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Application of the Management Procedure Framework for Outside Quillback Rockfish (*Sebastes maliger*) in British Columbia in 2021

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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.

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ABSTRACT

The purpose of this project is to provide scientific advice to support management of Outside Quillback Rockfish (*Sebastes maliger*). The stock is expected to be prescribed as a major fish stock, at which time its sustainable management will be legislated under the Fish Stocks Provisions of the *Fisheries Act*. This analysis applied the Management Procedure (MP) Framework, recently developed for British Columbia (BC) groundfishes, to evaluate the performance of index-based and constant catch MPs, with respect to meeting policy and fishery objectives.

To account for uncertainty in underlying population dynamics and data sources, we developed five alternative operating model (OM) scenarios, which differed with respect to specific model and data assumptions. Operating models were conditioned on historical catches, indices of abundance, and age composition. Three reference OMs varied on either the assumption of the natural mortality value or historical recreational catch for Outside Quillback Rockfish. Two additional robustness OMs were developed, with evaluating a lower stock-recruit steepness value, and another that modeled lower than average recruitment in the projection. The reference OMs indicated the stock was above the limit reference point (LRP) of 0.4 B_{MSY} with very high probability in 2021.

Three fixed-catch MPs and eight index-based MPs that adjust the catch based on the recent trend in the index of abundance from the outside hard-bottom longline (HBLL) survey were tested in the closed-loop simulations. In the reference set, almost all MPs, except for the fixed catch at 125 percent of recent catch, passed the proposed satisficing criteria with the stock: (1) exceeding the LRP with at least 75% probability, (2) exceeding the upper stock reference (USR) of 0.8 B_{MSY} with at least 50% probability, and (3) less than the removal reference of F_{MSY} with at least 50% probability, during the projections of two generations (54 years) duration. All index-based MPs also met the satisficing criteria in the two robustness operating models.

Visualizations present trade-offs in tabular and graphical formats to support the process of selecting the final MP. Among satisficed MPs, there is a trade-off between biomass and fishery catch levels after two generations. We propose operating models to be identified in the reference set when used to identify stock status. We also provide future research recommendations regarding commercial fishery biological sampling and Food, Social, and Ceremonial (FSC) catch. We make recommendations to use the HBLL index of abundance to identify triggers for future re-assessment.

1. INTRODUCTION

The purpose of this project is to provide scientific advice to support management of the outside stock of Quillback Rockfish (*Sebastes maliger*) (DFO 2022a). The advice provides guidance to ensure harvest rates are consistent with the Precautionary Approach and the newly legislated Fish Stocks Provisions of the *Fisheries Act*. We also provide candidate reference points, including a Limit Reference Point (LRP) and Upper Stock Reference (USR), and a stock status estimate relative to these reference points.

The project follows the Management Procedure (MP) Framework for groundfish (Anderson et al. 2021). The MP Framework approach evaluates the performance of alternative management procedures (MPs) with respect to sustainability and fishery objectives for the outside stock of Quillback Rockfish (hereafter Outside Quillback Rockfish or OQB). These MPs are tested across multiple plausible states of nature, explicitly accounting for uncertainty in population biology, fleet dynamics, and data process error. We identified the MP Framework to be the best approach for providing science advice for Outside Quillback Rockfish that can meet the requirements of the Fish Stocks Provisions (see Section 1.1).

1.1. POLICY AND LEGISLATIVE OBLIGATIONS

The Canadian Sustainable Fisheries Framework (SFF) lays the foundation for the Precautionary Approach (PA) to fisheries management in Canada (DFO 2006, 2009). The PA Framework (DFO 2009) relies on the definition of biological reference points (BRPs), which define biomass targets and low biomass thresholds that are to be avoided with high probability. The approach requires that fishing mortality be adjusted in relation to two levels of stock status—an Upper Stock Reference (USR) and a Limit Reference Point (LRP) (Figure 1). The LRP and USR delineate three stock status zones (“Critical”, “Cautious”, and “Healthy”).

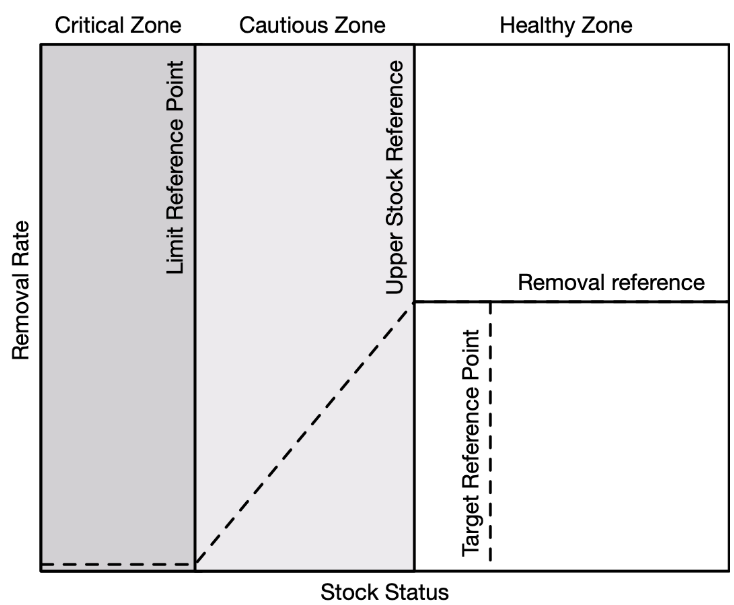

Figure 1. Illustration of the Precautionary Approach Framework. Based on DFO (2009).

In June 2019, major amendments to Canada’s *Fisheries Act* legislated many key components of the SFF, which are encoded in the Fish Stocks Provisions (Section 6 of the *Fisheries Act*). The

Fish Stocks Provisions require that major stocks be managed at sustainable levels, specifically at biomass levels above the LRP. If a stock is found to be below its LRP, the development of a Rebuilding Plan is triggered under Subsection 6.2(1) to increase the stock above that threshold. The first batch of major fish stocks have been designated under these regulations (Batch 1). Outside Quillback Rockfish is proposed for inclusion in Batch 2.

In 2009, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed Quillback Rockfish as a single coastwide species, comprised of both inside and outside stocks, and designated it as "Threatened" (COSEWIC 2009). While a decision by Governor in Council to list this species under the *Species at Risk Act* (SARA) is still pending, COSEWIC is still required to review the classification of each species at risk every 10 years (s.24 of SARA). Results from this project will inform the COSEWIC re-assessment (see Appendix H).

1.2. BACKGROUND

Quillback Rockfish is a long-lived species (up to 95 years for the Outside stock), commonly occurring in rocky marine habitats along the coast of British Columbia (Yamanaka et al. 2011). It is widely distributed in the Pacific Northeast, ranging in the north up into the Gulf of Alaska and south into southern California. In British Columbia, Quillback Rockfish are found at shallow depths (<20 m) to depths around 150 m. Juveniles settle in shallow, benthic habitat, and exhibit ontogenetic migration to deeper depths.

Outside Quillback Rockfish occur in Groundfish Management Areas 3C, 3D, 5A, 5B, 5C, 5D, and 5E (3CD5ABCDE) in British Columbia (BC) (Figure 2). It is separate from Inside Quillback Rockfish which is found in Area 4B, and was considered in a previous CSAS Regional Peer Review meeting using a similar approach.

The Outside stock is proposed to be a major fish stock, at which time its sustainable management will be legislated under the Fish Stocks Provisions in the *Fisheries Act*. In 2011, the median biomass of the Inside stock was assessed to be 6,480 tonnes (with a coefficient of variation of 1.21), with an 81% probability of being above the LRP of 0.4 B_{MSY} (Yamanaka et al. 2011). The stock was designated to be in the "Cautious" zone. The uncertainty around the 2011 median estimate, however, spans all three zones, and illustrates the difficulty of estimating status for data-limited stocks.

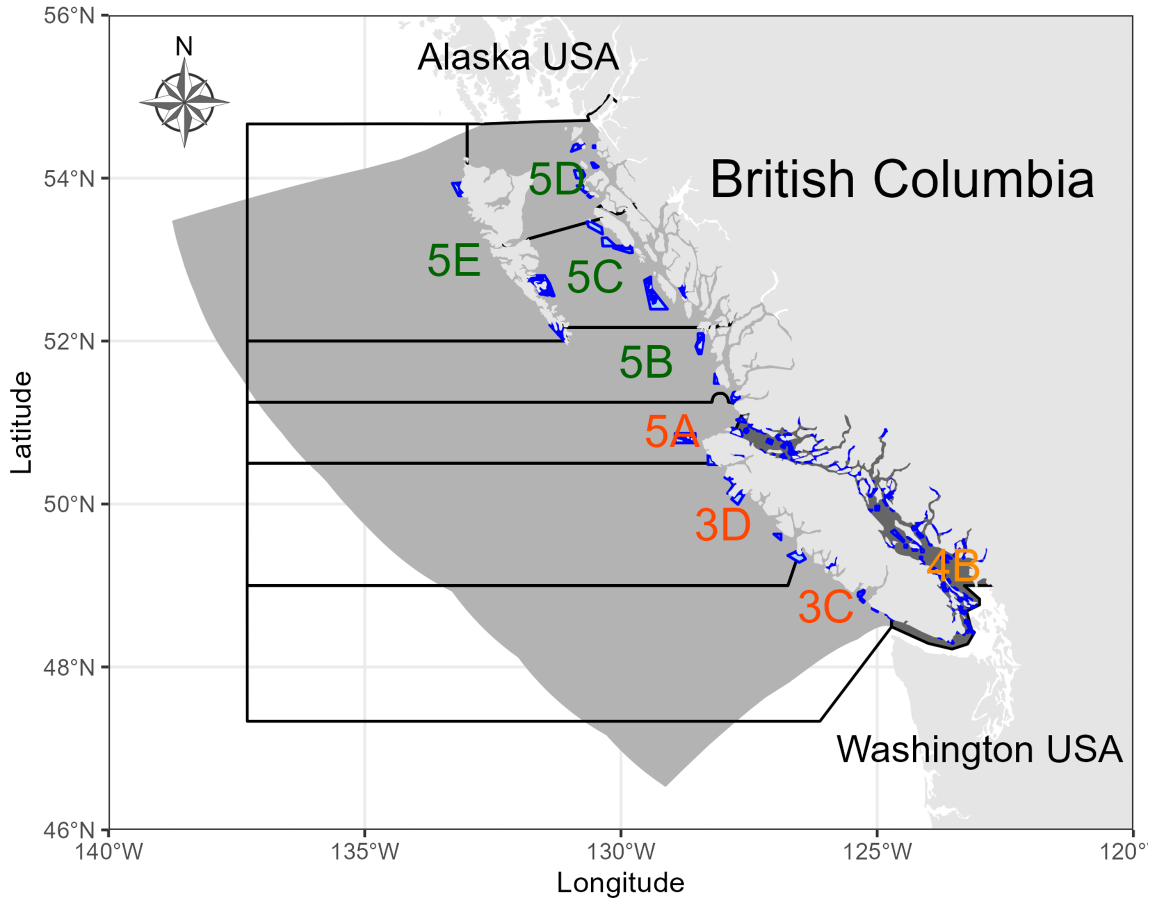

Figure 2. Map of Groundfish Management Areas for the Outside (3CD5ABCDE) and Inside (4B) Quillback Rockfish Designatable Units (DU). Offshore light grey region denotes the Canadian Exclusive Economic Zone (EEZ) and blue regions denote the locations of Rockfish Conservation Areas (RCAs).

1.3. MANAGEMENT STRATEGY EVALUATION (MSE)

Worldwide, the provision of scientific advice for managing fisheries has been moving towards management strategy evaluation (MSE), or procedure-oriented approaches (e.g., Butterworth and Punt 1999; Rademeyer et al. 2007; Berkson and Thorson 2015; Punt et al. 2016). MSE focuses on testing management procedures in a "closed-loop" simulation environment and identifying those that meet and satisfy agreed-upon policy and fishery objectives (Figure 3). For output-controlled fisheries, such as the quota-managed BC groundfish fishery, MPs describe algorithms for calculating the catch advice. MPs can vary greatly in their data demands, from data-rich approaches, including statistical catch-at-age stock assessments with harvest control rules, to simple empirical algorithms, for example, using catch data and an index of abundance (e.g., Geromont and Butterworth 2015; Carruthers et al. 2016).

Closed-loop simulation simulates feedback between implementation of MPs and the underlying system (the fish stock and its environment), which is described by one or more operating models (OMs). This is distinct from conventional stock assessment approaches that do not incorporate the feedback between management advice and the operating model in projections. The closed-loop simulation approach takes into account the effect of the MPs on the system, as well as the future data collected from the system and their use in the MPs (Punt et al. 2016; Carruthers and Hordyk 2018a; Anderson et al. 2021).

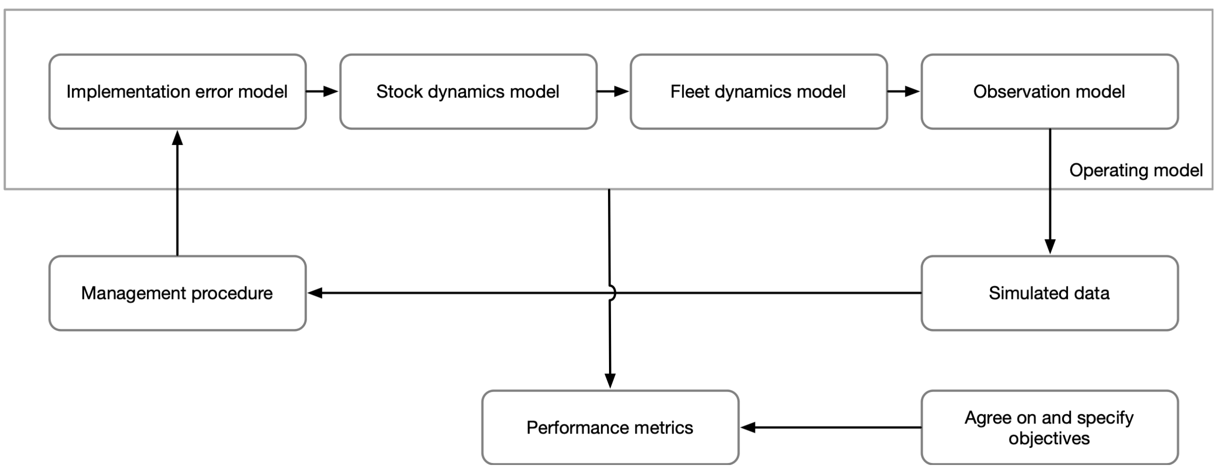

Figure 3. Illustration of the fisheries closed-loop simulation process from Anderson et al. (2021) following Punt et al. (2016). The management procedure may be based on a simple data rule (e.g., decrease the allowable catch x% if the survey index decreases y%) or it might be an estimation model combined with a harvest control rule.

1.4. APPROACH

In 2020, the Management Procedure Framework (MP Framework) for Groundfish in British Columbia (Anderson et al. 2021) was developed to demonstrate its use to evaluate MPs for groundfish species, including data-limited stocks. The MP Framework uses the functionality of openMSE (consisting of the DLMtool, MSEtool, and SAMtool R packages), with additional supporting code and visualization tools in the ggmse R package (Anderson et al. 2022b) written by the authors of Anderson et al. (2021).

The MP Framework was identified as a suitable tool for further assessment for Outside Quillback Rockfish since there was considerable variation around the status estimate of the stock during the 2011 assessment (Yamanaka et al. 2011).

We follow the MP Framework for selecting MPs to set catch advice for Outside Quillback Rockfish (Anderson et al. 2021). The framework follows six best practice steps described below and in greater detail in Anderson et al. (2021). The best practice steps are based on a review by Punt et al. (2016), who identified five key steps in the MSE process (Steps 2–6 below). An additional first step of the MP Framework, defining the decision context, was identified by Gregory et al. (2012) and Cox and Benson (2016). In large part, the openMSE software (Carruthers and Hordyk 2018a) has been designed to allow practitioners to follow these steps (Figure 4).

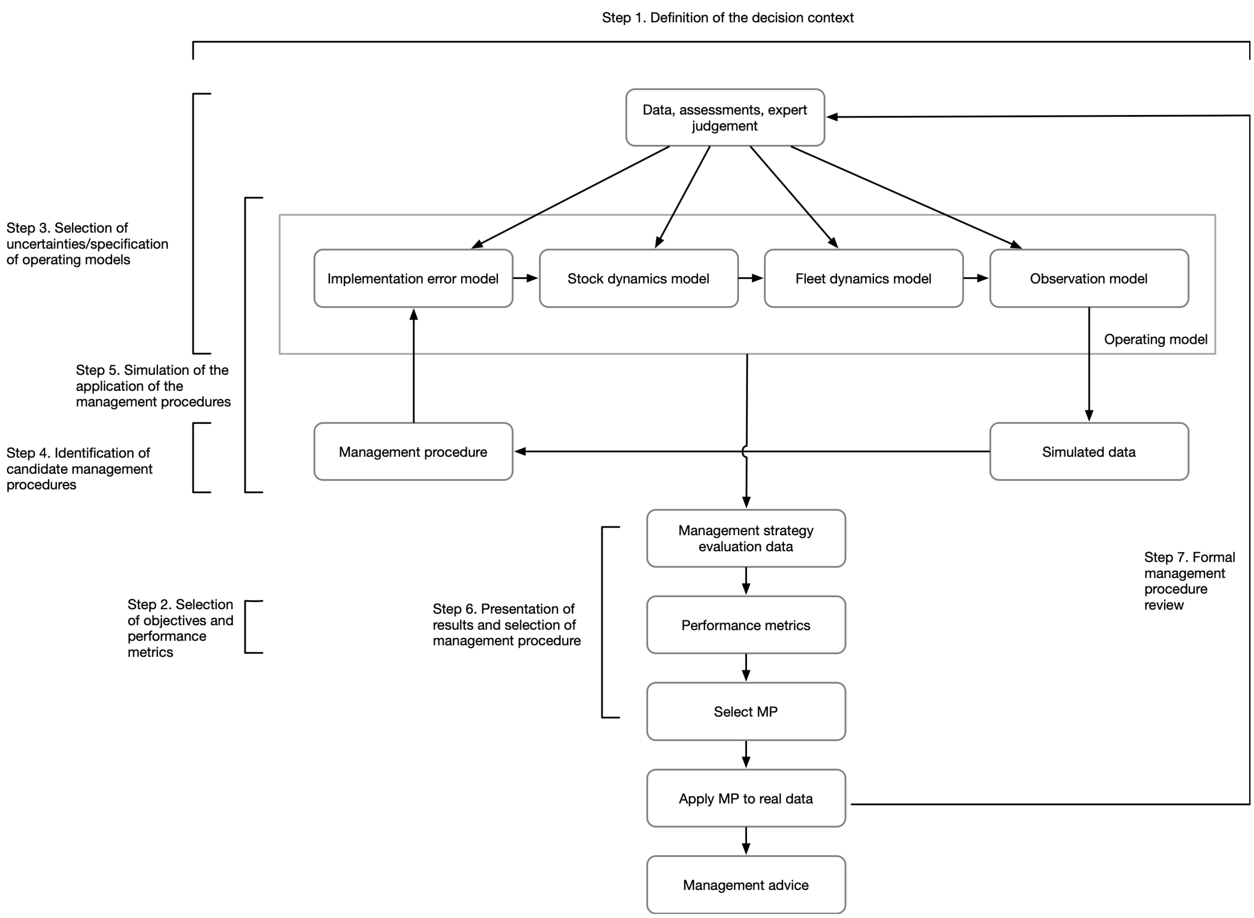

Figure 4. The steps of the MSE process following Punt et al. (2016) as implemented in openMSE, copied from Anderson et al. (2021) and adapted from Carruthers and Hordyk (2018a). This figure expands on Figure 3.

The six steps are as follows:

Step 1: Definition of the decision context.

Step 2: Selection of objectives and performance metrics.

Step 3: Selection of uncertainties/specification of operating models.

Step 4: Identification of candidate management procedures.

Step 5: Simulation of the application of the management procedures.

Step 6: Presentation of results and selection of management procedure.

After selection and implementation of the MP for setting the catch limit (Figure 4; e.g., applying the selected MP algorithm to the observed survey index), a final necessary step is to periodically monitor and evaluate the performance of the MP (DFO 2013; Carruthers and Hordyk 2018a). This may be done through informal means, e.g., via feedback from fishers and survey information (e.g., Cox and Kronlund 2008), or through formal statistical measures, where observed data are compared to predictions from the Operating Models (OMs) to test whether the system is performing as expected (Butterworth 2008; Carruthers and Hordyk 2018b; discussed in Anderson et al. 2021).

1.5. OBJECTIVES WORKSHOP

In support of the MP Framework, DFO hosted a series of workshops in early 2021, bringing together Fisheries and Oceans Canada (DFO) scientists and managers, Indigenous representatives and knowledge-holders, commercial and recreational (public) fishing representatives, non-governmental organizations (NGOs), and external scientists, to identify strategic objectives for the Outside Quillback Rockfish stock (Haggarty et al. 2022). Information gathered at the workshop was used to identify operational objectives and performance measures for this analysis. Additional objectives and feedback, for example, the desire to consider age structure, was taken into account in the MP Framework results for Outside Quillback Rockfish. Other sustainability objectives, e.g., spatial flexibility in fishery access, were identified as topics suited for groundfish management.

In the following sections, we describe our approach for identifying suitable management procedures for Outside Quillback Rockfish, following the six best practice steps listed in Anderson et al. (2021).

2. DECISION CONTEXT

Key questions to guide defining the decision context for the MP Framework include:

- What is the exact decision to be made?
- What is the time frame for making the decision?
- What are specific roles and responsibilities of parties involved? Parties include Science, Management, First Nations, industry, and/or non-governmental organizations (NGOs).
- How will the final decision be made?

For this analysis, the decision to be made is to determine a management procedure by the Groundfish Management Unit to use to determine catch recommendations for the time period until the next available catch advice.

Science requires an evaluation of the operating models to determine stock status relative to the LRP and a consideration of environmental conditions are provided to meet the requirements of the Fish Stocks Provisions.

The decisions should be made based after consensus by the Regional Peer Review (RPR) committee, after review of the scientific content of the advice (including the structure and content of the operating models), and consideration of the relative performance of the MPs and trade-offs among performance metrics. Objectives and performance metrics are informed by policy as well as interested parties, such as First Nations and by fishery industry representatives.

3. OBJECTIVES AND PERFORMANCE METRICS

Clear management and fishery objectives must be identified, along with the performance metrics that measure how well the objectives are achieved. Objectives may span a wide range of policy or legislated objectives (e.g., maintaining the stock above the LRP), economic objectives (e.g., maintaining an average catch or reducing variability in catch), and cultural objectives (e.g., maintaining access to the stock or specific fishing areas). A simulation framework allows us to evaluate trade-offs, if any, between legislative and other short and long-term fishery objectives, so long as the primary legislative requirements are met.

Fully quantified objectives include a metric or target, the desired probability of success, and a time frame to achieve the objective (e.g., probability the stock is maintained above the LRP is greater than 75 percent after two generations). Performance metrics are quantified measures of the objectives. In closed-loop simulation, they can be calculated in the operating model at each time step of the projection or over a range of years.

3.1. OBJECTIVES AND MILESTONES

We present a set of objectives and associated performance metrics for Outside Quillback Rockfish. Key policy objectives are based on the PA Framework (DFO 2006, 2009). Additional objectives related to fisheries yield were considered based on broad strategic objectives identified in Haggarty et al. (2022).

As informed by the Guidelines on the implementation of the Fish Stocks Provisions, the proposed policy objectives are:

1. Maintain the stock above the LRP during two generations (54 years) with at least 75% probability of success.
2. Maintain the stock above the USR during two generations with at least 50% probability of success.
3. Maintain fishing mortality below the reference removal during two generations with at least 50% probability of success. To be compliant with the United Nations Fish Stocks Agreement (from which the PA Policy was developed), the removal reference cannot exceed F_{MSY} (DFO 2006).

The probabilities used here are the minimum required values as stated in the Guidelines. Following general international practice, the desired probability of success for the LRP objective was set at 75% to represent high probability, while the 50% probability represents moderate to high probability (Marentette et al. 2021). For more information on generation time, please see Appendix A, Section A.3. For this analysis, these probabilities are interpreted as the mean from a projected time series.

We also propose the following additional objectives, further specified in Section 3.2:

4. Maintain fishery access and catches both in the short-term and in the long-term.

No target probability is assigned to Objective 4 as it is used to evaluate trade-offs with Objectives 1-3.

3.2. PERFORMANCE METRICS

We calculate the following performance metrics to measure the objectives, where *B* represents spawning biomass, *MSY* refers to maximum sustainable yield, B_{MSY} refers to equilibrium spawning biomass at MSY, *GT* represents generation time, and *ST* represents short term.

We define the LRP and USR as 0.4 B_{MSY} and 0.8 B_{MSY}, respectively, following definitions in the PA Framework (DFO 2006), as used in the 2011 stock assessment (Yamanaka et al. 2011).

Technical considerations on the estimation of the LRP and USR are addressed in Section 4.3.1.3.

In the closed-loop simulations, all reference points and performance metrics are calculated in the operating model. In support of the Objectives 1-4, five performance measures are presented:

1. **LRP 2GT**: P(B > 0.4 B_{MSY}) during 2 generations (2022–2075, years 1–54 of the projection period)
2. **USR 2GT**: P(B > 0.8 B_{MSY}) during 2 generations
3. **FMSY 2GT**: P(F < F_{MSY}) during 2 generations
4. **C ST**: Average catch during the short term (during 2022–2028, years 1–7 of the projection period)
5. **C 2GT**: Average catch after 2 generations (in 2075, year 54 of the projection period)

Performance metrics 1–3, related to policy objectives, are probability based. The performance statistic was averaged across simulation replicates and years for the defined time window (Anderson et al. 2021).

Simulations over the 2-generation timeline provides insight on the behavior of management procedures relative to the biological dynamics of the stock. Since Outside Quillback Rockfish is a long-lived species, catch over a shorter time scale will also be of interest to the fishery. Thus, we report short-term catch during the first seven years of the projection. The short-term period of 7 years was chosen because it was identified by fishing representatives as a duration when changes in stock abundance may be noticeable in response to management actions (Haggarty et al. 2022). This time period also closely corresponds to important biological traits such as the age of maturity (Appendix A).

The behavior of management procedures may not be evident unless several generations have elapsed and there is turnover in the age structure in the simulated population. Therefore, the catch is also evaluated after two generations (long-term) corresponding to the time period of the policy-based performance metrics. The long-term catch performance measure can evaluate whether there is inter-generational access to the fishery (Haggarty et al. 2022).

No catch threshold could be readily identified for calculating performance metrics, for example, to calculate the probability that the catch recommendation exceeds or drops below a certain value. Several constant catch management procedures were evaluated (Section 5). These MPs explicitly ensure continued access for the fishery, a strategic objective identified in the Objectives Workshop (Haggarty et al. 2022).

Additional performance metrics were calculated to inform comparison of candidate management procedures:

6. **IAV 2GT**: Average variability in catch during 2 generations. This metric takes the absolute value of $(C_{y'} - C_{y'-k})/C_{y'-k}$, where C is catch, k is the update interval of 2 years, and y' is the subset of projection years when the catch advice is updated in the management

procedure. The mean is then taken across all update years and simulations and is reported as a proportion.

7. **B/B0 2GT**: The median ratio of spawning biomass to average unfished biomass (B/B_0) after 2 generations (in 2075)
8. **B/BMSY 2GT**: The median ratio of B/B_{MSY} after 2 generations
9. **MA 2GT**: Mean age after 2 generations (median value across 200 simulations)

Predictability and flexibility in fishery access are both desirable objectives from the fishery standpoint (Haggarty et al. 2022). A combination of catch magnitude and catch variability performance measures can inform selection of a management procedure that supports these strategic objectives.

In addition to the probability that the stock remains above the LRP and USR, the ratios of B/B_0 and B/B_{MSY} are reported.

Population age structure provides a complementary perspective on stock abundance in addition to total biomass. Thus, we report the mean age after 2 generations (in 2075). The mean age is calculated with the selectivity of the Hard-Bottom Longline Survey (HBLL) to demonstrate predicted values from a fishery-independent survey. As a general rule of thumb, a depleted stock can be characterized by a truncated age structure (lower mean age) as fewer fish survive to old ages.

To support comparison of management procedures, stock trends during the projection period are summarized by calculating the probability that the stock biomass has increased at intervals of ten years. Two probabilities are calculated, either unconditionally, i.e., probability of biomass increase without any additional qualifiers, or conditional on the USR, i.e., the increasing biomass condition is still met so long as the stock is above the USR. The USR qualifier supports the Precautionary Approach policy objective to promote stock growth when below the USR.

Equations describing the calculation of the performance metrics in the operating model are presented in Table 1.

Table 1. Summary of equations used to calculate the performance metrics for Outside Quillback Rockfish. Variables $i = 1, 2, ..., 200$ and y index simulation and projection year, respectively, in the operating models. $I()$ is an indicator function that returns 1 when the condition in the parentheses is met and zero otherwise. N is the abundance vulnerable to the HBLL survey where a indexes age and A is the maximum age in the operating model. Performance metrics are calculated for each management procedure.

Performance metric	Units
LRP 2GT $= \frac{1}{200}\frac{1}{54}\sum_{i=1}^{200}\sum_{y=1}^{54} I(B_{i,y} \geq 0.4B_{\mathrm{MSY}(i)})$	Probability (0-1)
USR 2GT $= \frac{1}{200}\frac{1}{54}\sum_{i=1}^{200}\sum_{y=1}^{54} I(B_{i,y} \geq 0.8B_{\mathrm{MSY}(i)})$	Probability (0-1)
FMSY 2GT $= \frac{1}{200}\frac{1}{54}\sum_{i=1}^{200}\sum_{y=1}^{54} I(F_{i,y} \leq F_{\mathrm{MSY}(i)})$	Probability (0-1)
C ST $= \frac{1}{200}\frac{1}{7}\sum_{i=1}^{200}\sum_{y=1}^{7} C_{i,y}$	Tonnes
C 2GT $= \frac{1}{200}\sum_{i=1}^{200} C_{i,y=54}$	Tonnes
IAV 2GT $= \frac{1}{200}\frac{1}{27}\sum_{i=1}^{200}\sum_{y\prime} \dfrac{C_{i,y\prime} - C_{i,y\prime-k}}{C_{i,y\prime-k}}, y\prime = 2, 4, 6, \ldots, 54$	Relative proportion
B/B0 2GT $= \mathrm{median}\left(\dfrac{B_{i,y=54}}{B_{0,i}}\right)$	Biomass ratio
B/BMSY 2GT $= \mathrm{median}\left(\dfrac{B_{i,y=54}}{B_{\mathrm{MSY},i}}\right)$	Biomass ratio
MA 2GT $= \mathrm{median}\left(\dfrac{\sum_{a=0}^{A} aN_{i,a,y=54}}{\sum_{a=0}^{A} N_{i,a,y=54}}\right)$	Age (years)

4. OPERATING MODELS

Outside Quillback Rockfish exhibit little to no population genetic structure (Nathan Sykes and Gregory Owens, University of Victoria, personal communication, 27 April 2023). Initial analyses of survey data, however, indicated that there is spatial heterogeneity in abundance trends along the BC coast. The Hard-Bottom Longline index was observed to be increasing in the North Coast while holding constant in the South Coast (Appendix B). Spatial heterogeneity has been seen in other inshore rockfish species, i.e., Yelloweye Rockfish, which have led to 2-area population modeling for Outside stocks (Cox et al. 2020). Therefore, it was desirable to estimate historical population trends over at least 2 separate areas across the BC Coast (Haggarty et al. 2022).

We followed the same area structure to model Outside Quillback in the North, incorporating Areas 5A3CD, and the South, incorporating Areas 5BCDE (Figure 2). The scale of the spatial analyses was limited by the sample sizes of the survey age compositions. Spatially-explicit modeling of age-structured populations also require more assumptions about distribution and movement among areas and may result in lower precision in abundance estimates than in a model with fewer assumptions.

It is believed that there is little movement of juveniles and adults, at least between the North and South coast, once larvae recruit to rocky habitat. Thus, the mechanism for population connectivity throughout the BC coast would be through pelagic larval dispersion.

Best practice recommends calibrating or conditioning OMs with observed data so that historical observations can be reproduced. Stock Synthesis 3 (hereafter, “SS3”) was identified as the best conditioning model to accommodate a 2-area structure. To model population connectivity, the predicted recruitment coastwide is predicted from coastwide spawning biomass. The proportion of recruitment that is apportioned to each of the two areas is then estimated, with no movement after the recruitment phase of the life cycle (Appendix D). These features appear to best describe the life history and genetics of Quillback Rockfish.

SS3 is an age-structured model that provides flexibility in model structure and fitting to the various data types that are collected for Outside Quillback Rockfish. Generally, age-structured models incorporate our best understanding of fisheries population dynamics. For long-lived species such as Quillback Rockfish, it is desirable to incorporate delays in recruitment due to differences in size and age-based selectivity between fishing gears. Emergent from the longer generation time of Quillback Rockfish are delays in responses to management actions as cohorts need to progress through the population age structure. These properties are best captured in an age-structured model over other types of models, e.g., surplus production models. Model equations for SS3 are available in the Supplementary Materials of Methot and Wetzel (2013).

Operating models (OMs) can be organized into four main components representing a real fished system:

1. population dynamics of the fish stock (e.g., growth, recruitment, mortality);
2. fishery dynamics (e.g., selectivity);
3. observation processes (e.g., precision in survey indices); and
4. management implementation (e.g., catch overages).

OM development follows two broad steps:

1. Fit the SS3 model to the historical data, including catches, indices of abundance, and any available years of age and length composition data, and life history parameters. Biological parameters were informed from specimens collected from the Outside stock from both fishery and survey sources (Appendix A). Other parameters, i.e., natural mortality and stock-recruit steepness, were informed by the scientific literature (Appendix D). The model estimates the historical fishing mortality and abundance that are consistent with the observed data.
2. Pass the conditioned parameter values from SS3 to an operating model (now the “conditioned” OM). The historical period of the operating model spans all years from the first year t_1 to the final year t_c (where “c” represents the “current” year) of the catch time series and replicates the stock dynamics estimated in SS3. The historical period, including abundance in the current year, then informs the stock dynamics of the simulated projections, starting in year t_{c+1} to the final projection year t_N.

The projections were performed through the `MSEtool` package version 3.6.2 (Hordyk et al. 2023).

It is often not possible to incorporate all sources of uncertainty into a single operating model, for example, when alternative values of population parameters are considered. In such situations, multiple OMs are developed that change the value (or distribution) of one or more parameters and/or data sources of interest (Section 4.2). Results from conditioning the set of OMs are in Section 4.3.

4.1. DATA SOURCES

Commercial fishery and survey data were extracted using the `gfdata` R package, which applies standard SQL routines to several databases and reconstructs the various time series accordingly (Keppel et al. 2022).

