SCIENTIFIC COMMITTEE
EIGHTTEENTH REGULAR SESSION

ELECTRONIC MEETING

11-18 August 2022

Stock assessment of Southwest Pacific Shortfin Mako shark

WCPFC-SC18-2022/SA-WP-02

August 03 2022

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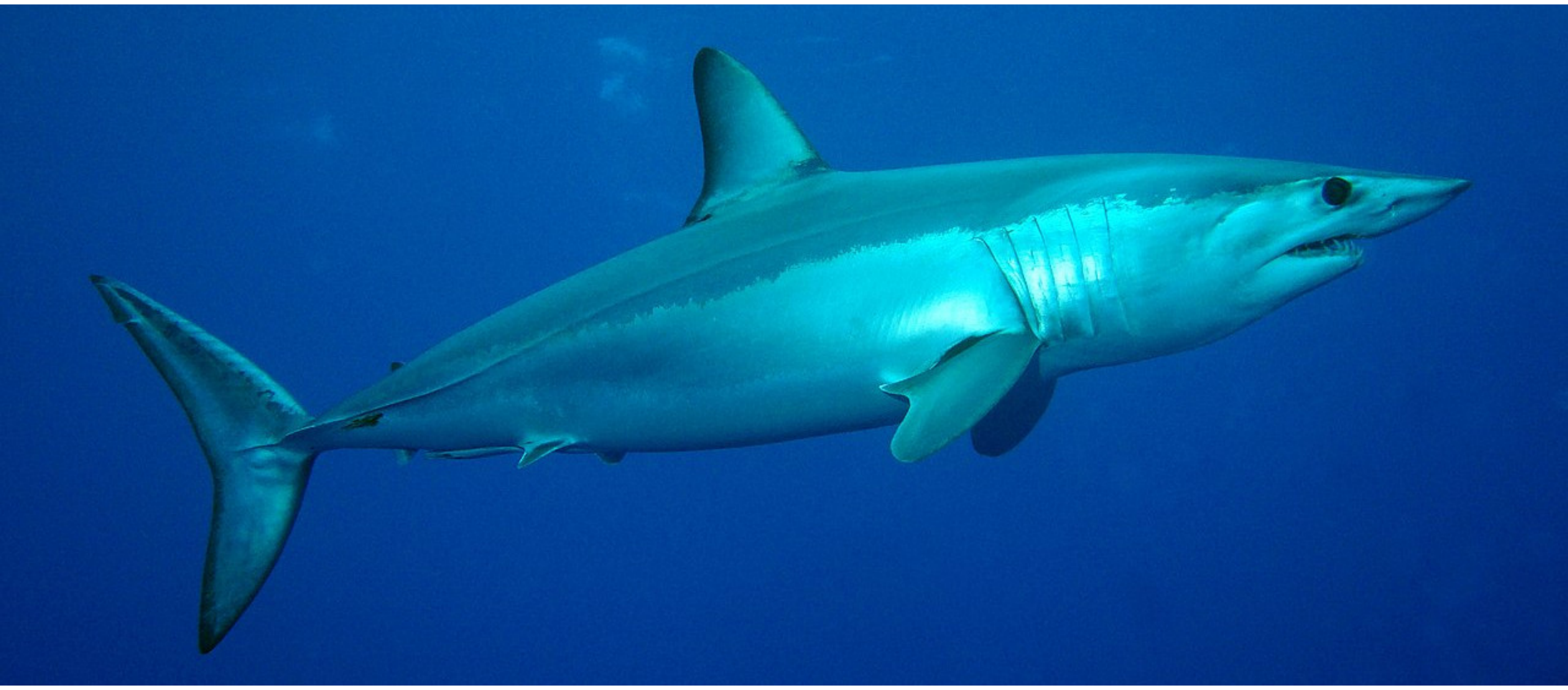

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To be cited as:

Large, Kath; Brouwer, Stephen; Neubauer, Philipp (2022). Stock assessment of Southwest Pacific Shortfin Mako shark, 40 pages. WCPFC-SC18-2022/SA-WP-02. Report to the WCPFC Scientific Committee. Eighteenth Regular Session, 11–18 August 2018.

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EXECUTIVE SUMMARY

This analysis assesses the southwest Pacific shortfin mako shark stock in the Western and Central Pacific Ocean (WCPO) hereafter referred to as the Southwest Pacific.

South Pacific mako sharks have been caught in longline fisheries since their inception in the 1950s, but have only been reported in catch records since the 1990s. They are thought to consist of two stocks, a southwest and southeastern stock which are both separated from those in the north Pacific at the Equator. Shortfin mako sharks in the north Pacific have been assessed and that stock is currently considered not to be overfished and overfishing is not taking place. This is the first attempt at undertaking an assessment of the southwest Pacific stock.

The stock assessment was set up in Stock Synthesis as a two-fleet model. The fisheries were structured into a low latitude high seas fleet (between 15 and 35°south) and a high latitude fleet (between 35 and 45°south) based on several observations that suggest: spawning may occur more often in higher latitudes; there may be lower catchability of smaller individuals in the warmer surface water in lower latitudes; and potential species identification issues in the most southern part of the fishery. The model was run for a 26 year period from 1995 to 2020, with the start year taken to be 1995 due to highly uncertain catches prior to 1995. The catches were reconstructed from observer data, producing relatively high catches between the mid-1990s and early 2000s, with relatively strong reductions in catch since about 2010. The catch reconstruction model also produced high uncertainties in catch between the mid-1990s and early 2000s, and in the early to mid-2010s.

Two CPUE series, one from New Zealand, representing high latitude fisheries capturing young-of-year and juvenile fish, and one from Japan representing low latitude fisheries on juvenile (mainly age 1+ but sub-mature) individuals, were used as indices of abundance. The high latitude index suggested a decline in the late 1990s, with subsequent increase since the early 2000s, and relatively variable, yet over-all flat trends in recent years. The low latitude index suggested a time-lagged decline compared to the New Zealand high latitude index in the later 1990s and early 2000s, but did not show a subsequent increase. Corresponding length frequencies appeared relatively consistent with indices: a decline and subsequent recovery in mean lengths for high latitude mean lengths, and relatively stable mean lengths for low latitude fisheries.

Despite numerous attempts, very few of our attempted models yielded plausible outcomes. In the diagnostic model, initial fishing mortality F_{init} was estimated from assumed equilibrium catches prior to the start of the time series in 1995. The resulting estimation uncertainty was large, leading to very large uncertainty around unfished biomass and stock status. The model also showed strong retrospective patterns, with only the addition of recent data providing signal to estimate scale parameters (R_0). The estimated initial equilibrium fishing mortality was largely driven by length composition data. Alternative assumptions about catch or biological parameters (e.g., M) often lead to implausible estimates for initial fishing mortality (i.e., near zero). CPUE indices appeared in conflict for both the estimation of R_0 and F_{init}. In addition, the model required highly correlated recruitment deviations to explain changes in abundance indices, suggesting that the assumed catch history alone was insufficient to explain early declines in abundance indices.

Together, these patterns suggest that the model inferences are highly dependent on assumptions and input data, and that the model solution for the diagnostic model is not stable. As result we suggest that the assessment model, while delivering information on stock biomass and fishing mortality trends, is not robust enough for providing management advice.

Despite the documented shortcomings, we suggest that the present assessment delivers some useful metrics. Fishing mortality and associated reference point metrics, for example, were consistently estimated (Table 2). The assessment therefore provides preliminary indications that recent fishing mortality may have declined below critical (i.e., $F_{crash,\text{AS}}$) levels, and may currently be near levels of F_{MSY}. However, due to the inherent instability of the present model, we did not explore the sensitivity of these estimates to uncertainty in the catch and discard assumptions. Our models used an estimate of natural mortalty from New Zealand studies, that was noted as being high. As a consequence, F based reference points derived here may be overly optimistic. As alternative model runs did not succeed in providing plausible outputs, we therefore caution that the present analysis is preliminary and only gives ranges of values from a single assumption of life history, and our most-likely catch and discard scenarios only

Main Assessment Conclusions

- The assessment was un-stable, with high estimation uncertainty and sensitivity to a range of inputs. We therefore consider this assessment preliminary and suggest it should not be used for providing management advice.
- Poor representation of mature females in commercial fishing data suggests that all inferences for this important partition of the stock are derived from assumptions and estimates of biological and fisheries parameters, with no direct observations to assess the appropriateness of these assumptions/estimates. In the absence of alternative data sources on trends in this component of the stock, this issues will likely remain in future, and alternative assessment approaches should be explored.
- Relatively consistent estimates of fishing mortality and related reference points suggest that recent declines in catch may have been sufficient to reduce fishing mortality below critical levels. However, we note that these statistics are based on a single set of assumptions, and further work will be required to test the robustness of these preliminary statistics.

Given some of the fundamental uncertainties highlighted above, we recommend:

- Future assessments should spend increased effort to reconstruct spatio-temporal abundance patterns for shortfin mako, and develop a better understanding of how these patterns drive regional abundance indices.
- Providing more time, either as inter-sessional projects, or by extending time-frames for shark analyses will allow more thorough investigation of input data quality and trends, which shape assessment choices. In addition, this approach would allow input analyses to be completed in time to be presented to the March pre-assessment workshop prior to the stock assessment commencing. Moreover, this will provide more time for the assessments themselves allowing a more thorough investigation of alternative model structures or assessment approaches.
- Increased effort should be made to re-construct catch histories for sharks (and other bycatch species) from a range of sources. Our catch reconstruction models showed that model assumptions and formulation can have important implications for reconstructed catch. Additional data sources, such as log-sheet reported captures from reliably reporting vessels, may be incorporated into integrated catch-reconstruction models to fill gaps in observer coverage.

- Additional tagging should be carried out using satellite tags in a range of locations, especially known nursery grounds off southeast Australia and New Zealand, as well as high seas areas to the north and east of New Zealand, where catch-rates are high. Such tagging may help to resolve questions about the degree of natal homing and mixing of the stock.

- Tagging may also help to obtain better estimates of natural mortality, if carried out in sufficient numbers. This could be taken up as part of the WCPFC Shark Research Plan to assess the feasibility and scale of such an analysis.

- Additional growth studies and validation of aging methods from a range of locations could help build a better understanding of typical growth, as well as regional growth differences. Current growth data are conflicting, despite evidence that populations at locations of current tagging studies are likely connected or represent individuals from the same population.

- Genetic/genomic studies could be undertaken to augment the tagging work to help resolve the stock/sub-stock structure patterns. To support this work, a strategic tissue sampling program for sharks is recommended with samples to be stored and curated in the Pacific Marine Specimen Bank.

- Aggregated data are currently submitted as annual totals for the WCPFC area only, making them uninformative for a stock specific assessment. Therefore, shortfin mako shark aggregated data (and probably other Key Sharks) should be reported by ocean area not simply as WCPO and, where possible, these data should be retrospectively corrected. As such we propose that paragraph 1 bullet point 3 of the *Scientific Data to be Provided to the Commission* should include the following sentence: "**For Key Sharks, estimates of annual catch should be separated into catch north and south of the Equator. The WCPFC secretariat should work with CCMs to get these data retrospectively corrected where possible.**"

1. INTRODUCTION

Shortfin mako sharks (*Isurus oxyrinchus*) are wide ranging inhabiting both coastal and oceanic habitats (Francis et al. 2019; Gibson et al. 2021). There are some genetic linkages between the southwest Pacific, southern Indian and south Atlantic Oceans (Corrigan et al. 2018). South Pacific mako shark are thought to consist of two stocks, a southwest and southeastern stock which are both separated from those in the north Pacific at the Equator (Francis et al. 2019).

While south Pacific mako sharks have been caught in longline fisheries since their inception in the 1950s, they have only been reported in catch records since the 1990s (Brouwer et al. 2022, Large et al. 2022). In the past, sharks were often lumped together and reported to a generic shark code (SHK). Mako sharks consist of two distinct species longfin (*Isurus paucus*) and shortfin mako and these have also been lumped together in a single "mako" code (MAK). While the generic shark code is seldom used after 2015 the generic mako code is still used, but most makos are now reported to species specific codes in the observer data (Brouwer et al. 2022). The reporting issues have led to a paucity of data which is exacerbated by a lack of logsheet reporting of bycatch in general, but particularly for sharks. Adding to the generic reporting issues, poor observer coverage for most flags in Pacific Ocean longline fisheries (Williams et al. 2020) means that observer records for this species are relatively sparse. While a fair amount of data exist for this species the data sets are inconsistent in time and space and between fleets, suggesting the data that would be informative for an assessment are relatively deficient. The paucity of data requires that prior to an assessment being undertaken, catch histories need to be estimated as one cannot rely on reported or observed data alone. As a result prior to this assessment being conducted Large et al. (2022) attempted to estimate the catch histories of south Pacific mako sharks.

Biological information is available (Bishop et al. 2006, Francis et al. 2019) as well as movement data (Sippel et al. 2016; Abascal et al. 2011; Francis et al. 2022). General data improvements as well as the availability of biological data led Brouwer and Hamer (2020) to conclude that a data rich assessment[1] could be attempted for this stock. However, they also noted the need for the development of a reliable catch history prior to undertaking the assessment.

This paper reports on the 2022 stock assessment of Southwest Pacific mako sharks in the Western and Central Pacific Fisheries Commission Convention Area (WCPFC-CA). This is the first attempt at undertaking an assessment of this stock. Shortfin mako sharks in the north Pacific have been assessed and that stock is currently considered not to be overfished and overfishing is not taking place (ISC 2018).

A catch data series has been estimated and CPUE indices have been developed from multiple fleets (Large et al. 2022). These data along with estimates of growth, and observed length data from the population were available as inputs to this assessment. The assessment results are presented here, but as there are no agreed reference points for Western and Central Pacific Ocean (WCPO) sharks, where possible a range of metrics are provided as recommended by Brouwer and Hamer (2020) for SC18s consideration. This report should be considered along with the data inputs (Large et al. 2022) and fisheries characterisation work (Brouwer et al. 2022) that have been undertaken as part of this assessment.

[1] Fully integrated stock assessment model using multiple sources of data including catch, effort and biological information in a model such as MULTIFAN-CL, Stock Synthesis or similar.

2. METHODS

2.1 Length compositions and stock structure assumptions

Length composition data show smaller individuals (<100 cm) reside near the New Zealand and Australia coasts in larger numbers than in lower latitudes (Figure 1). A mode of small individuals is present elsewhere in the southwest Pacific, and small individuals are occasionally caught elsewhere. Length frequencies (LF) suggest that spawning may occur more often in higher latitude areas. Alternatively, stronger vertical structure and deeper water in low latitudes, where surface water may be too warm for shortfin mako, may lead to lower catchability of small individuals in lower latitudes. While we cannot distinguish between these hypotheses based on available data, we decided to structure fisheries into low latitude (between 15 and 35°south) and high latitude (between 35 and 45°south). The southern restriction was included to remove potential species identification issues between porbeagle and mako shark (Large et al. 2022).

Fleets south of 35°south were mainly JP, AU and NZ, while lower latitude data came from a larger fleet. Although length-frequency sampling was spatially representative of the whole area, it is temporally dominated by early samples from Australia and Japan (Figure 2). Between the late 1990s and mid-2010s most samples came from New Zealand, while recent samples reflect a larger number of fleets such as Fiji and Chinese-Taipei. Given the temporal bias towards particular fleets within the length frequency samples, we only consider fits to aggregate LFs here, by latitudinal bands and fisheries, although the model is fitted to annual LF samples.

Fleet definitions used in this assessment were:

1. High latitude fleets catching age-0 and juvenile mako shark south of 35°South, mainly in New Zealand and the South Tasman Sea;
2. Low latitude fleets, capturing largely juvenile mako (<=250 cm), but with a notable absence of mature females.

