Australia's National
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Eastern zone Orange Roughy (*Hoplostethus atlanticus*) stock assessment based on data up to 2020 DRAFT

OCEANS & ATMOSPHERE

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This document was internally reviewed by Professor André Punt and Dr Geoff Tuck.

Executive Summary

This document updates the 2017 eastern zone Orange Roughy stock assessment to include revised modelling assumptions and new data for 2020 using Stock Synthesis version 3.30.17. The 2017 eastern zone Orange Roughy assessment (Haddon 2017) and subsequent cross-catch risk assessment (Tuck et al. 2018) identified that the model is extremely sensitive to the assumed value of natural mortality (*M*). The objective of the 2021 assessment was to account for the uncertainty in *M* by estimating it within the assessment using an informative prior developed from New Zealand Orange Roughy assessments.

To provide inter-sessional review of the work the South East Resource Assessment Group (SERAG) established the Orange Roughy Steering Committee (ORSC) comprising Daniel Corrie, Mike Steer, Geoff Tuck, Paul Burch, André Punt, Andrew Penney, Matt Dunn (NIWA), Kevin Stokes and Simon Boag. The details of the development of the preliminary base-case assessment and its review by the ORSC, SESSFRAG and SERAG are described at the end of the Introduction to this report.

The 2021 base-case assessment updates the 2017 assessment with recent catch, relative estimates of female spawning biomass from the 2019 acoustic towed surveys at St Helens Hill and St Patricks Head, and new age composition data from the 2019 acoustic survey. Two major changes were made to the previous assessment, natural mortality is now estimated within the assessment and the plus group is increased from 80 to 120 years.

An initial Markov Chain Monte Carlo (MCMC) analysis identified that the estimated status is higher from the maximum posterior density (MPD) point estimate than that from MCMC's and this difference has an impact on the estimated Recommended Biological Catch (RBC). In addition uncertainty from the posterior of the width parameter of the logistic selectivity function was much higher than the asymptotic confidence intervals from the MDP. As SERAG does not have a formal procedure to choose between RBCs obtained from MPD and MCMC when both are available AFMA decided to convene the ORSC prior to the November 2021 SERAG meeting to review the MCMC analysis.

The ORSC evaluated the MCMC analysis and determined that the diagnostics suggested that the MCMC had converged and that the level of variability in the width parameter of the logistic selectivity was not extreme. The ORSC noted that while it was unusual that the median of the MCMC analysis did not correspond with the MPD, similar situations have occurred for Orange Roughy in New Zealand.

The ORSC advised that

1. The current MCMC analysis that estimates the width parameter of the logistic selectivity function should be retained,
2. The MCMC analysis should be used to provide advice in setting RBCs, not the MPD, and
3. Uncertainty in future stock status should be quantified using several constant catch projections.

The median estimate of unfished female spawning biomass from the MCMC analysis was 38,924 t, slightly lower than the MPD estimate of 40,479 t. The current 2022 female spawning biomass is estimated to be 11,644 t from the MCMC and 13,126 t from the MPD. Relative spawning biomass in 2022 is estimated at 30.0% of unfished levels from the MCMC and 32.4% of unfished levels from the MPD. Natural mortality was successfully estimated within the assessment. The median estimate of natural mortality from the MCMC analysis is M=0.0393 yr^{-1} , which is slighlty higher than the MPD estimate of M=0.0386 yr^{-1}.

The recommended biological catch (RBC) for 2022 from the MCMC analysis is 681 t, lower than the MPD estimate for 2022 of 944 t. The average RBC over the next three years (2022-2024) is 737 t from the MCMC analysis and 1,025 t from the MPD. There is a high level of uncertainty in the estimated RBC, with the 75% and 95% credible intervals from the MCMC analysis for the 2022 RBC being 287 – 1,316 t and 119 – 1,645 t respectively.

Additional projections are being undertaken to quantify the probability of falling below the limit reference point under different fixed catch scenarios and these should be available for review by SERAG at its November 2021 meeting.

Introduction

Biology

Orange Roughy (*Hoplostethus atlanticus*) are a long lived bentho-pelagic that inhabit deep waters 700-1300 m on the slope of the continental shelf and on seamounts. They feed on bentho- and mesopelagics, including prawns, fish and squid. Orange Roughy are long lived with maximum ages in excess of 150 years having been recorded. They reach a maximum length of 35-45 cm when they mature at around age 30. They form both spawning and non-spawning aggregations on seamounts where they are targeted by demersal trawling.

The stock structure of Orange Roughy in Australian waters remains uncertain. The 2021 eastern zone base-case assessment assumes the “combined” stock hypothesis of Wayte (2007), i.e., that the Eastern Zone (primarily St Helens Hill and St Patricks Head) and Pedra Branca from the Southern Zone form a single stock. Further details of Orange Roughy stock structure are provided below.

Previous Assessments

Early stock assessments of the eastern stock of Orange Roughy (Bax, 2000) used stock reduction analysis (Kimura et al., 1984) to generate plausible estimates of unfished biomass and current biomass and then considered the outcome of projecting the modelled stock forward under different catch scenarios. In the early 2000s stock assessments that used relatively simple age-structured stock assessment models that were fitted using maximum likelihood methods and Bayesian approaches were developed (e.g., Wayte and Bax 2002). From 2006, fully integrated stock assessments using the Stock Synthesis software were conducted in 2006, 2007 and 2011, though their structure remained relatively simple (Wayte 2006, 2007, Upston and Wayte 2011).

In May 2014, prior to the 2014 eastern zone Orange Roughy assessment, a workshop was held in Hobart with the objectives of resolving the issue of differing biomass estimates from the acoustic optical surveys and the stock assessment and provide advice on appropriate reference points for eastern zone Orange Roughy (AFMA 2014). The 2014 assessment was then undertaken with informative priors developed for the acoustic biomass surveys based on the methods discussed during the workshop (Upston et al 2015).

The 2017 eastern zone Orange Roughy assessment (Haddon 2017) and subsequent cross-catch risk assessment (Tuck et al. 2018) identified that the assessment results are extremely sensitive to the assumed value of natural mortality (M).

Approach for the 2021 Assessment

In 2020, following a request from the Australian Fisheries Management Authority (AFMA), the South East Resource Assessment Group (SERAG) discussed the uncertainty surrounding the estimate of M used in the most recent stock assessment of eastern zone Orange Roughy and how to accommodate the uncertainty in M within the 2021 assessment. At its November 2020 meeting, SERAG requested CSIRO develop a robust process for estimating M for the 2021 eastern zone Orange Roughy stock assessment for review. CSIRO proposed estimating M within the assessment using an informative prior for *M* developed using an updated version of the combined posterior for *M* for New Zealand Orange Roughy stock assessments (Cordue 2014). SERAG supported the proposed process but also wanted to ensure that there was a viable alternative available should the proposal to estimate *M* fail.

The Orange Roughy Steering Committee (ORSC) comprising Daniel Corrie, Dan Hogan, Mike Steer, Geoff Tuck, Paul Burch, André Punt, Andrew Penney and Matt Dunn (NIWA) was established to provide inter-sessional review of the work. Prior to the August 2021 meeting of the ORSC Kevin Stokes joined the ORSC and Dan Hogan was replaced by Simon Boag as the industry representative.

To address the potential failure of estimating *M* it was proposed to use a decision table with alternate states of nature and management actions (e.g. Tuck et al. 2018). The work plan, developed in consultation with the ORSC, was:

1. Undertake a bridging analysis to update the 2017 assessment with the most recent data on catch, age and survey index of abundance.
2. Calculate likelihood profiles for *M* (noting the likelihood profile for *M* will be wider than the distribution for *M* estimated by the assessment, which is constrained by an informative prior) and steepness (*h*) to provide the ORSC with information to choose values of *M* and *h* for the decision table.
3. Review the Pacific Fishery Management Council terms of reference and identify a potential approach for identifying the values for *M* and *h* that correspond to a 90% confidence bound for the proposed cross-catch risk assessment.
4. Develop a process for constructing an informative a prior for *M*.

Following review by the ORSC to discuss the updated assessment, likelihood profiles and proposed parameters for the cost-catch risk assessment the assessment would proceed using the agreed data and methodology.

Review by SESSFRAG March 2021

The Southern and Eastern Scalefish and Shark Fishery Resource Assessment Group (SESSFRAG) reviewed the above proposal at its March 2021 Chairs Meeting. The key points and recommendation from the minutes of the SESSFRAG meeting are reproduced below, with some additional clarification provided in brackets.

- *Several meeting attendees raised concerns with using a decision table to select values of M, with their view being that this is a more risky approach than using a model or likelihood profiles [the proposed approach is not planning to use a decision table to select M].*
- *Concerns were also raised regarding previous decisions relating to the selection of M, with the value determined through a likelihood profile, not being used in the assessment; and instead opting for an 'assumed' value, determined through a comparison of Australian and New Zealand orange roughy stocks. It was noted that this occurred due to procedural issues, resulting from an alternate base case not being provided with sufficient time prior to the RAG meeting; and the level of impact of the value of M (determined through likelihood profile) on the assessment.*
- *It was emphasised that the process for selecting M needs to be clearly identified, to ensure that the value of M is selected based on the best available science.*

SESSFRAG recommended that the eastern zone Orange Roughy 2021 stock assessment proceeds using the agreed data, to attempt to estimate *M* using an informative prior, with the fall back approach being the construction of a decision table with alternate states of nature and management actions, using the agreed values of *M* and *h*; with a progress update to be provided to the SESSFRAG Data Meeting (August 2021).

Advice from Orange Roughy Steering Committee August 2021

The ORSC met via video conference on Friday 13 August 2021 to review a draft of the preliminary base-case assessment report (Burch and Curin-Osorio 2021) that included an updated preliminary base-case model with fixed natural mortality of M=0.04 yr^{-1}, likelihood profiles for *M* and *h* and proposed parameters for a decision table with alternate states of nature and management actions.

During the development of the preliminary base-case with fixed *M*, a small number of changes and corrections were made to the data used in the 2017 assessment, these were:

- Catches for 2015 and 2016 were updated from 460.4 t and 360 t respectively to 457.3 t in 2015 and 384.5 t in 2016.
- The model used to estimate ageing error for 2017 assessment had not fully converged so the ageing error matrix was updated.
- The priors and intial values for the two acoustic surveys and the fixed value of the egg survey were rounded to two decimal places in the Stock Synthesis input files of the 2014 and the 2017 assessments. The update increased the number of decimal places to nine.
- The fixed value of the standard deviation of recruitment (σ_R) was reported as 0.58 in Haddon (2017). However, σ_R was set to 0.7 in the assessment model.

The preliminary base-case assessment model with fixed *M* of 0.04 yr^{-1} was developed by adding each of these model changes and data streams sequentially to the previous final base-case assessment model (Haddon 2017) to identify the effect of each new source of information using a formal bridging analysis. Data weighting (tuning) was then applied, and likelihood profiles for *M* and *h* were produced.

The bridging of the 2017 assessment to produce a preliminary base-case assessment with fixed *M of* 0.04 yr^{-1} was supported by the ORSC with the following recommendations:

1. There are currently 80 age-classes in the assessment, with the maximum age-class treated as a plus group that comprises 5-9% of individuals in age samples for earliest years with age data. This may result in bias when *M* is estimated and increasing the number of age-classes in the assessment to 100 and 120 should be explored.
2. Undertake a sensitivity removing the 1992 egg survey.
3. Correct the retrospective analysis to estimate fewer years of recruitment deviations (year classes) when sequentially removing data from the assessment in each year. The retrospective analysis in the draft report did not reduce the number of estimated recruitment deviations, which is incorrect.
4. Age-specific maturity and selectivity should be plotted in the same figure to identify the magnitude of the difference between maturity and selectivity.

The ORSC discussed the process of estimating *M* using an informative prior and supported the approach of using an updated prior for *M* that uses the most recent available assessments for New

Zealand Orange Roughy assessments for ORH 2A+2B+3A, ORH 3A (NWCR), ORH 3B (ESCR), ORH (Puysegur). The prior has been updated by Patrick Cordue as part of the submission for the extension of Marine Stewardship Council certification for New Zealand Orange Roughy in the ORH 3B region but is not yet publicly available. The ORSC noted the following:

- The prior of Cordue (2014) is relatively uninformative between plausible values of *M* for Orange Roughy (M=0.03 yr^{-1} - M=0.045 yr^{-1}).
- The Cordue prior assumes the data and model assumptions of the New Zealand Orange Roughy assessments are correct. Any bias in the New Zealand Orange Roughy assessments would likely be reflected in the prior.
- There was a discussion of how the relative weighting of the biomass indices and the age data in the assessment could potentially influence the estimation of *M*. Francis weighting gives more weight to the biomass indices, that suggest a lower *M*, and less weight to the age data that suggest a higher *M*. Francis weighting is the current best practice utilised across all SESSF stock assessments. The ORSC did not suggest that the 2021 assessment move away from this practice.

The ORSC discussed the construction of a decision table to be used to provide advice for setting eastern zone Orange Roughy TACs should the process to estimate *M* with an informative prior fail. The ORSC noted that it was important to develop a consistent approach for constructing decision tables to reduce the potential for confusion and that ideally a decision table would have a small number of states of nature and management actions. They also noted that a decision table should contain the mean or the median of the parameter of interest and be bounded by an even amount to each side. The ORSC recommended that;

- The decision table with five values of *M* taken from the 5%, 12.5%, 50%, 87.5% and 95% quantiles (90% and 75% bounds) from the likelihood profile on *M* and that a small number of sensible catch scenarios be chosen to reduce the complexity of the table.
- There was no information in the likelihood profile to inform the steepness of the stock recruitment relationship (*h*). The decision table for eastern zone Orange Roughy should be based on a fixed value of h=0.75 for all scenarios. The impact of varying *h* should be explored as a sensitivity to the base-case assessment. The cross-catch risk assessment of Tuck et al. (2018) used a fixed value of steepness (h=0.75) with two potential values of *M* and three catch series.

The advice from the ORSC was presented to the August 2021 SESSFRAG Data Meeting and it agreed the process recommended by the ORSC for undertaking the eastern Orange Roughy Tier 1 stock assessment and decision table be adopted.

Preliminary base-case assessment

Four candidate preliminary base-case assessments were presented to SERAG in October 2021. These were the model with fixed *M* of 0.04 yr^{-1} that was presented to the ORSC and three models that estimated *M* using an informative prior based on New Zealand Orange Roughy assessments with plus groups at 80 (the default from previous assessments), 100 and 120 years.

Criteria to select the number of age-classes were determined based on discussions with André Punt (CSIRO and University of Washington) and Matt Dunn (NIWA). The plus group (number of age-classes) should be chosen so that:

1. The proportion of individuals in the plus group is small and
2. The number of age-classes with no individuals in them is small.

SERAG was then asked to select the base-case assessment based on the ability of the model to estimate *M* and inspection of the fits to the age and index data.

The posteriors for *M* from the three candidate preliminary base-case assessments that estimated *M* showed that *M* was being well estimated, with the range of plausible values for Orange Roughy of M=0.03 yr^{-1} - M=0.045 yr^{-1} (Figure A1). The fits to biomass indices and the age data for the three candidate preliminary base-case assessments that estimated *M* were very similar to those of the model with fixed natural mortality of M=0.04 yr^{-1} and SERAG endorsed the estimation of natural mortality within the assessment.

The models with plus groups at 100 and 120 years had slightly better fits to the age data and there was no discernible change in the fits to the acoustic biomass indices, suggesting that the number of age-classes in the assessment should be increased above 80. Distinguishing between the models with plus groups at 100 and 120 years was challenging however, because there was little difference in the fits to the age data between the two models and both models had a small proportion of individuals in the plus group and a small number of age-classes with no individuals, at least for the early age samples. As there was no evidence to reject the model with the higher plus group, SERAG decided to choose the model with a plus group at 120 years as the base-case for the 2021 assessment.

SERAG decided that a decision table with alternate states of nature and management actions would not be required to limit the amount of work required and scenarios presented. The uncertainty in model outputs will be appropriately characterized using a Bayesian posterior based on MCMC sampling, with model sensitivities undertaken using fixed natural mortality values chosen as the 12.5% and 85% quantiles from the posterior of *M*.

Advice from Orange Roughy Steering Committee November 2021

In the preparation of the final assessment report it was identified that the estimated status is higher from the maximum posterior density (MPD) point estimate than that from MCMC's and this difference is enough to have an impact on the estimated Recommended Biological Catch (RBC). In addition uncertainty from the posterior of the width parameter of the logistic selectivity function was much higher than the asymptotic confidence intervals from the MDP (Figure 15). As SERAG does not have a formal procedure to choose between RBCs obtained from MPD and MCMC when both are available AFMA decided to convene the ORSC prior to the November 2021 SERAG meeting to review the MCMC analysis.

The ORSC evaluated the MCMC analysis and determined that the diagnostics suggested that the MCMC had converged (although the results needed to be checked because it appeared the burn-in may have been included) and that the level of variability in the width parameter of the logistic selectivity was not so extreme as to suggeset that parameter should be fixed in the model. The ORSC noted that while it was unusual that the median of the MCMC analysis did not correspond with the MPD, similar situations have occurred for Orange Roughy in New Zealand.

The ORSC advised that

1. The current MCMC analysis that estimates the width parameter of the logistic selectivity function should be retained,
2. The MCMC analysis should be used to provide advice in setting RBCs, not the MPD, and
3. Uncertainty in future stock status should be quantified using several constant catch projections.

Methods

Model Structure

The 2021 stock assessment for Eastern Zone Orange Roughy (*Hoplostethus atlanticus*, Collett 1889) uses an integrated stock assessment model implemented using Stock Synthesis 3.30.17 (Methot and Wetzel 2013). As in the previous two assessments, it assumes a stock structure that combines the Eastern Zone (primarily St Helens Hill and St Patricks Head) and Pedra Branca from the Southern Zone (Table 1, Figure 1). New data included since the previous stock assessment (Haddon 2017) are recent catches, relative estimates of female spawning biomass from the 2019 acoustic towed surveys at St Helens Hill and St Patricks Head, and new age-composition data from the 2019 acoustic survey. Additional recruitment residuals were also estimated. Two major changes were made to structure of the assessment from previous assessments they are;

1. the assessment uses a plus group at 120 years (an increase from a plus group at 80 years that was used previously), which also required the ageing error matrix to be re-estimated for 120 ages and,
2. *M* is estimated within the assessment using a log-normal prior developed from the most recent available assessments for New Zealand Orange Roughy stock assessments for ORH 2A+2B+3A, ORH 3A (NWCR), ORH 3B (ESCR), ORH (Puysegur) and ORH 7A. Previous assessments have assumed a fixed *M* of 0.04 yr^{-1}.

The process of updating the model from the 2017 base-case to the 2021 base-case model, including increasing the number of age classess within the model and the estimation of *M* within the assessment is described in preliminary base-case report (Burch and Curin Osorio 2021). The data and assumptions used in the 2021 base-case assessment are described in more detail below.

Stock Structure

Five stock structure hypotheses have been used in past assessments of Eastern Zone Orange Roughy (Table 1). Model scenarios corresponding to these stock structure hypotheses were tested and reported on in the 2006 preliminary eastern zone assessment (Wayte 2006) and results of these scenarios did not differ greatly from each other. The 2021 eastern zone base-case assessment assumed the “combined” stock hypothesis of Wayte (2007), i.e., that the Eastern Zone (primarily St Helens Hill and St Patricks Head) and Pedra Branca from the Southern Zone form a single stock.

The reasoning behind the “combined” stock structure hypothesis is reproduced below from Wayte (2007).

Early analysis of otolith shape data by the Central Ageing Facility indicated that Orange Roughy caught in the spawning aggregation at St. Helens in the winter were not distinguishable from those caught in the Southern Zone for the rest of the year, but were different from those caught in the Eastern Zone outside the time of the spawning aggregation, and were different from those caught in the Southern Zone in winter. This implied that spawning Eastern Zone Orange Roughy and Southern Zone non-spawning Orange Roughy may comprise a common stock, which is distinct from an eastern non-spawning and southern winter caught ‘stock’. A subsequent analysis was less clear and reviewers have questioned the statistical approach used.

Observations from fishers and processors suggested that Orange Roughy schools from Maatsuyker are part of a west coast Tasmania 'stock', while the Pedra Branca schools are part of the combined stock. Fishers' observed little interchange of pelagic Orange Roughy schools between Pedra Branca and Maatsuyker, while processors suggested that fish from the two areas are morphologically distinct. Maatsuyker is on the western slope of the seabed continuation of Tasmania, while Pedra Branca is on the east.

Overall this evidence and earlier studies of stock structure based on parasites, genetics and otolith microchemistry have been inconclusive on whether Orange Roughy around Tasmania comprise one or several stocks. Only one substantial winter spawning aggregation (St Patricks and St Helens Hill) has been found and only one large consistent summer aggregation has been fished (Southern Zone main Maatsuyker and Pedra Banca). Low levels of spawning have been detected elsewhere and an analysis of catch data shows elevated winter catches in the Far Western Zone. The hypothesis that includes all Orange Roughy in the SEF (with the exception of the Cascade Plateau) as one stock is included on the recommendation of the 2002 review of the stock assessment.

Table 1. Stock structure hypotheses for Eastern, Southern and Western zone Orange Roughy. Reproduced from Wayte (2007).

Stock hypothesis	Description	Catch data required
East	All Orange Roughy in Eastern Zone, spawning and non-spawning	Total Eastern Zone catch (all months)
2002 Combined	Eastern Zone spawning Orange Roughy and Pedra Branca non-spawning Orange Roughy	Eastern Zone winter catch (June - August) and Pedra Branca non-winter catch (all months except June - August)
Combined[1]	All Eastern Zone and Pedra Branca Orange Roughy	Total Eastern Zone catch (all months) and Pedra Branca catches (all months)
East + South	All Orange Roughy in Eastern and Southern zones	Total Eastern Zone catch and total Southern Zone catch (all months)
East + South + West	All Orange Roughy in Eastern, Southern and Western zones	Total Eastern Zone catch and total Southern Zone catch and total Western Zone catch (all months)

[1] Used as the base-case stock hypothesis for the eastern zone Orange Roughy assessment since Wayte (2007).

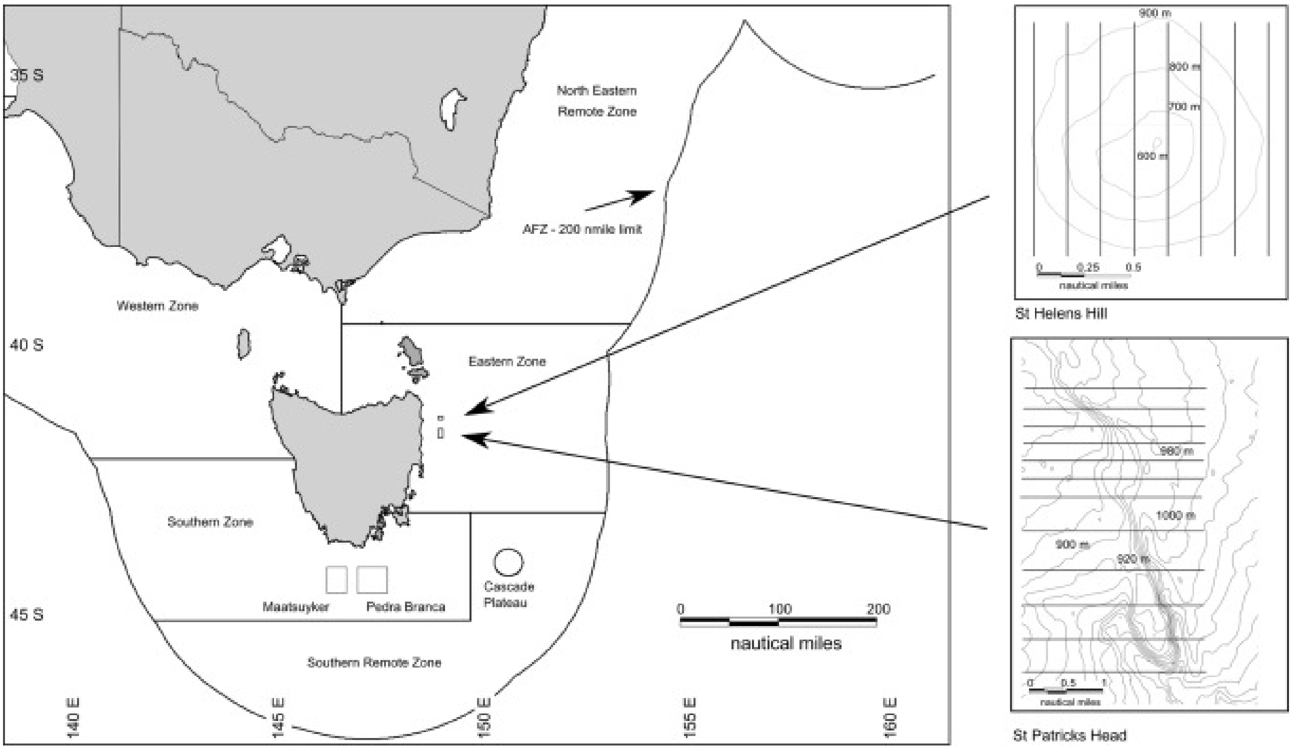


Figure 1. Map of Australian Orange Roughy management zones and areas.

Biological Parameters

No changes have been made to the pre-specified biological parameters used in the 2017 assessment. However, the fixed value for recruitment variability (σ_R) is now correctly reported as 0.7 (see Table 2 for a summary of the fixed and estimated parameters).

Male and female Orange Roughy are assumed to have the same biological parameters except for their length-weight relationship. In the absence of representative length data, none of the four parameters relating to the Von Bertalanffy growth equation are estimated within the model-fitting process. Maturity is modelled as a logistic function of length, with 50% maturity at 35.8 cm. The assumption is made that the maturity would approximately match fishery selectivity as estimated on the spawning aggregations (which are assumed to consist of mature animals). Fecundity-at-length is assumed to be directly proportional to weight-at-length, which is important for the estimation of the Spawning Potential Ratio, which can act as a proxy for fishing mortality; a requirement for the determination of stock status.

The length-weight relationship of spawning fish caught during AOS surveys at St Helens Hill and St Patrick Hill over the last decade is different than that assumed in the base-case assessment, with fish now being around 10% heavier (Kloser and Sutton 2020). This may indicate a change in the condition of spawning fish off the east coast of Tasmania. Prior to the next eastern zone Orange Roughy stock assessment, it is recommended that the length-weight relationship and other pre-specified biological parameters be re-estimated with recent data to evaluate whether they may have changed, with any changes to be incorporated into the next assessment.

Table 2. The pre-specified model parameters used in the 2021 base-case assessment.

