



Fisheries and Oceans  
Canada

Pêches et Océans  
Canada

Ecosystems and  
Oceans Science

Sciences des écosystèmes  
et des océans

**Canadian Science Advisory Secretariat (CSAS)**

---

**Research Document 2026/031**

**Newfoundland and Labrador Region**

**Scientific Basis for Developing a Rebuilding Plan for Atlantic Cod (*Gadus morhua*) Stock in NAFO Subdivision 3Ps in 2022 Using MSE-Lite Simulation Approach**

Varkey, D.A., Gullage, N., Kumar, R., Regular, P., Perreault, A., Wheeland, L.J.

Fisheries and Oceans Canada  
Science Branch  
PO Box 5667  
St. John's, NL A1C 5X1

---

## Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

### Published by:

Fisheries and Oceans Canada  
Canadian Science Advisory Secretariat  
200 Kent Street  
Ottawa ON K1A 0E6

[http://www.dfo-mpo.gc.ca/csas-sccs/  
DFO.CSAS-SCAS.MPO@dfo-mpo.gc.ca](http://www.dfo-mpo.gc.ca/csas-sccs/DFO.CSAS-SCAS.MPO@dfo-mpo.gc.ca)



© His Majesty the King in Right of Canada, as represented by the Minister of the Department of Fisheries and Oceans, 2026

This report is published under the [Open Government Licence - Canada](#)

ISSN 1919-5044

ISBN 978-0-660-99134-4 Cat. No. Fs70-5/2026-031E-PDF

### Correct citation for this publication:

Varkey, D.A., Gullage, N., Kumar, R., Regular, P., Perreault, A., and Wheeland, L.J. 2026. Scientific Basis for Developing a Rebuilding Plan for Atlantic Cod (*Gadus morhua*) Stock in NAFO Subdivision 3Ps in 2022 Using MSE-Lite Simulation Approach. DFO Can. Sci. Advis. Sec. Res. Doc. 2026/031. v + 46 p.

### ***Aussi disponible en français :***

Varkey, D.A., Gullage, N., Kumar, R., Regular, P., Perreault, A. et Wheeland, L.J. 2026. *Fondement scientifique pour l'élaboration d'un plan de rétablissement du stock de morue franche (Gadus morhua) dans la sous-division 3Ps de l'OPANO en 2022 à l'aide de l'approche de simulation de l'ESG allégée. Secr. can. des avis sci. du MPO. Doc. de rech. 2026/031. iv + 50 p.*

---

---

## TABLE OF CONTENTS

ABSTRACT .....	v
INTRODUCTION .....	1
REBUILDING PLAN .....	1
MSE-LITE .....	1
OPERATING MODELS IN MSE-LITE .....	2
NATURAL MORALITY SCENARIOS SIMULATED FROM OPERATING MODELS .....	3
RECRUITMENT SCENARIOS SIMULATED FROM OPERATING MODELS .....	4
Low Recruitment .....	5
Sigmoidal Beverton-Holt Stock-Recruit Relationship .....	5
Partial Beverton-Holt Stock-Recruit Relationship .....	6
DEFINING PREVAILING .....	7
DESCRIPTION OF HYBRID OPERATING MODEL: PROJECTIONS .....	8
Setting Up the First Year of the Model .....	8
Population Dynamics .....	8
Fishing Mortality .....	9
REBUILDING PLAN OBJECTIVES AND PERFORMANCE METRICS .....	10
BIOMASS-BASED PERFORMANCE METRICS .....	11
Milestone .....	11
Short Term Objective .....	11
Rebuilding Target .....	11
Catch-Based Performance Metrics .....	11
MANAGEMENT PROCEDURES .....	12
CRITICAL NO DIRECTED FISHING .....	13
ELBOW .....	13
RAISED ELBOW .....	14
F BRACKET .....	14
SIMULATION OUTPUT .....	14
PERFORMANCE METRICS .....	21
SOURCES OF UNCERTAINTY .....	26
NATURAL MORTALITY .....	27
RECRUITMENT .....	27
OTHER FACTORS .....	28
CONCLUSIONS .....	28
ACKNOWLEDGEMENTS .....	28
REFERENCES CITED .....	28
APPENDIX A: PARAMETERIZATION OF NATURAL MORTALITY (M) IN THE HYBRID MODEL .....	31

---

APPENDIX B: ADDITIONAL TABLES AND FIGURES .....	32
TABLES .....	32
FIGURES .....	36
APPENDIX C: LONGTERM PROJECTIONS OF SSB HISTORICAL SERIES (1959–2022) FOR ALL COMBINATIONS OF M AND R UNDER ALL MPS.....	42
APPENDIX D: TIME TO REACH THE REBUILDING TARGET .....	45
APPENDIX E: FUNCTION TO CALCULATE F FROM CATCH.....	46

---

## ABSTRACT

A simplified Management Strategy Evaluation (MSE-lite) framework has been developed to enable closed-loop simulations for exploring various rebuilding plan (RP) options for the Atlantic Cod (*Gadus morhua*) stock in Northwest Atlantic Fisheries Organization (NAFO) Subdivision (Subdiv.) 3Ps. Management procedures (MPs) (i.e., alternate approaches for rebuilding the stock) are applied in the projections from operating models (OMs) conditioned on historical data. The base OM for MSE-lite is based on the current integrated state-space assessment model for this stock known as Hybrid (Varkey et al. 2022). The growth of the stock is currently constrained by increases in natural mortality (M) rates and low recruitment (R). Therefore, long-term simulations of the RPs presented incorporate a series of hypotheses regarding future M rates and R trends for the stock. Simulation results for alternate MPs are assessed across different scenarios for R and M rates, and the performance of MPs is evaluated based on their effectiveness in meeting the various RP objectives.

---

## INTRODUCTION

### REBUILDING PLAN

In April 2022, the new Fish Stock Provisions came into effect. The first 30 major stocks prescribed by regulation included the Northwest Atlantic Fisheries Organization (NAFO) Subdivision (Subdiv.) 3Ps Atlantic Cod (*Gadus morhua*) stock. The most recent stock assessment (DFO 2022) indicated that the 3Ps cod stock was in the Critical Zone (48% of the limit reference point [LRP]), therefore, developing a rebuilding plan (RP) for this stock was a legal requirement. A Rebuilding Plan Working Group (RP-WG) was convened to support the development of this plan. The RP-WG was a diverse group, including participants from fishery stakeholder groups, Resource Management, Science, Policy and Economics, and non-governmental organizations. The RP-WG met several times to define the rebuilding target, discuss and refine the prevailing conditions, which are needed for projections and set measurable objectives for the RP. At the RP-WG meetings, the Management Strategy Evaluation (MSE-lite) simulation approach, developed for simulating RP options, was presented, and multiple outputs from simulation of different strategies for the RP were discussed. Suggestions from the RP-WG were incorporated into the simulation framework. In November 2022, a Canadian Science Advisory Secretariat (CSAS) Regional Peer Review meeting was held to review the science supporting the RP development. This document, produced for the CSAS meeting, describes the rebuilding target, the prevailing conditions, and the measurable objectives determined by the RP-WG and provides a detailed description of the MSE-lite simulation approach and its application to support the development of a RP for the 3Ps cod stock.

### MSE-LITE

The current best approach for implementing management plans is through an MSE, which simulates stock dynamics and future projections under a variety of management plans, as well as alternative (e.g., recruitment [R]) assumptions (Punt et al. 2016). The essential components of an MSE (Figure 1a) include an operating model (OM), a management procedure (MP), which includes the stock assessment process and harvest control rule (HCR, also referred to as harvest decision rule [HDR]), and performance metrics (PMs). Operating Models describe the true dynamics of the population and are conditioned on historical data for the stock. However, multiple OM formulations are often considered in order to better capture uncertainties in the fishery system (e.g., various natural mortality [M] or R scenarios). Within the MSE, the estimation of the stock status based on data generated from the OM (i.e., the assessment process) provides the perceived state of the stock via a stock assessment model or trends in survey data. In an MSE, there is feedback between the true state described in the OM and the MP implemented in the assessment process. The HCRs set the level of catches (i.e., total removals) for the following year based on stock size (defined as spawning stock biomass [SSB]) and status (SSB/LRP) determined in the assessment process, and then applies estimated harvest rate to the simulated population. These components describe the core model, which is repeated over a pre-specified number of years to project the stock forward and model the dynamics of the stock in the future.

The MSE-lite is a simplified version of an MSE (Figure 1b) that contains all of the main components of an MSE (OMs, MPs, and PMs), but excludes data generating and assessment process steps. The MSE-lite does not separately model the true and perceived state of the stock; it is essentially closed-loop projections from the OM. The OM provides information on stock biomass to the MP, and therefore the feedback between the OM and MP is direct and

immediate. The major cost to the simplicity of MSE-lite is that in the real world management process, full information about the stock will never be available. However, from a planning perspective, rebuilding strategies that did not work in a perfect information scenario with perfect feedback (i.e., MSE-lite) are unlikely to be successful if explored with more uncertainty in an MSE.

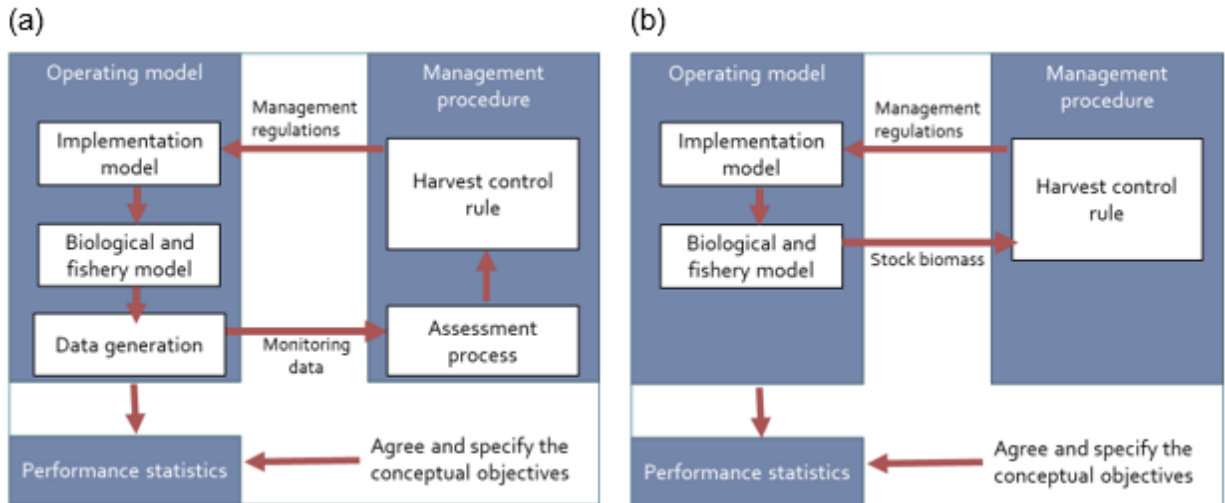


Figure 1: (a) Flow chart of MSE modified from Punt et al. 2016 (left). (b) Flow chart of MSE-lite implemented here (right).

## OPERATING MODELS IN MSE-LITE

The OMs parameterized in the MSE-lite are based on Hybrid (see Varkey et al. 2022 for model details) and state-space assessment model (SAM; Champagnat et al. 2024, Nielsen and Berg 2014) stock assessment models for the 3Ps cod stock. The Hybrid model is a custom state-space model written in Template Model Builder (TMB) that has been used to assess the stock since 2019. A complementary SAM developed for the 3Ps cod stock (Champagnat et al. 2024) has been presented at assessment meetings since 2019 to validate the Hybrid model predictions. Both models incorporate scientific data from bottom trawl surveys (Canada, 1983 – 2021; France, 1978 – 92; the Groundfish Enterprise Allocation Council [GEAC], 1998 – 2005), the Sentinel gillnet and line trawl surveys (1995 – 2020), and landings data. Although there are some differences in the underlying model structures, the major difference between the base case (Hybrid) and the SAM is the formulation of  $M$ . The  $M$  estimates in the Hybrid model were informed by a cod condition-based index of mortality; in SAM,  $M$  was fixed at 0.3 for all ages and years.

This document presents the details of only the OM based on the Hybrid model. Although a constant- $M$  hybrid OM was included in the original list of OMs, it was recognized that the SAM was sufficient to represent a scenario where  $M$  was age- and time-invariant. Simulations from the SAM have been presented at previous two WG meetings (Nov 7 - 8, 2022, and Nov 14, 2022) to check and verify consistency between simulations from the two main OMs. The behavior of both models was deemed consistent and, as such, the RP-WG agreed to focus on simulations based on the Hybrid OM.

The Hybrid OM has the following main features:

1. includes all the available surveys (Canadian research vessel survey, French ERHAPS [Evaluation des Ressources Halieutiques de la région 3PS] survey, industry trawl survey, and Sentinel gillnet and line trawl surveys),
2. commercial data—fisheries catch-at-age where the age composition is fit using continuation ratio logits, and the fisheries landings which are fit using a censored likelihood,
3. fishing mortality (F) is described using a Multivariate normal (MVN) random walk with a discontinuity in the random walk at the moratorium. Further, age-2 is decoupled from the MVN correlation,
4. time-varying M based on a condition-based index of mortality, and
5. the model starts in 1959 which is the first year for which landings data are available.

Age in the model spans from 2 to 14+. All model details and descriptions are found in Varkey et al. (2022).

It is important to capture the uncertainty inherent in the fishery system. Natural mortality and R drive population productivity and are well-known sources of uncertainty in stock projections. Therefore the MSE-lite, in exploring the impact of potential future scenarios, included several hypotheses of conditions about future M rates and R trends for the stock. Notably, M and R scenarios all fell within the conditions previously experienced by the stock, however in a changing ocean climate these conditions may not accurately capture future conditions. This is further discussed below in **SOURCES OF UNCERTAINTY**.

### NATURAL MORALITY SCENARIOS SIMULATED FROM OPERATING MODELS

Three alternate M scenarios were identified based on low, terminal, and high levels reached in the historical M trend from the assessment (Figure 2).

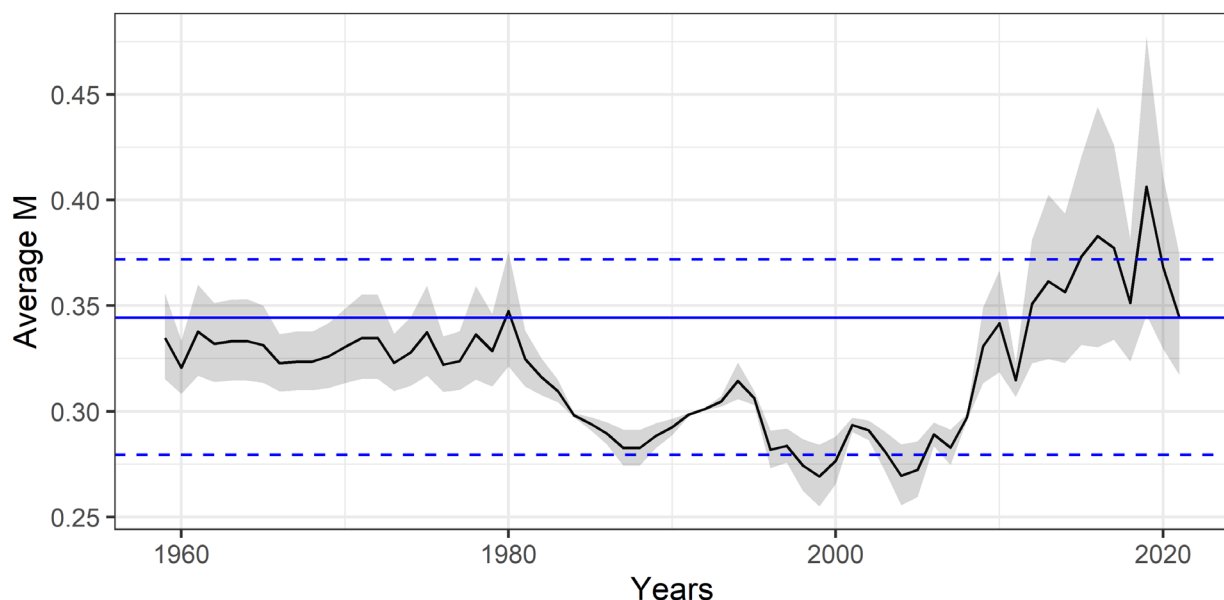


Figure 2: Natural mortality trend from the most recent assessment (DFO 2022). Blue horizontal lines show the M scenarios levels overlaid on the historical trend (prevailing: solid line, low and high values: dashed lines).

Natural mortality was low during the period from 1996 – 2005 and high from 2015 – 21. Natural mortality in 2021 was estimated to be 0.34. The  $M$  in the Hybrid OM was time-varying ( $M_{a,y}$ ), where the trend was based on an index of mortality due to poor fish condition (Regular 2022; Regular et al. 2022;  $M_c$ ; Table AB 1). The  $mpar$  parameter was applied to the standardized index and was estimated by two age groups (2–5 and 6+, roughly corresponding to immature and mature) to allow different age groups to respond differently to the trends in fish condition. More detail on parameterization is available in Appendix A. In simulating the projections, equation (Eq.) 1 was applied to the average condition index from the respective time periods to define the low, terminal year, and high  $M$  scenarios:

- Low: standardized  $M_c$  = average standardized  $M_c$  1996 – 2005
- Terminal: standardized  $M_c$  = standardized  $M_{c,2021}$
- High: standardized  $M_c$  = average standardized  $M_c$  2015 – 21

Uncertainty in  $M$  was simulated based on the variance in the estimate of the  $mpar_a$ , where  $\sigma_{mpar}$  was the standard error of the estimated  $mpar_a$  parameter.

$$mpar_{a,y} = mpar_a + e_{2:A,y}; e_{2:A,y} \sim N(0, \sigma_{mpar,a}) \quad \text{Eq. 1}$$

$$\log M_{a,y} = \log(0.3) + mpar_a * \left( \frac{M_{c,y} - \mu_{M_c}}{\sigma_{M_c}} \right); \quad \text{Eq. 2}$$

In the application to the projections,  $M_c$  (the condition index) changed between scenarios. As described in Appendix A, the mean ( $\mu_{M_c}$ ) and standard deviation ( $\sigma_{M_c}$ ) were calculated for the first 35 years of data available for fish condition; therefore, the normalization of  $M_c$  was based on a reference period (1978 – 2012). These values remained constant between scenarios.

The  $mpar$  estimate for ages 2–5 was close to ‘0’ (see Varkey et al. 2022) and the trend of  $M$  for these ages was essentially flat at 0.3. The  $mpar$  estimate for ages 6+ (0.127) allowed the  $M$  to vary for these ages. Hence, in all the alternate scenarios of  $M$  simulated, the  $M$  for ages 2–5 was very close to the base value of 0.3; the variation was only in the  $M$  for ages 6+.

## RECRUITMENT SCENARIOS SIMULATED FROM OPERATING MODELS

Recruitment success has varied throughout the available timeseries and predicting future  $R$  was highly uncertain. Recruitment in this stock was high in the 1960s, but declined in the 1970s (Figure 3). In the 1980s,  $R$  was quite variable. From 1993 onward,  $R$  has been well below the long-term average. The lowest levels in the time series were reached during 2016 – 17. Recruitment scenarios examined here were characterized as low, Sigmoidal BH (sigBH), and Partial Beverton-Holt (BH). The age-2 recruits for each simulation and in each year of the simulation were calculated using a value for mean  $R$  and standard deviation estimate, both of which depended on the  $R$  scenario.