An obvious complication for assessing mako sharks is the absence of mature females from fisheries data. Given the continued capture of small age-zero recruits in the high latitude fisheries, and therefore the presence of mature females in these latitudes, there is very little information about their habitat preferences or interactions with fisheries. With large, old mako sharks known to reach well over 400 cm in length, but sharks of this size ate likely to have very low catchability in longline fisheries. As a result, the lack of data from large fish poses problems for the stock assessment.

2.2 Catch assumptions

Fisheries interactions were reconstructed between 1990 and 2020 using an ensemble of spatial GLMM models (Large et al. 2022) that included effects for oceanographic predictors as well as targeting clusters and total effort per stratum (5x5 degree grid, flag, year, month). Catch estimates were restricted to latitudes between 15 and 45°south. The restriction in the north resulted from very high uncertainties for fisheries around Papua New Guinea, an area with high effort but very low observe coverage (Figure 5).

Catch estimates were combined with a model for annual discard rates per flag (Figure 6), which was used to produce scenarios of total fishing-induced mortalities. Due to high discard uncertainties, especially before increased observer coverage in the 2010s, we considered the possibility of high and low discards alongside the base assumption of the median discard estimate from the discard model (Figures 7, 8, 9). Post-release mortality was included at a rate of 15.3% in the calculations of total fishing-related mortality (Large et al. 2022). Due to difficulties with model fitting, we only considered median estimates of interactions and discard fate. However, for full exploration of fishing mortality, other catch and discard scenarios could be tested in the future.

2.3 CPUE indices

A range of CPUE indices were available for consideration in the analysis (Large et al. 2022; Figure 11). As discussed in Large et al. (2022), CPUE indices from observer data suffer from representation issues meaning that they do not represent any particular area for the entirety of the time-series from 1990-2020, with the exception for New Zealand.

To represent relative biomass trends for assumed fleets, we used the New Zealand CPUE index for high latitude fisheries, and the Japan longline index north of 35°South. While both indices are not without potential issues – fleet composition changes in the New Zealand fleet, and the number of hooks fished increases steadily in the retained Japanese fleet – these indices are the least problematic, and were considered the most likely to represent abundance trends in the respective latitudinal strata.

We applied the procedure advocated by Francis (2011) to assume total error (estimation plus observation error) – fitting a LOESS smoother through the index and calculating the resulting CV in residuals. For New Zealand, we omitted two highly suspect points in 1999 and 2000 from this procedure, as the latter strongly influenced residual CVs. Given mako life history, these data points are highly suspicious, and they were given a high SE of 0.45 to reflect our uncertainty that these points represent true shifts in abundance (nevertheless, similar patterns can be seen across the low latitude New Zealand flagged fleet at the time). Given that both indices had similar estimated CVs after omitting the two NZ time-points, we gave both series the same CV for all points where the estimated total error was larger than the estimation error, effectively giving them equal weight in the assessment model except for points where estimation uncertainty exceeded total estimated error.

For our initial models we tried both models with and without CPUE adjusted for the estimated number of sharks cut-free before being brought on board. We found that this adjustment made very little difference to the over-all performance and uncertainty in the assessment, which is dominated by stability issues. Nevertheless, we suggest that both scenarios should be considered as sensitivities in the future.

2.4 Model setup

The model used Stock Synthesis [Version V3.30.17.01] (Methot et al. 2021). We used Southwest Pacific specific parameters where possible (Clarke et al. 2015, Bishop et al. 2006), but reverted to North Pacific and North Atlantic parameters/analyses where necessary. CPUE data were included from 1995 (when suitable CPUE data became available) up to and including 2020. Models were run from 1995 to 2020, and outputs were analysed with respect to stock status in 2020.

2.4.1 Growth

Growth assumptions were based on studies described in Bishop et al. (2006). Size-at-birth is about 61 cm for both males and females (Francis 2016). Growth rates for the two sexes diverge as males mature, with male growth slowing compared to females. Francis (2016) notes that in growth studies for mako sharks sampled in New Zealand fisheries, growth differences appear only after about 16 years. Few sharks over the age of 16 were sampled and Francis (2016) concluded that the question of whether the sexes grow at different rates remains open. Shortfin mako sharks have a high longevity of about 30 years, with males maturing at 8–9 years and females maturing late at about 20 years old.

2.4.2 Reproductive output and recruitment

We followed ISC (2018) in using a low fecundity stock recruitment relationship. The function is parametrised where survival fraction is in terms of the survival of recruits as a function of stock size (labelled **survival fraction**) and a parameter (β) dictating the amount of density dependence in the stock recruit curve. Both parameters were taken from ISC (2018).

Shortfin mako sharks have a low fecundity averaging 12.5 pups per litter range (4–25), and the reproductive cycle is thought to be 2 years, but may be 3 years (Mollet et al. 2000). We therefore assumed a constant reproductive output of 4 pups annually, corresponding to Mollet et al. (2000), and note that the 2016 north Pacific assessment assumed a reporoductive cycle of 2 years, with 3 years as a sensitivity. Length-at-50% maturity was assumed to be 280 cm (Bishop et al. 2006).

2.4.3 Selectivity

The diagnostic model was set up to estimate selectivities based on available length-composition data. Selectivities for northern (low latitude) and southerns (high latitude) fisheries were assumed to be double-normal, reflecting both spatial availability to the fisheries, as well as the lack of mature animals in fisheries composition data. To estimate selectivities, the LF weighting was initially set to high values. Selectivity parameters were fixed at their MLE for ascending limb in the high latitude data, and for the length of the plateau of the double normal, for both selectivity curves, due to a lack of information in the model. In subsequent runs LF data were weighted according to Francis (2011).

2.4.4 Initial fishing mortality

Equilibrium catch was set to the mean catch from the catch-reconstruction predictions for the 1990-1994 years. Initial fishing mortality corresponding to those catches was estimated by assuming that catch is known with little error. We attempted to estimate initial F by assuming the population is at equilibrium with either one of the two fleets. While there is no natural assumption for this model – neither fishery was evidently more active at the start of the time series than the other – in practice only estimation assuming equilibrium with high latitude fleets was successful. In an attempt to provide minimal curvature (information) to the model to aid estimation of initial fishing mortality, we set a truncated (at zero) normal prior with mean 0.1 and SD of 0.1. In practice, this prior did little to help estimates in models where initial F could not be estimated.

2.4.5 Other parameters

Growth was set to von Bertalanffy growth, with fixed CVs reflecting growth variation found in Bishop et al. (2006). Natural mortality was assumed fixed at 0.14 (Bishop et al. 2006). Due to the sample sample size in that study and the absence of the oldest makos, Bishop et al. (2006) concluded that their estimates of M are probably too high. We note that natural mortality was assumed fixed at 0.126 in the 2016 North Pacific Assessment (ISC 2018). Alternative model runs with lower M were not successful, as initial fishing mortality consistently approached zero – a clearly implausible result.

2.4.6 Reference points

Clarke and Hoyle (2014) and Zhou et al. (2018) evaluated methods to derive reference points for elasmobranchs in the Western and Central Pacific Ocean (WCPO). However, to date, there are no formally agreed reference points for sharks in the WCPO. Recent assessments of oceanic whitetip shark, for example, compared fishing mortality to F_{lim} as a tentative limit reference point for sharks, and to F_{crash}, the fishing mortality that would lead to extinction in the long-term. If one assumes a simple Schaefer surplus production model, then $F_{crash} = R_{max}$, the maximum population growth rate (intuitively, a population cannot be sustained if fishing removes more individuals than the population can maximally produce), and $F_{lim} = 0.75R_{max}$. Because the versions of these reference points as used in the present assessment were approximated from integrated stock assessment runs, we use a subscript AS to show that these are not derived from R_{max}, but from the yield curve estimated in Stock Synthesis. Unlike for blue shark, which have higher productivity than many other shark species, we did not apply alternative reference points used for target fisheries.

3. RESULTS

3.1 Diagnostic model runs

3.1.1 Model fits

The diagnostic model run showed reasonable fit of early CPUE for both series, but due to conflicting trends in the latter part of the series, predicted CPUE did not fit either CPUE well in recent years (Figure 13). The model fitted in between both indices, predicting indices lower than the high latitude index and above the low latitude index. There were clear patterns in residuals for fits to individual indices, and aggregate residuals appeared approximately normal (Figure 14). Nevertheless, the fit suggested additional process error that the model did not capture. For example, the model could not reproduce the slope of either the early decline in high latitude CPUE, nor the more recent increase since the early 2000s. We found this was largely due to life-history assumptions incompatible with the rate of change in high latitude CPUE.

The model produced a relatively good fit to over-all length composition data (Figures 15). In addition, trends in mean length were temporally aligned with CPUE trends (Figure 16), which were fitted similarly to the CPUE, and the model could not explain changes in LF over time given life-history assumptions in the model. Estimated selectivity was high for early juvenile mako in high latitudes, lowering quickly to around 0.25. In low latitudes, estimated selectivity was unimodal at juvenile sizes (120 cm/age 1) to 250 cm (Figure 17), but large, mature (280 cm+) females are not selected by any fishery.

3.1.2 Model population trajectory

The model suggested an over-all increase in fishing mortality up to the early-mid 2000's (Figure 18), driven largely by the capture of larger individuals in high-seas/low-latitude fisheries (Figure 19). The initial catch assumption led to an estimate of initial catch that was exclusively attributed to the high latitude fishery. Although the high latitude fleets accounted for a large number of captures, the fishing mortality from those captures was estimated to be somewhat lower than that inflicted by the low-latitude and high seas fisheries. Trends in F led to an early decline in total biomass, with recent stabilisation, despite a steady decline in the spawning biomass over the assessment period (Figure 20). The model required a prolonged period of negative early recruitment deviations to fit early declines in indices. Recent declines in fishing mortality from high latitude effort, due to discarding and declines, led to a subsequent recovery of total biomass, driven by increased juvenile abundance.

3.1.3 R_0 profile

Negative log-Likelihood profiles of R_0 and initial fishing mortality, suggested that the lower bound of R_0 was largely driven by the CPUE index data, length frequencies and the prior on recruitment deviations (Figure 21). Nevertheless, splitting the CPUE likelihood into its components revealed a clear conflict between indices, with the estimated R_0 falling near the intersection of the negative log-likelihood profiles for the two CPUE series. The length-frequencies from the New Zealand samples were in agreement with the estimated R_0. All length frequencies showed a sharp increase at higher values of log(R_0)>6.5. Inspection of individuals models suggested that this was not due to non-convergence or other technical issues; rather, the model switched to alternative modes with very low initial F, as evidenced by the high penalties for "F_Ballpark", suggesting a potentially complex likelihood surface and trade-offs between initial F and R_0, with a minimum at high R_0 and low initial F.

Log-Likelihood profiles for initial fishing mortality showed that initial F was largely driven by length frequency samples from high latitudes (Figure 22), with conflicting information coming from CPUE indices, the influence of which is largely cancelled by the conflicting trends.

3.1.4 Retrospective patterns

Retrospective patterns were high for biomass related quantities, such as stock status (Figure 23), with recent status progressively higher for more recent peels. Although all patterns are within uncertainty intervals, these patterns suggest that biomass estimates are only just beginning to stabilise with the addition of recent data. The retrospective pattern and recent stabilisation of estimates is mirrored in the estimate of unfished average recruitment R_0 (Figure 24). Fishing mortality related patterns were stable (Figure 23), as were fits to CPUE (Figure 25). MASE predictive checks indicated poor predictive ability for the models (Figure 26), linked to their intermediate fit between both indices in recent years.

3.1.5 Estimation uncertainty from MCMC

Estimation uncertainty was high for relative biomass trajectories (Figure 27). This uncertainty was derived from uncertain estimates for both R_0 and F_{init} (Figure 28). Despite this uncertainty, fishing mortality was estimated to be at or below MSY in recent years (Figures 29, 30), and uncertainty in F and related reference point metrics was lower than that for biomass (Table 2).

4. DISCUSSION

This assessment presents a first attempt at estimating the stock status of shortfin mako in the southwest Pacific Ocean. Although initial assessments of data availability concluded that an integrated stock assessment could be attempted (Brouwer and Hamer 2020), we found that, in practice, the life-history, combined with patchy and poor data quality, made constructing a robust assessment model challenging. While we were successful, in technical terms, in running a diagnostic model for this stock, we found that the model was very sensitive to input data (most alternative configurations we tried did not give plausible outputs). The assessment was also strongly driven by the length of the time-series, with recent data driving estimates of unfished recruitment and stock size. In addition, we found that initial fishing mortality was estimated imprecisely, leading to high variability in estimates of unfished stock size. Lastly, the near complete absence of mature females in the input data means that any measures of mature biomass are model predictions that cannot be verified with the available data, and therefore cannot be scrutinised. Together, these difficulties suggest that, at present, the available model for southwest Pacific shortfin mako sharks is not robust enough for providing management advice.

Although alternative assessment approaches have been suggested for shark species (e.g., Neubauer et al. 2019), these may not overcome fundamental challenges that stem from the life-history of late pupping and the absence of important components of the population (mature females) from fisheries data, as well as the presence of conflicting signals in regional trends. Surplus production models, for example, only model the vulnerable part of the stock, and would therefore not represent mature stock. Similarly, any inferences drawn from available data for use in spatial risk assessments would have to be made in the absence of data on mature individuals. We therefore suggest that, despite the problems listed above, the integrated assessment approach offers the most promising avenue to scrutinise the appropriateness of assessment models for shortfin mako.

The outcomes of this assessment highlight the deficiencies in the data, both in its sparsity and quality. The diagnostic model indicated a declining trend in southwest Pacific shortfin mako shark mature biomass. The estimated catch inputs are uncertain, and the assessment outcomes were particularly sensitive to estimates of initial exploitation, where slight changes in initial F scaled the mature biomass anywhere from highly depleted to a mostly un-depleted stock. In addition, the CPUE trends were variable over the assessment period, and did not provide agreement on the trajectory of the stock biomass, with increasing CPUE trends from the early 2000s in the high latitudes, and an over-all declining trend in the low latitude/high-seas CPUE, and with stable CPUE in recent years. This disagreement leads to conflicting signals for key parameters in the model.

A marked conflict between the rate of change in both high latitude CPUE and corresponding length frequencies, compared with model fits, suggests that either the assumed biology or indices are wrong, or that the model may not be accounting for important processes. High latitude CPUE trends were relatively consistent between fleets (New Zealand, Australia and Japan), unlike low latitude trends. Together with consistency in length composition trends over time, this suggests that patterns in high latitude data may be relatively representative. Assuming alternative biological assumptions in initial models (faster (female) growth, lower M), made little difference to over-all model outcomes when working with fixed initial F (these models did not work with estimated initial F), suggesting that alternative biological parameters do not significantly improve model fits.

Francis et al. 2019 suggested that shortfin mako may exhibit significantly stronger residential behaviour than previously assumed, with a potentially resident population migrating between

New Zealand and the tropics. The degree of connectivity with other geographical areas, however, was unclear. Nevertheless, these findings suggest that shortfin mako may be comprised of geographically relatively distinct stocks or migratory contingents, the structure of which may be poorly captured in the present assessment. Furthermore, tagging in Australia suggested that some sharks move between the Tasman Sea around Tasmania to the South Australian Bight and west of the Australian continent, suggesting that southwest Pacific shortfin mako may not form a closed population (Corrigan et al. 2018). Although one could, in theory, assume more structured fisheries in the stock assessment (e.g., CPUE and selectivities by fleet) to capture potential geographical trends, we found that, in practice, length composition data are too sparse for many fleets, and operational CPUE trends are not useful due to significant changes in fleets over time, and/or poor reporting, especially in early years for most fleets. The currently available resolution of the data may therefore be incompatible with the development of models that reflect stock structure and spatial dynamics.

