time available since SC12. It is expected that this model, and similarly, the reference case model structure, will continue to be improved in the future with respect to the robustness of input data, modelling assumptions, diagnostics and fit to the data.

While the model with the alternative spatial structure is perhaps the major development presented herein, many of the other suggestions made by CCMs in the SC12 summary report are addressed as sensitivity models, and inferences from them are presented with respect to the stock assessment of McKechnie et al. (2016a). These include a suite of models with different parameterisation of the natural-mortality-at-age function, an alternative maturity schedule and further development of likelihood profiles disaggregated by data component. Suggestions such as utilising growth functions with an L_∞ of ∼60–65cm were not considered as they are implausible given the proportion of fish larger than this caught in some fisheries. Furthermore, several recommendations such as increased involvement of CCMs in the assessment process are defined by commission structures and are not topics that can be addressed by the scientific services provider in a paper such as this.

This paper will present each CCM suggestion in-turn, stating the perceived issue raised, the models that were formulated to address their concern, and the results and conclusions that can be drawn by comparing them to the results of the stock assessment presented by McKechnie et al. (2016a). The overall conclusions that can be made from this additional work and suggestions for further developments that are desirable before the next full stock assessment of skipjack in the WCPO are then presented in the discussion (Section 3).

2 Formulation and fitting of sensitivity models

2.1 Form of the natural mortality function

Two CCMs raised concerns about the biological validity of the natural mortality-at-age (hereafter M-at-age) function estimated by MFCL. It was noted that "no biological and ecological explanations were made" for the lower natural mortality rate for age-class 1 and the fluctuating mortality rate for fish older than age-class 6. It was recommended that "it would be more parsimonious and biologically accurate to estimate a single natural mortality rate parameter for ages older than 10 quarters and similarly, to set the natural mortality rate for age-1 quarter fish to be equal to the estimated age-3 quarter natural mortality rate parameter". These concerns were addressed through a series of additional model runs with different parameterisation of the M-at-age function.

At the time of the stock assessment, estimation or specification of M-at-age in MFCL was limited to a mean rate and age-specific deviations from it, both of which could be penalised to constrain them somewhat, or by specifying these parameters and turning off estimation. Subsequent to SC12 considerable effort has been put into the development of functional forms for M-at-age which allows a more parsimonious approach to addressing the concerns of the CCMs than by utilising penalisation or fixed M-at-age values. We constructed a set of three sensitivity models which were formulated as:

1. (***ConstantM***; red line in figures) This model assumes age-invariant natural mortality by only estimating a constant mortality parameter. While this parameterisation is probably unrealistic, it is simple to model and is a component of the request to "test alternative natural moralities such as constant one or one that decreases as ageing".

2. (***Spline4***; dark blue line) This model uses a newly developed spline formulation for estimation of M-at-age. The function is parameterised in the same manner as the spline functions for age-based selectivity with the number of nodes being user-defined. Four nodes were specified for the estimation of M-at-age in *Spline4* which allowed for a functional form relatively similar to that estimated by the reference case model, except that mortality of age-class-1 fish was estimated to be higher than for older age-classes (Figure 1). Comparing this model with the

reference case model indicates the consequences of addressing the concerns of the CCMs about a potentially unrealistic mortality rate for age-1 quarter fish.

3. (***Lorenzen***; green line) This model implements the suggestion to "use an expected Lorenzen-type allometric scaling of natural mortality rate to body mass" (and also the request by the CCM quoted in the *ConstantM* section above) by using the newly developed function that imposes a power function form of M-at-age based on the length-at-age as suggested by Lorenzen (1996). The parameterisation is given such that natural mortality of age-class a is given by

$$M_a = c \times {l_a}^b \tag{1}$$

where l_a is the mean length of age-class a, and b and c are the mortality rate parameters determining the shape of the function. Comparing this model with the reference case model indicates the consequences of addressing the concerns of the CCMs about both the mortality rate for fish in age-class 1, and the fluctuating mortality rates of fish older than age-class 6. Comparing this model with *Spline4* gives some indication of the consequences of addressing the concerns of the CCMs about a potentially unrealistic mortality rate for older fish.

The estimated functional forms of the sensitivity models are shown in Figure 1, and estimated model quantities of interest are presented in Figures 2–4 and Table 3. The *constantM* model estimated a constant natural mortality (all rates are per quarter) of 0.42, the *Spline4* model estimated a function relatively similar to the reference case with the main difference being a much higher mortality rate for age-class 1, and the *Lorenzen* model estimated a function decreasing from a very high (>0.7) natural mortality in the 1st few age-classes to stablilse at a lower rate below 0.4 for age-classes 5 and older.

While model *constantM* is likely to be an unrealistic representation to M-at-age, the results it provides are broadly similar to the reference case model. Spawning biomass and recruitment were scaled down moderately (Figures 2–3) but the trends and relative fluctuations were very similar to the reference case model, and the stock was estimated to be slightly less depleted (Figure 4), with $SB_{latest}/SB_{F=0}$ estimated to be 0.63 (0.05 higher than the reference case model). It is reassuring for the robustness of the stock assessment that such an extreme sensitivity model still provides estimates of stock status and management quantities relatively similar to the reference case and the other natural mortality sensitivities.

The M-at-age function for *Spline4* shows some differences from the reference case function across the age range, but the most important difference is at the first age-class (Figure 1). Therefore, comparing *Spline4* with the reference case model gives some indication of the consequences of preventing lower M for age-classes 1 than 2. Model *Spline4*, with constrained mortality, compensates for this higher early mortality by increasing recruitment (Figure 3), with most of these extra recruits dying due to the higher age-class 1 mortality rate, which results in a relatively similar number/biomass of fish in age-class two. Consequently, estimates of spawning biomass (Figure 2) and depletion trajectories

(Figure 4) are very similar between *Spline4* and the reference case model. Furthermore, all commonly reported reference points are near identical (Table 3; $F_{recent}/F_{\mathrm{MSY}} = 0.46$ and 0.45, $SB_{latest}/SB_{F=0}$ = 0.57 and 0.58, for *Spline4* and the reference case respectively).

Comparing *Lorenzen* with the reference case model provides an indication of the consequences of restricting mortality to decrease from highest mortality at the youngest age-classes to a relatively constant (low) rate for older age-classes. It therefore attempts to address both concerns of the CCMs - potentially unrealistic M for age-class 1, and for fish in age-classes 10 and older. This model estimated recruitment to be scaled up slightly relative to the reference case model (Figure 3), while spawning biomass was scaled downwards moderately (Figure 2). Depletion was estimated to be slightly lower than the reference case model (Figure 4) and reference points were again very similar to the reference case model (Table 3; $F_{recent}/F_{\mathrm{MSY}} = 0.41$ and 0.45, $SB_{latest}/SB_{F=0} = 0.60$ and 0.58, for *Lorenzen* and the reference case respectively).

Despite substantially different formulations of the M-at-age function, and the importance of natural mortality to stock assessment results, the range of models explored do not provide any reason to modify the scientific recommendations of the 2016 stock assessment. All important model quantities and reference points (Table 3, Figure 23) were very similar to the reference case model and showed smaller differences than many of the models in the one-off sensitivity analysis and structural uncertainty grid explored in the full assessment.

The more parsimonious method of investigating the consequences of potentially unrealistic patterns - by defining functional forms for M-at-age, has now been implemented in MFCL and will strengthen future assessments that estimate natural mortality. Using fixed values and penalisation is therefore no longer needed to investigate potentially unrealistic variation in M-at-age. A full exploration of these functional forms, including testing of different numbers of spline nodes, will be an important component of the next skipjack stock assessment.

2.2 Sensitivity to age-at-maturity

All models investigated during the 2016 stock assessment assumed a knife-edged maturity schedule with all fish becoming mature at age-class 3. Alternative datasets with information on skipjack maturity-at-length in several oceans were provided by the IATTC in the margins of SC12 and are summarised in Schaefer (2001). The length at 50% maturity for 3 studies presented in that paper for the Atlantic and Indian Oceans was 42–43cm and almost all fish were mature by 50cm.

Based on the growth function utilised in the stock assessment a similar maturity-at-length relationship would correspond to most fish becoming sexually mature between age-classes 3 and 4. We therefore fit a sensitivity model identical to the 2016 reference case model except with all fish becoming mature at age-class 4 (*Mature4*).

Increasing the knife-edge maturation schedule from 3 to 4 quarters-of-age effectively changes the definition of "spawner" and affects processes such as the fitting of the spawner-recruit relationship (SRR). A comparison of *Mature4* with the reference case reflects this, with differences in absolute quantities related to the spawning fraction such as a reduction in spawning biomass (Figure 5), but limited differences in relative changes in biomass and other model quantities such as recruitment (Figure 6; Table 4).

Despite the changes in the absolute scaling of spawning biomass, few changes were evident in quantities dependent on the SRR including MSY, $Y_{F_{recent}}$ and the fishing-mortality-based reference point ($F_{recent}/F_{\text{MSY}}$; Table 4). Similarly, the depletion-based reference points were similar to the reference case model, with $SB_{latest}/SB_{F=0}$ estimated to be 0.55, compared to 0.58 for the reference case model. The plot of temporal changes in fisheries depletion of spawning biomass at the WCPO scale shows more depletion for *Mature4* than the reference case model (Figure 7), which indicates higher depletion of older age-classes (one of which, age-class 4, is no longer included in the calculation of $SB/SB_{F=0}$ in Table 4) over time rather than differences in the estimated model dynamics, as the depletion of total biomass ($B/B_{F=0}$) is almost identical for the two models (Figure 8).

Future developments of MFCL will include implementation of maturity-at-length rather than maturity-at-age which will simplify the modelling process, particularly when sensitivity runs with different growth curves, or estimation of growth, are carried out.

2.3 Likelihood profile by data component

A common diagnostic for integrated stock assessment models is the likelihood profile of a parameter, or parameters, often those that scale the population dynamics of the stock (e.g. $R0$ when using the stock synthesis modelling software; Lee et al., 2014). Profiles have been routinely fitted for the reference case models of recent stock assessments conducted in the WCPO using MFCL (e.g. Harley et al., 2014, Harley et al., 2015, McKechnie et al., 2016a), however these have been restricted to the overall objective function value rather than the individual likelihood components, due to the absence of reporting of these quantities by MFCL.

Development of these diagnostics will aid in an increased understanding of the influence of each data component on model dynamics, and similarly, the consequences of different data weighting schemes. Consequently, a CCM indicated they felt that "overall model diagnostics are lacking and necessary to evaluate full range of likelihood for all data to check robustness of the base case model" and so we utilise recent developments in MFCL (including a new output file that reports likelihood values by component) to provide preliminary diagnostics to meet this request.