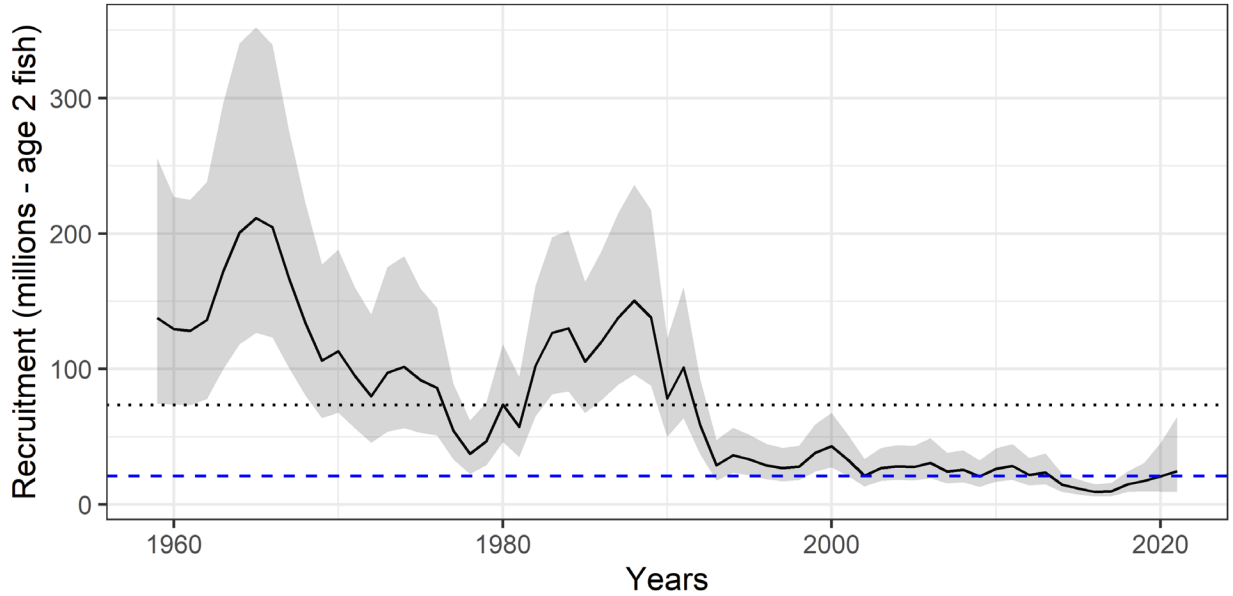


Figure 3: Recruitment ( $R$ ) trend from the most recent assessment (DFO 2022). Black dotted line shows the long-term average  $R$ . Blue horizontal dashed line shows the level used for the ‘low’  $R$  scenario, the average  $R$  for 2019 – 21.

### Low Recruitment

The low  $R$  scenario was defined as the average of the recent low period in  $R$  from 2019 – 21. This scenario simulated a constant  $R$  (with uncertainty) into the future. This was considered a low scenario based on the presumption that  $R$  would continue to remain at the recently observed low levels. The log of age-2 recruits was sampled from a normal distribution with mean  $\log \mu_R$ , where  $\mu_R$  was the mean  $R$  from the last three years and standard deviation  $\sigma_R$  which was estimated during the conditioning of the OM.

$$\log N_{2,y} = \log \mu_R + \eta_{2,y}; \eta_{2,y} \sim N(0, \sigma_R) \quad \text{Eq. 3}$$

### Sigmoidal Beverton-Holt Stock-Recruit Relationship

Perälä et al. (2022) showed evidence of depensation in 3Ps cod by fitting stock-recruit data to a sigBH model (Eq. 4), an approach to represent Allee effects in  $R$ . Allee effects are a small population phenomenon in which population growth rate is reduced by undercrowding (Drake and Kramer 2011; Kramer et al. 2009), or an increase in predation pressure at low population levels (Myers et al. 1995; Walters and Kitchell 2001). Perälä et al. (2022) applied two different models for determining evidence of depensation for 3Ps cod and found that the sigBH model provided the best fit to data among the models tested. The sigBH model was refit to the most recent stock-recruit trends. An upper bound on  $R$ —defined as the  $R$  for the time-series high SSB—was added to avoid  $R$  from reaching unrealistically large values at high SSB levels in the simulation.

Mean  $R$  value was calculated using the sigBH function; the  $R_\infty$  is the asymptotic  $R$ ,  $S_{50}$  is the level of SSB for which  $R$  is  $0.5R_\infty$ , and  $c$  is the parameter for depensation. Figure AB 1 shows the posterior parameter distributions.

$$R = \frac{R_{\infty}}{1 + \left(\frac{S_{50}}{S}\right)^c} \quad \text{Eq. 4}$$

In the model fitting process,  $R$  was modelled using a lognormal likelihood

$$R|S, \theta, \sigma^2 \sim \text{Lognormal}(\mu, \sigma^2) \quad \text{Eq. 5}$$

where the location parameter  $\mu$  was defined as

$$\mu = \log(E(R|S, \theta)) - \frac{1}{2}\sigma^2 \quad \text{Eq. 6}$$

and the expected (E) number of recruits given the spawning stock biomass  $S$  and stock-recruit model parameters  $\theta = (R_{\infty}, S_{50}, c)$

$$E(R|S, \theta) = \frac{R_{\infty}}{1 + \left(\frac{S_{50}}{S}\right)^c} \quad \text{Eq. 7}$$

When  $R$  was modelled using a lognormal likelihood, the median was smaller than the expectation and there was a need to do a bias correction. In sampling the  $R$  for the simulations, the mean  $R$  needed to be corrected by a factor equal to  $-\frac{1}{2}\sigma^2$ . This correction was applied in the simulated mean (see Eq. 8, following original application Eq. 9).

$$\log N_{2,y} = \log\left(\frac{R_{\infty}}{1 + \left(\frac{S_{50}}{S}\right)^c}\right) - \frac{1}{2}\sigma^2 + \eta_{2,y}; \eta_{2,y} \sim N(0, \sigma_{RSBH}) \quad \text{Eq. 8}$$

$$N_{2,y} \sim \text{Lognormal}\left(\log\left(\frac{R_{\infty}}{1 + \left(\frac{S_{50}}{S}\right)^c}\right) - \frac{1}{2}\sigma_{RSBH}^2, \sigma_{RSBH}^2\right) \quad \text{Eq. 9}$$

Residual plots provided in Figure AB 2 did not show any major patterns except a phase in the late 1990s and early 2000s where the model predictions were consistently higher for several years. This corresponded to SSB values in the approximate range from 50,000–70,000 t. In simulating  $R$ , parameter uncertainty was incorporated by drawing parameters for each simulation from the Markov chain Monte Carlo (MCMC) samples (Figure AB 3) of the model fit to Eq. 4. The posterior median of the sigma parameter for the observation model was used to simulate the uncertainty in predictions.

### Partial Beverton-Holt Stock-Recruit Relationship

The estimated  $R$  trend from the assessment model showed that since 1993,  $R$  has been below the long-term mean of the  $R$  time series. A BH stock-recruit relationship (Partial-BH) was fit to the data from 1993 onwards in order to generate a stock-recruit relationship that represented the data from a more recent period. Residual plots provided in Figure AB 4 did not show any major patterns except a temporal dependence since 2010. In the implementation of the simulations (Eq. 11), parameter uncertainty was incorporated by sampling the  $\alpha$  and  $\beta$

parameters from the covariance matrix of the parameters fitted to Eq. 10 (Figure AB 5). Uncertainty in predictions was simulated based on observation error standard deviation from the fit to the Partial-BH stock-recruit model.

$$R = \frac{\alpha S}{1 + \beta S} \quad \text{Eq. 10}$$

$$\log N_{2,y} = \log \left( \frac{\alpha S}{1 + \beta S} \right) + \eta_{2,y}; \eta_{2,y} \sim N(0, \sigma_{RBH}) \quad \text{Eq. 11}$$

Comparison of the sigBH and the Partial-BH curves (Figure AB 6) showed considerable differences in magnitude, with predicted R deviating considerably at SSB levels higher than around 50,000 t (higher when the full time series was used, i.e., with the sigBH curve). The level of SSB (around 50,000 t) where the two functions diverged was at a critical point just below the LRP (66,000 t); this deviation between the two R functions was important to consider when evaluating mid- to long-term projections.

## DEFINING PREVAILING

The RP process requires a definition of prevailing conditions. To be consistent with guidance to Science in developing rebuilding plans the “timeline to rebuild a stock to its rebuilding target must be between  $T_{min}$  and a maximum of two to three times  $T_{min}$ , where  $T_{min}$  is the time the stock would take to rebuild to the rebuilding target in the absence of all fishing ( $F = 0$ ) under prevailing productivity conditions”. However, no formal definition of prevailing productivity exists.

The RP-WG recommended a stock-recruit relationship fit to the entire available time series of SSB and R (since 1959) to determine prevailing R within the context of the RP and the LRP defined for the stock. Concerns were raised over the fit of the sigBH model to stock and recruit input over the last three decades and at SSB levels just below the LRP, and it was noted that there was significant uncertainty in future R trajectories for the stock. However, if prevailing conditions were defined not considering the full history of the stock and recruit series, this may have implied an irreversible change in productivity within this stock which was not supported by published analyses (Perälä et al. 2022), and was inconsistent with the current definition of the LRP for this stock.

The RP-WG recommended that prevailing M be defined as the terminal M from the latest assessment (2021) as this is most representative of the current natural mortality level for the stock.

In accordance with the guidance for developing RPs under the Fish Stock Provisions, an estimated rebuilding timeline was derived from  $F = 0$  under prevailing conditions (Figure 4). Under the prevailing conditions for both M and R recommended by the RP-WG, the rebuilding target (above the LRP with a 75% probability) would be achieved in 2036, therefore  $T_{min} = 14$  years. To be consistent with the guidance for rebuilding plan development, the rebuilding target must therefore be between 14 and a maximum of 28–42 years. The current defined rebuilding target objective was to achieve an SSB level greater than the LRP with a 75% probability within 25 years.

Time to reach the rebuilding target under each MP x R x M combination is shown in Appendix D.

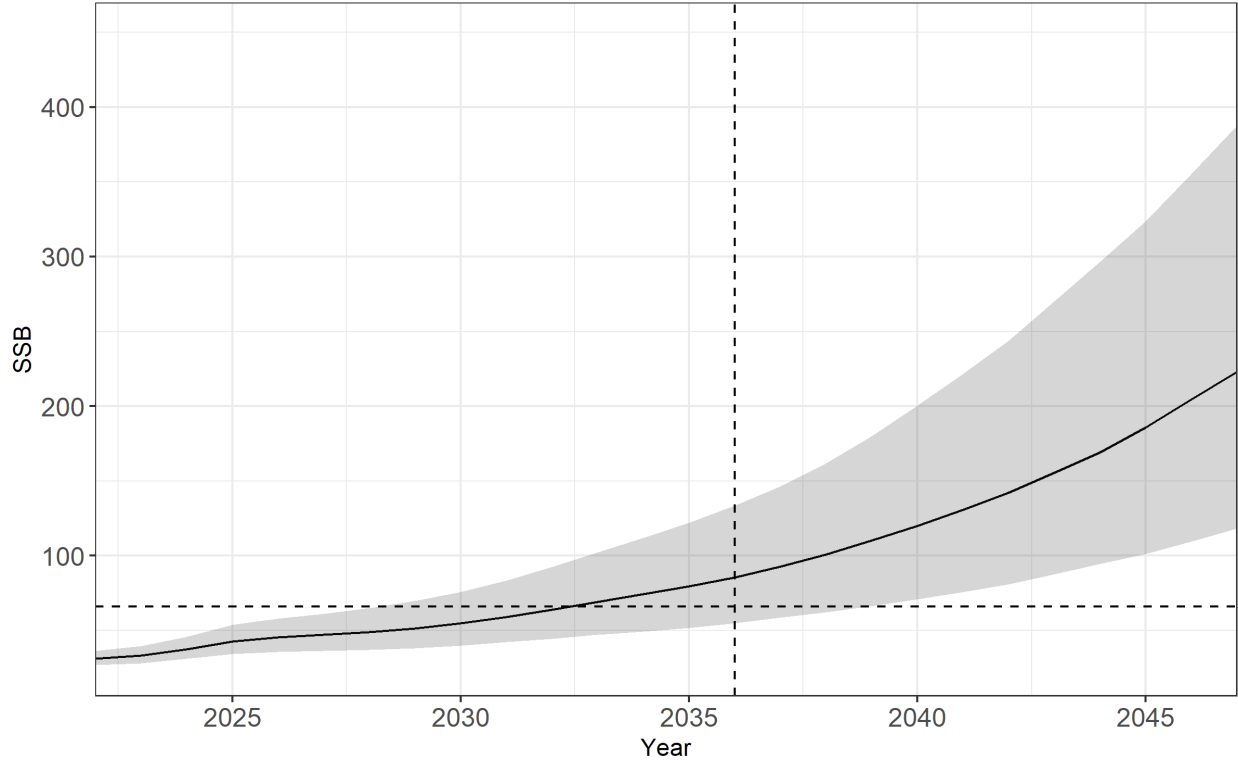


Figure 4: Spawning stock biomass (SSB, in kt) projection with no fishing ( $F = 0$ ) under prevailing  $M$  and  $R$  conditions. Horizontal dashed line indicates the LRP at 66kt, vertical dashed line shows the year when the stock rebuilds to a level that is above the LRP with a 75% probability (2036).

## DESCRIPTION OF HYBRID OPERATING MODEL: PROJECTIONS

### Setting Up the First Year of the Model

Ten thousand threads of closed loop model projections were simulated within MSE-lite. The first year in the projections was 2021 and began from the abundance estimates (Table AB 2) of the terminal year (2021; Tables AB 2–3) from the Hybrid assessment model,

$$\log N_{a,1} = \log N_{a,2021} + \eta_{a,1}; \quad \eta_{a,1} \sim N(0, \sigma_p) \quad \text{Eq. 12}$$

where  $\sigma_p$  was the process error standard deviation. For the first year (2021), the  $F$  and  $M$  values were taken from the terminal year values of the assessment model.

### Population Dynamics

From the second year onwards, abundances for age-3 and up were calculated using the standard cohort equations:

$$\log N_{a,y} = \log N_{a-1,y-1} - F_{a-1,y-1} - M_{a-1,y-1} + \eta_{a,y}; \quad 3 \leq a < A - 1; \quad \eta_{3:A-1,y} \sim N(0, \sigma_p) \quad \text{Eq. 13}$$

$$\log N_{A,y} = \log \left( \frac{N_{A,y-1} * \exp(-F_{A,y-1} - M_{A,y-1}) + N_{A-1,y-1} * \exp(-F_{A-1,y-1} - M_{A-1,y-1})}{N_{A-1,y-1} * \exp(-F_{A-1,y-1} - M_{A-1,y-1})} \right) + \eta_{A,y}; \quad A = 14 + \quad \text{Eq. 14}$$

The SSB was calculated as the sum-product of abundance, stock weight-at-age, and maturity-at-age.

$$SSB_y = \sum_{2:A} N_{a,y} \cdot Sw_a \cdot mat_a \quad \text{Eq. 15}$$

## Fishing Mortality

In addition to simulating process error and error in R, error was also simulated in selectivity and M. Selectivity in the projections was based on the average F for 2019 – 21 from the assessment; to simulate error in selectivity in the projections, an MVN sample was drawn from the MVN random walk of F (Eq. 15).

$$Fsel_{a,y} = \exp(\log(F_{a,2019:2021}) + e_{2:A,y}); e_{2:A,y} \sim MVN_{2:A}(0, \Sigma) \quad \text{Eq. 16}$$

Selectivity was calculated by scaling the average fishing mortality  $Fsel_{a,y}$  by the maximum  $Fsel_{a,y}$  (Eq. 16, Figure AB 7):

$$sel_{a,y} = \frac{Fsel_{a,y}}{\max_a(Fsel_{a,y})} \quad \text{Eq. 17}$$

Catch weight-at-age was the average from the last three years of catch weights (obtained from commercial sampling).

For 2021, F values were available from the assessment. For 2022, the F corresponding to the specified removals (1,346 t) was calculated using a Newton approximation ('solveF'; see Appendix E), which used information on selectivity, numbers-at-age, M-at-age, and catch weights. This approximation method is effectively the inverse of the Baranov catch equation, taking an input for total catch and outputting a value for F.

For 2023 onwards, the trajectories of biomass, F, and yields were determined by the applied MP. Several MPs were available in the MSE-lite; MPs could be catch- or F-based. Fishing mortality-based MPs defined a value of F that was applied to the stock (Eq. 18). This value was referred to as  $F_{bar}$ . In a given simulation and year, the  $F_{bar}$  was calculated based on the MP function and the SSB in the beginning of the year. In a catch-based MP, the total removals (TR) for a given simulation and year was calculated based on the MP function and the SSB in the beginning of the year (Eq. 19). The  $F_{bar}$  corresponding to the TR was calculated using a solveF function (Appendix E); this was the value of average F that would result in TR under these conditions. The F-at-age was obtained as the product of  $F_{bar}$  and selectivity.

$$\text{F-based MP: } F_{bar_y} = f(MP, SSB_y) \quad \text{Eq. 18}$$

$$\text{Catch-based MP: } TR_y = f(MP, SSB_y); F_{bar_y} = solveF(TR_y) \quad \text{Eq. 19}$$

$$F_{a,y} = F_{bar_y} * sel_{a,y} \quad \text{Eq. 20}$$

As for the first year for which removals were specified, the catch numbers-at-age were calculated based on the F-at-age:

$$C_{a,y} = N_{a,y}(1 - \exp(-Z_{a,y}))^{F_{a,y}}/Z_{a,y} \quad \text{Eq. 21}$$

The yield was calculated as the sum over ages of catch in weight-by-age.

$$Y_y = \sum_{a=2}^A C_{a,y} * CW_a \quad \text{Eq. 22}$$

$$aveF_y = \frac{\sum_{a=5}^8 F_{a,y} * N_{a,y}}{\sum_{a=5}^8 N_{a,y}} \quad \text{Eq. 23}$$

The MPs were applied to the stock each year of the projection, and the population responded to the newly implemented F levels. This led to either an increase or decrease in, or maintenance of the population the following year. This feedback between the population levels and the MP continued to the end of the simulation. At the end of the simulation, all the information from biomass, yield,  $F_{bar}$ , and population-weighted average F ( $aveF$ ; Eq. 23) were compiled to evaluate the performance of the MPs. The population-weighted F was the F-at-age, weighted by the numbers-at-age for ages 5–8.

## REBUILDING PLAN OBJECTIVES AND PERFORMANCE METRICS

The objectives for the RP were designed by the RP-WG; these included a milestone that tracks the trajectory of the population over the next five years, one short-term objective for 15 years, and the rebuilding target for 25 years. Performance metrics (PMs) were developed based on the RP-WG objectives (Table 1). Performance Metrics considered both the trajectory and status of the stock, as well as fishery yield and variation in removals.

A long-term objective was considered by the RP-WG (increase SSB to 35% above the LRP [ $B_{lim}$ ] within 35 years [3.5 generation time] with a 75% probability). However there was considerable uncertainty in long-term projections, especially upon including different future M and R conditions and we were unable to reliably measure performance relative to this objective. The RP-WG agreed to remove this objective from the RP process, but it was noted that this would be something considered in a future Integrated Fisheries Management Plan (IFMP) process for when the stock is above the LRP.

Table 1: Summary of Rebuilding plan objectives and performance statistics and metrics. Prop is proportion and med is median.

-	Rebuilding plan objective	Performance statistic	Metric
<b>Milestone</b>	Achieve a positive stock growth trajectory with a 75% probability over the five year timeframe	$SSB_{2027} > SSB_{2022}$	Prop $\geq$ 0.75
<b>Short-term Objective</b>	Increase SSB above 75% of the LRP within 15 years with a 75% probability.	$SSB_{2037} > 0.75LRP$	Prop $\geq$ 0.75
<b>Rebuilding Target</b>	Increase the SSB above the LRP within 25 years (2.5 generation time) with a 75% probability.	$SSB_{2047} > LRP$	Prop $\geq$ 0.75

-	Rebuilding plan objective	Performance statistic	Metric
<b>Catch-based Performance Metrics</b>	Maximize yield in the short term	Average Catch: 2023 – 27	med(80%CI)
	Maximize yield in the long term	Average Catch: 2023 – 47	med(80%CI)
	Keep variation in inter-annual total allowable removals below an established threshold	Average annual variation: 2023 – 47	Prop ≤ 0.20

## BIOMASS-BASED PERFORMANCE METRICS

### Milestone

The first PM was to ensure that the MPs achieved a positive trajectory of the stock in the short term. It was calculated as the proportion of simulations where the SSB in 2027 is greater than the SSB in 2022. It would be considered a pass if the proportion is greater than or equal to 0.75.

$$SSB_{2027} > SSB_{2022}; \text{ Prop} \geq 0.75 \quad \text{Eq. 24}$$

### Short Term Objective

The second PM was to ensure that the MPs allowed the stock to reach SSB levels above 75% of the LRP within 15 years. It was calculated as the proportion of simulations where the SSB in 2037 is greater than 0.75 \* LRP. It would be considered a pass if the proportion is greater than or equal to 0.75.

$$SSB_{2037} > 0.75 \text{ LRP}; \text{ Prop} \geq 0.75 \quad \text{Eq. 25}$$

### Rebuilding Target

The third PM was to ensure that the MPs allowed the stock to reach SSB levels above the LRP within 25 years. It was calculated as the proportion of simulations where the SSB in 2047 is greater than the SSB in 2022. It would be considered a pass if the proportion is greater than or equal to 0.75.

$$SSB_{2047} > LRP; \text{ Prop} \geq 0.75 \quad \text{Eq. 26}$$

## Catch-Based Performance Metrics

### Maximise yield in the short term

This was calculated as the average yield in the first five years the MP is applied.

$$C_{short} = \bar{Y}_{2023:2027} \quad \text{Eq. 27}$$

### Maximise yield in the long term

This was calculated as the average yield in the first 25 years the MP is applied.

$$C_{long} = \bar{Y}_{2023:2047} \quad \text{Eq. 28}$$

### Average annual variability in yield

This PM presents an index of variability in catch advice over the 25-year simulation of the MP (Forrest et al. 2018).

$$AAV = \frac{\sum_{2023}^{2047} |Y_y - Y_{y-1}|}{\sum_{2023}^{2047} Y_y} \quad \text{Eq. 29}$$

## MANAGEMENT PROCEDURES

Several catch- and F-based MPs were explored within the MSE-lite simulation model following the basic principles of the precautionary approach (DFO 2006). The MPs presented here are F-based MPs applied to the simulated stock that defined F ( $F_{bar}$  used interchangeably with F in this section) for each year of the simulation. These MPs were carried forward by the RP-WG and are a subset of MPs presented at previous RP-WG meetings. A no fishing scenario (defined here as catch = 0.001 in all years) was a requirement for the RP simulation and was used to support the decision making on rebuilding timelines. Four MP structures and the no fishing scenario were implemented (Figure 5). Detailed definitions of these MPs are provided below.