We suggest that future assessments may be able to more thoroughly investigate spatio-temporal patterns of abundance, using both CPUE and observer data. By matching expected capture rates of shortfin mako in time and space between observer and CPUE data, for example, one may be able to estimate reporting trends, and therefore construct more consistent CPUE indices. In addition, further scrutiny of observer CPUE models and their use in predicting catch rates could yield insights into appropriate model selection methods that may reduce uncertainties about regional interaction trends. However, to do such analyses would require more resources and time than are currently available for most shark assessments. Nevertheless, we suggest that more thorough inspections of available assessment inputs is the most promising avenue to improve stock assessments for shortfin mako as well as other shark species.

Despite the documented shortcomings, we suggest that the present assessment delivers some useful metrics. Fishing mortality and associated reference point metrics, for example, were consistently estimated (Table 2). The assessment therefore provides preliminary indications that recent fishing mortality may have declined below critical (i.e., $F_{crash,\text{AS}}$) levels, and may be near levels of F_{MSY}. However, due to the inherent instability of the present model, we did not explore the sensitivity of these estimates to uncertainty in life history, catch and discard assumptions. Our models used a higher estimate for natural mortality derived from Bishop et al. (2006), who noted that their estimate may be high. As a consequence, F based reference points derived here may be overly optimistic. As alternative model runs did not succeed in providing plausible outputs, we therefore caution that the present analysis is preliminary and only gives ranges of values from a single assumption of life history, and presenting our most-likely catch and discard scenarios only.

4.1 Main Assessment Conclusions

- The assessment was un-stable, with high estimation uncertainty and sensitivity to a range of inputs. We therefore consider this assessment preliminary and suggest it should not be used for providing management advice.
- Poor representation of mature females in commercial fishing data suggests that all inferences for this important partition of the stock are derived from assumptions and estimates of biological and fisheries parameters, with no direct observations to assess the appropriateness of these assumptions/estimates. In the absence of alternative data sources on trends in this component of the stock, this issues will likely remain in future, and alternative assessment approaches should be explored.
- Relatively consistent estimates of fishing mortality and related reference points suggest

that recent declines in catch may have been sufficient to reduce fishing mortality below critical levels. However, we note that these statistics are based on a single set of assumptions, and further work will be required to test the robustness of these preliminary statistics.

Given some of the fundamental uncertainties highlighted above, we recommend:

- Future assessments should spend increased effort to reconstruct spatio-temporal abundance patterns for shortfin mako, and develop a better understanding of how these patterns drive regional abundance indices.
- Providing more time, either as inter-sessional projects, or by extending time-frames for shark analyses will allow more thorough investigation of input data quality and trends, which shape assessment choices. In addition, this approach would allow input analyses to be completed in time to be presented to the March pre-assessment workshop prior to the stock assessment commencing. Moreover, this will provide more time for the assessments themselves allowing a more thorough investigation of alternative model structures or assessment approaches.
- Increased effort should be made to re-construct catch histories for sharks (and other bycatch species) from a range of sources. Our catch reconstruction models showed that model assumptions and formulation can have important implications for reconstructed catch. Additional data sources, such as log-sheet reported captures from reliably reporting vessels, may be incorporated into integrated catch-reconstruction models to fill gaps in observer coverage.
- Additional tagging should be carried out using satellite tags in a range of locations, especially known nursery grounds off southeast Australia and New Zealand, as well as high seas areas to the north and east of New Zealand, where catch-rates are high. Such tagging may help to resolve questions about the degree of natal homing and mixing of the stock.
- Tagging may also help to obtain better estimates of natural mortality, if carried out in sufficient numbers. This could be taken up as part of the WCPFC Shark Research Plan to assess the feasibility and scale of such an analysis.
- Additional growth studies and validation of aging methods from a range of locations could help build a better understanding of typical growth, as well as regional growth differences. Current growth data are conflicting, despite evidence that populations at locations of current tagging studies are likely connected or represent individuals from the same population.
- Genetic/genomic studies could be undertaken to augment the tagging work to help resolve the stock/sub-stock structure patterns. To support this work, a strategic tissue sampling program for sharks is recommended with samples to be stored and curated in the Pacific Marine Specimen Bank.
- Aggregated data are currently submitted as annual totals for the WCPFC area only, making them uninformative for a stock specific assessment. Therefore, shortfin mako shark aggregated data (and probably other Key Sharks) should be reported by ocean area not simply as WCPO and, where possible, these data should be retrospectively corrected. As such we propose that paragraph 1 bullet point 3 of the *Scientific Data to be Provided to the Commission* should include the following sentence: "**For Key Sharks, estimates**

of annual catch should be separated into catch north and south of the Equator. The WCPFC secretariat should work with CCMs to get these data retrospectively corrected where possible."

5. ACKNOWLEDGEMENTS

We would like to thank Paul Hamer and Jemery Day for their constructive input throughout the assessment and for review comments on this paper. The authors would like to thank SPC, particularly Peter Williams, Emmanuel Schneiter and Aurélien Panizza for providing the WCPFC Members data for these analyses. We would also like to thank Silver Bishop for providing her length-at-age estimates for the calculation of a combined male-female growth curve. Finally, we acknowledge the funding of this work this work from the WCPFC Scientific Committee Project 111.

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7. TABLES

Table 1: Description of the symbols used in the yield and stock status analyses. In this assessment, 'recent' is the average of the metric over the period 2017–2020, and 'latest' is 2020.

Symbol	Description
SB_0	Equilibrium unfished spawning biomass under average recruitment
SB_{latest}	Spawning biomass in the last year of the assessment (2020)
SB_{recent}	Spawning biomass in a recent period of the assessment (2017–2020)
SB_{latest}/SB_0	Spawning biomass in the latest time period (2020) relative to the equilibrium spawning biomass under $F = 0$ and average recruitment
SB_{recent}/SB_0	Spawning biomass in the recent time period (2017–2020) relative to the equilibrium spawning biomass under $F = 0$ and average recruitment
F_{MSY}	Fishing mortality producing the maximum sustainable yield (MSY)
F_{limAS},	Fishing mortality resulting in 0.5 of SB_{MSY}
$F_{crashAS}$	Fishing mortality resulting in population extinction when sustained on the long-term
F_{latest}/F_{MSY}	Average fishing mortality-at-age for the last year of the assessment (2020)
F_{recent}/F_{MSY}	Average fishing mortality-at-age for a recent period (2017–2020)
F_{latest}	Latest fishing mortality (2020) relative to F would produce maximum sustainable yield (MSY)
F_{recent}	Recent fishing mortality (2017–2020) relative to F would produce that producing maximum sustainable yield (MSY)
F_{latest}/F_{limAS}	Latest fishing mortality (2020) compared to that resulting in 0.5 of SB_{MSY}
F_{recent}/F_{limAS}	Recent fishing mortality (2017–2020) compared to that resulting in 0.5 of SB_{MSY}
$F_{latest}/F_{crashAS}$	Latest fishing mortality (2020) compared to that resulting in population extinction
$F_{recent}/F_{crashAS}$	Recent fishing mortality (2017–2020) compared to that resulting in population extinction

Table 2: Summary of reference point metrics for an initial Markov Chain Monte Carlo (MCMC) run of the diagnostic model for shortfin mako, using a total of 1494 iterations from No-U-Turn sampling (Monnahan et al. 2019). Reference point metrics based on $F_{lim,\text{AS}}$, and $F_{crash,\text{AS}}$ use maximum *a posteriori* estimates for these parameter values as they were not available from MCMC.

	Mean	Median	Min	10%	90%	Max
F_{MSY}	0.031	0.031	0.027	0.030	0.032	0.034
$F_{lim,\text{AS}}$	0.045	0.045	0.045	0.045	0.045	0.045
$F_{crash,\text{AS}}$	0.062	0.062	0.062	0.062	0.062	0.062
F_{latest}	0.020	0.020	0.006	0.014	0.026	0.036
F_{recent}	0.026	0.026	0.008	0.018	0.033	0.046
$F_{latest}/F_{\text{MSY}}$	0.64	0.64	0.20	0.46	0.83	1.17
$F_{recent}/F_{\text{MSY}}$	0.83	0.83	0.26	0.59	1.07	1.49
$F_{latest}/F_{lim,\text{AS}}$	0.44	0.44	0.14	0.31	0.57	0.80
$F_{recent}/F_{lim,\text{AS}}$	0.57	0.57	0.18	0.41	0.74	1.02
$F_{latest}/F_{crash,\text{AS}}$	0.32	0.32	0.10	0.23	0.42	0.59
$F_{recent}/F_{crash,\text{AS}}$	0.42	0.42	0.13	0.30	0.54	0.75

8. FIGURES

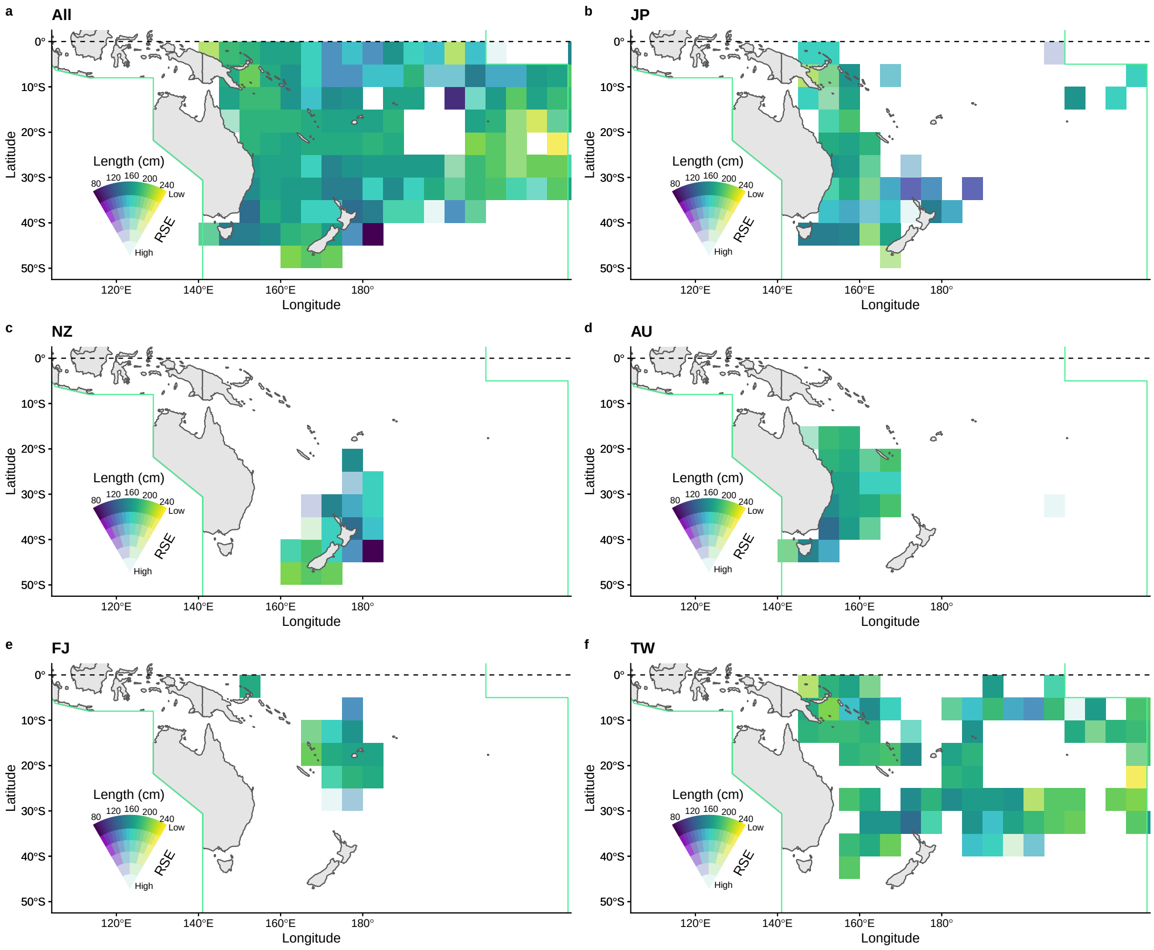

Figure 1: Maps of average length shaded by variability in lengths (SE of mean length). Samples are from a) Combined dataset, b) Japan, c) New Zealand, d) Australia, e) Fiji, f) Chinese Taipei.

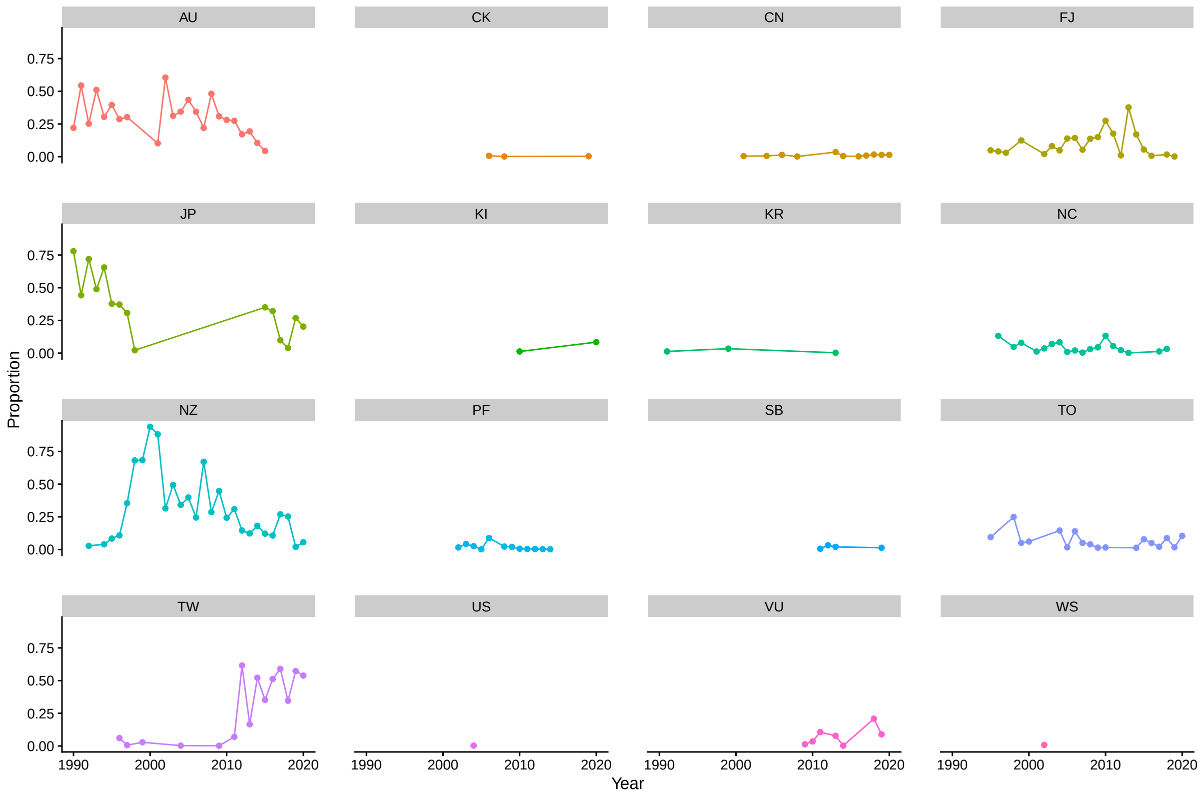

Figure 2: Proportion of length frequency samples across all flags over time by each CCM in the observer dataset.