The procedure is undertaken by fitting the reference case model and then running a grid of additional models from the resulting solution. Twenty models were fitted by fixing values for the total population scaling parameter (*totpop*) at equidistant intervals either side of the maximum likelihood estimate (MLE), turning off the estimation of the *totpop* parameter and running until convergence during a further estimation phase. The total likelihood is then expected to display a decline in fit with distance from the MLE. Several additional models with jittered starting values were run for each value of *totpop* to lessen the chance of obtaining a local, rather than global, maximum.

By monitoring and plotting the likelihood values for each data component it is possible to display individual likelihood profiles that indicate their influence on the scaling of the population. The components applicable for the skipjack assessment model are the fit to the catch data (*Catch*), the tagging data (*Tag*), the effort deviates which measure the fit to the CPUE data (*Effort*), and the size composition data (*Size*).

The likelihood profile for *totpop* for the reference case model is shown in Figure 9, both for the overall objective function (black line) and the individual components (other colours). Relatively smooth functions are observed for each component with the tagging component having the most influence on the total objective function. The tagging component is best fitted at a higher value of *totpop* while the other components are fitted better at lower values of that parameter. The overall objective function is optimised between these extremes and the procedure reinforces the importance of the tagging data which was emphasised in the stock assessment.

As was clearly indicated at SC12, these profiles show very predictable patterns given the extensive sensitivity analyses that were undertaken during the assessment, where the weightings of the various data sources were altered. When the tagging data were given less weight (high overdispersion parameter values) the population was scaled downwards, while when the size composition data was given less weight (lower effective sample sizes) the population was scaled upwards.

2.4 Sensitivity model with an alternative spatial structure

2.4.1 General considerations

In the SC12 summary report a CCM suggested the investigation of a "different area definition to present more plausible skipjack movement in the WCPO and to improve estimates of movement rate among areas" and propose an alternative regional structure (see Kiyofuji and Ochi, 2016) with the intention of aiding MFCL in improving estimates of finer-scale and seasonal movements of fish between tropical, subtropical and more temperate zones.

Investigating alternative spatial model structures takes time because; all inputs (CPUE, size compositions, tagging, catch, effort) must be recalculated, fisheries structures must be altered and choices of parameterisation of the model for new fisheries must be made and explored (e.g. groupings for selectivities, tag reporting rates etc.), and problems such as the absence of a reliable standardised CPUE index for a proposed region or instability in a region with little data may be encountered. For these reasons a full analysis of the alternative spatial structure is considered an ongoing exercise.

Our intention herein is to provide preliminary inferences from early development of this new spatial structure. We rely heavily on the model structure of the reference case model and fit a very similar model (with parameterisation extended for the new fisheries structure) to the data files for the alternative spatial structure. The parameterisation of the model is largely described in McKechnie et al. (2016a) and only the differences from the reference case model, and considerations necessary when extending the fisheries structure to 7 regions, are presented below.

2.4.2 Region boundaries and fisheries structure

The regional boundaries suggested by Kiyofuji and Ochi (2016) were utilised and the changes from the spatial structure used for the reference case model are shown in Figure 10. Of the original 5 regions, only the boundaries of region 5 were maintained. However, because most of the boundary modifications were relatively minor the fisheries definitions for these regions were unchanged, and so the only difference from the reference case model was the addition of the fisheries in regions 6 and 7 (fisheries F24–F29; Table 1). Fisheries in these regions were defined in the same manner as region 1; a pole-and-line fishery, a purse-seine fishery and a longline fishery which was given arbitrary catch and missing effort, in each region. Data for vessels under all flags were aggregated within these fisheries definitions.

2.4.3 Input data and model parameterisation

All catch and effort, tagging and size composition data were reconstructed for the new regional structure using methods identical to the reference case model and outlined in McKechnie (2016), McKechnie et al. (2016b) and Abascal et al. (2014), respectively. The standardised CPUE indices for pole-and-line fisheries in regions 1–3 had to be re-estimated due to the boundary changes and additional indices had to be created for regions 6 and 7, and these analyses are presented in Kiyofuji (2016). The standardised indices in region 6 and 7 were applied to the pole-and-line fisheries F24 and F27, respectively, and the effort deviation penalties were time-variant and calculated in the same manner as those for the other regions. The cpue index used for region 5 in the reference case model was also used in this model as the region boundaries were maintained (the index is applied to F21 in the sensitivity model). Similarly, the index in region 4 was also maintained in this model, despite a modification to the north-east region boundaries. This is justified because a negligible proportion of the data used in the standardisation occurred in the area removed from region 4 in the alternative spatial structure.

The other fisheries-specific parameterisations for the new fisheries were defined in a manner consistent with the structures in other regions: pole-and-line fisheries (F24, F27) had temporally constant (but seasonal) catchability, time-variant effort deviation penalties, and independent selectivity functions; purse seine fisheries (F25, F28) had time-variant catchability, low, temporally constant effort deviation penalties and independent selectivity functions; longline fisheries (F26, F29) had missing effort at all time-periods except the last 4 quarters, no seasonal catchability, and had independent, asymptotic selectivity functions (Table 2). All the fisheries in regions 6 and 7 were grouped with the northern (JP-dominated) group of fisheries for tag reporting rates (group 1; Table 2). The alternative spatial structure sensitivity model will be referred to as *AltSpatial* throughout.

2.4.4 Modelling results

Overall, the alternative spatial structure model produced similar results to the reference case. The fit to the cpue indices for regions 1–5 was similar to that in the reference case model and was very good for the new regions 6 and 7 (Figure 13).

Biomass trajectories are highly variable both within regions and overall (Figure 17) although *AltSpatial* estimated relative changes in biomass that were extremely consistent with the reference case model, although the absolute level of biomass was significantly higher for the former (Figure 21). The recent period of high abundance in the equatorial regions highlighted during the stock assessment is also estimated by *AltSpatial* but there is also some evidence for declining spawning biomass over the last decade in regions 1 and 7, in particular.

Recruitment was estimated to be highly variable in all regions and a moderate increase in overall recruitment was estimated over the assessment period (Figure 16). Relative changes in recruitment were very consistent between *AltSpatial* and the reference case model, including the significant pulse in recruitment in the last few years of the model (Figure 20).

Estimated fisheries depeletion varied among regions with regions 4 and 5 displaying the largest declines over the assessment period (Figure 18). The northern regions, 1, 6 and 7 showed lower rates of fisheries depletion, thus the model is predicting that the estimated declines in biomass (Figure 17) are attributable to recruitment rather than fishing mortality. Overall depletion declined over most of the time-series with an increase over the last several years, which was very similar to the dynamics observed for the reference case model although the rate of decline was higher for the latter. Consequently, the depletion-based reference point for *AltSpatial* was 0.66, moderately higher than the estimate for the reference case model and well above the interim target reference point (Figure 18; Table 5).

3 General discussion

This report presents the results of a suite of sensitivity models constructed to address concerns raised by CCMs at SC12. While the time period available for this work has been limited, the major concerns of the CCMs have been addressed, including those modelling changes that we expect to have the most influence on model outputs and management recommendations. Several recommendations of additional analyses, or practices, made by CCMs have not been raised herein. These are addressed as follows:

- **Alternative growth functions;** The suggestion of using the growth curves of Ochi et al. (2016), was not considered as; there were concerns about the reliability of skipjack otoliths aged using daily rings, the systematic poor fit of the growth models, and the parameter estimates that are inconsistent with observed length composition data. However, growth is an important area of research for SPC and current work is investigating several datasets for all of the tropical tunas and so we expect further development of this component of the assessment model in the future.

- **Alternative modelling platforms;** The suggestion to use alternative modelling platforms such as SEAPODYM and SS3 to check modelling assumptions. These are long-term projects that require significant amounts of time and person-power which precludes their routine use for all stock assessments. However, it should be noted that the 2014 skipjack stock assessment and the 2015 South Pacific albacore stock assessment have both been subsequently fitted using SS3 (Takeuchi and Langley, 2016 and Cao et al., 2016, respectively). Furthermore, there appears to be limited utility in fitting the skipjack stock assessment in SS3 until the limitations of the tagging component of that platform have been addressed (Takeuchi and Langley, 2016).

- **Consideration of steepness;** The suggestion that steepness should perhaps not be assumed to be similar between skipjack and the larger tropical tunas. The 2016 stock assessment was shown to be very robust to a wide range of steepness values (0.65–0.95) and this range and value for the reference case (0.8) has been decided by the SC and at pre-assessment workshops over a number of years. Changes to these values should be directed by those forums.

- **Density dependent vital rates;** The suggestion of the potential for density dependent vital rates such as growth and maturity. While there is the potential for many biological parameters to be time-variant or density dependent, the estimation of these rates must be supported by data and also must be parameterised in the modelling software. MFCL is not currently capable of estimating these relationships, and given the data available it is extremely unlikely that reliable estimates would be achieved. We are not aware of any tuna species where models with these structures have been successfully fitted.

- **Purse seine CPUE indices;** Developing CPUE indices for purse seine fisheries is an important priority and they may eventually support or replace the pole-and-line indices which are suffering from declines in fishing effort. Their development is a significant challenge however, and this research is expected to have a long time-frame.

Several of the sensitivity models explored have significantly different model parameterisation from the reference case model. In spite of this however, the modelling results and management recommendations presented at SC12 remain robust to these changes and all model quantities were well within the envelope of parameter estimates resulting from the one-off sensitivities and structural uncertainty grid of the stock assessment (McKechnie et al., 2016a). The commission is encouraged to consider this additional modelling when interpreting the recommendations of the SC12 report.

This additional work has lead to some profitable modelling developments, including changes to MFCL source code to implement functional M-at-age, and will lead to further improvements to the model when the skipjack stock is next assessed. Several avenues of research such as investigating growth rates using tag increments and/or otolith data, purse seine CPUE and data issues such as the variable size compositions in fishery 1 that were highlighted in McKechnie et al. (2016a), will continue to be investigated in the interim.

Perhaps the most significant ongoing work will be further development of the alternative spatial structure model as substantial further work will be needed to compare model estimates with empirical information on inter-regional movements, regional recruitment and seasonal population dynamics. Preliminary results however have not suggested any major changes in inferences from the reference case model. In fact, early estimates of stock status are slightly more optimistic for this model. This is perhaps not surprising given that the standardised CPUE indices are relatively stable in all regions and it is these together with recruitment estimates that largely determine depletion estimates.

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4 Tables

Table 1: Definition of fisheries for the MULTIFAN-CL skipjack analysis. Gears: PL = pole and line; PS = purse seine unspecified set type; LL = longline; DOM = the range of artisanal gear types operating in the domestic fisheries of Philippines and Indonesia. Flag/fleets: JPN = Japan; PH = Philippines; ID = Indonesia; ALL = all nationalities.