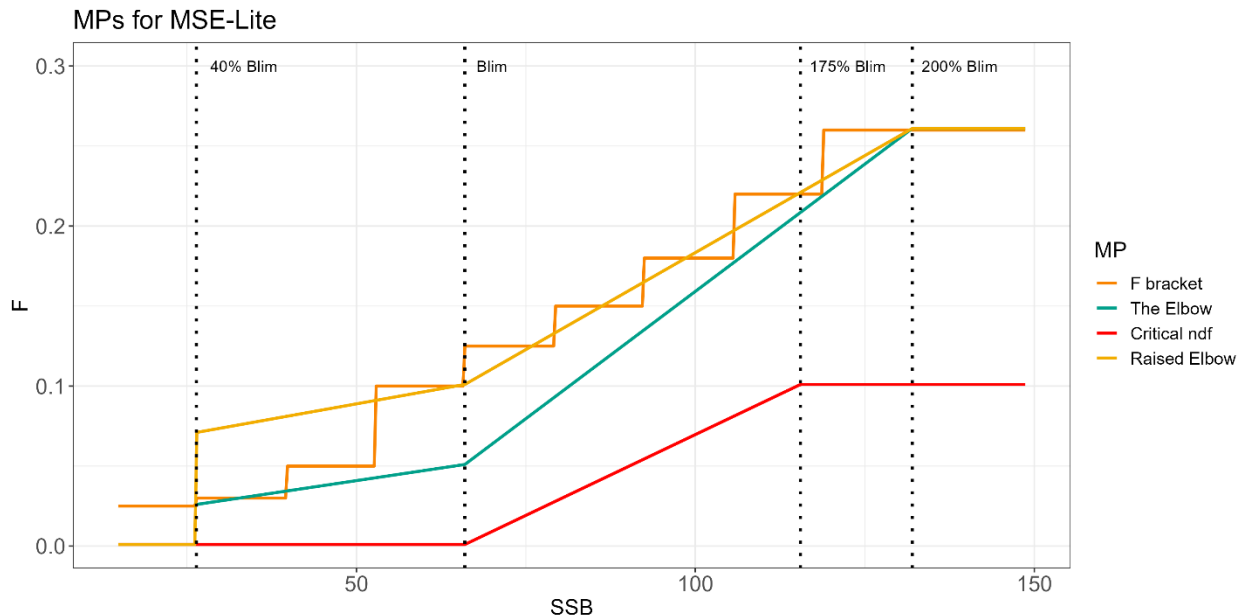


Figure 5: Trends in F with respect to SSB for each proposed MP. Vertical dotted lines indicate SSB values at which changes in F trends occur under the Critical no directed fishing (ndf), Elbow, and Raised Elbow MPs.

All MPs in the simulation had minimum total removals of 100 t to account for removals outside of directed fishing, including bycatch and survey captures. If a derived F would achieve less than the pre-defined minimum of 100 t, removals for that year were instead set to 100 t and F

was set to the value required to achieve those removals. This did not apply to the no fishing scenario. In the equations below, this is denoted  $F|_{C=100 t}$ , which reads as F evaluated at catch levels of 100 t.

### CRITICAL NO DIRECTED FISHING

There is no fishing when the stock is below  $B_{lim}$ .

Above  $B_{lim}$ , F increases linearly to an upper level associated with a higher SSB,

$$F_y(SSB_y) = \begin{cases} F|_{C=100 t}, & SSB_y < B_{lim} \\ \text{lin}(SSB_y), & B_{lim} \leq SSB_y \leq 1.75 * B_{lim} \\ F_{upper}, & SSB_y > 1.75 * B_{lim} \end{cases} \quad \text{Eq. 30}$$

in the Critical Zone, where  $SSB < B_{lim}$ , F is fixed at minimum removals,

above  $B_{lim}$ , but below  $1.75 * B_{lim}$ , F is defined by a linear function, ranging from  $F = 0$  at  $SSB = B_{lim}$  and  $F = F_{upper} = 0.1$  at  $1.75 * B_{lim}$

$$\text{lin}(SSB_y) = \frac{0.1}{0.75} \left( \frac{SSB_y}{B_{lim}} - 1 \right), \quad \text{Eq. 31}$$

where  $B_{lim} = LRP = 66$  kt. At or above  $1.75 * B_{lim}$  F is fixed at  $F_{upper} = 0.1$ .

### ELBOW

Fishing mortality increases linearly between  $0.4 * B_{lim}$  and  $B_{lim}$ . Above  $B_{lim}$  F increases at a faster rate, reaching an upper F threshold at  $2 * B_{lim}$ ,

$$F_y(SSB_y) = \begin{cases} F|_{C=100 t}, & SSB_y \leq 0.4 * B_{lim} \\ \text{lin}_1(SSB_y), & 0.4 * B_{lim} < SSB_y \leq B_{lim} \\ \text{lin}_2(SSB_y), & B_{lim} < SSB_y \leq 2 * B_{lim} \\ 0.26, & SSB_y > 2 * B_{lim} \end{cases}, \quad \text{Eq. 32}$$

where SSB is less than 40% of  $B_{lim}$ , catch = 100 t.

If  $0.4 * B_{lim} \leq SSB < B_{lim}$ , low F rates are allowed and follow a linear increase with SSB, where  $F = 0.025$  at  $SSB = 0.4 * B_{lim}$  and  $F = 0.05$  at  $SSB = B_{lim}$ ,

$$\text{lin}_1(SSB_y) = \frac{0.025}{0.6 * B_{lim}} SSB_y + \left( 0.05 - \frac{0.025}{0.6} \right), \quad \text{Eq. 33}$$

where  $B_{lim} = LRP = 66$  kt. From  $B_{lim}$ , F increases linearly with SSB until SSB reaches  $2 * B_{lim}$ , where  $F = 0.05$  at  $SSB = B_{lim}$  and  $F = 0.26$  at  $SSB = 2 * B_{lim}$

$$\text{lin}_2(SSB_y) = \frac{0.21}{B_{lim}} SSB_y - 0.16, \quad \text{Eq. 34}$$

where  $SSB \geq 2 * B_{lim} = 132$  kt, F is fixed at 0.26.

## RAISED ELBOW

This structure is the same as Elbow, but F values between  $0.4 * B_{lim}$  and  $B_{lim}$  are increased. Fishing mortality at  $0.4 * B_{lim}$  is defined at 0.07, allowing for removals in 2023 to be near status quo.

$$F_y(SSB_y) = \begin{cases} F|_{C=100t}, & SSB_y \leq 0.4 * B_{lim} \\ \text{lin}_1(SSB_y), & 0.4 * B_{lim} < SSB_y \leq B_{lim} \\ \text{lin}_2(SSB_y), & B_{lim} < SSB_y \leq 2 * B_{lim} \\ 0.26, & SSB_y > 2 * B_{lim} \end{cases} \quad \text{Eq. 35}$$

where  $SSB < 0.4 * B_{lim}$ , catch = 100 t. If  $0.4 * B_{lim} \leq SSB < B_{lim}$ , F rates follow a linear increase with SSB, where  $F = 0.07$  at  $0.4 * B_{lim}$  and  $F = 0.1$  at the  $B_{lim}$ ,

$$\text{lin}_1(SSB_y) = \frac{0.03}{0.6 * B_{lim}} SSB_y + 0.05, \quad \text{Eq. 36}$$

where  $B_{lim} = \text{LRP} = 66$  kt. From  $B_{lim}$ , F increases linearly with SSB until SSB reaches  $2 * B_{lim}$ , where  $F = 0.1$  at  $B_{lim}$  and  $F = 0.26$  at  $2 * B_{lim}$ ,

$$\text{lin}_2(SSB_y) = \frac{0.16}{B_{lim}} SSB_y - 0.06 \quad \text{Eq. 37}$$

where  $SSB \geq 2 * B_{lim} = 132$  kt, F is fixed at 0.26.

## F BRACKET

Fishing mortality changes according to a pre-defined list of values for SSB (Table 2). While relative SSB ( $SSB/B_{lim}$ ) is within a specified range of values, F is fixed at the value associated with that SSB range.

Table 2: A list (bracket) of F values and relative SSB values used for the F Bracket MP.

SSB / B <sub>lim</sub>	F
<0.4	0.025
0.4–0.6	0.03
0.6–0.8	0.03
0.8–1.0	0.05
1.0–1.2	0.1
1.2–1.4	0.125
1.4–1.6	0.15
1.6–1.8	0.18
1.8–2	0.22
>2	0.26

## SIMULATION OUTPUT

Projections were run to 2047 for each combination of R and M, and each MP. Projections were carried out for 10,000 threads (each thread representing one simulation), and the results are summarized in this document. Stock values (e.g., SSB, F<sub>5-8</sub> population-weighted F) and PMs were calculated at the end of each simulation set and stored. At the end of a simulation set, the

---

MSE-lite calculated PMs, which were described as probability thresholds (e.g., quantiles) of the PMs.

Given considerable uncertainty in long-term projections, the only simulation output presented here is for 25 years (2023 – 47), which coincides with the rebuilding target timeline outlined in the objectives. All long-term projections are associated with considerable uncertainty, and we caution against over-interpretation of median estimates.

All MPs were predicted to achieve the milestone objective (SSB in 2027 higher than 2022 levels), regardless of the assumptions made about R and M. However, stock trajectories varied greatly between OM scenarios, and the stock's ability to achieve the remaining objectives relied heavily on our assumptions about R and M, as well as our MP selection.

In the long term, the sigBH R allowed the stock projection to reach or exceed historical highs observed for this stock at the start of the time series (1959 – 60) when M was at or below current levels. In contrast, the stock leveled off after 2030 – 35 under the low R scenario modelled along recent R estimates (average 2019 – 21), and when low R was paired with high M the stock was unable to reach the LRP.

Spawning Stock Biomass projections were shown here relative to the historic time series for lowest R x highest M (R = avg3yr, M = High), WG defined prevailing conditions (R = sigBH, M = Terminal), and highest R x lowest M (R = sigBH, M = Low) conditions to show the range of projection outcomes (Figure 6). Similar figures for SSB projections under other combinations of M and R are shown in Appendix C.

Projections of SSB, F, F (population-weighted), and estimated yield were presented across all MPs in Figure 7–Figure 10 with 80% confidence intervals (CIs) on all estimates.

The Raised Elbow MP was the only MP tested that allowed total fishing removals to be at or near status quo levels; in all other cases, F and yield in at least the short term (five years) declined from 2022 levels.

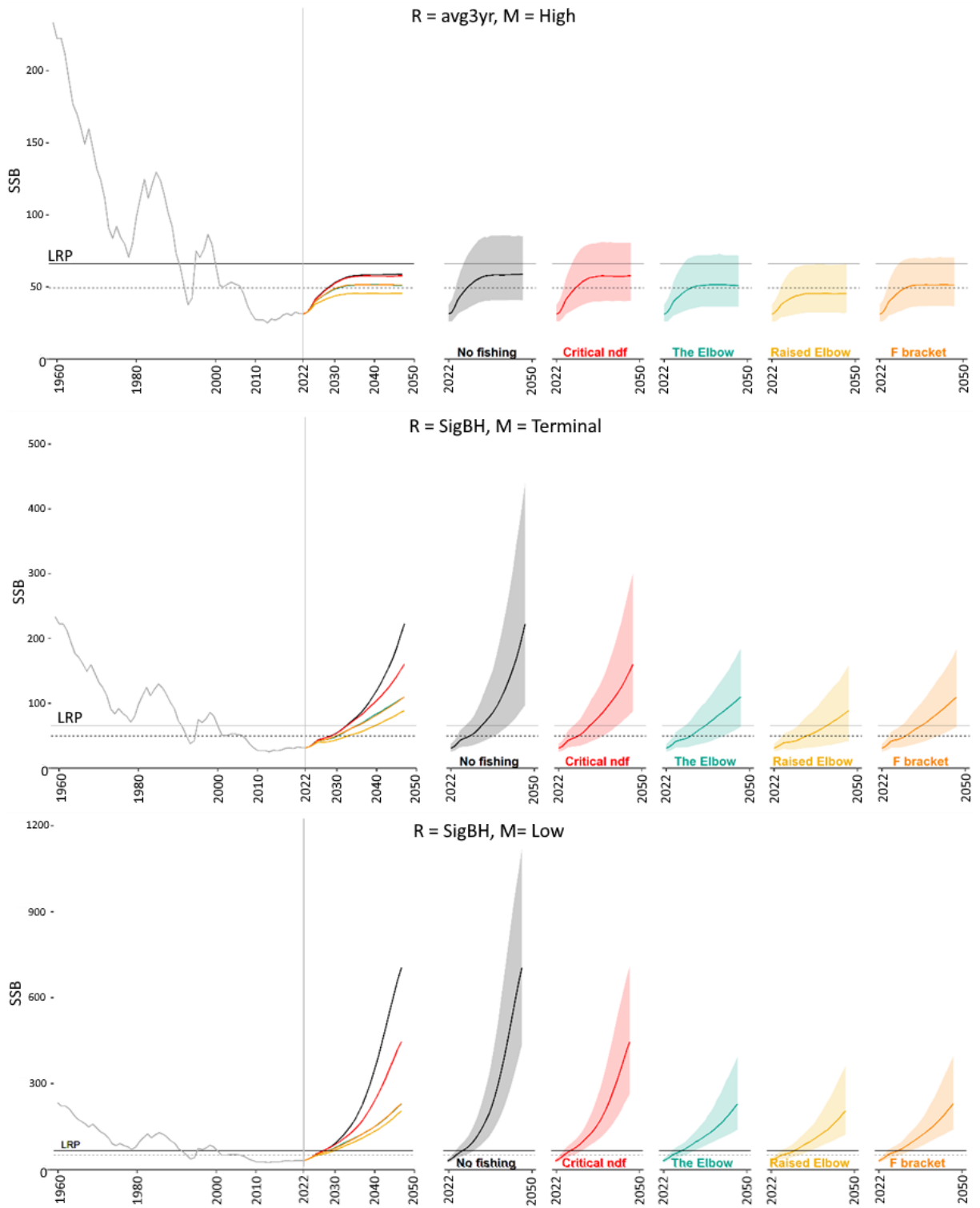


Figure 6: Stock size (SSB) projections compared to historical stock size estimates (1959 – 2022). The panels on the left show median estimates for 1959 – 2022, while on the right the projections under each MP are shown with associated 80% CIs. A solid horizontal line is at  $SSB = B_{lim}$ , dashed horizontal line is at  $SSB = 0.75B_{lim}$ . The panels show three different combinations for recruitment (R; avg3yr – average for 2019 – 21; sigBH – Sigmoidal Beverton-Holt relation), and natural mortality (M; High-average for 2015 – 21, Terminal-value for 2021, Low-average for 1996 – 2005).

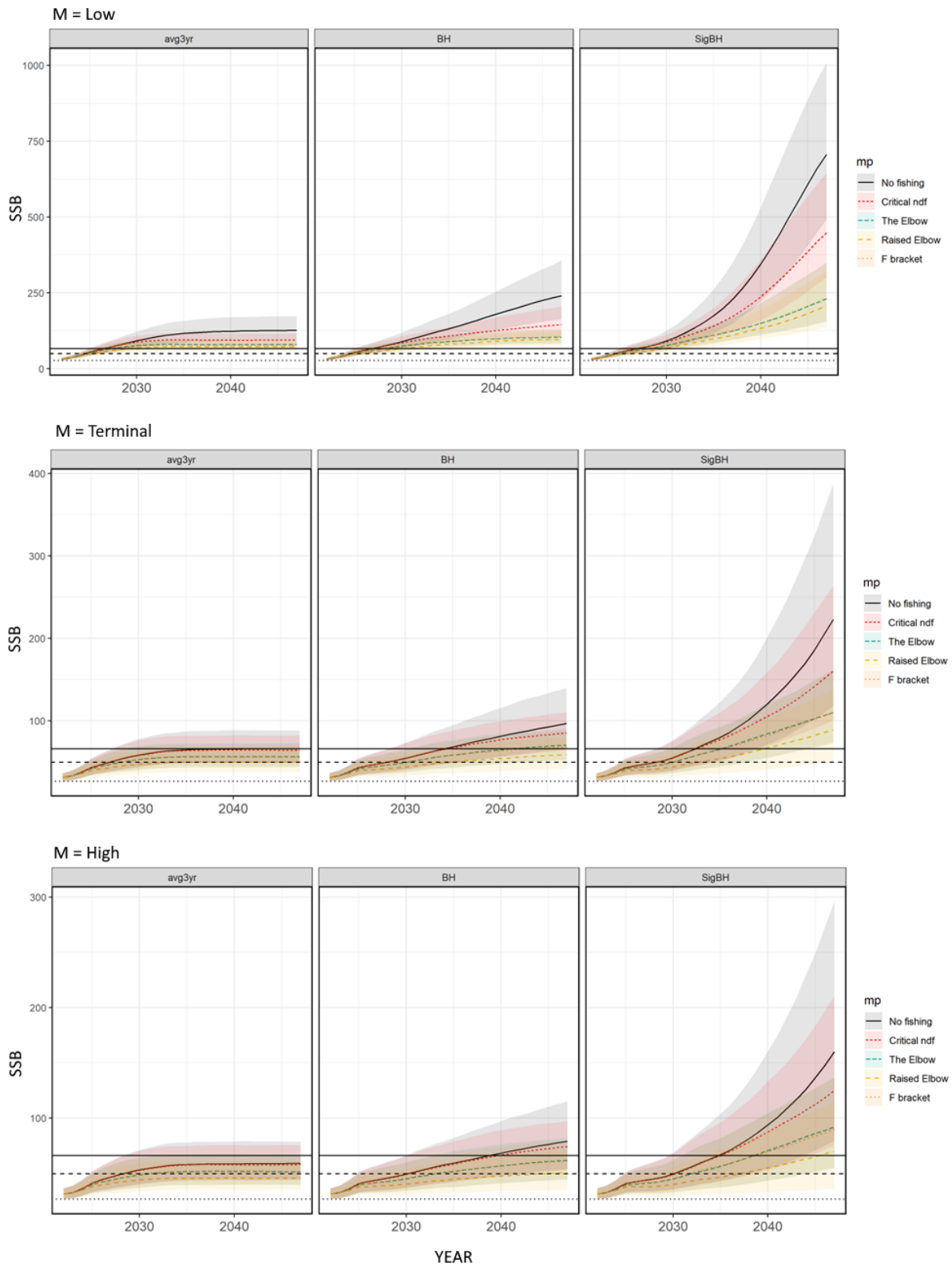


Figure 7: Stock size (SSB) projections for each of the candidate MPs are shown with associated 80% CIs under R (avg3yr: average for 2019 – 21, BH, sigBH) and M (Low, Terminal, High) conditions for the Hybrid assessment OM. A solid horizontal line is at  $SSB = B_{lim}$  and a dashed horizontal line is at  $SSB = 0.75B_{lim}$ .