The databases accessed were:

1. GFBioSQL: Contains all modern biological sample data for surveys and commercial fisheries. This database includes most of the groundfish specimen data collected since the 1950s.
2. PacHarvTrawl: Contains Canadian trawl landing and discard data from 1996 to March 31, 2007.
3. PacHarvHL: Contains Canadian hook and line landing and discard data from 1986 to March 31, 2006.
4. GFFOS: Contains Canadian trawl landings and discards from April 1, 2007 to present and hook-and-line landings and discards from April 1, 2006 to present. This database is essentially a copy of the Fisheries and Oceans Canada (DFO) Fishery Operations (FOS) database.

4.2. OPERATING MODELS

Best practice recommends identification of a "reference set" of core OMs that include the most important uncertainties, e.g., a range of natural mortality values, as well as a "robustness set" that captures a wider range of uncertainties that may be less plausible but should nonetheless be explored (Rademeyer et al. 2007).

Results are reported for individual operating models, but Anderson et al. (2021) recommended that reference set performance metrics should also be averaged together (an ensemble approach to integrate across OM uncertainties) but that performance metrics from individual OM robustness set scenarios should primarily be presented separately. Presenting robustness results separately allows managers to see how MPs that performed well in the reference set perform under a set of more diverse assumptions (Rademeyer et al. 2007). Following guidance from the technical working group, averaged quantities from the reference set were calculated with twice the weight of OM (1) relative to the other reference operating models.

Since natural mortality has not been directly estimated for Outside Quillback Rockfish, we established two reference set OMs which varied by the value of natural mortality (M): (1) M = 0.056, and (2) M = 0.046 (Table 2). These means were based on various regression equations that use maximum age to indirectly predict M.

A third reference set operating model evaluated a low recreational catch scenario.

Finally, two robustness set OMs encompassing additional sources of uncertainty: (A) an OM with a lower steepness value than in the reference set, and (B) an OM that assumes lower than average recruitment in the projection (Table 2).

A technical description of the operating model specification, including parameter settings, is provided in Appendix D.

Table 2. Outside Quillback Rockfish operating model scenarios.

Scenario name	Type
(1) M = 0.056	Reference
(2) M = 0.046	Reference
(3) Low IRec	Reference
(A) Low steepness	Robustness
(B) Low Recruitment	Robustness

4.2.1. Reference set

The following OMs were developed as the reference set. We hereafter refer to them by their numbers, e.g., OM Scenario (1).

Data sources are provided in Appendices A through C. Here, we here provide a brief description of OM (1), which was subsequently adjusted for the other operating models.

Fishery removals were informed by the historical commercial and recreational catch time series (details in Appendix C). Prior to the introduction of 100% at-sea monitoring in the groundfish hook and line fleet in 2006, commercial rockfish catch was frequently reported in aggregate as Other Rockfish (ORF; rockfish species other than Pacific Ocean Perch) and the magnitude of catch discarded at sea was not recorded. A reconstruction algorithm was used to estimate catch going back to 1918 (Haigh and Yamanaka 2011, see Appendix C). Since 2006, the nominal catch has been used. The reconstruction algorithm provided the best catch estimates from the commercial fishery, and no other information was available to indicate whether there were over- or under-estimates for any particular time period.

Biological samples from the commercial fishery were collected during 1988-2010. Age samples from the handline and longline gears were collected during 1988–1995 (Appendix C). However, catch from the various hook and line sectors could not be separated between these two gears. Therefore, it was decided to use the handline age samples to estimate selectivity for the hook and line fishery. In this way, fishing mortality of smaller fish from handlines is accounted for. Flat-topped selectivity also accounts for mortality from longline gears which tended to catch larger fish.

Length samples were available from the trawl fishery from three years during the 2000s. Mean weight in the commercial fishery since 2006 indicated that the trawl sector caught larger fish, on average, than in the hook and line fishery (Figure C.5). These time series were also included in the model so that the trawl selectivity was estimated to be greater than the hook and line selectivity.

Recreational catch was estimated from the Internet Recreational Effort and Catch (iRec) reporting program which provides estimates throughout the BC coast since 2012. Linear interpolation was needed to model the development of the recreational fishery between 1945–2012 (Appendix C).

No length samples were available to estimate selectivity in the recreational fishery. Instead, selectivity was fixed to values estimated for Inside Quillback Rockfish, for which there were length samples collected from dockside interviews in the creel survey. The age of 50 and 95 percent selectivity was 12.7 and 23.3 years, respectively (Huynh et al. 2024).

Three fishery-independent surveys were used to develop indices of abundance: the outside Hard Bottom Longline (HBLL) Survey, the International Pacific Halibut Commission Fishery Independent Setline Survey (“IPHC FISS” or “IPHC”), and the Synoptic Trawl survey in Hecate Strait (Appendix B). From the HBLL and IPHC surveys, indices were separately developed for the North (5BCDE) and South (5A3CD) regions. The Synoptic Hecate Strait index was assumed to be representative of biomass trends in the North.

Age samples are also available from all surveys. However, age samples from the 2021 HBLL survey were not available for this analysis.

Growth and maturity parameters were estimated from the biological samples collected from surveys and fisheries (see Appendix D).

Steepness, the predicted reduction in recruitment at 20 percent of unfished spawning biomass, was fixed at 0.67. This value is based on a posterior estimate from a meta-analysis of Pacific rockfish species (Appendix D, Section D.3.7). The Beverton-Holt stock-recruit relationship was used, in which steepness ranges from 0.2–1.0.

Natural mortality was also fixed in the model (see values in sections 4.2.1.1 - 4.2.1.2). Initial model fits that attempted to estimate steepness and/or natural mortality resulted in high estimates (approximately 0.9 for steepness and 0.08 for *M*). From these values, the model inferred that the stock was large and lightly fished, with the depletion estimate close to unfished conditions. This outcome was deemed to be highly unlikely given the concerns about rockfish abundance that led to the rockfish conservation strategy in the early 2000s (Yamanaka and Logan 2010).

The model was initialized under the assumption that spawning biomass (B_y) was in an unfished equilibrium state prior to 1918, the first year of the time series, i.e., $B_{1918} = B_0$.

4.2.1.1. (1) M = 0.056

Since natural mortality has not been directly estimated for Outside Quillback Rockfish, we consider two alternative natural mortality (*M*) values in the reference set. In operating model 1, $M = 0.056$ (Appendix D, Section D.3.1). This value is based on the updated literature on predictors of natural mortality based on other life history traits, specifically, maximum observed age. The mean of 0.056 is based on the log-log regression of direct estimates of *M* and maximum observed age from a variety of fish taxa (Then et al. 2015).

4.2.1.2. (2) M = 0.046

In OM (2), natural mortality is lower than in (1), with $M = 0.046$. This mean was estimated from an older dataset than that used in Then et al. (2015) to establish the relationship between *M* and maximum age (Hoenig 1983). This value is consistent with the natural mortality value considered in the 2011 assessment (Yamanaka et al. 2011). The lower value assumes that the stock is less productive in the other scenarios.

4.2.1.3. (3) Low iRec

Recreational catch was obtained from the Internet Recreational Effort and Catch (iRec) reporting program which provides estimates throughout the BC coast since 2012. Catch estimates are based on self-reported surveys and expanded for non-respondent license holders. In areas with dual coverage with the creel survey, i.e., Strait of Georgia and West Coast Vancouver Island, catch rates reported to iRec were relatively higher compared to the creel survey (Robichaud and Haggarty 2022). Recreational catch can be overestimated in iRec if, for example, the catch expansions for non-respondents are too high.

Therefore, an additional reference model was developed for the scenario where iRec catch is overestimated. Operating model 3 is conditioned assuming that the true recreational catch were 50 percent lower than estimated. As a result, the ratio of the recreational to commercial catch changes.

4.2.2. Robustness set

The following two OMs were developed for the robustness set. For both, the natural mortality in OM (1) was used. We hereafter refer to them by letters.

4.2.2.1. (A) Low steepness

All reference operating models fixed steepness at 0.67. This operating model was conditioned with steepness fixed at 0.50, implying a less productive stock. Average recruitment decreases more rapidly at low stock sizes.

4.2.2.2. (B) Low recruitment

This scenario tests a scenario in which environmental conditions contribute to lower than average recruitment (as defined by the stock recruitment relationship) of Quillback Rockfish in the future. For example, increased predation of juvenile and larger rockfish by Coho Salmon and Lingcod can contribute to lower recruitment to adult sizes (Beaudreau and Essington 2007; Frid and Marliave 2010; Fennie et al. 2020).

In all other scenarios, the mean of the recruitment deviations from the stock-recruitment relationship in the projections is one (in normal space). Here, the mean was set to 0.7. The historical dynamics here are identical to those in OM (1). Compared to operating model (A), recruitment is on average lower at all stock sizes.

This scenario is intended to evaluate how management procedures would perform in such circumstances and is not intended to make any statements regarding future stock conditions.

4.3. CONDITIONING THE OPERATING MODELS

After specifying the structure of the SS3 model (Appendix D), we fitted the model to estimate historical recruitment and abundance, as well as fishery and survey selectivity, from the various data series. Fishery removals in the model are equal to the observed values. Three fisheries (hook and line, trawl, and recreational) were separately modeled with differing selectivity for the historical period.

Normal priors were placed on selectivity parameters while a uniform prior was placed on the natural logarithm of the unfished recruitment R_0 parameter (Appendix Table D.3).

After finding the maximum posterior density (MPD) estimates, the posterior was sampled using Markov Chain Monte Carlo (MCMC) simulation (details in Appendix D.4). For each operating model, the historical stock was reconstructed from 200 MCMC samples to incorporate uncertainty in estimated parameters.

These 200 simulation replicates then inform the stock and fishery dynamics in the projection period. In the projections, fishery selectivity is derived from the fishing mortality-at-age in the final historical year (t_c). This relative selectivity-at-age is effectively weighted by catch across all fisheries and is constant in the projection period. Selectivity parameters for the indices of abundance estimated in SS3 are also passed to the operating model. These selectivity-at-age functions are used to simulate new observations of the catch and indices in the projection for the testing of management procedures.

Use of a single index of abundance for deriving catch recommendations is consistent with many MPs, unless otherwise specified (Appendix E). During the projection period, the HBLL index was used to calculate catch advice in index-based management procedures. It is believed that the HBLL survey provides the best index for Outside Quillback Rockfish as it targets rocky habitat. In contrast, the Synoptic Hecate Strait survey does not target rocky habitat and was not considered for index-based management procedures. While there is value in the biological samples from the IPHC survey, i.e., to detect the abundance of large and old fish, the large hook size used does not catch Quillback Rockfish well, and there is resultant high uncertainty in index trends from this survey. Thus, the IPHC survey was not considered for index-based MPs.

In the operating model, projected recruitment deviations were sampled in log space with standard deviation $\tau = 0.4$, with autocorrelation estimated post-hoc from the historical recruitment deviates estimated in SS3. Observation error in the projected index values was simulated with random deviates from a lognormal distribution with mean of one. The standard deviation and autocorrelation of the deviates were estimated from the residuals from the fit to the conditioning model (Appendix Figure D.6).

4.3.1. OM conditioning results

The following sections describe the estimates from SS3. Results for OM (B) are not shown here because the historical period of this operating model is identical to OM (1).

4.3.1.1. Fits to data

The SS3 models were able to fit to the indices of abundance reasonably well in most cases (Figures 5). Notably, the HBLL index in the North has been increasing since 2005. The corresponding predicted trend in the SS3 model is also increasing, although not to the extent of the observed values. The HBLL index in the South is noisier although a somewhat similar increasing trend could be inferred since 2014. The IPHC index reveals no apparent trend since 1998 in either area. Similarly, the Synoptic Hecate Strait index shows no strong trend except for a large increase in 2021. The 2021 index value is too recent for the model to fit and was not supported by the corresponding age data.

Model fits to the fishery and survey composition data are in Figures 6 - 12. The model predicts high abundance in the 70+ age group in many of the surveys. The survey and fishery age composition do see 70+ fish in some years although not as consistently as predicted in the model. No age series span the time period from the 1980s to the current day to inform depletion from the time period when the fishery catches were highest. Besides this behavior in the plusgroup, no further systematic trends in the residuals of the composition data were readily apparent (Figures 13 – 14) and the distribution of residuals were approximately Gaussian (Figure 15). A high value of natural mortality somewhat improved the residuals in the plusgroup. However, when estimated in SS3, the high natural morality also coincided with a large, lightly fished stock biomass which was not considered realistic (Appendix D.6).

The corresponding mean ages (calculated from the age composition) in the HBLL and IPHC surveys indicate a decreasing trend since 2003 (Figure 16). Mean age can decrease for various reasons, including an increase in mortality that reduces survival of fish to old ages or an increase in recruitment where the population structure comprises of more young fish. With the increasing HBLL index and the fact that catches in the commercial fisheries have been decreasing, the model infers the latter, that is, there has been strong recruitment in the year classes (age-0 recruitment in early 2000s) that are selected by the HBLL and IPHC surveys (Figure 28; see also section 4.3.1.2). Recent recruitment (since 2010) that would be detected in the Synoptic Hecate Strait age composition is predicted to be lower. Comparison of the two age samples show larger fish in the 2021 sample compared to the 2005 sample (Figure 12). There are also fewer small fish in the 2021 length composition compared to previous years (Appendix Figure A.4).

Flat-top selectivity functions were estimated for surveys and fisheries and did not appreciably change between operating models (Figure 18). The age of 50% selectivity for the HBLL survey was approximately 20 years (Table 3). The IPHC survey catches slightly older fish, with 50%

selectivity at around 22 years. Other gears from the commercial fishery and Synoptic Hecate Strait trawl survey caught smaller fish than in the HBLL and IPHC surveys.

The fits to the mean weight from the commercial fishery are in Figure 17. There is more interannual variability in mean values from the trawl fishery than in the hook and line fishery. Higher mean weights in the trawl fishery implies that larger fish are caught compared to the hook and line fishery (Table 3).

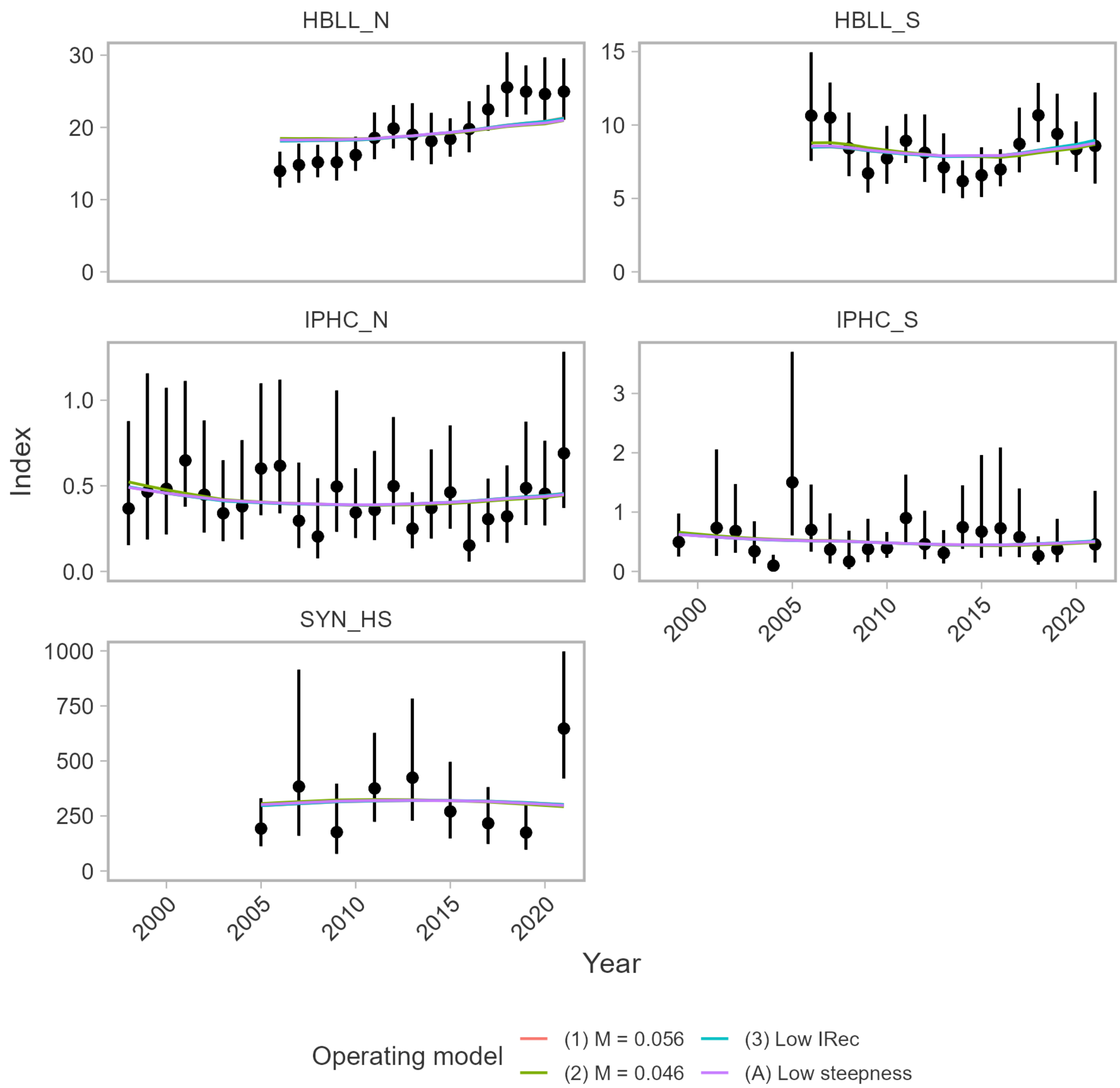

Figure 5. Maximum posterior density (MPD) fits to the indices of abundance by operating model. Dots represent index mean and line segments represent 2 times the standard error. Black lines represent predicted values by the model.

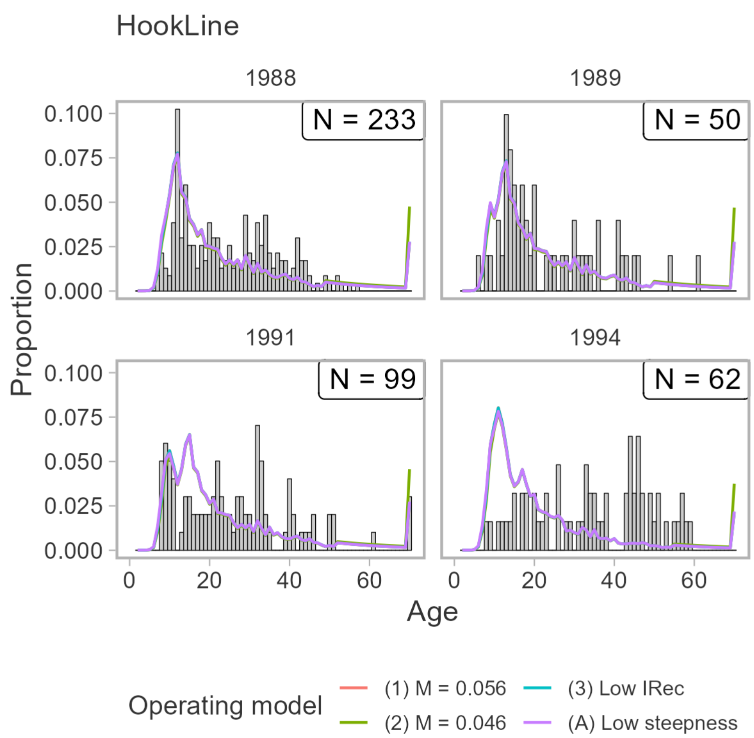

Figure 6. Maximum posterior density (MPD) fits to the age composition data in the hook and line fishery in the four operating models, showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples for the corresponding year.

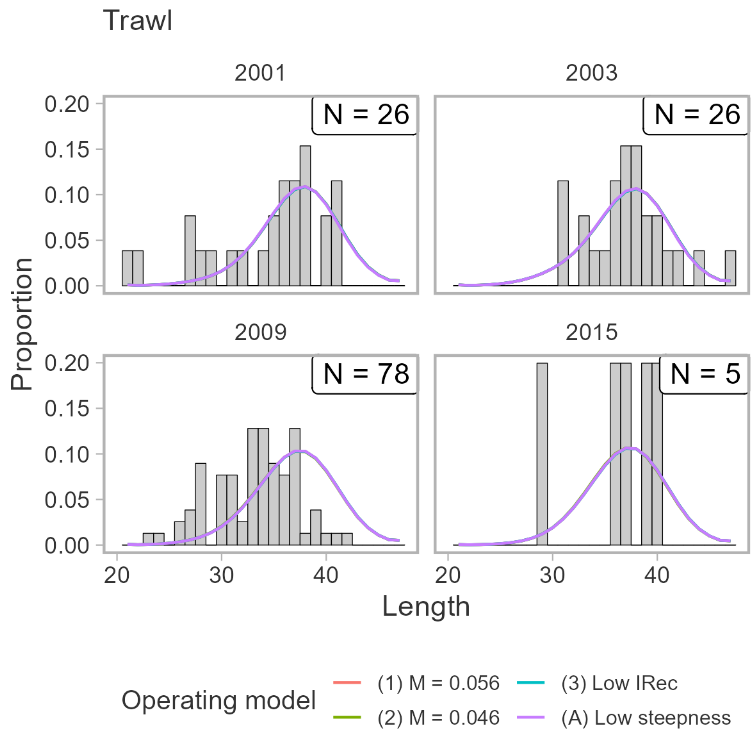

Figure 7. Maximum posterior density (MPD) fits to the length composition data in the trawl fishery in the four operating models, showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples for the corresponding year.

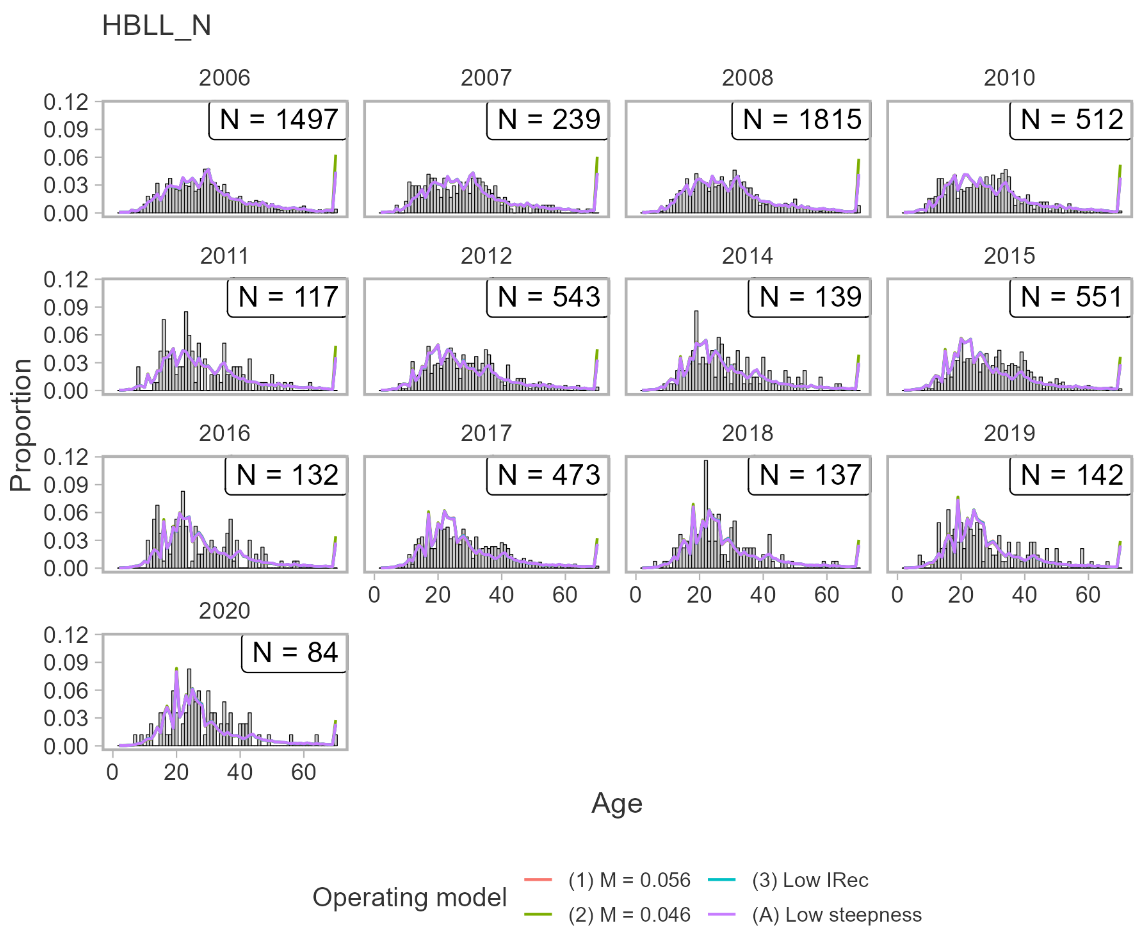

Figure 8. Maximum posterior density (MPD) fits to the age composition data in the HBLL North survey in the four operating models, showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples for the corresponding year, but were downweighted in the multinomial likelihood function.

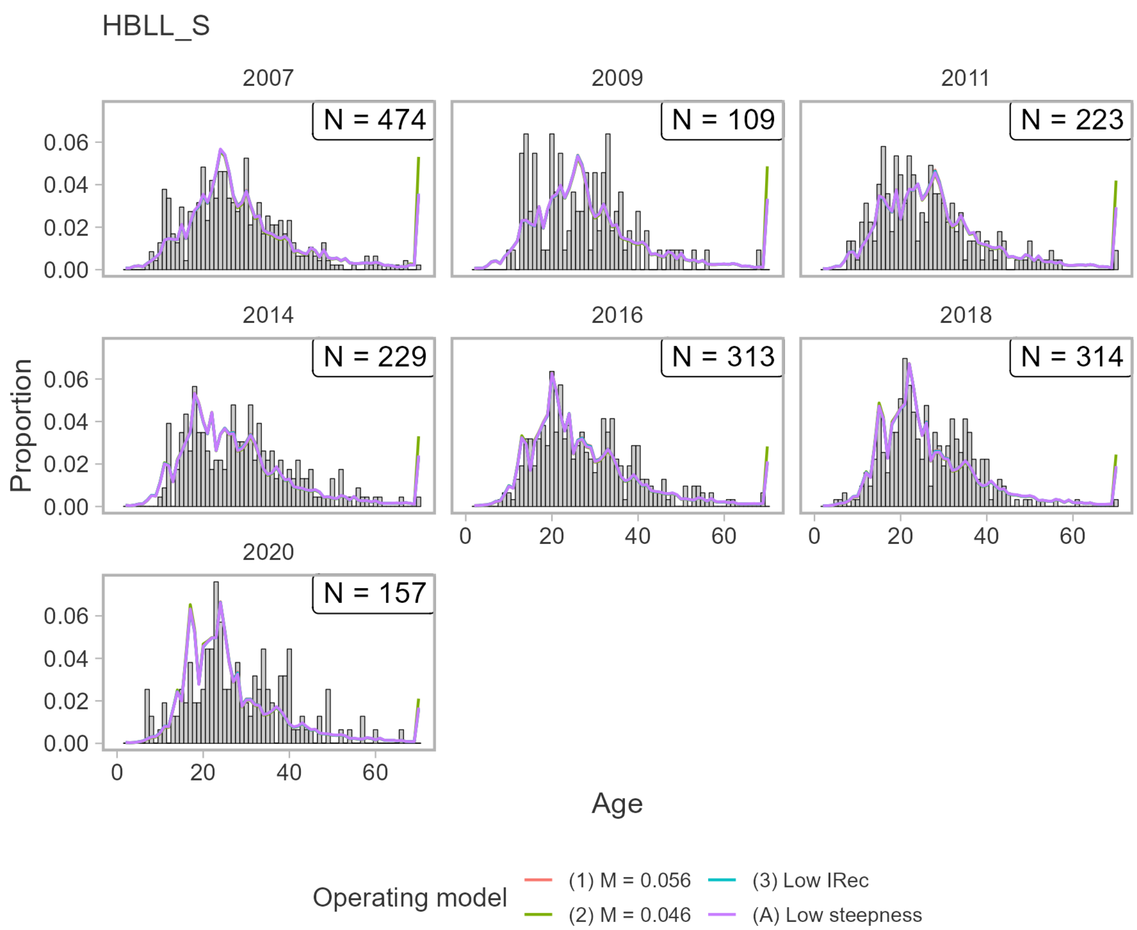

Figure 9. Maximum posterior density (MPD) fits to the age composition data in the HBLL South survey in the four operating models, showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples for the corresponding year, but were downweighted in the multinomial likelihood function.

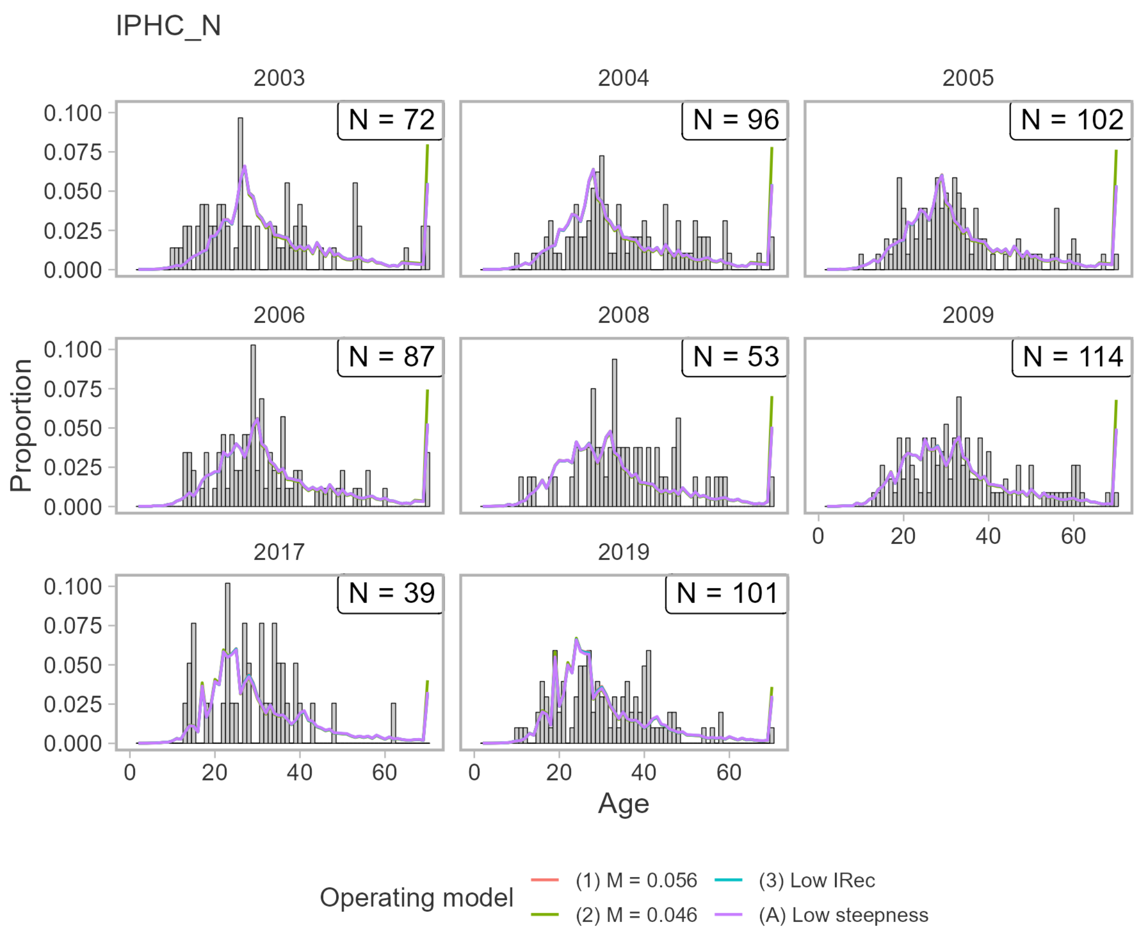

Figure 10. Maximum posterior density (MPD) fits to the age composition data in the IPHC North survey in the four operating models, showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples for the corresponding year, but were downweighted in the multinomial likelihood function.

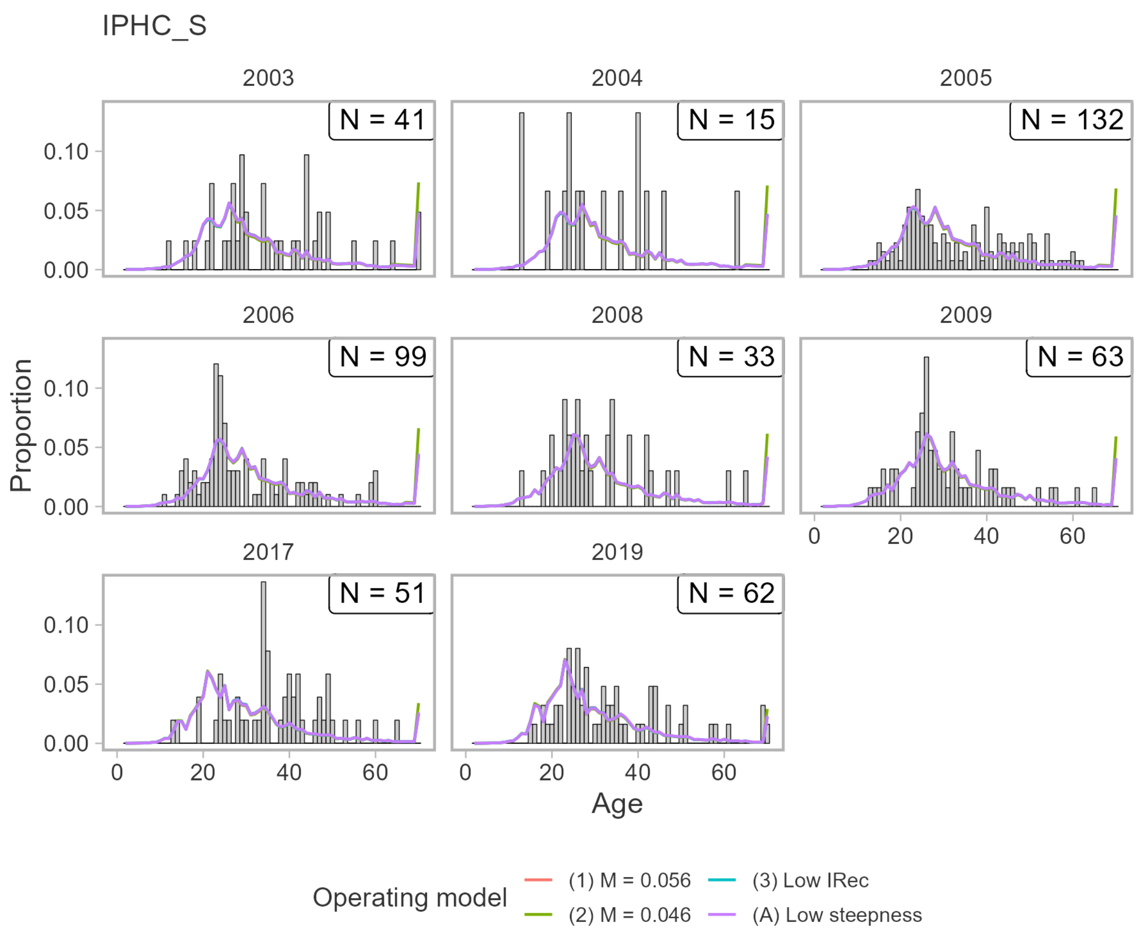

Figure 11. Maximum posterior density (MPD) fits to the age composition data in the IPHC South survey in the four operating models, showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples for the corresponding year.