Fixed parameters	Values		Source
Recruitment steepness, h	0.75		Annala (1994) cited in CSIRO & TDPIF (1996)
Recruitment variability , σ_R	0.7		
Maturity logistic inflection	35.8 cm		Upston et al (2015)
Maturity logistic slope	-1.3 cm^{-1}		Smith et al. (1995)
Von Bertalanffy K	0.06 yr^{-1}		Smith et al. (1995)
Length at 1 year Female	8.66 cm		
Length at 70 years Female	38.6 cm		
Length-weight scale, a	3.51×10^{-5}	Female	Lyle et al. (1991)
	3.83×10^{-5}	Male	
Length-weight power, b	2.97, 2.942	Female Male	Lyle et al. (1991)
Plus-group age (years)	120		
Length at age CV for age 1	0.07		Estimated from data
Length at age CV for age 70	0		Expected offset from young
q egg survey catchability	0.9		Bell et al. (1992), Koslow et.al (1995), Wayte (2007)

Data

The data sources included in the eastern zone Orange Roughy assessment are catch (including discards), three indices of abundance (the egg survey estimate treated as an estimate of absolute abundance, and the two sets of acoustic biomass estimates treated as relative abundance indices) and age-composition data from the acoustic surveys and on-board sampling. A summary of the time periods of the data for the 2021 assessment is provided in Figure 2.

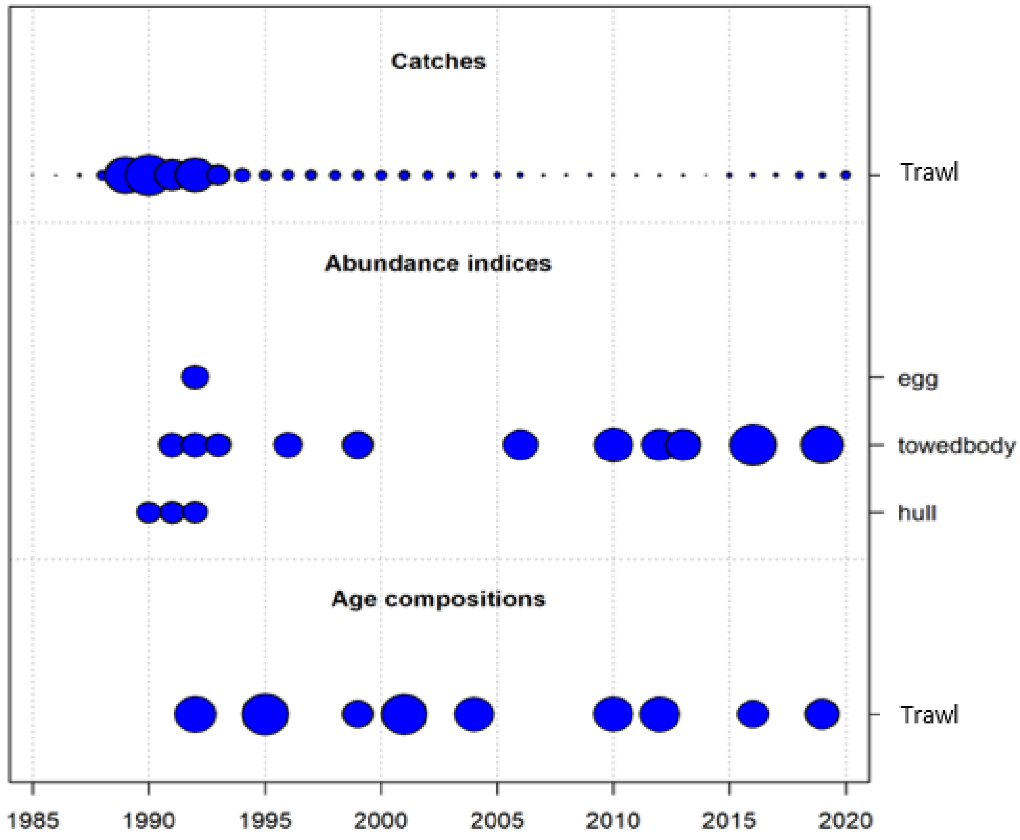


Figure 2. Data availability for the eastern zone Orange Roughy assessment by type and year.

Catch

The assessment uses the agreed catch history series from the 2014 assessment (Upston et al 2015, originally compiled by Wayte 2007) and updates the landed catches for 2015 – 2020 using logbook and catch disposal records (CDRs; Figure 3, Table 3). The agreed catch history adjusted the reported catches as a result of estimates of burst bags and other initially unreported catches. Wayte (2007) provides details about how the catches from 1989–1994 were adjusted for the five stock structure hypotheses. The "combined" stock hypothesis uses all catches from the Eastern Zone and catches from Pedra Branca in the Southern Zone (Table 1).

The agreed catch history that is used in the base-case assessment for the early years of the fishery is reproduced below from Wayte (2007).

The Eastern Zone catches have been adjusted for under-reporting in 1992, mis-reporting in 1993, and general losses in 1989-1994. It is believed that reported catches in 1992 were 55% of actual catches, so catches in this year were increased accordingly. In 1993, Eastern Zone catches were misreported as Southern zone catches. To estimate the level of this misreporting, reported Southern Zone winter (June –August) catches for each of the years 1989-1992 and 1994 were calculated as the proportion of total reported Eastern and Southern zone catches in those years. The total Southern and Eastern zone catch in 1993 was multiplied by the mean of these proportions to estimate actual Southern Zone winter catch. Reported 1993 Southern Zone catch above this estimate was assumed to have been caught in the Eastern Zone. These calculations resulted in 2,665 t being transferred from the Southern Zone catch total to the Eastern Zone catch total in 1993.

Other adjustments were made for burst bags, lost gear and burst panels. It was assumed, based on discussions with operators, that 30% of the total fish caught were lost in 1989 and 1990, 20% lost in 1991, and 10% lost in 1992, 1993 and 1994. The reported catches were increased accordingly. A catch series with half the value of these proportions lost was also calculated (based on different industry participants views). Assessments undertaken in 2006 using this alternative catch series gave very similar results to the other catch series (Wayte 2006).

Orange Roughy stock structure hypotheses and historical catches were reviewed at a workshop between AFMA, CSIRO, industry representatives and New Zealand scientists, held in Hobart in May 2014 (AFMA 2014). The workshop concluded that it is unlikely to be able to improve on the previously agreed catch time series but may still be worth examining the assessment implications of different catch histories on stock assessments.

The quota year was changed in 2007 from calendar year to the year extending from 1 May to 30 April. The assessment, however, continues to be conducted according to the calendar year as most catches occurred prior to 2007.

Discarded catches were estimated for the period 2015–2020 from discard weight observations obtained by onboard observers using the method of Bergh et al (2009) as implemented in Deng et al (2020). Discarded catch estimates prior to 2015 have been incorporated in the agreed catch history under the assumption that discarding occuring randomly with respect to length and age.

Total removals for 2021 are assumed to be the same as the 2020 removals. Sensitivities are undertaken using estimated total removals for 2021 (obtained from AFMA on 25 October 2021) and the agreed 2021 TAC of 1569.4 t.

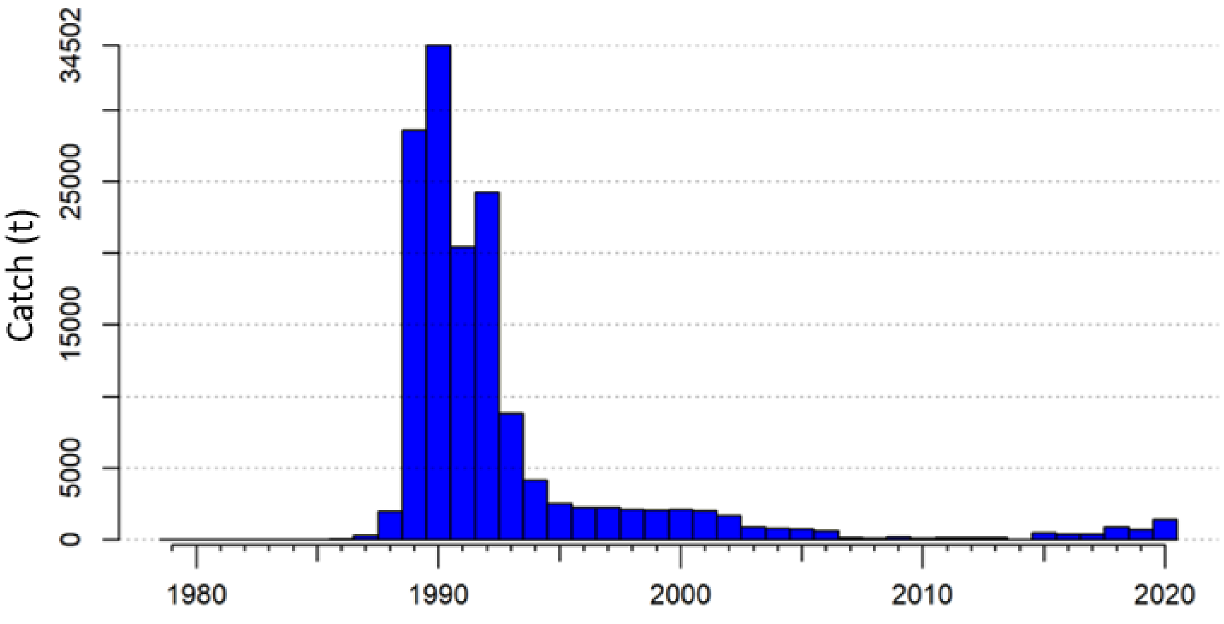


Figure 3. Catch, including discards, for the eastern zone Orange Roughy assessment. Catches for 1989 – 1994 incorporate adjustments for the proportion lost due to lost gear and burst bags/ burst panels, other losses, and misreporting (Wayte 2007).

Table 3. Agreed catches, in tonnes, of eastern zone Orange Roughy, where the eastern zone stock includes Pedra Branca (PB) from the Southern Zone. * The catches for the years 1989–1994 incorporate adjustments for the proportion lost due to lost gear and burst bags/ burst panels, other losses, and misreporting (Wayte 2007). † Total removals for 2021 in the base-case assessment are assumed to be the same as the 2020 removals.

Year	East	Pedra	South (Exc Pedra)	Discards	Total Removals
1985	6	0	58		6.0
1986	33	27	604		60.0
1987	310	0	353		310.0
1988	1,949	0	469		1,949.0
1989*	26,236	2,339	8,547		28,575.0
1990*	23,200	11,302	24,128		34,502.0
1991*	12,159	8,277	6,149		20,436.0
1992*	15,119	9,146	6,908		24,265.0
1993*	5,151	3,647	1,839		8,798.0
1994*	1,869	2,271	2,557		4,140.0
1995	1,959	585	1,572		2,544.0
1996	1,998	233	569		2,231.0
1997	2,063	187	267		2,250.0
1998	1,968	119	131		2,087.0
1999	1,952	100	74		2,052.0
2000	1,996	113	198		2,109.0
2001	1,823	204	153		2,027.0
2002	1,584	90	77		1,674.0
2003	772	105	105		877.0
2004	767	30	50		797.0
2005	754	18	81		772.0
2006	614	1	4		615.0
2007	113	16	6		129.0
2008	98	0	0		98.0
2009	193	0	10		193.0
2010	113	0	18		113.0
2011	160	2	15		162.0
2012	163	0	22		163.0
2013	150	0	8		150.0
2014	20	0	20		20.0
2015	422	29	5	7	457.3
2016	352	29	19	3	384.5
2017	302	56	18	6	364.0
2018	862	45	8	3	909.5
2019	619	75	17	1	695.1
2020	1,320	60	19	18	1,397.5
2021					1,397.5†

Age Data

The age data were received from Fish Ageing Services (FAS). Several corrections have been made to the ageing data since the 2017 assessment (Josh Barrow pers. com.). The number of age samples that were provided by FAS in 2017 and the number that were provided in 2021 are shown in Table 4. Differences were mostly minor, except for 1995 where additional samples that had been mislabeled as being from 1996 were added. Age data were also collected in 1987. However, previous assessments have excluded these data due to concerns that large fish were preferentially selected so that sampling was not representative (Malcolm Haddon pers. com.).

Table 4. Number of female and male age samples used for the 2017 and 2021 base-case models.

	Female samples			Male samples		
Year	**2017**	**2021**	**Difference**	**2017**	**2021**	**Difference**
1992	410	410	0	596	596	0
1995	538	610	72	699	757	58
1999	435	282	-153	394	298	-96
2001	652	652	0	641	641	0
2004	414	414	0	504	504	0
2010	693	693	0	251	251	0
2012	426	426	0	545	545	0
2016	338	338	0	247	247	0
2019	-	418	-		309	-

The age data for the 2017 assessment treated ages from St Helens Hill and St Patricks Head in 2012 and 2016 as simple random samples of the population and added these ages to those from earlier years in the 2014 assessment. The 2021 preliminary base-case assessments that used 80 age-classes also treated the 2019 age samples from St Helens Hill and St Patricks Head as simple random samples of the population and added them to the ages used in the 2017 assessment. Samples collected prior to 2012 were combined and weighted based on either the relative abundance implied by the acoustic estimates or the relative catch (Wayte, 2007).

We reviewed the methods used for weighting of age compositions in the 2007, 2011 and 2014 assessments (Wayte 2007, Upston and Wayte 2011, Upston et al 2015). While the weighting of age samples by relative abundance implied by the acoustic estimates or the relative catch at St Helens Hill and St Patricks Head was investigated, age compositions in both locations were similar in all years where both locations were sampled except for 1999. Subsequently, the age composition data was unweighted with the exception of 1999 where a weighting of 1.08 was applied to the age composition data from St Patricks Head (see Table 6.5 from Upston et al 2015). The weighting on the 1999 age composition was based on the acoustic survey estimating that around 85% of the population was at St Patricks Head and took into account that sample sizes at St Patricks Head were larger in this year (Wayte 2007).

It was necessary to recalcualte age frequencies using raw age data supplied by FAS in 2021 and historical data held by CSIRO due to increasing the number of age-classes in the model to 120 (and the 100 ages tested in the preliminary base-case). Age frequencies were unweighted except for 1999 where a weighting of 1.08 was applied to the age composition data from St Patricks Head, consistent with previous assessments. The data provided by Fish Ageing Services for 1999 did not have any samples identified as being collected from St Patricks Head, with all samples recorded as “Eastern Zone” or “St Helens Hill”. A spreadsheet with raw data from 1999 was found and used to calculate age frequencies for scenarios with a plus group at 120 years. The number of ages for St Patricks Head matched those in earlier assessments. However, there were 10 additional ages for St Helens Hill compared with those from earlier assessments (Wayte 2007). Information in the spreadsheet could potentially be used to correct the location of capture for the 1999 age data in the FAS database.

It is recommended that the age data and the relative weighting of age samples collected from St Helens Hill and St Patricks Head should be reviewed prior to the next eastern zone Orange Roughy assessment.

Ageing error

An estimates of the standard deviations of age reading error by age were calculated from multiple readings of otoliths supplied by Josh Barrow (Fish Ageing Services) using the method of Punt et al. (2008) and are provided in Table 5. The estimates were updated from those used in the 2017 assessment to include the new ageing data from 2019, recent corrections to the Fish Ageing Services database and a plus group at 120 years (Table 5).

The model converged (maximum gradient <0.001). However, it was sensitive to the starting values of the parameters. It is recommended that ageing error for Orange Roughy be investigated further before the next assessment.

Table 5. The estimated standard deviation of normal variation (age-reading error) around age-estimates for 120 age-classes in the 2021 base-case model.

Age	StDev	Age	StDev	Age	StDev	Age	StDev
0	<0.001	31	2.3748	62	4.766	93	7.094
1	<0.001	32	2.4529	63	4.842	94	7.168
2	0.0801	33	2.5309	64	4.918	95	7.242
3	0.1602	34	2.6089	65	4.994	96	7.316
4	0.2402	35	2.6868	66	5.070	97	7.390
5	0.3202	36	2.7647	67	5.145	98	7.464
6	0.4000	37	2.8425	68	5.221	99	7.538
7	0.4798	38	2.9202	69	5.297	100	7.612
8	0.5596	39	2.9978	70	5.373	101	7.685
9	0.6392	40	3.0754	71	5.448	102	7.759
10	0.7188	41	3.1529	72	5.524	103	7.832
11	0.7983	42	3.2304	73	5.599	104	7.906
12	0.8778	43	3.3078	74	5.674	105	7.979
13	0.9572	44	3.3851	75	5.750	106	8.053
14	1.0365	45	3.4624	76	5.825	107	8.126
15	1.1158	46	3.5396	77	5.900	108	8.199
16	1.1950	47	3.6167	78	5.975	109	8.272
17	1.2741	48	3.6937	79	6.050	110	8.345
18	1.3532	49	3.7707	80	6.125	111	8.418
19	1.4321	50	3.8477	81	6.200	112	8.491
20	1.5111	51	3.9245	82	6.275	113	8.564
21	1.5899	52	4.0013	83	6.350	114	8.637
22	1.6687	53	4.0781	84	6.425	115	8.710
23	1.7474	54	4.1547	85	6.499	116	8.783
24	1.8261	55	4.2313	86	6.574	117	8.855
25	1.9047	56	4.3079	87	6.648	118	8.928
26	1.9832	57	4.3843	88	6.723	119	9.000
27	2.0616	58	4.4607	89	6.797	120	9.073
28	2.1400	59	4.5371	90	6.872		
29	2.2183	60	4.6134	91	6.946		
30	2.2966	61	4.690	92	7.020		

Biomass indices and acoustic survey priors

There are now eleven estimates of relative abundance for the St Helens Hill and St Patricks Head area from the towed body acoustic surveys (Table 6). The acoustic survey data and methodology was reviewed thoroughly by Upston et al (2015). We added the biomass estimate from the most recent survey in 2019 (which found that mean female spawning biomass on the St Helens Hill and St Patricks Head area had increased to 36,900 t; Kloser and Sutton 2020) to the estimates used in the 2017 assessment.

Table 6. The three abundance indices used in the eastern zone Orange Roughy assessment. Values up to 2012 were sourced from Upston et al (2015). The original 2013 towed acoustic survey value was increased by 18% as a result of a recalibration of the equipment (Kloser, pers. comm), and the 2016 estimate is from Kloser et al, (2016). DEPS is the daily egg production survey. The DEPS estimate is treated as an absolute abundance estimate while the others are treated as relative abundance indices and the method used to determine the priors is described below.

Method	Year	Biomass (t)	CV	Catchability (*q*)
Hull				N(Ln(0.95), 0.92)
Hull	1990	120,239	0.63	
Hull	1991	71,213	0.58	
Hull	1992	48,985	0.59	
Towed				N(Ln(0.95), 0.3)
Towed	1991	59,481	0.49	
Towed	1992	56,106	0.50	
Towed	1993	22,811	0.53	
Towed	1996	20,372	0.45	
Towed	1999	25,838	0.39	
Towed	2006	17,541	0.31	
Towed	2010	24,000	0.25	
Towed	2012	13,605	0.29	
Towed	2013	14,368*	0.29	
Towed	2016	24,037	0.17	
Towed	2019	36,907	0.20	
DEPS	1992	15,922	0.50	0.9 (fixed)

The informative priors for the catchability coefficients (*q*) for the acoustic towed and hull biomass estimates were developed using the methods of Cordue (presentation to the Australian Orange Roughy workshop, 15 – 16 May 2014; Cordue 2014) for the New Zealand orange roughy assessments and modified for the Australian Eastern orange roughy situation using the available acoustic data for the hull and towed body surveys undertaken between 1990 and 2013 and expert judgement from the informal Orange Roughy acoustics working group in Hobart that included Judy Upston, Tim Ryan, Rudy Kloser and André Punt. The methods below are reproduced from Upston et al (2015):

Determine the sampling distribution, mean and CV associated with each of three components that we considered for the acoustic priors:

(i) uncertainty in acoustic target strength (TS), i.e. the ratio of true target strength to assumed target strength – lognormal distribution centred at 1 with CV=0.15 (after Cordue presentation 2014):

a) calculate the mean and standard deviation of two independent mean estimates of acoustic TS, -52.0 and -51.1 dB (ignores sampling variability), and assume TS ~ N(-51.6, sd=0.64),

b) convert TS from log scale to linear scale via $\log_e(10^{ts/10})$ where ts is random normal TS, to get $\log_e(10^{ts/10})$ ~ N(-11.88, 0.1476),

c) calculate mean and standard deviation of lognormal distribution centred on 1 (including bias correction);

(ii) percentage of the spawning stock on the Eastern grounds that acoustics is “seeing” – historically the assessment has assumed 100% and the current assessment assumes “most” (Beta distribution centred on 95%) but allows for the possibility that some spawning stock do not migrate to the Eastern grounds in some years (e.g. an estimated 10% of spawning fish from the South did not migrate to the East in 1992; Bell et al. 1992). Thus a Beta(95, 5) distribution, centred on 95% and with reasonably high values of α and β for an approximately normal shape, was chosen for this prior component. The distribution shape, with less probability mass towards the left-hand tail of the distribution (less probability of only 90% or fewer spawning fish migrating to the spawning grounds and being observed), seemed appropriate based on expert judgement. However, other Beta distributions could also have been used (e.g. Beta(950, 50);

(iii) random error component capturing other uncertainty (e.g. estimated density of fish in an area; species ID issues; sampling variability in target strength since (i) is an average of the mean estimates). The random error has a lognormal distribution centred on 1, with a nominal “low” CV for towed body surveys, and a wider CV for the hull surveys, given the uncertainty with species ID and other issues (Kloser and Ryan et al. 2001).

The next step was to combine the independent component distributions to obtain an overall distribution. The CVs associated with each of the three components (and hence the overall prior) were determined by data and expert judgement – in combining the three components and setting a prior on acoustic catchability (*q* scalar) we essentially have made a statement about how well the acoustic towed or hull series is thought to provide an absolute estimate of biomass of the spawning Orange Roughy stock in the East and South (Pedra Branca). i.e. the stock we are assessing.

We have assumed on average a constant percentage of fish migrating to the eastern grounds and spawning each year. The priors will undoubtedly be further developed as more information becomes available, thus the random error component (lognormal with CV=0.25 for the towed body and 0.8 for the hull) was explicitly included to accommodate this.

Distributions for each of the independent components, and the combined overall distribution for the acoustic *q* prior are shown in Figures 4-6.

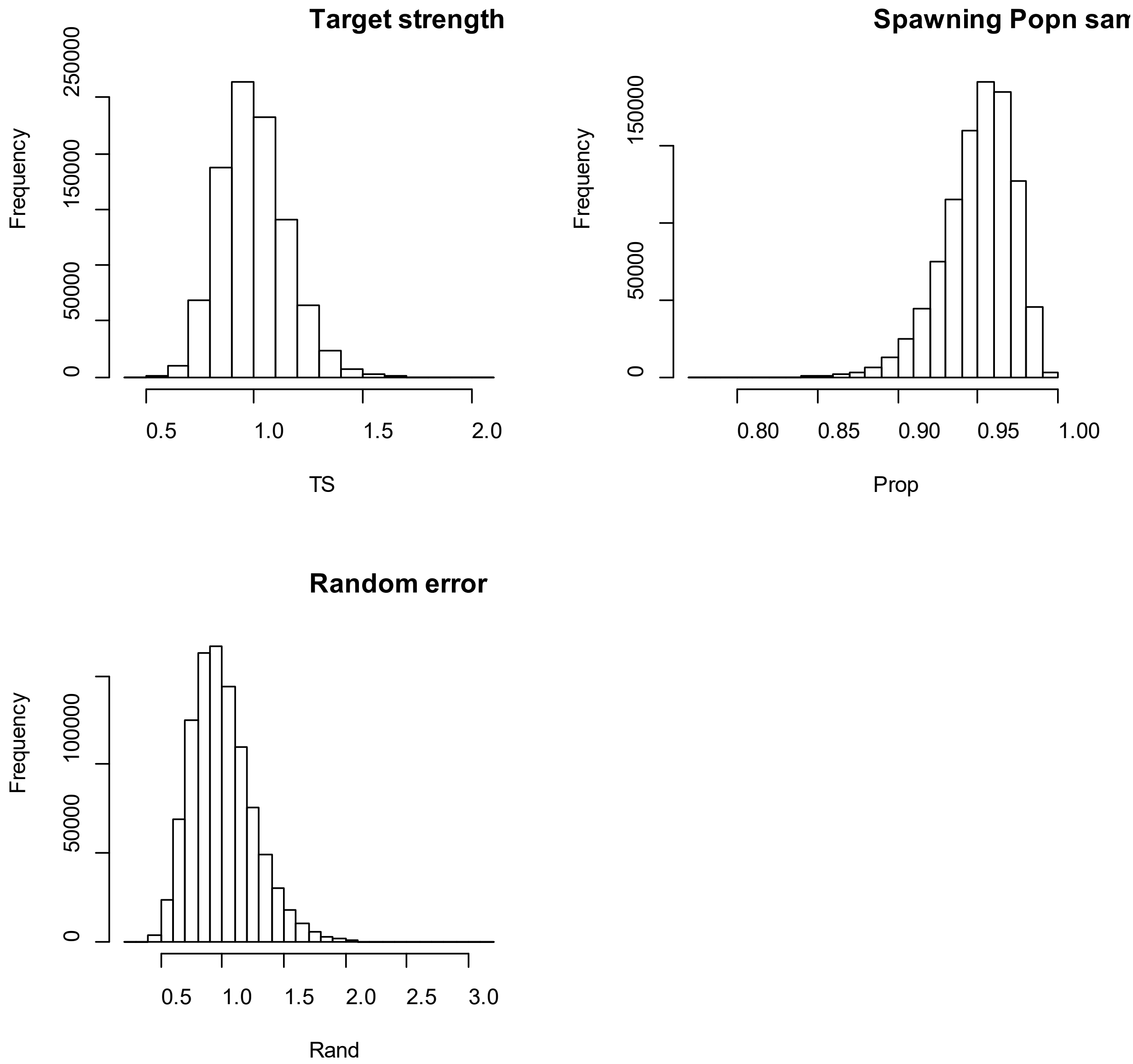


Figure 4. Prior component distributions for target strength, spawning population sampled, and random error for acoustics towed (reproduced from Upston et al 2015).

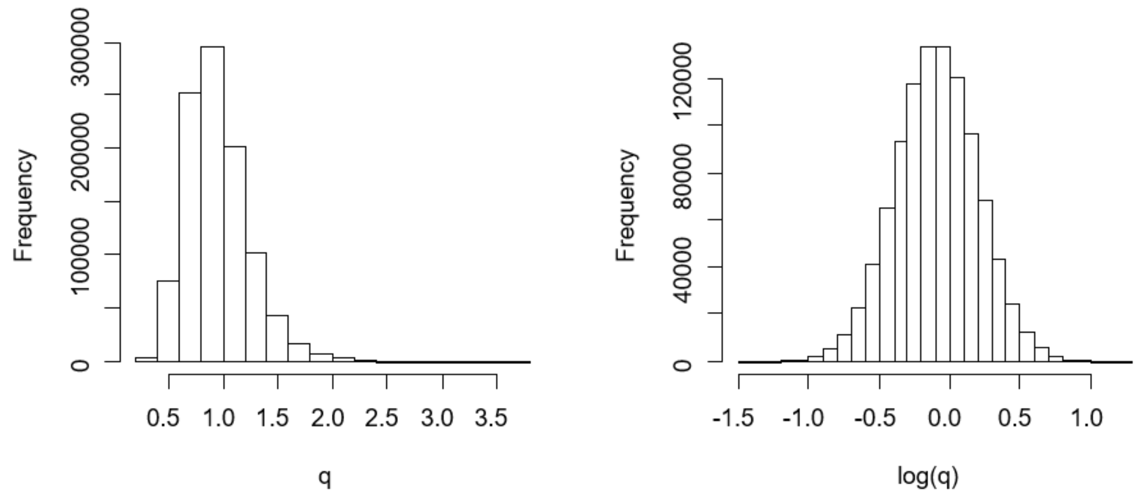


Figure 5. Histograms of data used to create priors for q and ln(q) for acoustics towed (reproduced from Upston et al 2015).