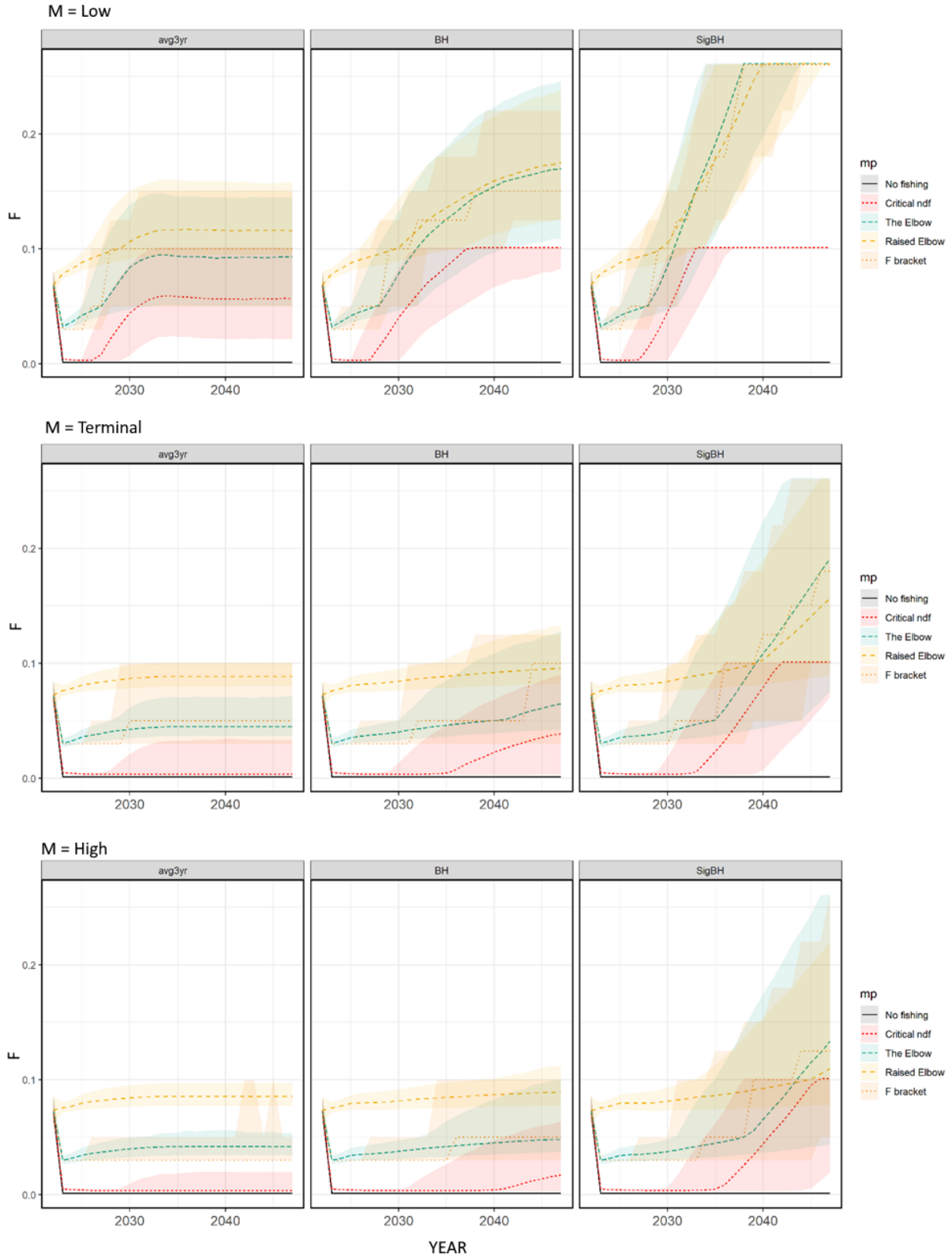


Figure 8:  $F_{bar}$  projections for each of the candidate MPs are shown with associated 80% CIs under  $R$  (avg3yr: average for 2019 – 21, BH, sigBH) and  $M$  (Low, Terminal, High) conditions for the Hybrid assessment OM.

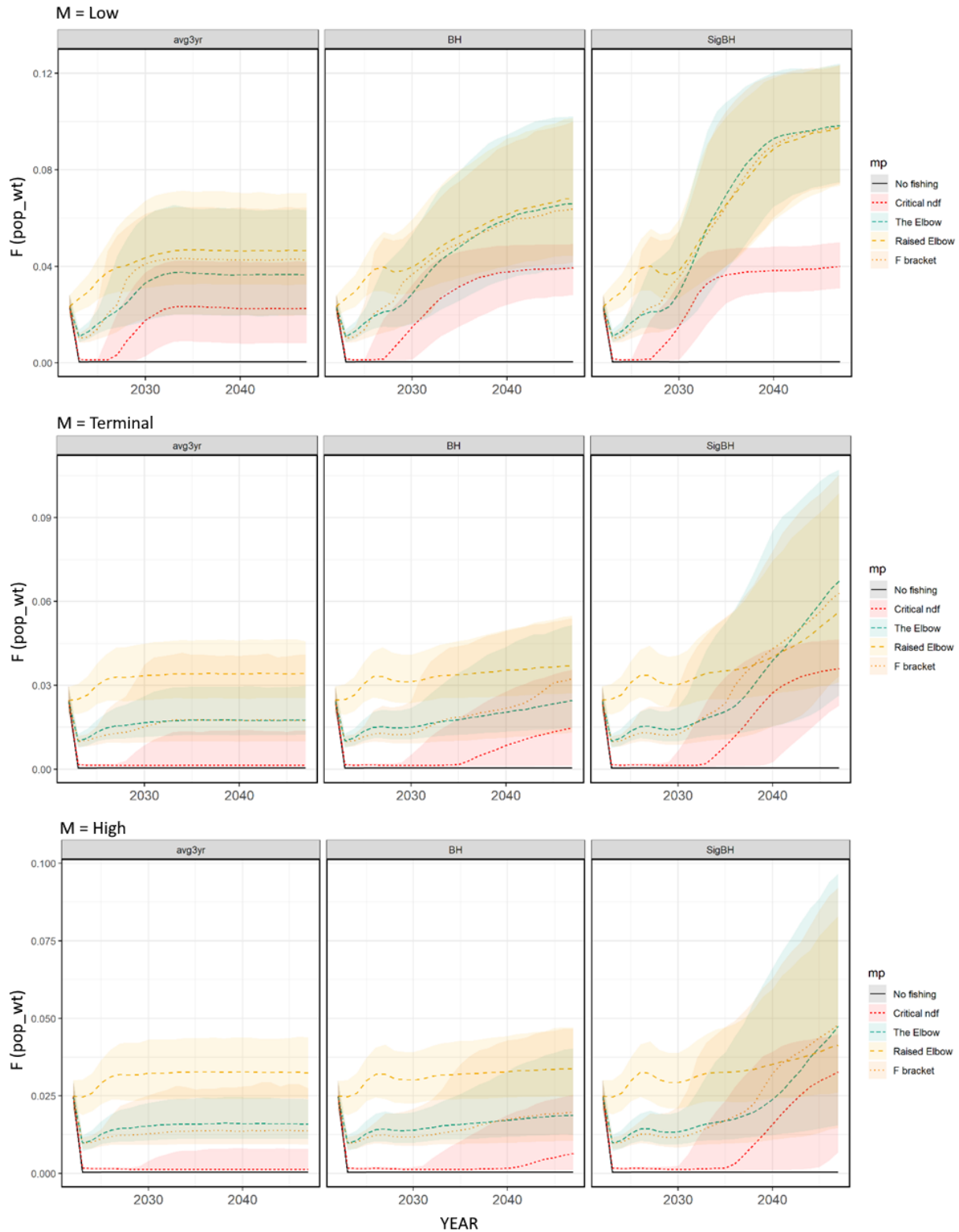


Figure 9: Population-weighted  $F$  projections for each of the candidate MPs are shown with associated 80% CIs under  $R$  (avg3yr: average for 2019 – 21, BH, sigBH) and  $M$  (Low, Terminal, High) conditions for the Hybrid assessment OM. Population-weighted  $F$  is the weighted average of  $F$ -at-age, weighted by the numbers-at-age for the same ages.

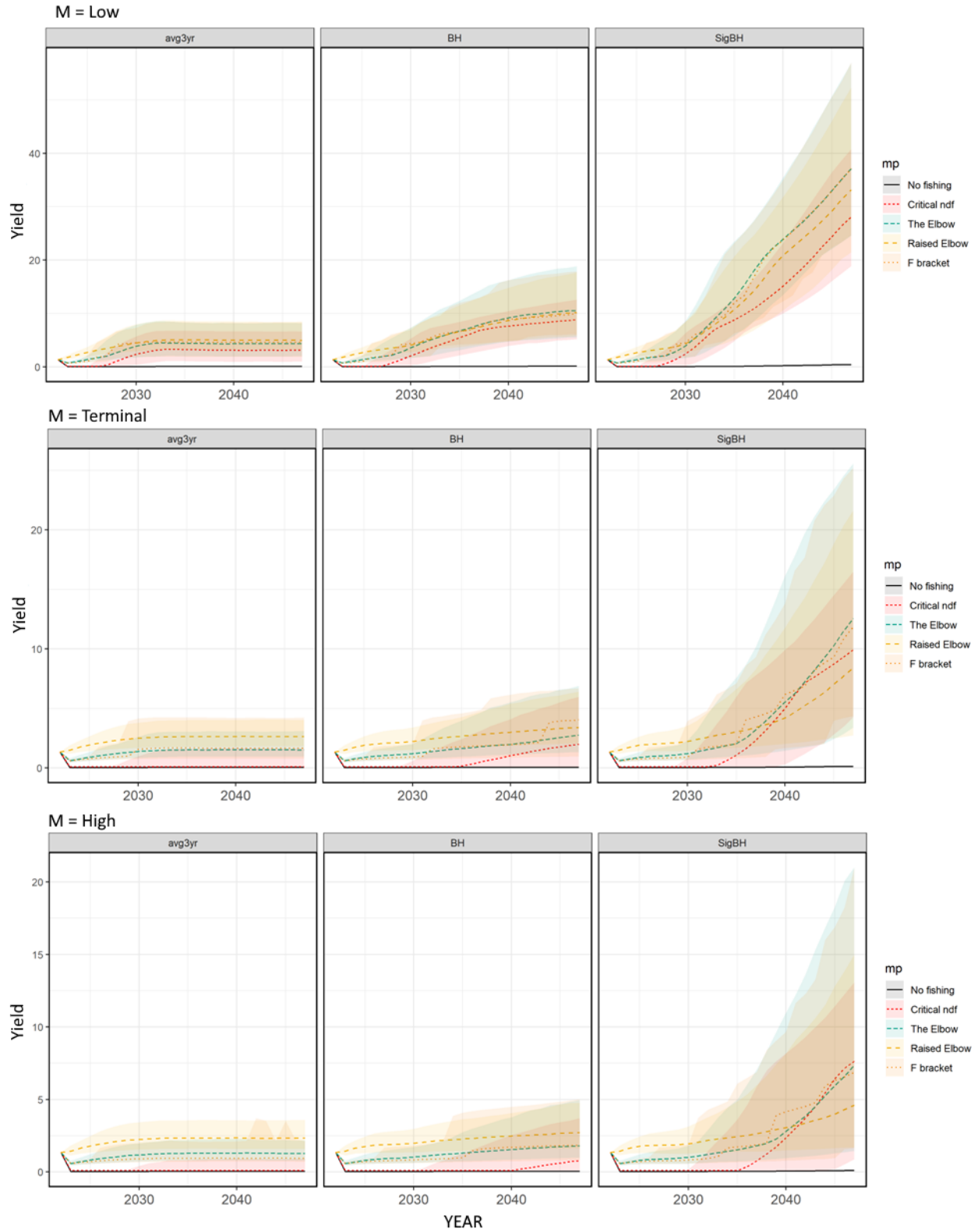


Figure 10: Yield projections for each of the candidate MPs are shown with associated 80% CIs under R (avg3yr: average for 2019 – 21, BH, sigBH) and M (Low, Terminal, High) conditions for the Hybrid assessment OM.

## PERFORMANCE METRICS

Performance of MPs was considered based on reaching the three biomass-based metrics (five year growth, 75% of the LRP in 15 years, above the LRP in 25 years; see Figures 11–14) and three catch-based metrics (short- and long-term yield, average annual catch variation [AAV]; see Figures 15–17). For each MP, the metric was shown across all R and M scenarios to inform on the robustness of the MP to potential future productivity conditions. The no fishing scenario was included for context of the stock’s ability to achieve these objectives in the absence of any removals from fishing.

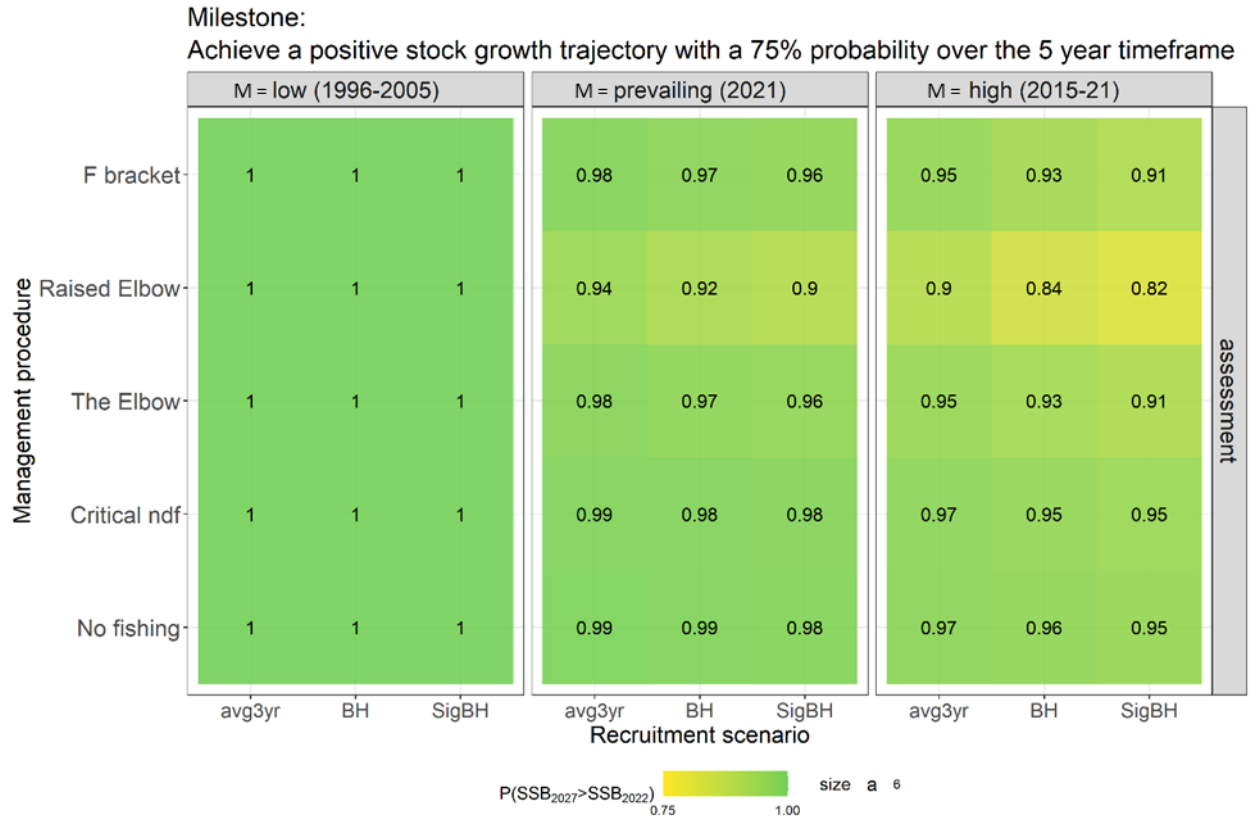


Figure 11: A summary of performance of MPs with respect to the rebuilding milestone. Each cell displays the probability of  $SSB_{2027} > SSB_{2022}$  for one combination of  $M \times R \times MP$ . This objective is considered achieved if  $P > 0.75$ .

For all PM scorecards presented here, the cell ( $M \times R \times MP$ ) was coloured grey if the objective was not achieved. Numbers in the cell indicated the probability of achieving the objective for the biomass-based metrics and showed the median estimate of AAV for the catch-based metrics (Figure 17).

Under all MPs and across all tested M and R scenarios, the milestone objective of stock growth in five years ( $SSB_{2027} > SSB_{2022}$ ) was achieved with at least an 82% probability. This objective did not quantify the magnitude of stock increase.

Achieving the short-term objective and rebuilding target required the SSB to increase to a level above  $0.75 * LRP$  with a 75% probability in 2037 and for SSB to increase to a level above the LRP with a 75% probability in 2047, respectively.

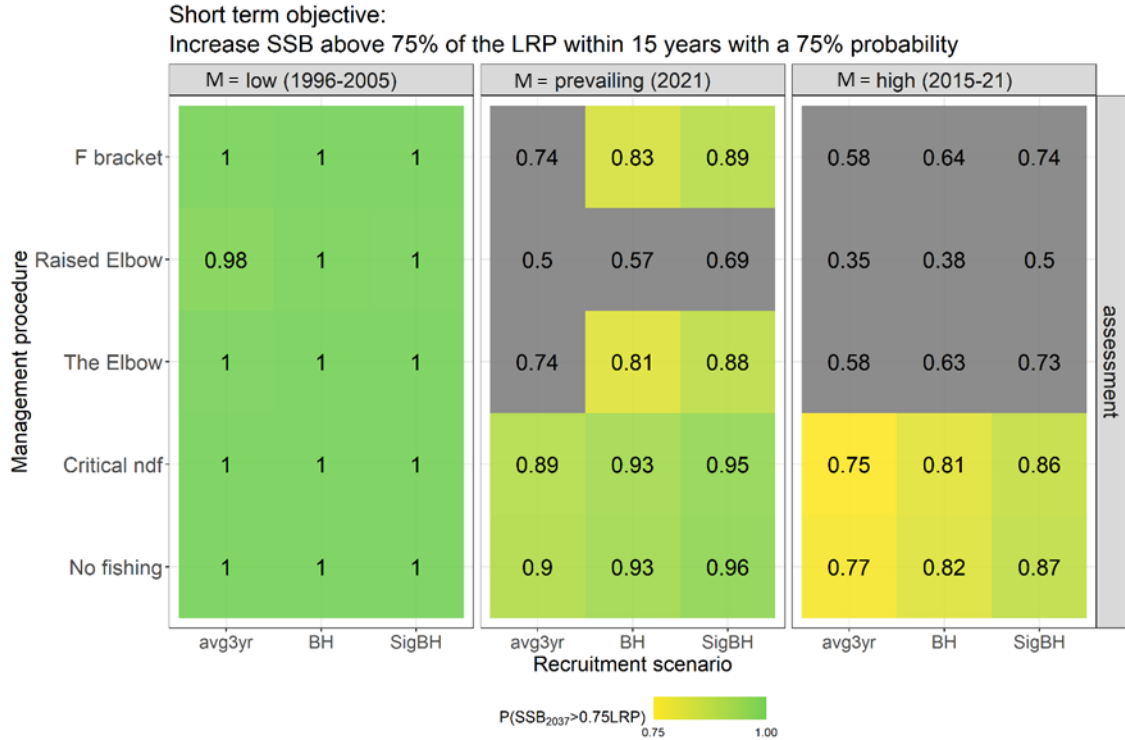


Figure 12: A summary of performance of MPs with respect to the short-term objective. Each cell displays the probability of  $SSB_{2037} > 0.75LRP$  for one combination of  $M \times R \times MP$ . This objective is considered achieved if  $P > 0.75$ . Grey cells indicate that the objective was not achieved.

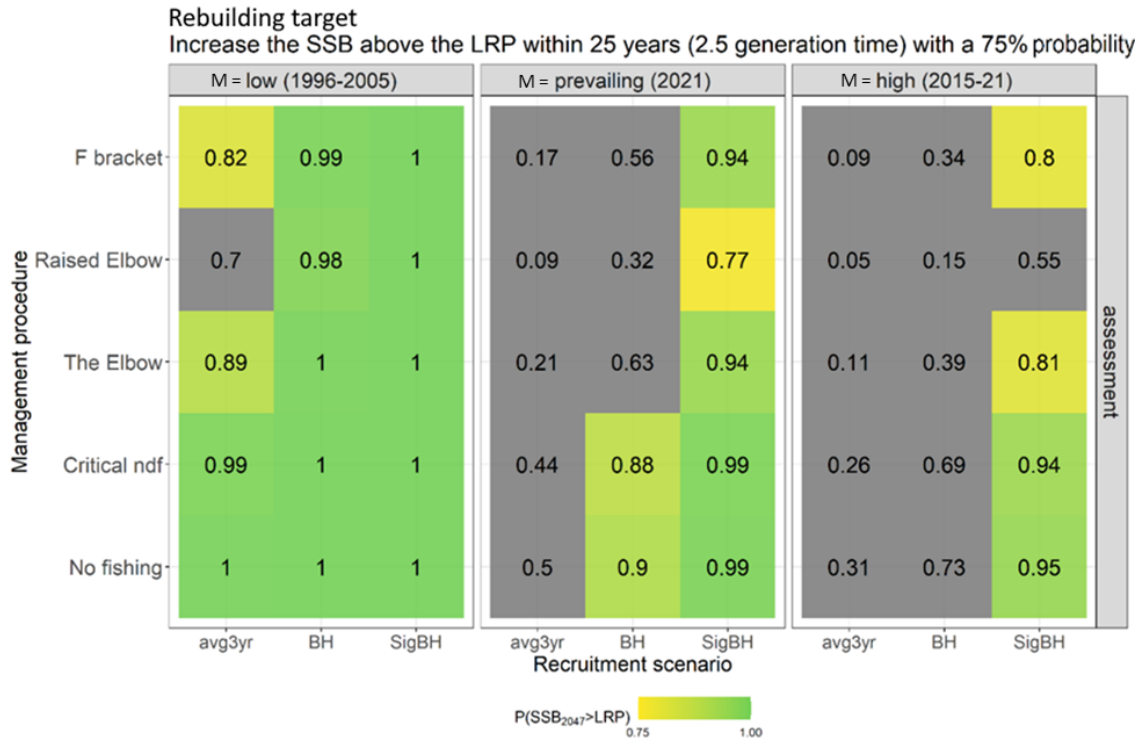


Figure 13: A summary of performance of MPs with respect to the rebuilding target. Each cell displays the probability of  $SSB_{2047} > LRP$  for one combination of  $M \times R \times MP$ . This objective is considered achieved if  $P > 0.75$ . Grey cells indicate that the objective was not achieved.