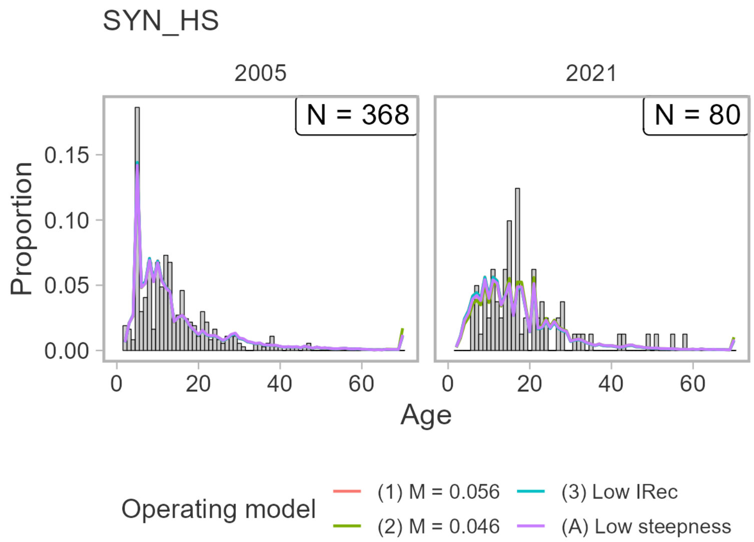

Figure 12. Maximum posterior density (MPD) fits to the age composition data in the Synoptic Hecate Strait survey in the four operating models, showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples for the corresponding year.

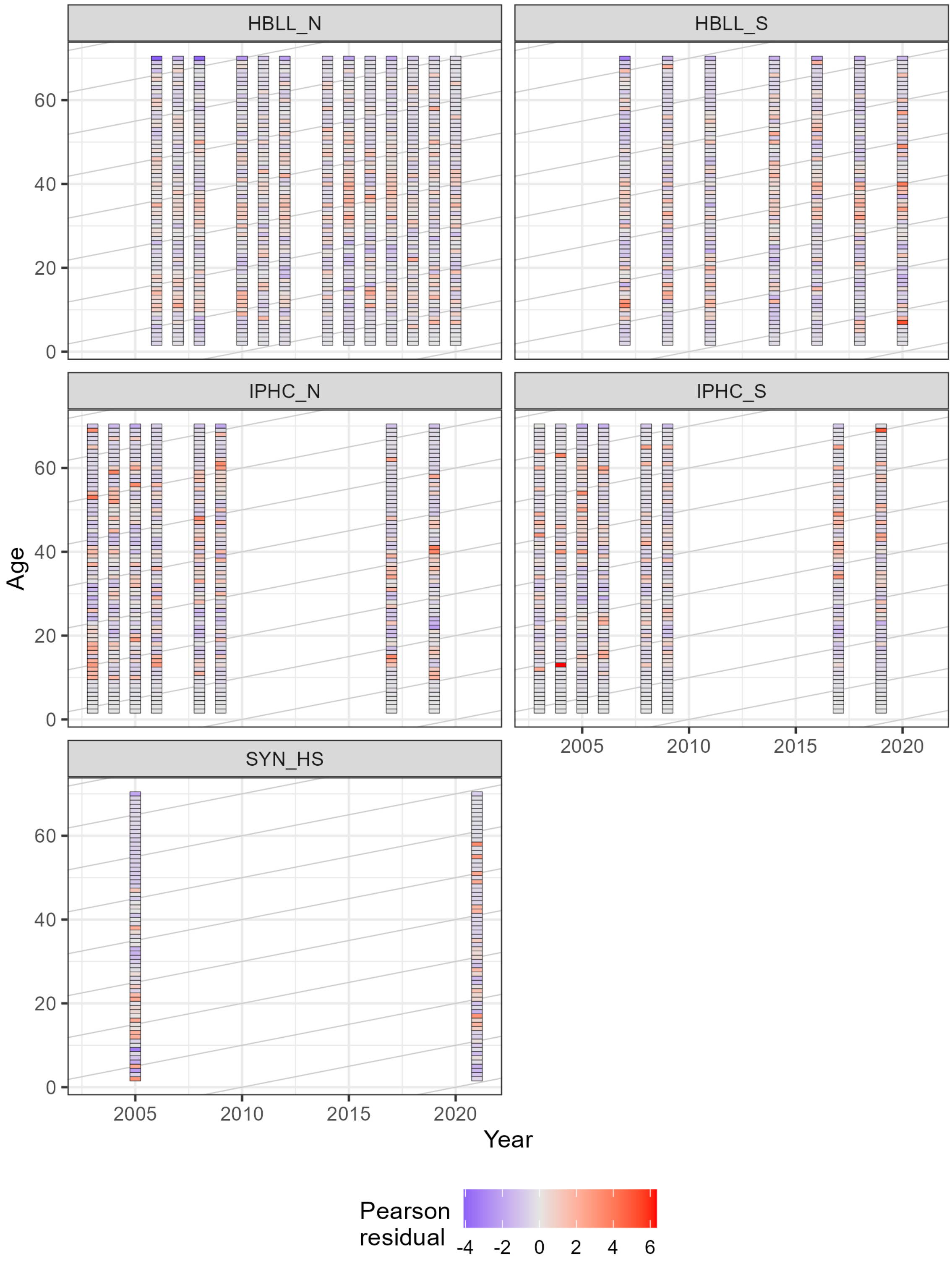

Figure 13. Pearson residuals in the survey age composition data for the conditioning of operating model 1. Red colours indicate the observed proportions exceeded the predicted proportions, while blue colours indicate that the predicted proportion exceeded observed values. Diagonal background lines have a slope of one to help track cohorts in the age structure through time.

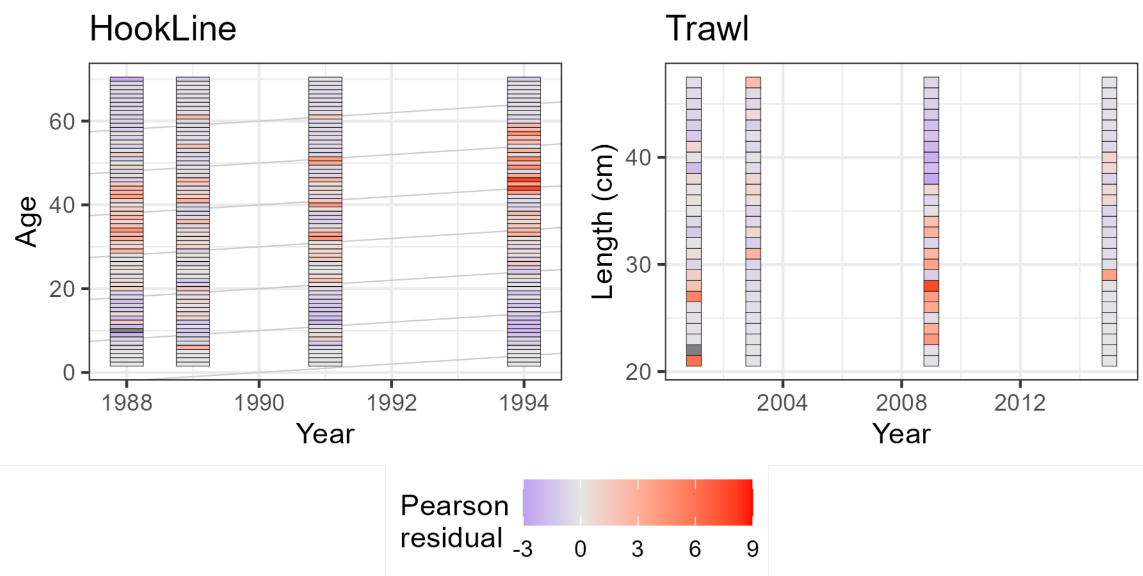

Figure 14. Pearson residuals in the fishery age and length composition data for the conditioning of operating model 1. Red colours indicate the observed proportions exceeded the predicted proportions, while blue colours indicate that the predicted proportion exceeded observed values. Diagonal background lines have a slope of one to help track cohorts in the age structure through time.

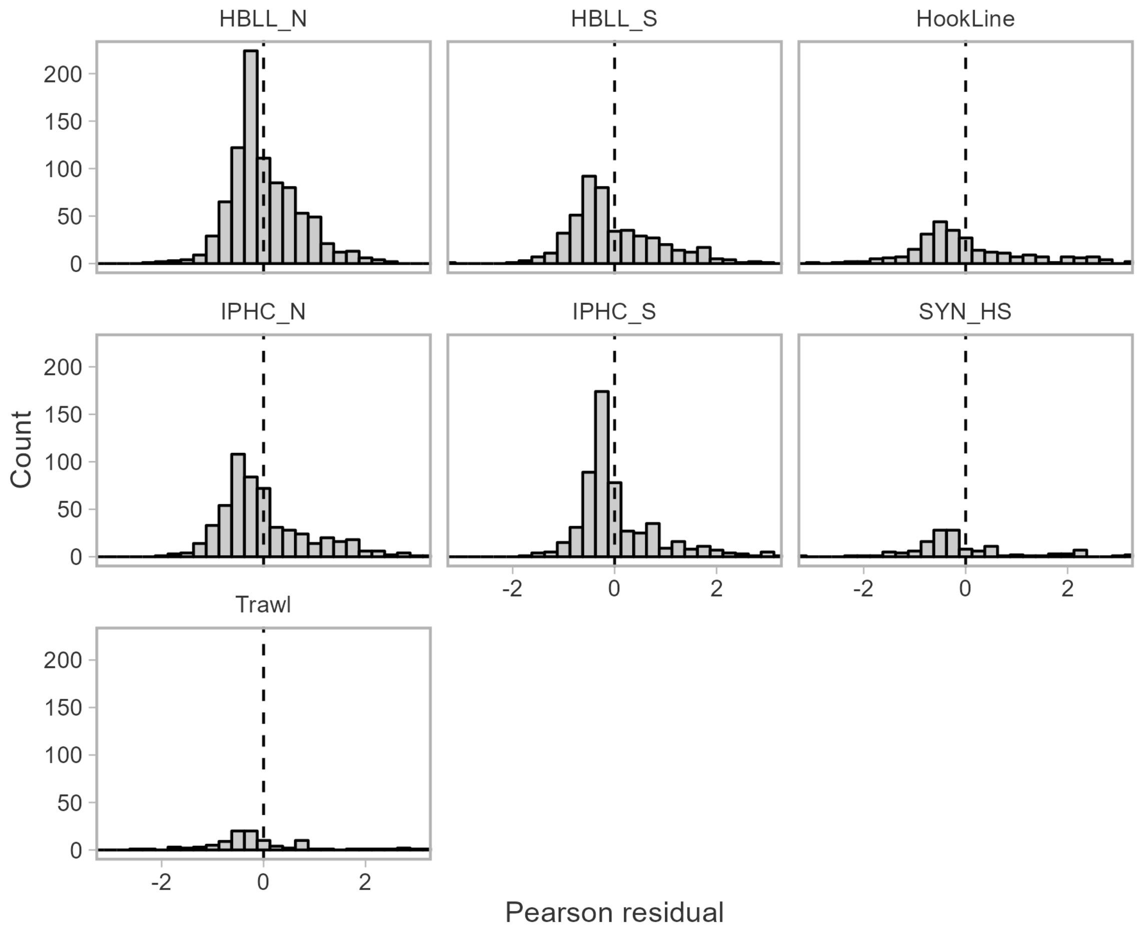

Figure 15. Histogram of Pearson residuals in the survey and fishery composition data for the conditioning of operating model 1. Pearson residuals are expected to have a Gaussian distribution. Vertical dotted line indicate zero on the x-axis.

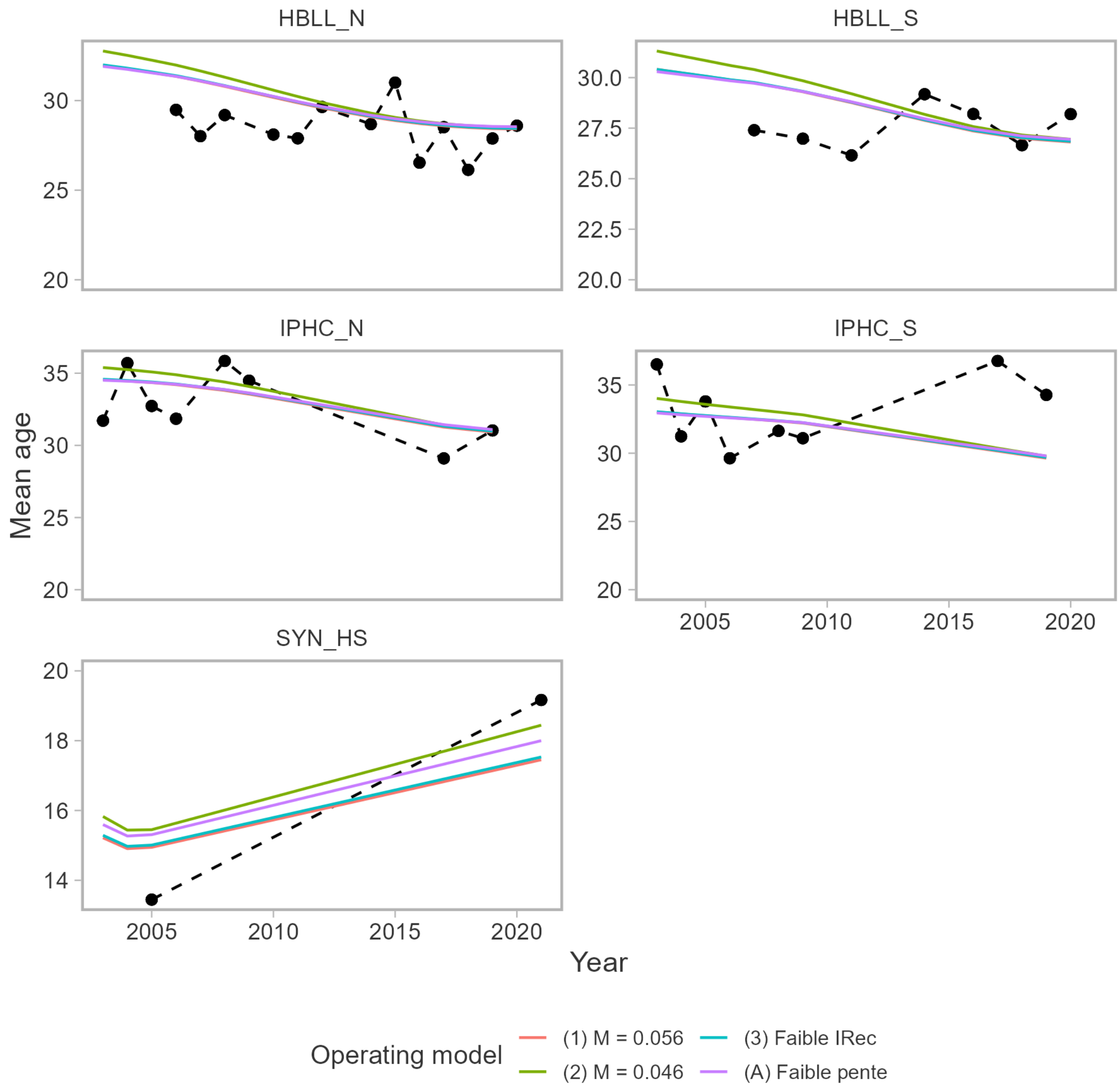

Figure 16. Observed (black lines) and predicted (coloured points) mean age in the survey age composition. These values were not used to fit to the model but can be used to summarize and evaluate trends in the age composition over time.

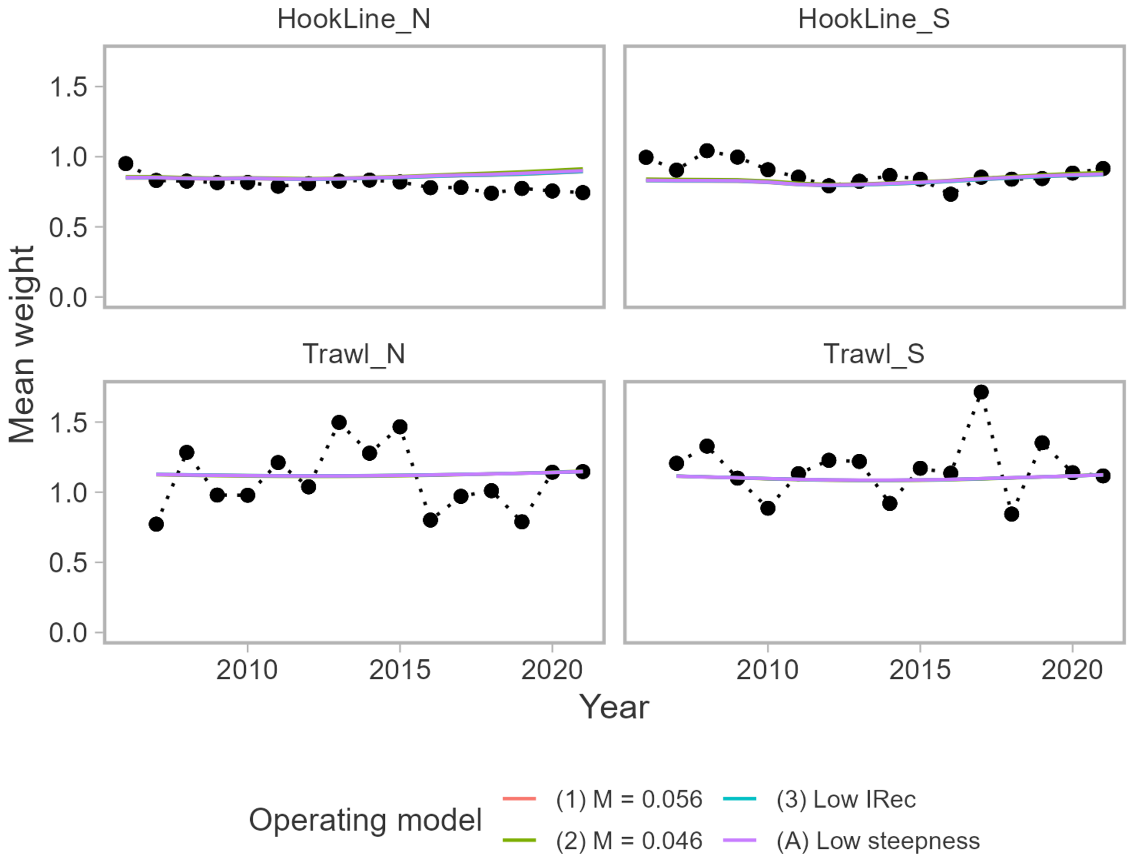

Figure 17. Observed (black lines) and predicted (coloured points) mean weights in the commercial fishery. These data series are calculated from catch weight and pieces (numbers) at the fishing trip level, and not from individual biological samples.

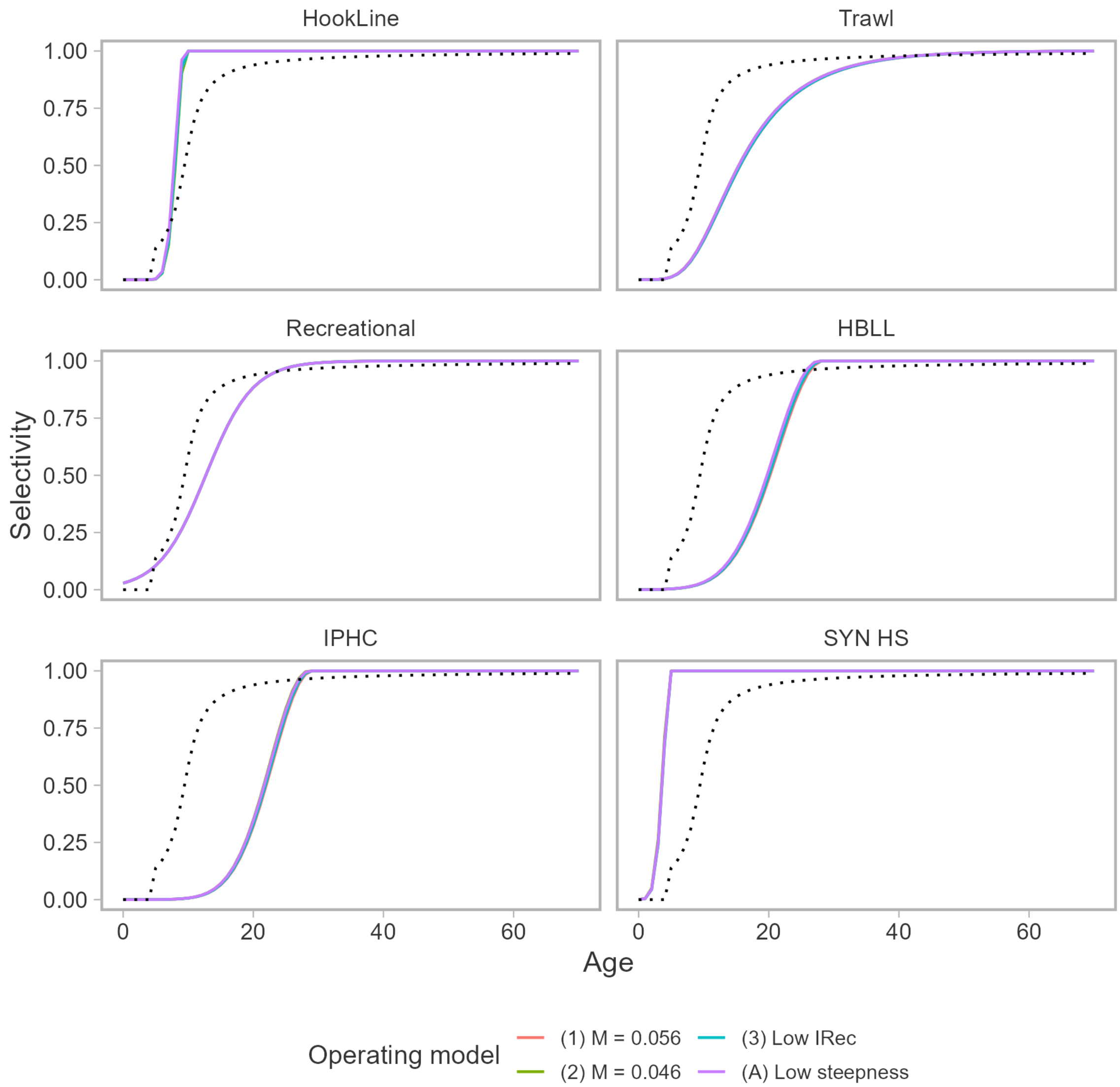

Figure 18. Selectivity at age (colored lines) at the maximum posterior density (MPD) of the SS3 models for the fisheries and surveys. The selectivity of the trawl fishery was estimated in terms of length units and was converted to the age-based equivalent for convenient comparison. The dotted line is the maturity-at-age for comparison.

Table 3. Posterior mean and standard deviation of the age of 50 and 95 percent selectivity in operating model 1. The recreational selectivity was fixed; hence, the standard deviation is zero.

Gear	a_{50}	a_{95}
HookLine	7.9 (0.4)	9.2 (0.5)
Trawl	15.6 (0.3)	35.4 (0.8)
Recreational	12.7 (0)	23.3 (0)
HBLL	20 (0.7)	26 (0.9)
IPHC	21.9 (0.7)	27.1 (0.9)
SYN HS	3.5 (0.2)	4.8 (0.3)

4.3.1.2. Historical estimates

In all operating models, it is estimated that the spawning biomass in 2021 was very likely above the LRP and USR (with greater than 95% probability, Figure 19). With respect to average unfished biomass, the stock was also very likely above 0.2 and 0.4 B_0.

The stock ranged from 1.64 B/B_{MSY} (0.48 B/B_0) in the low M operating model to 2.02 B/B_{MSY} (0.59 B/B_0) in the higher M operating model (Table 4). The estimated B/B_{MSY} and B/B_0 in 2021 is lower in operating models (2) and (A) when natural mortality and steepness are respectively lower (Figure 20 and Table 4). Absolute stock size is dependent on operating model, with a larger stock size inferred in operating models (1) and (A) (Figure 21). A slightly smaller stock is estimated for operating model (3) compared to (1). Comparison of the absolute magnitude of B_{MSY} and B_0 reference points can be seen in Figure 22).

All models inferred similar trends in stock biomass over time, with the largest declines during the late 1980s–2000 followed by more stable and slightly increasing trend since then (Figures 21-23). The stock has not been estimated to be below B_{MSY} in its history (Figures 24 and 25). Similarly, the stock has not been estimated to be below 0.4 B_0.

The large declines occurred during a period with high fishing mortality (Figures 26-27). Appendix G provides for a comparison of mortality rates estimated from catch curves with the HBLL and IPHC age compositions.

High recruitment in the early 2000s was predicted based on the decreasing trend in the mean age and increasing HBLL index (Figure 28). The model predicts that a majority proportion of the coastwide recruitment settles in the North (Figure 29). As a result, the stock abundance is estimated to be higher in the North. Since the early 2000s, the stock has been increasing in the North while remaining more constant in the South (Figures 21). These trends are informed by the HBLL index values between the two areas (Figure 5).

The 2011 assessment used a surplus production model with a symmetric yield curve, i.e., B_{MSY} at 0.5 B/B_0 (Yamanaka et al. 2011). In contrast, yield curves are typically right-skewed in age-structured models, i.e., with B_{MSY} at approximately 30% B/B_0 (Figure 30). Yield curves with respect to fishing mortality are presented in Figure 31 to inform harvest policy and other fishery objectives.

The LRP of 0.4 B_{MSY} is a low biomass state at which the age structure may also be expected to be severely truncated because fewer fish survive to old ages. The observed age composition from the HBLL and IPHC surveys in 2020 and 2019, respectively, was compared to the expected equilibrium age structure at the LRP. The observed age structure contained more older fish (30+ years) than expected at the LRP (Figure 32). In other words, the descending limb of the observed age structure declines more slowly than predicted at the LRP, indicating higher survival than expected at the LRP, and there are fish in the plus group in both surveys. While the LRP is defined with respect to biomass, age structure profiles can provide a complementary insight on conditions needed to identify the stock to be below the LRP, i.e., the age structure would need to be more severely truncated beyond what is currently observed in the HBLL survey.

Retrospective analysis explored whether the historical model estimates were consistent as data from recent years are excluded. If biomass estimates systematically and appreciably diverge as more years of data are removed, then it could be indicative of a problem with the model structure. With up to 7 years of data peeled from the model, there was some retrospective pattern for spawning biomass and depletion (Figure 33). The Mohn's rho statistic was negative, indicating that biomass and depletion were lower as more data are excluded, or both are systematically increasing going forward, independent of stock trends.

The magnitude of Mohn's rho was less than 0.20, which did not appear to present a major concern. Simulation analyses have shown that some retrospective patterns may still persist in well-specified models (Hurtado-Ferro et al. 2014). Some retrospective patterns may also be expected if there is a short and recent time series of data, for example, the age composition from the Hecate Strait survey in two recent years (2005 and 2021). If they are uniquely informative about stock trends, then the model estimates can be expected to diverge when these data are removed during the retrospective analysis.

Table 4. Estimates of MSY and unfished reference points, spawning biomass (B) and fishing mortality (F) in 2021, and corresponding ratios. Parameter values report the posterior mean and standard deviation, while status probabilities are calculated across 200 posterior samples. The Reference OM column reported the weighted average across the reference operating models (designated by numbers), with doubled weighting in OM 1 over the other two reference OMs.

Variable	(1) M = 0.056	(2) M = 0.046	(3) Low IRec	(A) Low steepness	Reference OM
$B_{2021}/B_{\mathrm{MSY}}$	2.02 (0.15)	1.64 (0.11)	2.02 (0.15)	1.65 (0.12)	1.930
B_{2021}/B_0	0.59 (0.043)	0.48 (0.0336)	0.59 (0.0453)	0.59 (0.0444)	0.570
B_{MSY}	1824.04 (125.32)	1600.34 (63.18)	1652.94 (123.38)	2368.76 (167.99)	1,725.340
B_0	6195.5 (421.45)	5424.56 (210.1)	5634.01 (416.1)	6660.73 (469.04)	5,862.390
B_{2021}	3696.77 (496.38)	2633.92 (267.25)	3363.03 (490.38)	3932.27 (559.29)	3,347.620
F_{MSY}	0.064 (0.0029)	0.055 (0.0016)	0.063 (0.0025)	0.039 (0.0013)	0.062
$F_{2021}/F_{\mathrm{MSY}}$	0.33 (0.0398)	0.54 (0.0527)	0.32 (0.0438)	0.51 (0.0666)	0.380
F_{2021}	0.021 (0.0029)	0.03 (0.0032)	0.02 (0.0031)	0.02 (0.0029)	0.023
MSY	126.73 (8.26)	92.46 (3.35)	115.16 (8.12)	98.64 (6.69)	115.270
LRP	729.62 (50.13)	640.14 (25.27)	661.18 (49.35)	947.5 (67.2)	690.140
USR	1459.23 (100.26)	1280.27 (50.55)	1322.36 (98.7)	1895.01 (134.39)	1,380.270
LRP/B_0	0.12 (0.0002)	0.12 (0.0002)	0.12 (0.0002)	0.14 (0.0001)	0.120
USR/B_0	0.24 (0.0003)	0.24 (0.0004)	0.23 (0.0003)	0.28 (0.0003)	0.240
R_0	619.14 (42.12)	390.44 (15.12)	563.03 (41.58)	665.64 (46.87)	547.940
$P(B_{2021} > 0.4B_{\mathrm{MSY}})$	1	1	1	1	1.000
$P(B_{2021} > 0.8B_{\mathrm{MSY}})$	1	1	1	1	1.000
$P(B_{2021} > 0.2B_0)$	1	1	1	1	1.000
$P(B_{2021} > 0.4B_0)$	1	1	1	1	1.000
$P(F_{2021} < F_{\mathrm{MSY}})$	1	1	1	1	1.000

	0.4 B_{MSY}	0.8 B_{MSY}	0.2 B_0	0.4 B_0
(1) M = 0.056	>0.99	>0.99	>0.99	>0.99
(2) M = 0.046	>0.99	>0.99	>0.99	>0.99
(3) Low IRec	>0.99	>0.99	>0.99	>0.99
(A) Low steepness	>0.99	>0.99	>0.99	>0.99

Figure 19. Probability that the 2021 spawning biomass is above the LRP (0.4 B_{MSY}), USR (0.8 B_{MSY}), as well as 0.2 and 0.4 B_0 from the four operating models. Probabilities are calculated from 200 posterior samples.

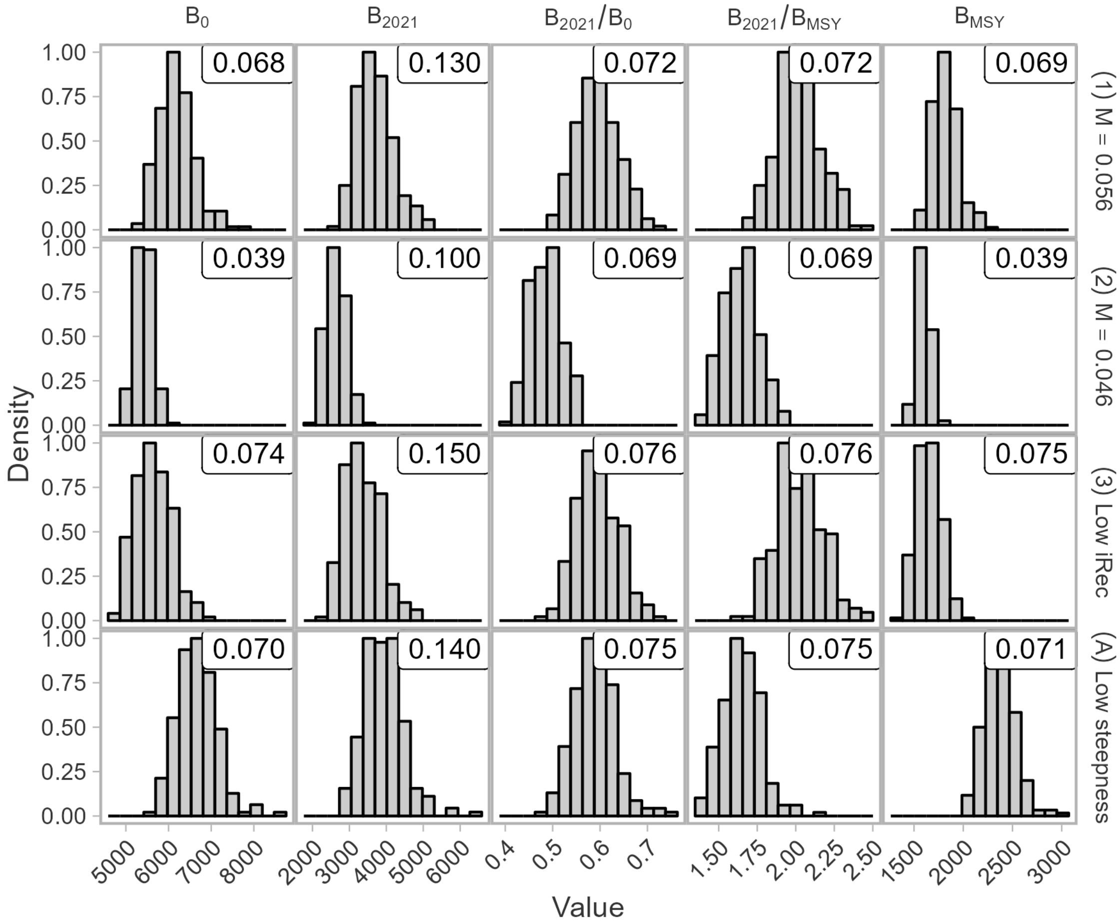

Figure 20. Posterior distribution of the spawning biomass in 2021 (B_{2021}*), along with* B_{MSY}*,* B_0*, and corresponding ratios for reference and robustness set OMs. Numbers in corresponding panels represent the coefficient of variation, the ratio of the standard deviation to the mean, and can be used to compare the precision of estimates.*

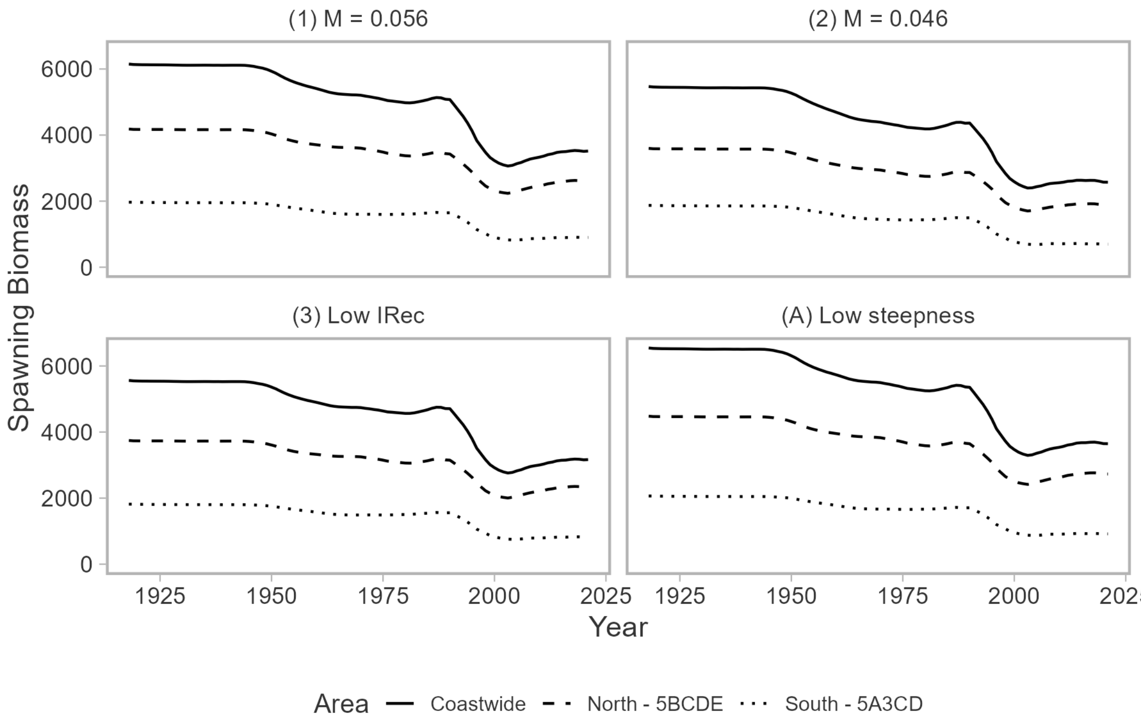

Figure 21. Historical spawning biomass estimates at the maximum posterior density (MPD) for reference and robustness set OMs, by area and coastwide.