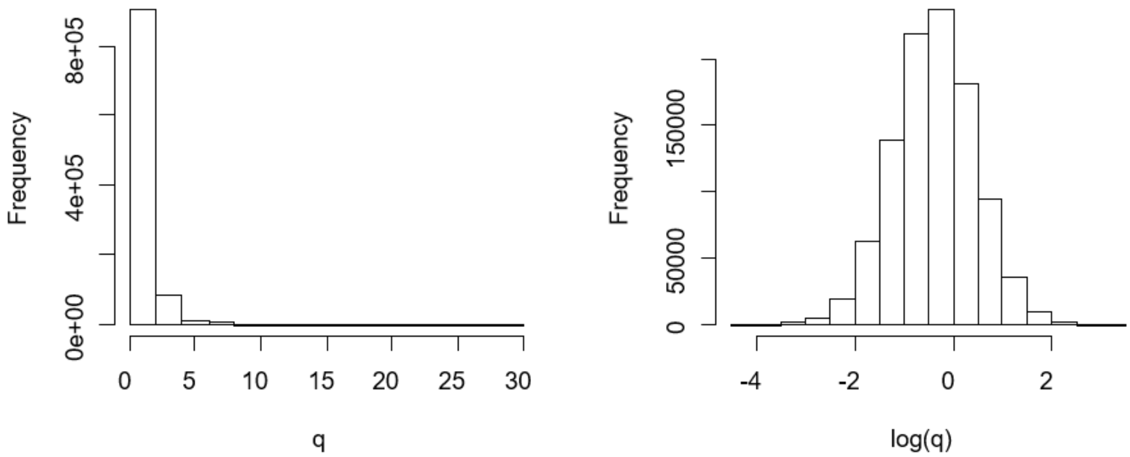


Figure 6. Histograms of data used to create priors for *q* and log(*q*) hull. The random error component is greater than that for towed body (reproduced from Upston et al 2015).

The prior for the towed body acoustic surveys has not been updated since the 2015 assessment. Before the next eastern zone Orange Roughy assessment the methods for constructing the acoustic survey *q* priors should be reviewed and the prior for the towed body survey should be updated to include information obtained after 2014.

Prior for natural mortality

Cordue (2014) developed a combined posterior for Orange Roughy *M* using the results from the New Zealand Orange Roughy stock assessments for ORH 2A+2B+3A, ORH 3A (NWCR), ORH 3B (ESCR), and ORH 7A. CSIRO proposed to use an updated version of the combined posterior for Orange Roughy *M* to develop a prior to use in the Australian eastern zone stock assessment to estimate *M*. The posterior for New Zealand Orange Roughy stocks was recently been updated by

Patrick Cordue to use the most recent available assessments for New Zealand Orange Roughy stock assessments (ORH 2A+2B+3A, ORH 3A (NWCR), ORH 3B (ESCR), ORH (Puysegur) and ORH 7A) as part of the submission for the extension of Marine Stewardship Council certification for New Zealand Orange Roughy but was not publicly available at this assessment was being undertaken.

We received permission from George Clement (Deepwater Group) to access to the updated combined posterior for New Zealand Orange Roughy *M*, and a sample of 5,000 *M* estimates from the updated combined posterior distribution was provided by Patrick Cordue (ISL). To obtain a functional form of the prior for *M* that could be used in Stock Synthesis, we fitted a log-normal distribution to the combined posterior for New Zealand Orange Roughy using the MASS package in R (Venables and Ripley 2002). Other distributions were evaluated in the preliminary base-case report (Burch and Curin Osorio 2021) and found to be very similar and the log-normal model was selected to use as the prior for *M* because of the slightly better fit to the left-hand side of the posterior distribution for New Zealand Orange Roughy *M*.

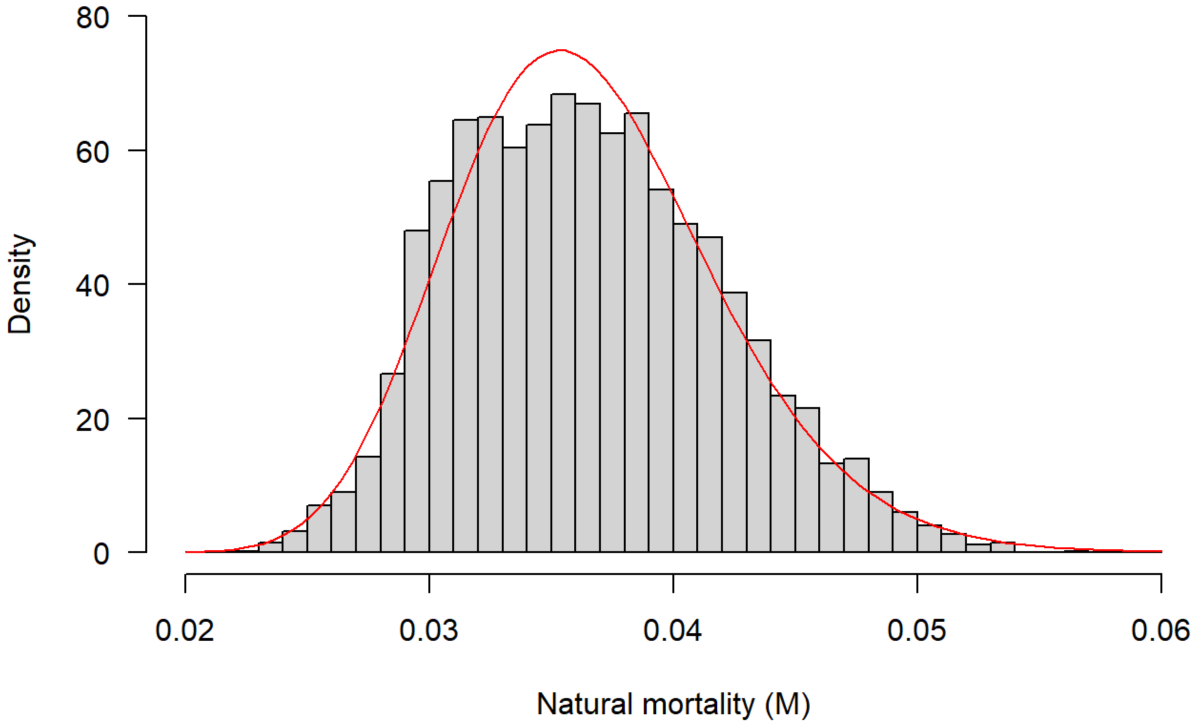


Figure 7. Combined posterior for New Zealand Orange Roughy stock assessments with fitted log-normal distribution. Distribution supplied by Patrick Cordue (ISL).

2021 base-case assessment

Fitting procedure

Assessment was undertaken using Stock Synthesis 3.30.17 (Methot and Wetzel 2013). Convergence was assessed be checking the final grandient was < 1e-4 (the default in Stock Synthesis) and the Hessian is positive definite. Estimates from the maximum posterior density (MPD) are presented along with median and uncertainty estimates from the MCMC analysis that is described below.

A jitter analysis that involved varying the starting values of the estimated parameters by up to 10% and re-running the assessment 100 times. Of these runs nonefailed to achieve converngence to the minimum of the objective function. Model outputs were summarised and plotted using R and the R package r4ss (Taylor et al 2014). A summary of the estimated parameters and their priors is provided in Table 7.

Table 7. Summary of the estimated parameters for the 2021 base-case assessment, their priors and source. Normal priors are defined by N (mean, standard deviation). The priors on acoustic survey catchability are Normal on log(q). Survey *q*'s are presented as exp(ln(*q*)), i.e. with no bias correction is applied.

Estimated parameters	Parameters	Prior	Prior Type / Source
Unexploited recruitment; ln(R0)	1		Uninformative
Recruitment deviations 1905-1986	82	N(0,σ^2)	Methot et al. (2021)
Selectivity logistic	2		Uninformative
q Acoustic towed catchability	1	N(Ln(0.95), 0.3)	Upston et. al. (2015)
q Hull catchability	1	N(Ln(0.95), 0.92)	Upston et. al. (2015)
Natural mortality *(M)*	1	Log-normal(-3.32, 0.148)	Cordue (ISL)

MCMC analysis

Markov chain Monte Carlo (MCMC) is a method for sampling parameter vectors from a posterior distribution in the Bayesian framework (Gelman et al. 2003). The MCMC simulation should be run long enough so that the algorithm converges in the sense that the parameter vectors are random independent samples from the posterior (i.e. the distribution of draws is close enough to the target posterior distribution $p(\theta|y)$; Gelman et al. 2003).

At its October 2021 meeting SERAG requested that that Bayesian posteriors based on MCMC be created for the eastern zone Orange Roughy assessment to permit comparison of the posteriors for *M* and the catchability of the acoustic surveys with their priors and to select 'low' and 'high' scenarios for *M* in the sensitivity analysis. Initial MCMC analysis identified that the width parameter from the age-based logistic selectivity of both the trawl fleet and the two acoustic surveys may have been mis-specified (Figure 15). An additional MCMC analyses was undertaken with the width parameter from the logistic selectivity fixed at its MPD estimate of 1.00198, however, this had minimal impact on the median stock status and RBCs from the MCMC analysis. The ORSC determined that the posterior of the width parameters from the logistic selectivity was not of concern and that the original MCMC analysis was used for the base-case assessment.

The MCMC was run for total of 2.5 million iterations with the first 500,000 iterations being discarded (the burn-in). For the remaining 2 million iterations, every 1,000th iteration was saved, providing a sample of 2,000 values of the posteriors. To assess inter-chain variability three chains were run, with the parameters and derived quantaties from the first chain compared with their MPD estimates.

MCMC convergence was assessed using the statistics:

i. The extent of batch auto-correlation (examined using trace plots), high autocorrelations indicate slow mixing and slow convergence,
ii. Whether the posterior distribution was approximately multivariate normal (we examined the plot of the posterior distribution), and whether the distribution of the chain is stationary, as judged by the p-value computed from the Geweke statistic (which should within the range ±1.96) and
iii. Whether the Heidelberger and Welch test is passed or not (Heidelberger and Welch 1981, 1983, Gelman et al. 2003).

The R package, coda (Plummer et al., 2006) and r4ss (Taylor et al., 2014), were used to produce the plots and statistics.

Tuning - Data Weighting

Iterative rescaling (reweighting) of input and output CVs or input and effective sample sizes is a repeatable way to ensure that the expected variation of the different data streams is comparable to what is input (Pacific Fishery Management Council, 2020). Most of the data sources (CPUE, surveys and composition data) used in fisheries underestimate their true variance by only reporting measurement or estimation error and not including process error.

In iterative reweighting, the effective annual sample sizes are tuned/adjusted so that the input sample size is equal to the effective sample size calculated by the model. An automated iterative tuning procedure was used to adjust the recruitment bias ramp and the weighting on the age composition data.

For the recruitment bias adjustment ramps:

1. Adjust the maximum bias adjustment and the start and finish bias adjustment ramps as predicted by r4ss at each step.

For the age composition data:

2. Multiply the initial samples sizes by the sample size multipliers for the age-composition data using the `Francis method' (Francis, 2011).

3. Repeat steps 1 - 2, until all are converged and stable (with proposed changes < 1%). This procedure constitutes current best practice for tuning assessments.

Calculating the Recommended Biological Catch

The SESSF Tier 1 harvest control rule specifies a target and a limit biomass reference point, as well as a target fishing mortality rate to determine a recommended biological catch (RBC) for each stock in the SESSF quota management system (Smith et al., 2008). Since 2005 various values have been used for the target and the breakpoint in the rule. In 2009, AFMA directed that the 20:35:48 (B_{lim}: B_{break}: F_{targ}) form of the rule is used, assuming a F_{targ} of F_{48}, the default economic target for B_{MEY} in the SESSF.

This 20:35:48 rule is used for the 2021 eastern zone Orange Roughy assessment with the long-term RBC and the time for the stock to reach the target reference point estimated by projecting the asseessment forward in time using mean recruitment (subject to the stock recruitment relatonship) and catches from the SESSF harvest control rule.

Sensitivities

Likelihood Profiles

Likelihood profiles are a standard component of the toolbox of applied statisticians (Punt 2018). They are most often used to obtain 95% confidence intervals. Many stock assessments "fix" key parameters such as *M* and *h* based on *a priori* considerations. Likelihood profiles can be used to evaluate whether there is evidence in the data to support fixing a parameter at a chosen value. If the parameter is within the entire range of the 95% confidence interval, this provides no support in the data to change the fixed value. If the fixed value is outside the 95% confidence interval, it would be reasonable for a review panel to ask why the parameter was fixed and not estimated, and if the value is to be fixed, on what basis and why should what amounts to inconsistency with the data be ignored. Integrated stock assessments include multiple data sources (e.g. commonly catch-rates, length-compositions, and age-compositions) that may be in conflict, due for example to inconsistencies in sampling, but more commonly owing to incorrect assumptions (e.g. assuming that catch-rates are linearly related to abundance), i.e. model-misspecification. Likelihood profiles can be used as a diagnostic to identify these data conflicts (Punt 2018).

Likelihood profiles for steepness of the stock recruitment relationship (*h*), female spawning biomass in 1980 (SSB_{1980}) and current stock status (SSB_{2021}/SSB_0) and natural mortality (*M*) were conducted using the base-case assessment. Confidence intervals were constructed using a Chi squared distribution with one degree of freedom. The 2.5% and 97.5% quantiles of the likelihood profiles (a 95% confidence interval) were therefore obtained at 1.92 log-likelihood units from the minimum.

Retrospective analysis

A retrospective analysis was undertaken to identify how the assessment outcomes may have changed as new data have been added to the assessment. We undertook assessments after removing four, seven and ten years of data from the base-case model.

The severity of retrospective patterns can be quantified using a statistic called Mohn's rho, which is defined as the average of the relative differences between an estimate from an assessment with a truncated time series and an estimate of the same quantity from an assessment using the full time series (Hurtado-Ferro et al. 2015). Mohn's rho values are calculated for a range of effects, including SSB, recruitment, *F* and stock status. As a general rule of thumb values of Mohn's rho higher than 0.20 or lower than −0.15 are cause for concern in an assessment (Hurtado-Ferro et al. 2015). Mohn's rho statistic was estimated from the retrospective analysis using the R package r4ss (Taylor et al. 2014).

Sensitivity analyses

The sensitivity of the base-case model to values of some fixed parameters, data weighting, the natural mortality estimate and the catch in 2021 are explored. The following sensitivities are undertaken:

- Low (*h*=0.6) and high (*h*=0.9) steepness of the Beverton-Holt stock recruitment relationship.
- Low (σ_R = 0.6) and high (σ_R = 0.8) recruitment variability.
- Set natural mortality at the 12.5% (low) and 87.5% (high) quantiles from the posterior of *M.*
- Halve and double the weights on the age data in the likelihood.
- Removing the 1992 egg survey.
- Use the estimated catch for 2021 of 1,350 t provided by AFMA.
- Use the 2021 TAC of 1,569.4 t, that includes undercatch from the 2020 season.

Fixed Catch Projections

The ORSC requested fixed catch projections be developed in consultation with AFMA to be presented to the November 2021 SERAG meeting. An MCMC analysis was undertaken projecting the 2021 base-case model to 2031 with constant catches of 550, 650, 737, 850 and 950 t per annum. Stock status and probability of being below the limit reference point were calculated in 2024 and 2031.

Results

2021 base-case assessment model

Parameter estimates and derived quantities

The base-case model (MPD estimate) converged with final gradient <$1e^{-4}$ and a positive definite Hessian. The jitter analysis found that there was less than $1e^{-4}$ variability among the likelihood components and parameter estimates from the assessments undertaken with different starting values, suggesting the base-case model is insensitive to the initial values of parameters.

The MCMC analysis converged after increasing the burn-in to exclude an additional 250,000 samples from the posterior (Figures A3-A9, Table A1). With the exception of the width of the selectivity function and one recruitment deviation, all parameters passed the standard diagnostic tests (Table A1, Figure A9). Estimates of parameters and derived quantities from the MPD were in most cases different from the posterior medians from the MCMC analysis (Figures 10, 11, 13-15, Table 8). This difference was discussed by the ORSC and while it is unusual that the MPD estimate and the posterior median from MCMC analysis differ it does occur from time to time and has occurred for some assessment models used for Orange Roughy in New Zealand.

The ORSC was not unduely concerned about the level of variability in the posterior of width parameter of the logistic selectivity, and it was believed that it was not so extreme as to suggeset that parameter should be fixed in the model. As a sensitivity the MCMC analysis was re-run with the selectivity width parameter fixed at its MPD estimate. This did not change the difference between the parameter estimates from the MPD and the MCMC (Figures A11, A12).

There was some correlation among the estimated parameters with natural mortality (*M*) and the catchability (*q*) of the towed acoustic survey was highly correlated with mean unfished recruitment (*R0*), which is not uncommon as these parameters are directly related to the productivity of the stock (Figure A10). The two parameters from the logistic selectivity function were also correlated, which again is not uncommon.

The median estimate of unfished female spawning biomass from the MCMC analysis was 38,924 t, which is slightly lower than the MPD estimate of 40,479 t (Figure 8, Table 8). The current 2022 female spawning biomass is estimated to be 11,644 t from the MCMC and 13,126 t from the MPD. Relative spawning biomass in 2022 is estimated at 30.0% of unfished levels from the MCMC and 32.4% of unfished levels from the MPD (Figure 8).

The estimated selectivity pattern is slightly different to the maturity ogive (Figure 9) and the width of the selectivity function was near its lower bound in both the 2021 and 2017 assessments. The fixed growth curve is shown in Appendix A (Figure A2). There is a strong trend in recruitment over time, with recruitment estimated to be above average prior to 1950 and below average afterwards (Figure 10). This trend in recruitment is similar to that from the 2017 assessment.

The median estimate of natural mortality from the MCMC analysis is M=0.0393 yr^{-1} slightly higher than the MPD estimate of M=0.0386 yr^{-1} (Table 8). The median estimates of catchability for the towed and hull acoustic surveys from the MCMC analysis are q=1.189 and q=1.521 respectively, which are higher than the MPD estimates of q=1.103 and q=1.49 respectively (Table 8). These estimates are all higher than the 2017 assessment and imply is was an increase in estimated of the q for the towed survey compared with the previous assessment with a fixed M of 0.04 yr^{-1}. While a catchability greater than 1 means the model is inferring that the biomass is greater than the survey estimate. However, both catchability estimates well within range of the priors for acoustic survey catchability (Figure 14).

The recommended biological catch (RBC) for 2022 from the MCMC analysis is 681 t, lower than the MPD estimate for 2022 of 944 t (Table 8). The average RBC over the next three years (2022-2024) is 737 t from the MCMC analysis and 1,025 t from the MPD. There is a high level of uncertainty in the estimated RBC with the 75% and 95% credible intervals from the MCMC analysis for the 2022 RBC being 287 – 1,316 t and 119 – 1,645 t respectively.

Table 8. The estimated parameters and derived quantities for the 2021 base-case model. The estimate along with 95% asymptotic confidence intervals (2.5%, 97.5%) and coefficient of variation from the MPD is shown along with the Median, 95% (2.5%, 97.5%) and 75% (12.5%, 87.5%) credible intervals from 1,750 samples of the posterior from the MCMC analysis.

	MPD				**MCMC**					
Quantity	**Estimate**	**2.5%**	**97.5%**	**CV**	**Median**	**2.5%**	**12.5%**	**87.5%**	**97.5%**	**CV**
M	**0.0386**	0.0324	0.0448	0.0820	**0.0393**	0.0337	0.0358	0.0432	0.0461	0.0812
$ln(R_0)$	**9.005**	8.616	9.394	0.022	**9.006**	8.639	8.782	9.253	9.441	0.023
towed *q*	**1.103**	0.782	1.556	1.794	**1.189**	0.833	0.962	1.456	1.687	1.043
hull *q*	**1.490**	0.785	2.830	0.820	**1.521**	0.813	1.050	2.230	2.888	0.778
Selectivity inflection	**35.086**	34.591	35.582	0.007	**35.169**	34.600	34.836	35.563	35.902	0.009
Selectivity width	**1.002**	0.873	1.131	0.066	**1.446**	1.019	1.101	2.070	2.516	0.268
SSB_0	**40,479**	37,039	43,919	0.043	**38,924**	33,578	35,771	41,779	44,185	0.069
SSB_{2022}	**13,126**	8,939	17,313	0.163	**11,644**	8,332	9,475	14,285	16,779	0.185
SSB_{2023}	**13,466**	9,466	17,465	0.152	**11,892**	8,687	9,792	14,453	16,861	0.175
SSB_{2024}	**13,753**	9,953	17,553	0.141	**12,107**	8,996	10,094	14,555	16,857	0.166
SSB_{2025}	**13,989**	10,394	17,584	0.131	**12,263**	9,271	10,355	14,625	16,832	0.158
SSB_{2022}/SSB_0	**0.324**	0.237	0.411	0.137	**0.300**	0.228	0.254	0.356	0.401	0.148
SSB_{2023}/SSB_0	**0.333**	0.251	0.414	0.125	**0.307**	0.237	0.263	0.359	0.403	0.138
SSB_{2024}/SSB_0	**0.340**	0.264	0.416	0.114	**0.313**	0.246	0.271	0.362	0.404	0.128
SSB_{2025}/SSB_0	**0.346**	0.275	0.416	0.104	**0.318**	0.254	0.278	0.363	0.403	0.119
RBC_{2022}	**944**	0	2,003	0.572	**681**	119	287	1,316	1,645	0.566
RBC_{2023}	**1,029**	0	2,076	0.519	**740**	168	345	1,332	1,648	0.514
RBC_{2024}	**1,102**	81	2,124	0.473	**789**	215	395	1,338	1,648	0.470
RBC_{2025}	**1,163**	177	2,149	0.433	**830**	260	441	1,339	1,644	0.433
Average RBC (2022-2024)	**1,025**				**737**					

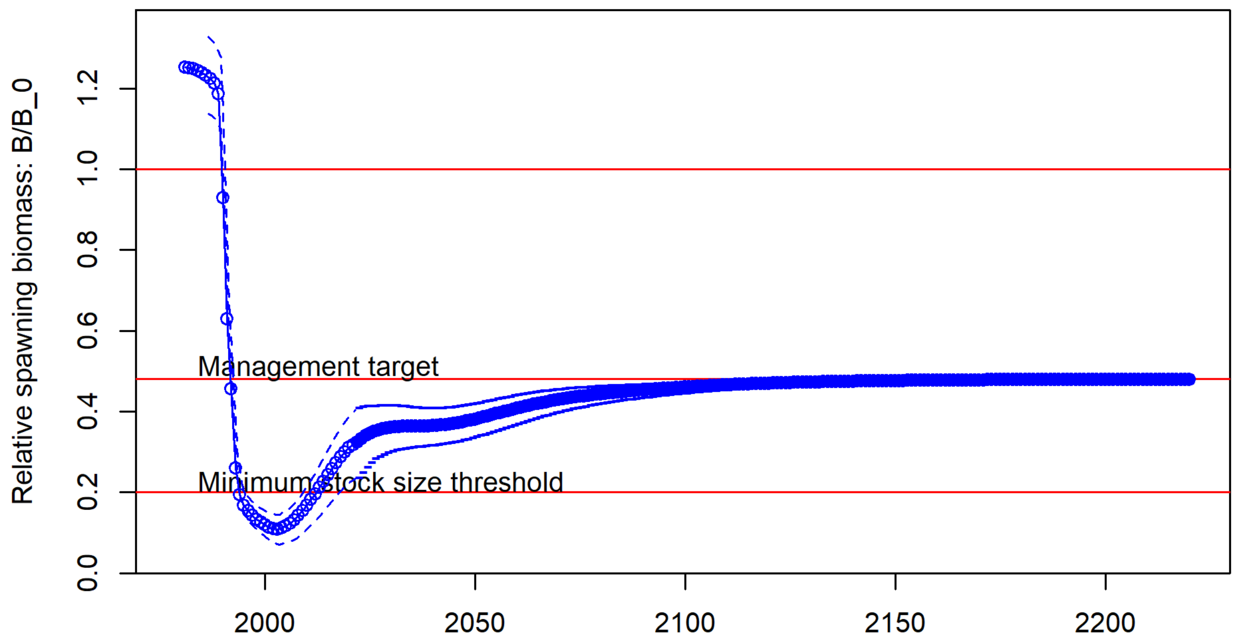


Figure 8. The MPD (point estimate) time-series of relative spawning biomass forecast 200 years into the future with catches set using the SESSF 20:35:48 harvest control rule for the 2021 base-case model. The dashed line indicates approximate 95% confidence intervals.

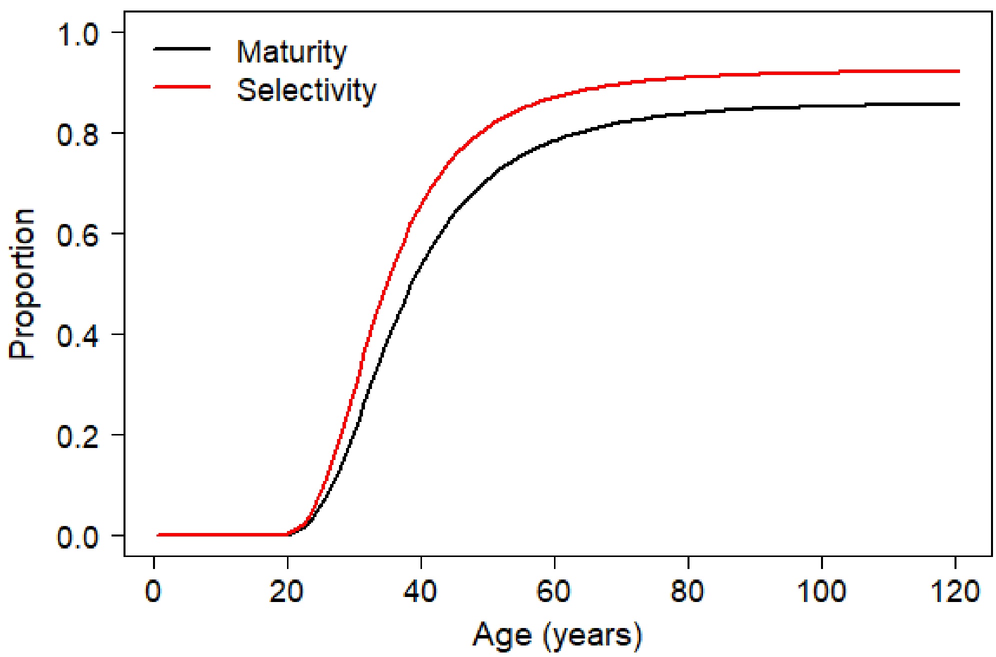


Figure 9. The estimated selectivity curve and prespecified maturity ogive for the 2021 base-case model.