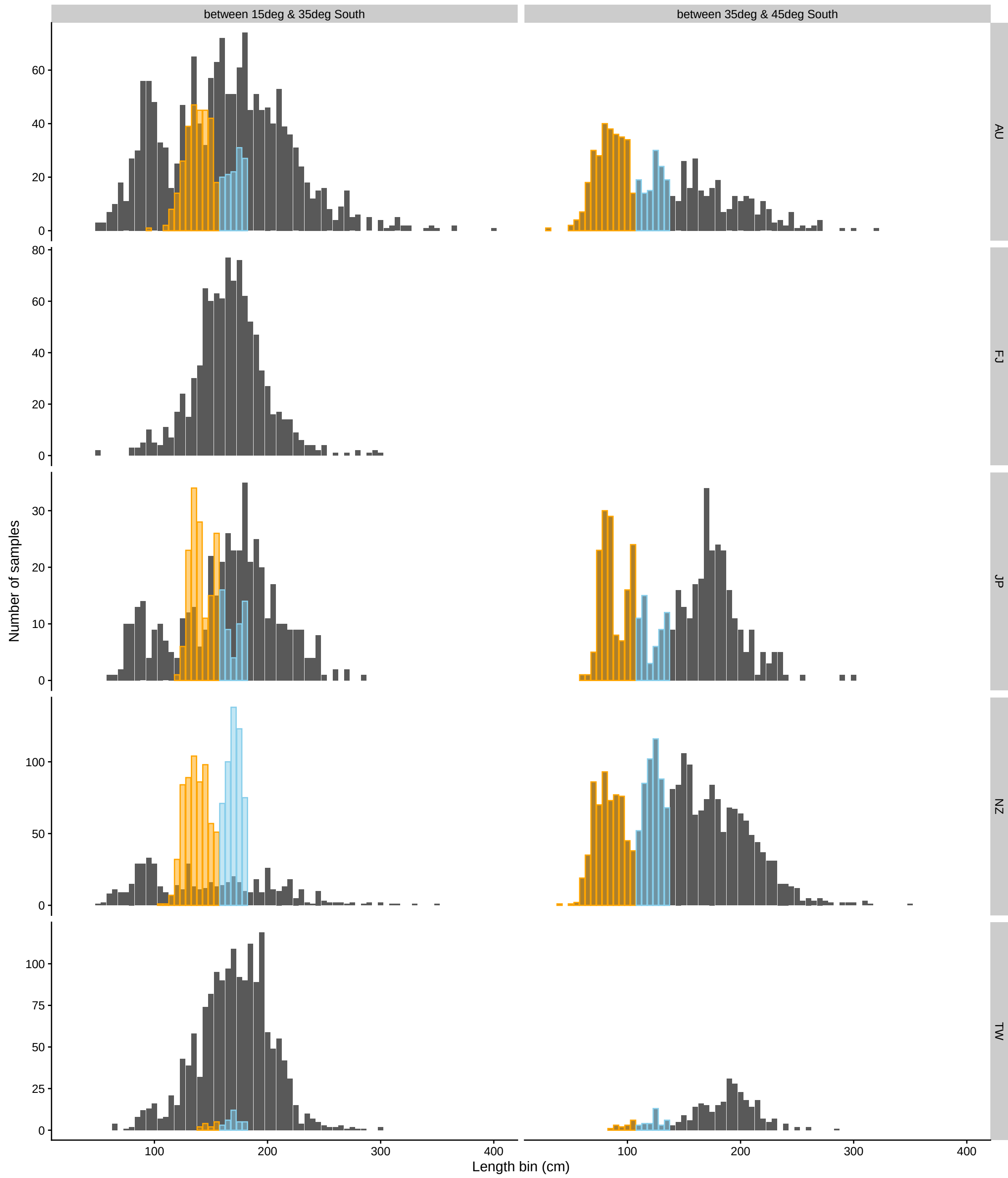

Figure 3: Length frequency by flag for flags with reasonable amounts of samples. Orange and blue histograms show samples of age-0 recruits and 1-year-olds ongrown according to Bishop et al. (2006) over 4 and 5 years respectiely. Samples of 1-year old fish appear to align with the common fishery peak at 180-200cm in lower latitudes, suggesting a lag of around 5 years from those areas before fish appear in lower latitude fisheries

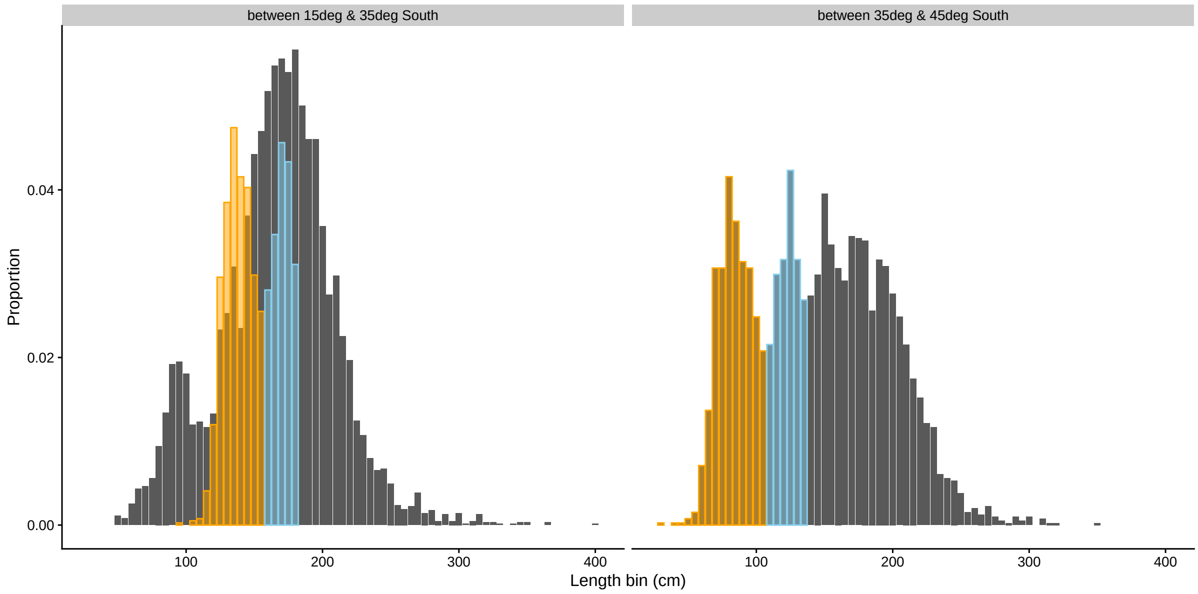

Figure 4: Length proportions by fleet definition in the stock assessment. Orange and blue histograms show samples of age-0 recruits and 1-year-olds grown according to Bishop et al. (2006) over 4 and 5 years respectiely.

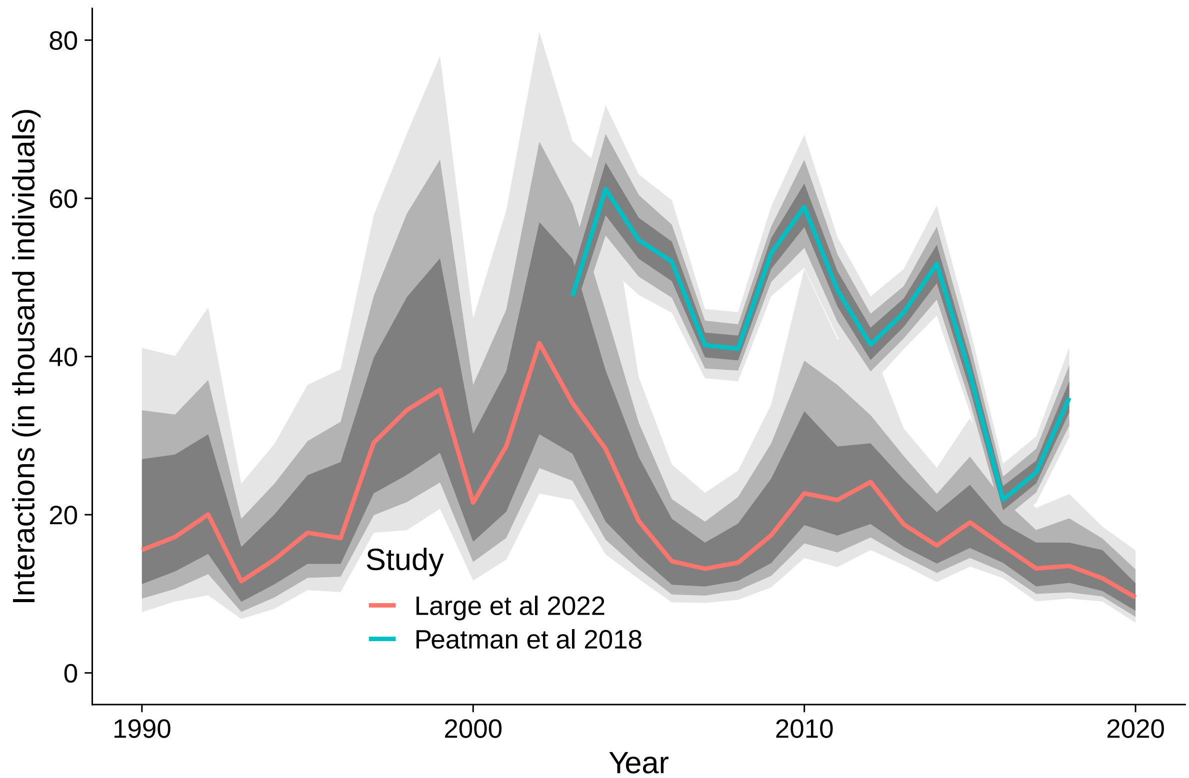

Figure 5: Predicted total shortfin mako shark captures (top) from the 18 catch reconstruction models (posterior median (red); 75% confidence (dark grey) and 80% confidence (light grey)) using the observer catch-rate GLMM in conjunction with L-BEST effort, and for predictions restricted to between latitudes 15°S and 45°S.

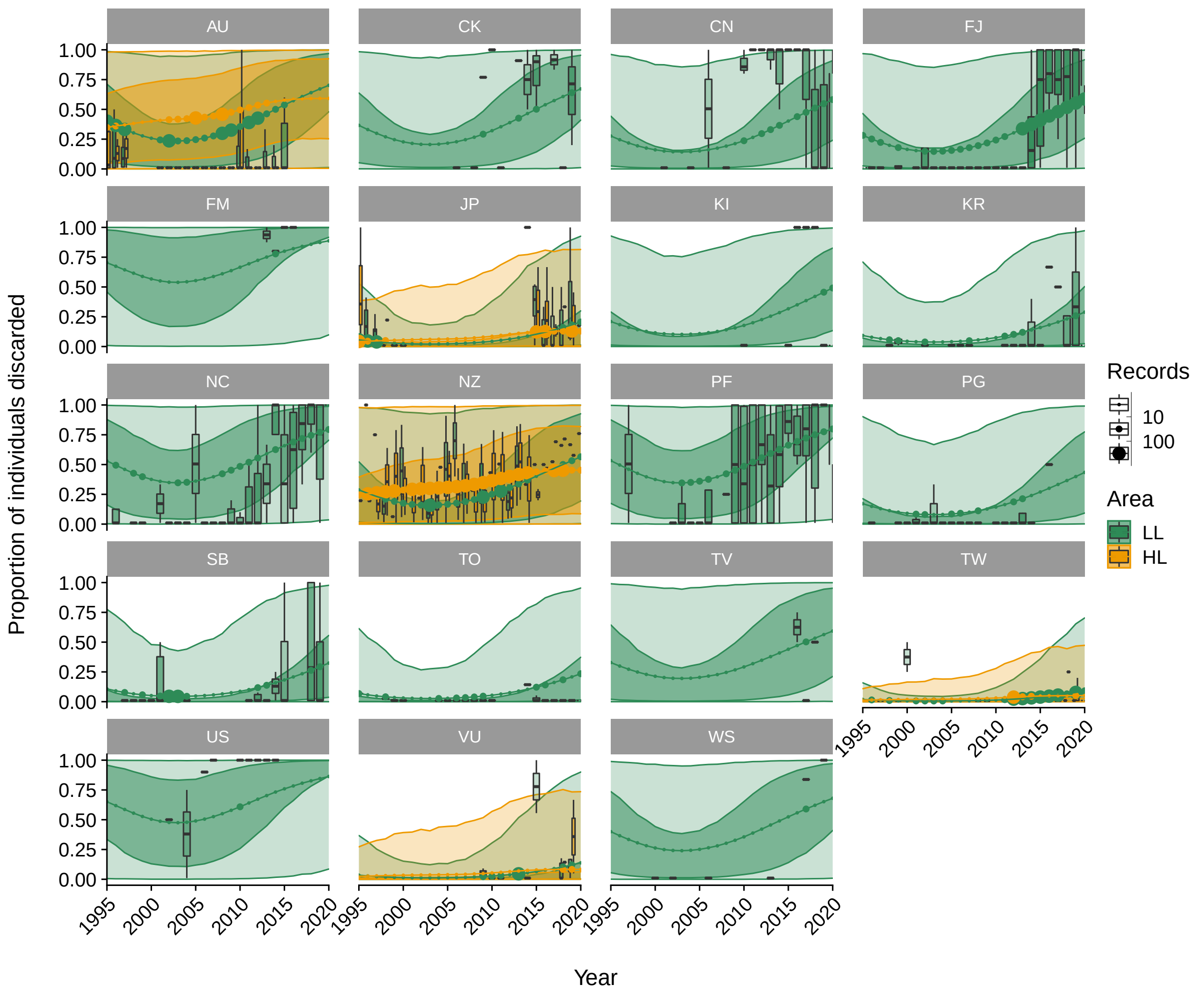

Figure 6: Estimated flag-year effects (expected proportion discarded) for flags in the observer dataset, split along low-latitude and high-latitude (>= 35 degree South), showing the posterior median, 75% (dark shade) and 95% (light shade) posterior confidence. The distribution of input data is shown by underlying boxplots.