Fishery	Nationality	Gear	Region
F1 P-JPN-1	JPN	PL	1
F2 S-ALL-1	ALL	PS	1
F3 L-ALL-1	ALL	LL	1
F4 P-ALL-2	ALL	PL	2
F5 S-ASS-ALL-2	ALL	PS	2
F6 S-UNA-ALL-2	ALL	PS	2
F7 L-ALL-2	ALL	LL	2
F8 P-ALL-3	ALL	PL	3
F9 S-ASS-ALL-3	ALL	PS	3
F10 S-UNA-ALL-3	ALL	PS	3
F11 L-ALL-3	ALL	LL	3
F12 Z-PH-4	PH	Dom	4
F13 Z-ID-4	ID	Dom	4
F14 S-ID.PH-4	ID.PH	PS	4
F15 P-ALL-4	ALL	PL	4
F16 S-ASS-ALL-4	ALL	PS	4
F17 S-UNA-ALL-4	ALL	PS	4
F18 Z-VN-4	VN	Dom	4
F19 L-ALL-4	ALL	LL	4
F20 P-ALL-5	ALL	PL	5
F21 S-ASS-ALL-5	ALL	PS	5
F22 S-UNA-ALL-5	ALL	PS	5
F23 L-ALL-5	ALL	LL	5
F24 P-ALL-6	ALL	PL	6
F25 S-ALL-6	ALL	PS	6
F26 L-ALL-6	ALL	LL	6
F27 P-ALL-7	ALL	PL	7
F28 S-ALL-7	ALL	PS	7
F29 L-ALL-7	ALL	LL	7

Table 2: Summary of the groupings of fisheries within the assessment for estimation of selectivity, catchability (used for the implementation of regional weights), tag recaptures, and tag reporting rates. Note that effort is missing for all L and Z fisheries and so effort deviation penalties only apply to the last four quarters. See Table 1 for further details on each fishery.

Fishery	Region	Selectivity	SeasCat	TimVarCat	TimVarCatCV	EffPen	EffPenCV	Recaptures	Reporting
F1 P-JPN-1	1	1	Y	N	NA	constant	0.11	1	1
F2 S-ALL-1	1	2	Y	Y	0.1	constant	0.71	2	1
F3 L-ALL-1	1	3	N	N	NA	constant	0.22	3	1
F4 P-ALL-2	2	4	Y	N	NA	time-variant	0.20	4	1
F5 S-ASS-ALL-2	2	5	Y	Y	0.1	constant	0.71	5	2
F6 S-UNA-ALL-2	2	6	Y	Y	0.1	constant	0.71	5	2
F7 L-ALL-2	2	7	N	N	NA	constant	0.22	6	1
F8 P-ALL-3	3	4	Y	N	NA	time-variant	0.20	7	1
F9 S-ASS-ALL-3	3	5	Y	Y	0.1	constant	0.71	8	3
F10 S-UNA-ALL-3	3	6	Y	Y	0.1	constant	0.71	8	3
F11 L-ALL-3	3	7	N	N	NA	constant	0.22	9	1
F12 Z-PH-4	4	8	N	N	NA	constant	0.22	10	4
F13 Z-ID-4	4	8	N	N	NA	constant	0.22	11	5
F14 S-ID.PH-4	4	5	N	N	NA	time-variant	0.20	12	6
F15 P-ALL-4	4	4	Y	Y	0.1	constant	0.71	13	1
F16 S-ASS-ALL-4	4	5	Y	Y	0.1	constant	0.71	14	7
F17 S-UNA-ALL-4	4	6	Y	Y	0.1	constant	0.71	14	7
F18 Z-VN-4	4	8	N	N	NA	constant	0.22	15	8
F19 L-ALL-4	4	9	N	N	NA	constant	0.22	16	1
F20 P-ALL-5	5	4	Y	Y	0.1	constant	0.71	17	1
F21 S-ASS-ALL-5	5	5	Y	N	NA	time-variant	0.20	18	9
F22 S-UNA-ALL-5	5	6	Y	Y	0.1	constant	0.71	18	9
F23 L-ALL-5	5	10	N	N	NA	constant	0.22	19	1
F24 P-ALL-6	6	11	Y	N	NA	time-variant	0.20	20	1
F25 S-ALL-6	6	12	Y	Y	0.1	constant	0.71	21	1
F26 L-ALL-6	6	13	N	N	NA	constant	0.22	22	1
F27 P-ALL-7	7	14	Y	N	NA	time-variant	0.20	23	1
F28 S-ALL-7	7	15	Y	Y	0.1	constant	0.71	24	1
F29 L-ALL-7	7	16	N	N	NA	constant	0.22	25	1

Table 3: Reference points and model results for the reference case model and the natural mortality sensitivity models.

Quantity	Ref16	ConstantM	Lorenzen	Spline4
C_{latest}	1,679,528	1,679,799	1,679,608	1,679,354
MSY	1,891,600	1,945,600	1,944,000	1,837,200
$Y_{F_{recent}}$	1,594,800	1,576,000	1,597,600	1,562,800
f_{mult}	2.23	2.49	2.44	2.17
F_{MSY}	0.24	0.28	0.27	0.25
$F_{recent}/F_{\text{MSY}}$	0.45	0.40	0.41	0.46
SB_{MSY}	1,626,000	1,484,000	1,498,000	1,546,000
SB_0	6,764,000	5,555,000	5,957,000	6,388,000
$SB_{F=0}$	7,221,135	6,004,226	6,333,832	6,943,850
SB_{latest}/SB_0	0.62	0.68	0.64	0.62
$SB_{latest}/SB_{F=0}$	0.58	0.63	0.60	0.57
$SB_{latest}/SB_{\text{MSY}}$	2.56	2.54	2.55	2.56
$SB_{recent}/SB_{F=0}$	0.52	0.58	0.55	0.51
$SB_{recent}/SB_{\text{MSY}}$	2.31	2.33	2.31	2.30

Table 4: Reference points and model results for the reference case model and the maturation sensitivity model.

Quantity	RefCase	HighMaturation
C_{latest}	1,679,528	1,679,531
MSY	1,891,600	1,869,200
$Y_{F_{recent}}$	1,594,800	1,600,800
f_{mult}	2.23	2.05
F_{MSY}	0.24	0.23
$F_{recent}/F_{\text{MSY}}$	0.45	0.49
SB_{MSY}	1,626,000	1,237,000
SB_0	6,764,000	6,233,000
$SB_{F=0}$	7,221,135	6,657,322
SB_{latest}/SB_0	0.62	0.59
$SB_{latest}/SB_{F=0}$	0.58	0.55
$SB_{latest}/SB_{\text{MSY}}$	2.56	2.98
$SB_{recent}/SB_{F=0}$	0.52	0.47
$SB_{recent}/SB_{\text{MSY}}$	2.31	2.54

Table 5: Reference points and model results for the reference case model and the alternative spatial structure model.

Quantity	RefCase	AltSpatial
C_{latest}	1,679,528	1,679,693
MSY	1,891,600	2,076,400
$Y_{F_{recent}}$	1,594,800	1,632,000
f_{mult}	2.23	2.60
F_{MSY}	0.24	0.25
$F_{recent}/F_{\mathrm{MSY}}$	0.45	0.39
SB_{MSY}	1,626,000	1,743,000
SB_0	6,764,000	7,367,000
$SB_{F=0}$	7,221,135	7,798,893
SB_{latest}/SB_0	0.62	0.70
$SB_{latest}/SB_{F=0}$	0.58	0.66
$SB_{latest}/SB_{\mathrm{MSY}}$	2.56	2.97
$SB_{recent}/SB_{F=0}$	0.52	0.59
$SB_{recent}/SB_{\mathrm{MSY}}$	2.31	2.64

5 Figures

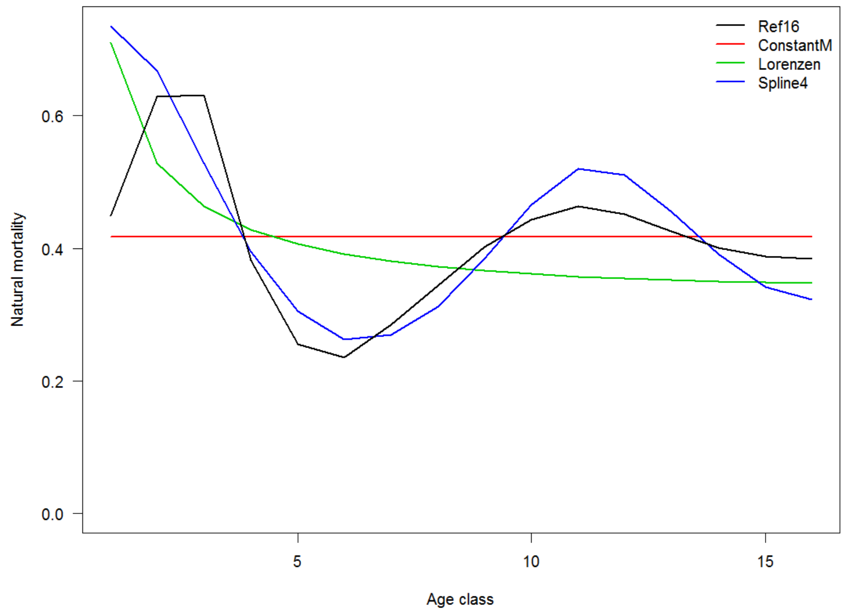


Figure 1: Age-specific (quarterly age-classes) natural mortality functions for the natural mortality sensitivity runs. The 2016 reference case model is in black and the sensitivity runs are outlined in section 2.1. The mortality rates are per quarter.

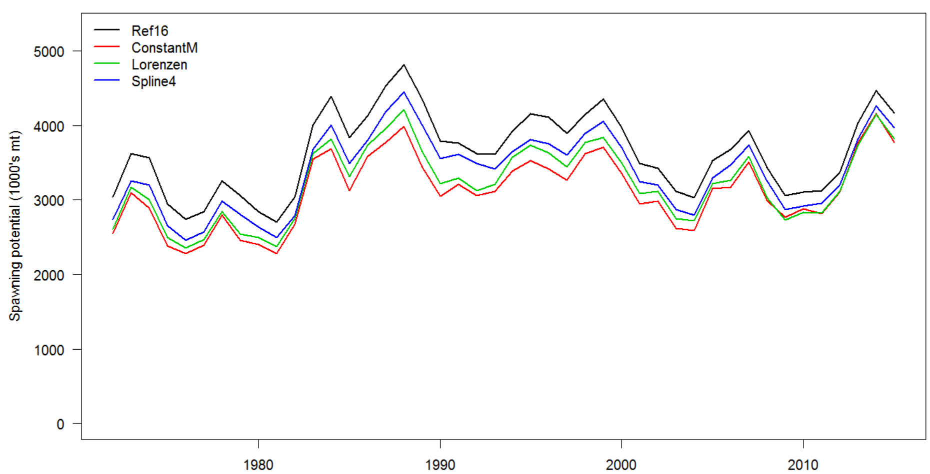


Figure 2: Estimated spawning biomass for each of the natural mortality sensitivity models.