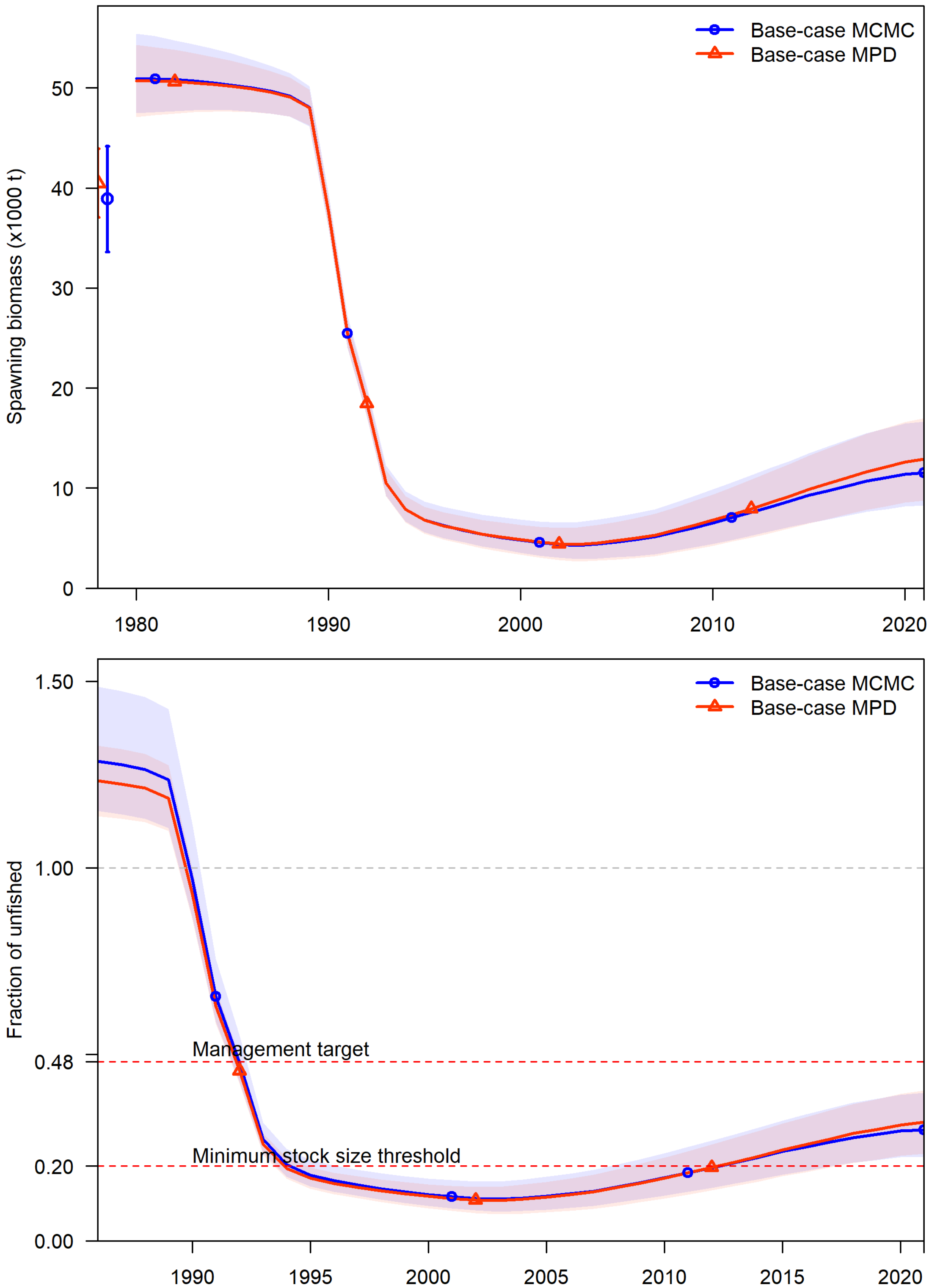


Figure 10. Comparison of time-series of absolute (top) and relative (bottom) spawning biomass (with ~95% intervals) for the 2021 base-case model. The red line and shading represent the point estimate and uncertainty from the MPD while the blue line and shading represents the median and uncertainty from 1,750 samples of the posterior from the MCMC.

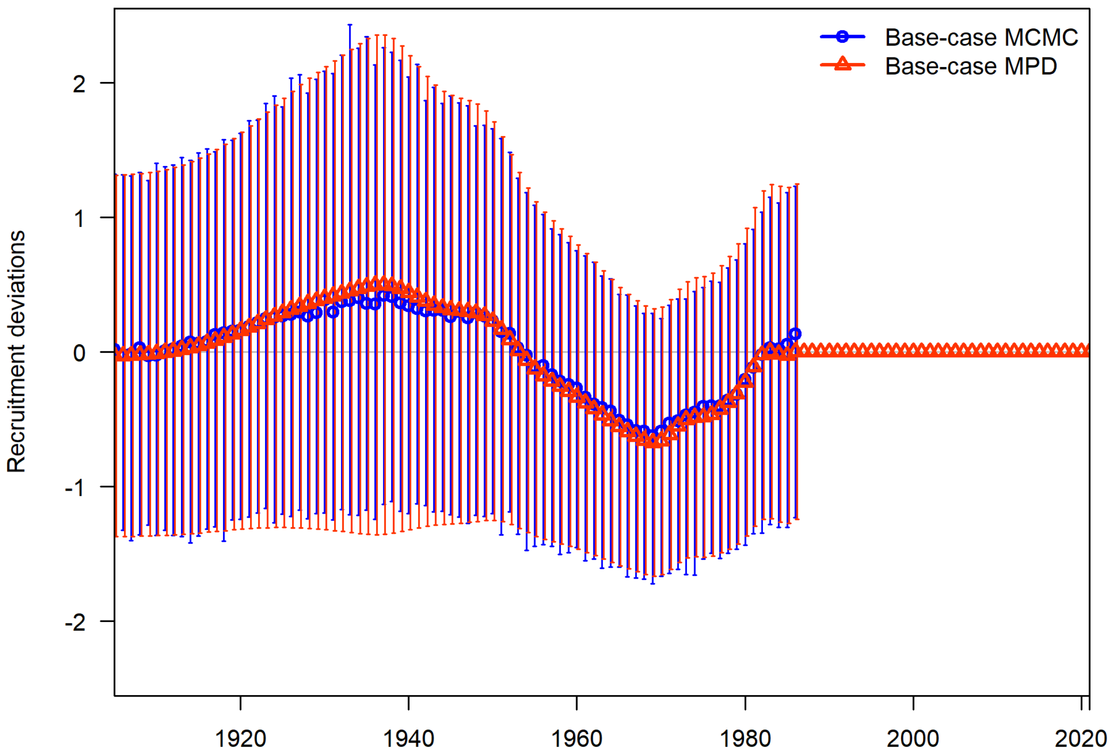


Figure 11. Comparison of time-series of recruitment deviations with ~95% intervals for the 2021 base-case model. The red line and shading represent the point estimate and uncertainty from the MPD while the blue line and shading represents the median and uncertainty from 1,750 samples of the posterior from the MCMC.

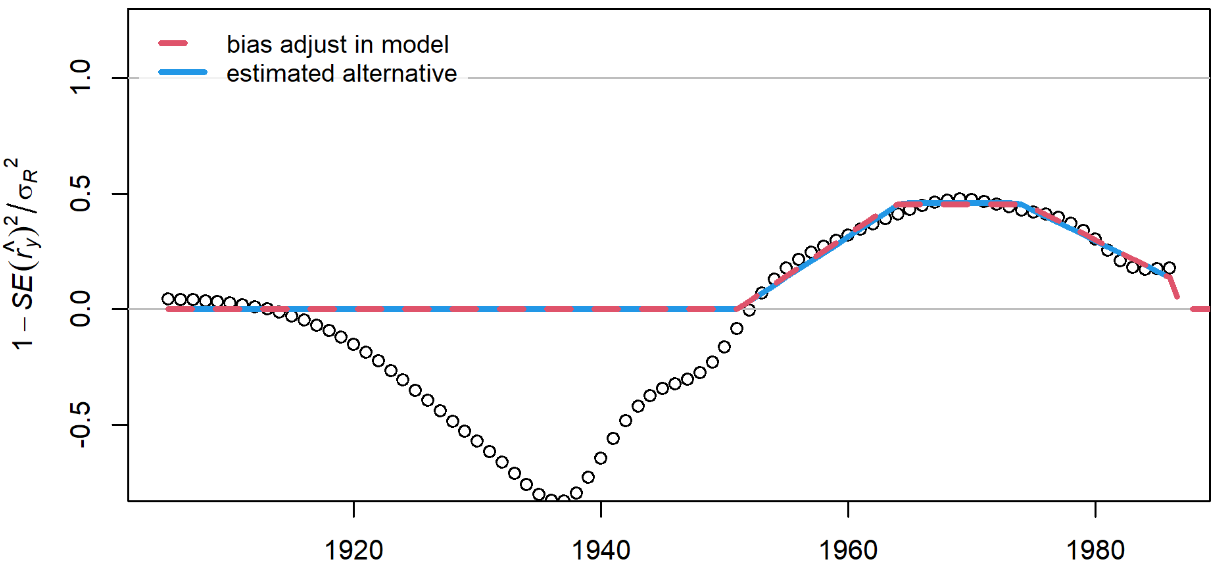


Figure 12. Bias ramp adjustment for the 2021 base-case model.

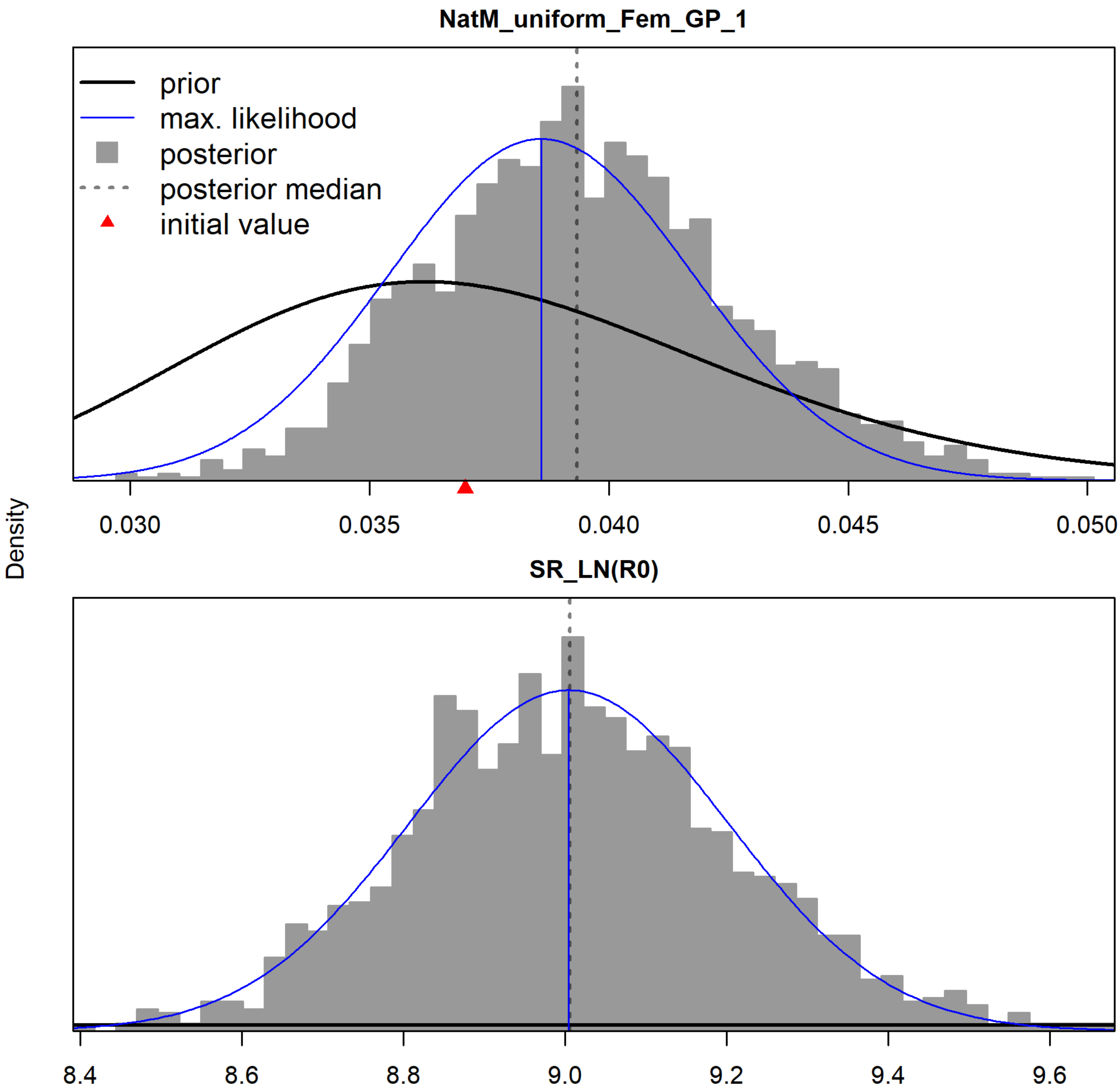


Figure 13. Histograms of the posterior of natural mortality (top) and the log of unfished mean recruitment (bottom) for the 2021 base-case model. The histogram comprises 1,750 samples from the posterior, the blue vertical and curved lines are the MPD estimate and asymptotic uncertainty and the black line is the prior.

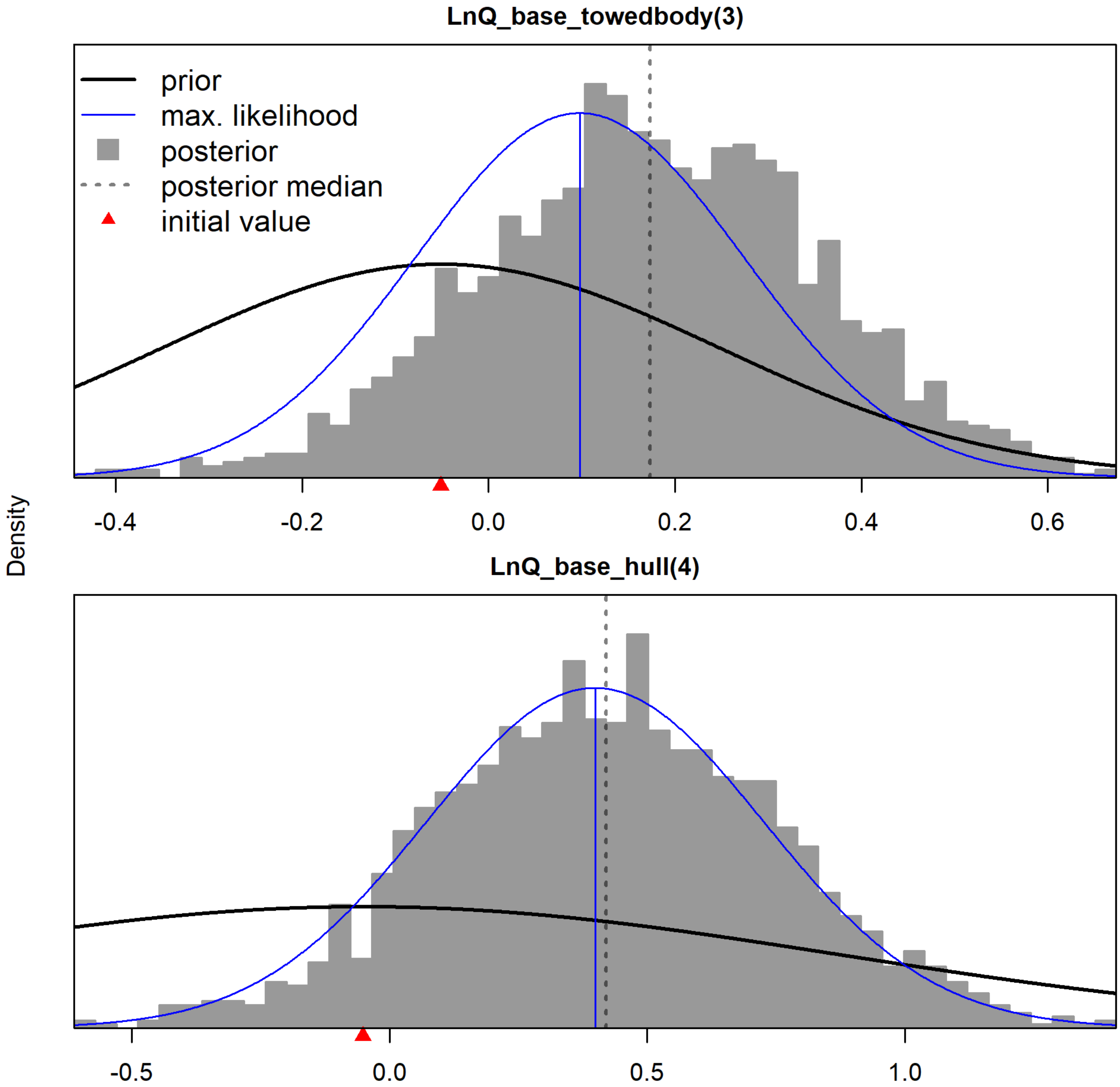


Figure 14. Histograms of the posterior of log catchability from the towed (top) and hull (bottom) acoustic surveys from the 2021 base-case model. The histogram comprises 1,750 samples from the posterior, the blue vertical and curved lines are the MPD estimate and asymptotic uncertainty and the black line is the prior. Note the acoustic catchability parameters are presented here as log(q), while they are presented as exp(log(q)) elsewhere in this report.

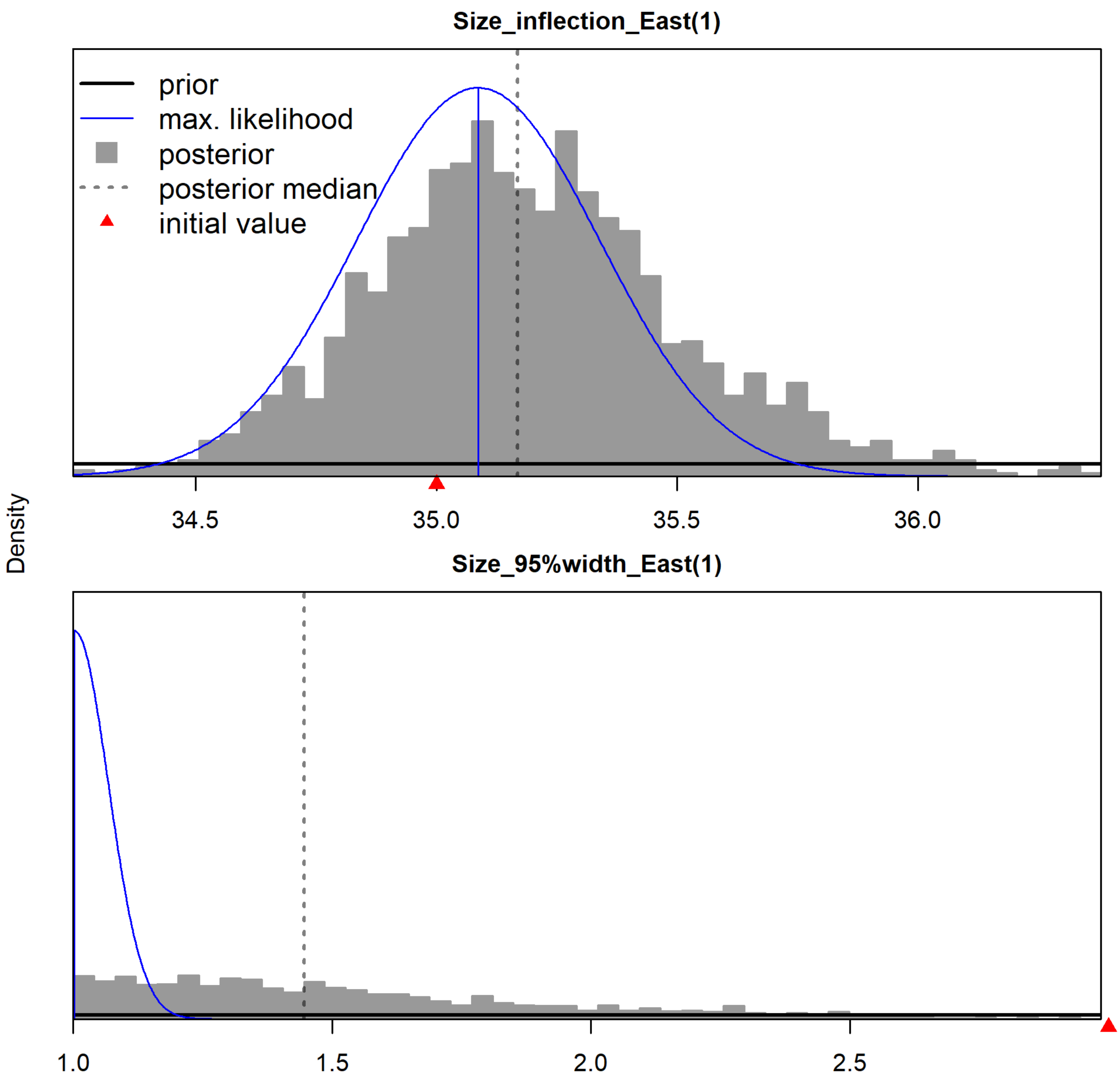


Figure 155. Histograms of the posterior of the inflection (top) and width (bottom) parameters of the length-based selectivity logistic selectivity for the 2021 base-case model. The histogram comprises 1,750 samples from the posterior, the blue vertical and curved lines are the MPD estimate and asymptotic uncertainty and the black line is the prior.

Fits to the data and diagnostics

Fits to the index data are reasonably good (Figures 16-19) and similar to those from the 2017 assessment. Residual plots of the fits to the index data show the model under-estimates the biomass from the towed body surveys before 2010 (Figure 19). However, the model estimates of survey-selected biomass are well within the confidence intervals of the survey biomass estimates.

The fits to the mean age by year show male ages are slightly over-estimated while female ages are slightly underestimated (Figure 20). The model under-estimates the proportion of younger age-classes in 1992 and 1995 and over-estimates the proportion of individuals in the plus group in 1999, while under-estimating the proportion of individuals in the plus group in most years after 2000 (Figures 21-25). There is no trend in the residuals of the fits to the age data (Figure 26).

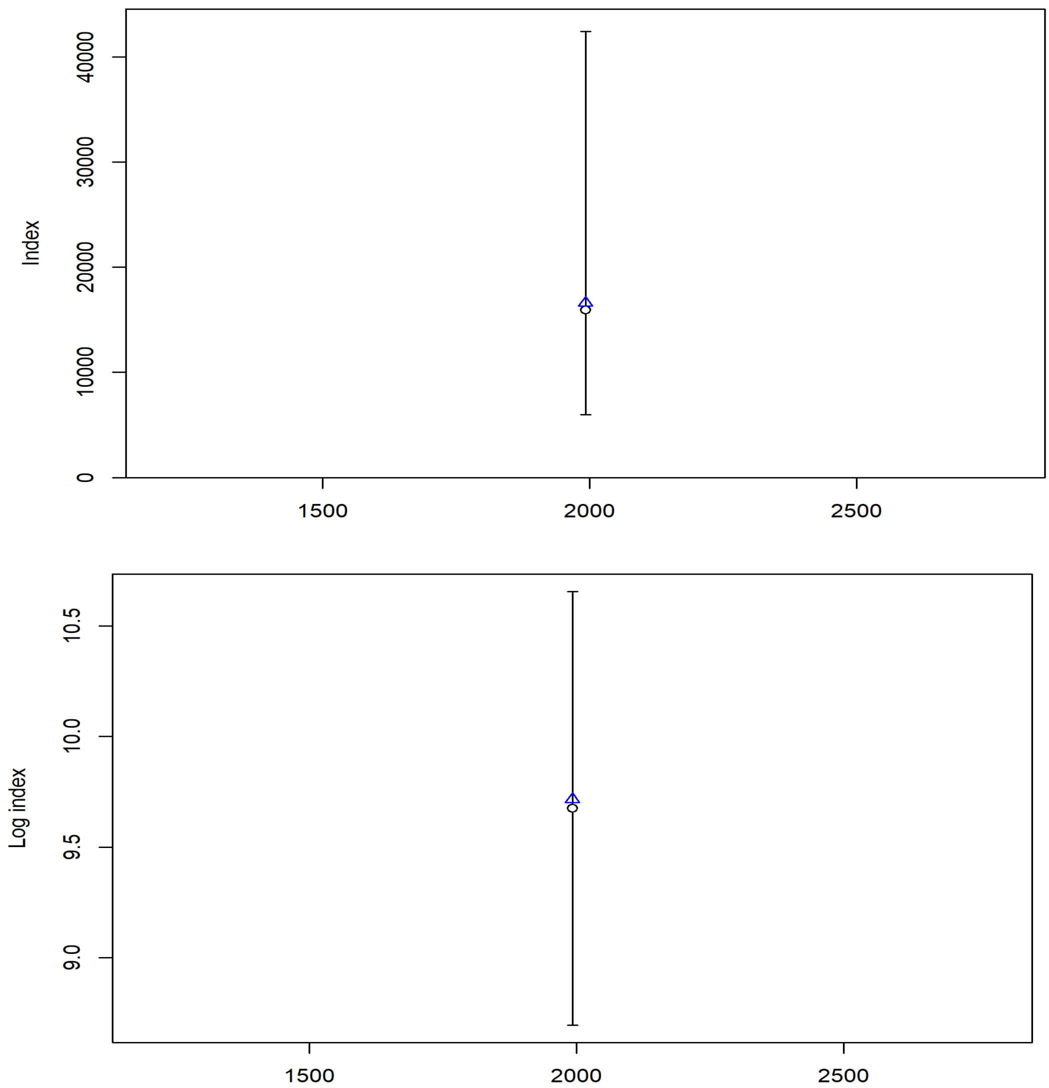


Figure 16. Fits to the biomass index (top) and log index (bottom) for the 1992 egg survey for the base-case model.