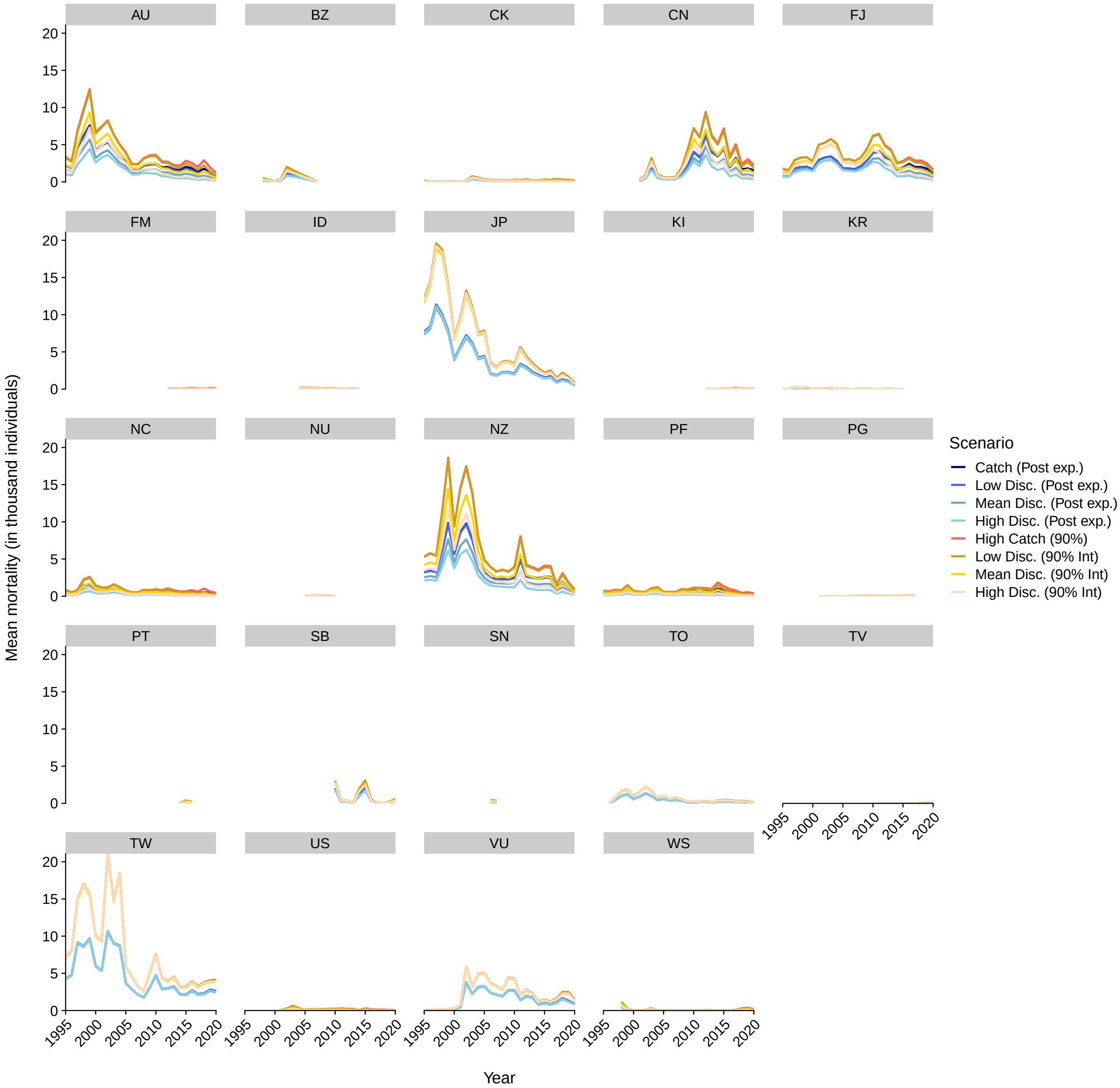

Figure 7: Predicted total fishing related mortality by flag, including 17% post release mortality for live-discarded south Pacific shortfin mako sharks. Interactions refer to the posterior median (50%) and 90^{th} percentile (90%) of the predicted catch from the observer catch rate model. Low, median and high discard scenarios refer to the 25%, 50% (median) and 75% discard estimates.

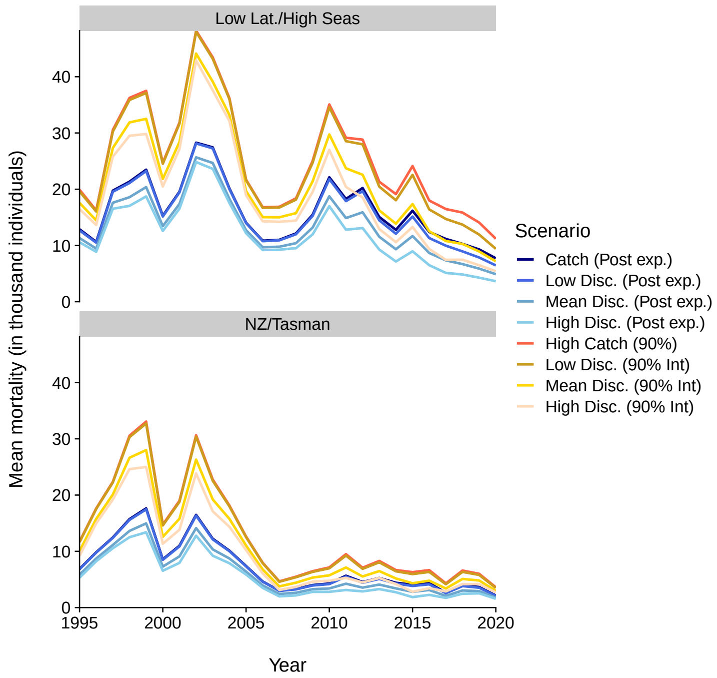

Figure 8: Predicted total fishing related mortality by latitudinal stratum (high [>= 35 degree South] and low latitude [< 35 degree South]), including 17% post release mortality for live-discarded blue sharks. Interactions refer to the posterior median (50%) and 90^{th} percentile (90%) of the predicted catch from the observer catch rate model. Low, median and high discard scenarios refer to the 25%, 50% (median) and 75% discard estimates. All discard estimates were applied at flag and latitudinal stratum level to overall interactions.

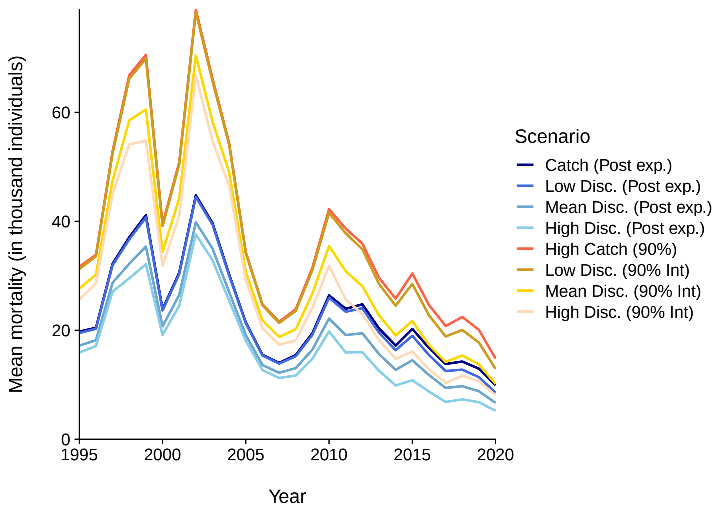

Figure 9: Predicted total fishing related mortality, including 17% post release mortality for live-discarded blue sharks. Interactions refer to the posterior median (50%) and 90^{th} percentile (90%) of the predicted catch from the observer catch rate model. Low, median and high discard scenarios refer to the 25%, 50% (median) and 75% discard estimates. All discard estimates were applied at flag and latitudinal stratum level to overall interactions.

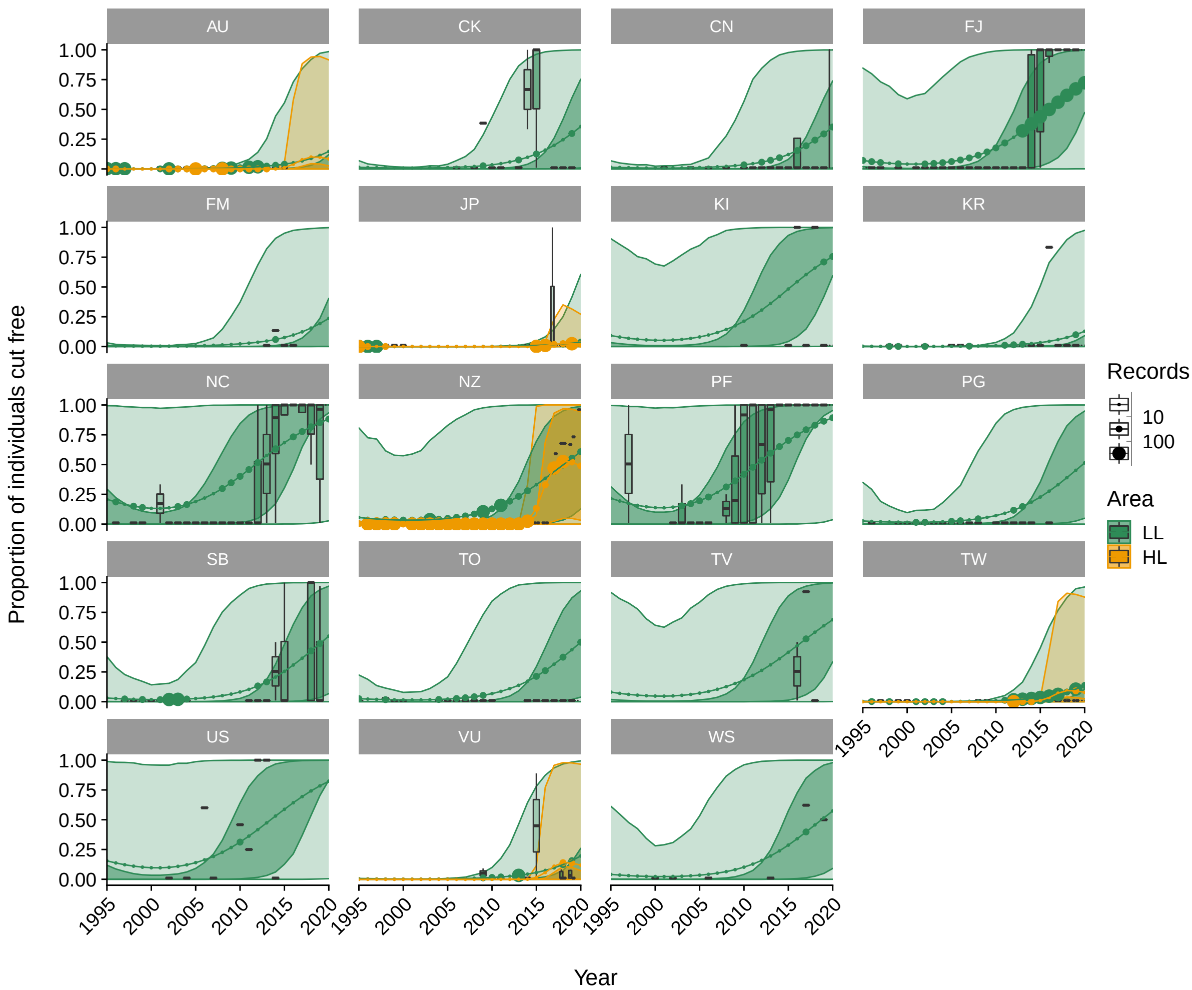

Figure 10: Estimated flag-year effects (expected proportion cut free) for flags in the observer dataset, split along low-latitude and high latitude (>= 35 degree South), showing the posterior median, 75% (dark shade) and 95% (light shade) posterior confidence. The distribution of input data is shown by underlying boxplots.

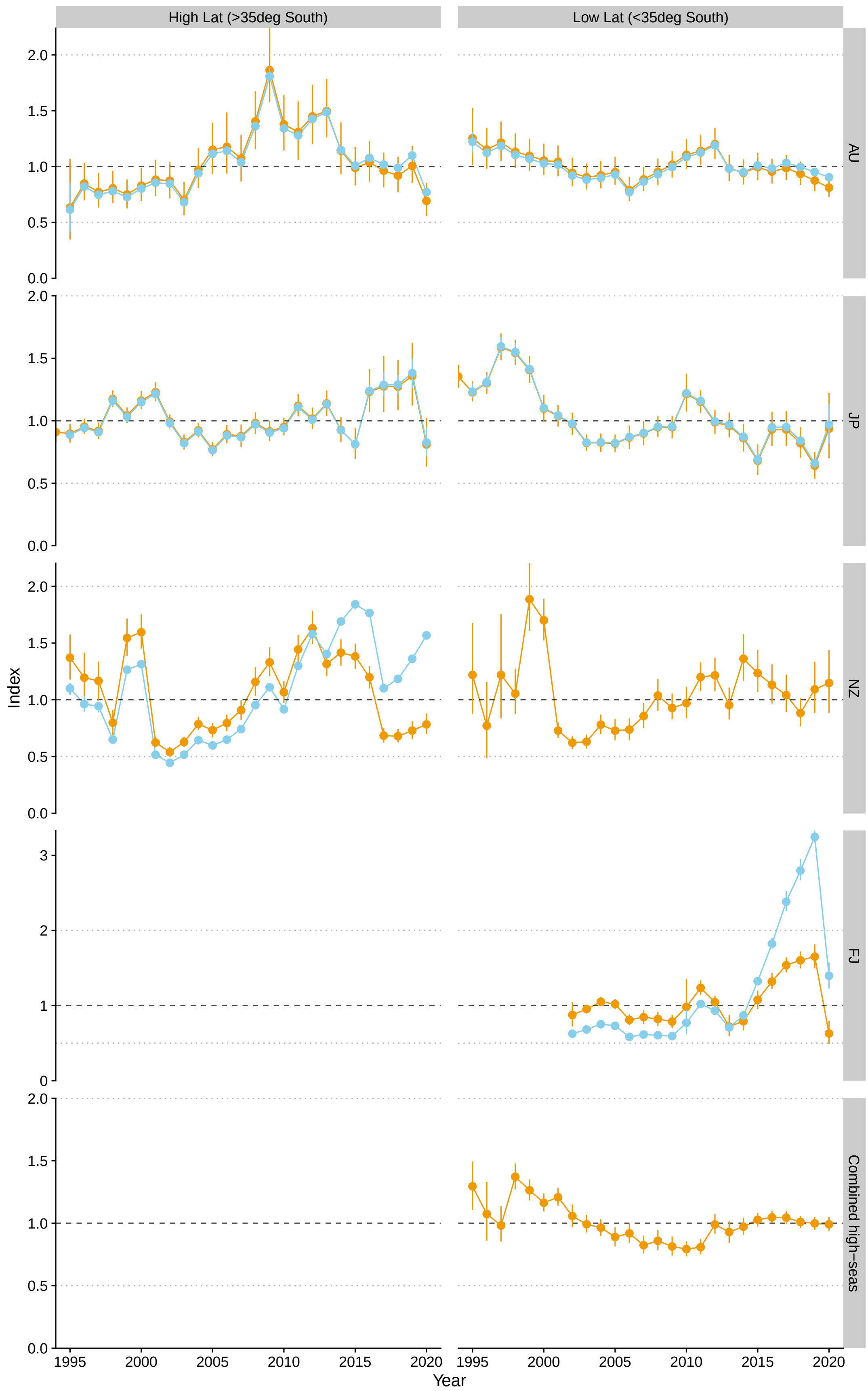

Figure 11: Standardised (circles with standard error) CPUE indices for CCMs included in the log-sheet CPUE analyses (orange), and adjusted by rates of sharks cut-free (blue circles).

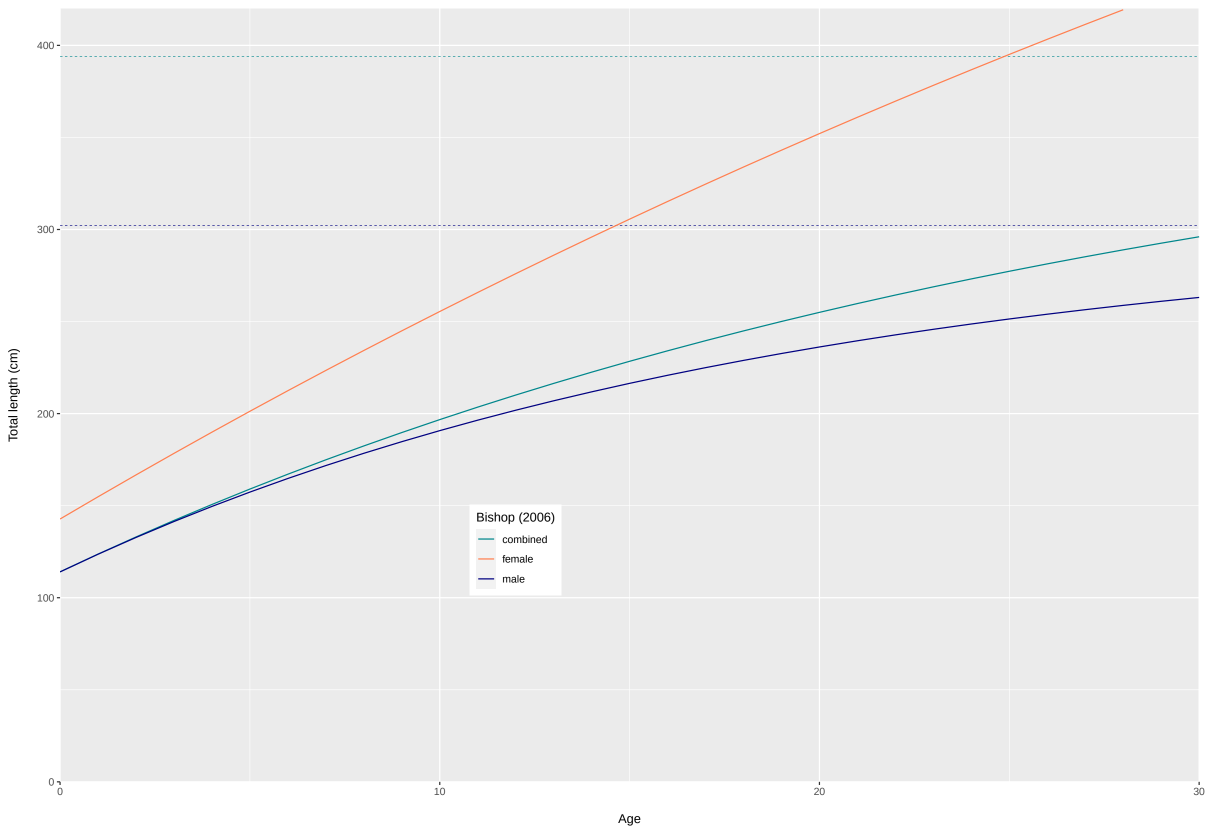

Figure 12: Comparison of growth curves for shortfin mako shark in the southwest Pacific Ocean used in the current assessment. Dashed lines show L_∞ for male and combined growth curves female L_∞ was estimated to be over 7m and is not shown in this plot.