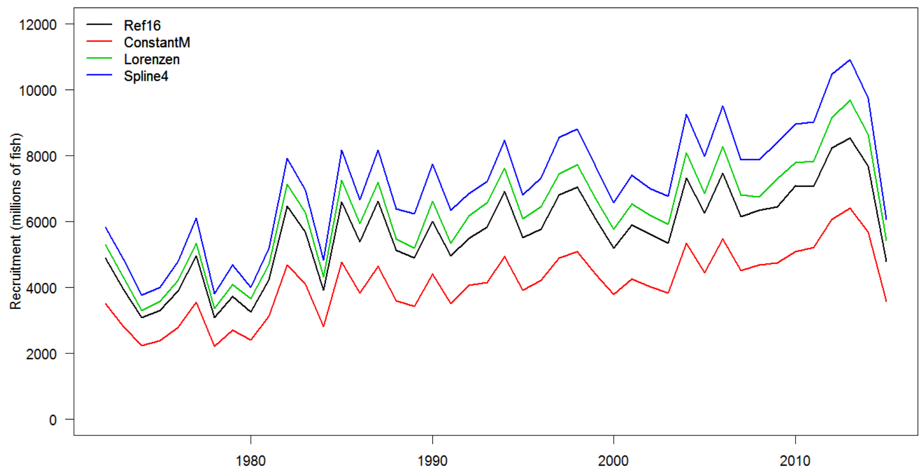


Figure 3: Estimated recruitment for each of the natural mortality sensitivity models. Note that the recruitments in the last 2 quarters were constrained to be the mean over the estimates for the remaining time period.

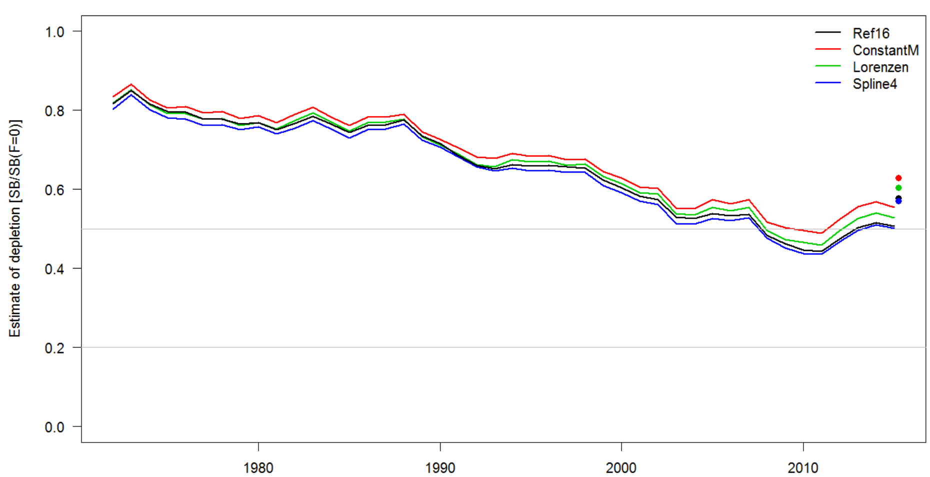


Figure 4: Estimated fisheries depletion, $SB/SB_{F=0}$, for each of the natural mortality sensitivity models. The points show the estimates of the reference point $SB_{latest}/SB_{F=0}$ for each model.

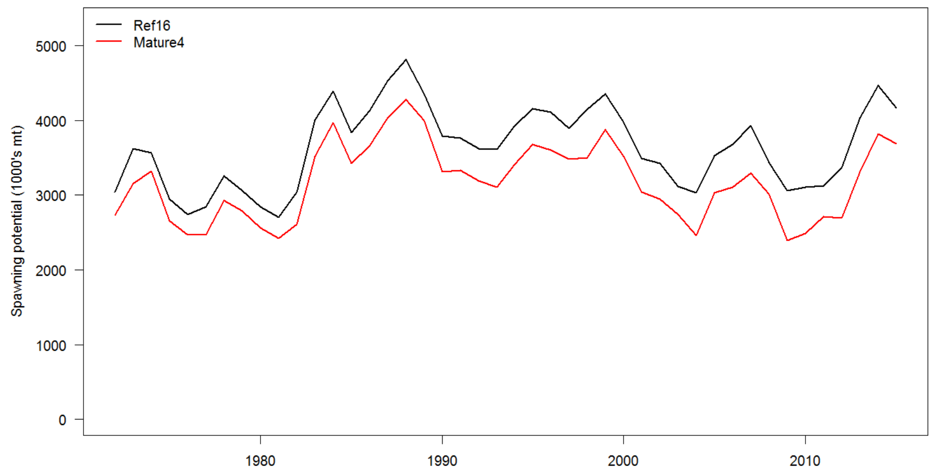


Figure 5: Estimated spawning biomass for the reference case and high maturation sensitivity model (*Mature4*).

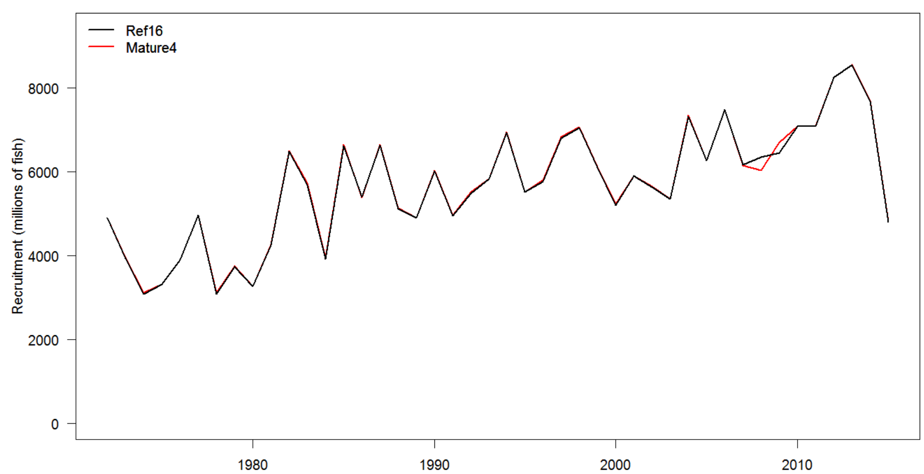


Figure 6: Estimated recruitment for the reference case and high maturation sensitivity model (*Mature4*). Note that the recruitments in the last 2 quarters were constrained to be the mean over the estimates for the remaining time period.

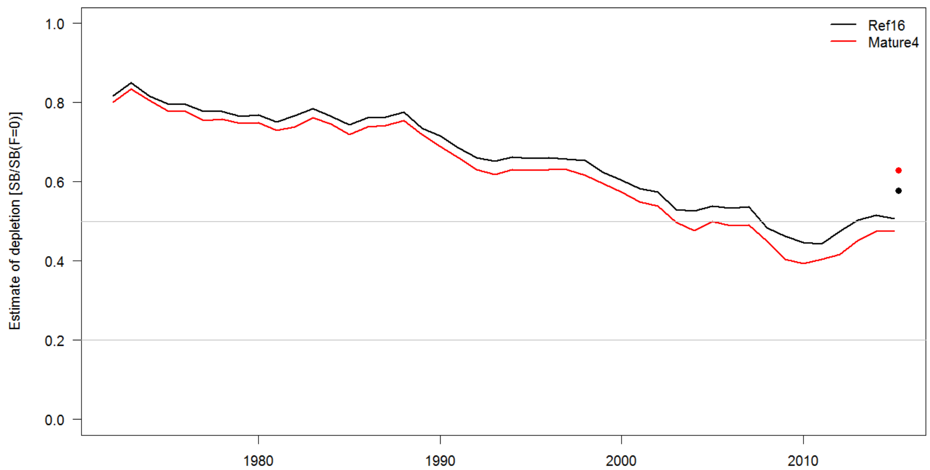


Figure 7: Estimated fisheries depletion of spawning biomass, $SB/SB_{F=0}$, for the reference case and high maturation sensitivity model (*Mature4*). The points show the estimates of the reference point $SB_{latest}/SB_{F=0}$ for each model.

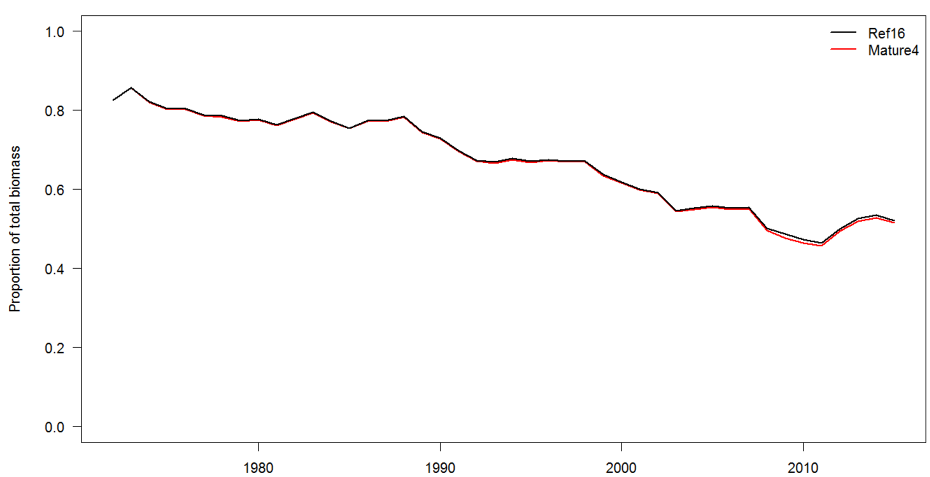


Figure 8: Estimated fisheries depletion of total biomass (juveniles and sexually mature fish), $B/B_{F=0}$, for the reference case and high maturation sensitivity model (*Mature4*).