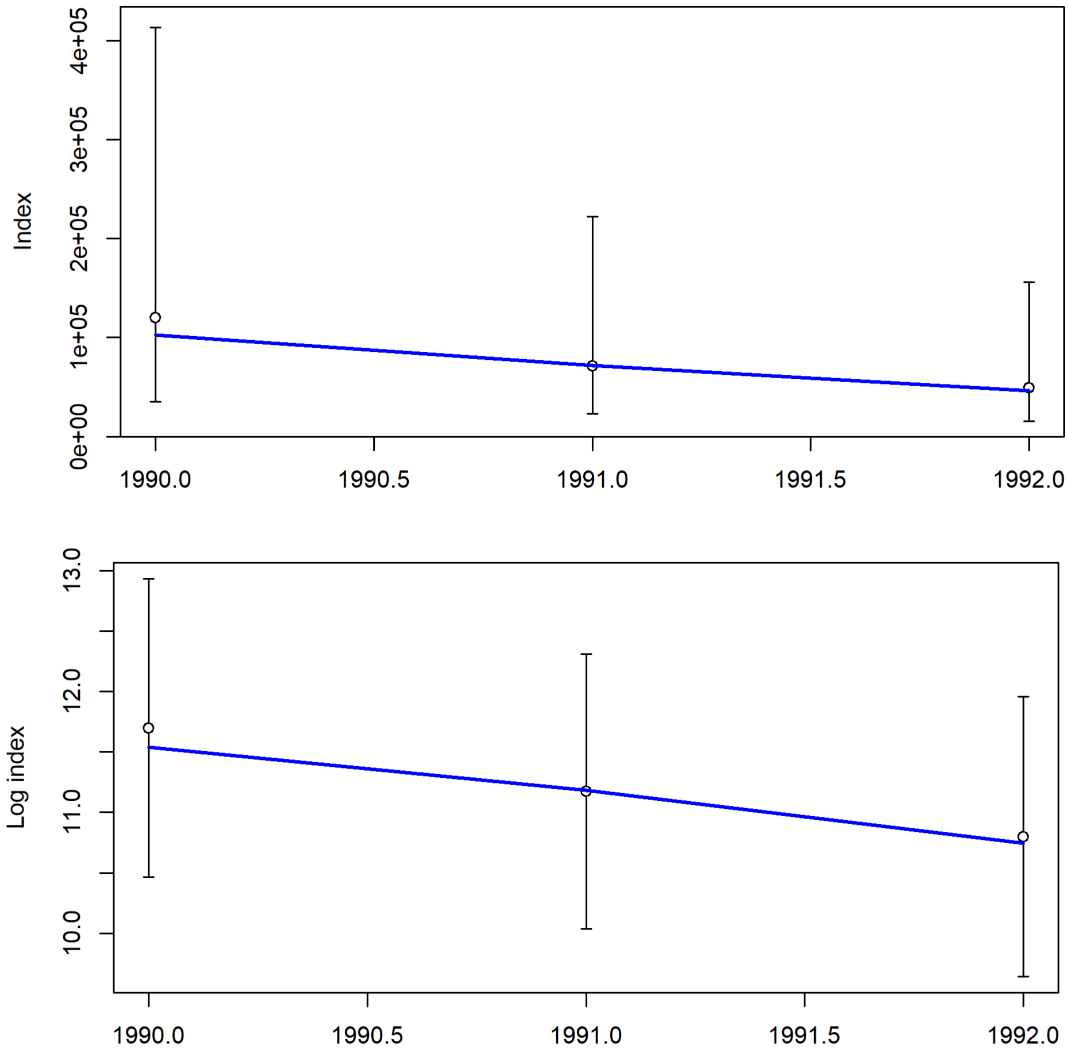


Figure 17. Fits to the biomass indices (top) and log indices (bottom) for the hull surveys for the 2021 base-case model.

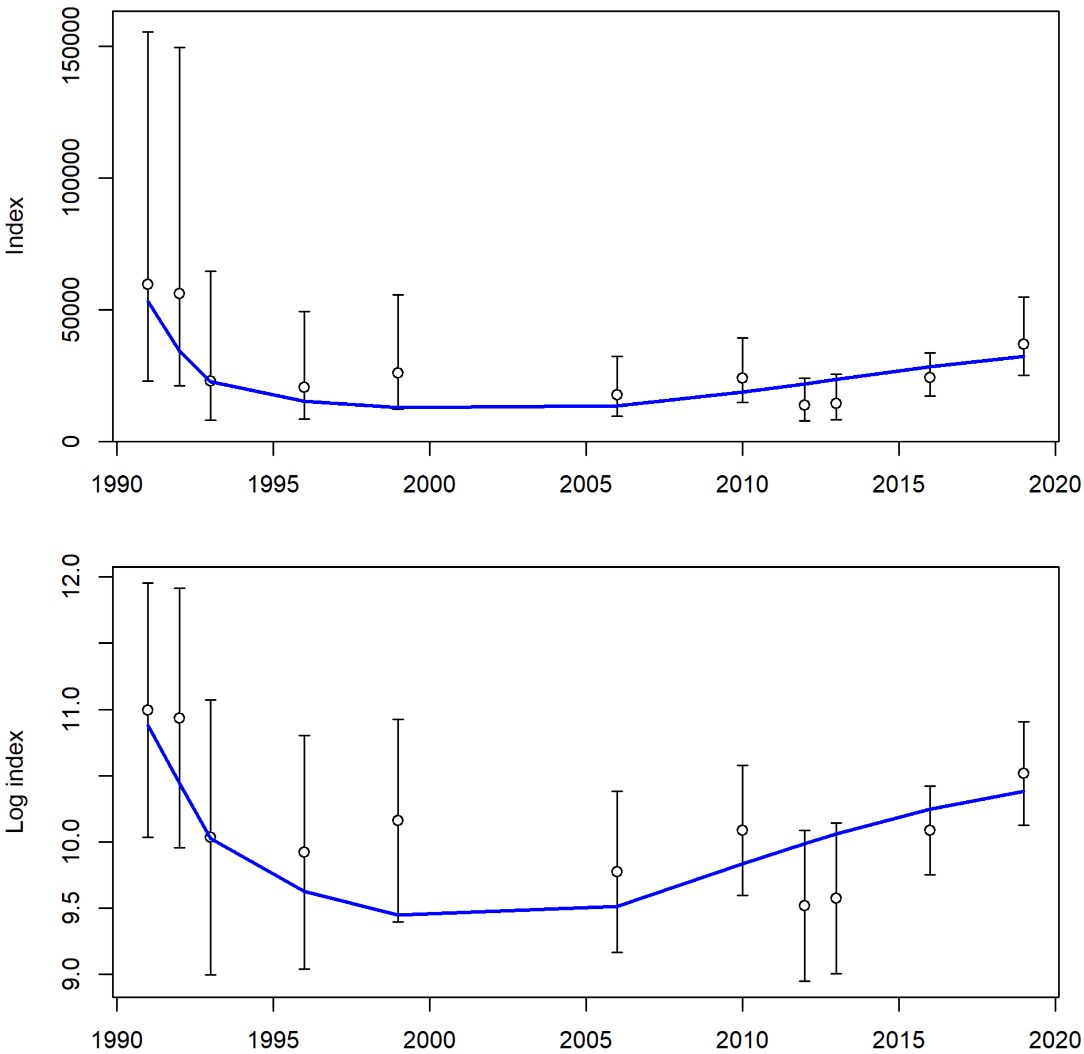


Figure 18. Fits to the biomass indices (top) and log indices (bottom) for the towed surveys for the 2021 base-case model.

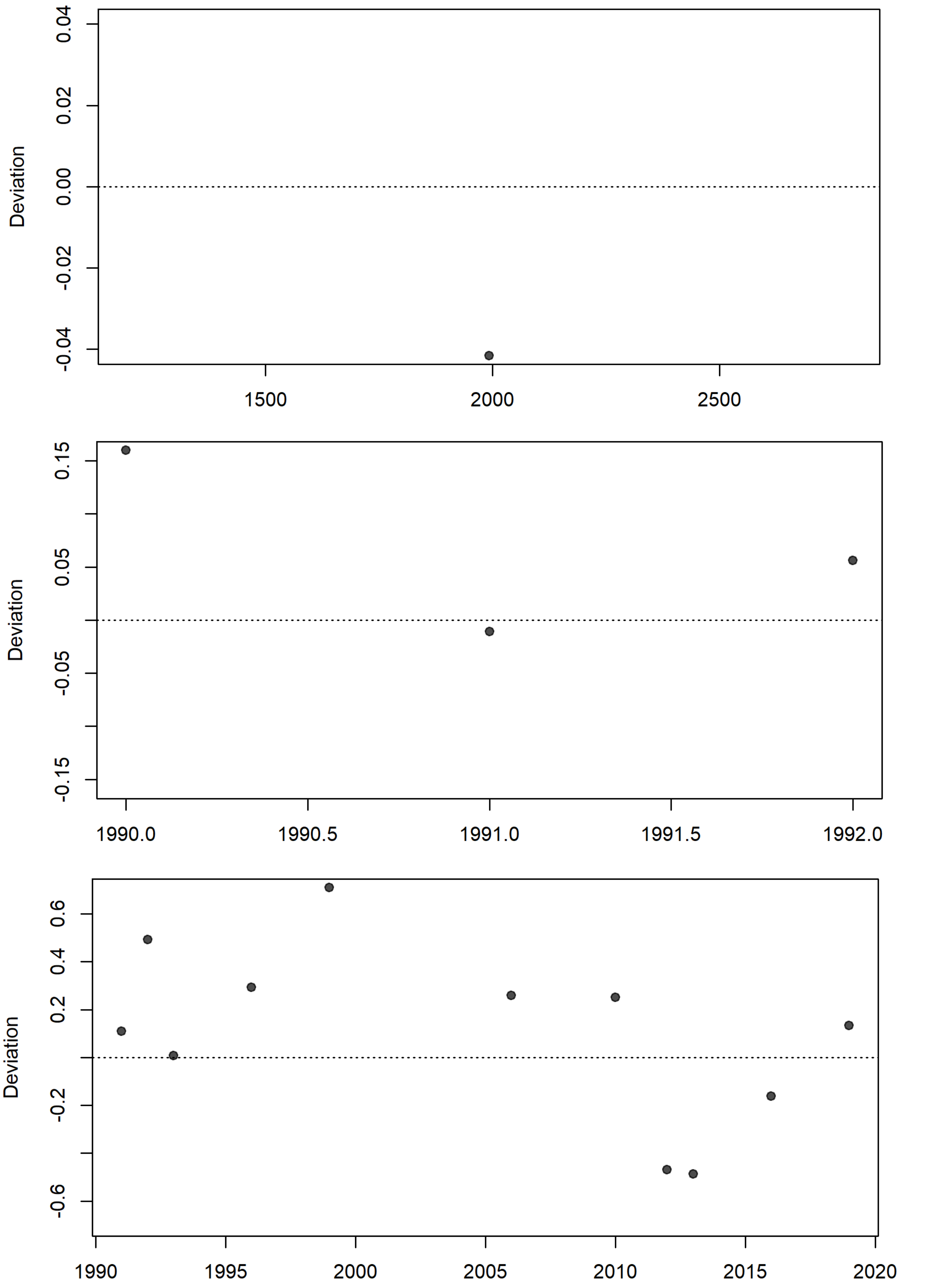


Figure 19. Standardized residuals from fits to the egg survey (top), hull survey (middle) and vessel survey (bottom) indices for the 2021 base-case model.

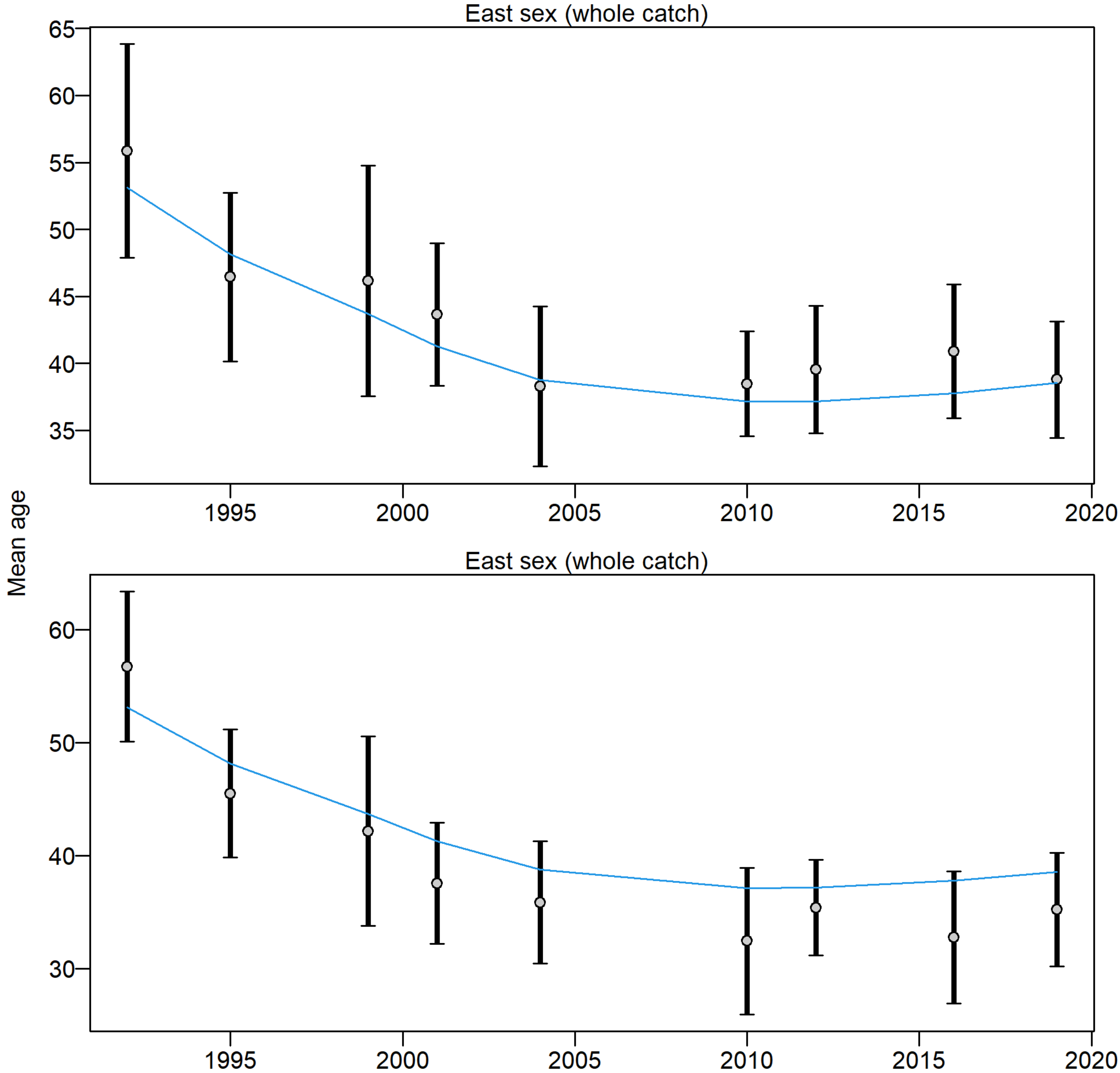


Figure 20. Mean age for male and female samples with 95% confidence intervals based on current sample sizes for the 2021 base-case model. The suggested multiplier for Francis data weighting method TA1.8 of age data with 95% interval is 1.0022 (0.7615-1.7396).

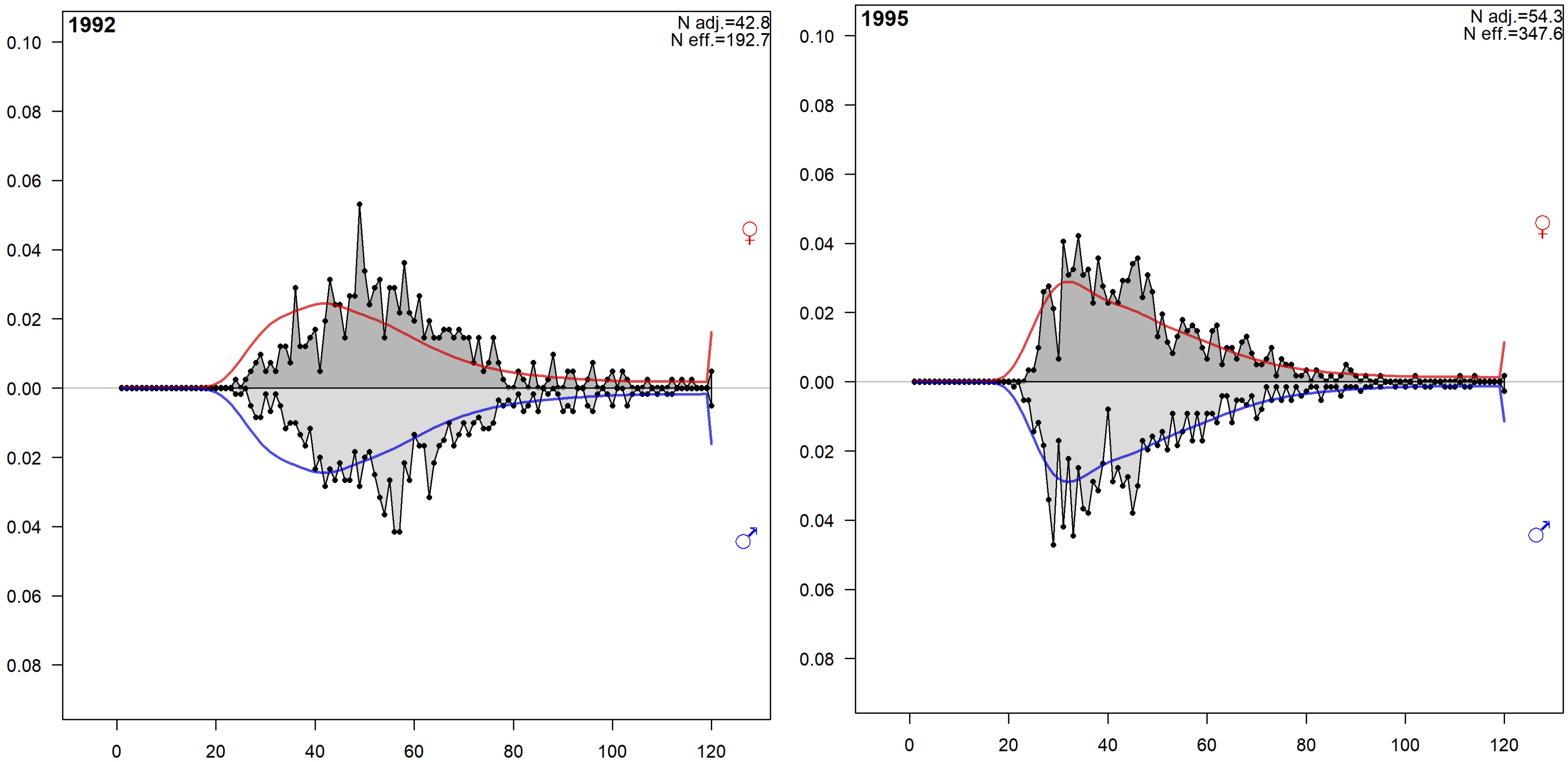


Figure 21. Fits to the 1992 and 1995 age data for the 2021 base-case model.

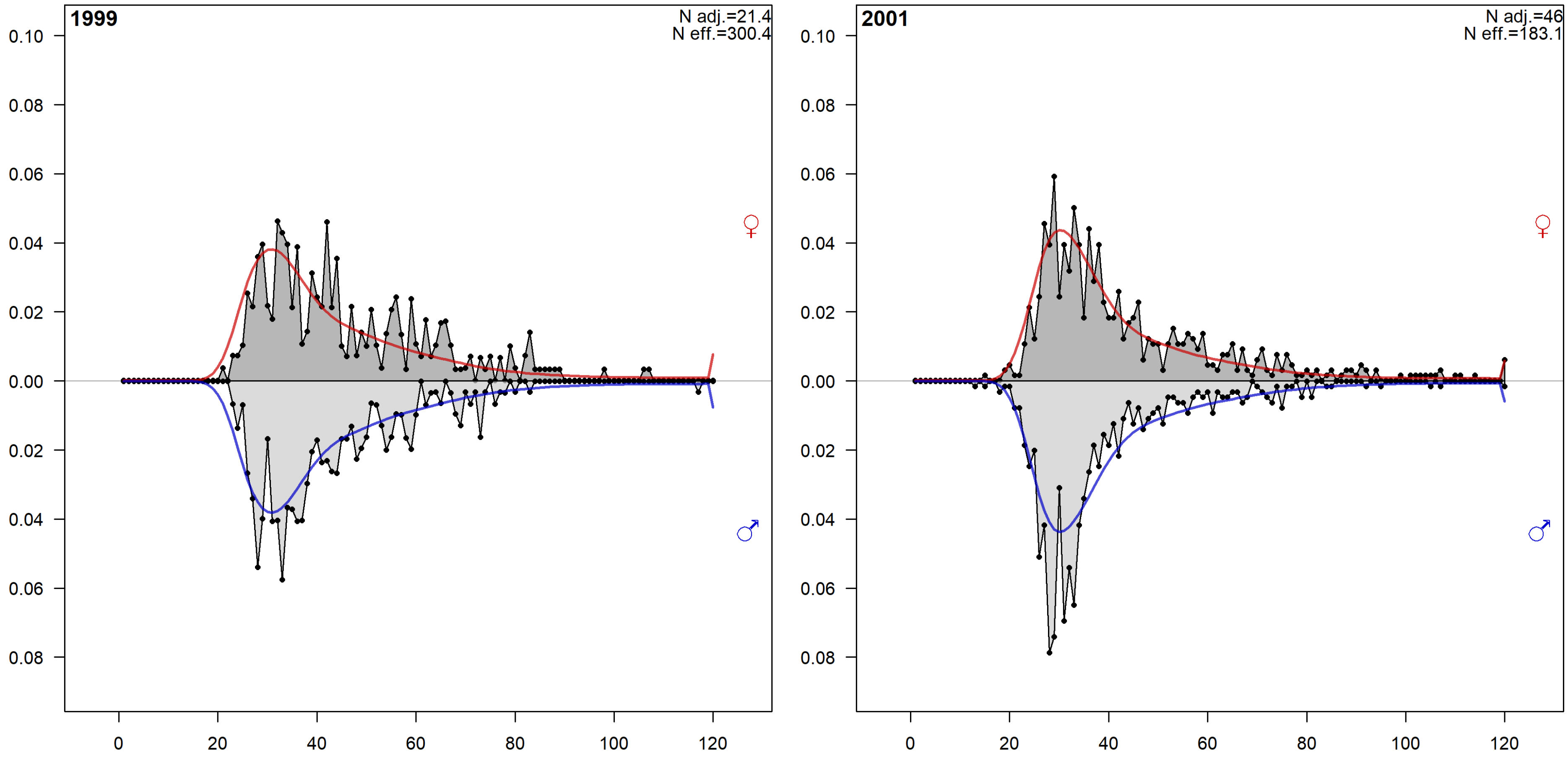


Figure 22. Fits to the 1999 and 2001 age data for the 2021 base-case model.

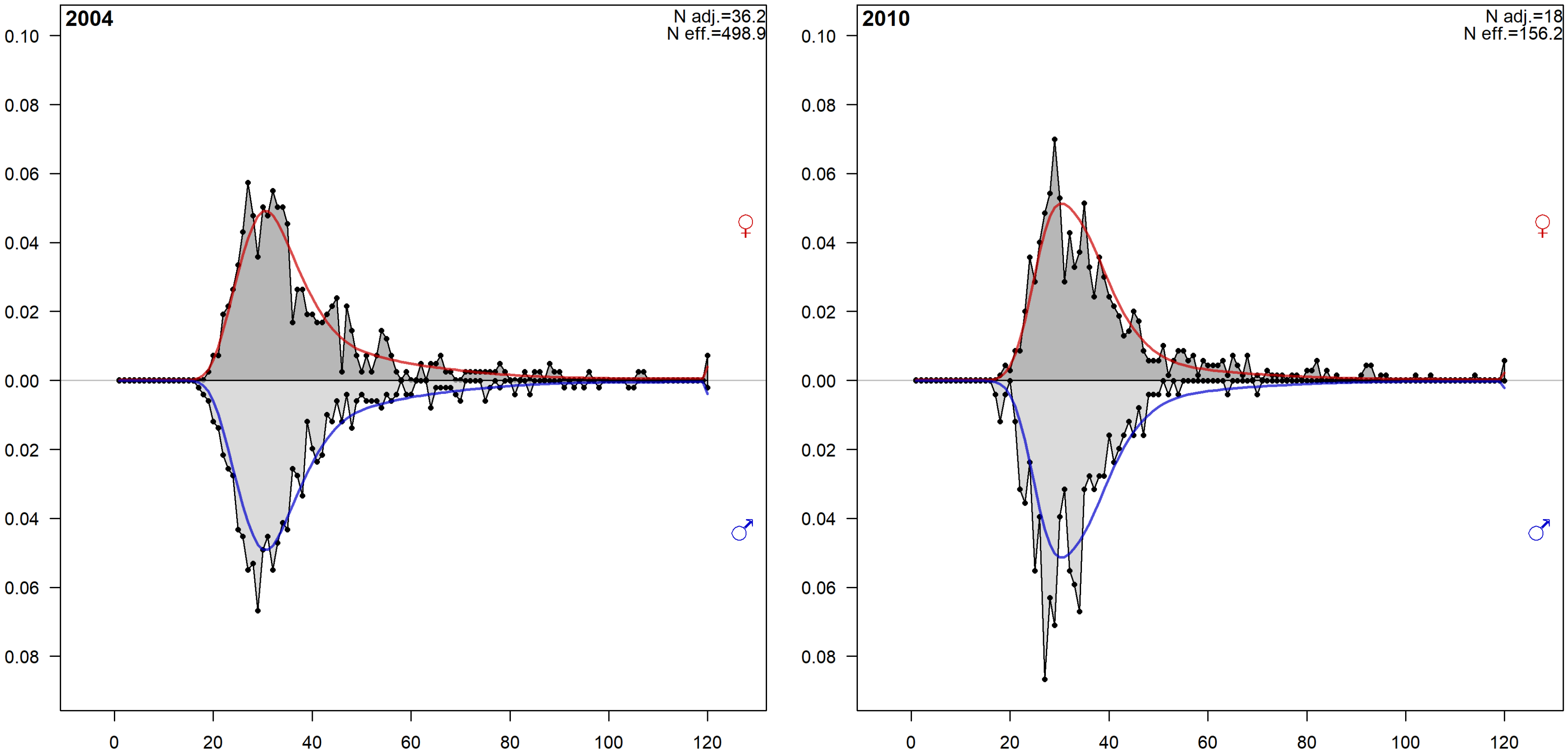


Figure 23. Fits to the 2004 and 2010 age data for the 2021 base-case model.