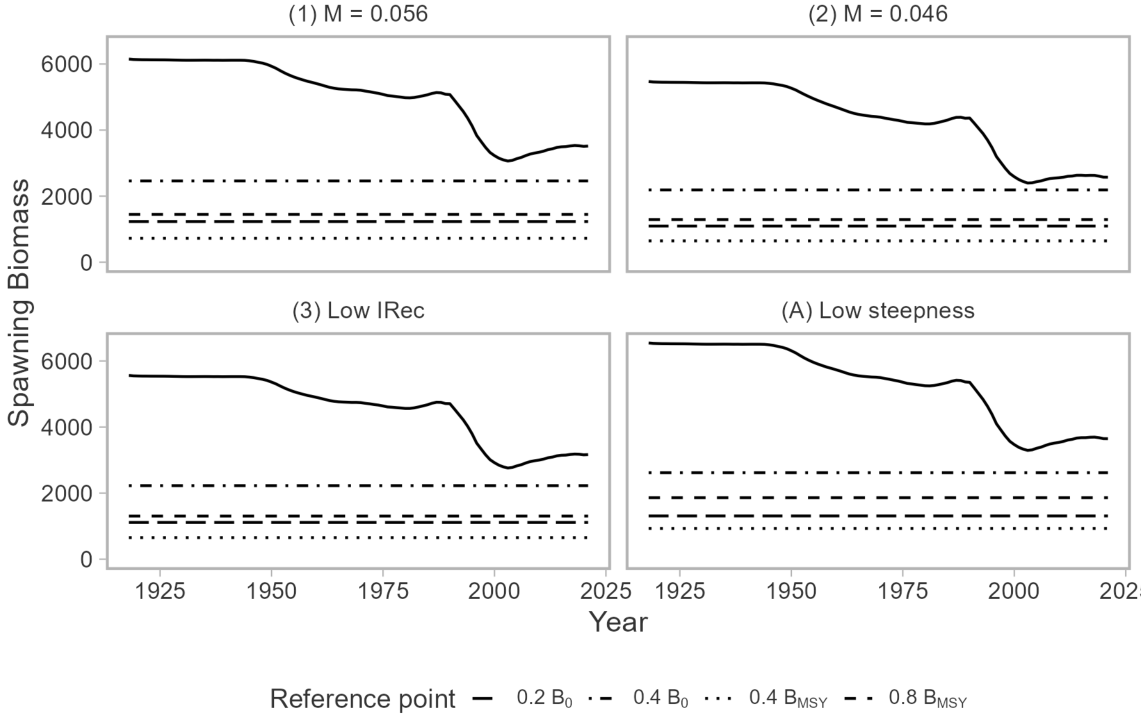

Figure 22. Historical estimates of coastwide spawning biomass at the maximum posterior density (MPD). Horizontal lines indicate the value of four biological reference points by line type.

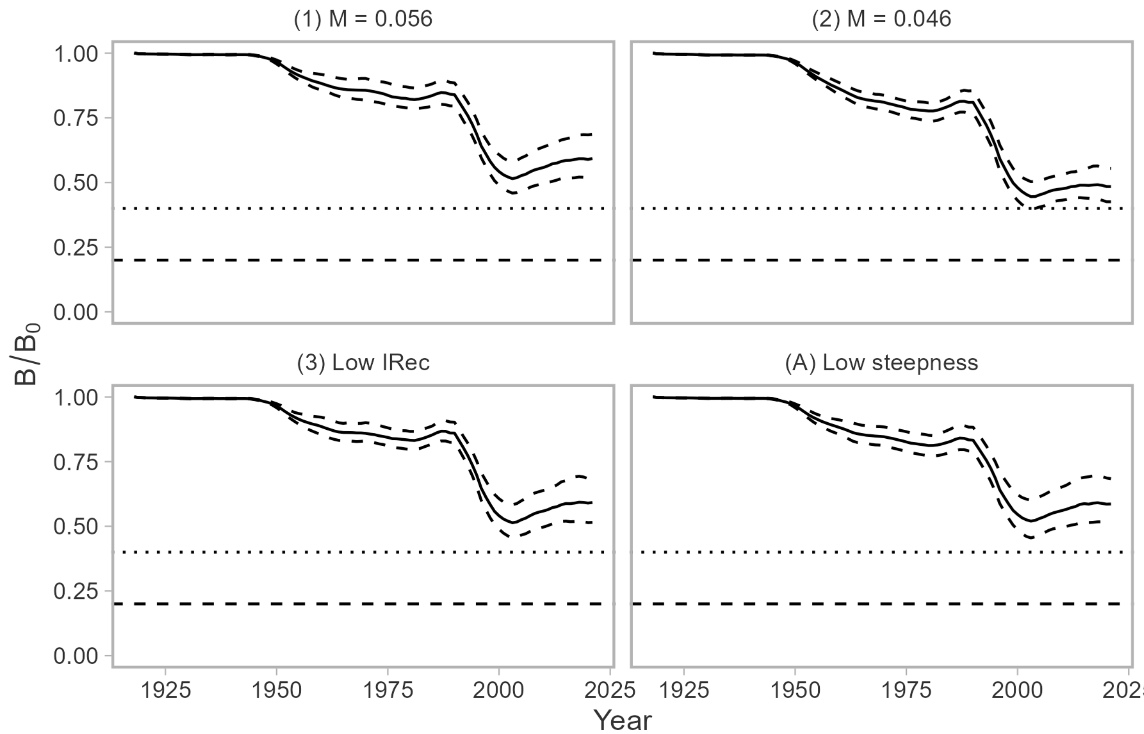

Figure 23. Spawning biomass (tonnes) relative to that at unfished conditions (B/B_0*) trajectories for reference and robustness set OMs. Solid lines represent medians from the posterior, and dotted lines span the 95% confidence interval across replicates. Dashed and dotted horizontal lines represent 0.2* B_0 *and 0.4* B_0*, respectively.*

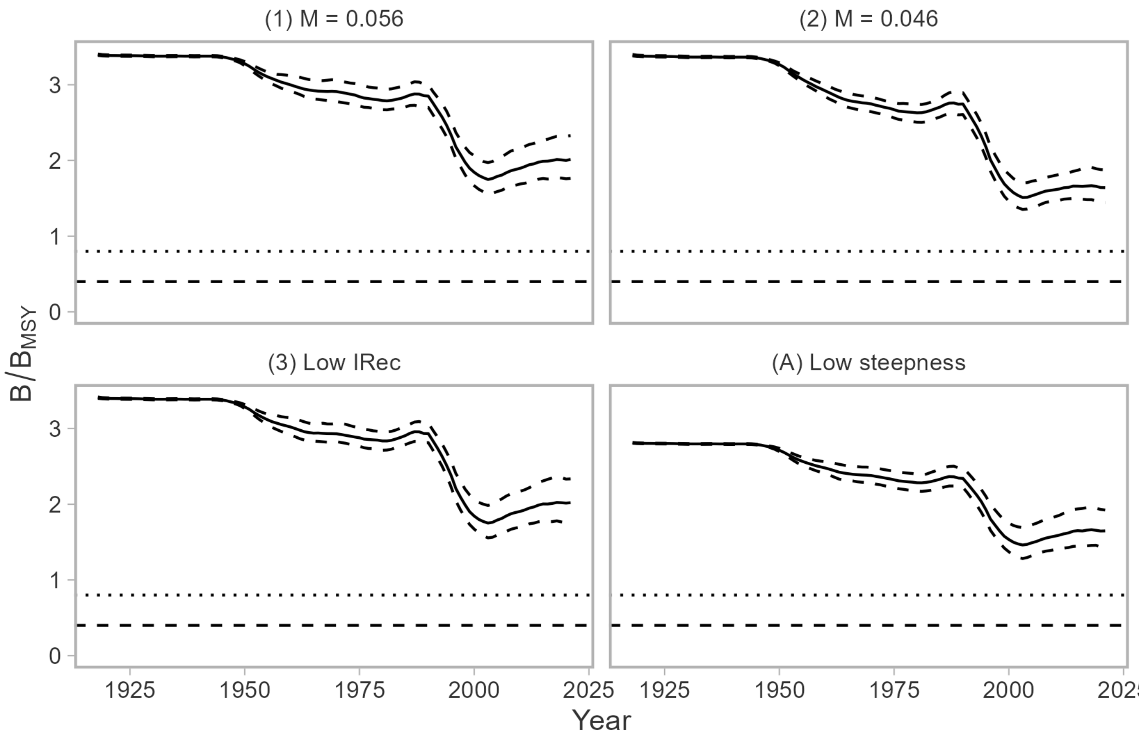

Figure 24. Spawning biomass relative to that at MSY (B/B_{MSY}*) trajectories for reference and robustness set OMs. Solid lines represent medians, and dark and light grey shading represent 50% and 95% quantiles across replicates, respectively. Dashed and dotted horizontal lines represent the LRP (0.4* B_{MSY}*) and USR (0.8* B_{MSY}*), respectively.*

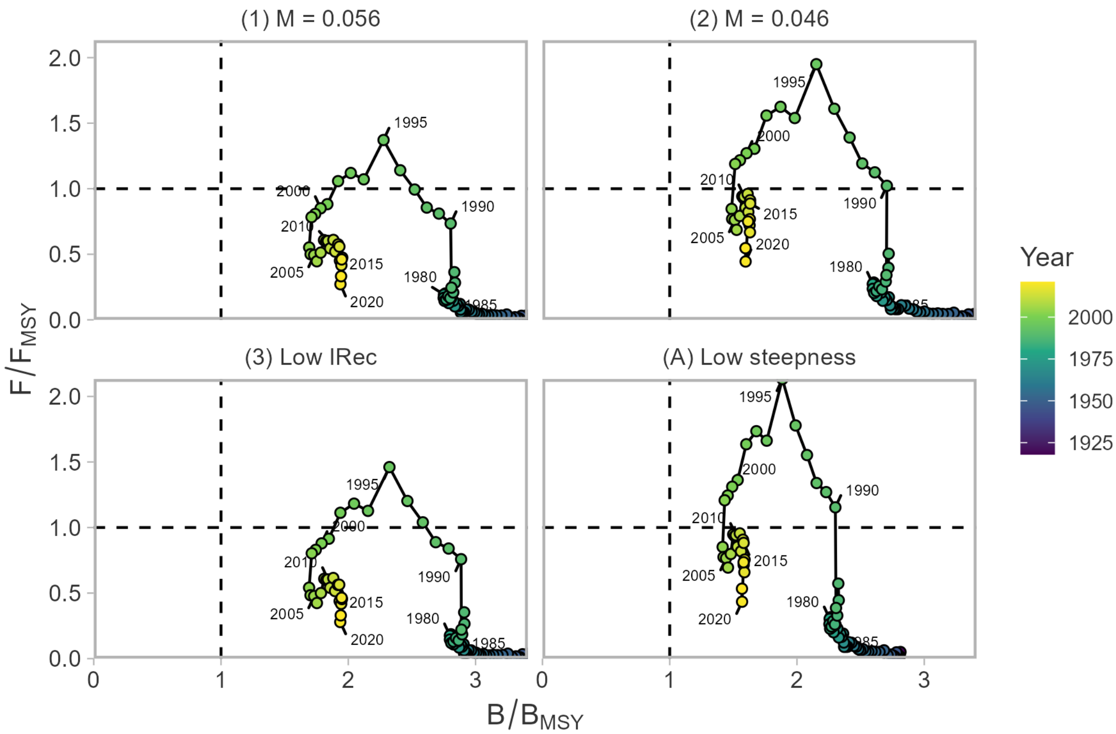

Figure 25. Kobe phase plot showing the historical stock trajectory in terms of B/B$_{MSY}$ *and* F/F$_{MSY}$*) for the reference and robustness set OMs at the maximum posterior density (MPD). Years are indicated by color.*

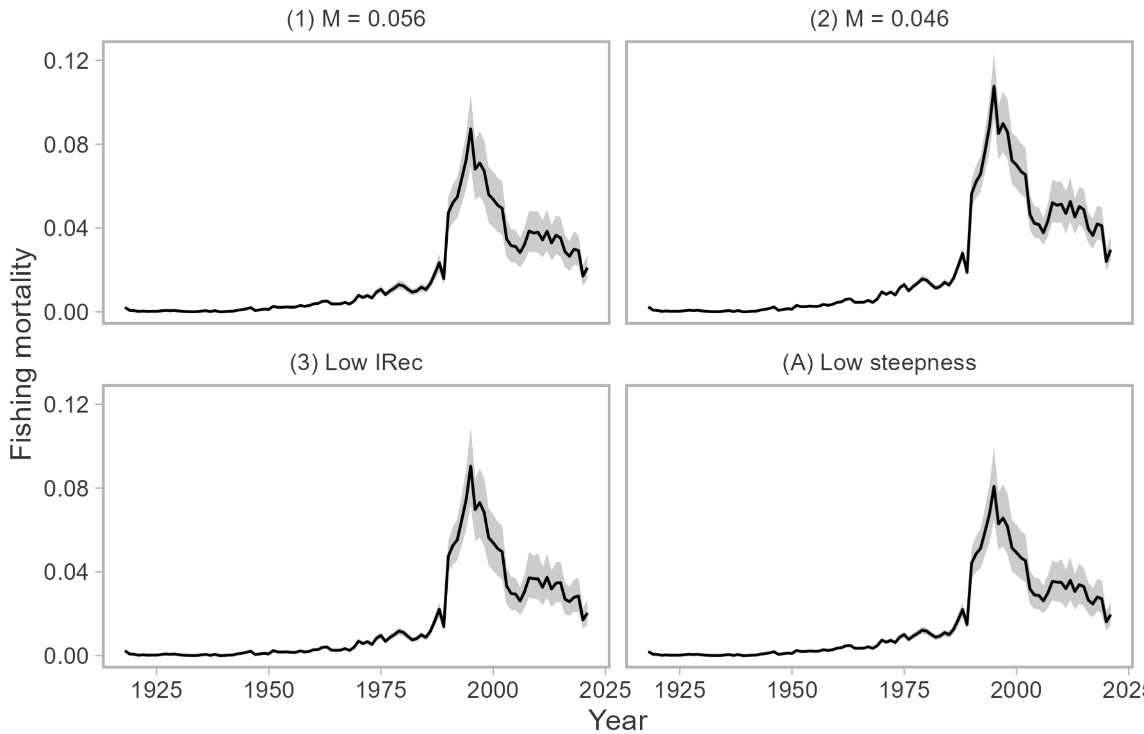

Figure 26. Historical fishing mortality time series for reference and robustness set OMs. Solid lines represent medians from the posterior, and dotted lines span the 95% confidence interval across replicates.

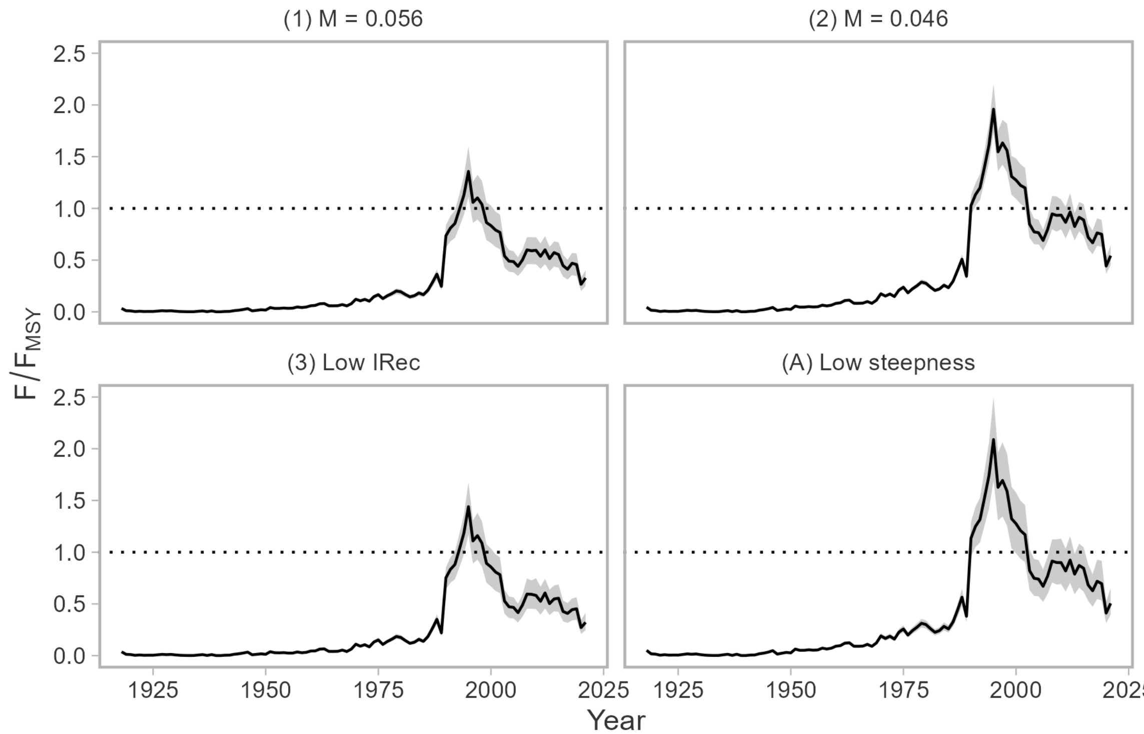

Figure 27. Historical F/F_{MSY} *time series for reference and robustness set OMs. Solid lines represent medians from the posterior, and dotted lines span the 95% confidence interval across replicates.*

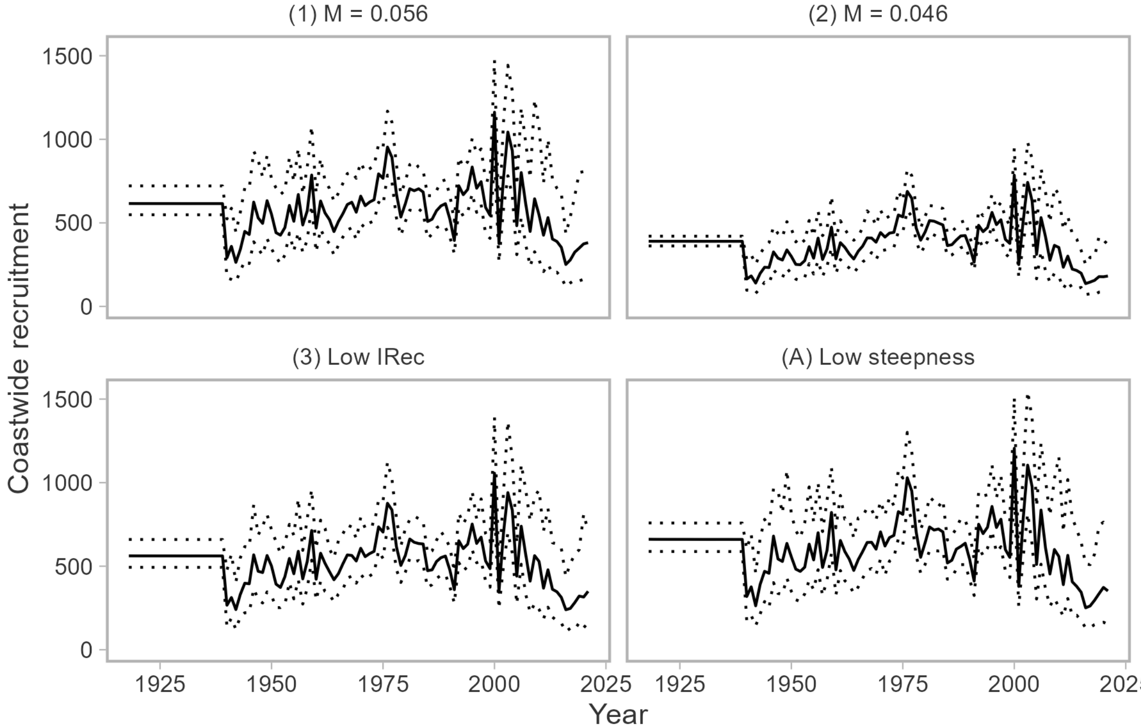

Figure 28. Historical coastwide recruitment (in units of thousands of fish) time series for reference and robustness set OMs. Solid lines represent medians from the posterior, and dotted lines span the 95% confidence interval across replicates.

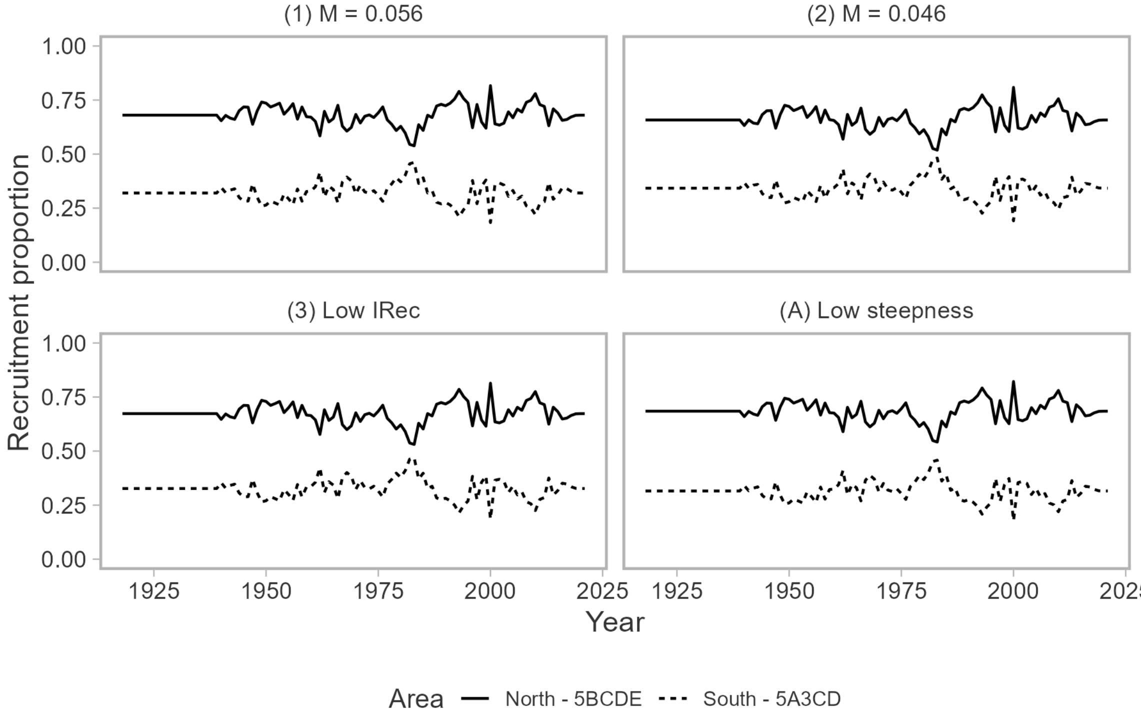

Figure 29. Estimated proportion of coastwide recruitment (from the maximum posterior density) assigned to the North and South regions in the reference and robustness set OMs.

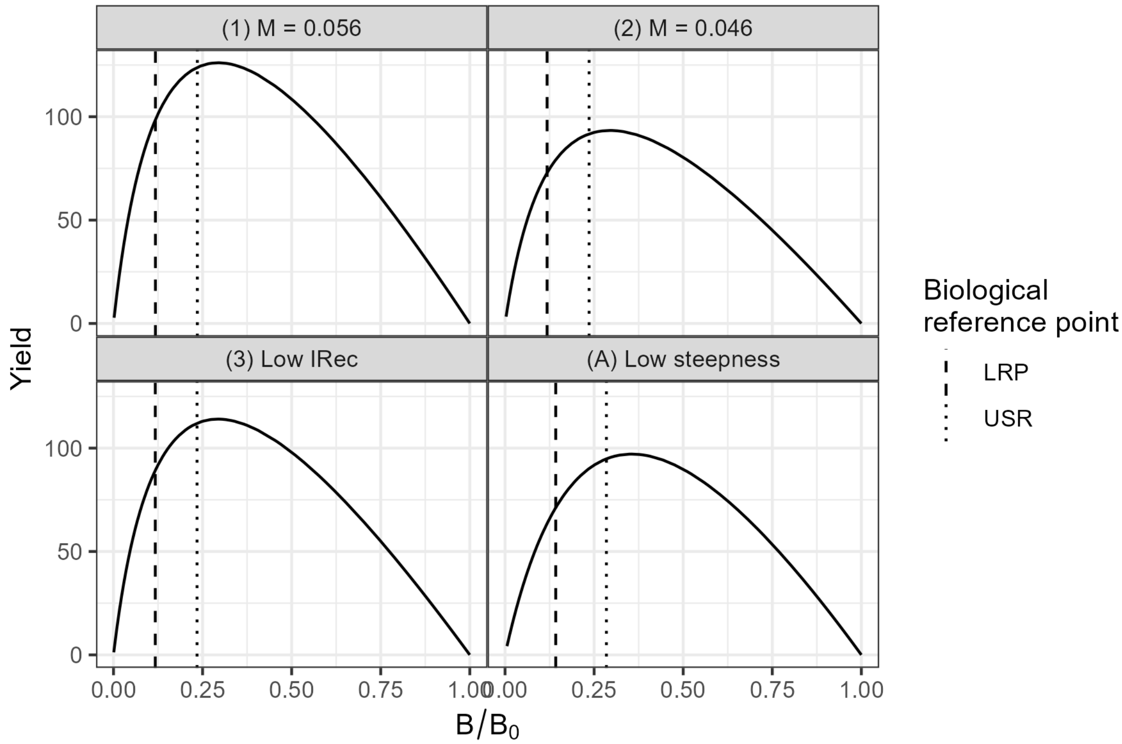

Figure 30. Yield curve as a function of depletion (B/B_0) *in the operating models, estimated at the maximum posterior density (MPD). Dashed and dotted vertical lines represent the value of 0.4* B_{MSY} *(LRP) and 0.8* B_{MSY} *(USR), respectively.*

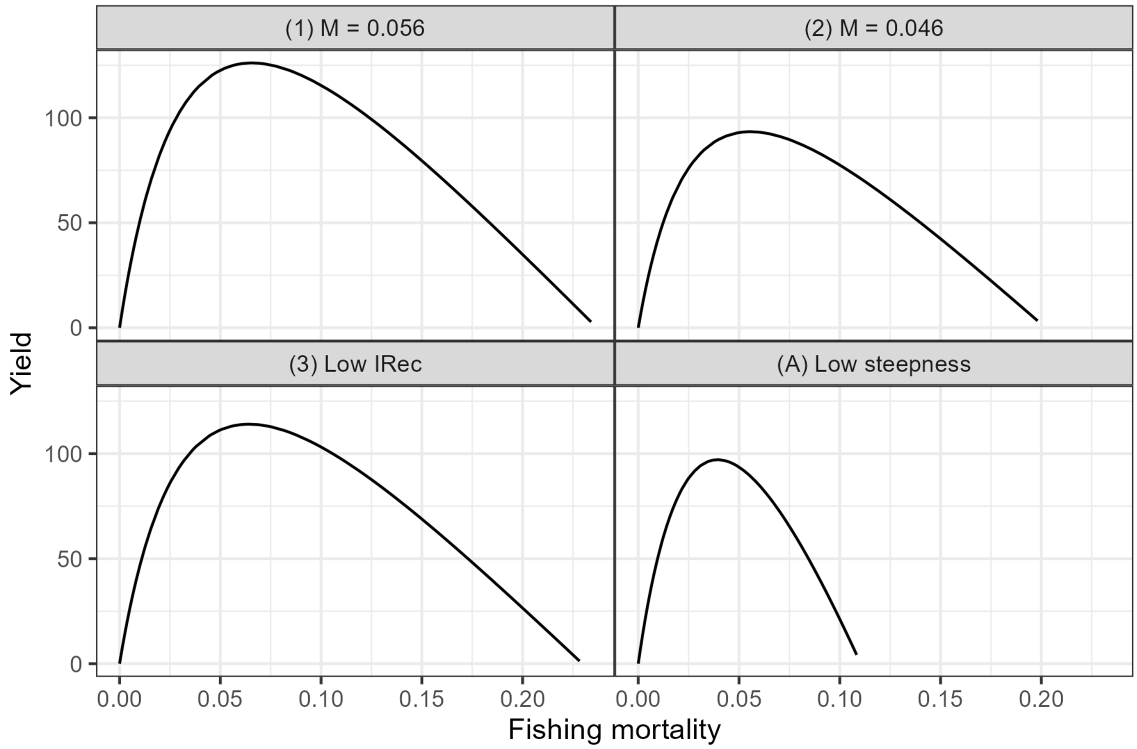

Figure 31. Yield curve as a function of fishing mortality in the operating models, estimated at the maximum posterior density (MPD).

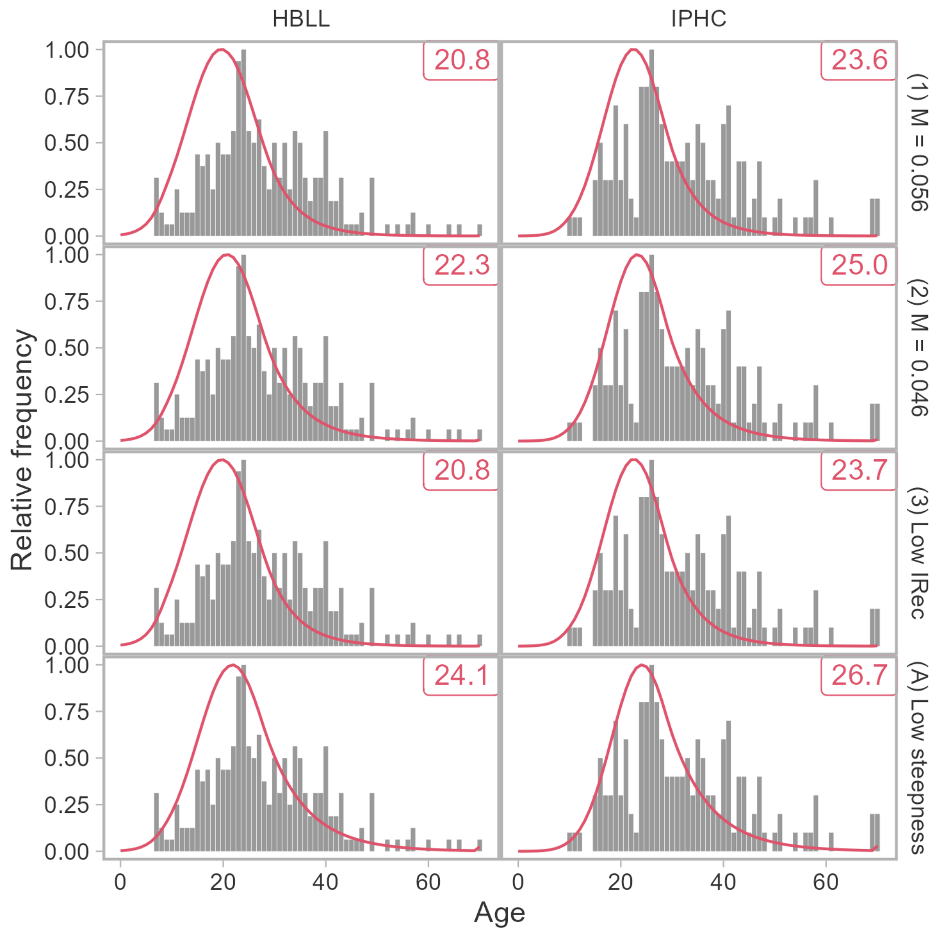

Figure 32. Age structure in the HBLL and IPHC surveys relative to the LRP. Bars represent observed proportions in 2020 and 2019 for the HBLL and IPHC surveys, respectively, across all areas. The red line is the predicted equilibrium age distribution at the LRP, with red numbers in the corner of each panel reporting the corresponding mean age. The observed mean age of the age composition is 28.3 and 32.2 years from the HBLL and IPHC surveys, respectively. This figure is intended to serve as a rule of thumb for complementary perspectives on status inference with respect to the LRP, which is based on biomass.