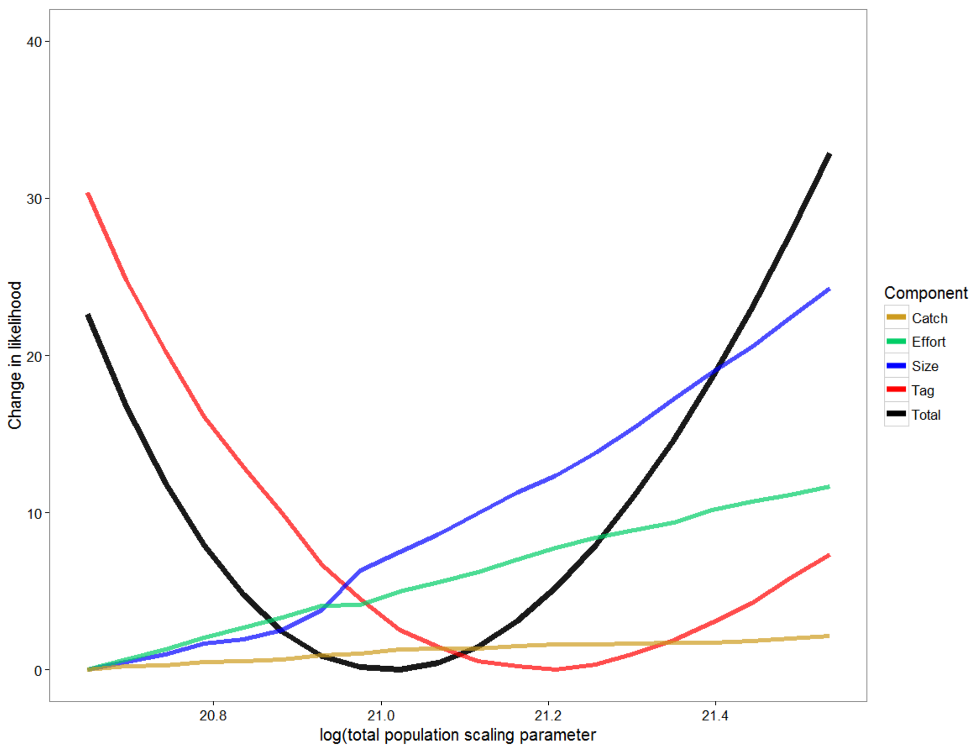
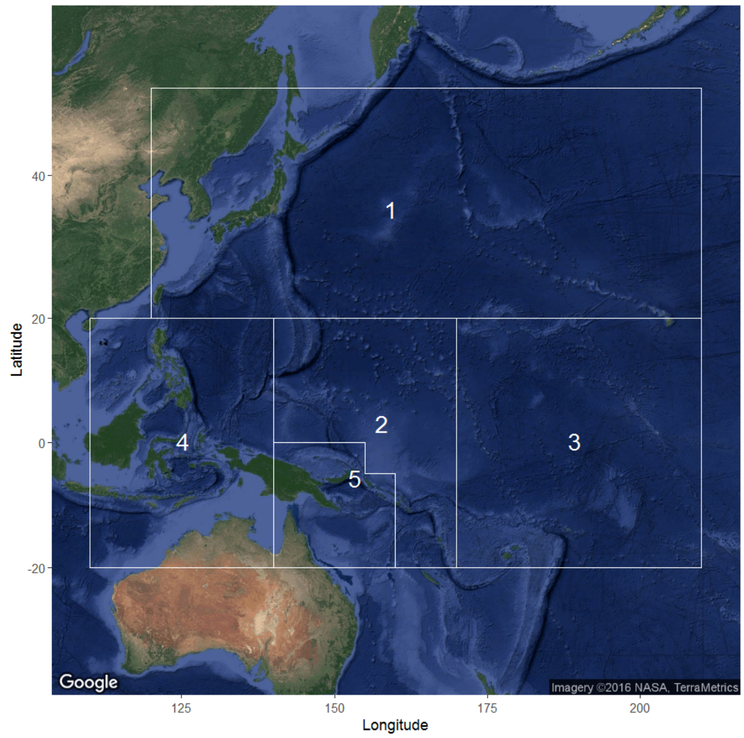
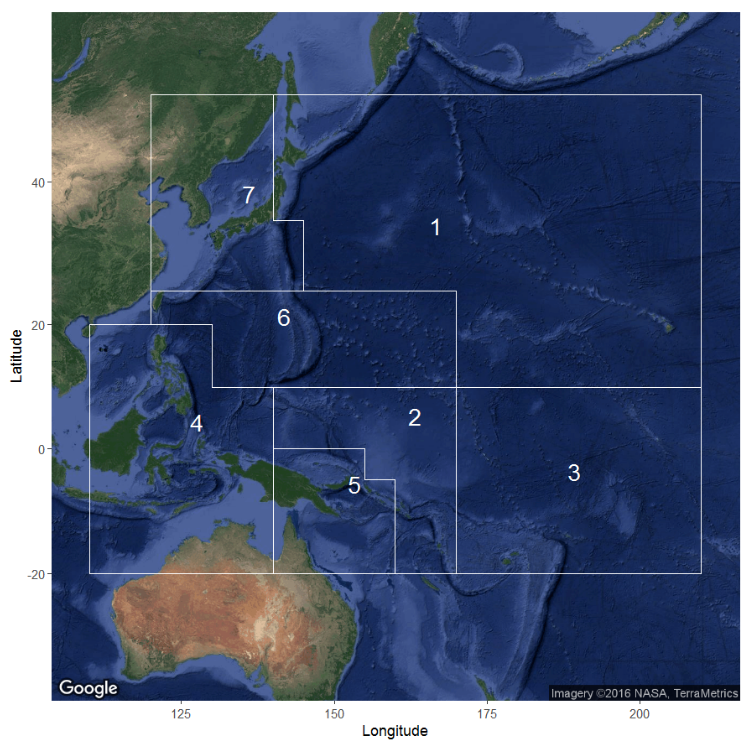


Figure 9: Results of the likelihood profile of the total population scaling parameter (“totpop”; on the log-scale) by data component, for the reference case model. The y axis shows the absolute change in negative log likelihood from the best fitting value, both overall (black) and by individual data component (other colours).



(a) Reference case.



(b) Alternative spatial structure.

Figure 10: Maps showing the region boundaries for the reference case and alternative spatial structure models.

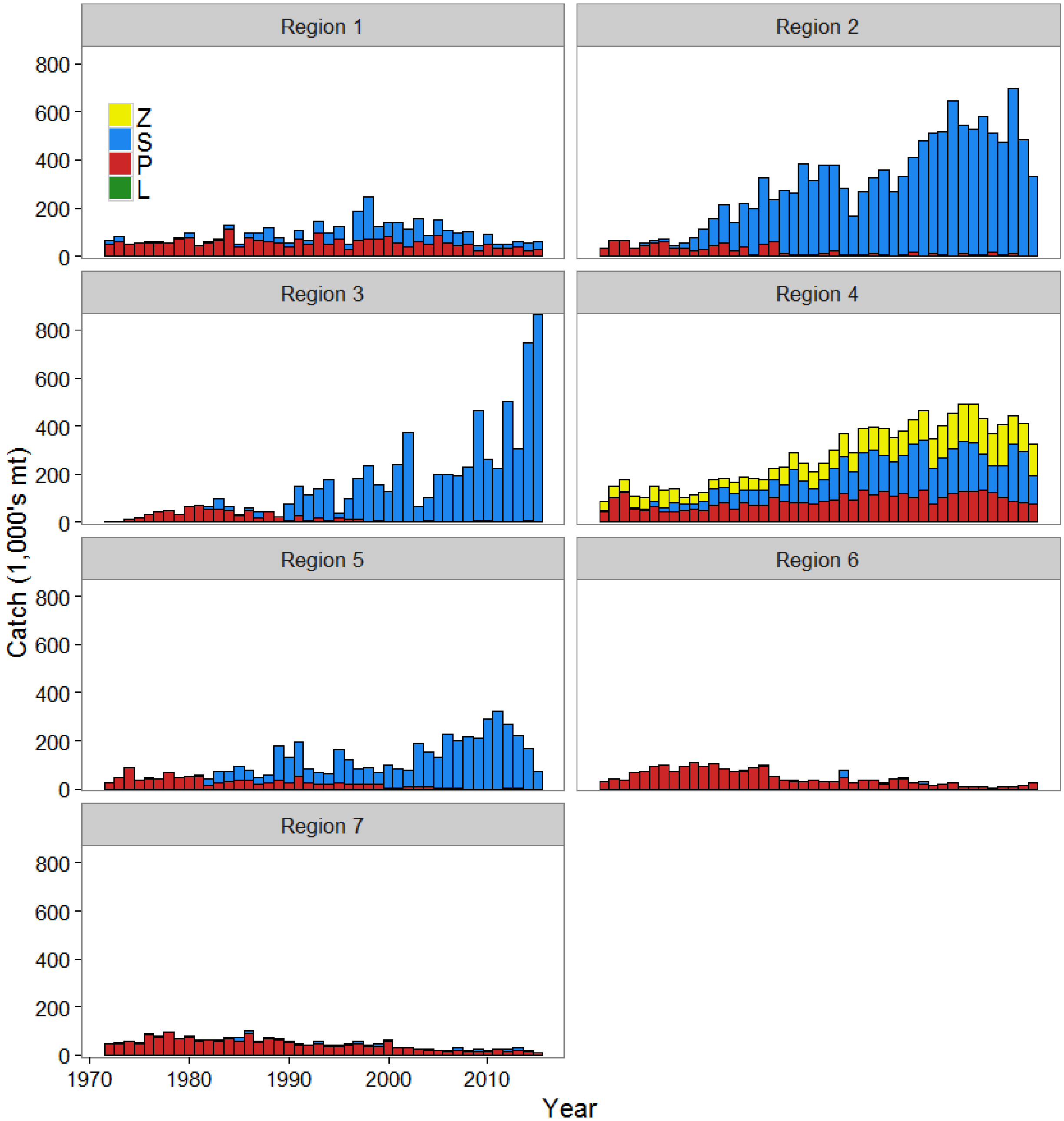


Figure 11: Time series of total annual catch (1000's mt) by fishing gear and assessment region from the alternative spatial structure model over the full assessment period. The different colours refer to longline (green), pole-and-line (red), purse seine (blue) and miscellaneous (yellow).