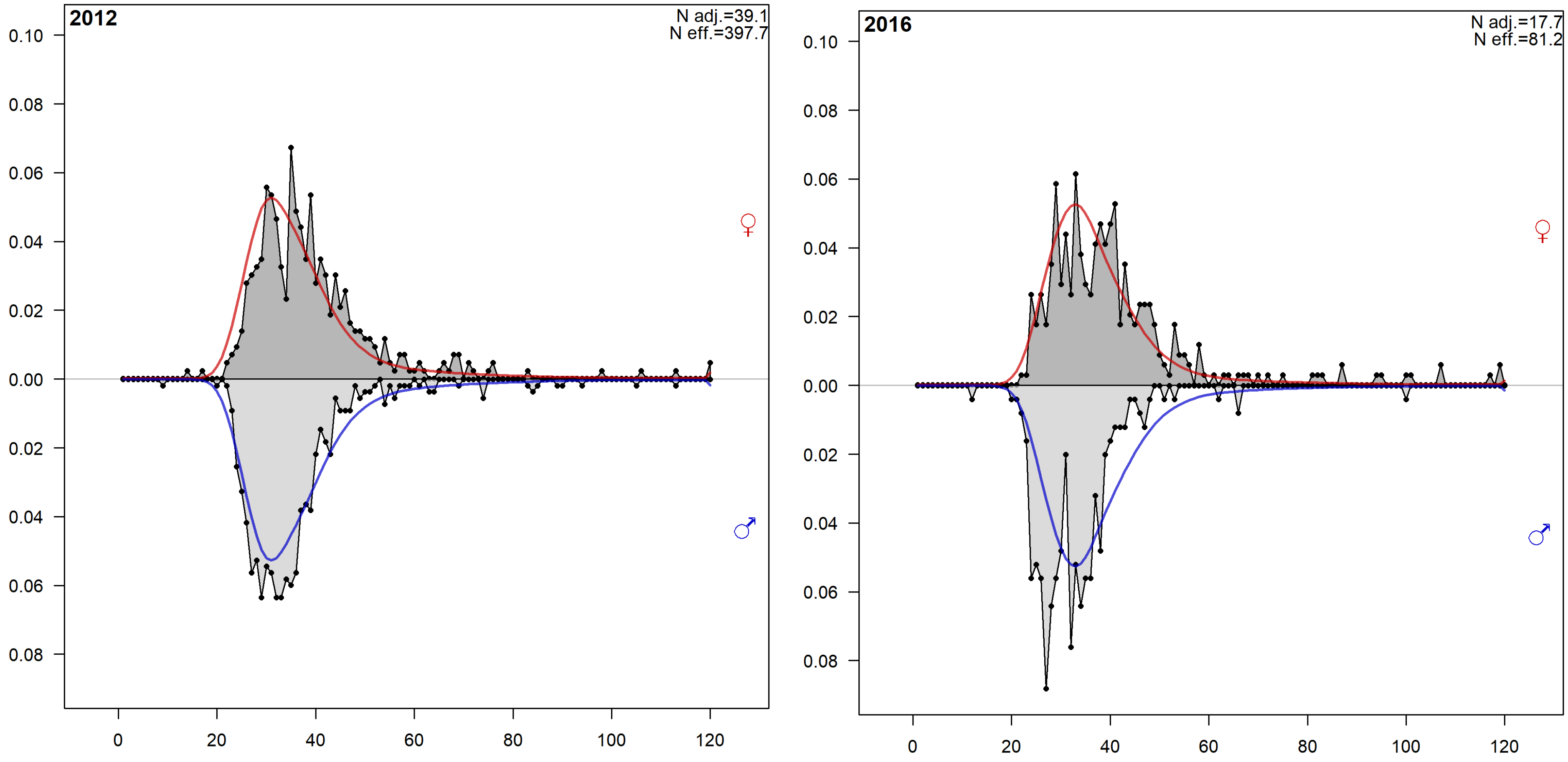


Figure 24. Fits to the 2012 and 2016 age data for the 2021 base-case model.

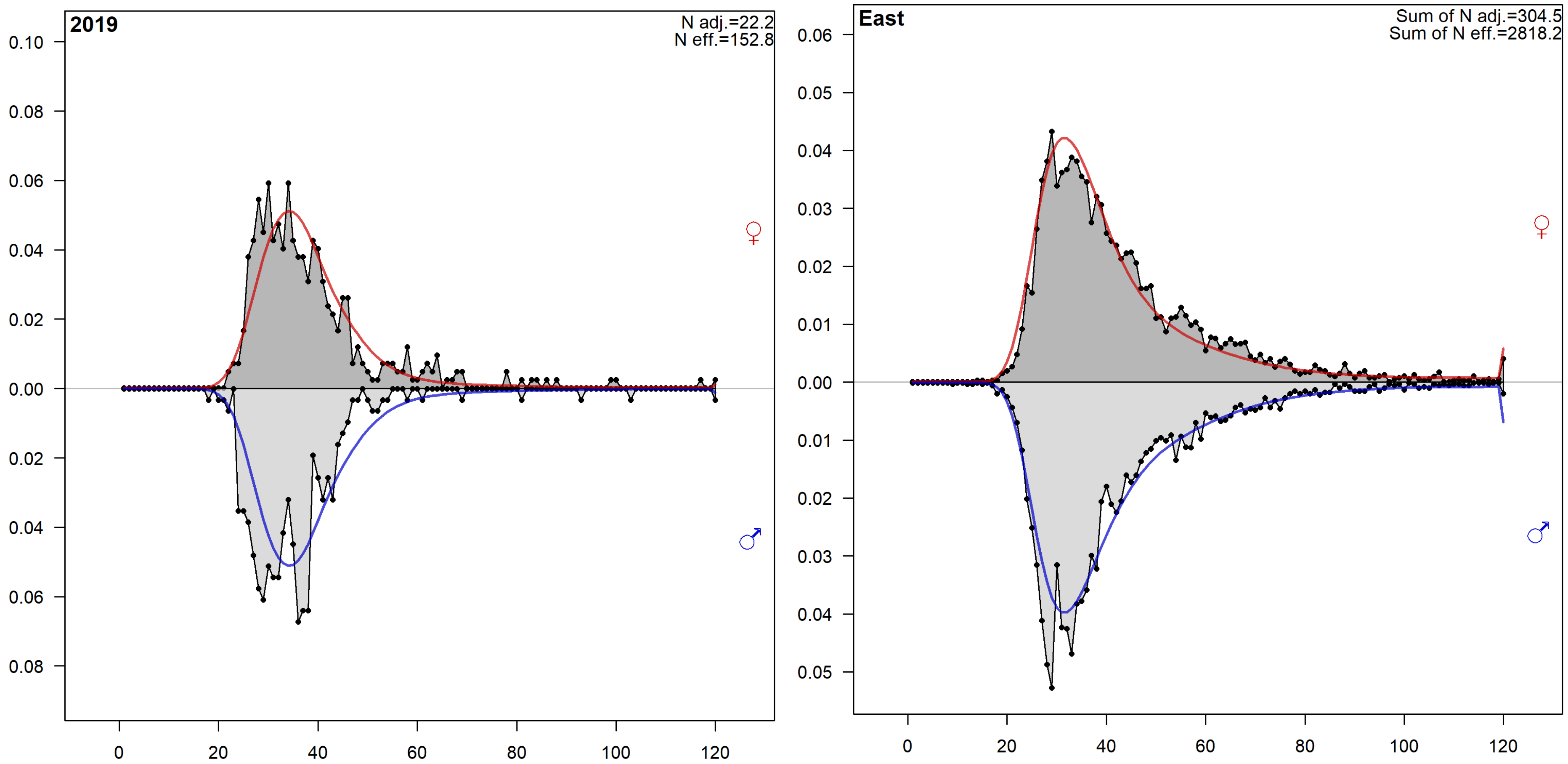


Figure 25. Fits to the 2019 age data (left) and the age data combined for all years (right) for the 2021 base-case model.

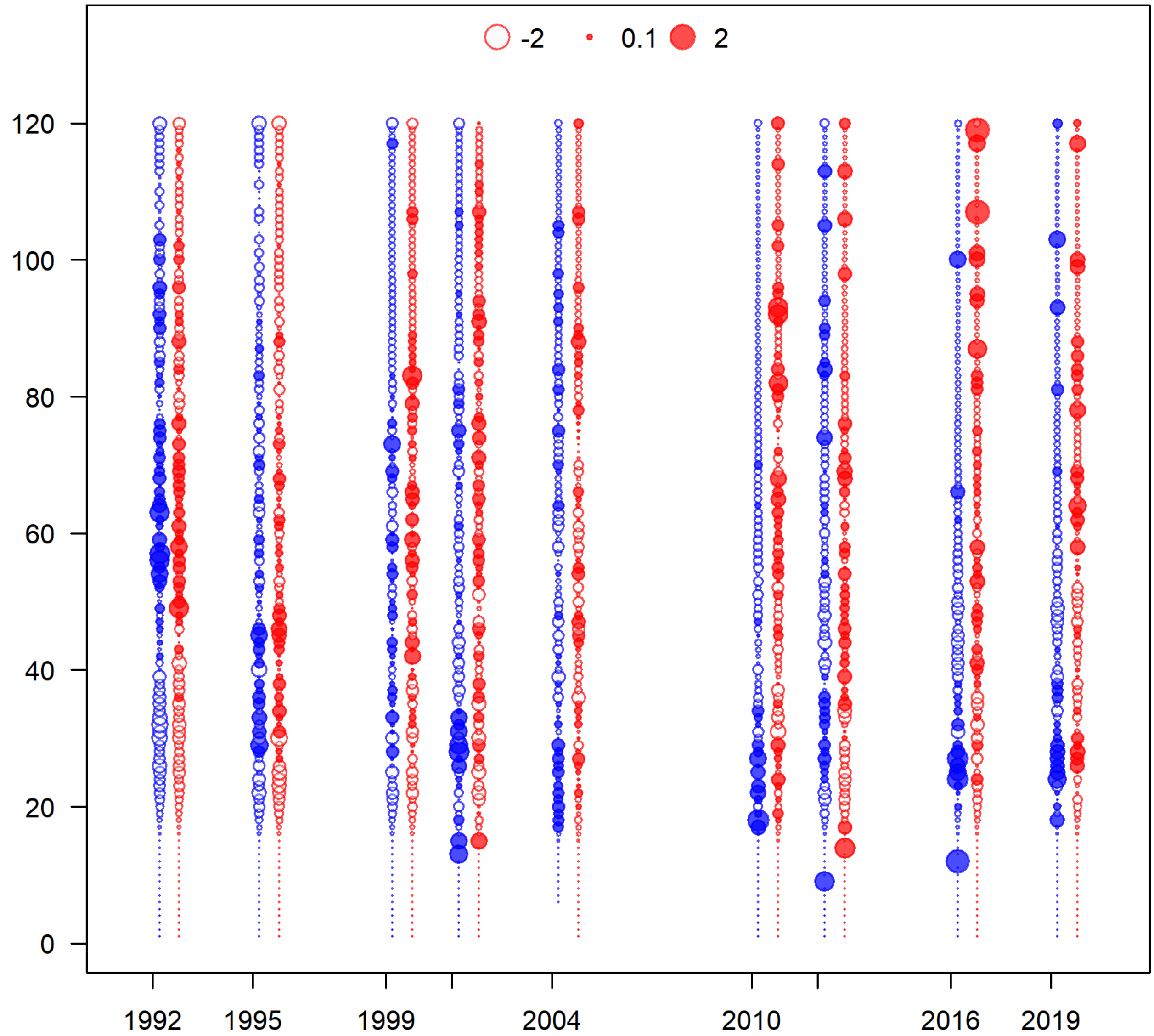


Figure 26. Pearson residuals for age data for the 2021 base-case model. Residuals for males are represented by blue circles and residuals for females by red circles. Filled circles represent positive residuals and unfilled circles represent negative residuals.

Additional calculations to the base-case (sensitivities etc)

Likelihood profiles

The likelihood profile for the steepness of the stock recruitment relationship, *h,* provides essentially no information about this parameter in the assessment (Figure 27). The likelihood profiles on SSB_{1980} and current stock status suggests female spawning biomass immediately prior to the beginning of the fishery was between 47,000 t and 55,000 t, and current stock status is between 24% and 40% of unfished levels (Figures 28 and 29). Note that the assessment estimates the female spawning biomass in 1980 to be around 20% higher than its unfished equilibrium. The likelihood for *M* shows that *M* is likely between 0.031 yr^{-1} and 0.046 yr^{-1} (Figure 30).

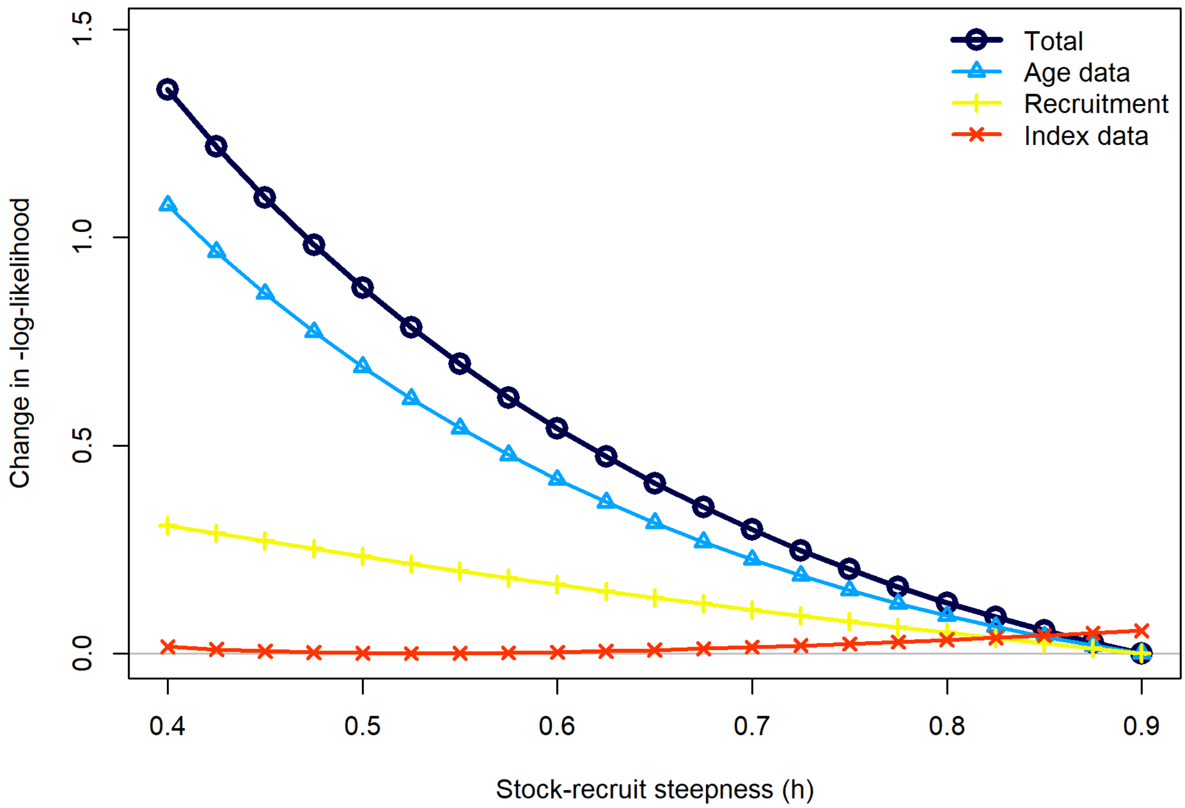


Figure 27. Likelihood profile for steepness of the stock recruitment relationship. The fixed value of steepness used in the 2021 base-case assessment is *h*=0.75.

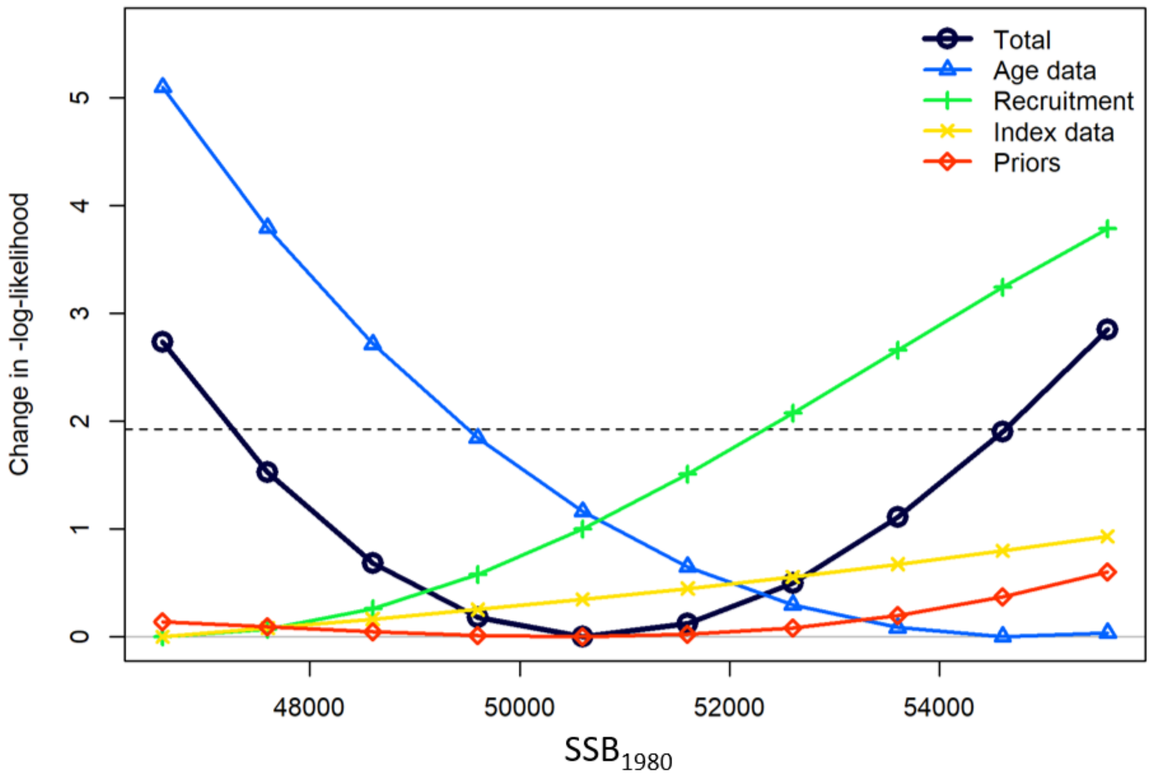


Figure 28. Likelihood profile for unfished female spawning biomass immediately prior to the beginning of the fishery (SSB_{1980}) for the 2021 base-case model. The MPD estimate of SSB_{1980} is 50,685 t. Note the estimate of female spawning biomass in 1980 is above the unfished equilibrium.

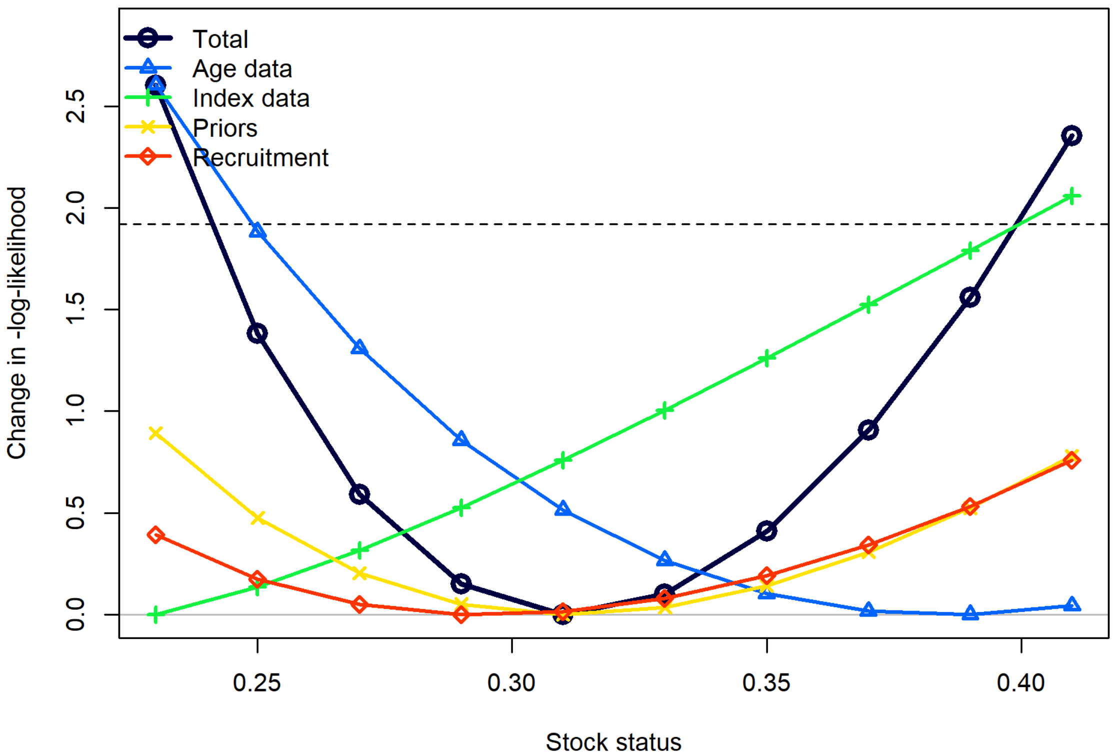


Figure 29. Likelihood profile for stock status in 2020 (SSB_{2020}/SSB_0) for the 2021 base-case model. The MPD estimate of 2020 stock status is 0.312.

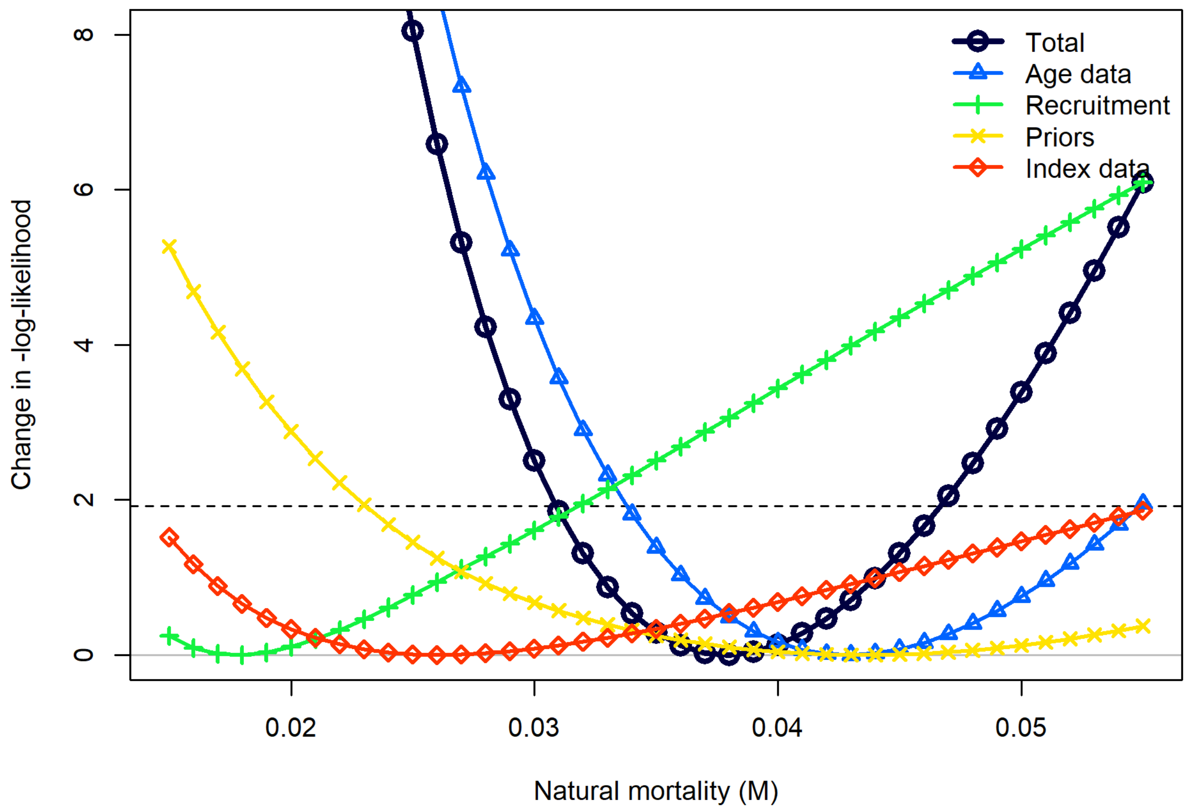


Figure 30. Likelihood profile for natural mortality for the 2021 base-case model. The MPD estimate of natural mortality is *M*=0.0386 yr^{-1}.

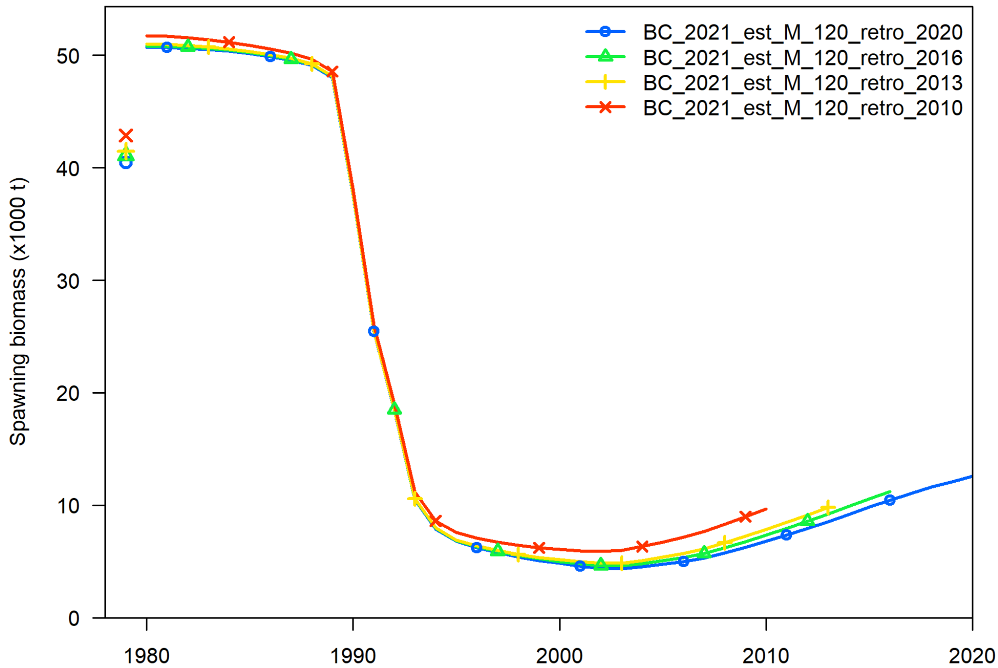
Retrospective analysis

While the trends in the retrospective assessments were the same, the above average absolute recruitment estimated prior to the commencement of the fishery declined by around a third and recent recruitment declined slightly as data were progressively added to the assessment (Figures 31 and 32). The decline in recruitment is observed as slightly lower absolute and relative spawning biomass estimates in each successive assessment. This shows that the estimated productivity of the eastern zone Orange Roughy stock has declined slightly with the collection of additional data over the last decade. The estimated decline is greatest between 2010 and 2013, with more gradual declines from 2013 onwards.

The estimated Mohn's Rho statistics for spawning biomass, recruitment, stock status and fishing mortality (Table 9) were all outside of the range where Hurtado-Ferro et al. (2015) consider the retrospective pattern is cause for concern in an assessment.

Table 9. Estimated Mohn's Rho statistics for the retrospective analysis 2021 base-case model. Values above 0.2 or below -0.15 suggest the retrospective pattern is cause for concern in an assessment (Hurtado-Ferro et al. 2015).