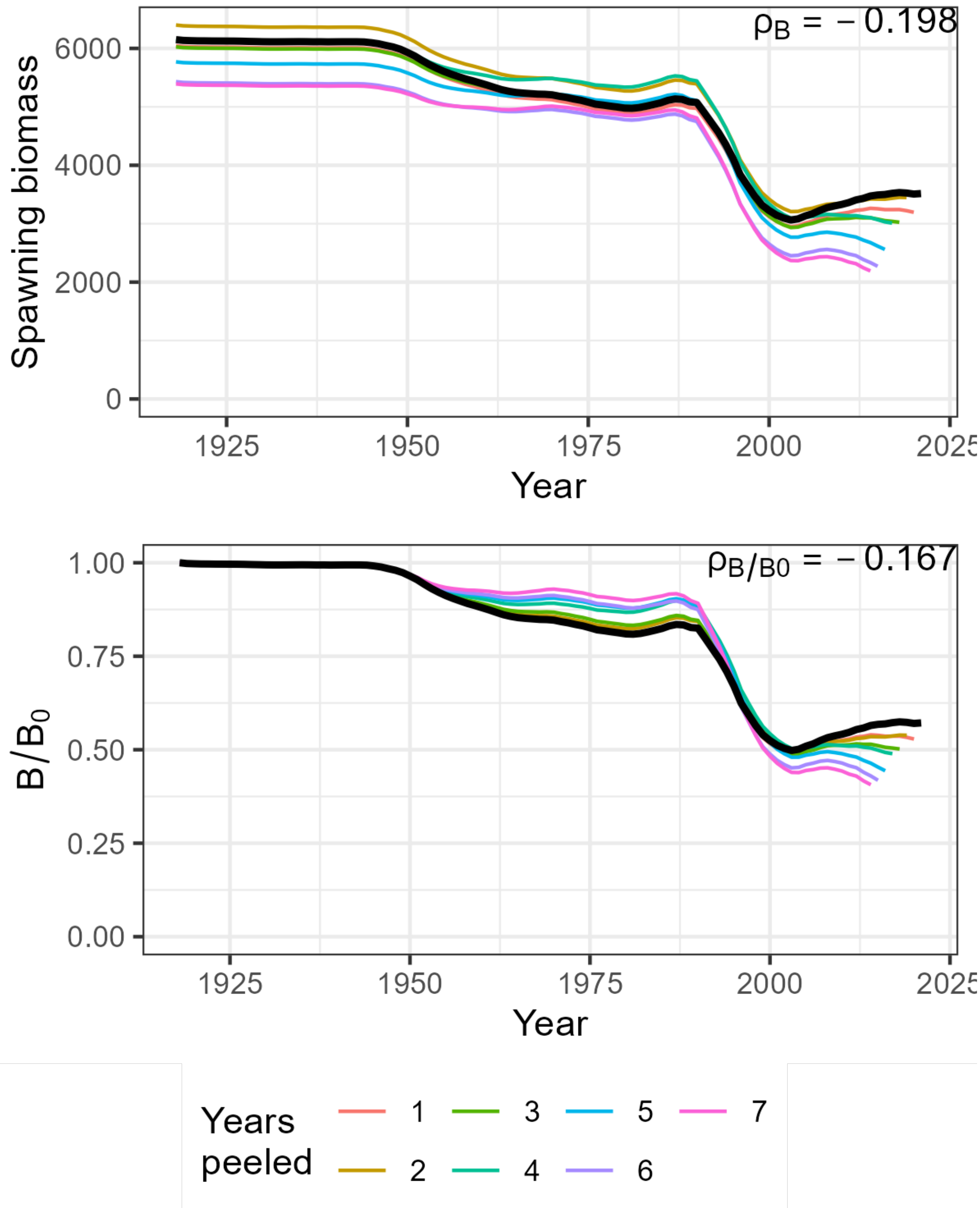

Figure 33. Retrospective analysis for biomass and depletion of the SS3 model for OM 1 with up to 7 years of recent data removed (colour lines). The black line is the original model with data to 2021. The Mohn's rho summary statistic is reported in the upper right corner of each panel.

4.3.1.3. Estimation of the limit reference point

Recent guidelines direct use of 0.4 B_{MSY} as the limit reference point (LRP) if technically feasible (DFO 2023). Use of 0.4 B_{MSY} as the LRP implicitly uses impaired surplus production as the metric for serious harm in DFO fisheries policy. Impaired surplus production is quantified by the yield curve, the average long-term catch that would keep the stock levels constant at a given size. The height and skew of the yield curve is determined by a combination of biological parameters, including growth, maturity, natural mortality, and stock-recruit steepness, along with fishery selectivity.

Technical considerations for the LRP include reliability and plausibility of the estimate, as well as the uncertainty around the estimate. Uncertainty in the estimation of the LRP is explored among the set of the operating models presented here, some of which demonstrate the marginal effects of individual parameters on the LRP.

As natural mortality M increases, the yield curve optimum increases although the skew did not appear to change for Outside Quillback Rockfish (see operating models 1 and 2 in 30). The two natural mortality values (M = 0.056, 0.046) used in the reference set appear to be plausible range based on the longevity of the species (maximum observed age of 95 years), and would be supported by total mortality estimates from the catch curves, which excludes higher values of M (Appendix G).

Quillback Rockfish appear to reach its average asymptotic size relatively early in its lifespan, which can be classified as a low M/K life history, where K is the von Bertalanffy growth coefficient (Prince et al. 2015). Growth (along with maturity) appear to be well-informed by the available biological samples (Appendix A). With the estimate of K = 0.11, the M/K ratio is 0.51 and 0.42 in operating models 1 and 2, respectively, values on the lower end of the spectrum of fish taxa based on the meta-analysis of Prince et al. (2015).

As steepness increases, recruitment is hypothesized to be more resilient at low stock sizes, and the yield curve optimum moves up and left. Thus, maximum sustainable yield increases and B_{MSY}/B_0 decreases. Several factors can make it difficult to estimate steepness in age-structured models (Walters and Ludwig 1981; Walters and Martell 2004). For example, the stock has not been estimated to have been low in the past (Figure 34). Thus, there is no historical inference on how productive recruitment would be at low stock sizes. Even then, there is also high variability between the historical annual recruitment estimates and the mean relationship between recruitment and spawning biomass, which increases the uncertainty around the steepness estimate.

Two steepness values are presented in the set of operating models. The reference set used a moderate value of 0.67, obtained from meta-analysis of Pacific rockfish species, while a robustness scenario evaluates management procedures with lower steepness of 0.50. Higher values of steepness were not considered because the resulting status were deemed to be overly optimistic with perceived historical trends in Quillback Rockfish abundance.

With regard to fishery selectivity, as the fishery selects younger ages, the height of the yield curve can be expected to move down and left, i.e., maximum surplus production is lower and occurs at a lower B_{MSY}/B_0 ratio (Maunder 2002). Available biological samples from the fishery indicate that small fish are targeted in the hook and line fishery (Appendix C; Haggarty et al. (2022)). Thus, it appears that the current yield curve which shows B_{MSY}/B_0 ratio between 0.30–0.35 would be appropriate for describing Outside Quillback Rockfish.

Average unfished biomass B_0 may also be considered for the LRP metric, ostensibly as a proxy for B_{MSY}. The yield curve would not be suitable to inform precautionary management when it does not show an optimum. For example, when fishery selectivity is much greater than the maturity curve, the yield curve implies that the stock can be fished without limit in the long-term without depleting the stock because a sufficient proportion of the spawning biomass is not vulnerable to the fishery. The value of the LRP (using B_0) would be based on the depletion value that corresponds to B_{MSY}, i.e, the B_{MSY}/B_0 ratio, in a "typical" yield curve (DFO 2023). Such ill-defined yield curves were not seen in the operating models for Outside Quillback Rockfish.

Within operating models, precision in the estimates of B_{MSY} and B_0, along with the corresponding ratio in 2021, can be compared using the posterior standard deviation, conditional on the model structure and parameterization (e.g., fixed versus estimated parameters; Figure 20). The parameters used to calculate B_0 are identical to those needed to calculate B_{MSY}, but fishery selectivity is only need for the latter. There did not appear to be higher precision of either metric in individual operating models.

Overall, these factors do not exclude consideration of the policy guidance for 40% B_{MSY} as the limit reference point. The MP Framework provides the opportunity to explore and evaluate the implications of the parameters that contribute to estimation of the LRP.

Potential loss of stock structure, from depletion or loss of population subunits, is another consideration for serious harm discussed in DFO (2023). No information is available to inform delineation of Outside Quillback Rockfish to smaller population subunits that are responsible for their own recruitment. Thus, it is believed that recruitment to any particular geographical subunit is contributed from spawning across the entire Outside unit.

However, juvenile and adult rockfish abundance is patchy and Quillback Rockfish do aggregate over rocky habitat. The current operating model is not able to inform spatial abundance on a finer scale than in the two areas used here. For relatively sedentary, inshore rockfish species, serial depletion can occur without effective spatial fishery management. Currently, it is not clear how the susceptibility of Quillback Rockfish to serial depletion contributes to defining a limit reference point. On the other hand, there are fishery and cultural implications that inform spatial management, and potentially in a target reference point (DFO 2009) because serial depletion can create loss of local fishing opportunities for communities.

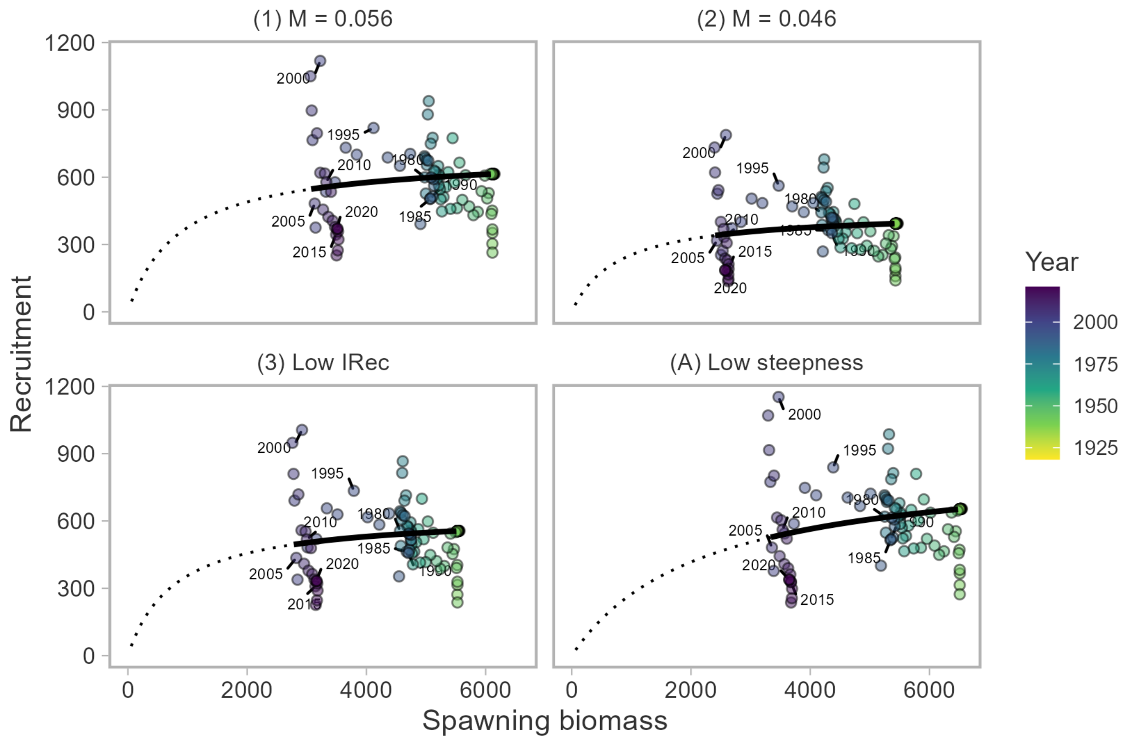

Figure 34. The stock-recruit relationship from the reference and robustness OMs. Points indicate estimates of historical spawning biomass and the resulting coastwide recruitment from the maximum posterior density (MPD), with colours denoting years. The curves indicate the mean predicted recruitment from the Beverton-Holt stock recruitment relationship. The solid curve denotes the range of historical stock sizes estimated in the model, while the dotted curve denotes extrapolation of the mean relationship at lower stock sizes. The steepness parameter is 0.67 in the reference operating models (denoted by numbers) and is 0.50 in operating model (A).

5. CANDIDATE MANAGEMENT PROCEDURES

Anderson et al. (2021) screened management procedures (MPs) available in DLMtool as of November 2019. A library of all MPs considered in the MP Framework is provided in Appendix D of Anderson et al. (2021).

The MP Framework currently only considers MPs that make catch recommendations, because most groundfish stocks are managed by quotas and commercial Total Allowable Catches (TACs). The catch recommendation specified in the management procedures would be inclusive of commercial, recreational, and Food, Social, and Ceremonial (FSC) catches. For comparison, the current commercial fishery TAC for Outside Quillback Rockfish is 4 tonnes (t) coastwide for the trawl sector, while for all other sectors, the TAC is 46 t for 5A3CD and 79 t for 5BCDE (DFO 2022a). In contrast, the recreational fishery is managed with a retention limit and seasonal closures (Table C.13).

Management procedures evaluated for Outside Quillback Rockfish are detailed in Appendix E. All management procedures specify the catch advice for each of the two areas in the operating model.

We evaluated two main types of MPs: constant catch and index-based MPs. We also evaluated two reference MPs.

5.1. CONSTANT CATCH MANAGEMENT PROCEDURES

Constant-catch MPs set the recommended catch to some fixed level, typically based on recent or historical catches. Constant-catch MPs do not incorporate feedback between the management system and the population—they make the same catch recommendation regardless of trends in the population index.

- RecentCatch: Constant annual catch of 81.6 tonnes in the North (5BCDE), 44 tonnes in the South (5A3CD).
- 125RecentCatch: Constant annual catch at 125 percent of the RecentCatch MP, i.e., 102 and 55 tonnes for the North and South, respectively.
- 75RecentCatch: Constant annual catch at 75 percent of the RecentCatch MP, i.e., 61.2 and 33 tonnes for the North and South, respectively.

The values for the RecentCatch MP is the average catch during 2012–2019 and is intended to reflect status quo conditions.

5.2. INDEX-BASED MANAGEMENT PROCEDURES

Index-based MPs, in general, adjust the catch based on changes in a population index over time.

Two broad families of index-based MPs, ratio and slope MPs, were considered. They differ in how the change in the index is calculated. Index-ratio MPs increase or decrease the catch in accordance with the ratio of the index from two different time periods. Index-slope MPs increase or decrease the catch in accordance with the estimated slope in the index over a recent period of time.

A third type, index-target MPs, adjusts the catch based on the ratio of the recent index and a fixed target index value, based on some pre-agreed historical period. We did not consider an index-target MP here, as further guidance would be needed in order to select the appropriate target value.

Within each family, various tuning parameters can be adjusted to alter (1) how the trend in the index is calculated, and/or (2) how the catch advice is calculated based on (1). For example, the change in catch advice can be some percentage of the change in the index, either with or without a maximum allowable percent change. Management procedures can be tuned such that the catch recommendation can be moderately or highly responsive to changes in the index.

We evaluated index-based MPs with biennial updates with fixed catch between updates, i.e., the most recent catch recommendation. The two-year update cycle is the minimum time period needed to process survey data to update the HBLL index.

We included the following index-based MPs: Iratio, GB_slope, and IDX, all with a variety of configurations (Appendix E).

5.3. REFERENCE MANAGEMENT PROCEDURES

In addition to the empirical candidate MPs, we included the following reference MPs:

1. No fishing ("NoFishing")
2. Fishing at F_{MSY} ("FMSYref")

The purpose of reference MPs is not to explore viable management strategies but to bound the range of possible performance and determine if differences among MPs are meaningful (Punt et al. 2016). For example, the "NoFishing" reference MP provides information on maximum possible stock levels and the rate of population growth in the absence of fishing.

On the other hand, "FMSYref" is a management procedure that perfectly implements fishing at the reference removal rate. However, it cannot be implemented in practice because it requires perfect information about the true state of nature. "FMSYref" implements different levels of fishing mortality for each operating model and simulation, and thus there is no single catch level that can be recommended for implementation at any given time. This management procedure is mainly used to compare management procedures within a single operating model.

Together, the two reference management procedures bound the expected performance from fishing at zero levels to the maximum allowable level.

Table 5. Names and types of candidate management procedures evaluated for Outside Quillback Rockfish.

Management procedure	Type
NoFishing	Reference
FMSYref	Reference
RecentCatch	Constant catch
125RecentCatch	Constant catch
75RecentCatch	Constant catch
GB_slope_10y_lam05	Index slope
GB_slope_10y_lam1	Index slope
GB_slope_5y_lam05	Index slope
GB_slope_5y_lam1	Index slope
IDX	Index ratio
IDX_smooth	Index ratio
Iratio_23	Index ratio
Iratio_55	Index ratio

6. APPLICATION OF MANAGEMENT PROCEDURES

We ran the closed-loop simulations across 200 stochastic replicates. The length of the projection period was set at 54 years (2 generations for Outside Quillback Rockfish). The compendium of timeseries trajectories of biomass, catch, and fishing mortality during the projections for all management procedures are presented in Appendix F.

Anderson et al. (2021) recommended filtering MPs with a “satisficing” step, where trial simulations are run to screen out MPs that do not meet a basic set of performance criteria (Miller and Shelton 2010; see Anderson et al. 2021). Following the guidelines on the implementation of the Fish Stocks Provisions, the following criteria were used to determine which MPs are satisficed: **LRP 2GT** > 0.75, **USR 2GT** > 0.50, and **FMSY 2GT** > 0.50.

Almost all management procedures met the satisficing criteria, except for the 125RecentCatch management procedure in all operating models (Figures 35 and 36). This static MP frequently fished the stock above F_{MSY} as the projection progressed forward in time (noting the low **FMSY 2GT** value). The stock subsequently declined by the end of the projection, as indicated by the low **B/B0 2GT** and **B/BMSY 2GT** values. The LRP and USR probabilities, averaged across all years, were high for most management procedures because of the status of the stock at the beginning of the projection.

While the RecentCatch MP met the satisficing criteria when averaged across the reference set (Figure 37), it did not perform well in the operating models with low productivity: OM (2) with low natural mortality and OM (A) with low steepness (Figures 35 and 36). These results illustrate the disadvantage of static management procedures in the long-term which are not responsive to changes in abundance. Static MPs frequently require lower catches, e.g., the 75RecentCatch MP which set catches at 75% of the recent historical mean, for better long-term performance in relation to biological risk.

All index-based management procedures met the three satisficing criteria for the reference set. Projected catches in the short term (**C ST**) were lower relative to the recent historical mean as a result of the operating model conditioning. Index-based MPs appear to produce lower short-term catch than the RecentCatch MP because the former adjusts catch from 2021 levels, which are lower than 2012-2019 average. The least reduction in the short term was seen in the Iratio_55 management procedure, but is accompanied with the highest variability in catch over time (panel d of Figure 40; Appendix Figures F.10 and F.11).

The performance of the candidate, satisficed management procedures, i.e., excluding the FMSYref reference MP and 125RecentCatch static MP, is presented in Figure 38.

Time series of projected catch and biomass are presented in Figures 41 – 43. Kobe plots for the projected B/B_{MSY} and F/F_{MSY} values (Figures F.8 and F.9), along with annual probabilities that the stock is above the LRP and USR in the simulation (Figures F.4 and F.5), inform stock trajectories during the projection period. These trajectories may provide additional insight which may be not easily summarized in individual performance metrics and are presented in Appendix F.

For all management procedures except the NoFishing MP, the stock declined in the first decade of the projection but remained above the USR (Figure 39). In subsequent decades, the stock is less likely to increase or remain above the USR with the RecentCatch and 125RecentCatch MPs. Among the index-based MPs, increasing biomass is more likely with Iratio and IDX MPs compared to the GB_slope MPs after the first decade. For all MPs, there is lower probability of biomass increase in the low recruitment operating model compared to the other four OMs.

6.1. TRADEOFFS

Among the set of satisficed MPs, there is no apparent tradeoff between risk probability with respect to the LRP and USR and long-term catches (panels a-b of Figure 40). The MPs varied in the levels of long term catch, but all maintained a high to very high LRP and USR probability during the projections. From these panels, the best MPs are those that achieved the highest long-term catch (pending other tradeoffs in catch variability, short-term catch, and long-term biomass). The RecentCatch MP (No. 2 in Figure 40) was not "efficient" because lower catch and lower risk probability were obtained relative to other MPs, i.e., the GB_slope MPs are superior in terms of both catch and risk probability (No. 4-7 in Figure 40).

The tradeoff between long-term catches occurs ultimately with relative biomass levels after two generations, in terms of either B/B_{MSY} or B/B_0 (panels e-f of Figure 40). Broadly speaking, higher catches were achieved with a lower biomass among the set of MPs, and vice versa. Again, RecentCatch MP was not "efficient" because higher catches and higher biomass were achieved with the GB_slope family of MPs during the projections. With respect to long-term catch and long-term biomass, GB_slope MPs are preferable over the RecentCatch MP.

The trade-off frontier with regards to short-term and long-term catch, i.e., after 2 generations, appears to be a choice between higher short-term catch in the RecentCatch and Iratio_55 MPs (right of the dotted one-to-one line) or higher long-term catch with the GB_slope family of MPs (left of the dotted one-to-one line, panel c of Figure 40). MPs that produced higher short-term catch tended to also produce higher long-term catch. Among the index-based MPs, catch variability over time was higher in the Iratio and IDX family of MPs compared to the GB_slope and IDX_smooth MPs (panel d of Figure 40). With respect to short-term catch, all index-based MPs appeared to produce relatively similar short-term catch, with the exception of higher short-term catch with Iratio_55.

6.2. SIMULATED INDEX

The range in the simulated HBLL index, based on the projected abundance, the estimated selectivity, and expected sampling error, is reported in Figure 44. Otherwise, the index-based management procedures mostly keep the HBLL index to values within range of historical values. Most index-based management procedures lead to a stable index by the end of the projection (Figure 44). The notable exceptions were in operating model (B) with the lower future recruitment, where the projected index is continually declined over two generations in almost all management procedures, and in most operating models with the RecentCatch and 125RecentCatch MPs.

After two generations, the mean age predicted from the survey is positively correlated to biomass level (Figure 38). However, the range in mean age values are fairly narrow (between 28-30 years for most candidate management procedures).

Static management procedures with high constant catch levels, i.e., RecentCatch and 125RecentCatch, are characterized by a continually decreasing index. This trend is in contrast to the FMSYref management procedure, where perfect information about the system dynamics allows the management procedure to reduce catch and keep the index constant as the stock approaches B_{MSY}. While index-based management procedures can be tuned for good performance relative to the operating models at hand, they do not have additional information about the stock dynamics besides the simulated index. The discrepancy between performance of the candidate management procedures and the reference MP show the cost of not having this perfect information.

(1) M = 0.056

	LRP 2GT	USR 2GT	FMSY 2GT	C ST	C 2GT	IAV 2GT	B/B0 2GT	B/BMSY 2GT	MA 2GT
75RecentCatch	1.00	1.00	1.00	94.20	94.20	0.00	0.54	1.84	29.38
IDX_smooth	1.00	1.00	1.00	80.46	82.70	0.03	0.60	2.04	30.16
NoFishing	1.00	1.00	1.00	0.00	0.00	0.02	0.91	3.13	33.67
Iratio_23	1.00	1.00	1.00	81.47	113.66	0.08	0.52	1.79	29.63
GB_slope_5y_lam1	1.00	1.00	1.00	83.49	125.84	0.03	0.48	1.66	29.12
IDX	1.00	1.00	1.00	81.24	80.84	0.07	0.61	2.06	30.26
GB_slope_10y_lam1	1.00	1.00	0.99	89.50	134.51	0.02	0.44	1.54	28.63
GB_slope_5y_lam05	1.00	1.00	0.99	83.62	135.51	0.02	0.46	1.57	28.80
Iratio_55	1.00	1.00	0.98	122.28	111.96	0.12	0.48	1.63	28.94
GB_slope_10y_lam05	1.00	1.00	0.98	86.60	140.94	0.02	0.43	1.50	28.51
FMSYref *	1.00	0.99	0.54	207.28	124.98	0.04	0.30	1.02	25.46
RecentCatch	1.00	0.99	0.94	125.60	125.60	0.00	0.39	1.31	27.30
125RecentCatch	0.95	0.80	0.48	157.00	143.20	0.00	0.20	0.67	23.72

(2) M = 0.046

	LRP 2GT	USR 2GT	FMSY 2GT	C ST	C 2GT	IAV 2GT	B/B0 2GT	B/BMSY 2GT	MA 2GT
75RecentCatch	1.00	0.93	0.78	94.20	94.09	0.00	0.32	1.07	27.79
IDX_smooth	1.00	1.00	0.98	80.56	79.96	0.04	0.42	1.46	29.70
NoFishing	1.00	1.00	1.00	0.00	0.00	0.02	0.86	2.93	35.18
Iratio_23	1.00	1.00	0.97	80.23	95.35	0.09	0.40	1.34	29.57
GB_slope_5y_lam1	1.00	0.98	0.83	83.15	107.77	0.03	0.33	1.11	28.36
IDX	1.00	1.00	0.97	81.02	76.02	0.07	0.44	1.52	30.09
GB_slope_10y_lam1	1.00	0.95	0.65	89.47	112.59	0.02	0.28	0.97	27.53
GB_slope_5y_lam05	1.00	0.94	0.63	83.58	119.18	0.02	0.27	0.93	27.38
Iratio_55	1.00	0.99	0.80	120.14	90.97	0.14	0.36	1.23	29.06
GB_slope_10y_lam05	0.99	0.90	0.54	86.73	122.84	0.02	0.24	0.83	26.72
FMSYref *	1.00	0.98	0.45	129.24	90.24	0.03	0.29	1.00	27.19
RecentCatch	0.79	0.49	0.11	125.60	78.18	0.03	0.04	0.23	17.68
125RecentCatch	0.47	0.27	0.01	157.00	5.55	0.17	0.00	0.01	7.81

(3) Low IRec

	LRP 2GT	USR 2GT	FMSY 2GT	C ST	C 2GT	IAV 2GT	B/B0 2GT	B/BMSY 2GT	MA 2GT
75RecentCatch	1.00	1.00	1.00	94.20	94.20	0.00	0.49	1.69	28.73
IDX_smooth	1.00	1.00	1.00	71.35	72.75	0.03	0.61	2.08	30.21
NoFishing	1.00	1.00	1.00	0.00	0.00	0.02	0.92	3.15	33.54
Iratio_23	1.00	1.00	1.00	72.39	103.45	0.08	0.52	1.79	29.61
GB_slope_5y_lam1	1.00	1.00	1.00	74.40	114.81	0.03	0.49	1.67	29.13
IDX	1.00	1.00	1.00	71.59	70.67	0.07	0.61	2.10	30.34
GB_slope_10y_lam1	1.00	1.00	0.99	79.88	123.03	0.02	0.45	1.55	28.65
GB_slope_5y_lam05	1.00	1.00	0.99	74.62	123.57	0.02	0.46	1.58	28.82
Iratio_55	1.00	1.00	0.98	108.41	102.22	0.12	0.47	1.63	28.95
GB_slope_10y_lam05	1.00	1.00	0.97	77.34	128.63	0.02	0.44	1.51	28.54
FMSYref *	1.00	0.99	0.51	187.47	114.03	0.04	0.30	1.02	25.48
RecentCatch	0.99	0.92	0.75	125.60	123.16	0.00	0.31	1.05	25.87
125RecentCatch	0.84	0.65	0.30	157.00	105.63	0.03	0.08	0.40	18.52

Figure 35. Performance measures of all MPs in individual reference set operating models. The colour shading uses the viridis palette and spans from zero (purple) to the highest value in each respective column (yellow). Italicized MPs with asterisks indicate reference MPs.

(A) Low steepness

	LRP 2GT	USR 2GT	FMSY 2GT	C ST	C 2GT	IAV 2GT	B/B0 2GT	B/BMSY 2GT	MA 2GT
NoFishing	1.00	1.00	1.00	0.00	0.00	0.02	0.87	2.46	33.23
IDX_smooth	1.00	1.00	1.00	80.46	79.51	0.03	0.54	1.50	30.00
IDX	1.00	1.00	0.99	80.98	74.97	0.07	0.54	1.54	30.17
Iratio_23	1.00	1.00	0.98	80.88	100.99	0.08	0.49	1.39	29.83
Iratio_55	1.00	1.00	0.86	121.50	97.41	0.11	0.45	1.29	29.41
*FMSYref **	1.00	1.00	0.39	142.61	100.98	0.03	0.37	1.04	28.03
GB_slope_5y_lam1	1.00	0.99	0.88	83.38	116.10	0.03	0.44	1.23	29.17
75RecentCatch	1.00	0.99	0.93	94.20	94.20	0.00	0.46	1.28	29.19
GB_slope_10y_lam1	1.00	0.98	0.77	89.55	123.85	0.02	0.39	1.12	28.70
GB_slope_5y_lam05	1.00	0.98	0.77	83.65	128.46	0.02	0.40	1.13	28.75
GB_slope_10y_lam05	1.00	0.97	0.70	86.71	133.61	0.02	0.37	1.06	28.45
RecentCatch	0.98	0.83	0.36	125.60	122.19	0.00	0.28	0.78	26.90
125RecentCatch	0.82	0.55	0.05	157.00	100.53	0.03	0.08	0.29	19.94

(B) Low Recruitment

	LRP 2GT	USR 2GT	FMSY 2GT	C ST	C 2GT	IAV 2GT	B/B0 2GT	B/BMSY 2GT	MA 2GT
NoFishing	1.00	1.00	1.00	0.00	0.00	0.01	0.64	2.20	35.17
IDX_smooth	1.00	1.00	1.00	80.46	72.13	0.03	0.35	1.19	30.44
IDX	1.00	0.99	1.00	81.23	63.04	0.07	0.38	1.27	30.84
Iratio_23	1.00	1.00	1.00	81.46	72.13	0.08	0.36	1.21	30.63
Iratio_55	1.00	1.00	0.99	122.27	64.10	0.11	0.36	1.23	30.45
*FMSYref **	1.00	0.57	0.54	207.20	77.78	0.05	0.19	0.64	26.15
GB_slope_5y_lam1	1.00	0.97	0.97	83.48	94.55	0.03	0.28	0.95	29.28
75RecentCatch	1.00	0.94	0.95	94.20	94.20	0.00	0.26	0.88	28.92
GB_slope_10y_lam1	1.00	0.92	0.91	89.50	99.28	0.02	0.24	0.83	28.50
GB_slope_5y_lam05	1.00	0.91	0.84	83.62	112.44	0.02	0.23	0.77	28.29
GB_slope_10y_lam05	0.99	0.88	0.78	86.60	116.60	0.02	0.20	0.69	27.69
RecentCatch	0.89	0.64	0.53	125.60	101.95	0.01	0.09	0.33	23.30
125RecentCatch	0.64	0.44	0.26	157.00	32.94	0.08	0.00	0.04	10.66

Figure 36. Performance measures of all MPs in individual robustness set operating models. The colour shading uses the viridis palette and spans from zero (purple) to the highest value in each respective column (yellow). Italicized MPs with asterisks indicate reference MPs.

Reference OMs

	LRP 2GT	USR 2GT	FMSY 2GT	C ST	C 2GT	IAV 2GT	B/B0 2GT	B/BMSY 2GT	MA 2GT
NoFishing	1.00	1.00	1.00	0.00	0.00	0.02	0.90	3.09	34.01
IDX_smooth	1.00	1.00	1.00	78.21	79.53	0.03	0.56	1.90	30.06
Iratio_23	1.00	1.00	0.99	78.89	106.53	0.08	0.49	1.68	29.61
IDX	1.00	1.00	0.99	78.77	77.09	0.07	0.57	1.94	30.24
Iratio_55	1.00	1.00	0.93	118.28	104.28	0.12	0.45	1.53	28.97
GB_slope_5y_lam1	1.00	1.00	0.96	81.13	118.56	0.03	0.45	1.53	28.93
FMSYref *	1.00	0.99	0.51	182.82	113.56	0.04	0.30	1.02	25.90
GB_slope_10y_lam1	1.00	0.99	0.91	87.09	126.16	0.02	0.41	1.40	28.36
GB_slope_5y_lam05	1.00	0.98	0.90	81.36	128.44	0.02	0.41	1.41	28.45
75RecentCatch	1.00	0.98	0.94	94.20	94.17	0.00	0.47	1.61	28.82
GB_slope_10y_lam05	1.00	0.97	0.87	84.32	133.34	0.02	0.39	1.33	28.07
RecentCatch	0.94	0.85	0.69	125.60	113.13	0.01	0.28	0.98	24.54
125RecentCatch	0.81	0.63	0.32	157.00	99.39	0.05	0.12	0.43	18.44

Figure 37. Average performance of all MPs across the OM reference set scenarios, with operating model 1 receiving twice the weight relative to the other two reference OMs. MPs are ordered by decreasing performance metric values from top to bottom starting with the left-most performance metric (LRP 2GT) and using columns from left to right to break any ties. The colour shading uses the viridis palette and spans from zero (purple) to the highest value in each respective column (yellow). Italicized MPs with asterisks indicate reference MPs.

Satisficed MPs

	LRP 2GT	USR 2GT	FMSY 2GT	C ST	C 2GT	IAV 2GT	B/B0 2GT	B/BMSY 2GT	MA 2GT
NoFishing	1.00	1.00	1.00	0.00	0.00	0.02	0.90	3.09	34.01
IDX_smooth	1.00	1.00	1.00	78.21	79.53	0.03	0.56	1.90	30.06
Iratio_23	1.00	1.00	0.99	78.89	106.53	0.08	0.49	1.68	29.61
IDX	1.00	1.00	0.99	78.77	77.09	0.07	0.57	1.94	30.24
Iratio_55	1.00	1.00	0.93	118.28	104.28	0.12	0.45	1.53	28.97
GB_slope_5y_lam1	1.00	1.00	0.96	81.13	118.56	0.03	0.45	1.53	28.93
GB_slope_10y_lam1	1.00	0.99	0.91	87.09	126.16	0.02	0.41	1.40	28.36
GB_slope_5y_lam05	1.00	0.98	0.90	81.36	128.44	0.02	0.41	1.41	28.45
75RecentCatch	1.00	0.98	0.94	94.20	94.17	0.00	0.47	1.61	28.82
GB_slope_10y_lam05	1.00	0.97	0.87	84.32	133.34	0.02	0.39	1.33	28.07
RecentCatch	0.94	0.85	0.69	125.60	113.13	0.01	0.28	0.98	24.54

Figure 38. Satisficed MPs averaged across the OM reference set scenarios. MPs are ordered by decreasing performance metric values from top to bottom starting with the left-most performance metric (LRP 2GT) and using columns from left to right to break any ties. The colour shading uses the viridis palette and spans from zero (purple) to the highest value in each respective column (yellow). This figure excludes the FMSYref reference management procedure.