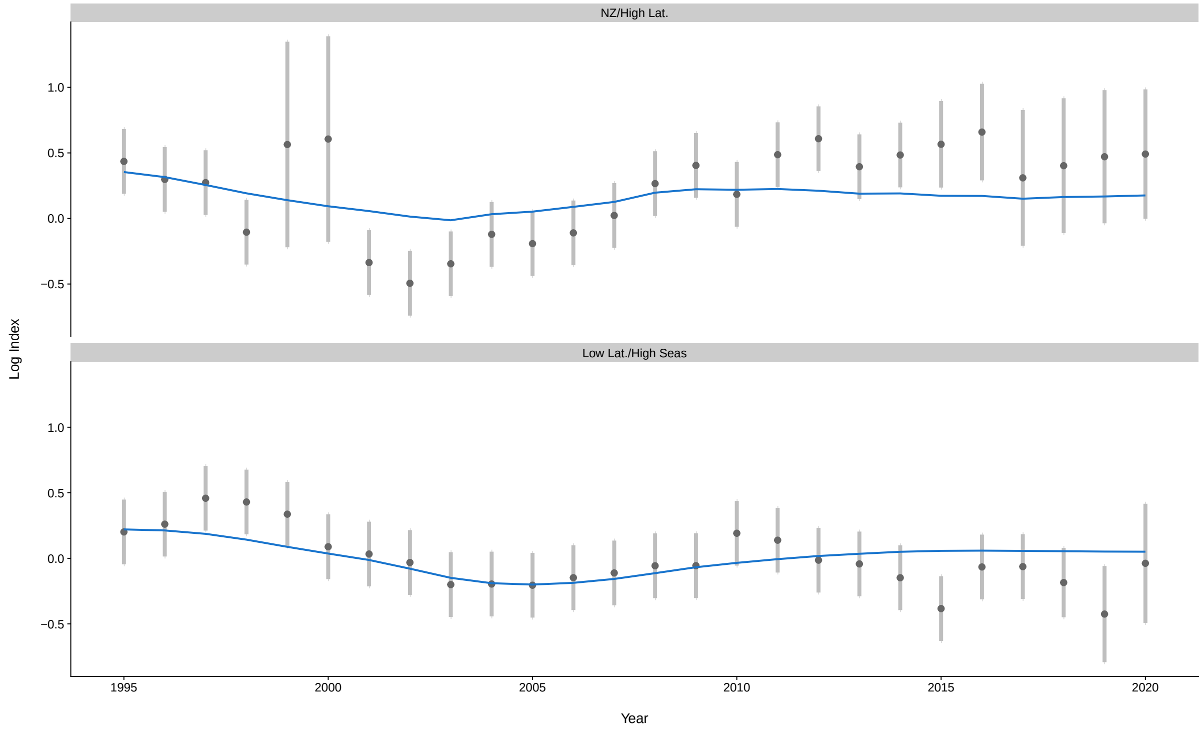

Figure 13: Observed (grey dots) vs. predicted (blue line) CPUE on the log-scale for index longline fleets under the diagnostic case, with vertical light grey bands showing the 95% confidence interval for each year index.

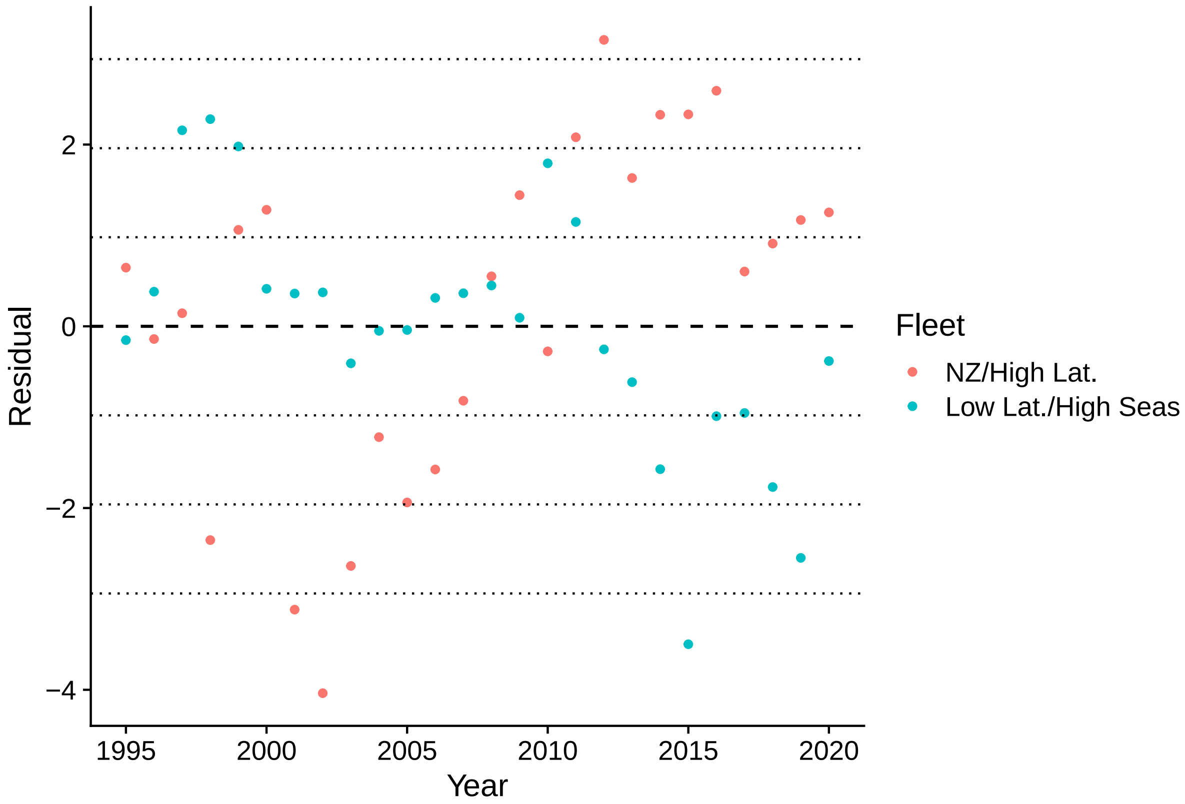

Figure 14: Residuals for CPUE indices from two longline fleets under the diagnostic case.

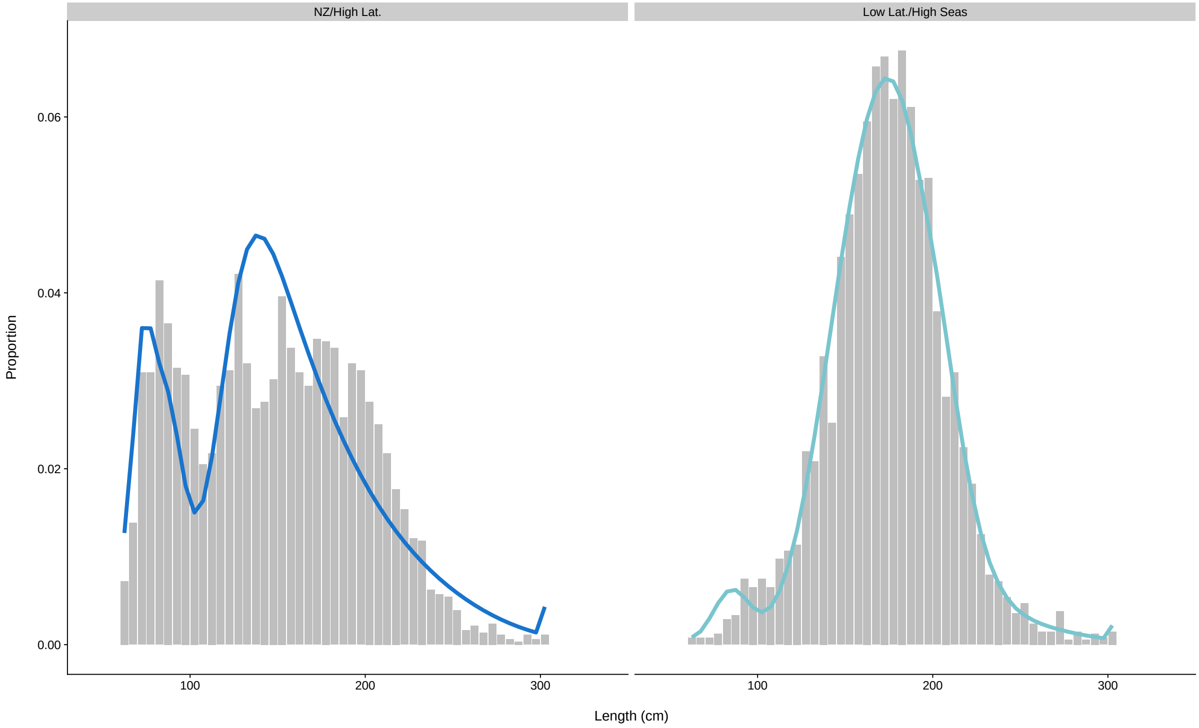

Figure 15: Observed (grey bars) vs. predicted (coloured line) catch-at-length for each fleet aggregated over all years for the diagnostic case.

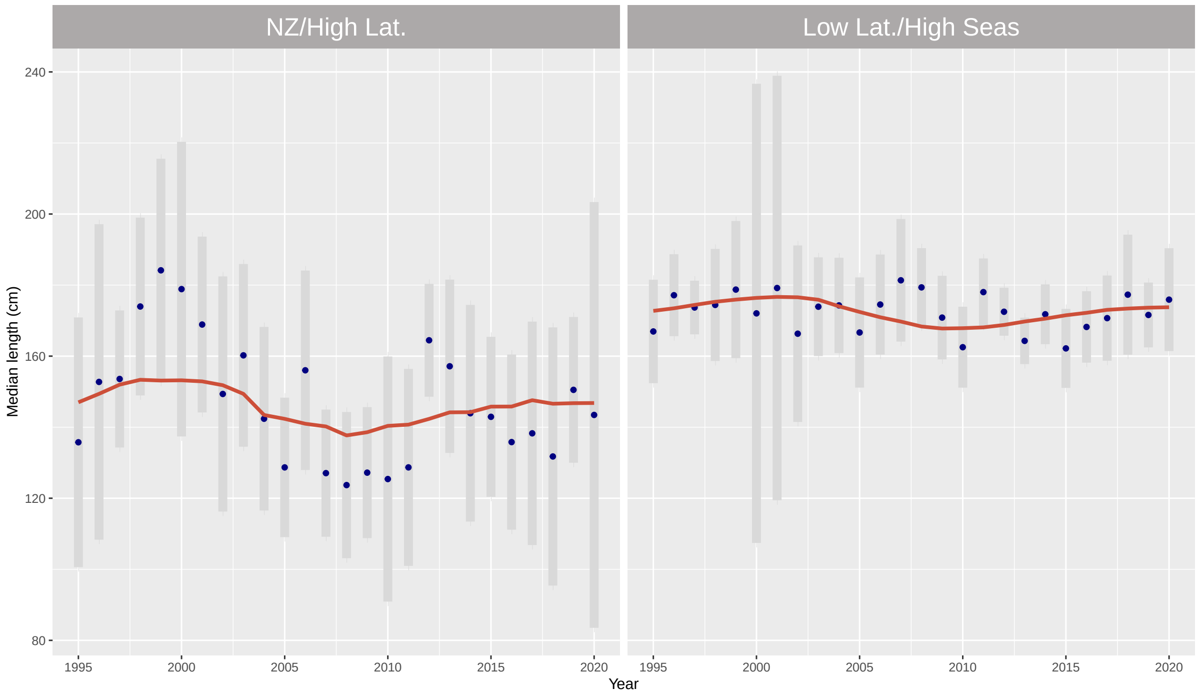

Figure 16: Temporal trend in the observed (navy points) vs. predicted (red line) catch-at-length for each fleet for the diagnostic case. The grey bands cover the 95% quantile range for the observations.

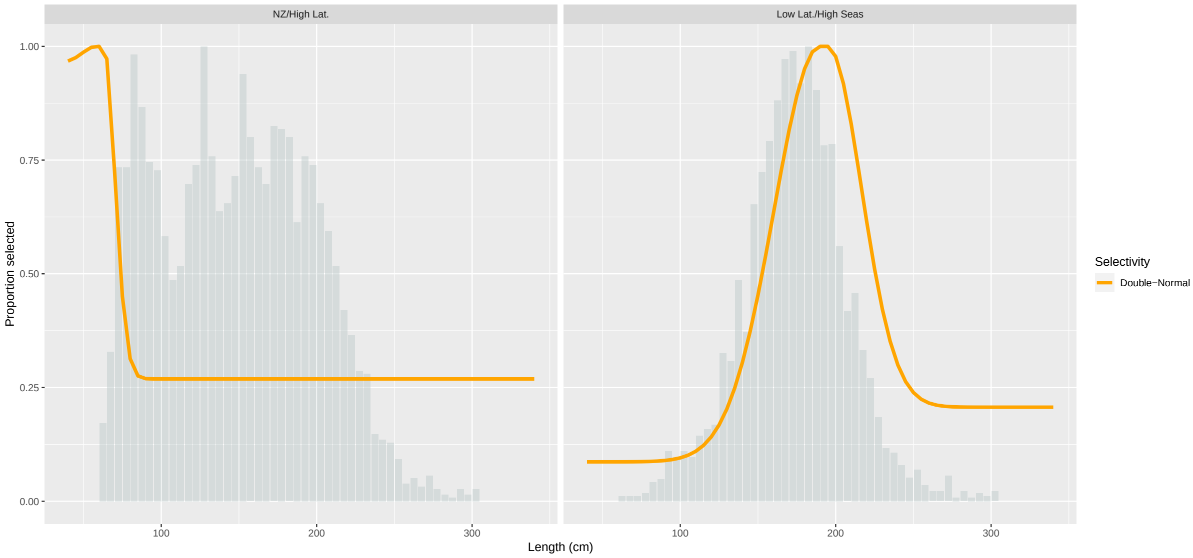

Figure 17: Observed (light blue bars) vs. predicted (coloured lines) catch-at-length for each fleet aggregated over all years under the double-normal size selectivity scenario.