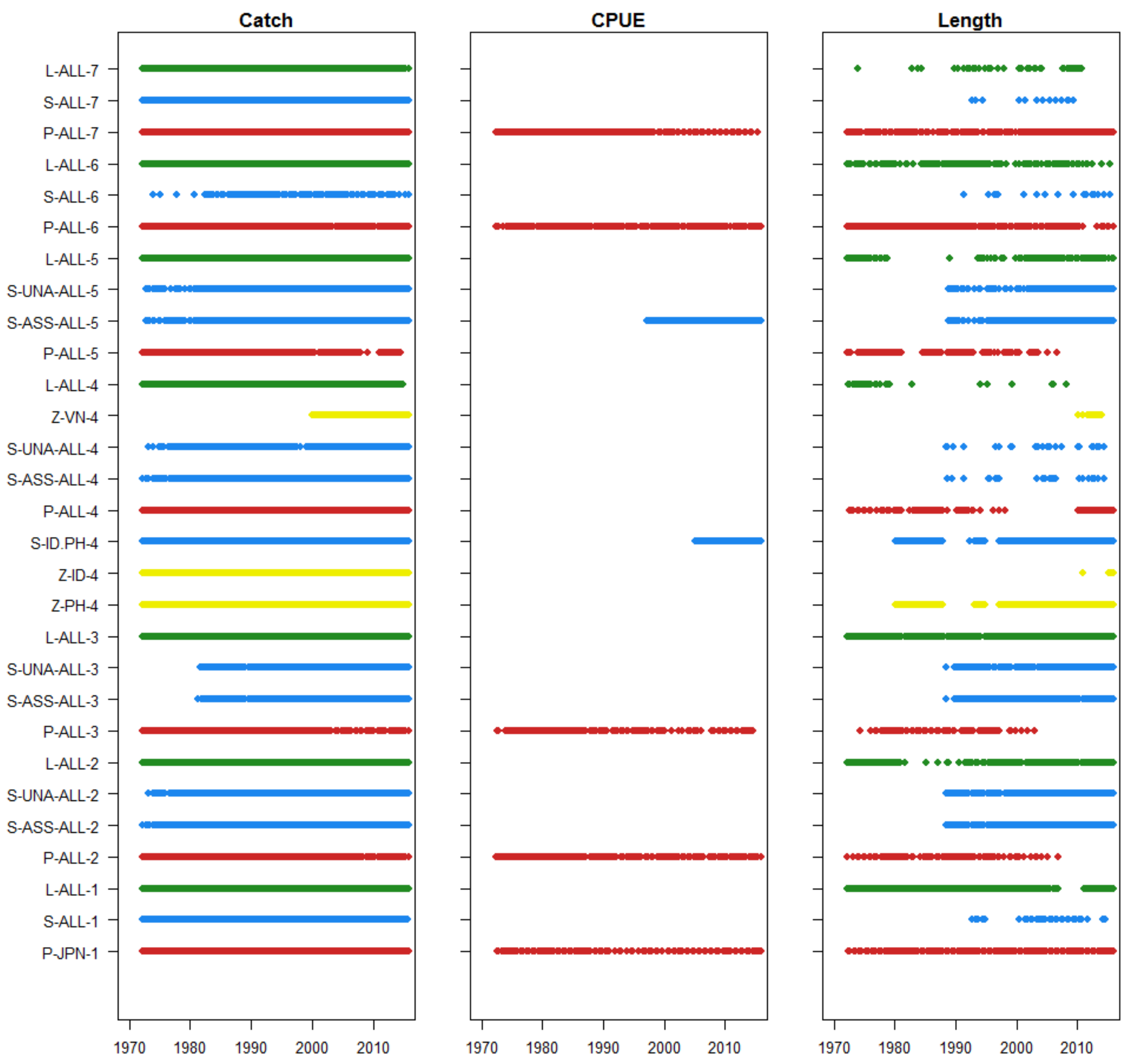


Figure 12: Presence of catch, standardised CPUE, and length frequency data by year and fishery for the alternative spatial structure model. The different colours refer to longline (green), pole-and-line (red), purse seine (blue) and miscellaneous (yellow).

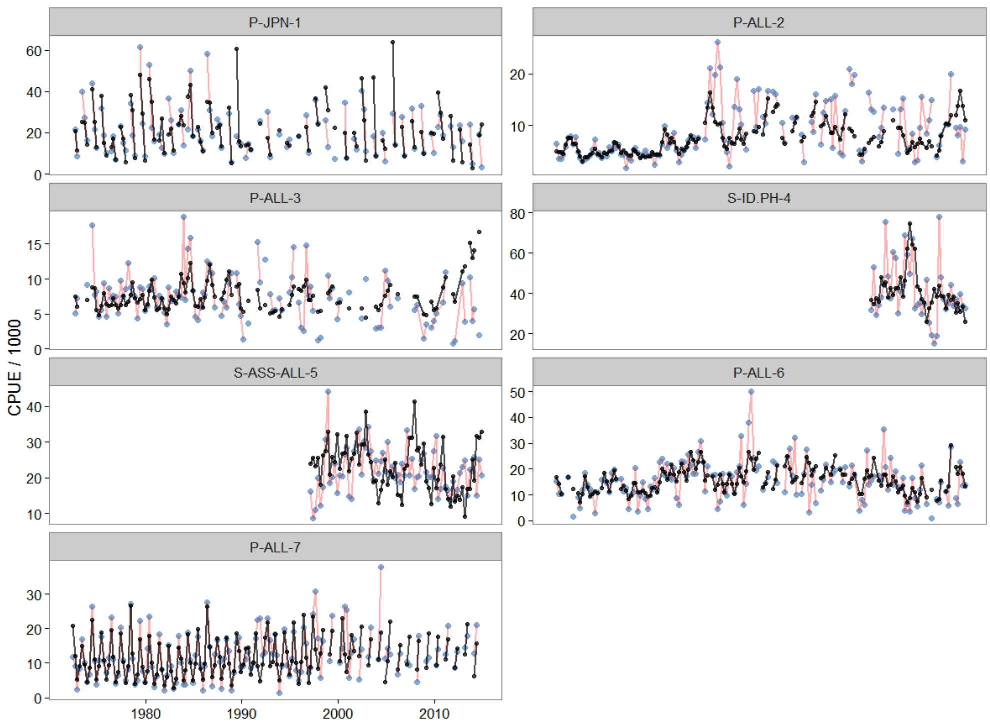


Figure 13: Observed (blue points and red lines) and model-predicted (black points and lines) CPUE for the seven fisheries which received standardised CPUE indices in the alternative spatial structure model (*AltSpatial*).

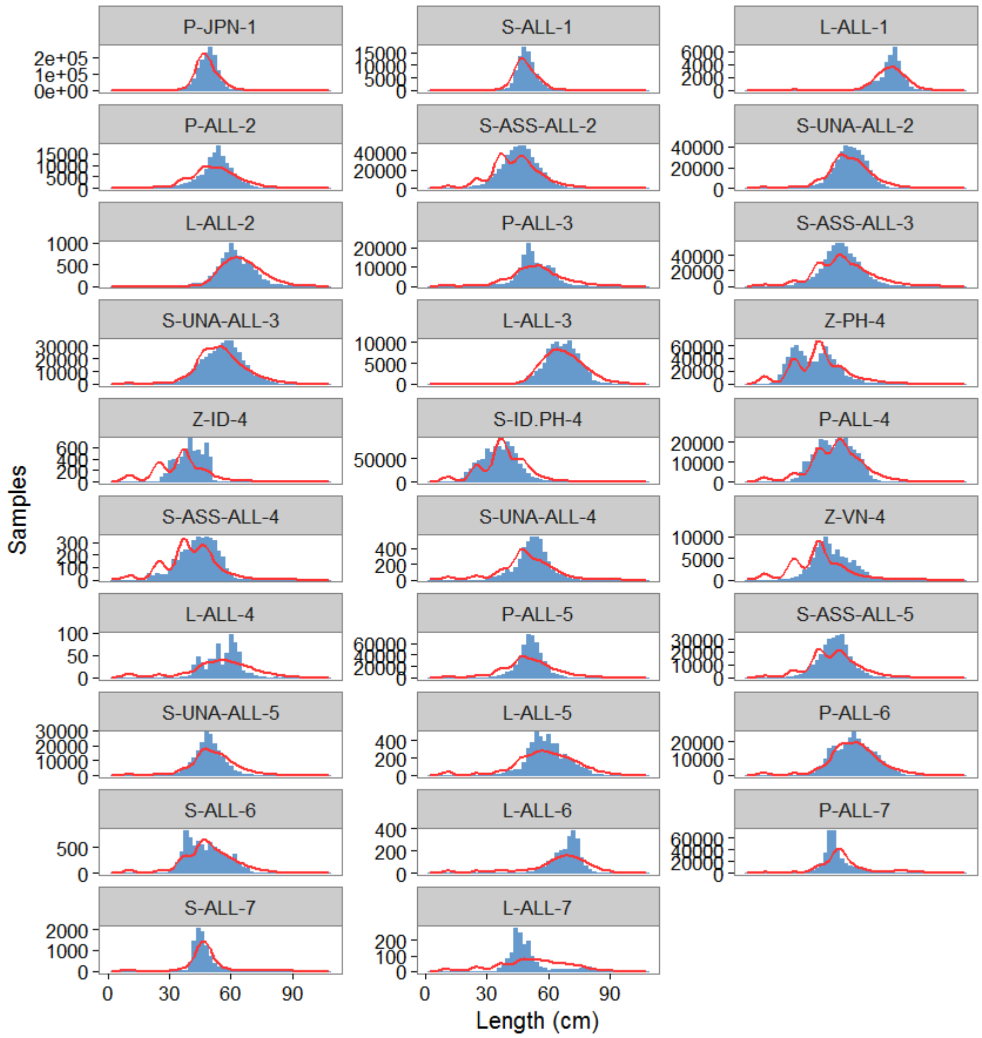


Figure 14: Composite (all time periods combined) observed (blue histograms) and predicted (red line) catch at length for all fisheries with samples for the alternative spatial structure model (*AltSpatial*).

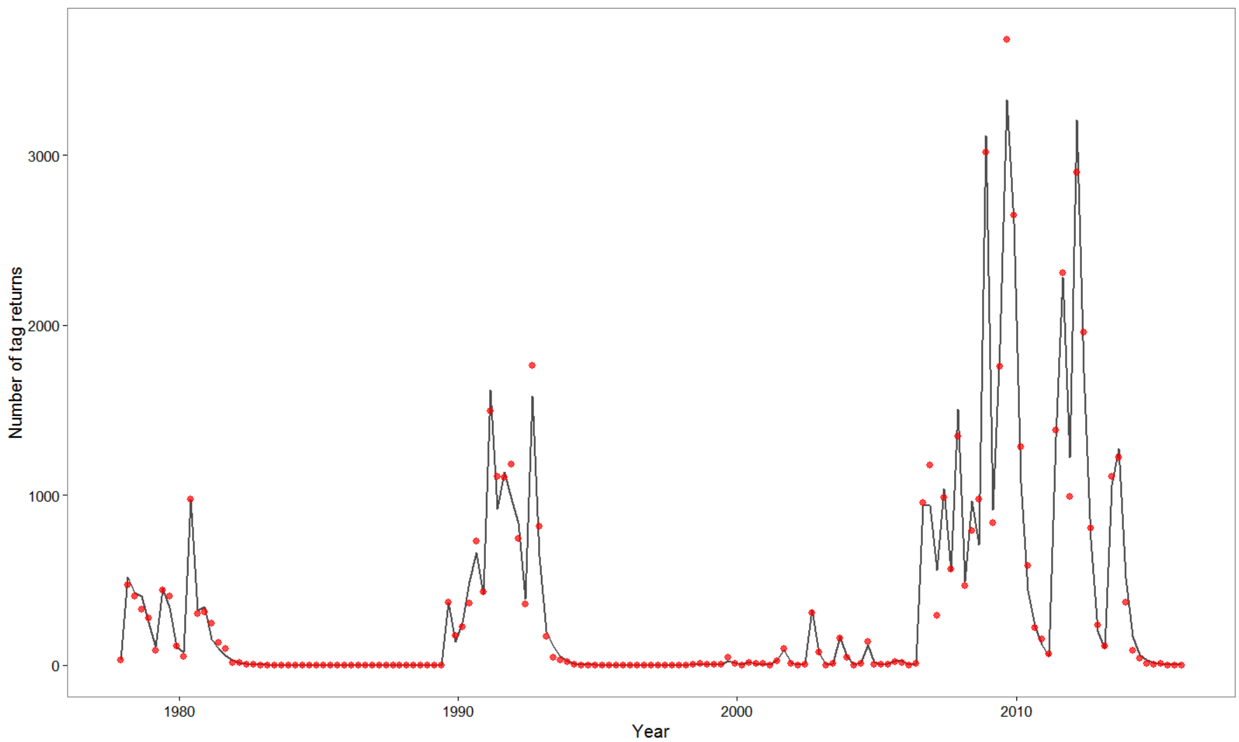


Figure 15: Observed (red points) and model-predicted (black line) tag returns over time for the reference case model across all tag release events with all tag recapture groupings aggregated.