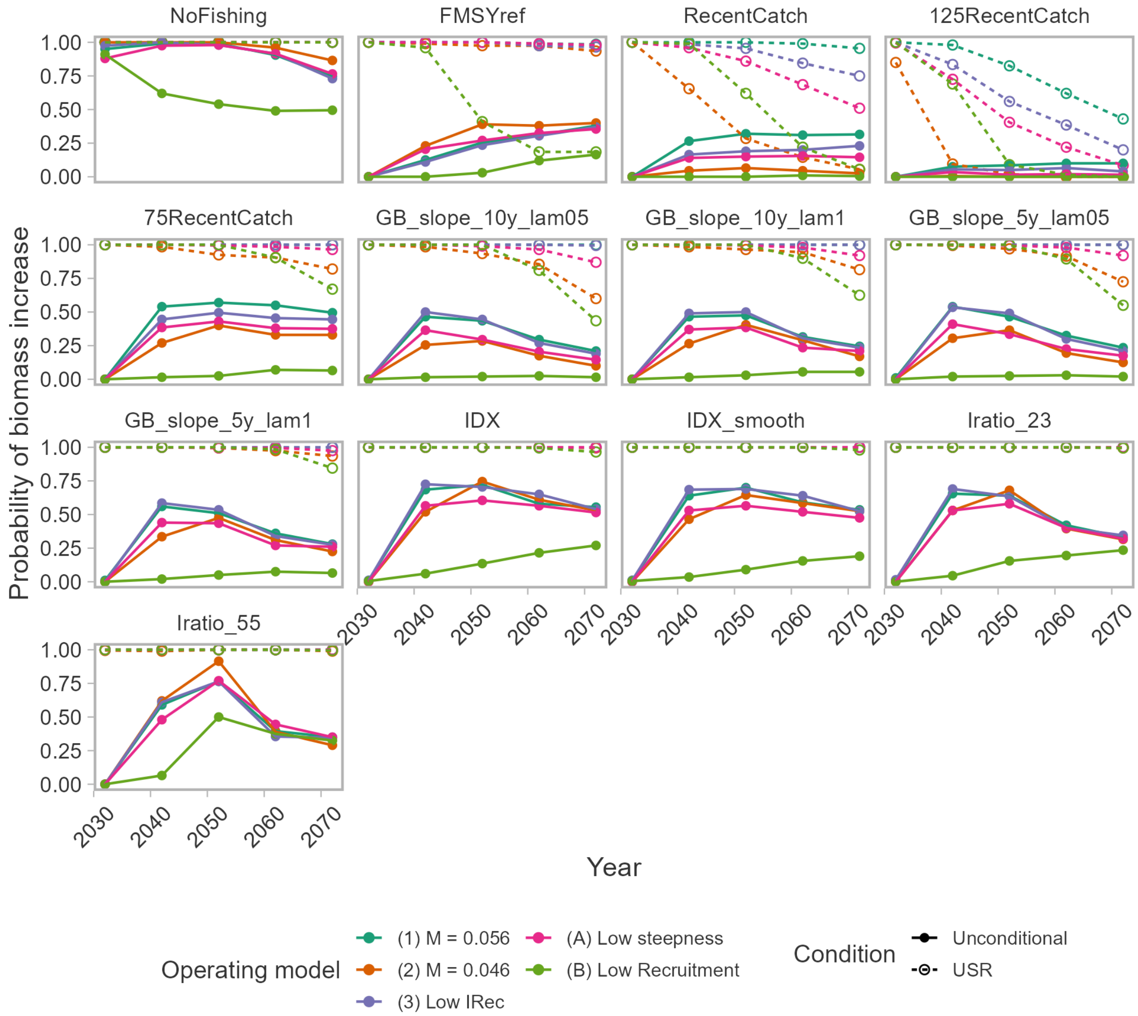

Figure 39. Probability of stock increase by operating model (colours) and management procedure (panels) at decadal intervals. The unconditional probability is calculated as $\frac{1}{200}\sum_i I(B_{i,y=y\prime} > B_{i,y=y\prime-10})$ across 200 simulations i at years $y\prime = 2032, 2042, ..., 2072$. $I()$ is an indicator function that returns 1 when the condition in parentheses is met and zero otherwise. When conditional on the USR, $I(.) = 1$ when $B_{i,y} > 0.8B_{MSY(i)}$ regardless of any other criteria.

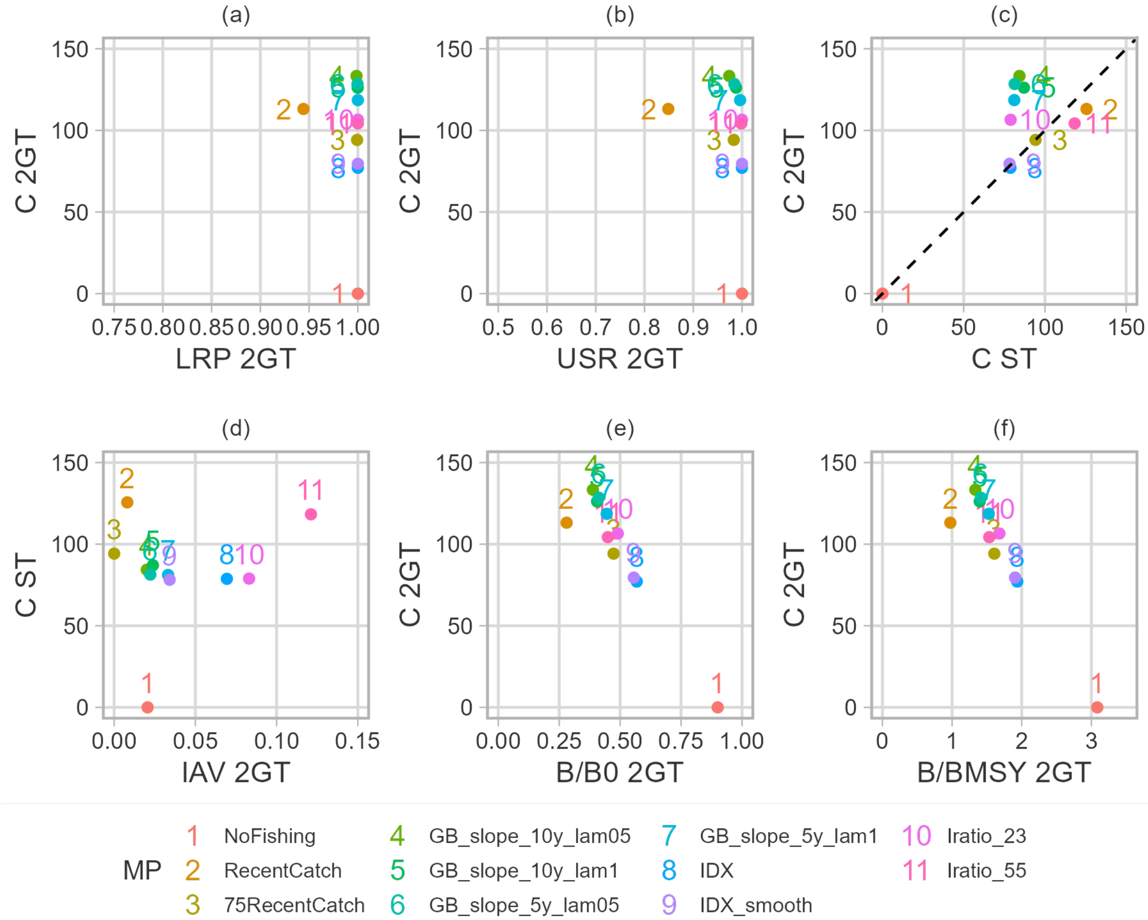

Figure 40. Trade-off plots (panels a-f) between various pairs of performance metrics (colored points with number legend) among the set of candidate management procedures. C 2GT is the average catch in the simulation after 2 generations (year 2075), LRP 2GT and USR 2GT are the probabilities of being above the LRP and USR, respectively, during two generations, C ST is the average catch during the first 7 years of the projection (2021-2028), IAV 2GT is the average change in catch during two generations, and B/B0 2GT and B/BMSY 2GT is the average stock status after 2 generations. Values are averaged across the reference set of operating models. Management procedures that perform well across both pairs of performance metrics are located in the top right corner of the corresponding panel. Conversely, management procedures that perform poorly across both pairs are located in the lower left corner. A trade-off (good performance of metric at the cost of another) in the management procedure set occurs when points are aligned along the top left to lower right corner of the panel, for example in panels (e) and (f). No trade-off occurs when management procedures are aligned from the bottom left to top right; the best management procedure is in the top right corner. The FMSYref reference management procedure is excluded here.

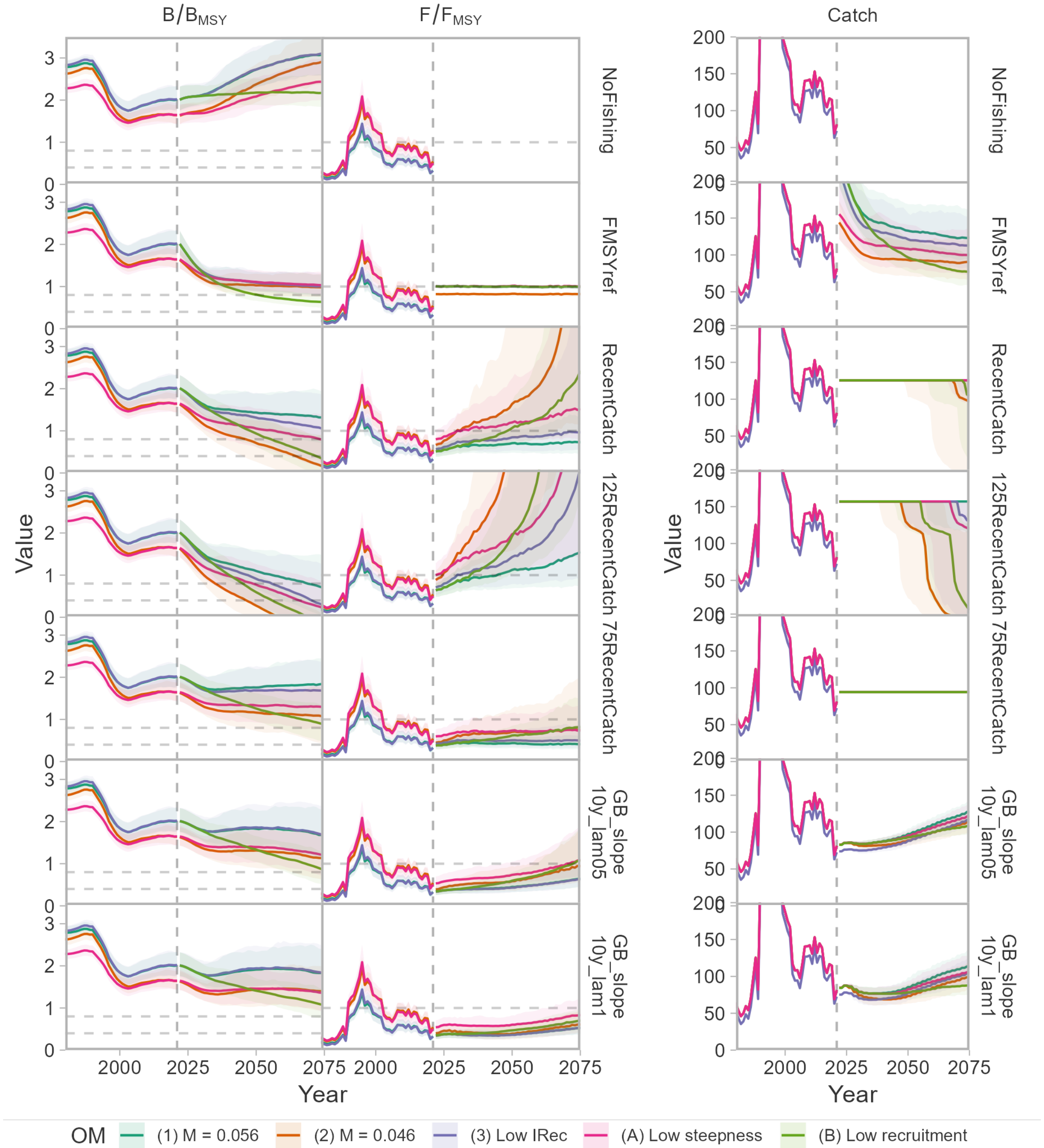

Figure 41. Historical and projected time series of B/B_{MSY} (left column, with horizontal grey lines denoting $0.4B_{MSY}$ and $0.8B_{MSY}$), F/F_{MSY}, (middle column, with horizontal grey line denoting $F/F_{MSY} = 1$) and catch (tonnes, right column) by operating model (colours) and management procedure (rows; set 1 of 2 figures). Lines indicate the median and the coloured bands span the 95% quantile across simulations. The historical period (prior to 2021, vertical dotted line) is truncated to 1980 and is identical among rows. The historical catch exceeded 200 tonnes during 1990-1998 and truncated in the right column. The projection period shows the resulting trajectories from implementation of the management procedures.

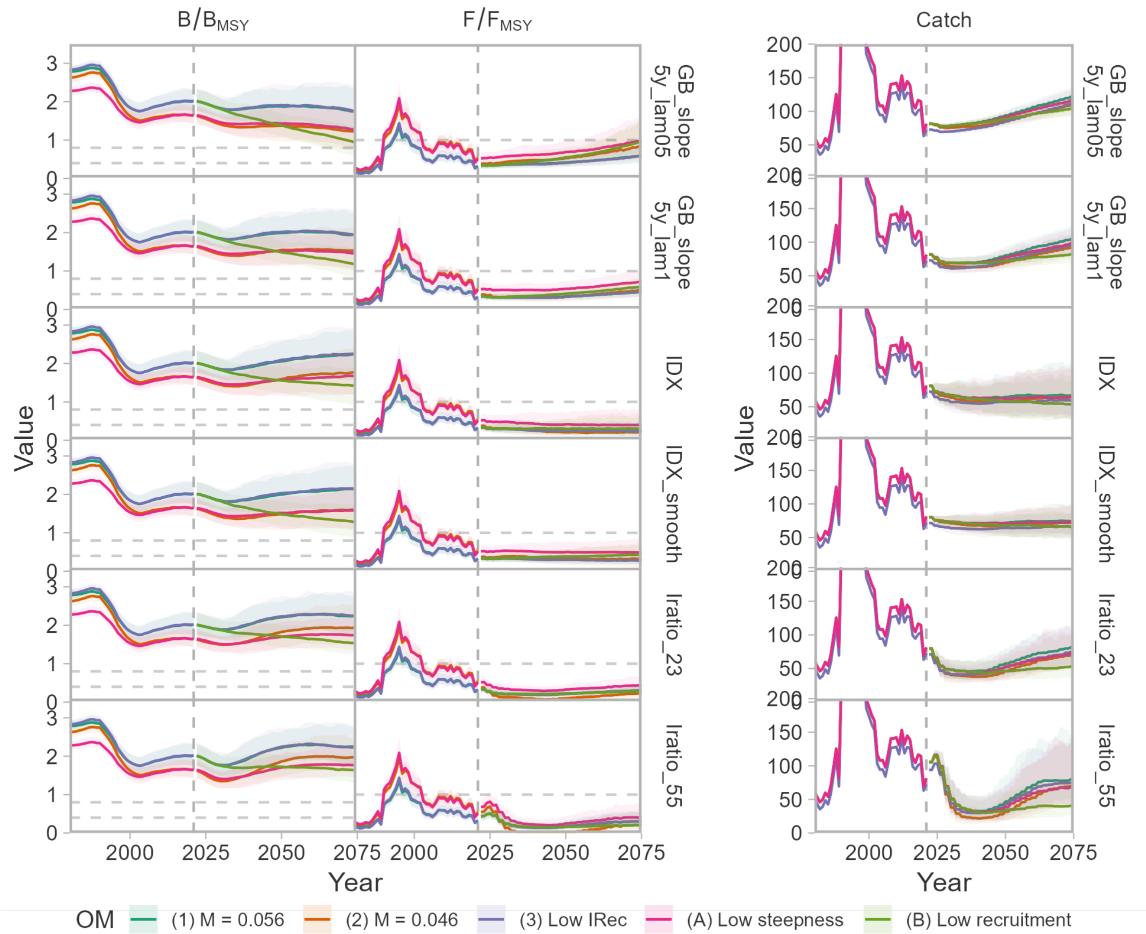

Figure 42. Historical and projected time series of B/B_{MSY} (left column, with horizontal grey lines denoting $0.4B_{MSY}$ and $0.8B_{MSY}$), F/F_{MSY}, (middle column, with horizontal grey line denoting $F/F_{MSY} = 1$) and catch (tonnes, right column) by operating model (colours) and management procedure (rows; set 2 of 2 figures). Lines indicate the median and the coloured bands span the 95% quantile across simulations. The historical period (prior to 2021, vertical dotted line) is truncated to 1980 and is identical among rows. The historical catch exceeded 200 tonnes during 1990-1998 and truncated in the right column. The projection period shows the resulting trajectories from implementation of the management procedures.

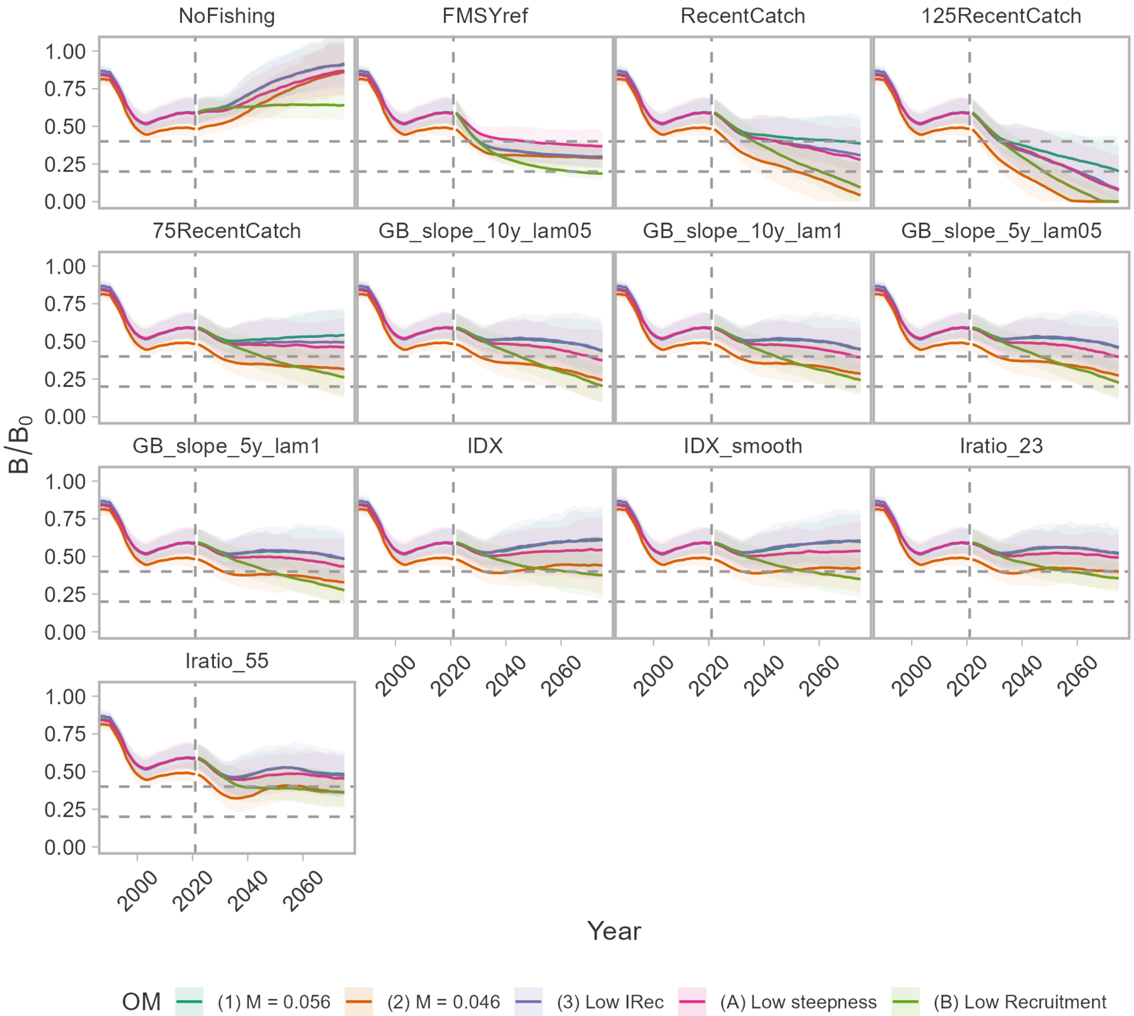

Figure 43. Historical and projected time series of B/B_0 by operating model (colours) and management procedure (panels). Lines indicate the median and the coloured bands span the 95% quantile across simulations. The historical period (prior to 2021, vertical dotted line) is truncated to 1980 and is identical among panels. The projection period shows the resulting trajectories from implementation of the management procedures. Horizontal, dotted grey lines denoting $0.2B_0$ and $0.4B_0$.

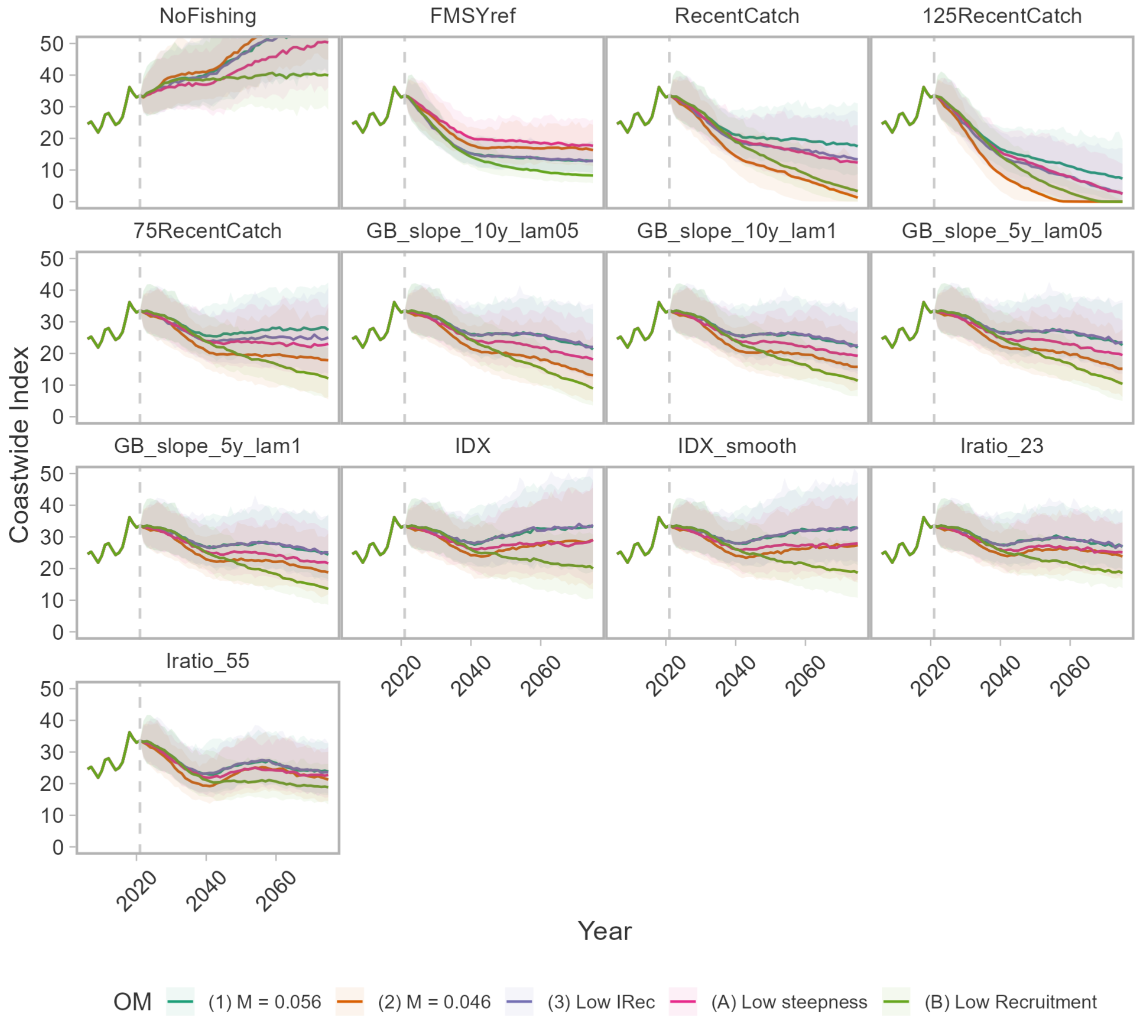

Figure 44. The coastwide index from the HBLL survey (prior to 2021 in vertical lines), with simulated values in the projections from 2022 and onward for each management procedure and operating model. Coloured bands denote the 95% range of values simulated in the projections. Area-specific indices in 5BCDE and 5A3CD were used in the operating model conditioning and simulated in the closed-loop projections; the coastwide value is the sum over the two areas and is presented here as a stock-wide index. Upon implementation of a management procedure, simulated indices can be used in part to monitor whether the stock is responding as predicted and determine when a re-assessment is necessary.

7. DISCUSSION

We applied the MP Framework for Pacific groundfishes (Anderson et al. 2021) to provide science advice for Outside Quillback Rockfish, including the evaluation of status and management procedures that meet sustainability objectives under the Fish Stocks Provisions as well as fishery objectives.

The stock was estimated to be above the LRP in 2021. We evaluated the performance of constant catch and index-based MPs (along with two reference MPs) with respect to meeting the objectives described in Section 3 across five operating models. We identified (1) **LRP 2GT** > 0.75, (2) **USR 2GT** > 0.50, and (3) **FMSY 2GT** > 0.50, averaged across the OM reference set scenarios, as the three criteria to identify management procedures that would meet policy requirements. Most MPs, including all index-based management procedures and some constant catch MPs, achieved these policy performance metrics. In all operating models, catches were set to levels such that the stock did not frequently enter the Critical zone during the projections, with OM (B) providing an important robustness test to evaluate performance if lower than average recruitment were to occur in the near future. Trade-offs were observed in long-term catch and long-term ratios of biomass relative to B_{MSY} and B_0.

In addition to projected stock trajectories, we presented various trade-offs among policy and catch objectives in tabular and graphical formats, intended to support the process of selecting the final MP to direct harvest policy and/or a target reference point (DFO 2009; see also Anderson et al. 2021). Final selection of the MP will have to balance biomass objectives with fishery objectives, such as ensuring that there are sufficient opportunities to catch Outside Quillback Rockfish (Haggarty et al. 2022).

Amongst the satisficed MPs, fixed catch MPs provide more predictability, but require more oversight and diligence to ensure that fishing mortality does not increase rapidly and result in higher proportional catches than is anticipated. Index-based MPs are more responsive to changes in stock abundance, as indicated by the index of abundance. The trade-off plots also provide information on how certain MPs may want to be eliminated from consideration. Within a plot, dominated MPs occur inside the arc of MPs that define the trade-off frontier. These dominated MPs would generally be less desirable, as a gain in one performance measure can be obtained without a corresponding trade-off in the other. If a subset of MPs are found to perform similarly across the set of reference OMs, then their performance in the robustness OMs can be used to help managers evaluate which MPs may be more desirable than others.

Many index-based MPs generated short-term catches below the recent 2012–2019 mean, regardless of current status relative to the LRP. In the short-term, this behavior is driven by the predicted decrease in the HBLL index in the early years of the projection. Ultimately, the realized catch advice from these management procedures will be determined by an updated index as new survey data are processed.

7.1. NATURAL MORTALITY

The reference set was intended to explore robustness of management procedures to alternative hypotheses regarding natural mortality in Outside Quillback Rockfish. The rate of natural mortality of fish populations is an important productivity parameter that affects estimation of biomass and calculation of reference points, yet it is frequently not directly estimated. Natural mortality can be directly estimated in several ways, for example, from a catch curve of an unexploited population or from multiple years of tag returns (although estimation can be confounded if the tag shedding rate and tag reporting rate is unknown).

Numerous methods have been developed to estimate *M* from available life history parameters. The Barefoot Ecologist's Toolbox provides a convenient Shiny App that indirectly estimates *M* using various published empirical methods. Estimates of *M* ranged from 0.05 to 0.25, depending on the empirical method. However, the high values were estimated from growth parameters and are unlikely for this stock given the high maximum observed age. Quillback Rockfish, as their name implies, have a particularly a high spiny dorsal fin, and, like all rockfishes, can deliver a poison through their spines. These characteristics also make growth-derived estimates of natural maturity unrealistic for Quillback Rockfish. Other Quillback Rockfish assessments, such as those on the US West Coast, have also used *M* values in the lower range (Langseth et al. 2021).

Natural mortality rates can change over time, for example, due to changes in predator population abundance. For example, Lingcod are predators of rockfish species, including juvenile Quillback Rockfish. However, stomach content studies are often not able to resolve rockfish species beyond unidentified rockfish (Beaudreau and Essington 2007).

Pinnipeds are also known to predate on rockfish (Fritz et al. 2019; Thomas et al. 2022). While it does not appear that rockfish constitute a large portion of the pinniped diet, pinniped predation on rockfish may have increased as a function of the increasing abundance of seals and sea lions in British Columbia. Harbour Seals have increased in BC from a low of approximately 10,000 individuals in the 1960s to over 100,000 in the early 2000s, with the population stabilizing since then (DFO 2022b). The most recent Steller Sea Lion assessment estimates that the BC population abundance was approximately 42,000 individuals in 2017 (DFO 2021). The population trajectory shows a dramatic increase in abundance since the time-series estimated minimum of approximately 8,000 individuals in the early 1970s.

Although genetic analysis of DNA in pinniped scat has been undertaken (S. Tucker, DFO pers. comm. 2020), Quillback Rockfish cannot be distinguished from closely related Copper, Brown and China Rockfishes. Therefore the proportion of Quillback Rockfish consumed is uncertain at this time.

7.2. ROCKFISH CONSERVATION AREAS

As part of the rockfish conservation strategy, 164 Rockfish Conservation Areas (RCAs), in which fisheries targeting or catching rockfish as bycatch are prohibited, were established in BC waters between 2004-2006 (Yamanaka and Logan 2010). There are 36 RCAs in the outer waters that encompass over 3,200 square kilometers (Dunham et al. 2020). Within those 3,200 square kilometers, approximately 970 square kilometers (29.7 percent) is suitable rockfish habitat. In total, about 14% of rockfish habitat in the outside waters is in an RCA. Additional habitat occurs in other protected areas and is not included in these numbers.

One Remotely Operated Vehicle (ROV) survey, looking at the effectiveness of the RCAs, sampled 7 RCAs along the west coast of Vancouver Island, but did not find a significant effect on either rockfish density or size. This study was done when those RCAs had only been in place for 6 - 7 years (Haggarty et al. 2016). It is expected that, given the longevity of rockfishes, it will take upwards of 20 years for populations to show responses to closed areas (Starr et al. 2015).

A SCUBA survey did find significantly higher densities of Quillback Rockfish in the Broken Group Islands RCA as compared to other sites in Barkley Sound (Haggarty et al. 2017). In an exploration on the effect of RCAs on rockfish body size after 13 to 15 years of protection, larger rockfish were found in the Central Coast at the two largest RCAs studied compared to control sites, but there was no difference in size at 3 other RCAs and one RCA had smaller fish than the control site (McGreer et al. 2020).

The RCAs have now been in place for 17 to 19 years, so we might expect to find more significant reserve effects such as increased densities and sizes of rockfish in RCAs in the near future. The extent that rockfish in RCAs can function as an unexploited source of recruitment to fisheries, however, has not yet been determined.

7.3. STOCK STATUS

With the MP Framework, the acceptable risk of breaching reference points is established at the beginning of the process, i.e., Step 2 of the best practices, and reference points and stock status need not be explicitly reported (Anderson et al. 2021). Reference points are built into the performance metrics as outcomes of management procedures, i.e., the probability of breaching the reference point with a certain MP in the projections. The Fish Stocks Provisions emphasizes identification of status relative to the limit reference point, following the PA Policy, as status determines policy objectives going forward (DFO 2009).

For Outside Quillback Rockfish, we identified three operating models for the reference set. Two differed in the natural mortality rate. The first OM used a “base” value for M based on the most recent scientific information available for predicting the parameter, with alternative value including a continuity scenario from the 2011 assessment in the other OMs. The third explored different catch levels for the recreational fishery as the historical catch time series is short and subject to expansion factors that may be imprecise. The status of the stock in 2021 was robust to these factors. Averaging across the three reference OMs results in a very high (>99%) probability that the stock in 2021 is above both the LRP and the USR.

COSEWIC Metric A measures the decline across a three generation time span (Appendix H). When the three reference OMs are averaged, our analysis shows that there is a high probability that the population has declined by 30% since 1941 (with 98–99% probability in individual operating models). The probability that the stock has declined by 50% was high only in the operating model (2) with low natural mortality. It is not likely that the stock has declined by 70%.

7.4. ENVIRONMENTAL CONSIDERATIONS

In anticipation of Outside Quillback Rockfish to be included in the second batch of major stocks prescribed to the Fish Stocks Provisions, we have considered the uncertain effects of environmental conditions by constructing OMs that vary in natural mortality and by including an OM with reduced recruitment (OM B).

Establishing a mechanistic relationship between environmental variables (EVs) and aspects of population productivity (e.g., growth, maturity, recruitment, natural mortality) is notoriously difficult for marine fishes (Rose 2000; Maunder and Thorson 2019; Punt et al. 2021). Even establishing correlations can be difficult, and these relationships may not even hold over time (Myers 1998; Tamburello et al. 2019). Incorporating environmental effects into assessments may bias advice depending on how well the environment-productivity relationship is understood (Haltuch et al. 2019). Furthermore, extreme longevity in rockfish, as a life history strategy, allows stocks to bridge periods of unfavourable environmental conditions (Beamish et al. 2006).

Despite the difficulty in establishing mechanistic relationships between marine fish productivity and climatic variability, some investigations into climate effects on the abundance and distribution of Pacific rockfishes have been conducted. In British Columbia, English et al. (2021) used bottom trawl survey data to show that the biomass trends of 38 demersal fishes, including Quillback Rockfish, are negatively associated with warming. However, when climate and biomass are converted to velocities - the speed and direction a population would have to move to maintain consistent conditions - the effect of temperature was dependent on local conditions. Locations that are presently cooler did not show a change in biomass with future warming. Locations that are presently warmer, however, did show a larger decline in local biomass with future warming.

A study on juvenile rockfish abundance in the California Current Ecosystem found that recruitment was at least partially driven by source water. High recruitment was associated with cooler water, containing higher concentrations of dissolved oxygen, indicative of Pacific subarctic water. Conversely, warmer, more saline water with a likely subtropic or equatorial origin that contains less dissolved oxygen was associated with lower rockfish recruitment (Schroeder et al. 2018). For species that live in benthic environments, relevant oceanographic models need to account for depth (Huff et al. 2012; Schroeder et al. 2018).

Model uncertainty remains a substantial barrier for developing ecosystem models for Ecosystem-based Fisheries Management (EBFM). As model complexity increases, more data are needed to inform model parameters to describe the current state of nature. Model uncertainty would be high for data-limited species, and model results may not be suitable to inform management advice (Plagányi 2007). However, ecosystem models can be strategically used within a Management Strategy Evaluation (MSE). Ecosystem models serve as operating models, the suite of which reflects specific assumptions identified by the user as important. This approach frees the user of the strict need to develop and defend a single best-case ecosystem model (Link et al. 2012).

Here, we do not directly model any individual environmental variable (e.g., temperature or dissolved oxygen) as we do not have any a priori hypotheses on the relationship between an EV and productivity. Rather, we consider environmental conditions on stock productivity by evaluating MPs across OMs with varying rates of natural mortality, and in low recruitment and low steepness scenarios. In this way, we assume that any number of biological interactions or environmental effects may be acting on the stock, resulting in different rates of natural mortality or reduced recruitment. In lieu of understanding any relationships between EVs and productivity, we are still able to test MPs considering these uncertainties. The use of ecosystem models in MSEs remains limited (Perryman et al. 2021), but as the demand for EBFM continues to increase, and if ecosystem models become more accessible, it will be important to consider how to incorporate ecosystem models into the MP Framework for future Quillback Rockfish assessments.

7.5. HISTORICAL CATCH

The other major source of uncertainty in our analyses is the magnitude of historical catch, as well as the lack of a fishery-independent survey before and during the period of highest exploitation observed through the 1980s and early 1990s.