The short-term objective was achieved under all M and R scenarios in the absence of fishing. However, even at  $F = 0$ , the stock was unable to achieve the rebuilding target if R remained at the low level of the last three years, unless M returned to historic lows, or if M was at high levels and R did not follow the sigBH stock-recruit relationship. The Critical ndf MP had minimal removals below the LRP and therefore performed similar to the no fishing base case for the short-term objective and rebuilding target.

The Elbow and F Bracket MPs performed similarly to each other with respect to the short-term objective and rebuilding target. Both achieved all objectives across R scenarios at low M, but required BH or sigBH R at prevailing M. None of the MPs tested that allowed more than minimum fishing removals in the Critical Zone were able to achieve the short-term objective under the high M scenario, irrespective of the R scenario applied.

The Raised Elbow was unable to achieve the short-term objective or rebuilding target under high M, and only achieved the rebuilding target under prevailing M with the sigBH R. Even with low M, the rebuilding target was not reached under this MP if R remained at the low levels of 2019 – 21.

To look at the combined performance of each MP, a score of either 1 (objective achieved) or 0 (objective not achieved) was given under each M and R scenario and the three SSB-based objectives were summed to give each MP a score out of 3 in each productivity scenario. All MP and R scenarios achieved all three objectives under low M, with the exception of the Raised Elbow MP at low R. The Elbow and F Bracket MPs received the same overall scores, and both achieved fewer objectives across prevailing and high M scenarios than the Critical ndf MP.

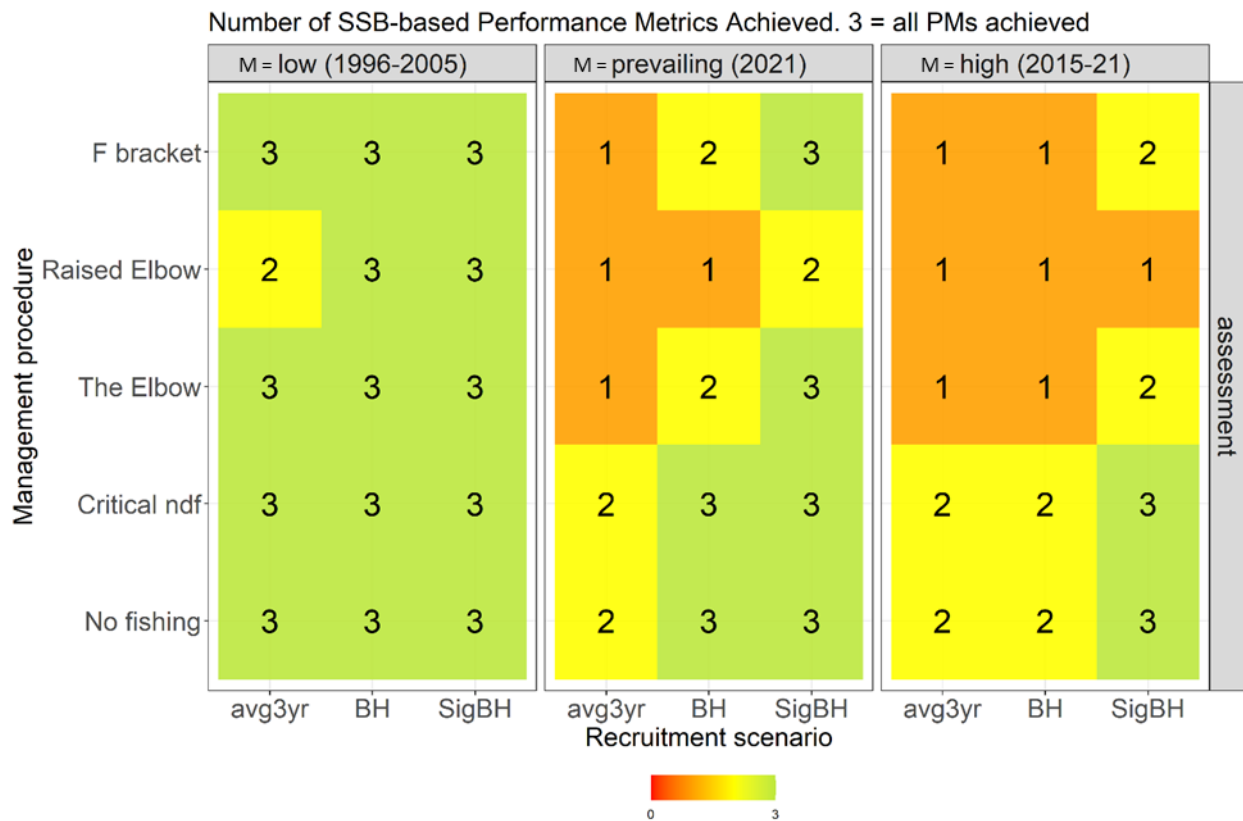


Figure 14: A summary of performance of MPs for PMs 1–3. Each cell displays the number of PMs successfully achieved (with probability of 0.75), where 0 (red) is no PMs met, and 3 (green) is all PMs achieved under one combination of  $M \times R \times MP$ .

Catch-based PMs were presented as median + 80% CIs for short- and long-term catch under each M and R scenario for each MP, and as a scorecard for AAV.

Short-term catch under Critical ndf was at or near minimum catch levels (defined as 100 t in the simulations) in all scenarios, as the stock remained below the LRP through this timeframe except in some simulations under low M. Generally, projected short-term catch was highest in the Raised Elbow MP. Short-term catch levels were similar between the Elbow and the F Bracket MPs (Figure 15).

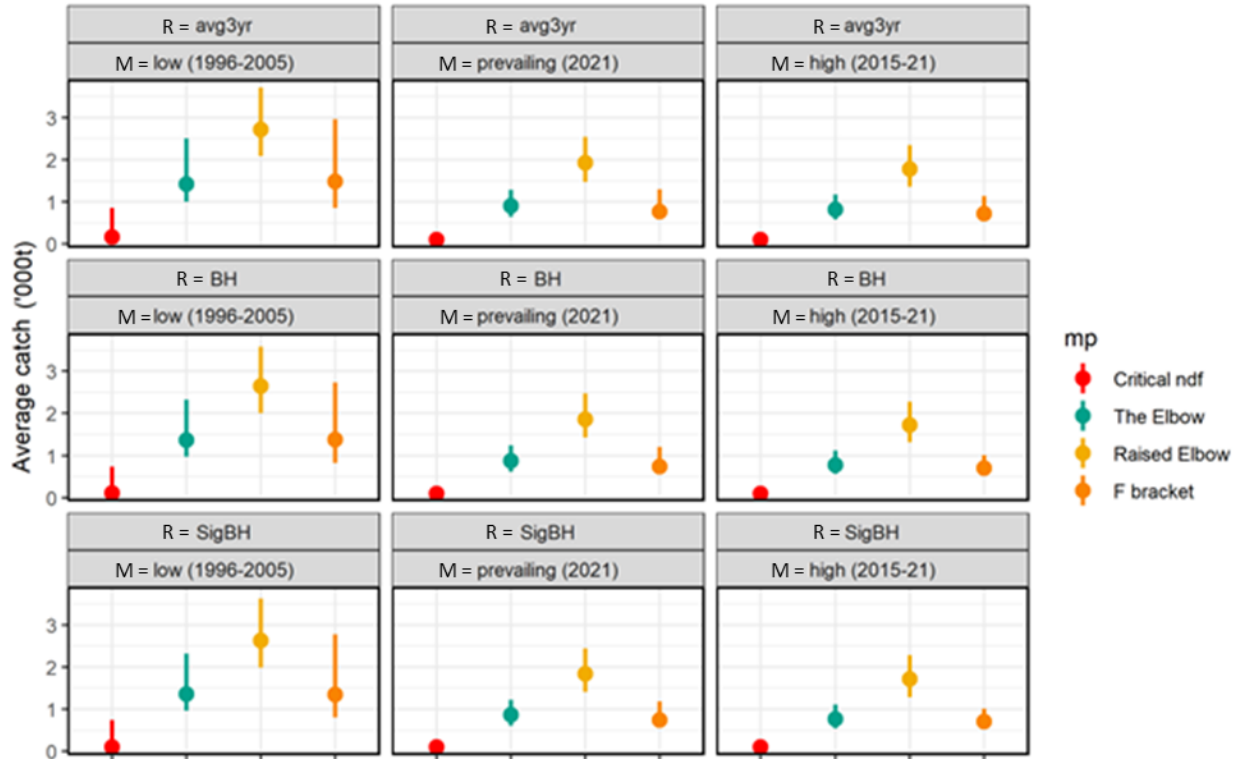


Figure 15: A summary of performance of MPs for PM 4, average short-term catch (2023 – 27) under three R (avg3yr: average for 2019 – 21, BH, sigBH) and M (low, prevailing, high) scenarios. The point indicates the median estimate and the line shows the 80% CI.

The magnitude of long-term (25-year average) catch, and differences between MPs depended largely on the mortality and R scenario (Figure 16). Catches were projected to be lowest under the low R, high M scenario, and increased with decreasing M and towards higher R, reflecting the difference in stock trajectories associated with these M and R scenarios. Under sigBH R across M scenarios, the 80% CIs on catch overlapped across several MPs, except the Critical ndf MP. There was also a high degree of overlap under BH R scenarios, though the median estimate was consistently lowest in the Critical ndf MP.

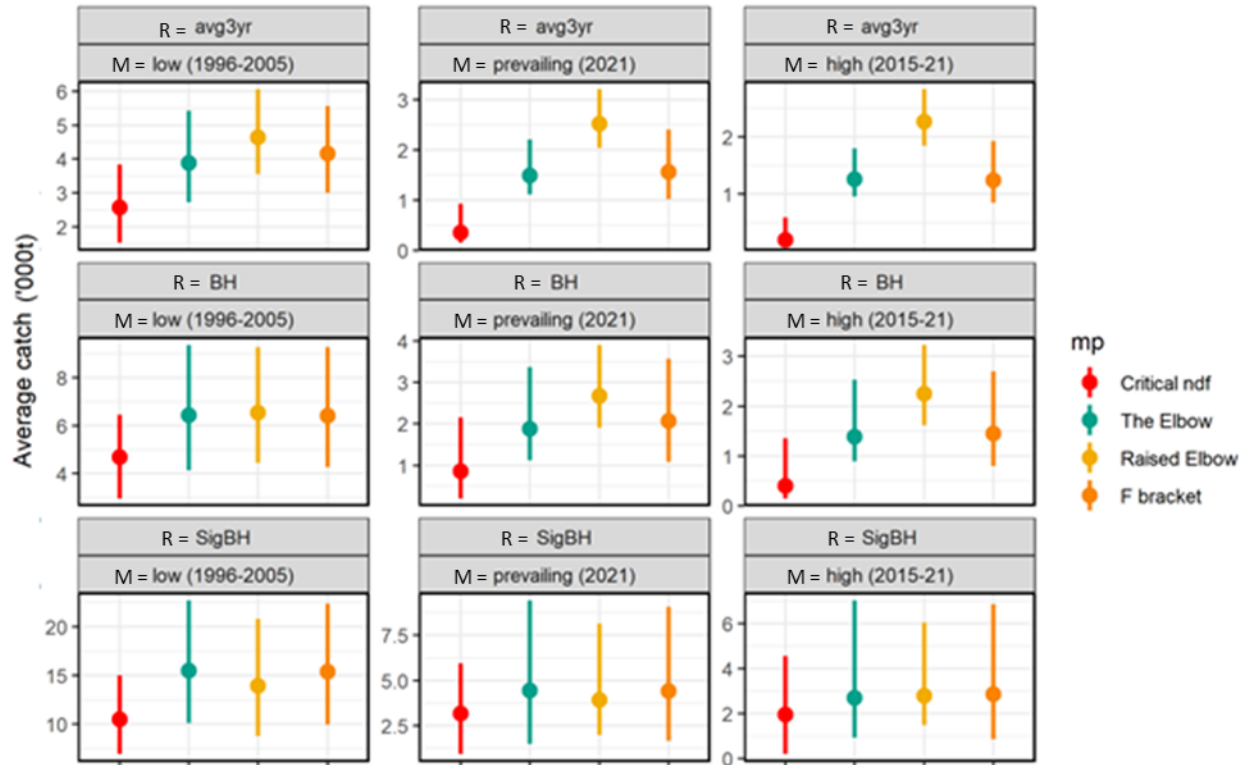


Figure 16: A summary of performance of MPs for PM 5, average long-term catch (2023 – 47) under three R (avg3yr: average for 2019 – 21, BH, sigBH) and M (low, prevailing, high) scenarios. The point indicates the median estimate, and the line shows the 80% CI.

A lower AAV indicates smaller overall year over year changes in total removals and generally indicates smaller variations in annual catch advice (Figure 17). The MPs that had break points where there was a larger change in catch advice over a small change in SSB (e.g., each bracket increased in F Bracket, at the LRP in Critical ndf) would be expected to be associated with higher average variation driven by these sudden changes. The Raised Elbow was the only MP that met the AAV < 0.2 threshold across all scenarios.

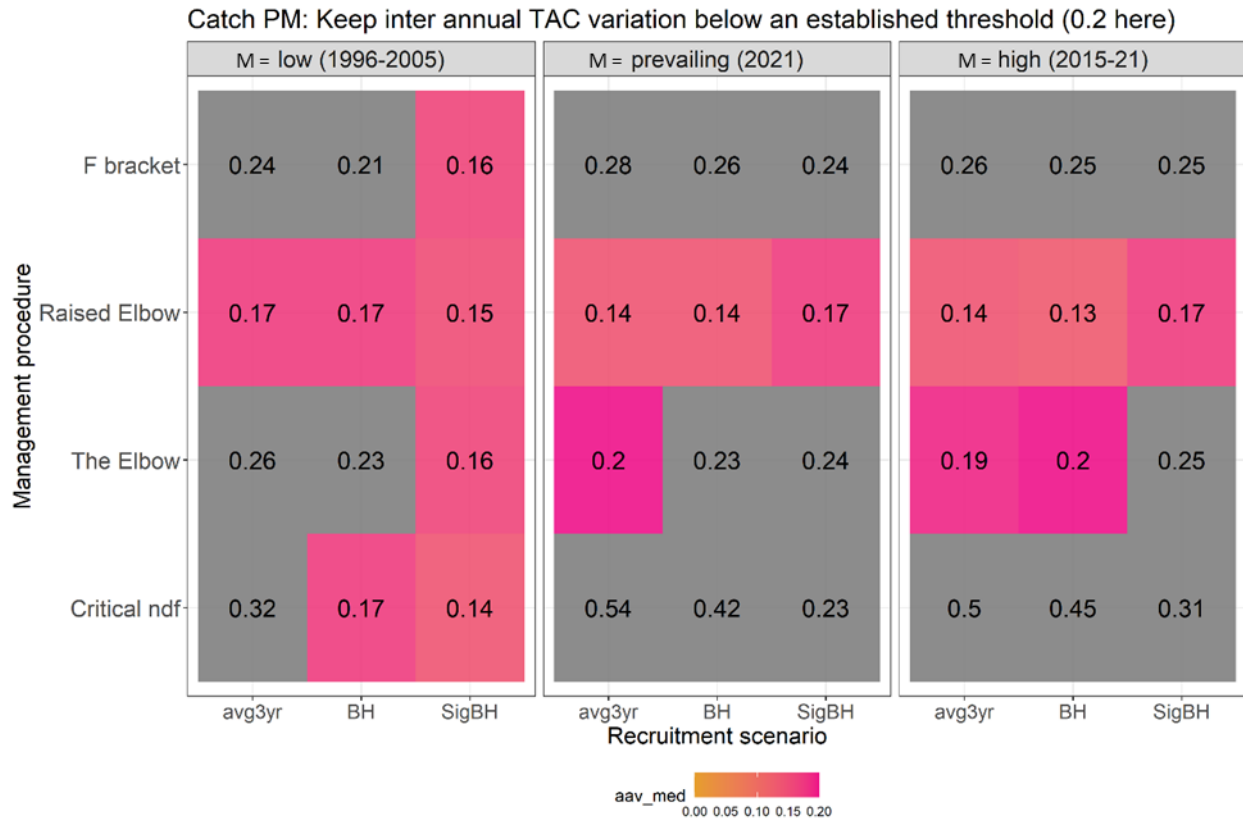


Figure 17: A summary of performance of MPs for PM 6, average annual catch variation (AAV). Each cell displays the AAV. Grey cells indicate variability greater than 0.2.

## SOURCES OF UNCERTAINTY

There was considerable uncertainty associated with long-term stock projections. Much of this was driven by uncertainty in future ecosystem conditions and stock productivity—including M and R—for which we tested various scenarios. We have not accounted for other potential changes within the stock including, but not limited to, changes in growth, distribution, movements, and mixing. Notably, the R and M scenarios all fell within the conditions previously experienced by the stock. In a changing ocean climate, these conditions may not accurately capture future conditions.

Near-bottom temperatures have experienced a general warming trend in 3Ps since 1990, with 2021 being the warmest year on record (data available from 1982 – 84, and since 1993; Cyr et al. 2022). Waters in 3Ps are projected to continue warming, with mean sea surface temperatures from 2046 – 65 projected to be 2–4 degrees warmer than the levels observed from 1986 – 2005 (see Figure 7.8 in Bush and Lemmen 2019). Atlantic Cod was the historically dominant species among predatory fishes in this ecosystem unit, but its dominance has been markedly reduced since 2010 due to increases in warm water species such as Silver Hake

---

(*Merluccius bilinearis*) (Koen-Alonso and Cuff 2018; NAFO 2021). Changes have also been noted in nutrient levels, phytoplankton (including bloom timing and duration), and zooplankton (including abundance and species composition) across the Northwest Atlantic, including in Subdiv. 3Ps (Bélanger et al. 2021). The distribution, abundance, and seasonality of predators, prey, and competitors can all impact cod growth, survival, and condition. The interaction between these, and other factors in a changing 3Ps environment are not well understood.

## NATURAL MORTALITY

Ongoing warming trends, together with more recent increased dominance of warm water fishes, indicate that the 3Ps ecosystem continues to experience structural changes. In this context, bottom-up effects contribute to poor fish condition and high M of cod in this stock (DFO 2022). The terminal estimate of M for 3Ps cod (and prevailing M condition defined within this RP process) is 0.34 (2021, ages 5–8). This is well below M levels reported for an adjacent cod stock—0.39 for age 5+ Northern cod (Div. 2J3KL; DFO 2019a) and for southerly cod stocks which occupy warmer environments—1.57 in Div. 4X5Y (Scotia-Fundy, Ages 5+; DFO 2019b), 0.81–0.85 in Div. 4TVn (Southern Gulf, Ages 5+; DFO 2019c), and 0.7 in Div. 3Pn4RS (Northern Gulf; DFO 2019d). However, we were unable to quantitatively predict future levels of M for 3Ps cod, and linkages to temperature changes and community shifts were not fully understood. It may reasonably be assumed that future M could exceed current and historic levels, in which case the scenarios examined within the MSE-lite framework would be underestimates of mortality, overestimating stock growth and future stock size, and underestimating the relative impact of F.

Preliminary analyses examined at the 2021 assessment of 3Ps cod suggested correlation between increasing bottom temperature in 3Ps and changing prey abundance with recent higher levels of M in this stock. It was recommended that work continue to explore these connections to better understand and quantify likely future mortality scenarios for this stock.