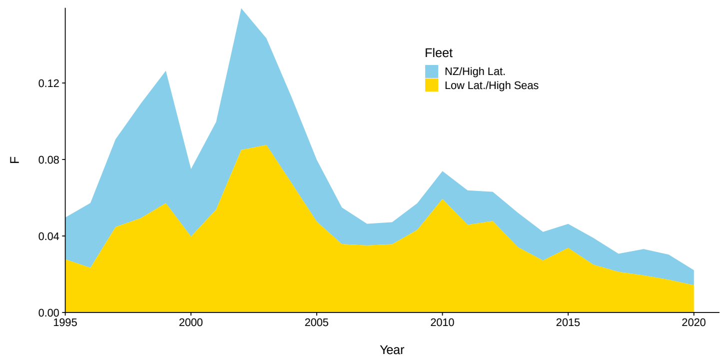

Figure 18: Fishing mortality by fleet estimated for the diagnostic case over the time-span of the assessment.

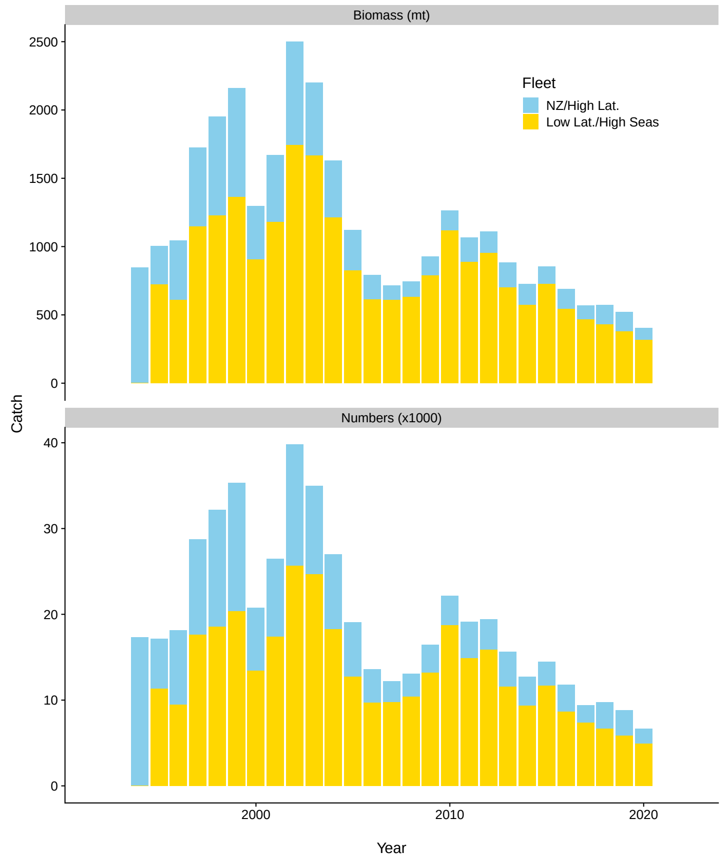

Figure 19: Catch by fleet in biomass and numbers.

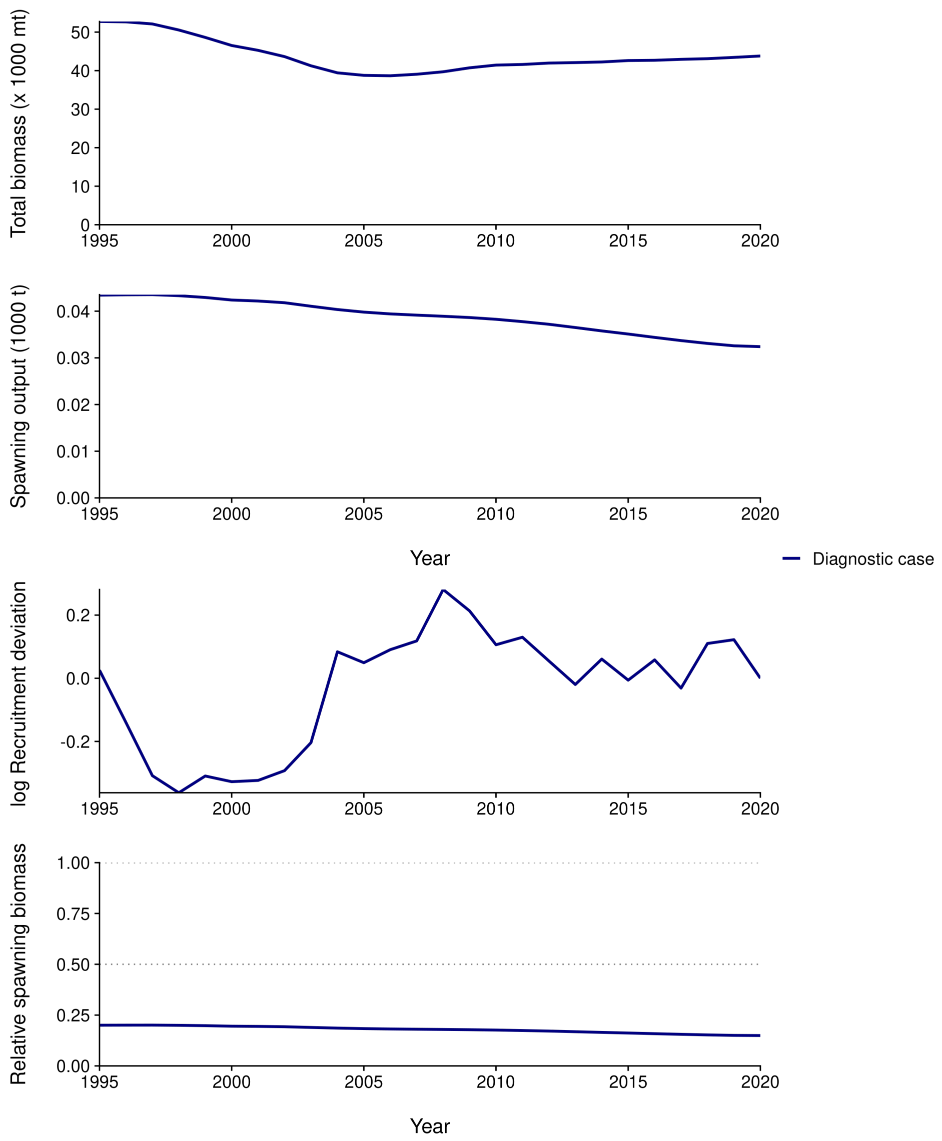

Figure 20: Total biomass, recruitment and spawning biomass for the diagnostic case estimated between 1995–2020.

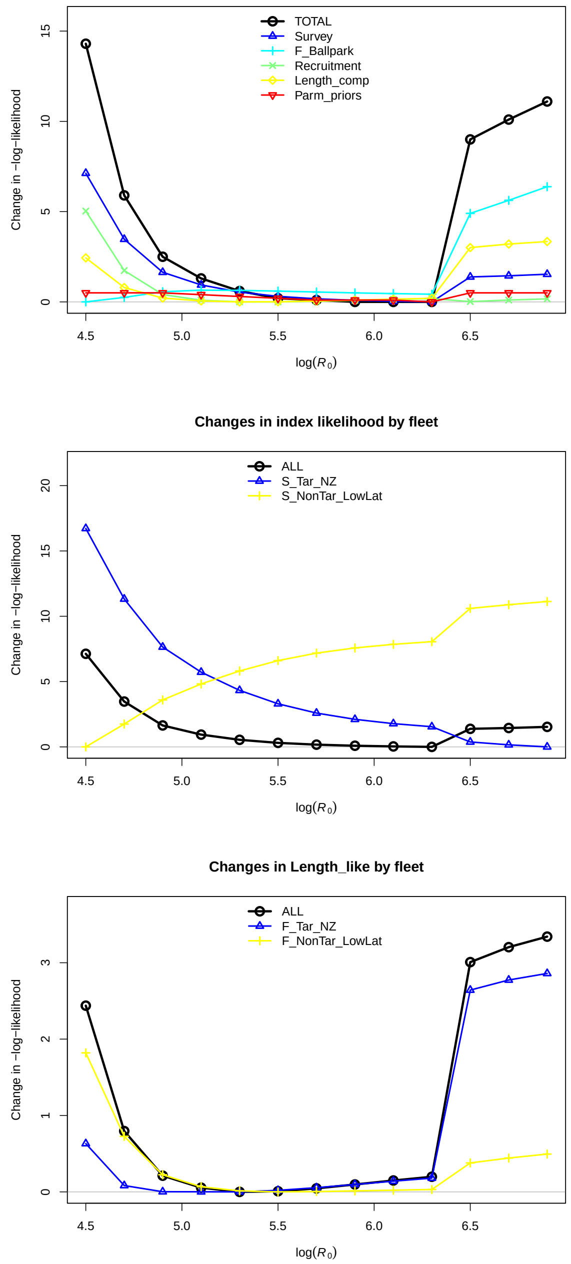

Figure 21: Relative change in log-likelihood for different values of $LN(R_0)$, for the total likelihood and contribution by each component (top), for the individual components by fleet for the CPUE (middle), and for the individual components by catch-at-length data (bottom)

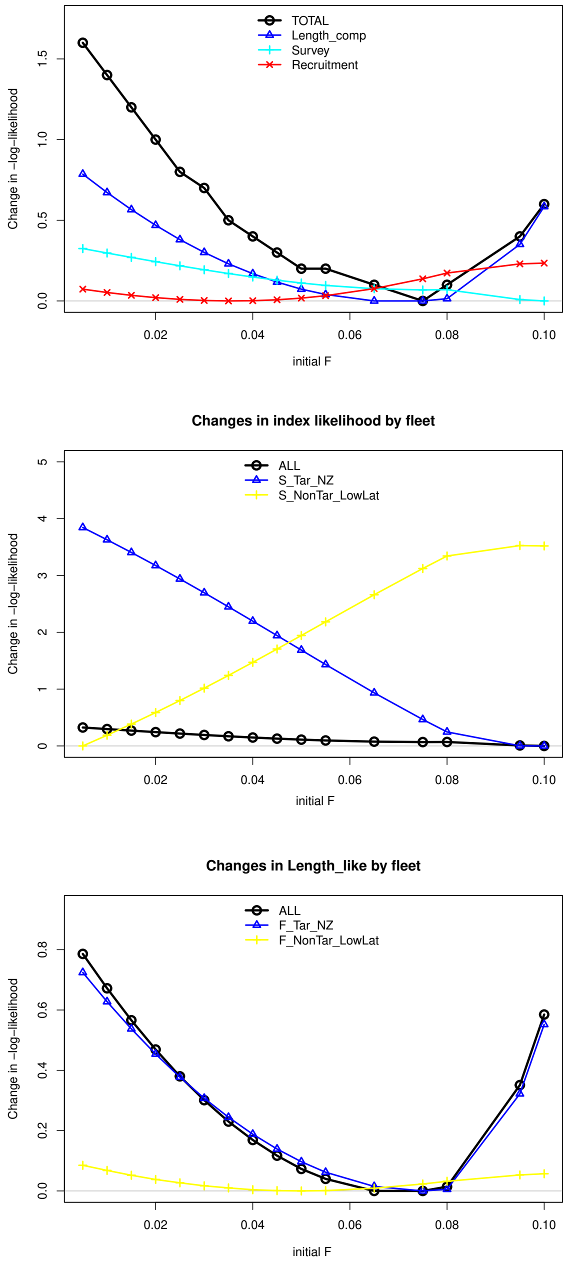

Figure 22: Relative change in log-likelihood for different values of $Initial\ F$, for the total likelihood and contribution by each component (top), for the individual components by fleet for the CPUE (middle), and for the individual components by catch-at-length data (bottom). Survey refers to the New Zealand CPUE and recruit refers to the low latitude CPUE.

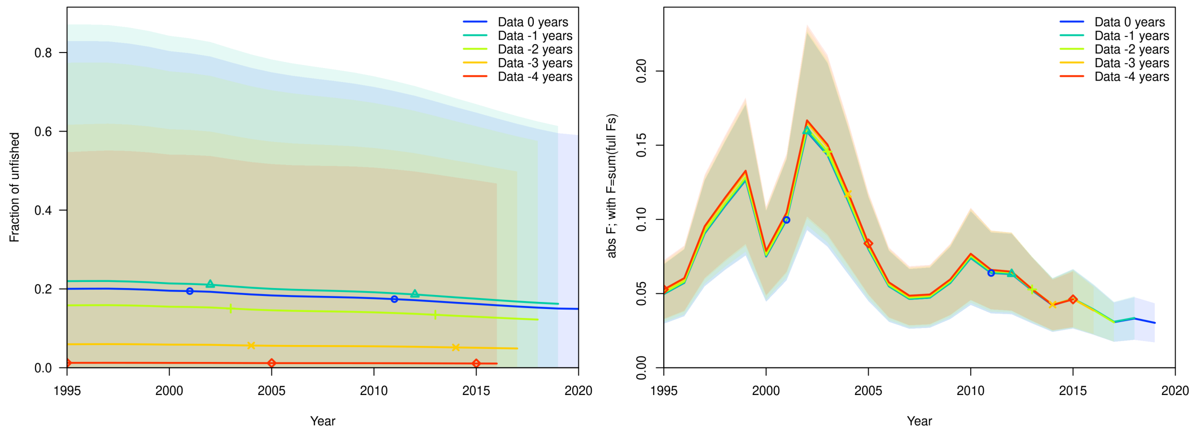

Figure 23: Retrospective patterns of spawning biomass and fishing mortality for the 2022 diagnostic case, compared with estimated uncertainty levels.

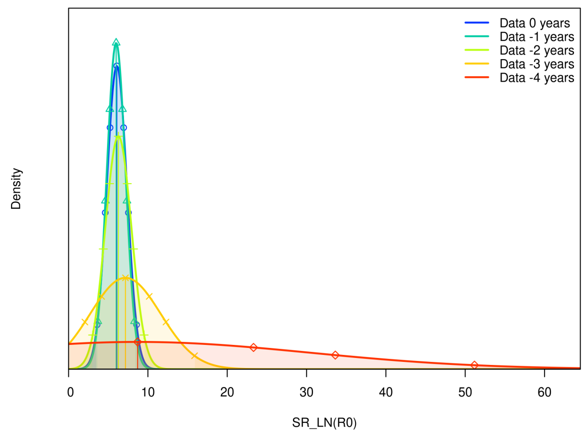

Figure 24: Retrospective patterns of estimated R_0 for the 2022 diagnostic case, compared with estimated uncertainty levels.

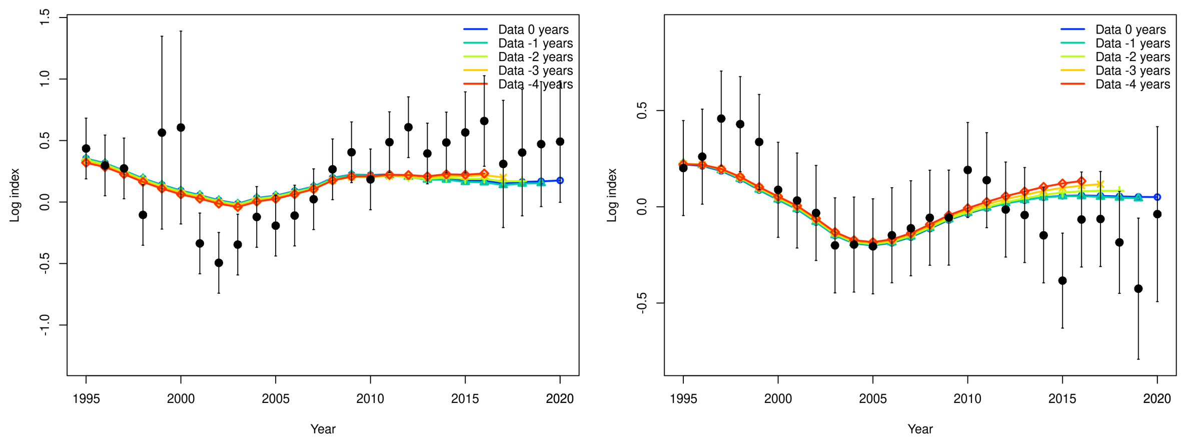

Figure 25: Retrospective patterns of fits to the high latitude (left) and low latitude (right) CPUE series for the 2022 diagnostic case, compared with estimated uncertainty levels.