Uncertainty regarding commercial catch is due to reporting of rockfishes other than Pacific Ocean Perch in an aggregate category before 1950, and the magnitude of unreported catch during 1986–2005. A reconstruction of historical catch data to 2005 was done by Haigh and Yamanaka (2011), which attempted to parse out Quillback Rockfish from the aggregated rockfish category and to account for discarded fish. We therefore followed the same approach to reconstructing historical recreational catch data and estimating current recreational catch data as Yamanaka et al. (2011). Reconstruction remains the best available estimate of the historical commercial catch. Alternative reconstructions, such as applying a high discard rate to the trawl fishery, were deemed to be highly improbable since the peak catches would have been greater than those from the hook and line fisheries that target Quillback Rockfish.

Biological samples have not been collected from the commercial fishery since 2010. Thus, it was not explicitly known how the age distribution of fish caught in the commercial fishery has changed over time. Mean weight was used to indirectly ascertain that fishing practices have not significantly changed since 2006. Developing a biological sampling protocol for a live fishery would fill in this information gap for future assessments.

As in the Inside Yelloweye Rockfish rebuilding plan review and Inside Quillback Rockfish MP Framework, FSC catch is not explicitly included and remains uncertain for the Outside Quillback Rockfish (Haggarty et al. 2021; Huynh et al. 2024). Some FSC catch, however, is part of the commercial catch (Appendix C.3) because some Quillback Rockfish will be caught and landed on “dual fishing” trips upon which both commercial and FSC fishing is conducted. The fish are landed and subject to dock-side monitoring so the data are included in DFO commercial databases.

Future applications of the MP Framework for this stock would benefit from more detailed collaborative work with First Nations to quantify contemporary and historical FSC catch in BC. Prioritizing collaborations will help DFO build mutually beneficial relationships that can help resolve uncertainties in FSC catch information.

7.6. REASSESSMENT FREQUENCY AND TRIGGERS

The MP Framework can be used to identify and select a management procedure that can be left in place for an agreed upon amount of time. Interim checks between MP updates to the catch advice are also recommended to ensure the selected MP is performing as expected. In addition to the MSE best practice steps, Carruthers and Hordyk (2018a) describe a final evaluation step, where performance of the selected MP is formally reviewed once it has been implemented. Departures from an MP’s expected performance have been termed “exceptional circumstances”. These may occur when the observed system dynamics fall outside the range of OM scenarios simulated in the operating models (Butterworth 2008).

Evidence for exceptional circumstances, occurring within the recommended assessment interval, would trigger a review of the OMs and MP, possibly resulting in a new OM, or an adjustment to the selected MP (Carruthers and Hordyk 2018b). Here, we presented the HBLL index and associated mean age as potential indicators for future re-assessment. These indicators were simulated in the projection as the corresponding real data are expected to be available in the future as the HBLL survey continues.

An example of a trigger for re-evaluation could be the observed index of abundance falling outside the 90% confidence interval of the index simulated here. Carruthers and Hordyk (2018b) and Huynh et al. (2022) provide statistical methodologies for formal evaluation procedures. Informal evaluation procedures, via feedback from stakeholders or visual comparison of observed data vs. projected data, can also be used to identify exceptional circumstances (e.g., Cox and Kronlund 2008).

Informal procedures that use multiple lines of evidence may be preferable to a formal, predefined criterion for determining exceptional circumstances. Informal procedures allow for different types of information to be considered that may be difficult to operationalize within a formal protocol. For Outside Quillback Rockfish, the GF Synopsis report can be used as a reference for identifying exceptional circumstances (Anderson et al. 2019). The index presented in GF Synopsis will likely be updated every year, and can be visually inspected for any unexpected changes. Biological information, such as length frequencies and age bubble plots, as well as length-weight relationship and growth plots, are also presented in GF Synopsis, providing complementary information to the biomass trends shown in the index (although other commitments for the DFO ageing lab may make monitoring of age data infeasible for periods of time). The informal procedures approach also ensures that information such as fisher observations (if applicable) can be included in discussions regarding exceptional circumstances.

7.7. DISCUSSIONS IN THE TECHNICAL WORKING GROUP

The development of operating models, performance metrics, and management procedures was informed by the technical working group (TWG, Appendix I) to the extent possible. Three meetings were held, but still did not provide sufficient time for TWG members to fully review all the components of an MSE process prior to the peer review meeting. For future planning, we recommend that more time (up to 2 weeks instead of 3–4 days) be given to allow members to review the work in progress before each TWG meeting. Feedback can be used to tune management procedures to achieve specific performance criteria, e.g., biomass or catch levels, and refine performance metrics and operating models prior to the review of the working paper.

With regard to performance metrics, the TWG spent a considerable amount of time discussing reference points for Quillback Rockfish within the broader policy context and guidelines, along with other possible indicators of stock and ecosystem health. While we recognize that these topics are bigger than what can be addressed in any individual stock assessment analysis, we feel these discussions will likely surface in other species assessments and contexts, and it is therefore worthwhile to begin documenting them, with possible higher level guidance to follow. These discussions are likely to be of greater relevance in the context of fisheries co-management and consistency with Indigenous Knowledge Systems (Kovach 2021).

The use of depletion-based B_0 reference points along with B_{MSY}-based reference points was discussed. Recent DFO guidance recommends using B_{MSY}-based reference points when technically feasible, which reflects an implicit policy decision to define serious harm in terms of reduction in surplus production (DFO 2023). Some TWG members voiced a preference for depletion-based reference points, as they find them more consistent with thinking about abundance trends over time, and more amenable for considering broader ecosystem effects and considerations (Reid et al. 2022). To this end, we accompanied all statements and figures pertaining to stock biomass in terms of both B_{MSY} and B_0.

The choice of unit for the reference point might be particularly relevant for species with high steepness, which skews the top of the yield curve towards a lower depletion level. In this analysis, we found that 40% B_{MSY} corresponds to approximately 12% of B_0, which may represent a disproportionately harmful state given additional ecosystem considerations, such as maintaining food web stability. Further research is needed to elucidate the extent to which Quillback Rockfish removal disrupts ecosystem processes.

It was also proposed to develop non-biomass indicators designed to evaluate truncating stock age and size structure. Here, we report the empirical age structure, and compare the observed age structure to the predicted equilibrium age structure if the stock biomass were at the LRP. We find this comparison to be particularly helpful for highlighting the persistence of older age classes in our observed data that may disappear if the stock approaches the LRP. Maintenance of older age classes is also one of the major conservation objectives of the RCAs and the Marine Protected Areas (MPAs) that are being established in British Columbia.

Recent DFO guidance on LRP development specifically references the PA Policy, and guidance is focused on avoiding serious harm to target stocks (DFO 2023). Guidance on broader ecosystem functions and additional environmental considerations are beyond the scope of guidance in

DFO (2023). We recognize the complexity involved in providing guidance related to ecosystem functioning and environmental considerations, and provide this discussion section as a means to document these issues as they continue to exist and become more prevalent in species stock assessment discussions.

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APPENDIX A. BIOLOGICAL DATA

The Outside Quillback Rockfish stock is defined to include Areas 3CD (West Coast Vancouver Island) and 5ABCDE (Central and North Coasts of British Columbia), excluding Area 4B (Strait of Georgia and Johnstone Strait) which comprises the inside stock.

A.1. AGE AND GROWTH

Age data for Outside Quillback Rockfish, derived from the break and burn or break and bake methods, are available from various surveys since 2003. Annual biological samples from the Hard Bottom Longline (HBLL) survey have regularly been aged since 2006, while samples from other surveys, including the Fishery-Independent Setline Survey of the International Pacific Halibut Commission (IPHC FISS), and synoptic trawl surveys in the Hecate Strait (SYN HS) and Queen Charlotte Sound (SYN QCS), have been aged less frequently. Otoliths from the West Coast Vancouver Island synoptic trawl survey (SYN WCVI) have not been aged. No Quillback Rockfish has been caught in the West Coast Haida Gwaii trawl survey. Proportions-at-age are shown by year in Figures A.1 and A.2.

The maximum observed age for Outside Quillback Rockfish is 95 years, which was collected in 1992 from commercial hook and line fishery and caught using longline gear.

Outside Quillback Rockfish grow up to 64 cm in length for males and 63 cm for females (Figures A.3 - A.4). The maximum recorded weight is 2.3 kg for males and 2.9 kg for females. Length-weight model fits and plots for all available survey data are shown in Figure A.5.

Growth was estimated from biological samples from both the commercial fishery (Appendix C) and surveys.

The length-weight function is of the form:

$$W_i = aL_i^b, \tag{A.1}$$

where W_i and L_i are the weight and length for fish i, respectively. Parameters a and b are estimated using maximum likelihood using the Student-t distribution in log-space:

$$\log(W_i) \sim \text{Student-t}(df = 3, \log(\hat{a}) + \hat{b}\log(L_i), \hat{\sigma}_W), \tag{A.2}$$

where σ_W is the residual standard deviation and the circumflex symbol (ˆ) denotes a parameter estimate. The degrees of freedom of the Student-t distribution was set to 3 to be robust to outliers (Anderson et al. 2019).

Length-at-age model fits and plots for Outside Quillback Rockfish are shown in Figure A.6. The von Bertalanffy growth curve is of the form:

$$L_i = L_\infty\{1 - \exp[-k(A_i - t_0)]\}, \tag{A.3}$$

where L_i and A_i represent the length and age of fish i, respectively, L_∞, k, and t_0 represent the growth parameters. These parameters were estimated using maximum likelihood from a lognormal distribution:

$$L_i \sim \text{Log-normal}\left(\log(\hat{L}_\infty\{1 - \exp[-\hat{k}(A_i - \hat{t}_0)]\}) - 0.5\hat{\sigma}_L^2, \hat{\sigma_L}\right), \tag{A.4}$$

where σ is the residual standard deviation and the bias adjustment term $-0.5\sigma^2$ for the lognormal distribution is used to model the mean length rather than the median. The model was fit in TMB as described in (Anderson et al. 2019).

Estimates of L_∞ and k appear to be fairly precise where the confidence intervals for the two parameters were 39.057 – 39.339 and 0.110 – 0.120, respectively.

Otoliths from several surveys are needed to estimate the growth curve over the full lifespan of Quillback Rockfish. Small fish (younger than age 10) needed to estimate the t_0 parameter are caught in the trawl surveys while older fish caught in longline gear inform the estimate of l_∞ (Figure A.7). Faster growing fish are more likely to be caught in the IPHC survey, indicating a strong hook effect.

Otoliths samples can also be used to evaluate potential changes in growth over time (Figure A.8). Since there may be strong survey effects that can potentially confound time effects, it is recommended that growth changes be explored through a single survey, i.e., the HBLL survey.

A.2. MATURITY

To estimate maturity at age, biological samples were analyzed for specimens that were identified as male or female with a valid maturity code and for which age was determined using the break and burn or break and bake methods.

Maturity ogives are fit using a binomial generalized linear model (GLM) to individual fish specimens, which are categorized as mature vs. not mature against age. The ages at 5, 50, and 95 percent maturity are reported in Figure A.9. The maturity ogive was estimated as:

$$y_i \sim \mathrm{Binomial}(\pi_i) \tag{A.5}$$

$$\mathrm{cauchit}\,(\pi_i) = \beta_0 + \beta_1 x_i + \beta_2 F_i \tag{A.6}$$

where $y_i = 1$ if fish i is considered mature and $y_i = 0$ otherwise. The β parameters are estimated coefficients, x_i is the age of fish i, and F_i is a categorical variable for sex (1 is female, 0 is male). The variable π_i represents the expected probability of fish i being mature. The cauchit function, the inverse of the cumulative distribution function of the standard Cauchy distribution, generated a better fit to the observed proportion mature-at-age compared to the logit function (Figure A.10). As a result, it was the preferred link function in the binomial GLM. Models are fit to all available survey samples regardless of time of year.

Predicted vs. observed proportions mature-at-age are shown in Figure A.10. Maturity frequency by each month is shown in the bubble plot in Figure A.11 for all specimens from which maturity was sampled. Categories of maturity are listed from most immature (top) to most mature (bottom); individual fish, once mature, cycle through the mature stages.

No fecundity estimates, i.e., egg production per individual female, were available from survey samples. Typically, measures of spawning output are indirectly calculated with weight-at-age used as a proxy for egg production. Meta-analysis of *Sebastes* rockfish has shown that egg production increases more greatly than weight as a function of size (Dick et al. 2017). From the meta-analysis, the predicted fecundity was $f = 3e^{-7}L^{3.701}$ for Quillback Rockfish (Figure A.12). The exponent in the fecundity-length relationship is much larger than in the weight-length relationship (3.11).

However, when the corresponding fecundity-at-age is calculated, the spawning output of an older fish relative to a younger fish does not differ as much compared to the ratio of their weights

(Figure A.13). Two factors appear to create this behavior. First, Outside Quillback Rockfish appears to have a low *M*/*K* life history (value of 0.51) (Prince et al. 2015). On average, fish stop growing in length, relatively early in their lifespan. Thus, the average size difference between a young, mature fish and an old, mature fish is smaller than in an animal with higher *M*/*K* life history. Second, there is notable variability in growth among fish, so there are small as well as large fish within many age classes (Figure A.6).

Initial modeling showed that trends in spawning output did not differ if calculated by weight or egg output. Thus, fecundity was not further considered here beyond use of weight as a proxy. However, future assessments of rockfish should consider direct fecundity estimates as egg production increases dramatically with size in some species such as Pacific Ocean Perch (Dick et al. 2017).

A.3. GENERATION TIME

This analysis updated the generation time of Outside Quillback Rockfish to 27 years. The previous stock assessment estimated the generation time as 32 years, but this was based on the natural mortality of M = 0.048 (Yamanaka et al. 2011). Since then, new meta-analyses have updated the relationship between natural mortality and maximum observed age (Hamel 2015; Then et al. 2015). Based on an updated value of M = 0.056 and 50% female maturity at 9.4 years, the generation time of 27 years (age at 50% maturity + 1/M) is used here.

See Appendix D for further discussion of natural mortality.

A.4. SUMMARY TABLE OF BIOLOGICAL DATA

Table A.1. Outside Quillback Rockfish biological samples by survey and year. HS MSA is the Hecate Strait Multispecies Assemblage Survey. Trawl surveys include the synoptic surveys in Hecate Strait (SYN HS), Queen Charlotte Sound (SYN QCS), and West Coast Vancouver Island (SYN WCVI). Otoliths have been collected from all specimens but only a subset have been aged.

Survey	Year	Number of specimens	Lengths	Weights	Maturities	Ages
HBLL N	2006	1,611	1,611	0	1,487	1,497
HBLL N	2008	1,960	1,960	0	1,817	1,815
HBLL N	2010	1,993	1,993	1,172	1,853	512
HBLL N	2012	2,474	2,473	1,409	2,005	543
HBLL N	2015	1,922	1,922	1,922	1,922	551
HBLL N	2017	1,687	1,687	1,687	1,684	473
HBLL N	2019	2,533	2,530	2,529	2,533	142
HBLL N	2021	1,951	1,946	1,941	1,950	0
HBLL S	2007	1,222	1,222	0	1,157	713
HBLL S	2009	687	687	385	612	109
HBLL S	2011	1,275	1,275	1,015	1,271	340
HBLL S	2014	1,426	1,424	1,205	1,315	368
HBLL S	2016	1,082	1,080	1,067	1,065	445
HBLL S	2018	1,687	1,687	1,660	1,659	451
HBLL S	2020	1,278	1,276	1,257	1,259	241
HS MSA	1984	28	28	0	0	0
HS MSA	1987	92	92	0	0	0
HS MSA	1989	141	141	0	0	0
HS MSA	1991	120	120	0	0	0
HS MSA	1993	132	132	40	40	0
HS MSA	1995	18	18	18	18	0
HS MSA	1996	54	53	53	54	0
HS MSA	1998	85	83	83	85	0
HS MSA	2000	49	47	47	49	0
HS MSA	2002	14	14	14	14	0
IPHC FISS	2003	115	115	0	114	113
IPHC FISS	2004	133	133	0	133	111
IPHC FISS	2005	234	234	0	233	234
IPHC FISS	2006	186	186	0	185	186
IPHC FISS	2007	119	119	0	119	0
IPHC FISS	2008	86	86	0	83	86
IPHC FISS	2009	177	177	171	177	177
IPHC FISS	2010	246	246	246	245	0
IPHC FISS	2011	180	179	179	177	0
IPHC FISS	2012	112	112	110	108	0
IPHC FISS	2014	150	150	150	148	0
IPHC FISS	2015	177	177	177	171	0
IPHC FISS	2016	128	128	121	128	0
IPHC FISS	2017	136	136	136	136	90
IPHC FISS	2018	173	173	172	172	0

Survey	Year	Number of specimens	Lengths	Weights	Maturities	Ages
IPHC FISS	2019	163	163	163	163	163
SYN HS	2005	565	562	384	565	368
SYN HS	2007	403	402	402	403	0
SYN HS	2009	248	248	248	247	0
SYN HS	2011	491	491	420	419	0
SYN HS	2013	397	397	272	272	0
SYN HS	2015	322	321	261	261	0
SYN HS	2017	339	339	307	250	0
SYN HS	2019	261	261	261	245	0
SYN HS	2021	497	496	497	411	80
SYN QCS	2003	61	59	29	61	0
SYN QCS	2004	166	161	161	166	166
SYN QCS	2005	164	161	142	142	142
SYN QCS	2007	135	134	80	79	0
SYN QCS	2009	49	49	25	25	0
SYN QCS	2011	108	108	108	82	0
SYN QCS	2013	103	103	103	52	0
SYN QCS	2015	68	68	68	36	0
SYN QCS	2017	176	176	176	125	0
SYN QCS	2019	177	177	177	98	0
SYN QCS	2021	66	66	66	66	0
SYN WCVI	2004	55	54	43	55	0
SYN WCVI	2006	42	42	42	42	0
SYN WCVI	2008	49	49	49	49	0
SYN WCVI	2010	33	33	18	14	0
SYN WCVI	2012	72	72	36	29	0
SYN WCVI	2014	19	19	0	0	0
SYN WCVI	2016	46	46	46	46	0
SYN WCVI	2018	40	40	40	39	0

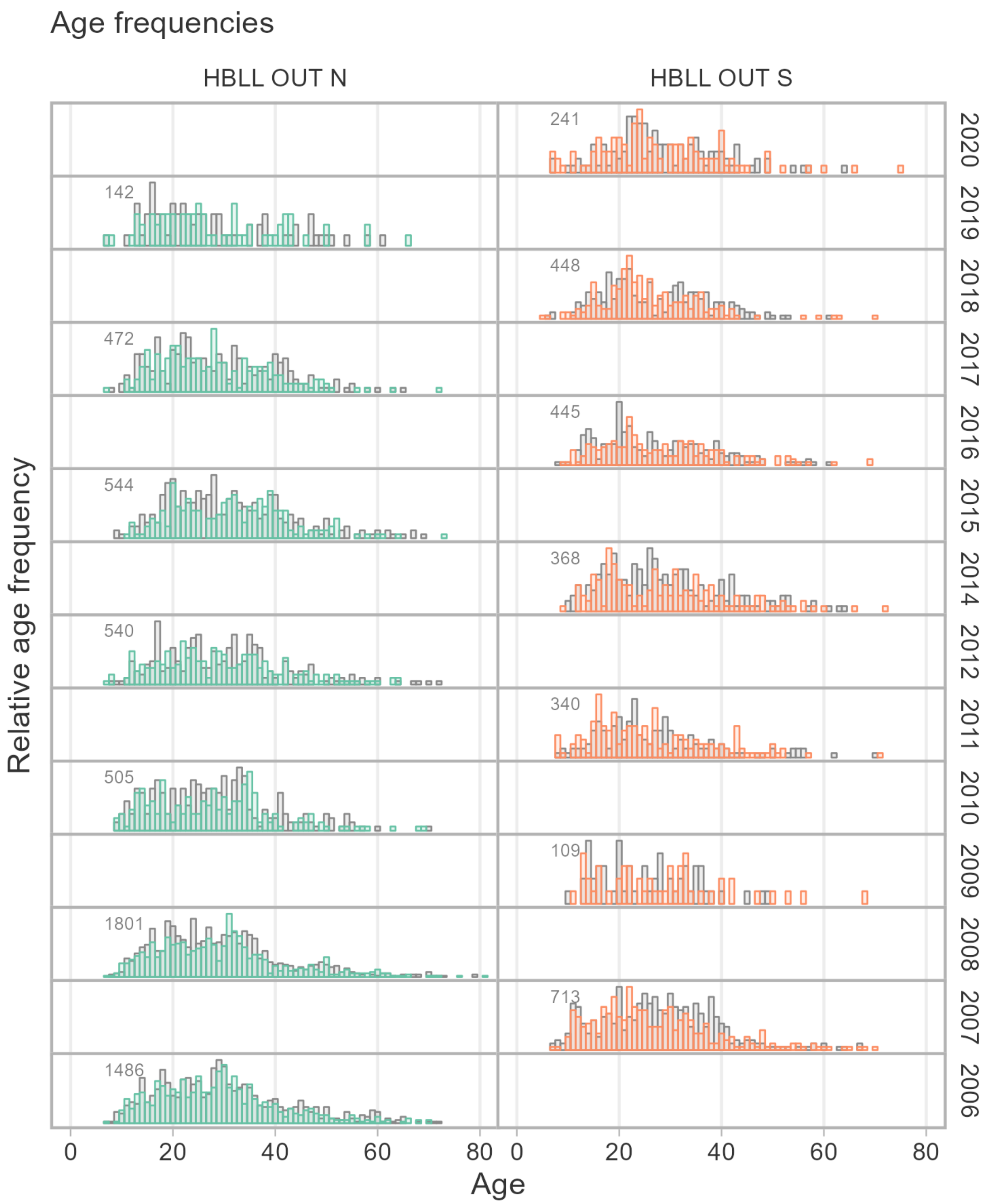

Figure A.1. Age-frequency plot for Outside Quillback Rockfish from the hard-bottom longline surveys (northern and southern) (HBLL OUT N/S). Female and male fish are shown as coloured bars and grey bars, respectively. The total number of aged otoliths for a given survey and year is indicated in the top left of each panel.

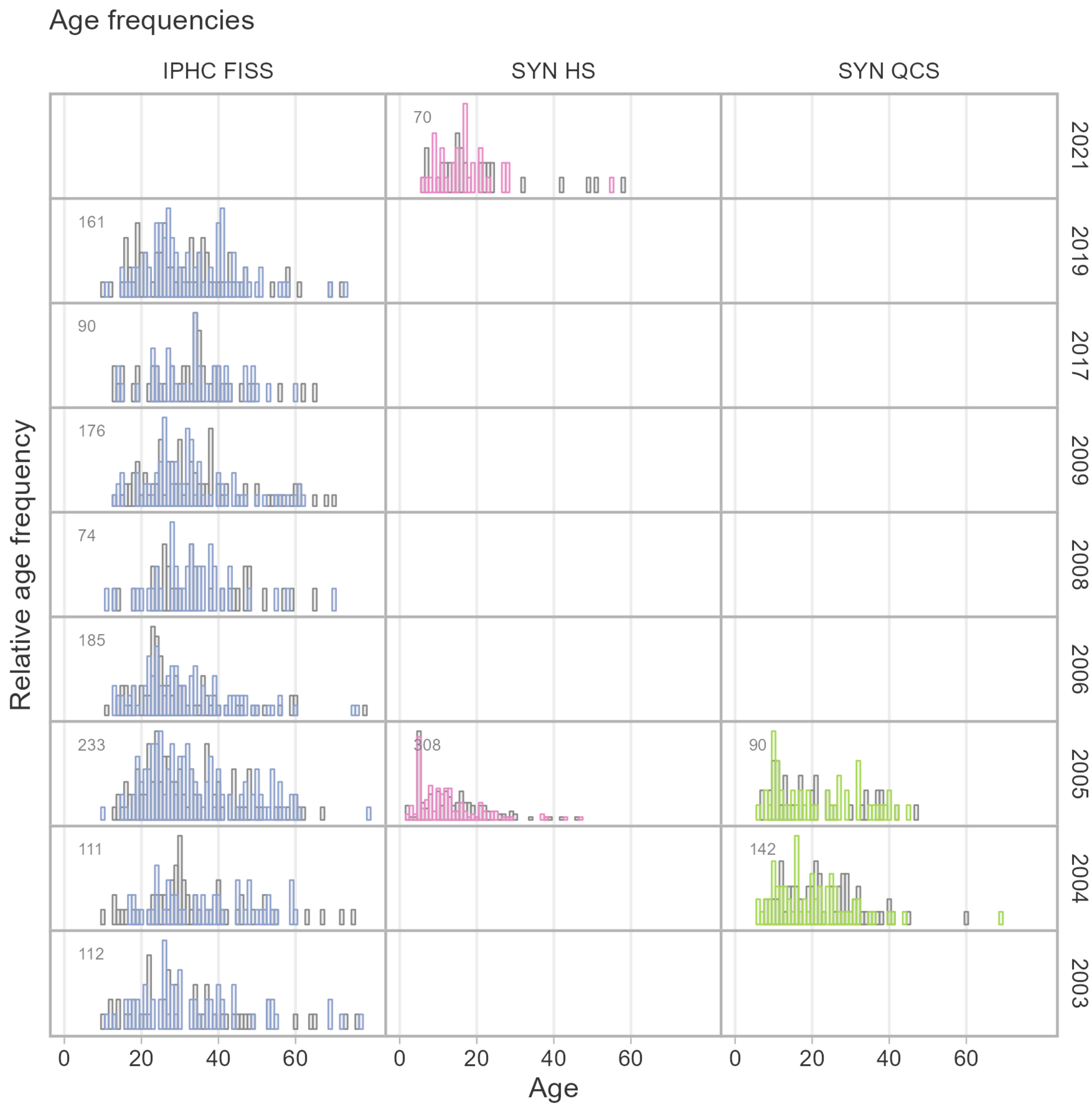

Figure A.2. Age-frequency plot for Outside Quillback Rockfish from IPHC FISS survey and synoptic trawl surveys in Hecate Strait (SYN HS) and Queen Charlotte Sound (SYN QCS). Female and male fish are shown as coloured bars and grey bars, respectively. The total number of aged otoliths for a given survey and year is indicated in the top left of each panel.

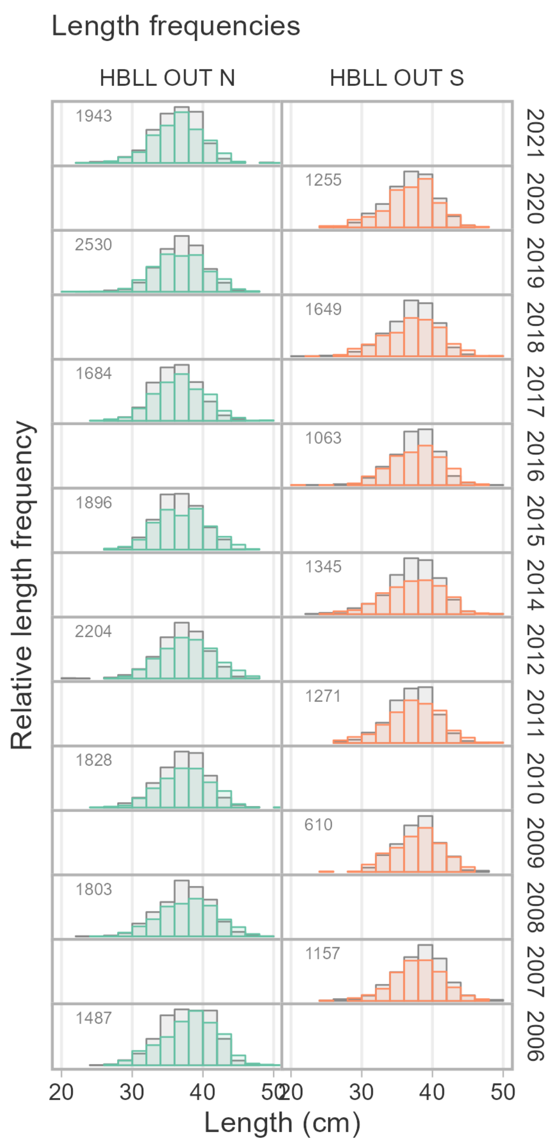

Figure A.3. Length-frequency plot from the hard-bottom longline surveys (northern and southern) (HBLL OUT N/S). Female and male fish are shown as coloured bars and grey bars, respectively. The total number of fish measured for a given survey and year is indicated in the top left of each panel.

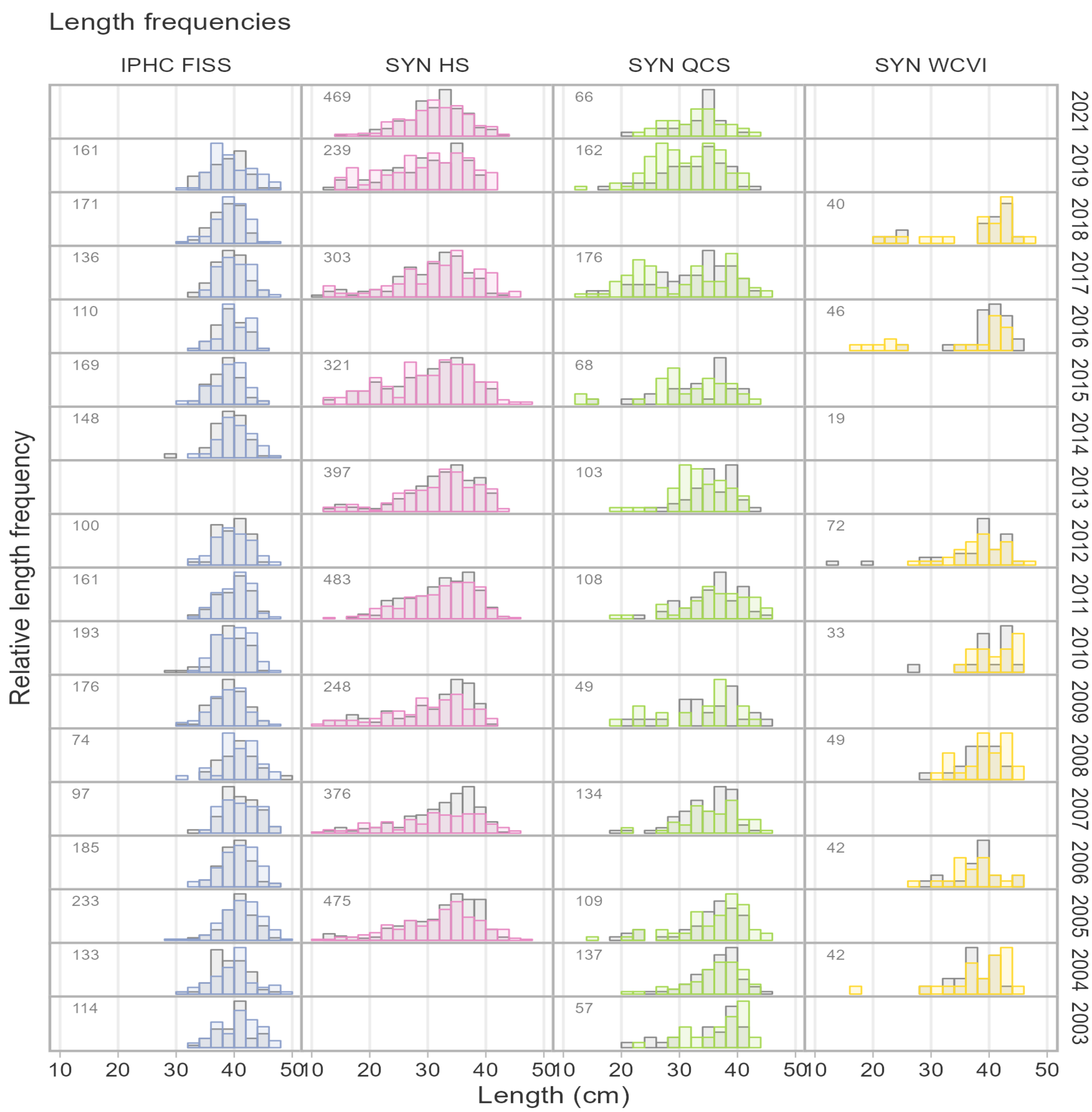

Figure A.4. Length-frequency plot from the IPHC FISS and synoptic trawl surveys in Hecate Strait (SYN HS), Queen Charlotte Sound (SYN QCS), and West Coast Vancouver Island (SYN WCVI). Female and male fish are shown as coloured bars and grey bars, respectively. The total number of fish measured for a given survey and year is indicated in the top left of each panel.

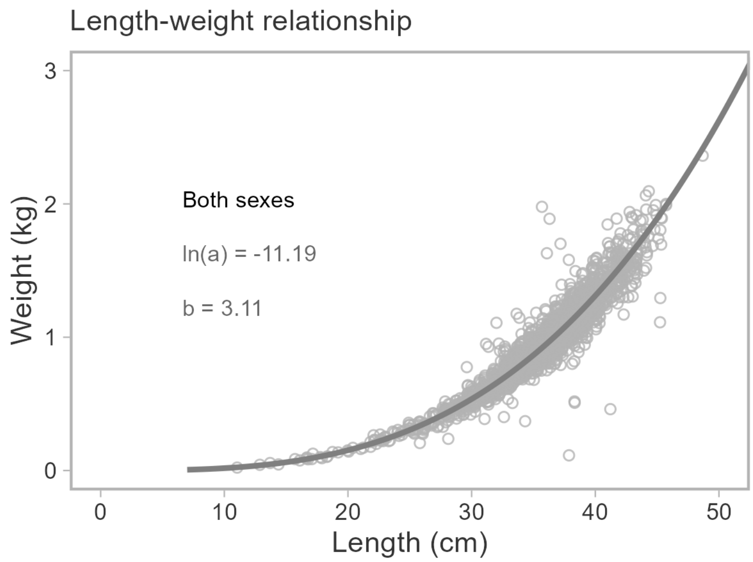

Figure A.5. Length-weight model fits and plots for Outside Quillback Rockfish. Text reports the parameter estimates of the weight-at-length relationship. A single set of parameters was estimated from both sexes.

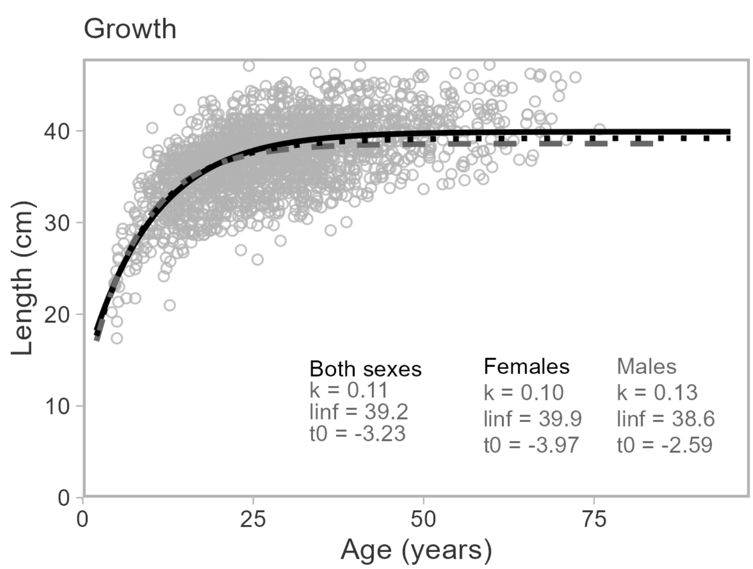

Figure A.6. Length-age model fits and plots for Outside Quillback Rockfish. The female model fit is indicated as a solid black line, male model fit is indicated as a dashed grey line, and combined sex model fit is indicated by a thin black line. Text shows the parameter estimates and open grey circles represent individual fish that the models are fit to.