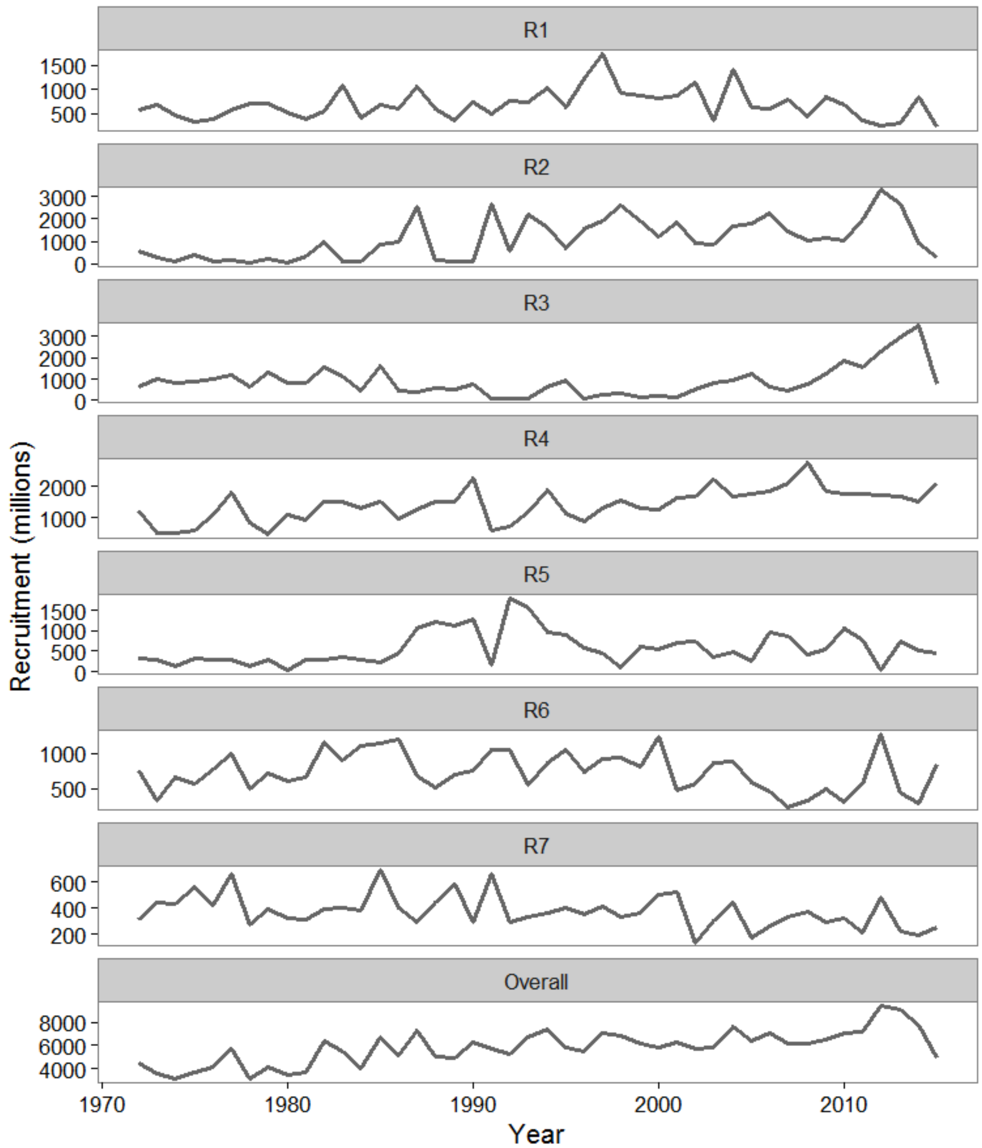


Figure 16: Estimated temporal recruitment by model region for the alternative spatial structure model (*AltSpatial*). Note that the scale of the y-axis is not constant across regions.

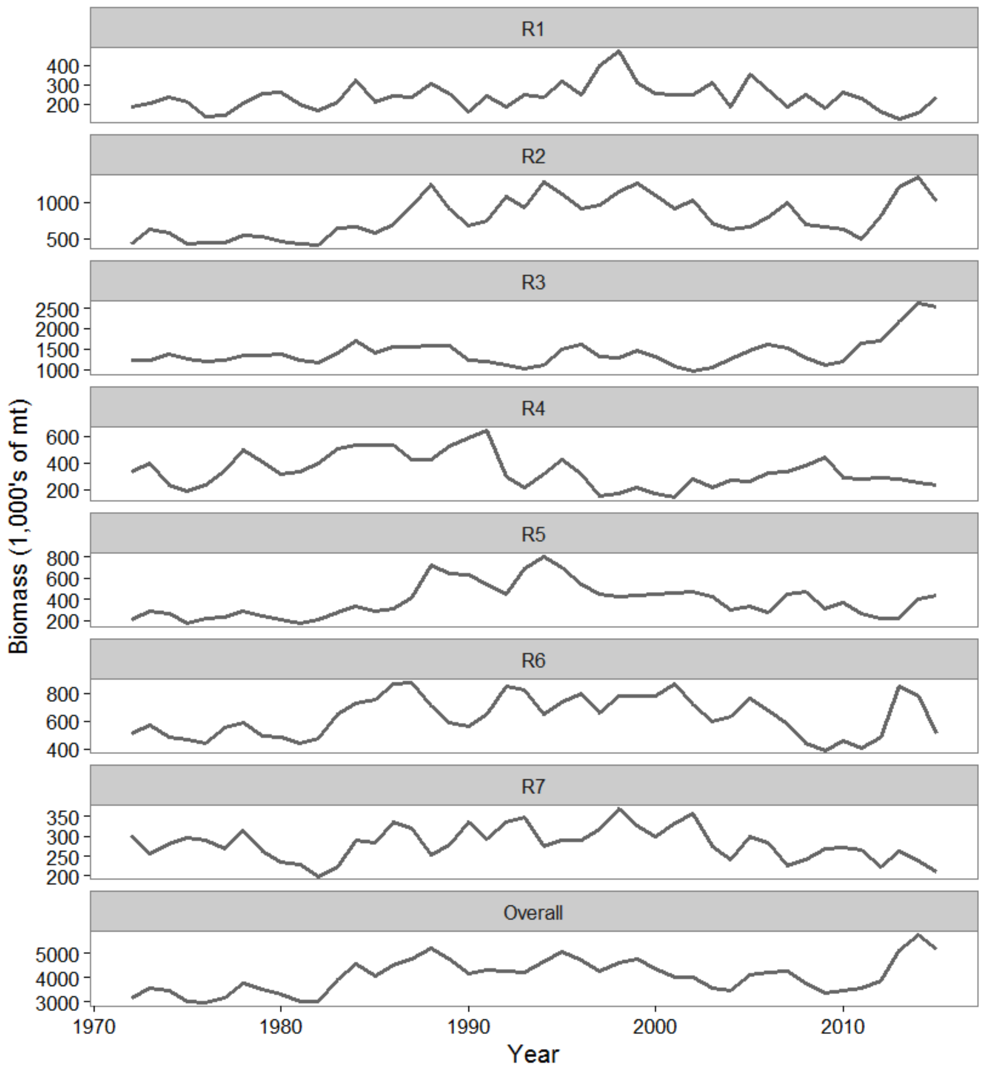


Figure 17: Estimated temporal spawning biomass by model region for the alternative spatial structure model (*AltSpatial*). Note that the scale of the y-axis is not constant across regions.

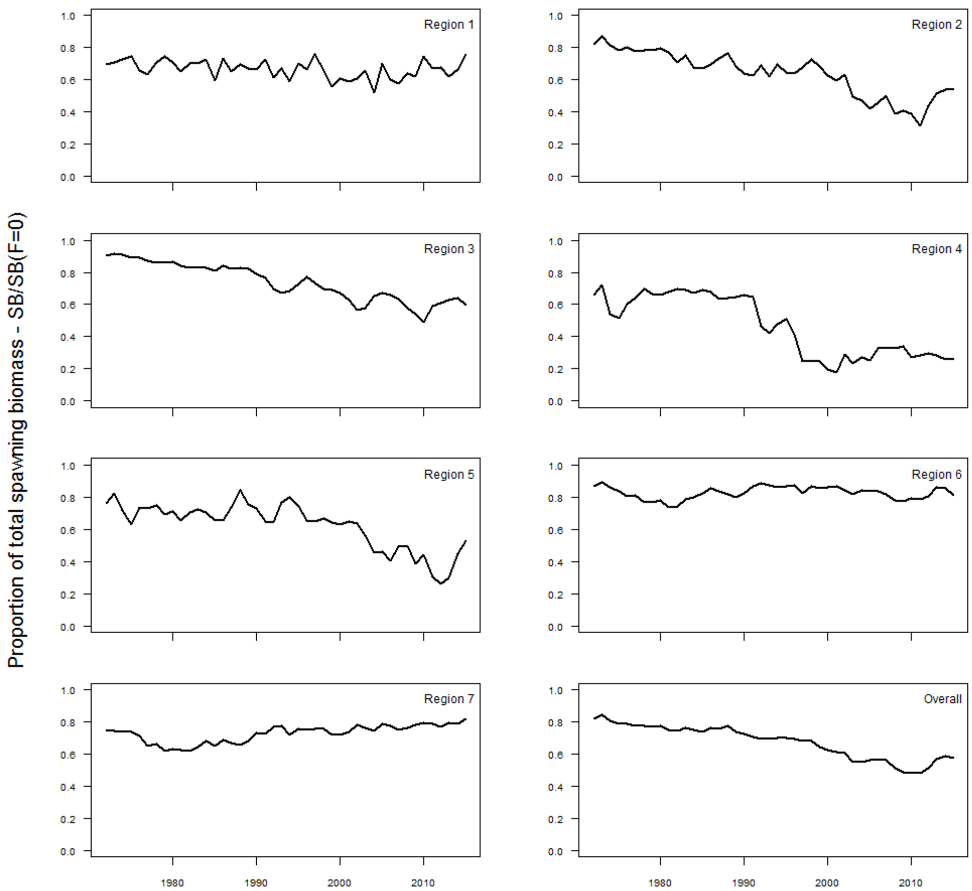


Figure 18: Ratio of exploited to unexploited spawning biomass, $SB_{latest}/SB_{F=0}$, for each region and overall for the alternative spatial structure model (*AltSpatial*).