A very small proportion of the Grey Seal (*Halichoerus grypus*) population in Atlantic Canada utilizes Subdiv. 3Ps. Satellite tagging data (Hammill et al. 2017) indicated that Grey Seals that travelled to this area were mostly found during the summer months. Harbour Seals (*Phoca vitulina*) are found in Subdiv. 3Ps throughout the year. An aerial survey for Harbour Seals was flown along the Newfoundland coastline during the summer of 2021 and data analysis was ongoing at the time of the assessment. Available dietary data collected the south coast of Newfoundland (particularly Placentia Bay and the Burin Peninsula) and Miquelon, France indicated that Atlantic Cod were rarely seen in the diets of Grey or Harbour Seals in Subdiv. 3Ps (Stenson and Hamilton, unpublished data). However, future changes in seal distribution and use of Subdiv. 3Ps may change the relative impact of seals on this cod stock.

## RECRUITMENT

Recruitment success has varied throughout the available time series and predicting future R is highly uncertain. A stock-recruit relationship fit to the entire available time series of SSB and R (since 1959) was used to determine prevailing R within the context of the RP and this stock's defined LRP. A sigBH stock-recruit relationship (Perälä et al. 2022) was modelled for this purpose. Concerns have been noted over the fit of this model to stock and recruit input over the last three decades and at SSB levels just below the LRP. However, this model had good fit to the high historic R levels above the LRP, and we did not have evidence of an irreversible change in productivity within this stock. However, projections under the sigBH would be significantly overly optimistic if future stock productivity cannot reach levels of the past. In addition, there was evidence of demographic Allee effects in 3Ps cod (Perälä et al. 2022) which would be exacerbated if rates of M increased and further limited growth of the spawning stock.

---

## OTHER FACTORS

The fish born in the 2011 year class that were age-11 in 2022 remained dominant in the population. This year class was not exceptional in size, but made up the bulk of the population as few younger fish have been born in each year since. This was reflected in the fishery catch which has primarily harvested this year class over the last 4 years. This year class accounted for 45% of the commercial catch in 2020 and at the 2021 assessment, this cohort accounted for about 29% of  $SSB_{2021}$  (DFO 2022). In our simulations,  $F$  was applied equally based on current selectivity (avg. 2019 – 21, see Figure AG 7) with equal  $F$  across ages 9+. The performance of the MP projections evaluated here might change if the shape of the  $F$ -at-age changes as the dominance of this year class decreases within the stock and the fishery. Compared to a full MSE which attempts to capture much of the uncertainty in the surveys, MSE-lite assumes perfect feedback to the MP (i.e., the MP receives perfect information about the status of the stock). Hence, the uncertainties associated with real world data collection are not captured here.

## CONCLUSIONS

The MSE-lite framework utilized closed-loop simulations to evaluate stock trajectory projections for different  $R$  and  $M$  scenarios, along with the application of a variety of MPs. At the CSAS peer review process, this framework was deemed scientifically reliable and appropriate for evaluating the potential for rebuilding Atlantic Cod in 3Ps, in support of creating a RP for this stock. However, the scenarios of  $R$  and  $M$  tested within MSE-lite only reflected the past conditions experienced by the stock. With a changing ocean climate, these conditions may not accurately reflect future conditions. However, the meeting concluded that the current prevailing  $R$  and  $M$  conditions were appropriate for calculating the minimum time required to rebuild the stock to the proposed target in the absence of fishing.

## ACKNOWLEDGEMENTS

We thank Tommi Perälä for his help with the application of the sigBH stock  $R$  in the simulations.

## REFERENCES CITED

- Bélangier, D., Pepin, P., and Maillet, G. 2021. Biogeochemical oceanographic conditions in the Northwest Atlantic (NAFO subareas 2-3-4) during 2020. Serial No. N7177. NAFO SCR Doc. 21/010.
- Bush, E., and Lemmen, D.S. (Editors). 2019. Canada's Changing Climate Report. Government of Canada, Ottawa, ON. 444 p.
- Cadigan, N.G. 2016. [A state-space stock assessment model for northern cod, including under-reported catches and variable natural mortality rates](#). Can. J. Fish. Aquat. Sci. 73(2): 296–308.
- Champagnat, J., Vigneau, J., Varkey, D.A., Regular, P., Ings, D.W., Babyn, J., and Morgan, J. 2024. [Development of a State Space Assessment Model for Cod \(\*Gadus morhua\*\) in NAFO Subdivision 3Ps](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2024/015. iv + 98 p.
- Cyr, F., Snook, S., Bishop, C., Galbraith, P.S., Chen, N., and Han, G. 2022. [Physical Oceanographic Conditions on the Newfoundland and Labrador Shelf during 2021](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2022/040. iv + 48 p.
- DFO. 2006. [A Harvest Strategy Compliant with the Precautionary Approach](#). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2006/023.

- 
- DFO. 2019a. [Stock assessment of Northern cod \(NAFO Divisions 2J3KL\) in 2019](#). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/050.
- DFO. 2019b. [Stock Assessment of Atlantic Cod \(\*Gadus morhua\*\) in NAFO Divisions 4X5Y](#). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/015.
- DFO. 2019c. [Assessment of Atlantic Cod \(\*Gadus morhua\*\) in the southern Gulf of St. Lawrence \(NAFO Div. 4T-4Vn \(Nov. – April\)\) to 2018](#). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/021.
- DFO. 2019d. [Assessment of the Northern Gulf of St. Lawrence \(3Pn, 4RS\) Atlantic Cod Stock in 2018](#). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/032.
- DFO. 2022. [Stock Assessment of NAFO Subdivision 3Ps Cod](#). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2022/022.
- Drake, J.M., and Kramer, A.M. 2011. Allee Effects. Nature Education Knowledge. 3(10): 2.
- Forrest, R.E., Holt, K.R., and Kronlund, A.R. 2018. [Performance of alternative harvest control rules for two Pacific groundfish stocks with uncertain natural mortality: Bias, robustness and trade-offs](#). Fish. Res. 206: 259–286.
- Hammill, M.O., den Heyer, C.E., Bowen, W.D., and Lang, S.L.C. 2017. [Grey Seal Population Trends in Canadian Waters, 1960–2016 and harvest advice](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2017/052. v + 30 p.
- Hilborn, R., and Liermann, M. 1998. [Standing on the shoulders of giants: learning from experience in fisheries](#). Rev. Fish Biol. Fish. 8(3): 273–283.
- Ings, D.W., Rideout, R.M., Wheeland, L., Healey, B.P., Morgan, M.J., Regular, P., and Vigneau, J. 2019a. [Assessing the status of cod \(\*Gadus morhua\*\) stock in NAFO Subdivision 3Ps in 2017](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2019/024.
- Ings, D.W., Rideout, R.M., Rogers, R., Healey, B.P., Morgan, M.J., Robertson, G.J., and Vigneau, J. 2019b. [Assessing the status of cod \(\*Gadus morhua\*\) stock in NAFO Subdivision 3Ps in 2018](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2019/069.
- Koen-Alonso, M., and Cuff, A. 2018. Status and trends of the fish community in the Newfoundland Shelf (NAFO Div. 2J3K), Grand Bank (NAFO Div. 3LNO) and Southern Newfoundland Shelf (NAFO Div. 3Ps) Ecosystem Production Units. Serial No. N7023. NAFO SCR Doc. 18/070.
- Kramer, A.M., Dennis, B., Liebhold, A.M., and Drake, J.M. 2009. [The evidence for Allee effects](#). Popul. Ecol. 51: 341–354.
- Kumar, R., Martell, S.M., Pitcher, T.J., and Varkey, D.A. 2013. [Temperature-driven decline of a cisco population in Mille Lacs Lake, Minnesota](#). North Am. J. Fish. Manage. 33: 669–681.
- Kurota, H., McAllister, M.K., Parkinson, E.A., and Johnston, N.T. 2016. [Evaluating the influence of predator–prey interactions on stock assessment and management reference points for a large lake ecosystem](#). Can. J. Fish. Aquat. Sci. 73(9): 1372–1388.
- Myers, R.A., Barrowman, N.J., Hutchings, J.A., and Rosenberg, A.A. 1995. [Population dynamics of exploited fish stocks at low population levels](#). Science. 269(5227): 1106–1108.
- NAFO. 2021. Report of the Scientific Council Working Group on Ecosystem Science and Assessment, 16 - 25 November 2021. Dartmouth, Nova Scotia, Canada. Serial No. N7256. NAFO SCS Doc. 21/21.
-

- 
- Nielsen, A., and Berg, C.W. 2014. [Estimation of time-varying selectivity in stock assessments using state-space models](#). Fish. Res. 158: 96–101.
- Perälä, T., Hutchings, J.A., and Kuparinen, A. 2022. [Allee effects and the Allee-effect zone in northwest Atlantic Cod](#). Biol. Lett. 18(2): 20210439.
- Punt, A.E., Butterworth, D.S., de Moor, C.L., De Oliveira, J.A.A., and Haddon, M. 2016. [Management strategy evaluation: best practices](#). Fish Fish. 17(2): 303–334.
- Regular, P. 2022. Fish condition based natural mortality. Appendix C in Varkey, D.A., Babyn, J., Regular, P., Ings, D.W., Kumar, R., Rogers, B., Champagnat, J., and Morgan, M.J. 2022. [A state-space model for stock assessment of cod \(\*Gadus morhua\*\) stock in NAFO Subdivision 3Ps](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2022/022. v + 78 p.
- Regular, P.M., Buren, A.D., Dwyer, K.S., Cadigan, N.G., Gregory, R.S., Koen-Alonso, M., Rideout, R.M., Robertson, G.J., Robertson, M.D., Stenson, G.B., Wheeland, L.J., and Zhang, F. 2022. [Indexing starvation mortality to assess its role in the population regulation of Northern cod](#). Fish. Res. 247: 106180.
- Robertson, G. 2022. Tagging based analysis of natural mortality. Appendix B in Varkey, D.A., Babyn, J., Regular, P., Ings, D.W., Kumar, R., Rogers, B., Champagnat, J., and Morgan, M.J. 2022. [A state-space model for stock assessment of cod \(\*Gadus morhua\*\) stock in NAFO Subdivision 3Ps](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2022/022. v + 78 p.
- Varkey, D.A., Babyn, J., Regular, P., Ings, D.W., Kumar, R., Rogers, B., Champagnat, J., and Morgan, M.J. 2022. [A state-space model for stock assessment of cod \(\*Gadus morhua\*\) stock in NAFO Subdivision 3Ps](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2022/022. v + 78 p.
- Walters, C., and Kitchell, J.F. 2001. [Cultivation/depensation effects on juvenile survival and recruitment: implications for the theory of fishing](#). Can. J. Fish. Aquat. Sci. 58(1): 39–50.

---

## APPENDIX A: PARAMETERIZATION OF NATURAL MORTALITY (M) IN THE HYBRID MODEL

When information on  $M$  is not available, a base assumption in fisheries stock assessments has been that  $M$  is invariant over age and year and often assigned a value of  $M = 0.2$  (Hilborn and Liermann 1998). For neighboring cod stocks (Northern cod 2J3KL and Flemish cap 3M),  $M$  is estimated to be higher than 0.2 (Cadigan 2016, and the two most recent assessments for 2J3KL and 3M cod), and for this reason,  $M = 0.3$  was chosen as the base level. Analysis of tagging data for 3Ps cod also suggested  $M$  levels to be higher than 0.2; although the tagging data is limited to the post-moratorium time period (Robertson 2022). Previous assessments also indicated an increase in total mortality (Ings et al. 2019a, Ings et al. 2019b).

The model applies time-varying  $M_{a,y}$ , where a trend based on fish condition is applied to a base level  $M$  ( $M_{base} = 0.3$ ).

$$M_{a,y} = M_{base} \exp(\delta_{a,y}) \quad \text{Eq. A.1}$$

The  $\delta_{a,y}$  term is covariate associated estimation such that the resulting  $M$  follows the trend in the covariate  $X_y$ .

$$\delta_{a,y} = mpar_a * X_y \quad \text{Eq. A.2}$$

Estimates of  $mpar$  close to zero suggest no/little influence of covariate on  $M$ , a positive  $mpar$  indicates that  $M$  follows the trend in the covariate and a negative  $mpar$  indicates an  $M$  trend opposite to the trend in the covariate. Here, the covariate  $X_y$  is a standardized index of  $Mc$ , a condition-based index of  $M$

$$X_y = \frac{Mc_y - \mu_{Mc}}{\sigma_{Mc}} \quad \text{Eq. A.3}$$

This scaling allows the treatment of the covariate as an anomaly resulting in estimates above or below the baseline  $M_{base}$  provided, similar to the scaling for temperature anomaly for time-varying carrying capacity (Kumar et al. 2013). The mean ( $\mu_{Mc}$ ) and standard deviation ( $\sigma_{Mc}$ ) are calculated for the first 35 years of data; therefore, the normalization of  $Mc$  is based on a reference period from 1978 - 12. The  $mpar$  parameter was estimated by two age groups (2–5 and 6+, roughly corresponding to immature and mature) to allow different age groups to respond differently to the trends in fish condition. A similar implementation of time-varying  $M$  is for the Kootenay lake kokanee population by Kurota et al. (2016). The final equation for  $M$  is:

$$M_{a,y} = M_{base} \exp\left(mpar_a * \left(\frac{Mc_y - \mu_{Mc}}{\sigma_{Mc}}\right)\right) \quad \text{Eq. A.4}$$

---

## APPENDIX B: ADDITIONAL TABLES AND FIGURES

### TABLES

Table AB 1: Condition-based index of natural mortality ( $M$ ) used to scale  $M$  within the Hybrid model.

Year	Condition-based index of $M$ ( $M_c$ )
1978	0.444
1979	0.431
1980	0.422
1981	0.352
1982	0.341
1983	0.341
1984	0.277
1985	0.258
1986	0.239
1987	0.211
1988	0.228
1989	0.231
1990	0.244
1991	0.275
1992	0.291
1993	0.302
1994	0.384
1995	0.308
1996	0.230
1997	0.205
1998	0.186
1999	0.165
2000	0.200
2001	0.258
2002	0.236
2003	0.202
2004	0.171
2005	0.187
2006	0.237
2007	0.210
2008	0.273
2009	0.413
2010	0.425
2011	0.347
2012	0.429
2013	0.518
2014	0.508
2015	0.494
2016	0.611
2017	0.482
2018	0.415
2019	0.537
2020	0.476

Table AB 2: Model estimated numbers-at-age (in millions), 1959 – 90.

Year	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Age11	Age12	Age13	Age14+
1959	137.77	108.45	188.22	50.90	45.45	33.30	6.71	9.04	6.91	6.96	3.73	0.59	0.01
1960	129.41	104.73	77.87	128.90	33.84	23.55	18.56	4.40	4.97	3.61	4.23	1.90	0.37
1961	128.28	94.47	82.12	51.50	74.81	17.25	16.26	9.25	2.79	2.67	1.96	2.82	1.18
1962	136.13	93.28	72.95	59.37	31.20	39.58	10.02	7.15	4.70	1.47	1.40	1.07	2.41
1963	171.93	95.36	63.57	50.20	35.37	17.95	20.81	6.60	3.46	2.51	0.81	0.80	2.06
1964	200.64	132.10	63.82	39.27	30.53	17.97	10.46	10.28	4.63	1.80	1.52	0.45	1.62
1965	211.32	156.12	95.02	38.02	23.55	15.32	10.19	5.83	4.54	3.03	0.85	0.81	1.09
1966	204.65	154.35	114.70	61.26	20.54	15.65	6.18	5.25	3.20	1.83	2.07	0.42	0.93
1967	166.78	164.14	118.52	72.94	34.59	11.50	7.34	2.97	2.42	1.57	0.67	1.31	0.71
1968	134.02	126.28	122.40	82.10	37.01	17.06	6.19	3.89	1.54	1.27	0.76	0.26	1.66
1969	106.30	94.35	94.52	78.97	42.91	19.51	7.56	2.95	2.11	0.71	0.64	0.36	0.97
1970	113.07	71.85	65.65	62.96	45.20	22.22	9.15	3.32	1.21	0.92	0.33	0.29	0.56
1971	95.01	92.34	48.17	39.46	31.38	24.23	9.83	4.02	1.70	0.57	0.45	0.17	0.36
1972	79.95	71.32	68.13	28.47	19.95	16.54	10.86	4.16	1.77	0.83	0.28	0.21	0.24
1973	97.24	52.56	52.10	45.81	14.84	10.66	6.57	4.94	1.87	0.76	0.40	0.13	0.21
1974	101.60	77.35	32.95	34.64	22.66	7.17	4.88	2.84	2.00	0.80	0.32	0.17	0.17
1975	91.95	75.32	55.03	17.10	18.61	13.84	2.88	2.00	1.15	0.82	0.33	0.14	0.16
1976	86.01	68.57	55.46	36.12	11.62	7.75	4.52	1.21	0.82	0.50	0.35	0.15	0.15
1977	54.53	74.64	52.45	37.26	19.94	5.23	2.53	2.59	0.67	0.46	0.30	0.21	0.18
1978	37.54	40.08	66.25	34.34	17.62	7.96	2.65	1.61	1.53	0.36	0.28	0.17	0.26
1979	46.75	24.09	31.86	57.97	22.63	9.33	4.34	1.49	0.91	0.74	0.20	0.16	0.30
1980	73.75	36.05	17.97	24.81	36.75	13.58	5.23	2.30	0.92	0.60	0.38	0.13	0.34
1981	57.51	67.00	30.51	13.83	17.60	21.77	7.10	3.16	1.36	0.58	0.40	0.20	0.29
1982	102.48	41.91	57.84	22.12	8.68	11.17	15.32	3.91	1.85	0.82	0.36	0.24	0.30
1983	126.65	79.45	33.85	44.93	14.08	5.87	5.57	7.88	2.44	1.09	0.50	0.23	0.33
1984	129.96	88.73	60.38	28.02	26.91	9.11	3.56	3.43	4.12	1.47	0.65	0.30	0.38
1985	105.37	98.29	70.60	43.57	19.60	16.28	5.87	2.37	2.37	2.31	1.11	0.43	0.50
1986	120.02	68.24	74.84	49.42	34.18	12.85	9.07	3.60	1.59	1.42	1.26	0.66	0.63
1987	137.62	81.63	40.26	47.87	32.47	19.85	6.71	4.65	2.10	0.98	0.84	0.72	0.81

Year	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Age11	Age12	Age13	Age14+
1988	150.58	91.58	52.72	22.04	29.44	18.22	7.80	3.34	2.36	1.13	0.60	0.46	0.79
1989	138.26	108.08	60.86	30.88	11.22	11.85	7.57	4.16	1.73	1.24	0.54	0.33	0.61
1990	78.32	106.15	75.39	36.30	14.24	6.08	6.17	3.79	2.07	0.83	0.62	0.25	0.50

Table AB 3: Model estimated numbers-at-age (in millions), 19912021.