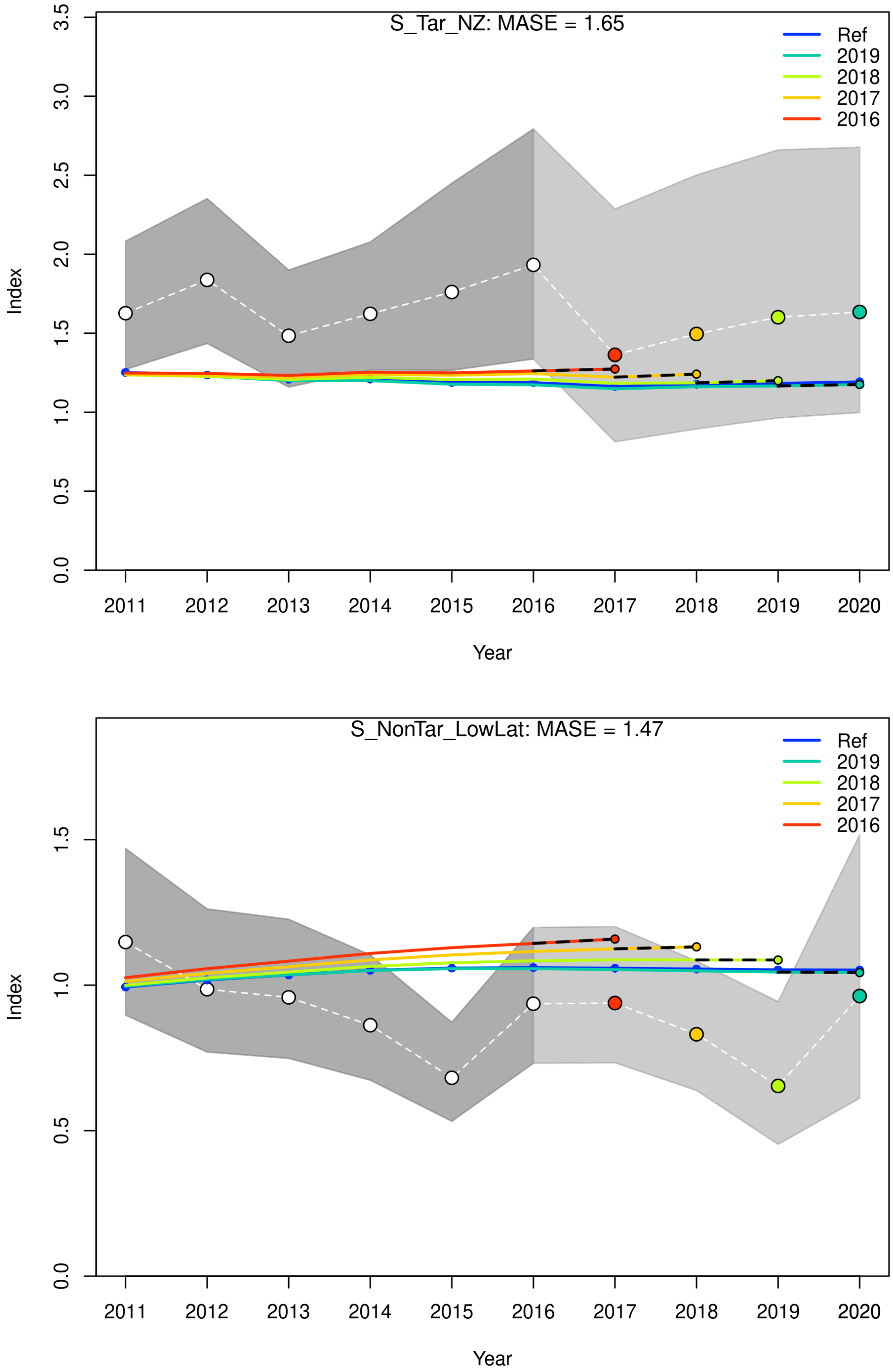

Figure 26: MASE for predictions from the model (coloured lines / points) relative to a naive prediction (blue) for the 2022 diagnostic case.

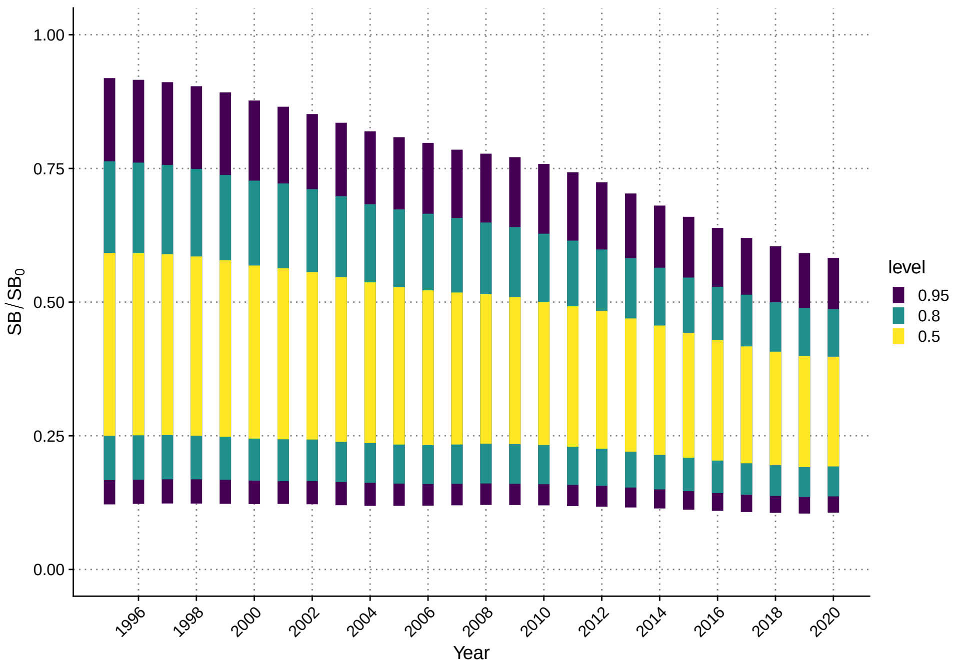

Figure 27: Posterior densities of stock status (SB/SB_O), with posterior percentiles indicated by the colour fill.

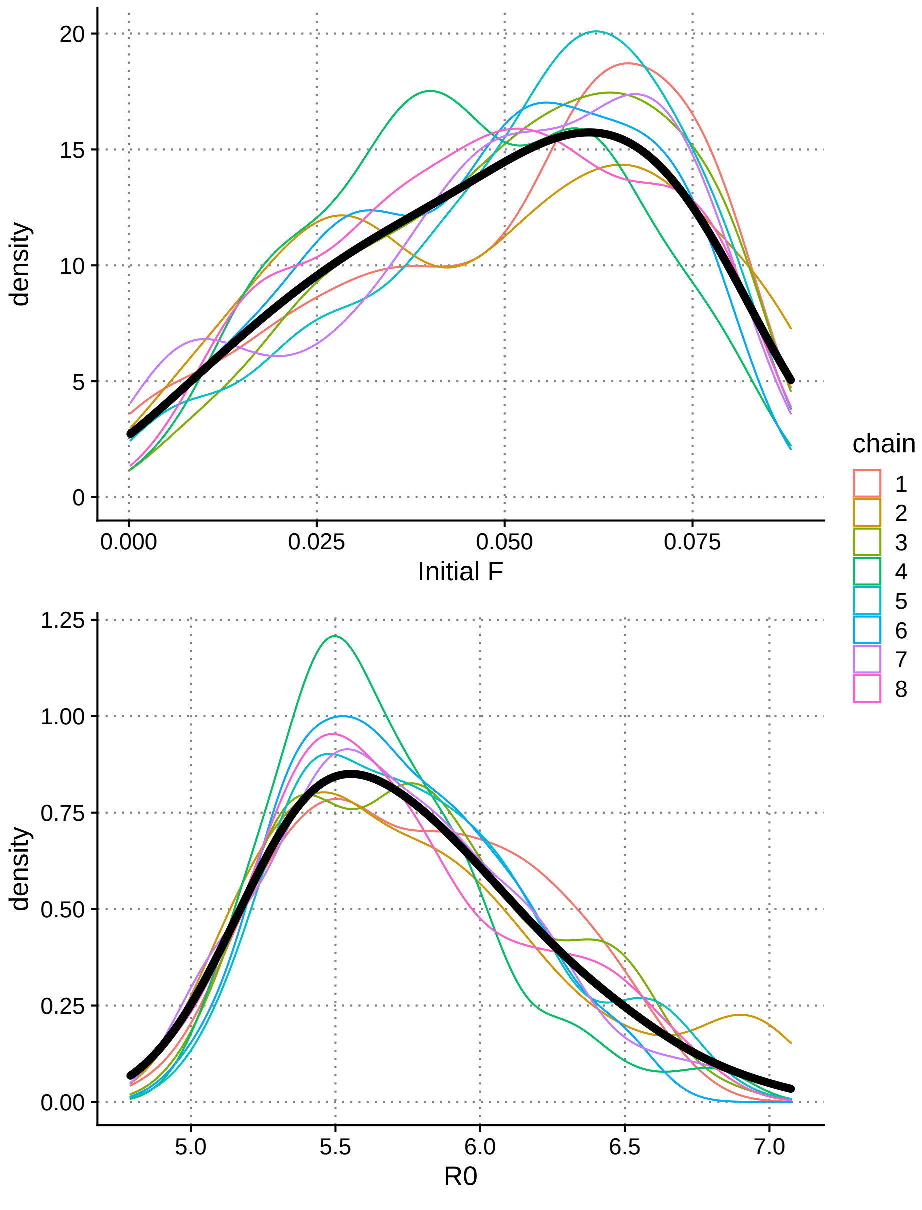

Figure 28: Posterior densities of R_O and initial fishing (black line), derived from 8 independent MCMC chains (coloured lines).

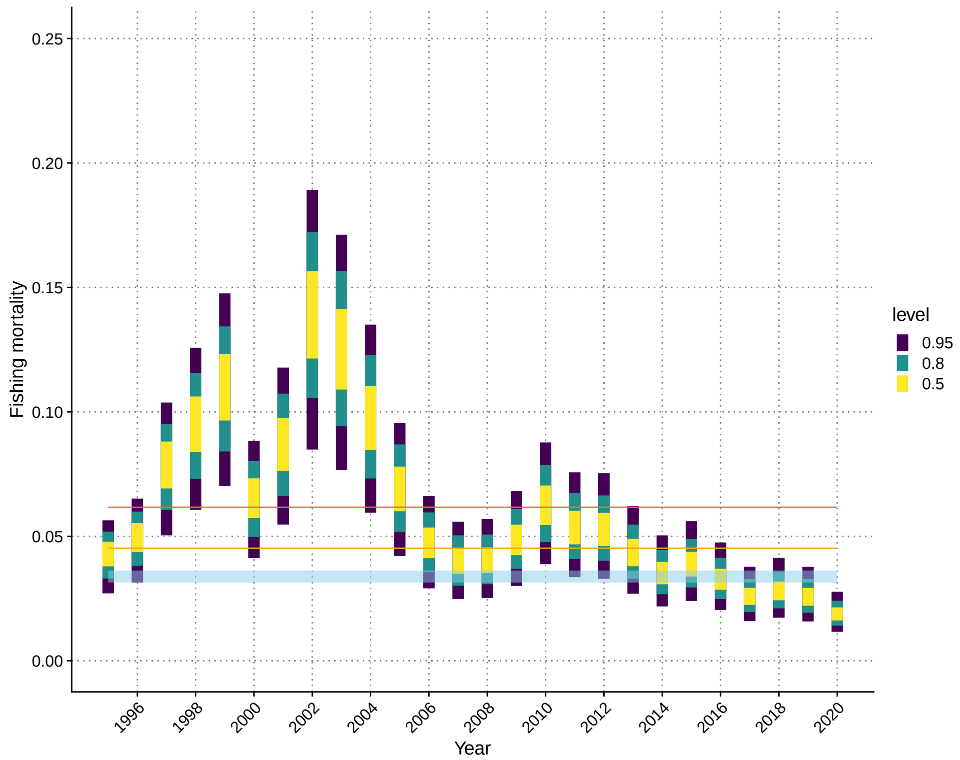

Figure 29: Posterior densities of Fishing mortality F, with posterior percentiles indicated by the colour fill. The posterior distribution of fishing mortality at MSY (F_{MSY}) is shown in blue, point estimates of $F_{lim,\text{AS}}$ and $F_{crash,\text{AS}}$ are given in orange and red, respectively.

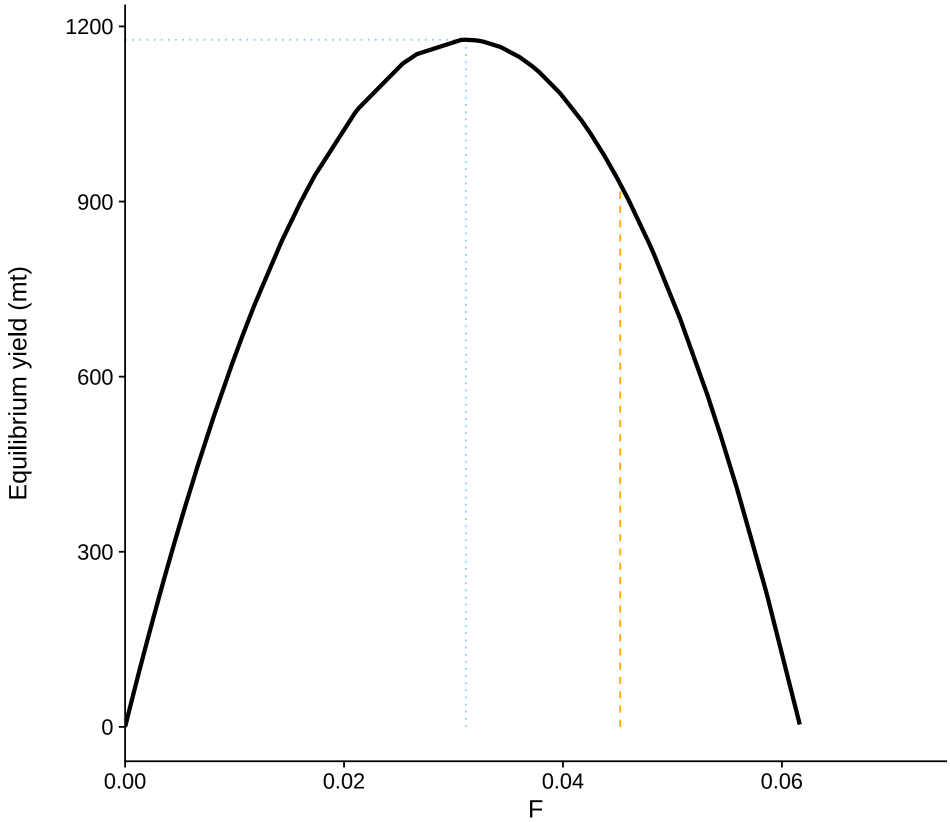

Figure 30: Yield profiles for Southwest Pacific shortfin mako shark for the diagnostic case model, with F_{MSY} indicated by dotted vertical lines, and $F_{lim,\text{AS}}$ shown as dashed lines.