Quantity	Mohn's Rho
Spawning Biomass	0.5974
Recruitment	0.2911
Stock Status	0.4757
Fishing mortality (*F*)	-0.4459



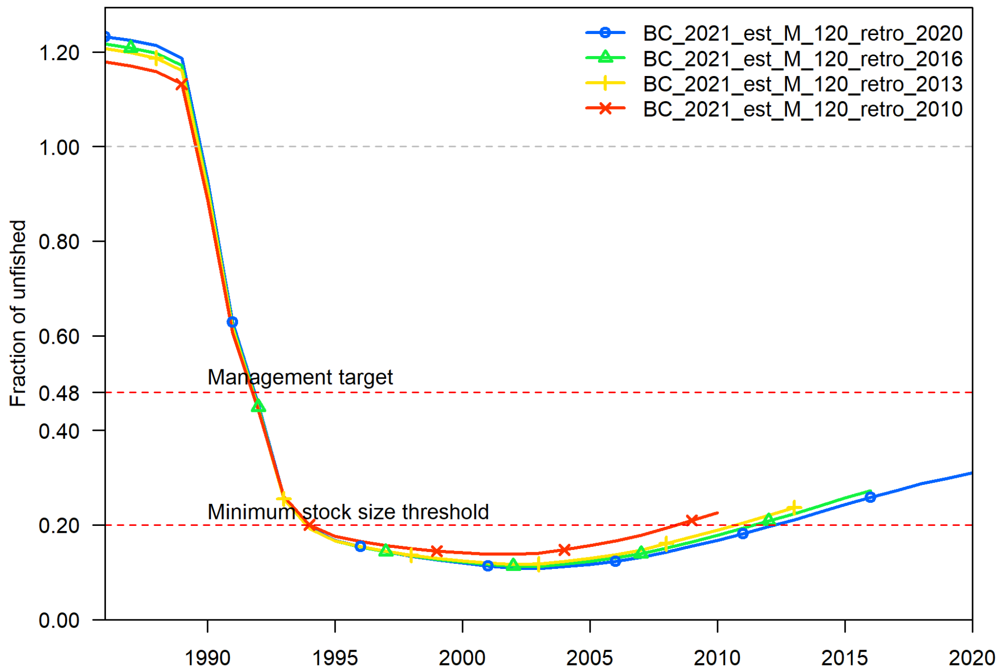
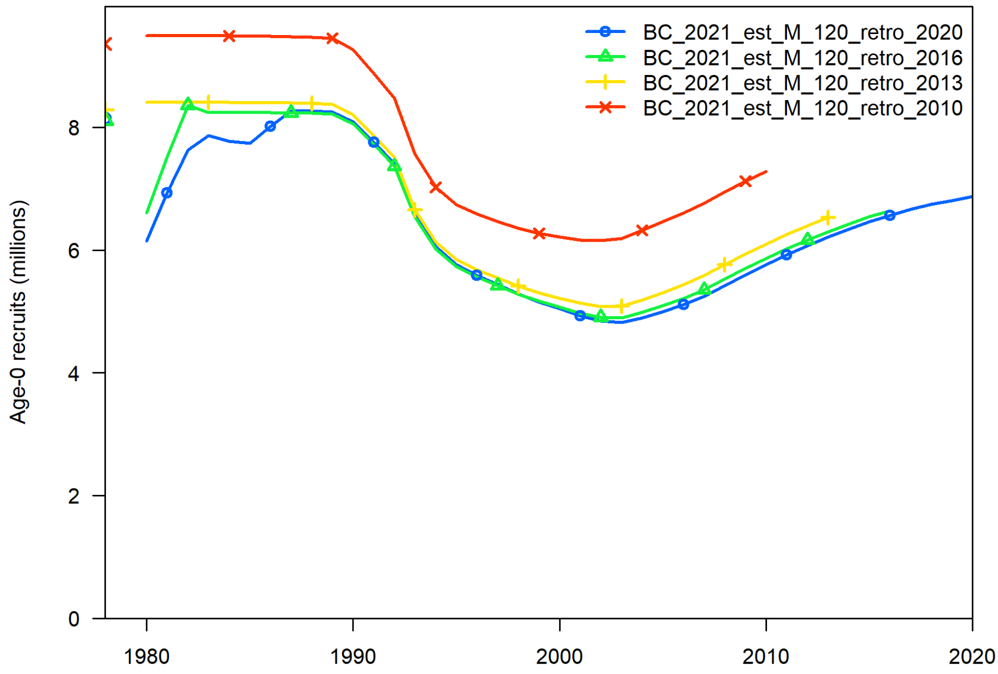


Figure 31. Retrospective analysis showing the absolute (top) and relative (bottom) spawning biomass from assessments that were undertaken after removing four, seven and ten years of data from the 2021 base-case model.



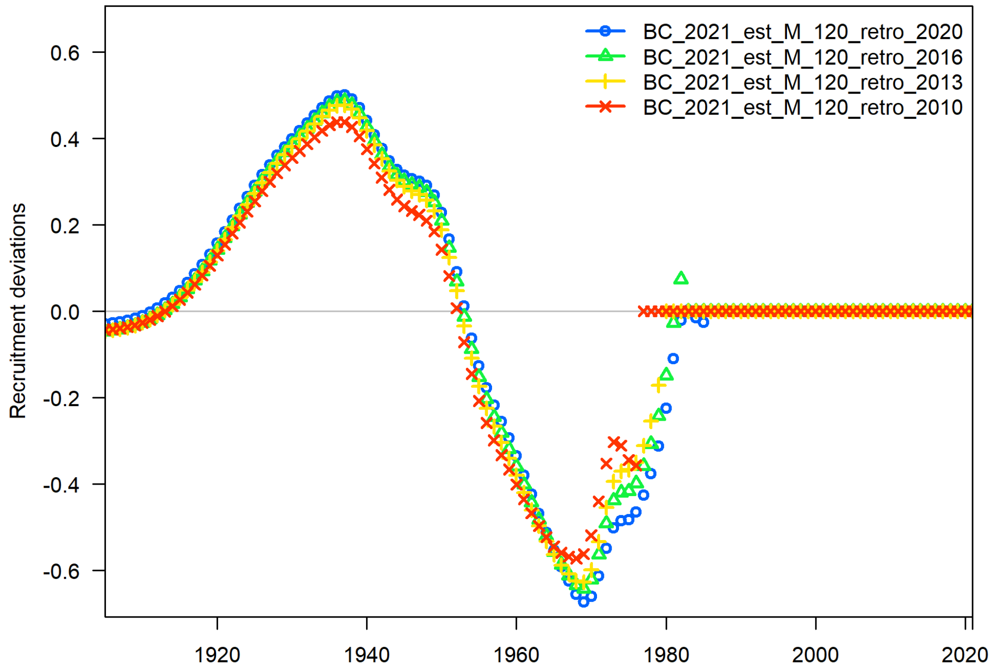


Figure 32. Retrospective analysis showing the absolute recruitment (top) and recruitment deviations (bottom) from assessments that were undertaken after removing four, seven and ten years of data from the 2021 base-case model.

Sensitivities

Sensitivities to the 2021 base-case are provided in Table 10. All sensitivites provide very similar estimates of unfished and current female spawning biomass. The greatest change in current stock status (SSB_0/SSB_{2022}) is between the low and high natural mortality scenarios that estimate current status to be 29.7% and 37.0% respectively.

Table 10. Sensitivities to the 2021 base-case model. NLL and ΔNLL represent the negative log-likelihood and change in negative log-likelihood compared with the base-case.

Scenario	NLL	ΔNLL	SSB_0	SSB_{2022}	SSB_0/SSB_{2022}
2021 base-case	83.72	0	40,479	13,126	0.3243
Low steepness (*h=0.6)*	84.06	0.3	40,363	12,783	0.3167
High steepness (*h=0.9)*	83.72	0.0	40,479	13,126	0.3243
Low recruitment variability (σ_R*=0.6)*	85.97	2.2	41,236	13,893	0.3369
High recruitment variability (σ_R*=0.8)*	82.05	-1.7	39,987	12,586	0.3148
Low natural mortality (*M*=0.0358)	84.14	0.4	40,612	12,067	0.2971
High natural mortality (*M*=0.0432)	83.97	0.2	40,606	15,029	0.3701
Halve the weighting on the age data	39.91	-43.8	42,225	13,740	0.3254
Double the weighting on the age data	166.27	82.5	38,660	12,298	0.3181
Remove the 1992 egg survey	84.41	0.7	40,485	13,135	0.3244
Use the estimated catch of 1,350t for 2021	83.72	0	40,479	13,138	0.3246
Use the 2021 TAC of 1,569t for 2021	83.72	0	40,479	13,083	0.3232

Discussion

The primary objective of the 2021 eastern zone Orange Roughy stock assessment was to account for the uncertainty in *M*. We proposed to do this by estimating *M* within the assessment using an informative prior developed from New Zealand Orange Roughy assessments. We were able to successfully estimate *M* within the assessment and SERAG chose to adopt the model that estimates *M* with a plus group at 120 years as the agreed base-case assessment.

The estimated parameters and derived quantities from the MPD of the assessment were sufficiently different from the MCMC analysis to have an impact on the estimated RBC. The ORSC provided clear advice that RBCs from the MCMC analysis were preferable to those from the MPD because the MCMC analysis better acounts for uncertainty within the data and parameter space.

There is a clear retrospective pattern in the assessment that shows the estimated productivity of the stock has declined as more data had been collected over the last decade. While the magnitude of the decine has slowed since 2013, the presence of the retrospecitive pattern should be considered by SERAG when providing management advice. Future assessments should investigate the potential misspecification in the assessment driving this pattern.

The 2021 eastern zone Orange Roughy stock assessment has focused on exploring the estimation *M* within the assessment using an informative prior developed from New Zealand Orange Roughy stocks. There are several other uncertainties associated with the eastern zone Orange Roughy assessment that should be investigated in future assessments. These are;

1. Review the method for developing catchability priors for the acoustic surveys and update the prior for the towed body survey.
2. Work with Fish Ageing Services to review the age data and the relative weighting of age samples collected from St Helens Hill and St Patricks Head.
3. The model that is used to estimate are reading error is sensitive to the starting values of the model parameters.
4. Maturity appears to be mis-specified in the assessment, as it should be the same as selectivity. Investigate whether there is sufficient data to estimate maturity within the assessment (as is done for some New Zealand Orange Roughy stocks). If there are insufficient data to estimate maturity within the assessment then update the fixed values of the maturity parameters if recent data is available.
5. The selectivity of the trawl fleet and the acoustic surveys is the same and poorly estimated. Investigate whether it is possible to separate them.
6. Kloser and Sutton (2020) have observed that length-weight relationship measured during acoustic surveys over the last decade has been consistently higher than length-weight relationship from Lyle et al. (1991). This may indicate a change in the condition of Orange Roughy since the early period of the fishery.
7. The stock structure hypothesis for Australian Orange Roughy should be further investigated. Exploratory fishing for Orange Roughy is currently being undertaken on non-spawning components of the Orange Roughy populations in the western and Albany and Esperance (GAB) zones. If the stock structure hypothesis for eastern zone Orange Roughy is incorrect there is the risk that the population being fished in the eastern zone is subject to additional fishing of the non-spawning component. An example of the

potential stock structure investigations is provided for New Zealand Orange Roughy by Dunn and Devine (2010).

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Appendix A – Additional tables and figures

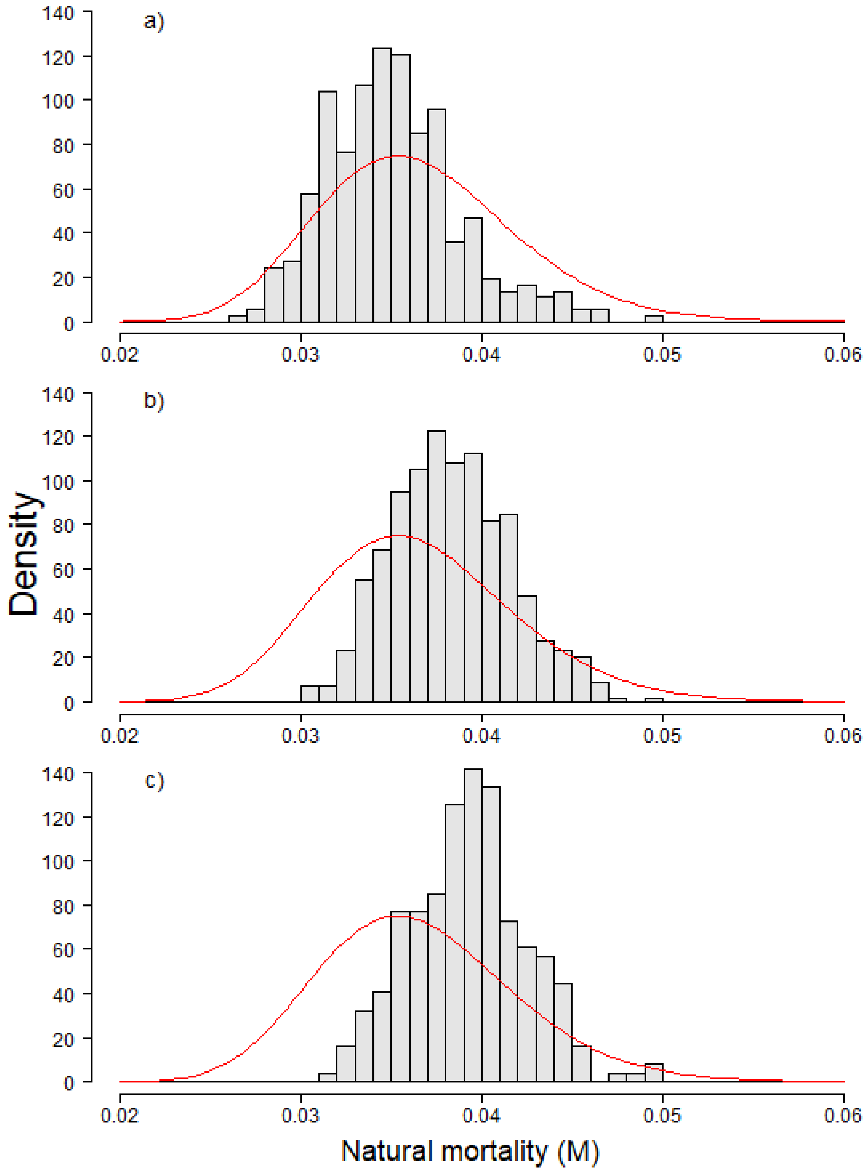

Figure 33. Histograms of natural mortality estimates from posteriors of candidate 2021 preliminary base-case models with plus-groups at 80 (a), 100 (b) and 120 (c) years. The red line represents the log-normal prior used to estimate *M* within the models. Reproduced from the preliminary base-case assessment (Burch and Curin Osorio 2021).

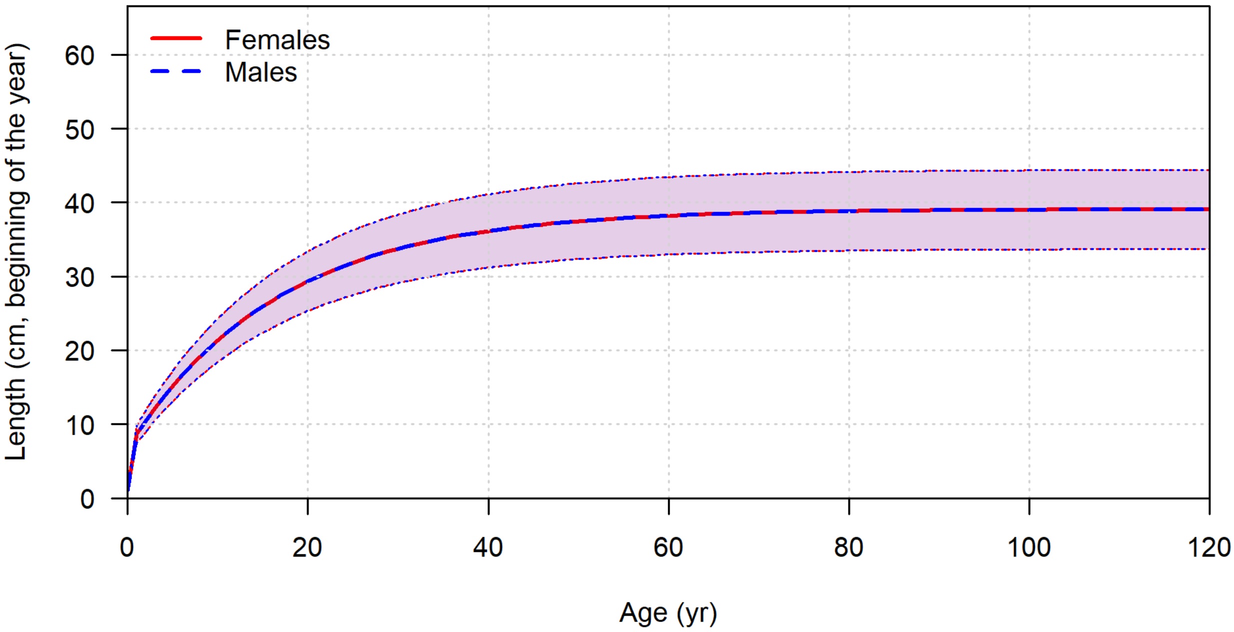

Figure 34. Prespecified growth for the 2021 base-case model.

Table 11. MCMC diagnostics from 1,750 samples of the posteriors for the estimated parameters (excluding the recruitment deviations) of the 2021 base-case model. Diagnostics are the autocorrelation, the Geweke statistic, the effective sample size (N_{eff}/N) and the Heidelberger-Welch convergence diagnostic.

Parameter	Autocorrelation	Geweke	N_{eff}/N	Heidel-Welsch
M	0.007	-0.733	1750	Passed
ln(R₀)	0.080	-1.780	1168	Passed
towed *q*	0.080	0.950	1181	Passed
hull *q*	0.020	1.244	1750	Passed
Selectivity inflection	0.335	0.614	186	Passed
Selectivity width	0.905	3.000	87	No test

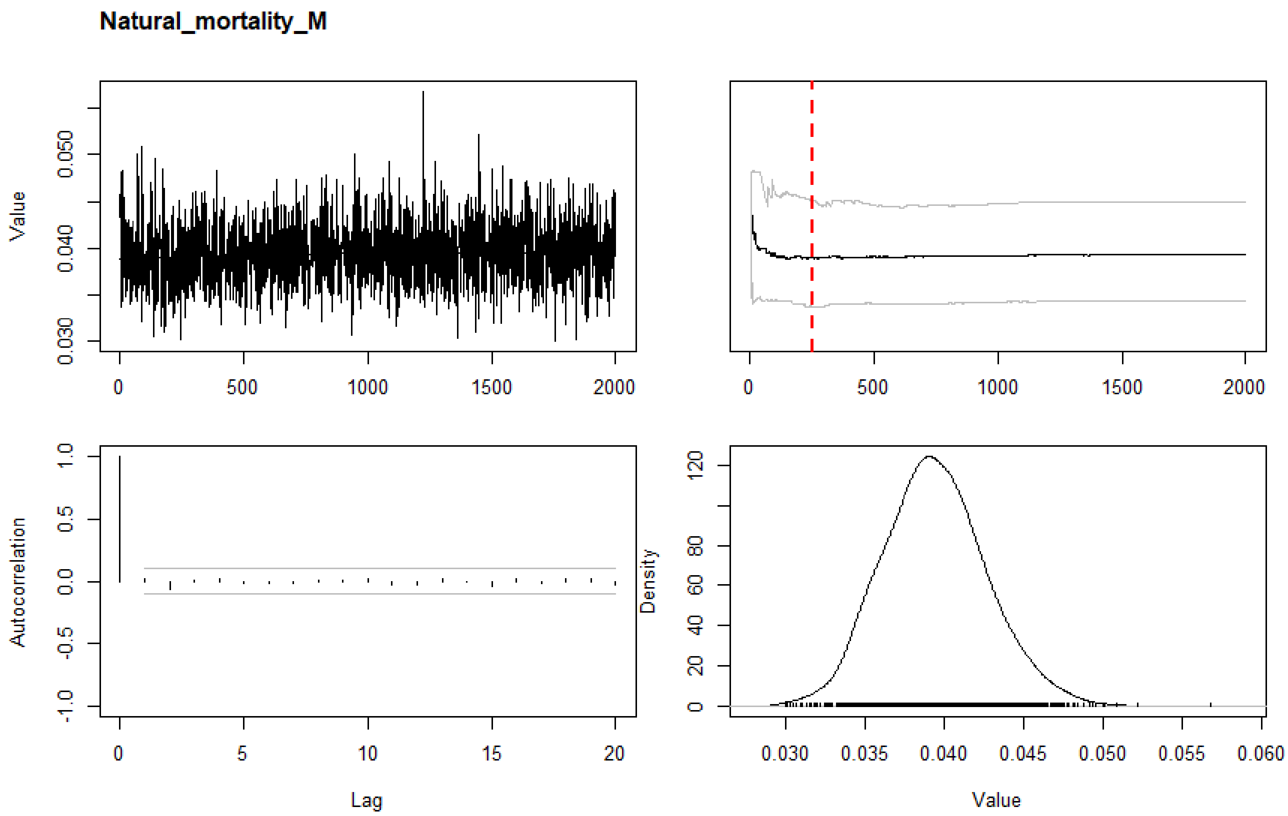

Figure 35. Plots of traces (top left), moving average (top right), autocorrelations (bottom left), and density (bottom right) for natural mortality from 2,000 samples of the posterior from the MCMC analysis of the 2021 base-case model. The dashed red line indicates the additional burn-in of 250 samples that has been excluded for providing management advice.

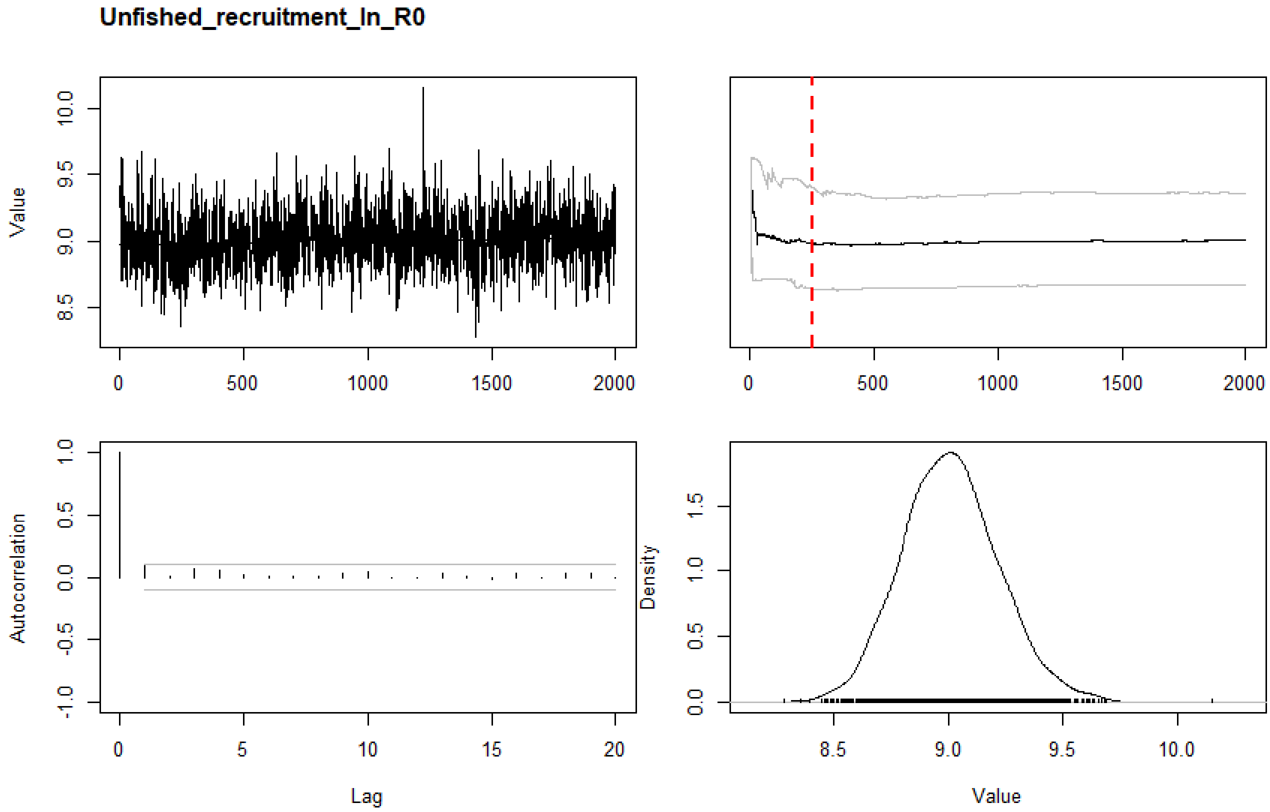

Figure 36. Plots of traces (top left), moving average (top right), autocorrelations (bottom left), and density (bottom right) for unfished recruitment (ln(R0)) from 2,000 samples of the posterior from the MCMC analysis of the 2021 base-case model. The red dashed line indicates the additional burn-in of 250,000 samples from the posterior that has been excluded for providing management advice.

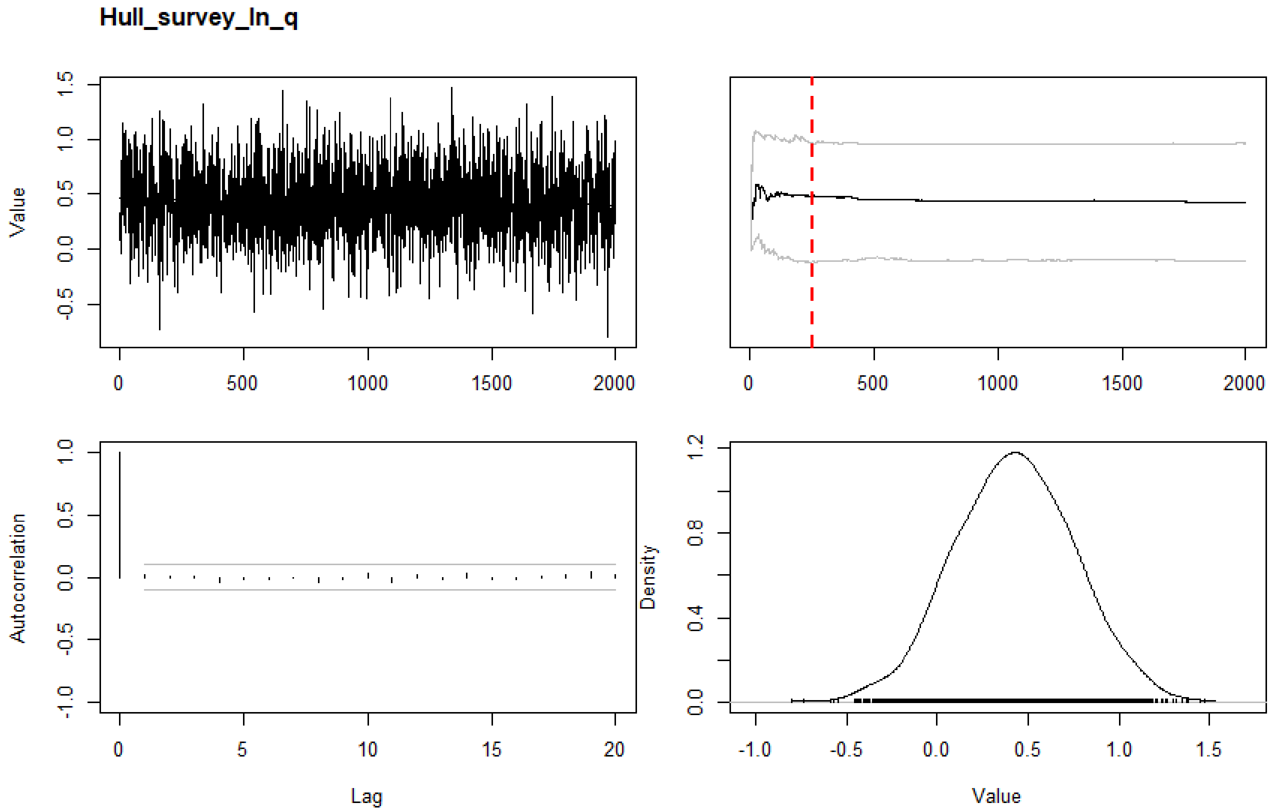

Figure 37. Plots of traces (top left), moving average (top right), autocorrelations (bottom left), and density (bottom right) for catchability of the hull acoustic survey (ln(q)) from 2,000 samples of the posterior from the MCMC analysis of the 2021 base-case model. The red dashed line indicates the additional burn-in of 250,000 samples from the posterior that has been excluded for providing management advice.