Year	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Age11	Age12	Age13	Age14+
1991	101.20	49.01	69.95	39.71	16.29	5.49	2.68	3.15	1.76	0.89	0.39	0.30	0.37
1992	58.55	74.63	27.38	34.86	15.55	4.65	1.38	0.93	0.85	0.42	0.23	0.09	0.21
1993	29.01	46.36	50.08	13.27	13.25	4.68	1.37	0.35	0.14	0.13	0.06	0.04	0.04
1994	36.51	19.35	39.43	36.60	7.85	5.91	1.80	0.60	0.16	0.06	0.05	0.02	0.03
1995	33.30	30.74	12.85	30.12	30.87	7.28	4.59	1.30	0.28	0.12	0.03	0.03	0.03
1996	29.05	29.54	31.51	10.42	15.86	16.32	3.96	2.18	0.76	0.19	0.10	0.02	0.03
1997	26.81	21.02	22.09	26.14	7.76	8.64	8.18	2.28	1.18	0.52	0.12	0.07	0.03
1998	27.83	19.91	16.32	15.12	13.73	5.25	6.17	5.68	1.39	0.67	0.31	0.09	0.05
1999	38.10	20.69	12.92	12.56	9.77	8.35	3.27	2.80	2.93	0.71	0.32	0.14	0.07
2000	42.98	31.24	15.36	9.18	7.74	5.31	4.51	1.61	1.36	2.00	0.35	0.13	0.10
2001	32.91	35.28	25.40	10.68	6.42	4.45	2.57	1.99	0.70	0.72	0.96	0.15	0.11
2002	21.26	26.35	22.93	16.86	6.88	3.66	2.18	1.13	0.91	0.32	0.36	0.44	0.09
2003	26.96	13.13	17.68	14.49	11.25	4.33	1.81	0.95	0.55	0.43	0.14	0.17	0.24
2004	28.17	21.52	9.63	10.23	10.06	6.96	2.32	0.90	0.46	0.31	0.19	0.07	0.20
2005	27.80	22.21	15.63	7.42	6.08	6.19	3.71	1.46	0.47	0.29	0.16	0.09	0.14
2006	30.82	21.81	15.55	11.40	5.71	3.72	3.83	2.13	0.85	0.26	0.15	0.08	0.11
2007	24.40	25.62	14.78	10.55	6.86	3.59	1.92	2.09	1.17	0.47	0.14	0.08	0.10
2008	25.60	16.50	18.69	9.47	7.27	4.03	2.05	1.01	1.01	0.57	0.25	0.07	0.09
2009	20.70	20.84	11.72	12.91	6.59	3.82	1.80	0.86	0.44	0.42	0.26	0.12	0.08
2010	26.54	13.16	16.56	8.57	7.94	3.24	1.44	0.59	0.32	0.15	0.16	0.10	0.07
2011	28.47	21.52	8.51	11.94	6.20	4.17	1.47	0.63	0.22	0.12	0.06	0.06	0.07
2012	21.93	23.23	15.18	5.67	7.20	4.16	2.02	0.66	0.28	0.09	0.06	0.02	0.06
2013	23.72	14.33	17.63	11.04	4.38	4.01	2.23	0.92	0.27	0.13	0.05	0.02	0.04
2014	14.54	19.38	9.09	13.02	6.86	2.36	2.55	1.06	0.41	0.10	0.06	0.02	0.03

---

<b>Year</b>	<b>Age2</b>	<b>Age3</b>	<b>Age4</b>	<b>Age5</b>	<b>Age6</b>	<b>Age7</b>	<b>Age8</b>	<b>Age9</b>	<b>Age10</b>	<b>Age11</b>	<b>Age12</b>	<b>Age13</b>	<b>Age14+</b>
<b>2015</b>	11.78	9.27	17.61	6.78	8.17	3.93	1.33	1.25	0.39	0.15	0.04	0.02	0.02
<b>2016</b>	9.40	8.34	7.16	16.55	5.83	4.97	2.16	0.72	0.56	0.13	0.07	0.02	0.02
<b>2017</b>	9.88	6.14	6.63	6.77	14.02	3.67	2.46	1.05	0.34	0.18	0.04	0.03	0.01
<b>2018</b>	14.94	6.20	5.10	4.57	5.75	9.49	2.57	1.07	0.50	0.15	0.07	0.02	0.02
<b>2019</b>	17.43	11.59	5.18	4.08	3.64	3.87	6.05	1.77	0.68	0.27	0.07	0.04	0.02
<b>2020</b>	20.78	12.24	8.39	3.97	3.56	2.61	2.34	4.35	1.07	0.38	0.14	0.04	0.03
<b>2021</b>	24.54	15.38	9.00	6.03	2.93	2.23	1.67	1.41	2.41	0.63	0.22	0.08	0.04

---

## FIGURES

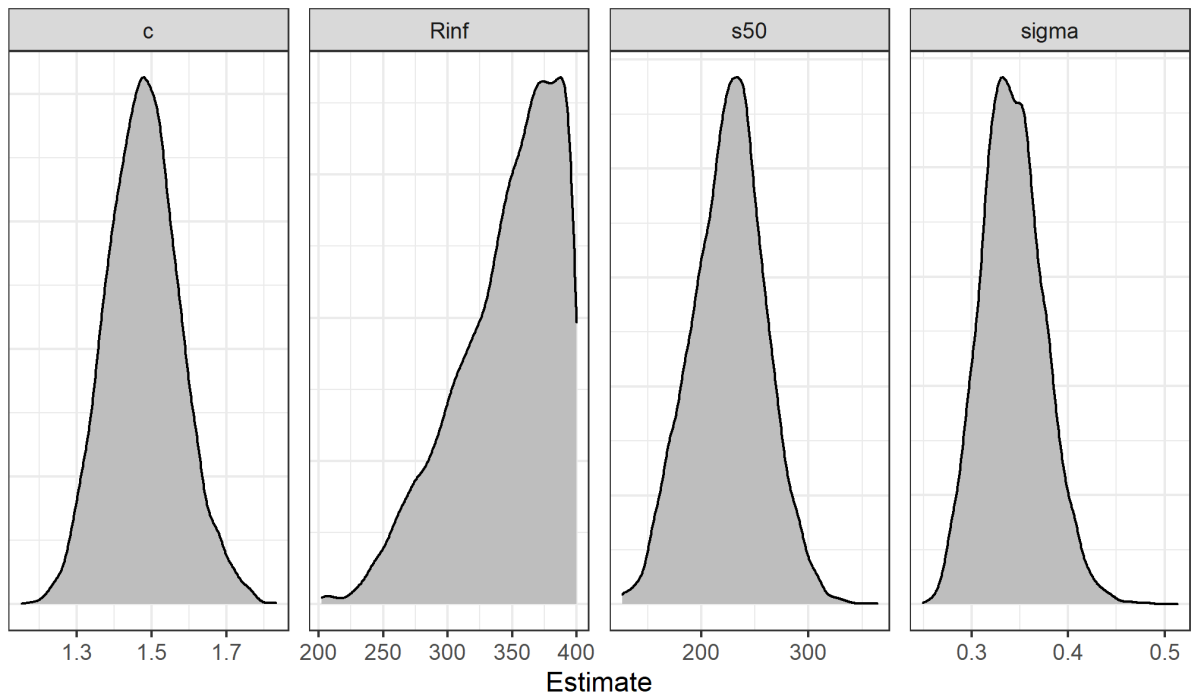


Figure AB 1: Posterior distribution of parameters for the Sigmoidal Beverton-Holt stock-recruitment curve.

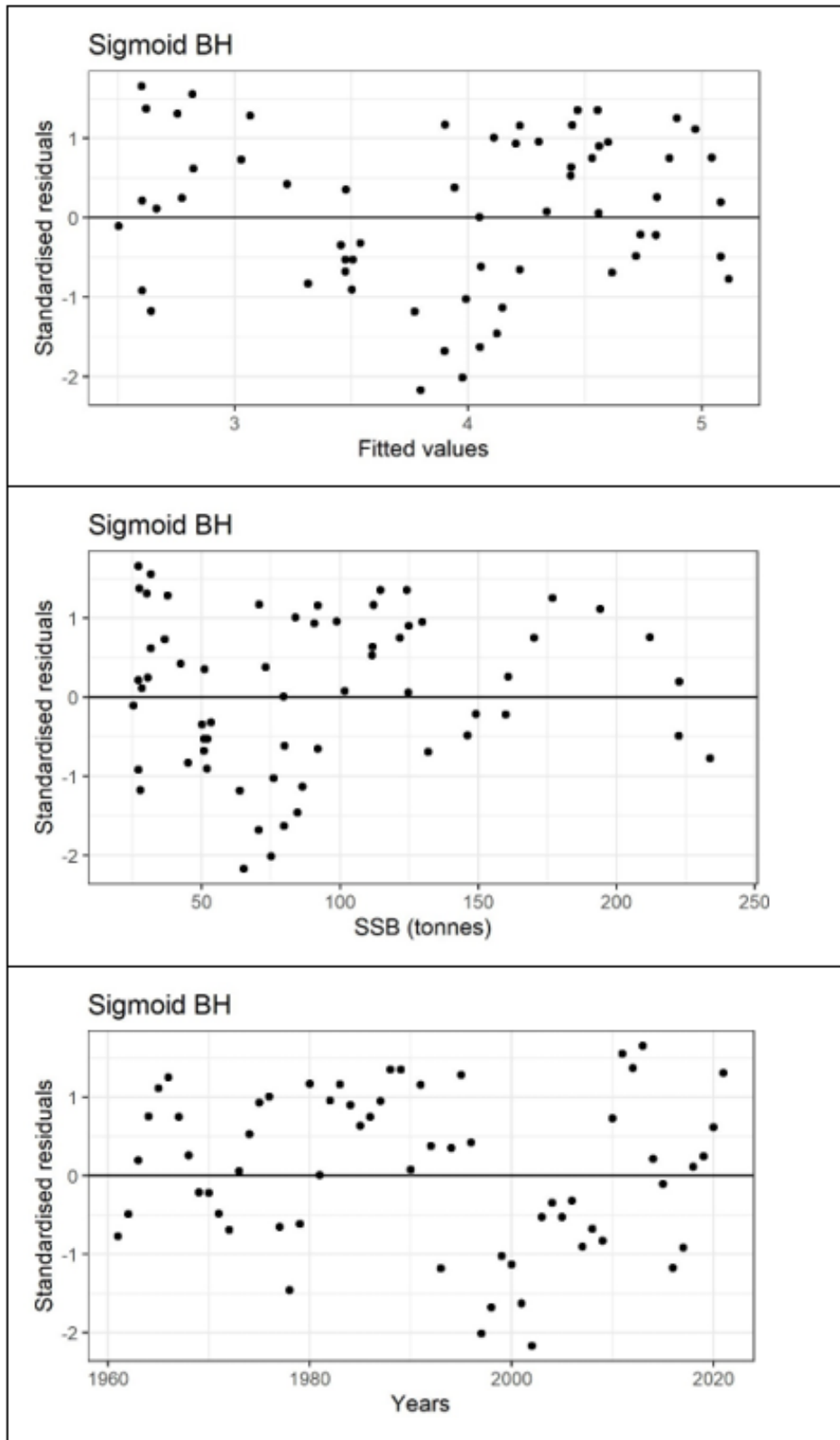


Figure AB 2: Residual plots for the Sigmoidal Beverton-Holt curve against fitted values (top panel) SSB (middle panel), and years (bottom panel).

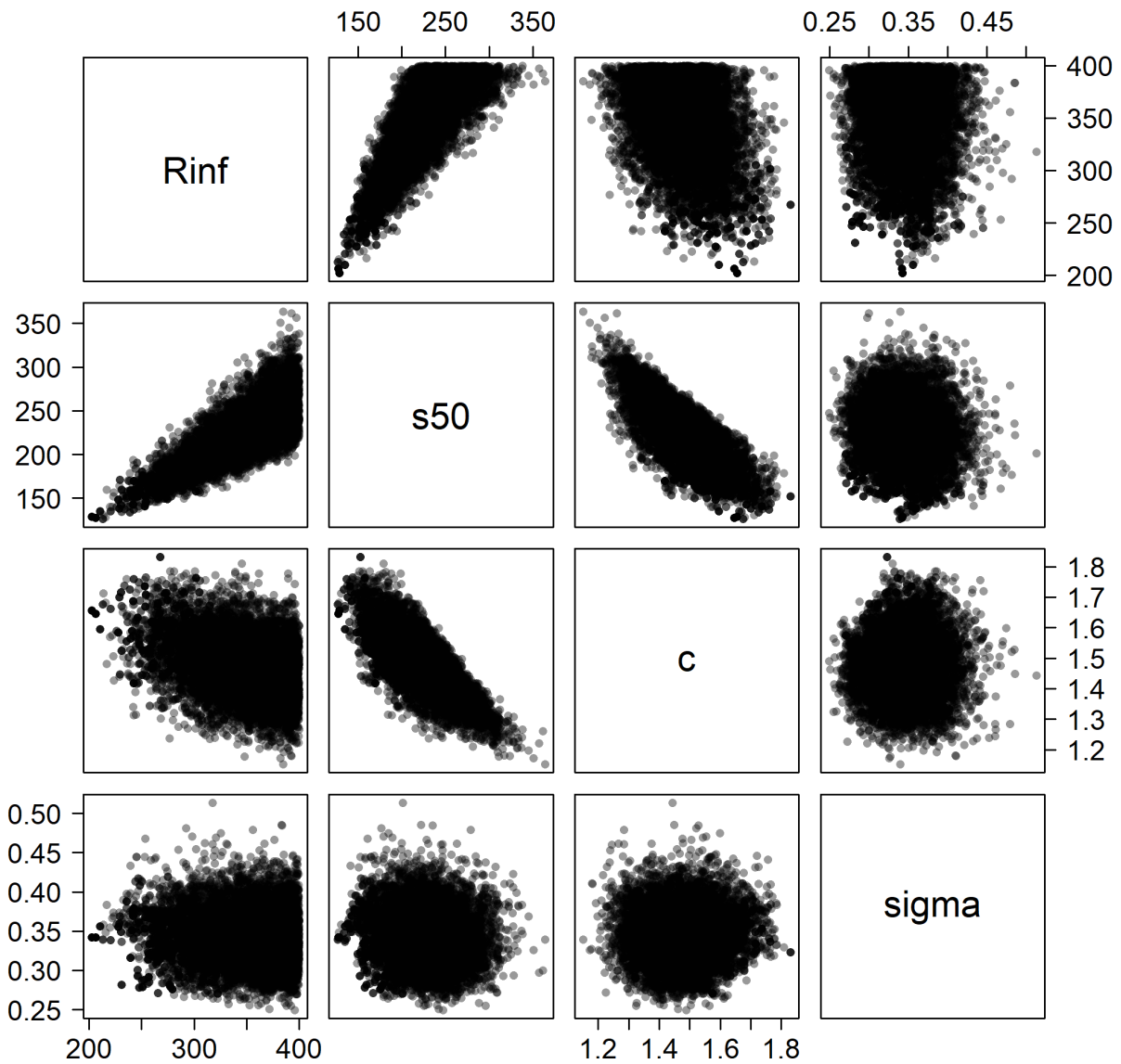


Figure AB 3: Parameter correlation plot for the Sigmoidal Beverton-Holt stock-recruitment ( $R$ ) curve. Parameter uncertainty was included in the  $R$  simulations by sampling from this set of MCMC samples for the parameters.

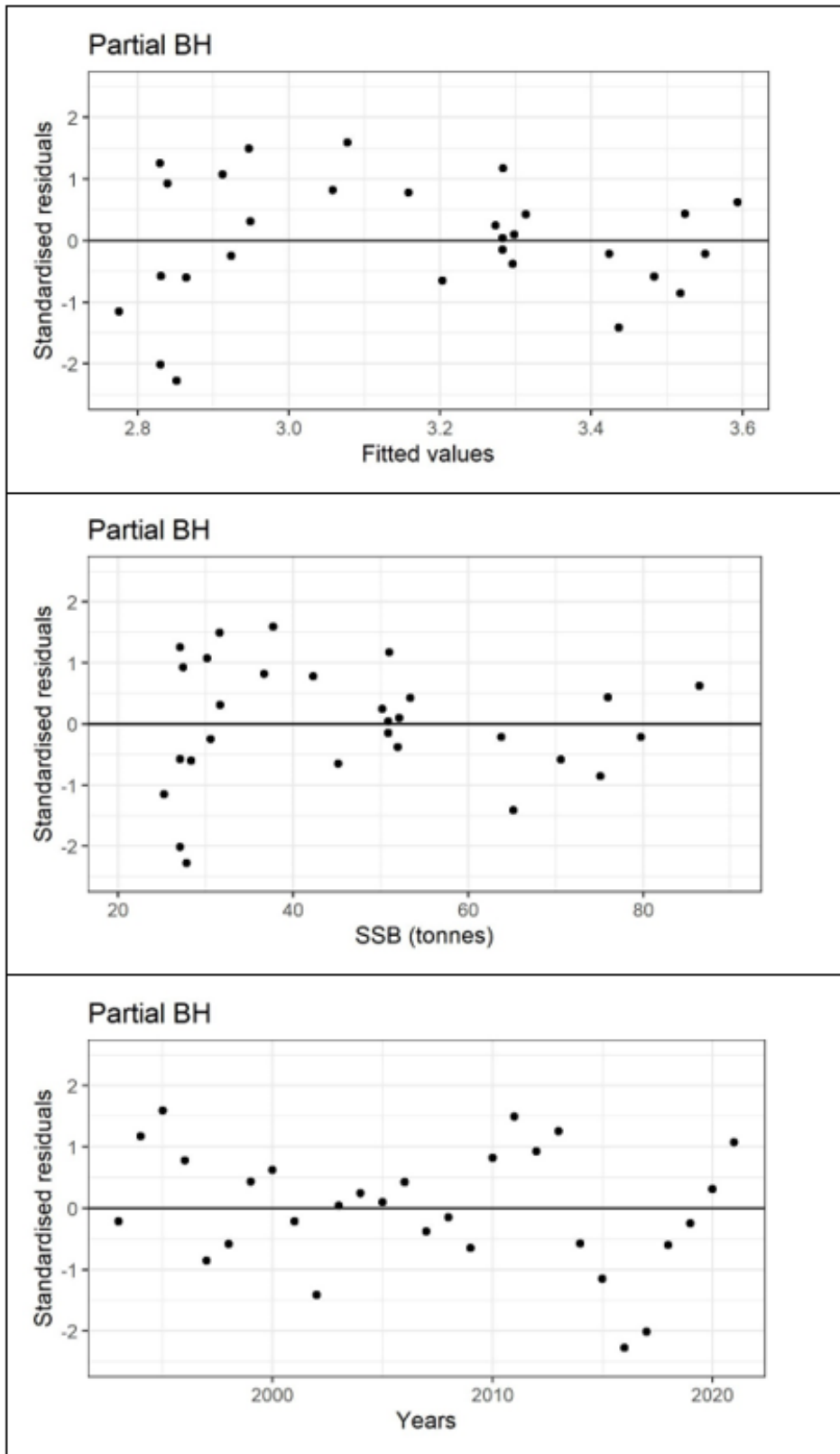


Figure AB 4: Residual plots for the Partial Beverton-Holt curve against fitted values (top panel) SSB (middle panel, Years (bottom panel).

## Beverton-Holt Parameter Covariance

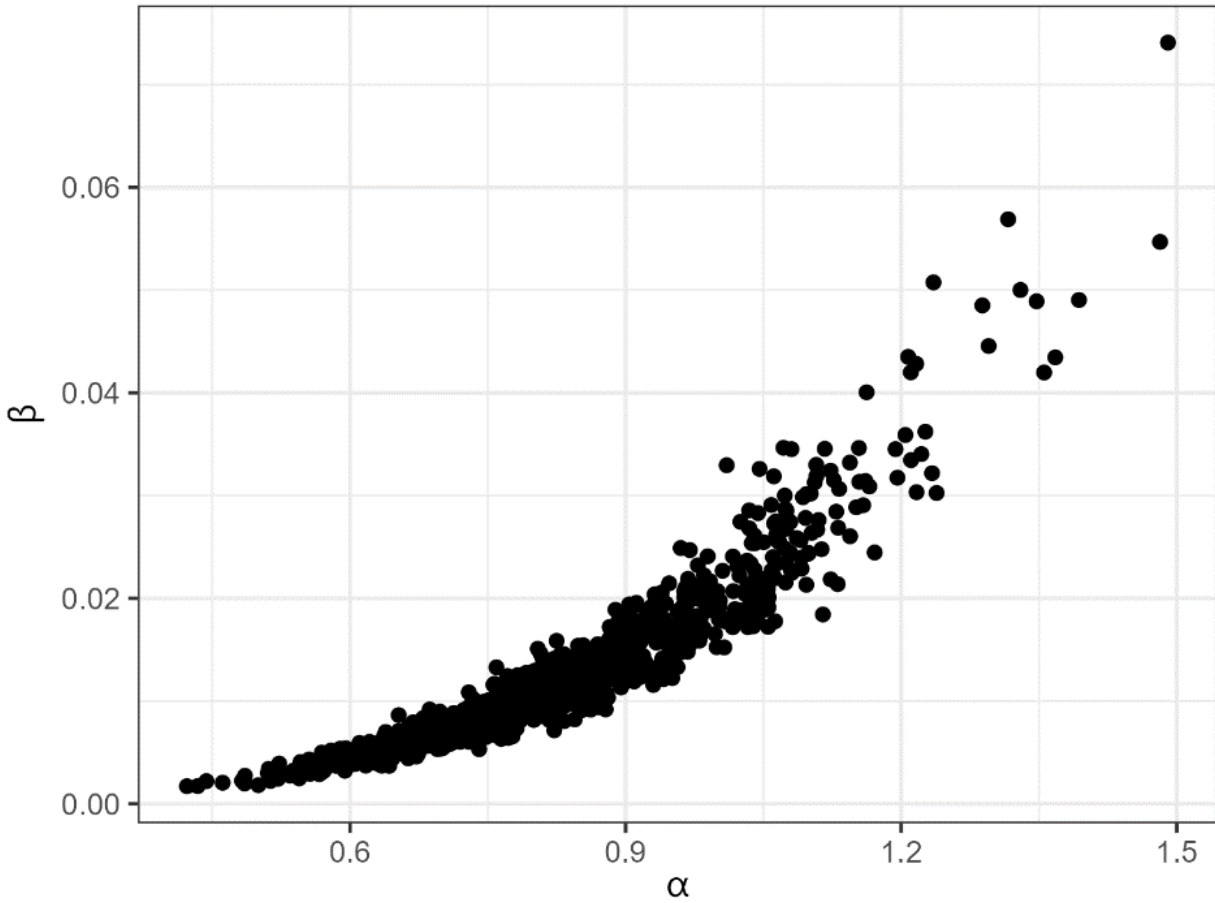


Figure AB 5: Parameter correlation plot for the partial Beverton-Holt stock-recruitment curve.