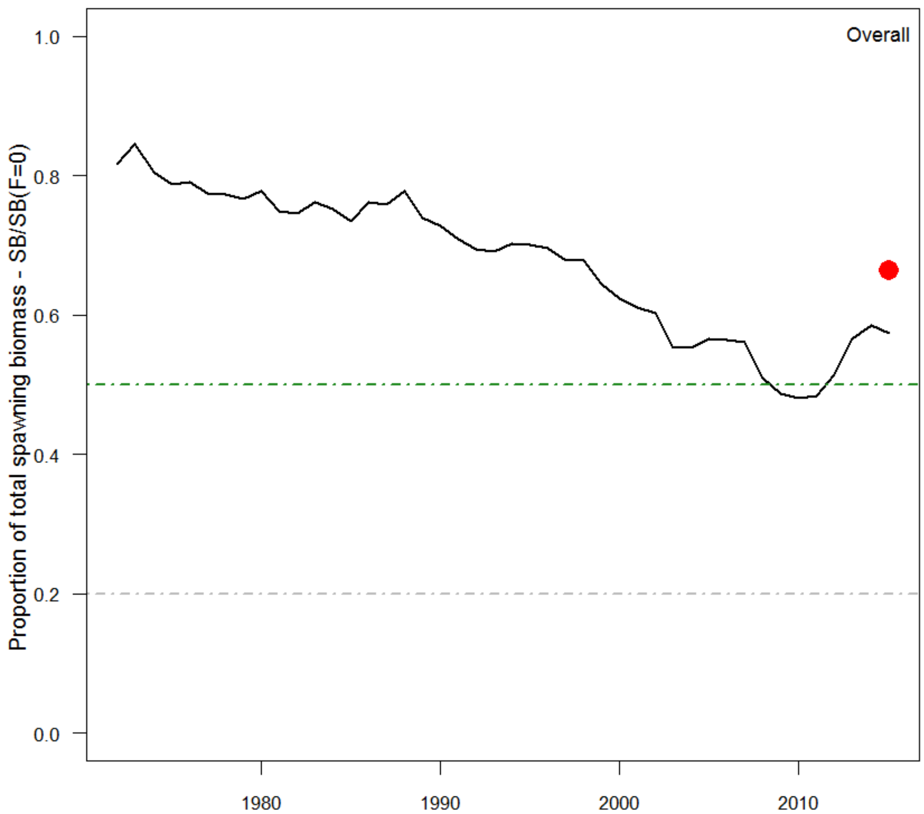


Figure 19: Ratio of exploited to unexploited spawning biomass, $SB_{latest}/SB_{F=0}$, for the alternative spatial structure model (*AltSpatial*). The current WCPFC limit reference point of $20\% SB_{F=0}$ is provided for reference as the grey dashed line, the adopted target reference point, $50\% SB_{F=0}$, is shown by the green dashed line, and the red circle represents, $SB_{latest}/SB_{F=0}$, the level of spawning biomass depletion based on the agreed method of calculating $SB_{F=0}$ over the last ten years of the model.

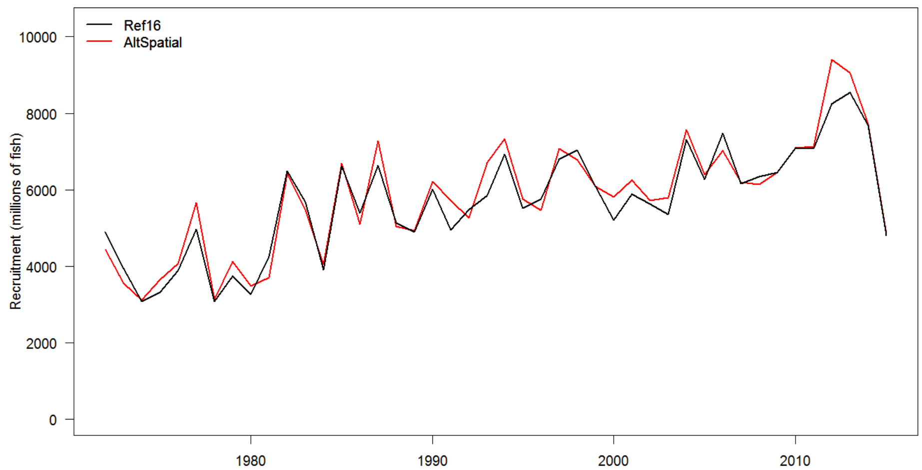


Figure 20: Estimated recruitment for the reference case and the alternative spatial structure models. Note that the recruitments in the last 2 quarters were constrained to be the mean over the estimates for the remaining time period.

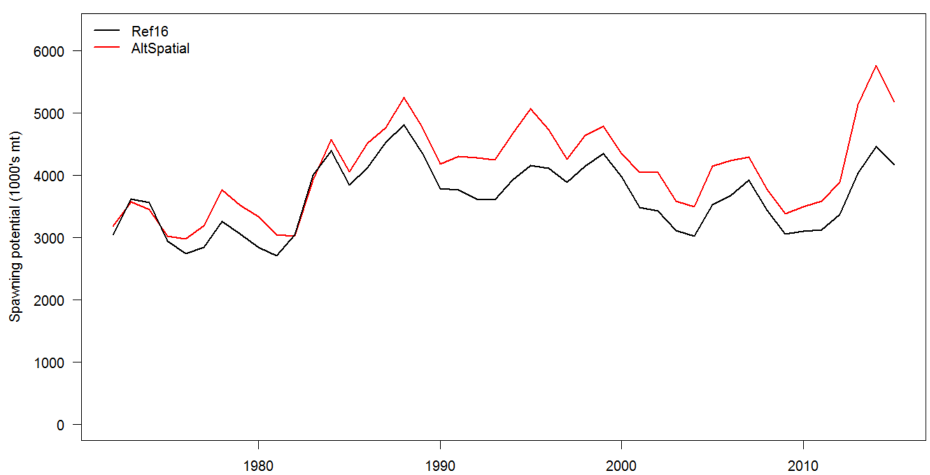


Figure 21: Estimated spawning biomass for the reference case and the alternative spatial structure models.

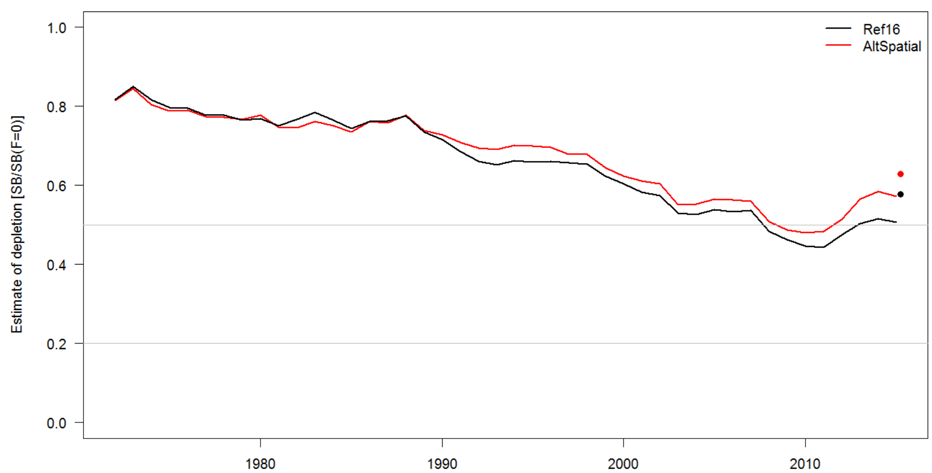


Figure 22: Estimated fisheries depletion, $SB/SB_{F=0}$, for the reference case and the alternative spatial structure models. The points show the estimates of the reference point $SB_{latest}/SB_{F=0}$ for each model.

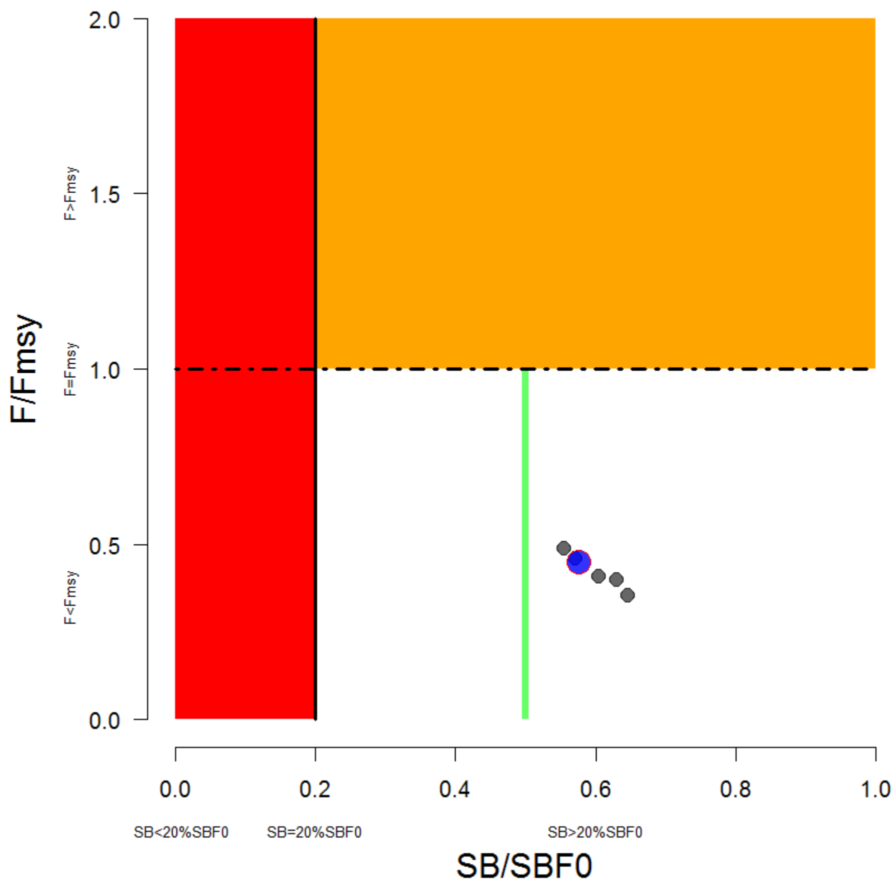


Figure 23: Majuro plot showing the estimated status for the reference case model (blue point) and all of the sensitivity models presented herein (grey points). Note that the points represent the reference points $F_{recent}/F_{\mathrm{MSY}}$ and $SB_{latest}/SB_{F=0}$. The red zone represents spawning biomass levels lower than the agreed limit reference point which is marked with the solid black line. The orange region represents fishing mortality greater than $F_{recent}/F_{\mathrm{MSY}}$ (marked with the black dashed line). The green line indicates the target reference point $50\%SB_{F=0}$.