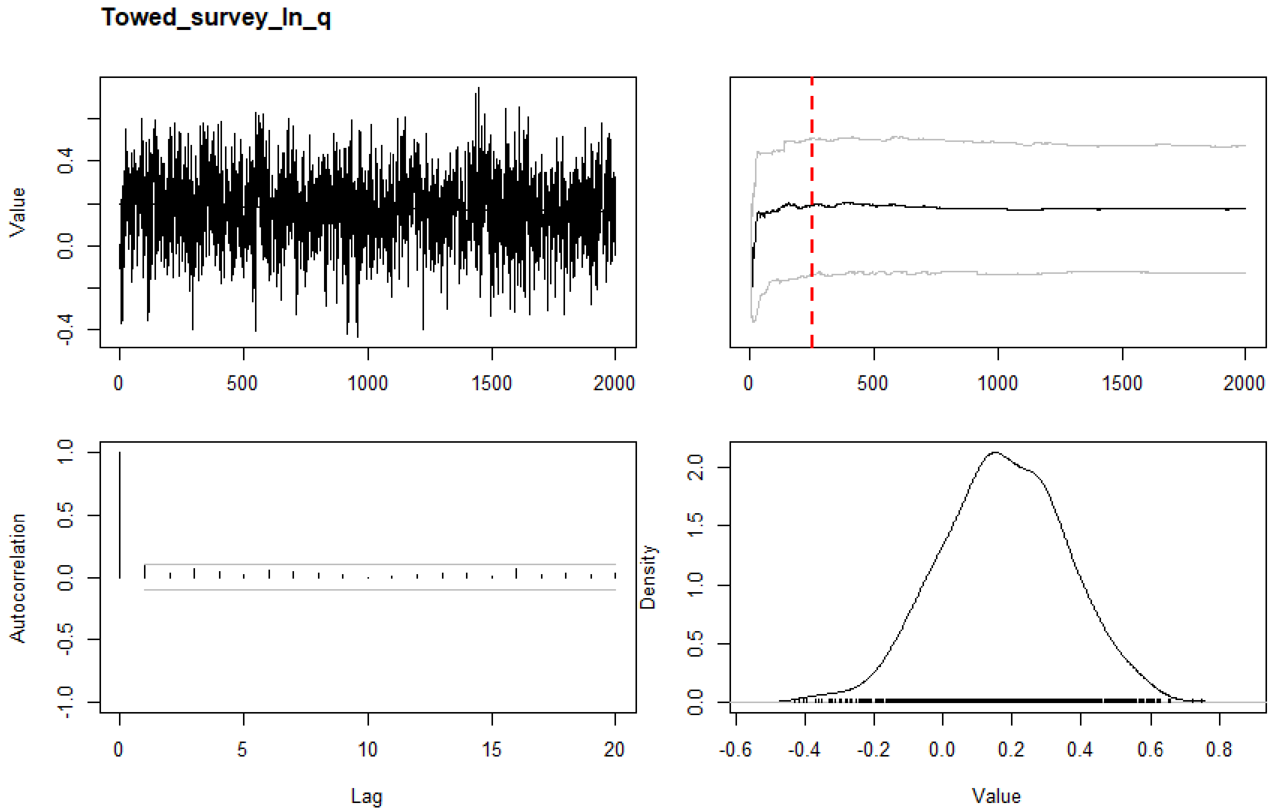

Figure 386. Plots of traces (top left), moving average (top right), autocorrelations (bottom left), and density (bottom right) for catchability of the towed body acoustic survey (ln(q)) from 2,000 samples of the posterior from the MCMC analysis of the 2021 base-case model. The red dashed line indicates the additional burn-in of 250,000 samples from the posterior that has been excluded for providing management advice.

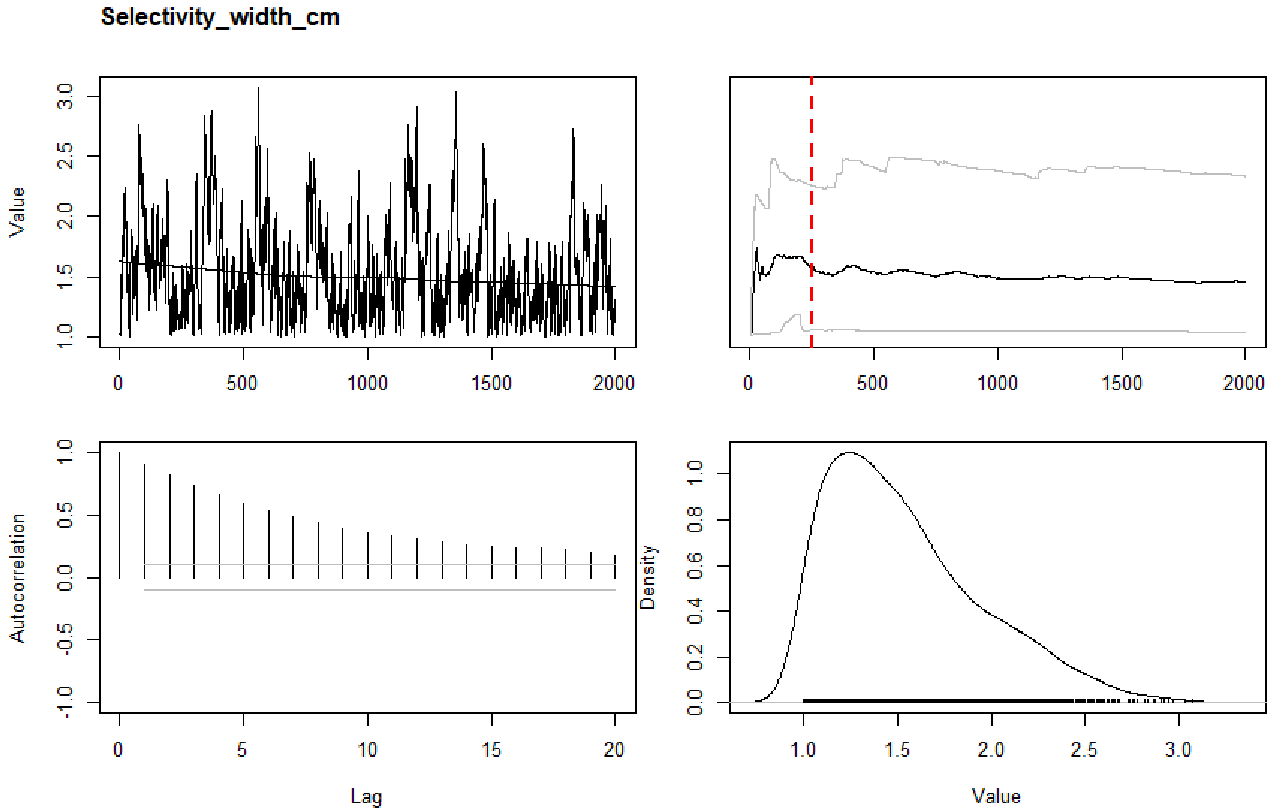

Figure 39. Plots of traces (top left), moving average (top right), autocorrelations (bottom left), and density (bottom right) for the width parameter of the logistic selectivity function from 2,000 samples of the posterior from the MCMC analysis of the 2021 base-case model. The red dashed line indicates the additional burn-in of 250,000 samples from the posterior that has been excluded for providing management advice.

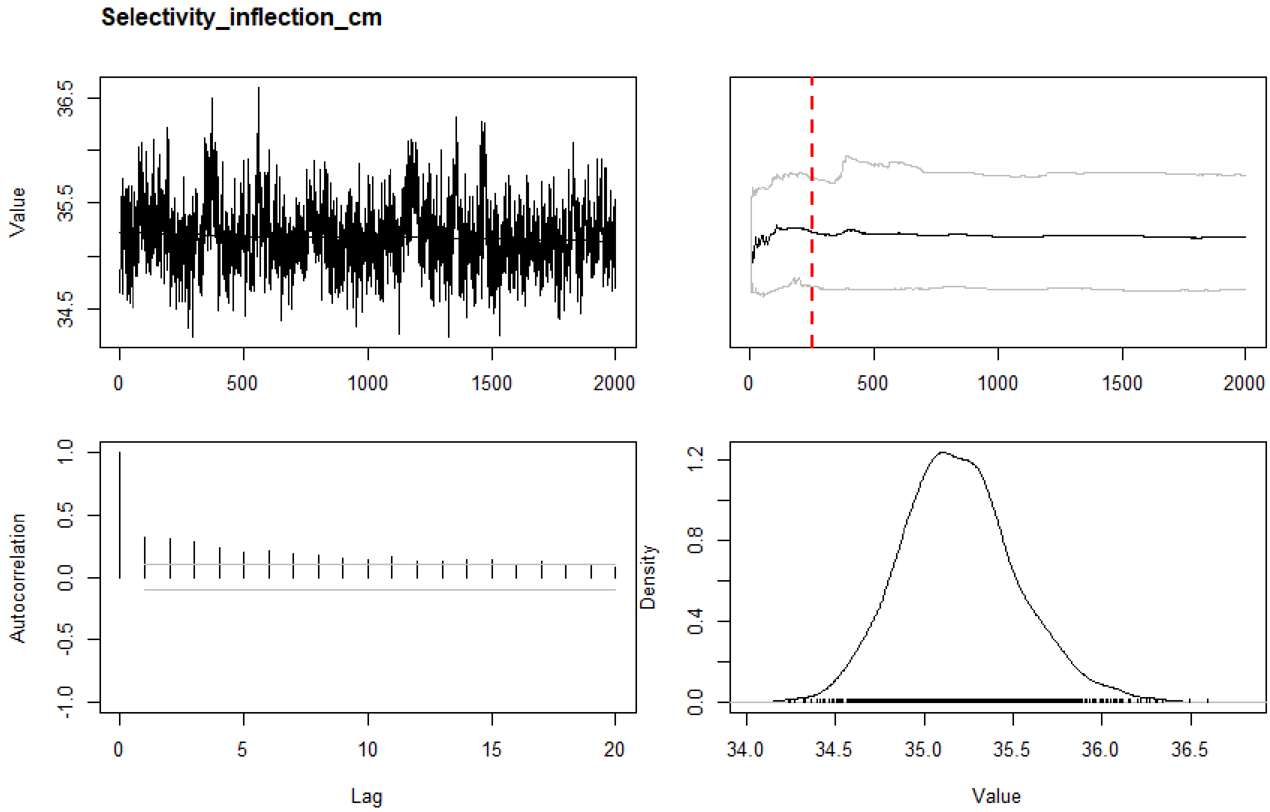

Figure 40. Plots of traces (top left), moving average (top right), autocorrelations (bottom left), and density (bottom right) for the inflection parameter of the logistic selectivity function from 2,000 samples of the posterior from the MCMC analysis of the 2021 base-case model. The red dashed line indicates the additional burn-in of 250,000 samples from the posterior that has been excluded for providing management advice.

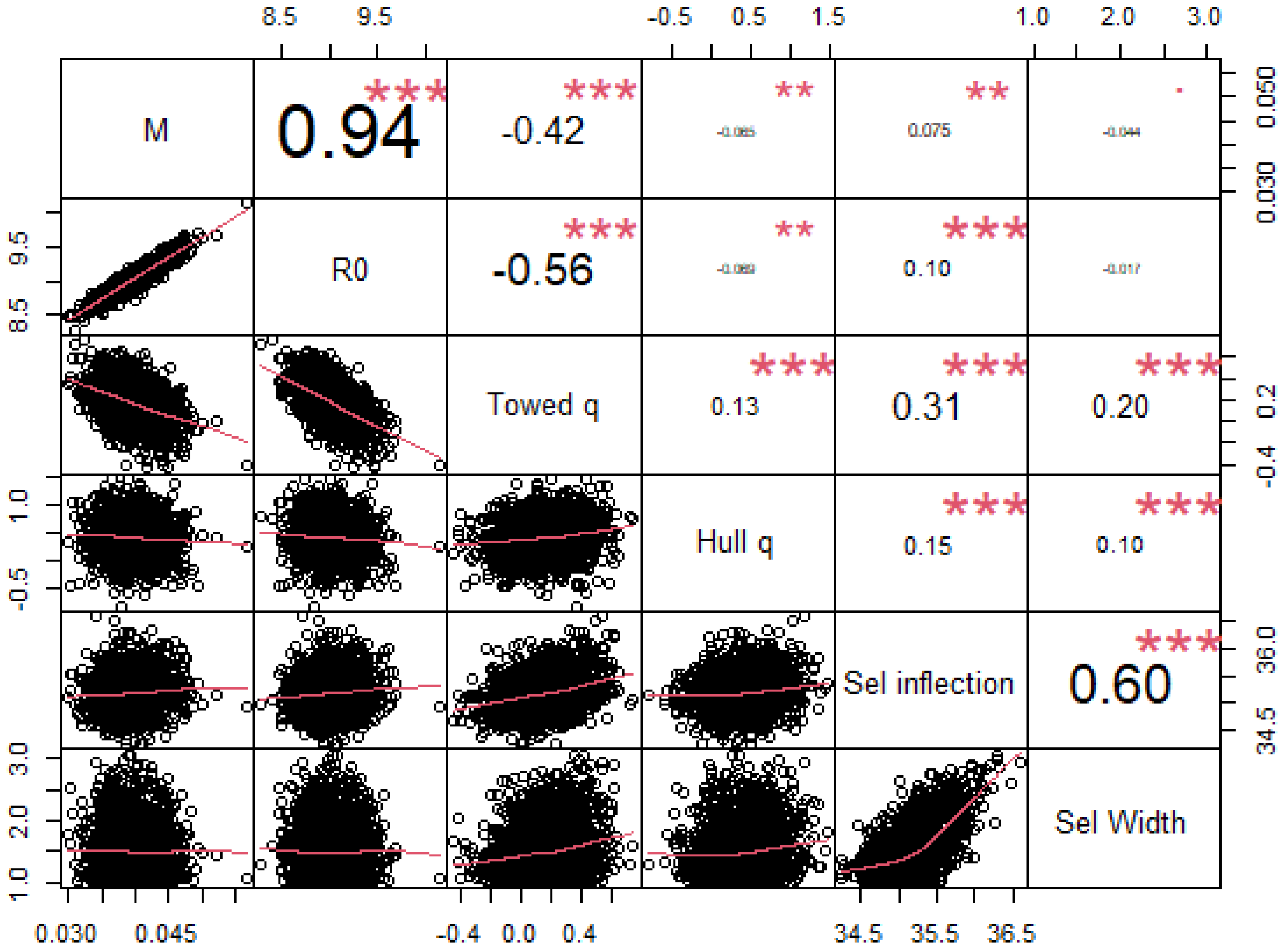

Figure 41. Cross correlations between parameters estimated parameters from 1,750 samples of the posterior from the MCMC analysis of the 2021 base-case model. The numbers in the diagonal above the parameter names are the Pearson correlation coefficients.

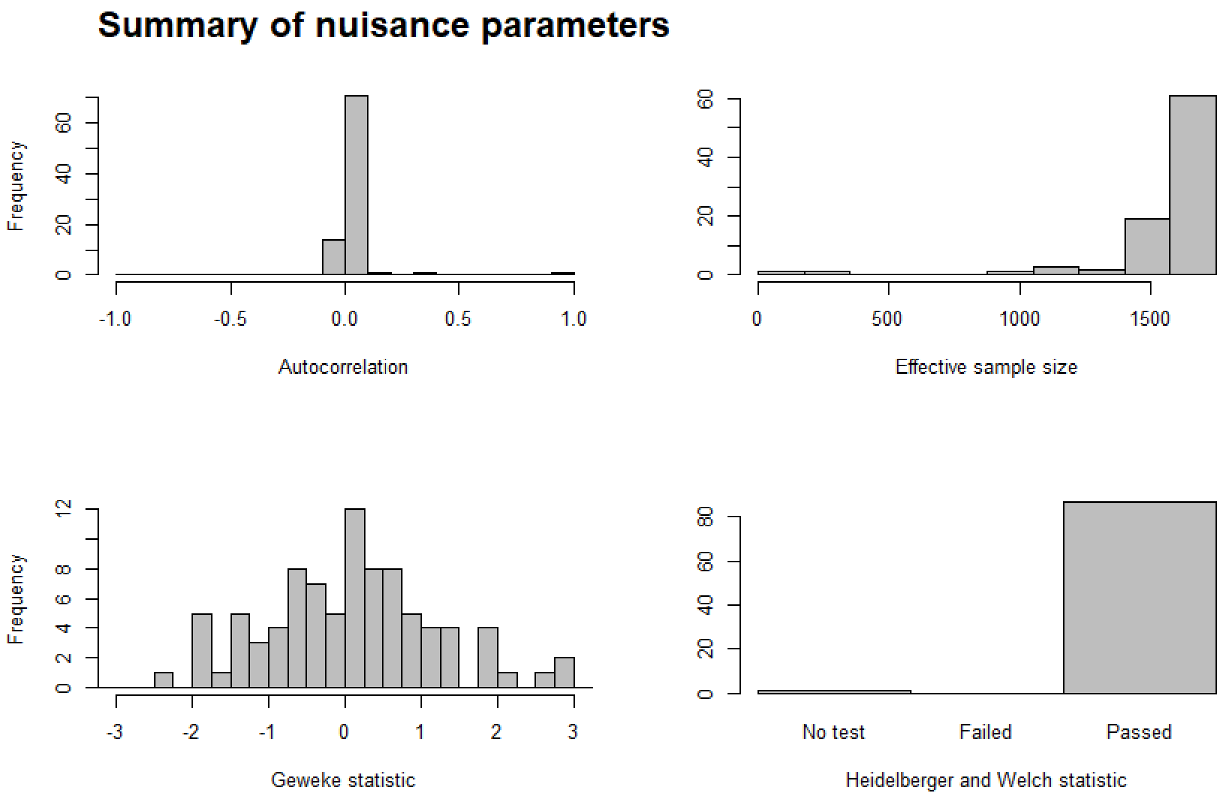

Figure 42. Histograms of autocorrelation, the Geweke statistic, the effective sample size (N_{eff}/N) and the Heidelberger-Welch convergence diagnostics for the 82 estimated recruitment deviations from 1,750 samples of the posterior from the MCMC analysis of the 2021 base-case model.

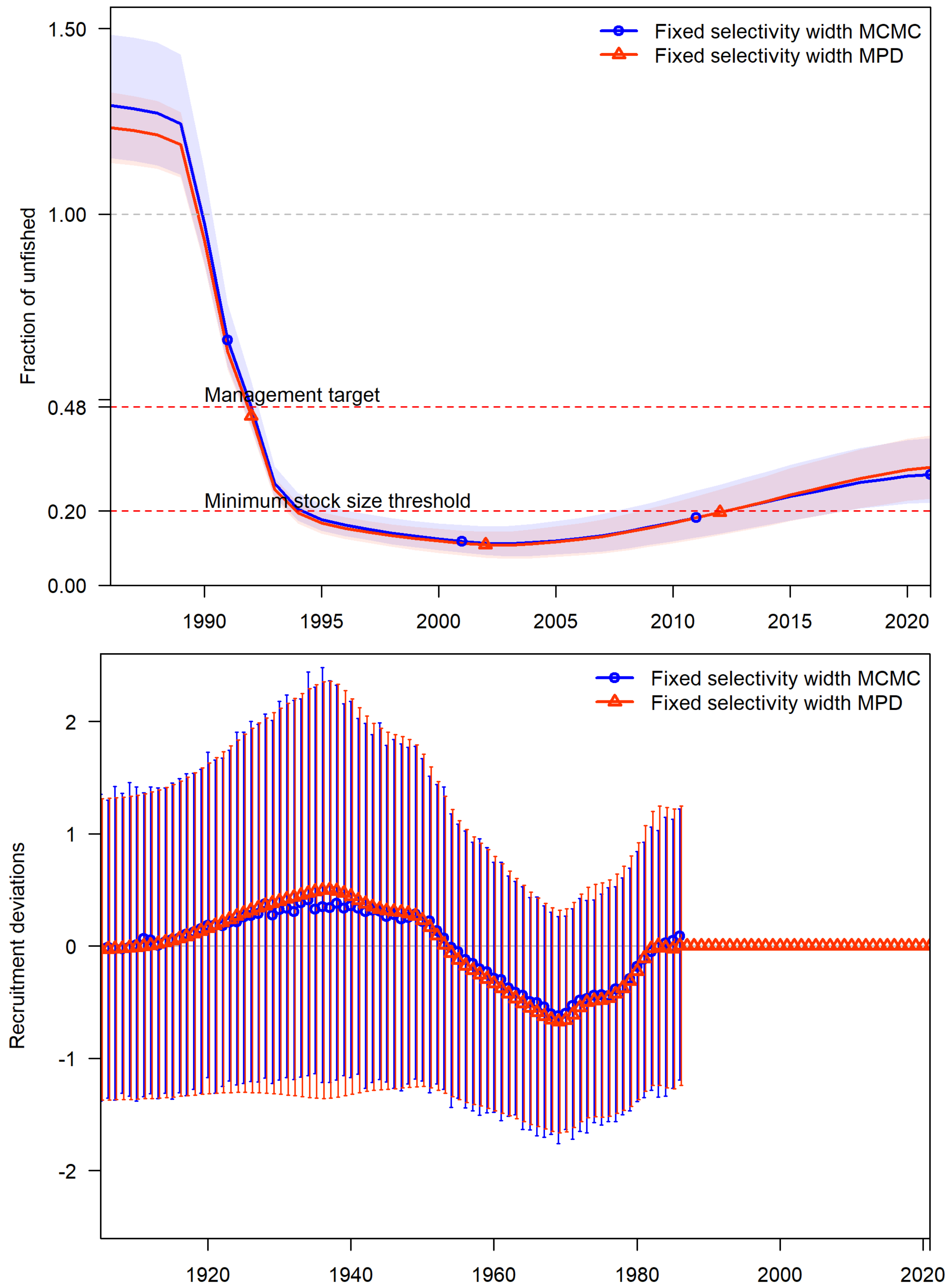

Figure 43. Comparison MPD and MCMC estimates of time-series of relative spawning biomass and recruitment residuals (with ~95% intervals) for the sensitivity to the 2021 base-case model with the selectivity width parameter fixed at its MPD estimate. The red line and shading represent the point estimate and uncertainty from the MPD while the blue line and shading represents the median and uncertainty from 1,750 samples of the posterior from the MCMC.

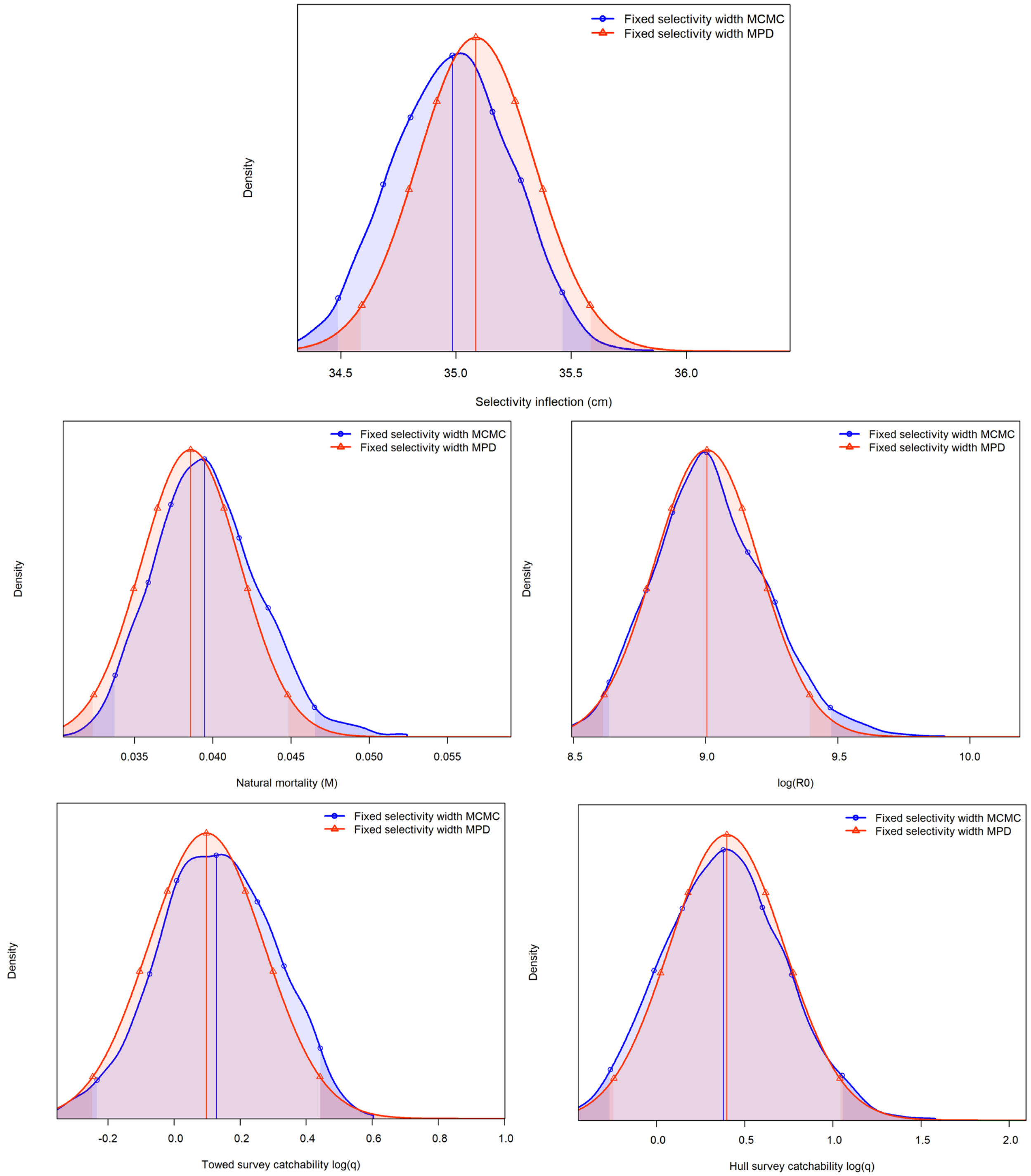

Figure 44. Comparison MPD and MCMC estimates of the logistic selectivity inflection (top), natural mortality (middle left) unfished recruitment (middle right) and catchability for the towed (bottom left) and hull (bottom right) acoustic surveys for the sensitivity to the 2021 base-case model with the selectivity width parameter fixed at its MPD estimate. The red line and shading represent the point estimate and uncertainty from the MPD while the blue line and shading represents the median and uncertainty from 1,750 samples of the posterior from the MCMC. Note the acoustic catchability parameters are presented here as log(q), while they are presented as exp(log(q)) elsewhere in this report.

Appendix B – AFMA Species Summary

To be added after SERAG #3

Appendix C –Summary for ABARES

To be added after SERAG #3

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