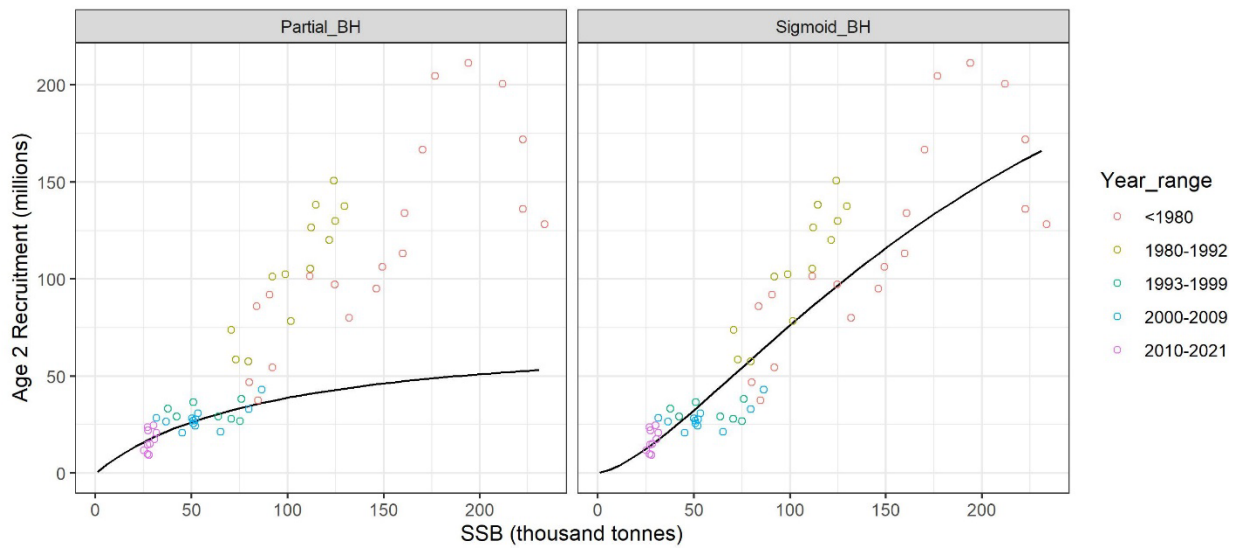


Figure AB 1: Fits of Partial Beverton-Holt (fitted only to data since 1993) and Sigmoidal Beverton-Holt (fitted to full time series) stock-recruitment curves.

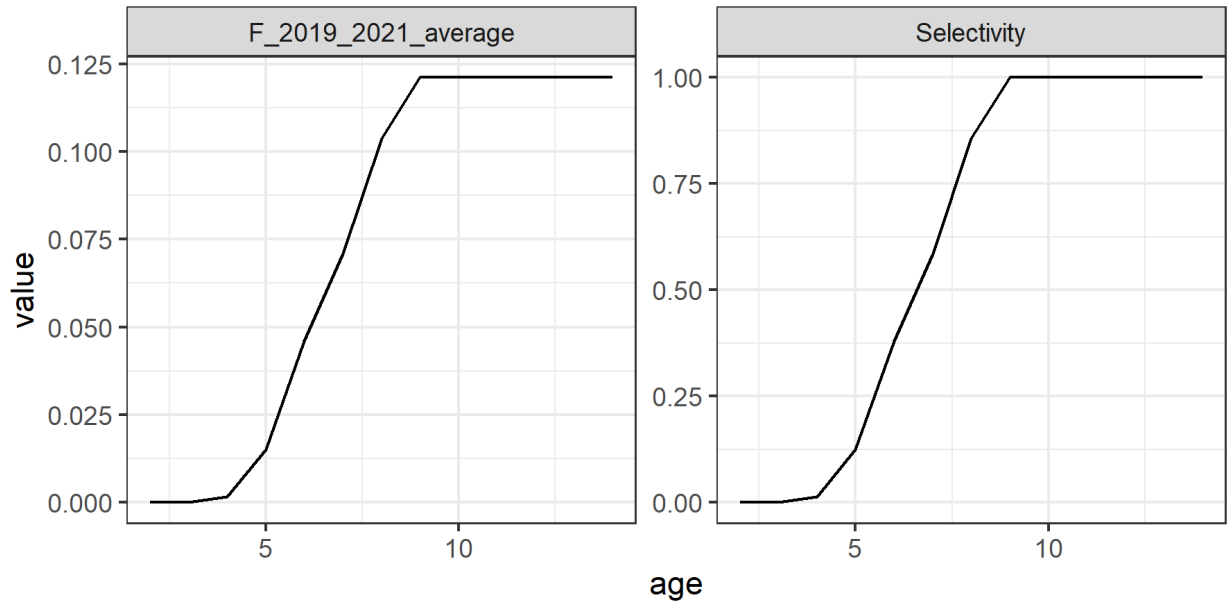


Figure AB 2: Average  $F$  from the years 2019 – 21 (left panel) are scaled by the maximum value to calculate selectivity (right panel).

**APPENDIX C: LONGTERM PROJECTIONS OF SSB HISTORICAL SERIES (1959 – 2022) FOR ALL COMBINATIONS OF M AND R UNDER ALL MPS**

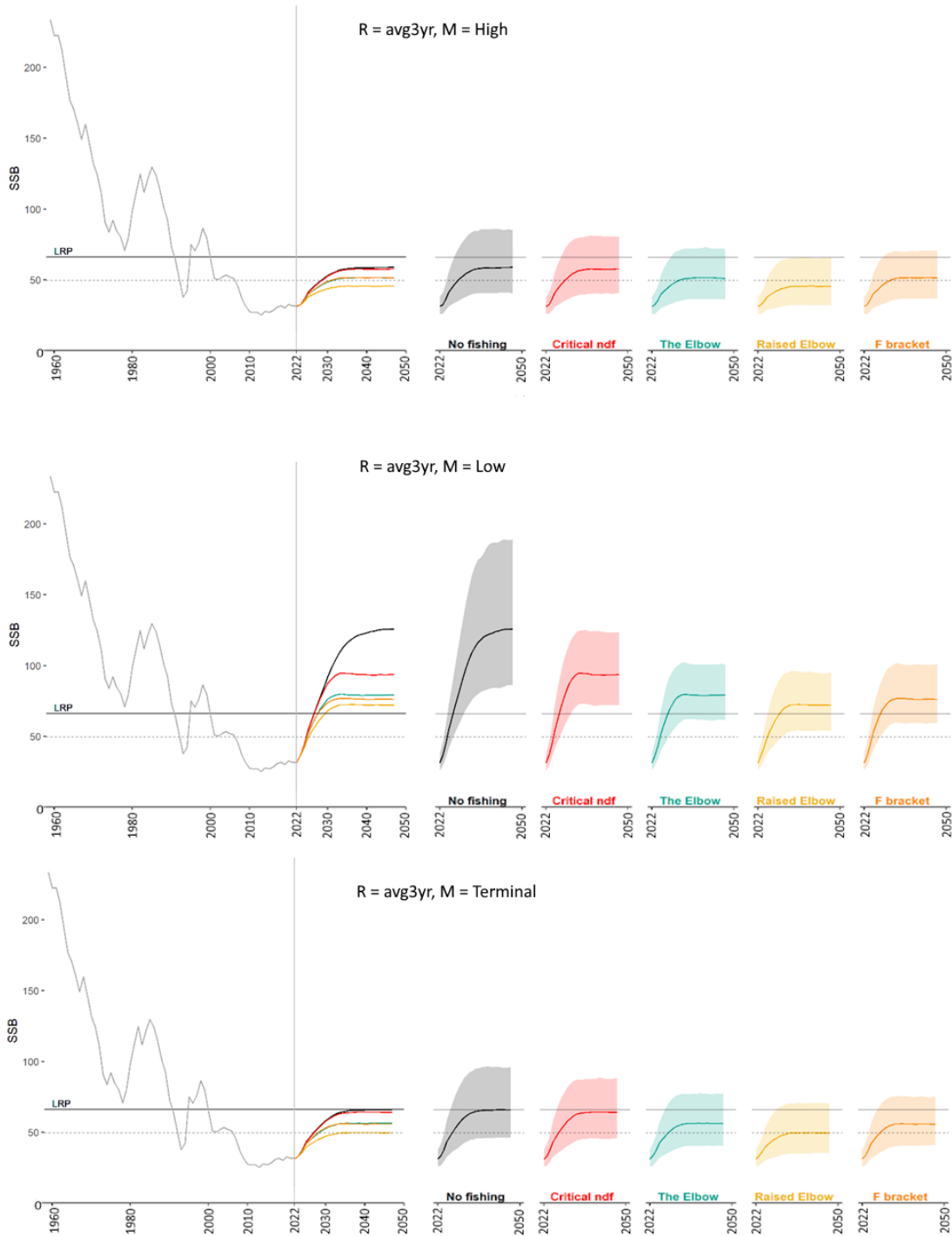


Figure AC 1: Stock size (SSB) projections compared to historical stock size estimates (1959 – 2022) for recruitment (R) scenario 'avg3yr' (2019 – 21). The panel on the left shows median estimates, while on the right the projections under each MP are shown with associated 80% CIs. Solid horizontal line at  $SSB = Blim$ , dashed horizontal line at  $SSB = 0.75Blim$ . Plot titles indicate the R and natural mortality (M) scenario.

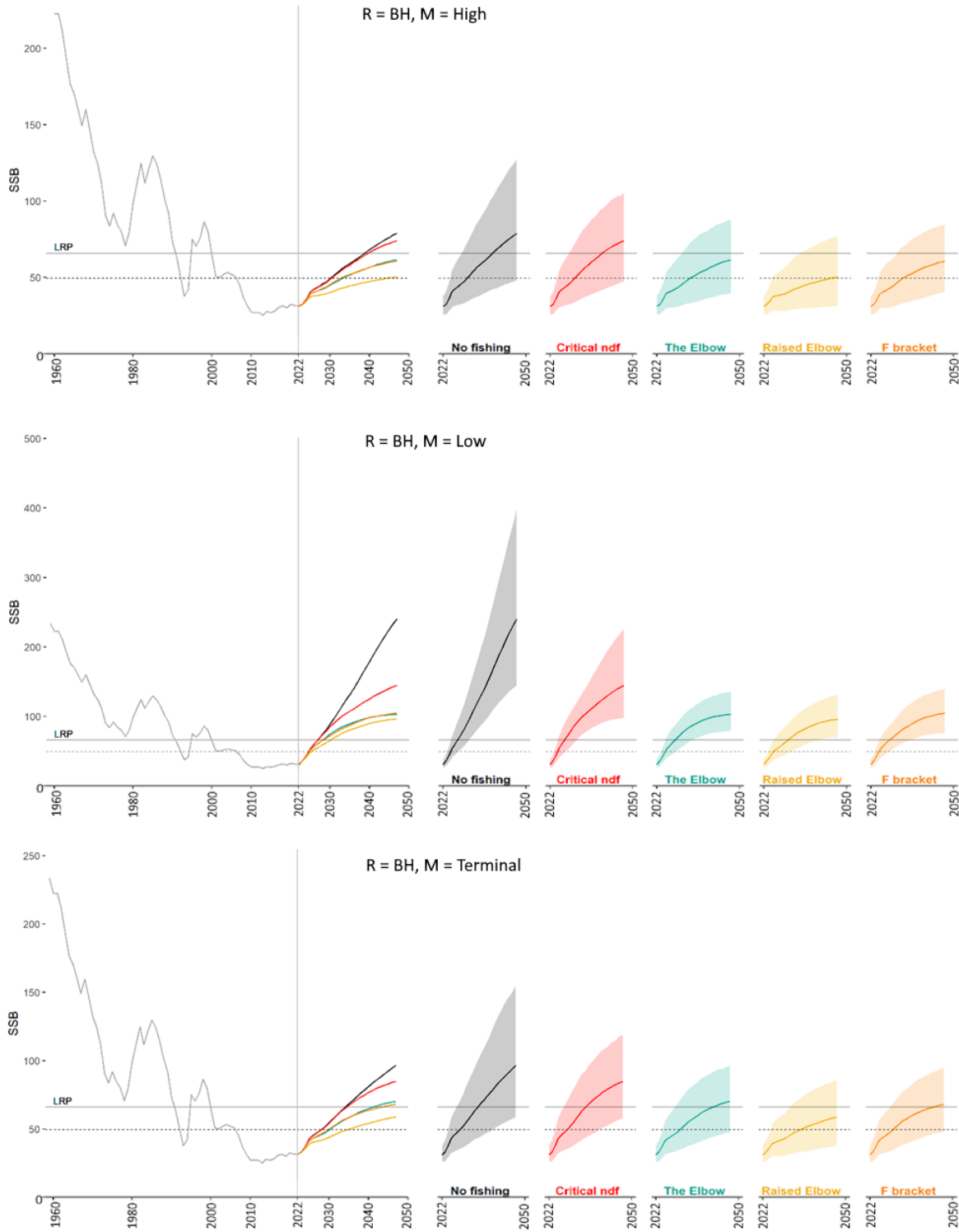


Figure AC 2: Stock size (SSB) projections compared to historical stock size estimates (1959 – 2022) for recruitment (R) scenario modelled based on Beverton-Holt relationship. The panel on the left shows median estimates, while on the right the projections under each MP are shown with associated 80% CIs. Solid horizontal line at  $SSB = B_{lim}$ , dashed horizontal line at  $SSB = 0.75B_{lim}$ . Plot titles indicate the R and natural mortality (M) scenario.

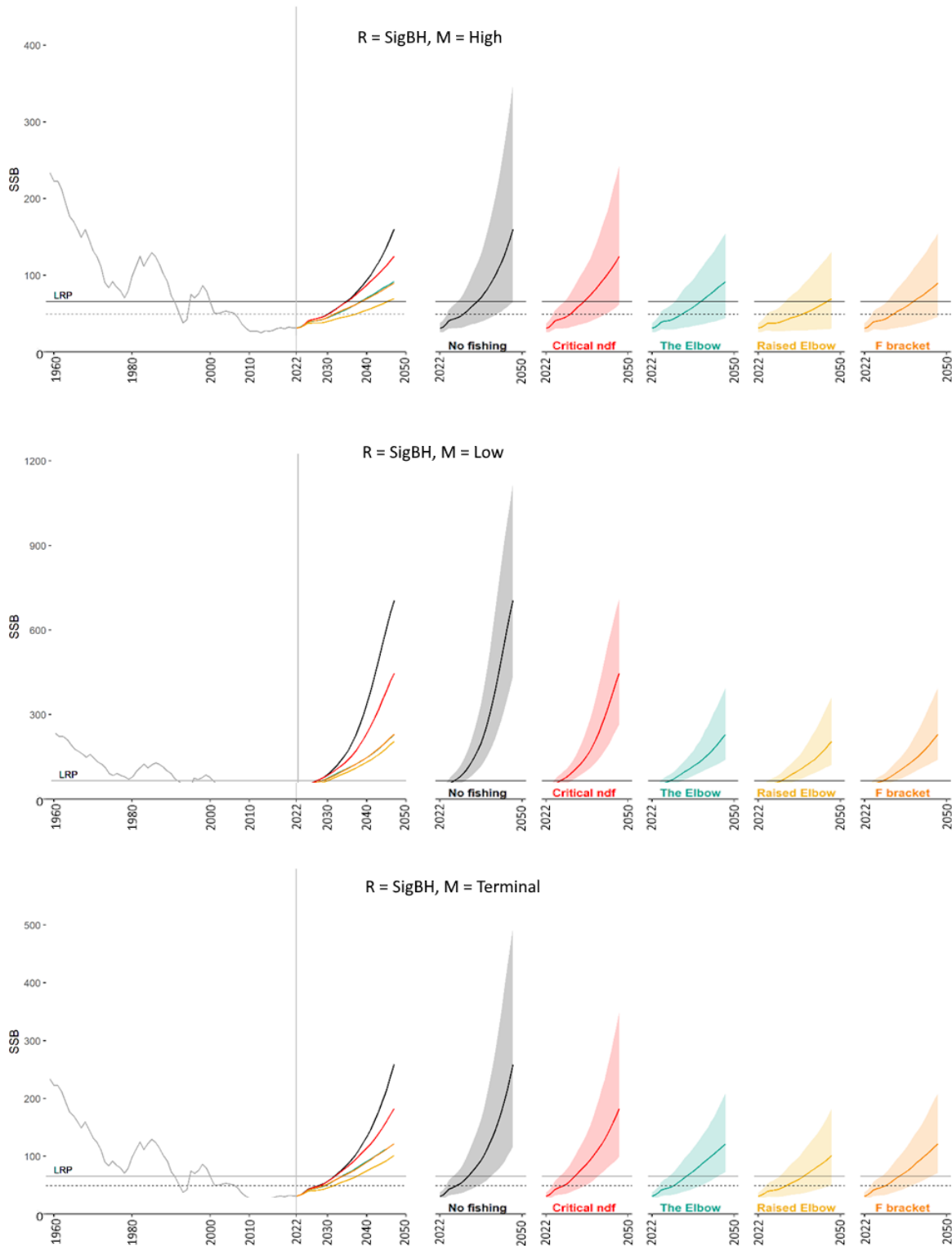


Figure AC 3: Stock size (SSB) projections compared to historical stock size estimates (1959 – 2022) for recruitment (R) scenario modelled based on Sigmoidal Beverton-Holt relationship. The panel on the left shows median estimates, while on the right the projections under each MP are shown with associated 80% CIs. Solid horizontal line at  $SSB = B_{lim}$ , dashed horizontal line at  $SSB = 0.75B_{lim}$ . Plot titles indicate the Rand natural mortality (M) scenario.

## APPENDIX D: TIME TO REACH THE REBUILDING TARGET

Projections are run under each M and R scenario and no fishing to calculate the time to reach the rebuilding target, which is defined as 75% of the simulations being above the LRP. The years when the rebuilding target is achieved varies considerably between the scenarios. Under lower M and higher R, the rebuilding target is achieved faster while the rebuilding target is not reached under some of the higher M and lower R scenarios.

*Table AD 1: The time to reach the rebuilding target (above the LRP with a 75% probability) under each M and R scenario for each MP and the no fishing scenario. Grey cells labelled n/a indicate the stock does not reach the rebuilding target. The yellow cell shows the time to rebuild under no fishing in prevailing conditions.*

	Recruitment	Natural mortality		
		High	Terminal year	Low
<b>No Fishing</b>	avg3yr	n/a	n/a	2028
	BH	2049	2040	2029
	sigBH	2039	2036	2029
<b>Critical n.d.f</b>	avg3yr	n/a	n/a	2028
	BH	2053	2041	2029
	sigBH	2040	2036	2029
<b>F Bracket</b>	avg3yr	n/a	n/a	2030
	BH	n/a	n/a	2031
	sigBH	2045	2040	2030
<b>"The Elbow"</b>	avg3yr	n/a	n/a	2030
	BH	n/a	2069	2030
	sigBH	2045	2040	2030
<b>Raised Elbow</b>	avg3yr	n/a	n/a	n/a
	BH	n/a	n/a	2033
	sigBH	2057	2047	2032

---

## APPENDIX E: FUNCTION TO CALCULATE F FROM CATCH

The following function called 'solveF' takes the predicted TAC (*projC*), an initial estimate of *F* (*Finit*), a vector of selectivity-at-age (*S*), a vector of natural mortality values by age (*M*), a vector of abundances-at-age (*N*), and the vector of catch weights-at-age (*Cw*) as arguments. This function performs a Newton approximation of the *F* value given the initial guess (*Finit*) and solves for the root (i.e., zero) of the objective function. It was found that 7 iterations of this algorithm (*niter* = 7) were sufficient to solve for *f* with the required precision. Convergence issues occur when *projC* = 0 or when the estimated yield was close to total biomass, so *F* was bound between  $10^{-3}$  and 1. This methodology was obtained from the projection code for Northern cod assessment model used for assessing the Northern cod stock (Paul Regular, personal communication); we slightly modified the function because here the catch weights are different from the stock weights.

```
solveF <- function(projC, Finit, S, M, N, Cw)
{
  niter = 7
  F = Finit
  for(i in 1:niter){
    Z = F * S + M;
    eZ = exp((-1.0) * Z);
    Mort = 1.0 - eZ;
    Y = F * sum(N * Mort * S * Cw/Z);
    derY = sum(N * S * Cw * (Mort * M/Z + eZ * F * S)/Z);
    F = F + ((projC - Y)/derY);
  }
  return(F) }
```