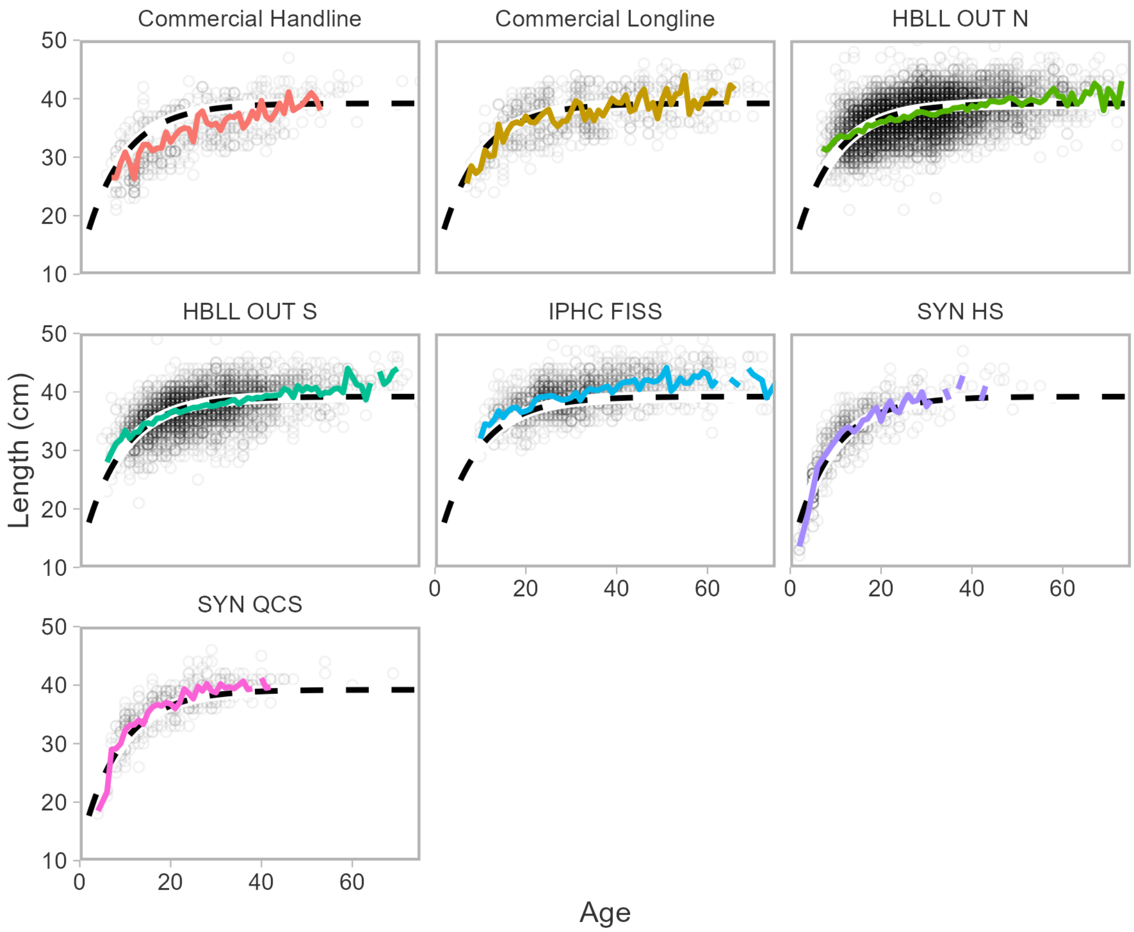

Figure A.7. Individual length-age observations (translucent black points) of Outside Quillback Rockfish from various gears and surveys. The dotted black line indicates the von Bertalanffy mean length-at-age estimated from all biological samples while the colored line indicate the empirical mean length-at-age from the gear and survey in the corresponding panel.

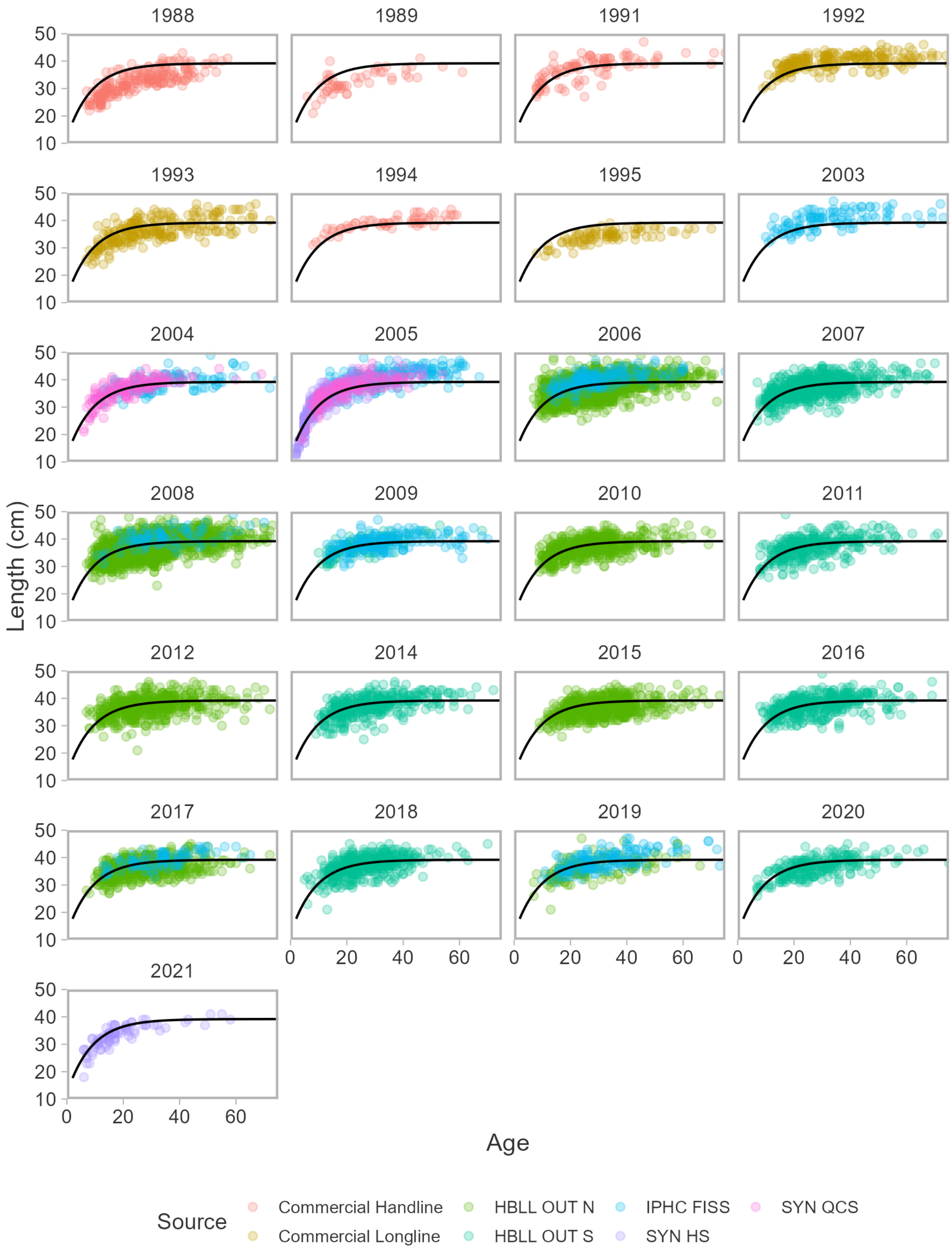

Figure A.8. Individual length-age observations (translucent black points) of Outside Quillback Rockfish from various gears and surveys through time. The black line indicates the von Bertalanffy mean length-at-age estimated from all biological samples.

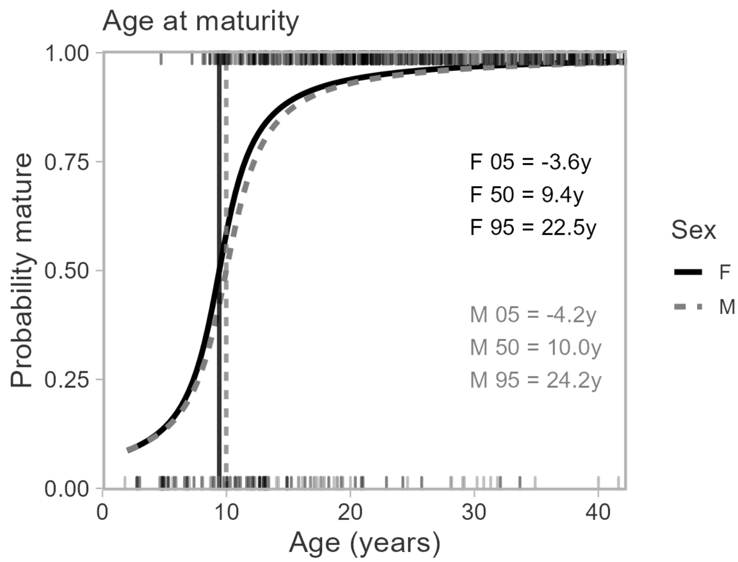

Figure A.9. Age-at-maturity ogive plots for Outside Quillback Rockfish. The solid black lines represent fits to female fish and the dashed grey lines represent fits to male fish. The vertical lines indicate the estimated age at 50% maturity. Text indicate the estimated age at 5, 50 and 95% maturity for females (F) and males (M). Short rug lines along the top and bottom represent up to 1500 randomly chosen individual fish with a small amount of random jittering to help differentiate individual fish.

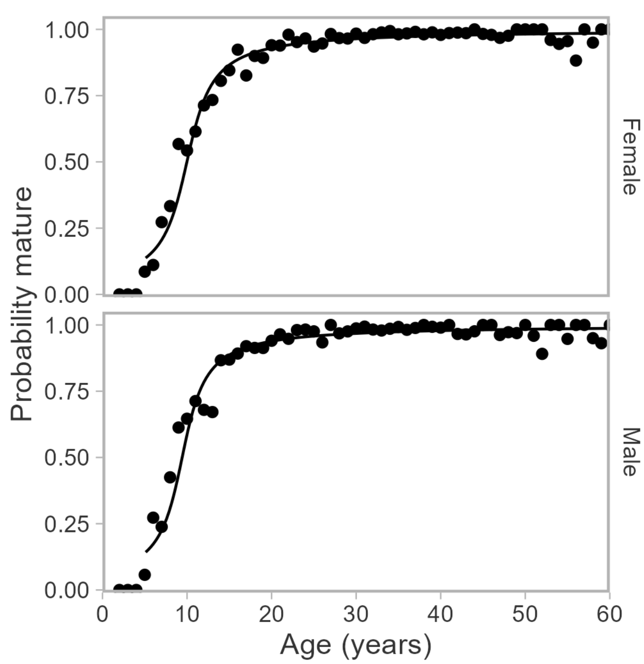

Figure A.10. Predicted and observed proportions mature-at-age.

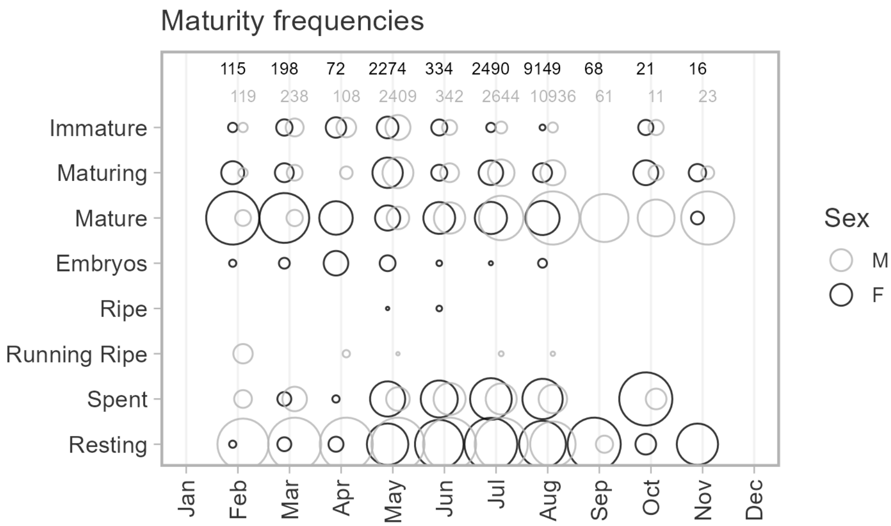

Figure A.11. Maturity frequency-by-month for Outside Quillback Rockfish. The area of each circle corresponds to the number of fish specimens in a given maturity category, based on macroscopic analysis, for the given month. Female fish are indicated by black circles and male fish are indicated by light grey circles behind. The total number of fish specimens for each month are indicated by the numbers at the top of the plot. To estimate the maturity ogive, all fish in the 'Mature' category and categories in the subsequent rows are considered to be mature.

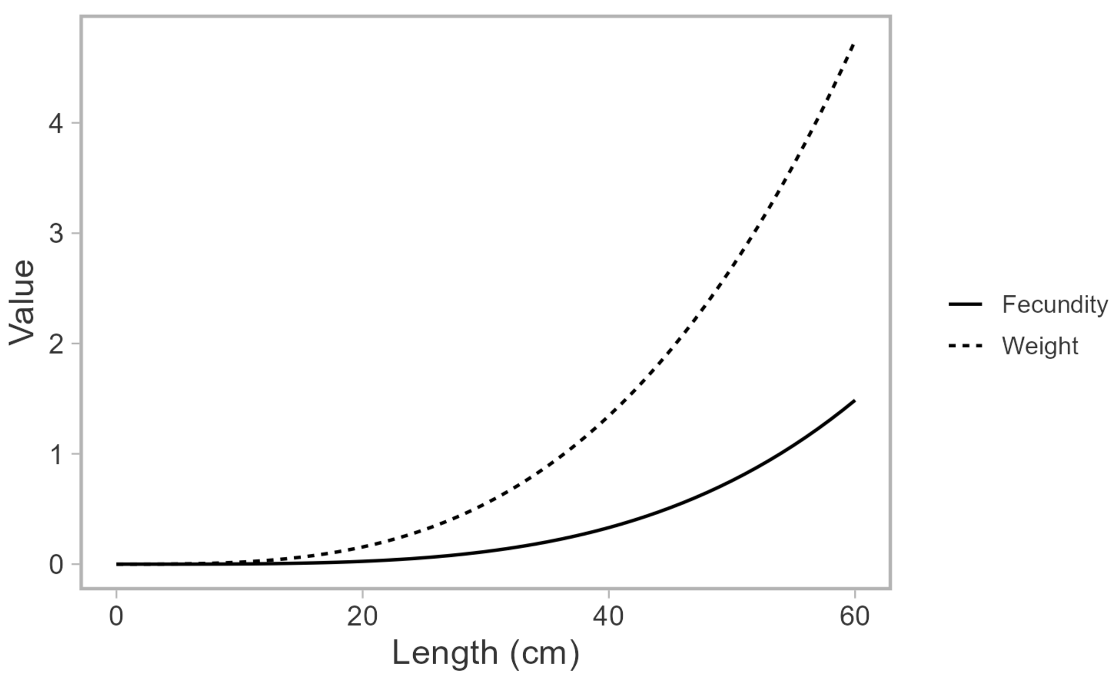

Figure A.12. Comparison of fecundity (units of eggs) and weight (kg) at length. Weight is typically used as a proxy of fecundity.

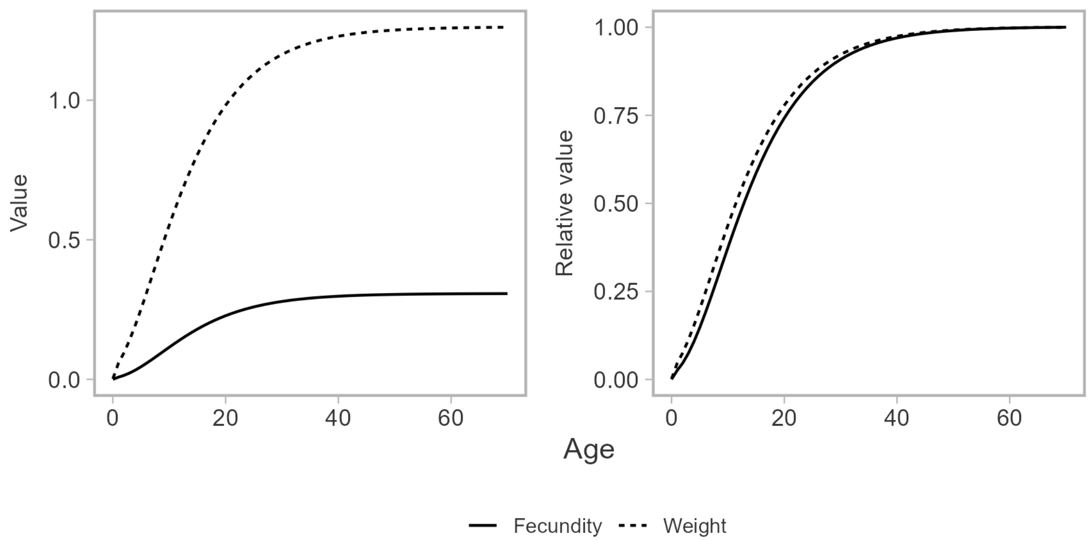

Figure A.13. Comparison of fecundity and weight at age after converting from length. Raw values are presented in the left panel, while values relative to the maximum in the oldest age is presented in the right panel.

APPENDIX B. FISHERY-INDEPENDENT SURVEY DATA

We conditioned the operating models using indices of abundance from three surveys. Survey design and modelling of indices for each survey are described here.

B.1. OUTSIDE HBLL SURVEY INDEX

The Outside HBLL Survey is conducted by DFO in collaboration with the Pacific Halibut Management Association (PHMA) and takes place on several chartered commercial fishing vessels each year since 2006. The HBLL survey covers most of the hard bottom, i.e., untrawlable habitats, of British Columbia coastline, excluding the inlets and protected waters east of Vancouver Island, i.e., excluding Statistical Areas 12-–20 and 27–29. The PHMA provides the chartered commercial fishing vessels and field technicians, while DFO provides support for running the surveys, including survey design and equipment. The survey excludes Rockfish Conservation Areas.

The survey has a depth-stratified (shallow: 20-70 m; medium: 71-150 m; deep: 151-260 m), random design consisting of 2 km by 2 km survey blocks. The survey uses size 14/0 circle hooks, baited with frozen squid. Each set has a two-hour soak time. Hook-by-hook data, which has been collected since the start of the survey, is electronically collected and stored in a database. For further details on survey design, see Doherty et al. (2019) and Yamanaka and Logan (2010).

The survey area is divided into northern and southern regions (Figure B.2), which are fished in alternating years. Both regions incorporate some parts of Management Areas 5B and 5C. The survey was not run in 2013. The 2012 survey covered the northern region and the 2014 continued the alternating scheme and sampled the southern region. Design-based indices are generated by the GF synopsis report (Figure B.1).

We applied a geostatistical spatiotemporal model to standardize a coastwide index (e.g., Shelton et al. 2014; Thorson et al. 2015; Anderson et al. 2019) that account for habitat effects, hook competition, and alternating-year survey coverage (Section B.1.2). Additionally, an annual index for a subset of areas that cross the northern and southern boundaries of the survey design is possible through this approach. Previous work indicated that this approach can stitch together the north and south survey regions with relatively little bias to generate an index for an entire region (Haggarty et al. 2021).

B.1.1. HOOK COMPETITION

A longline index of species abundance may not be proportional to actual abundance under certain conditions. For example, if there is a high degree of competition among species for baited hooks, the actual catch may not accurately reflect the true abundance of less competitive species (Kuriyama et al. 2018). A large component of HBLL survey catch includes North Pacific Spiny Dogfish (*Squalus suckleyi*; hereafter “Dogfish”), which are potentially a major hook competitor with rockfishes (Obradovich 2018). As in Yamanaka et al. (2011), we applied a hook competition correction, which accounts for the competition between individual fish for the bait on hooks and gear saturation, to the HBLL survey catch rate. To apply the correction, a competition adjustment factor is estimated for each individual set. This adjustment factor, $A_{i,t}$, scales up the observed number of Quillback Rockfish caught, $N_{i,t}$, for each set i in year t to give the expected number of fish caught after accounting for competition, $N_{i,t}^{(0)}$:

$$N_{i,t}^{(0)} = A_{i,t} N_{i,t}. \tag{B.1}$$

The adjustment factor is calculated from the proportion of observed hooks that are returned with bait still on them, $P_{i,t}$ (Figure B.4):

$$A_{i,t} = \frac{-\log(P_{i,t})}{1 - P_{i,t}}. \tag{B.2}$$

As $P_{i,t} \to 0$, $A_{i,t} \to \infty$, the expected number $N_{i,t}^{(0)} \to \infty$. Therefore, in cases where zero hooks were returned with bait, we set the number of baited hooks to one. For further details on the hook competition correction, see Anderson et al. (2019) (their Appendix G, Section G.5). The catch rate adjusted for hook competition (Figure B.5) were used in the spatiotemporal model to develop the index of abundance.

B.1.2. GEOSTATISTICAL MODEL

We fit a spatiotemporal generalized linear mixed model (GLMM) of the form:

$$y_{s,t} \sim \mathrm{Tweedie}\left(\mu_{s,t}, \phi, p\right) \tag{B.3}$$

$$\mu_{s,t} = \exp\left(\boldsymbol{X}_{s,t}\boldsymbol{\beta} + O_{s,t} + \boldsymbol{\omega_s} + \boldsymbol{\epsilon_{s,t}}\right), \tag{B.4}$$

where $y_{s,t}$ is the observed catch count at spatial point s and time t and is modeled from a Tweedie distribution, ϕ is the Tweedie dispersion parameter, p is the Tweedie power parameter ($1 < p < 2$), $\mu_{s,t}$ is the expected value, $\boldsymbol{X}$ is the design matrix, and $\boldsymbol{\beta}$ is the corresponding vector of estimated coefficients. The offset $O_{s,t}$ with a fixed coefficient of 1 is $\log\left(S_{i,t}/A_{i,t}\right)$, where $S_{i,t}$ represents the area "swept" by the set. The area swept (km^2) is based on the number of hooks in the set ($N_{i,t}^{\mathrm{hooks}}$):

$$S_{i,t} = N_{i,t}^{\mathrm{hooks}} \times 0.0024384 \times 0.009144 \times 1000. \tag{B.5}$$

The value 0.002438 corresponds to the spacing between hooks (8 ft) in km, 0.009144 to an assumed 30 ft area swept around the set that fish are catchable (in km), and 1000 scales the area swept from km to m. Note that the 30 ft assumption only serves to scale the density up or down for all years, which ultimately affects the catchability estimate of the survey but does not influence the trend in the index. With the Tweedie distribution, the variance of $y_{s,t}$ is a power function of the mean, i.e., $\mathrm{Var}(y_{s,t}) = \phi\mu_{s,t}^{p}$, which provides more flexibility in fitting over the Poisson and negative binomial distributions.

The spatial random effects (ω_s) are constrained by a multivariate normal distribution with a covariance matrix $\boldsymbol{\Sigma}_\omega$:

$$\boldsymbol{\omega} \sim \mathrm{MVNormal}\left(\boldsymbol{0}, \boldsymbol{\Sigma}_\omega\right). \tag{B.6}$$

We constrained the spatial random effects to follow a Matérn covariance function, which defines the rate at which spatial correlation decays with distance.

The Matérn function describes the covariance $\Phi_\omega\left(s_j, s_k\right)$ between spatial locations s_j and s_k as:

$$\Phi_\omega\left(s_j, s_k\right) = \tau_\omega^2/\Gamma(\nu)2^{\nu-1}(\kappa d_{jk})^\nu K_\nu\left(\kappa d_{jk}\right), \tag{B.7}$$

where $\tau_\omega = \frac{0.5}{\sigma_\omega \kappa \sqrt{\pi}}$ determines the spatial variance σ_ω, Γ is the Gamma function, K_ν is the Bessel function, d_{jk} is the Euclidean distance between locations s_j and s_k, and κ is the estimated range parameter. The ν parameter controls the smoothness of the covariance function. We set $\nu = 1$, which lets us take advantage of the Stochastic Partial Differential Equation (SPDE) approximation to Gaussian Markov Random Fields (GMRF) to greatly increase computational efficiency (Lindgren et al. 2011).

Two methods of modeling the spatiotemporal random effects $\boldsymbol{\epsilon}$ were considered here. First, $\boldsymbol{\epsilon}$ can be independent among years with covariance matrix $\boldsymbol{\Sigma}_\epsilon$:

$$\boldsymbol{\epsilon}_t \sim \mathrm{MVNormal}\left(\mathbf{0}, \boldsymbol{\Sigma}_\epsilon\right). \tag{B.8}$$

Covariance matrix $\boldsymbol{\Sigma}_\epsilon$ is also constrained to follow a Matérn covariance function with the same κ parameter as for the spatial random effects, but unique τ parameter:

$$\Phi_\epsilon\left(s_j, s_k\right) = \tau_\epsilon^2 / \Gamma(\nu) 2^{\nu-1} (\kappa d_{jk})^\nu K_\nu\left(\kappa d_{jk}\right). \tag{B.9}$$

where $\tau_\epsilon = \frac{0.5}{\sigma_\epsilon \kappa \sqrt{\pi}}$ determines the spatiotemporal variance σ_ϵ. For simplicity, the Matérn function described here is isometric (spatial correlation is the same in all directions), but we allowed for anisotropy in the spatial and spatiotemporal correlation (e.g., Thorson et al. 2015). The effective range is dependent on direction and is calculated as the product of the range parameter and the two-dimensional rotation matrix.

Second, $\boldsymbol{\epsilon}_t$ can be modeled as a random walk over time, where

$$\boldsymbol{\epsilon}_t = \boldsymbol{\epsilon}_{t-1} + \delta_t \tag{B.10}$$

$$\delta_t \sim \mathrm{MVNormal}\left(\mathbf{0}, \boldsymbol{\Sigma}_\epsilon\right), \tag{B.11}$$

The spatial random effects implicitly accounted for spatial factors that affect abundance and are constant across time, for example, depth and substrate type. The spatiotemporal random effects implicitly accounted for factors that varied spatially from year-to-year, such as bottom temperature, water circulation patterns, species interactions, and species movement.

With a random walk, the change in the spatiotemporal field can constrain the change in the index. This feature can be desirable for a rockfish species because demographically, total abundance cannot rapidly fluctuate from year to year for a long-lived species. Due to the smoothing nature of the random walk, it is also recommended to regularly compare indices amongst various model configurations as well as with the design-based index to ensure that spurious trends are not estimated.

We fit our model with the sdmTMB R package (Anderson et al. 2022c). For the spatial and spatiotemporal random effects, a mesh with 250 predictive-process knots was generated by INLA (Lindgren et al. 2011; Rue et al. 2016) with locations determined by a K-means clustering algorithm (Figure B.6). We estimated the fixed effects via maximum likelihood with the random effects set to the values that maximized the joint likelihood conditional on the estimated value of fixed effects. With the estimated random effects at the knots, the value of the random effect at spatial point s is obtained by bilinear interpolation along the mesh (Figure B.6).

Four spatiotemporal GLMMs were fitted and varied by the structure of the spatiotemporal random effects and covariates used:

- Model 1: Year effects were estimated as independent fixed effects (and corresponding spatiotemporal effects were IID). Habitat variables, i.e., depth and substrate, were also included in the design matrix to explain survey catch rates. Therefore, the random effects incorporate processes that affect distribution but is not accounted for by depth and substrate.
- Model 2: Spatiotemporal effects were estimated as a random walk. Habitat variables remained as fixed effects. The year effects are not longer in the design matrix but implicitly incorporated in the random walk structure.
- Model 3: Same as Model 2, but no habitat fixed effects are included. In this way, the random effects implicitly incorporate all processes that affect animal distribution.

- Model 4: Same as Model 2 but the effort offset no longer includes the hook competition adjustment factor (swept area only).

Habitat variables include the depth at the set location and distance to rock substrate and mixed substrate, chosen based on previous analyses (Carrasquilla-Henao et al. 2021). Substrate geospatial data for the BC coast were obtained from Gregr et al. (2021) (Figure B.7). The distance of each survey set to the nearest cell identified as rock substrate and mixed substrate was calculated. Habitat covariates were then transformed into Z-scores in log-space for fitting so that estimated effect sizes were on the same order of magnitude. The depth variable in the design matrix included a quadratic term because catch rates were highest between 50–100 m in the survey (Figure B.8).

From the fitted models, stock density was predicted to the full survey domain using the estimated fixed and random effects and the bilinear interpolation mesh provided by INLA (Lindgren et al. 2011; Rue et al. 2016) (Figures B.6 and B.9).

We then calculated the expected index I_t in year t as:

$$I_t = \sum_j w_j \times \exp\left(\boldsymbol{X}_{j,t}\boldsymbol{\beta} + \boldsymbol{\omega_j} + \boldsymbol{\epsilon_{j,t}}\right), \tag{B.12}$$

where j references a grid cell within the survey domain and w_j represents the area of that grid cell (Figure B.9). In other words, the index is the sum of the predicted abundance across all grid cells within the survey domain for each year. We generated standard errors on the annual estimates of the log of the index via the delta method implemented in TMB (Kristensen et al. 2016). In terms of the model components, the fixed effects and spatial random effects were, by definition, constant across years, while the spatiotemporal random effects are year-specific. A coastwide index as well as area-specific indices for 5A3CD and 5BCDE were developed.

The resulting standardized population index accounts for any irregular sampling of the survey domain, hook competition, and “stitches” the northern and southern regions together for the coastwide index. The random walk in spatiotemporal random effects can also impute the abundance across unsampled areas and years through the statistical properties of the random walk and spatial autocorrelation in the random effects.

B.1.3. MODEL COMPARISON

Overall, trends in the estimated index are similar among the four spatiotemporal GLMMs (Figure B.10). The index in the North (5ABCDE) has been increasing since 2006 while the index in the South (5BCDE) is relatively more constant. The ratio of the index in the North and South, indicative of relative stock size, are similar as in the design-based index, although the area boundaries between indices differ (Figure B.1).

The inclusion of the random walk in Models 2-4 vs. 1 smooths out the trend in the index over time. There are residual inter-annual differences in the index in Model 1 due to the survey sampling location in the particular year that could not be resolved without the random walk structure. In other words, Model 1 is incorrectly assigning spatial effects as year effects.

In Models 1-3, the hook adjustment factor provides higher abundance estimates compared to Model 4, as expected, but trends are not appreciably different among models. There are apparent differences in the index during 2019–2021, particularly in the North (Figure B.10). Nominal catch rates are slightly decreasing, but inclusion of hook competition returns a more stable index.

When habitat covariates are included in the design matrix, all estimated coefficients were statistically significant at $\alpha = 0.05$, with higher catch rates expected closer to rock and mixed substrate (Table B.2). The coefficient of the quadratic term for depth was negative because catch rates are downwards concave with respect to depth (Figure B.8). With habitat covariates in Model 2, the magnitude of the index is smaller than in Model 3 because the depth covariate predicts little to no abundance of Quillback Rockfish at cells of deeper waters (> 150 m) in the prediction grid.

Model 2 has a lower AIC score than Model 3 with ΔAIC > 1100 and is the preferred model for the HBLL index (Table B.3). The spatial random effects show a onshore-offshore gradient consistent with decreasing abundance predicted in non-rocky habitat further from shore, for example, off of the West Coast of Vancouver Island (Figure B.11). The spatiotemporal time series show a gradual change consistent with the random walk (Figure B.12).

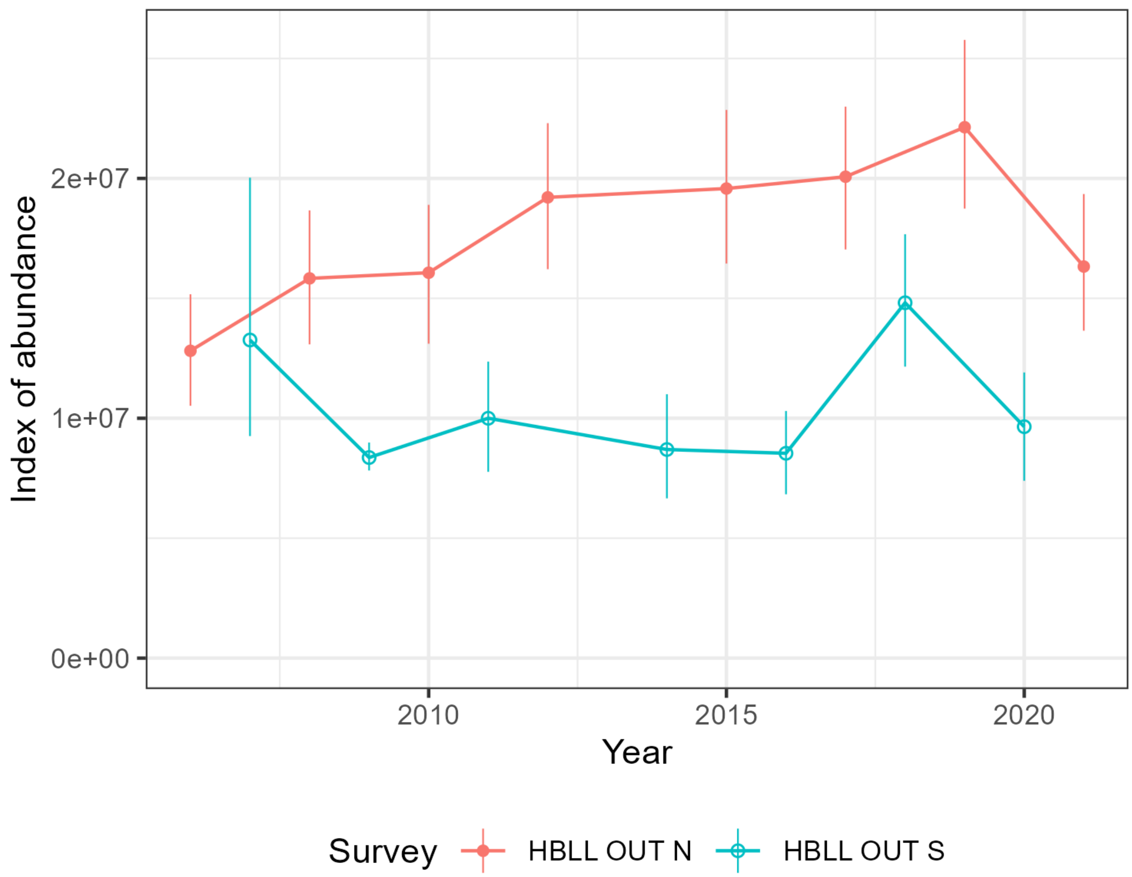

Figure B.1. Design-based indices from the HBLL survey, as reported through the GF synopsis report. The northern index consists of area 5DE and some parts of 5BC, while the southern index consists of 5A3CD and parts of 5BC. Unlike the spatiotemporal model, the design-based index cannot account for missing time-area strata to calculate a coastwide index. This index does not incorporate hook competition.

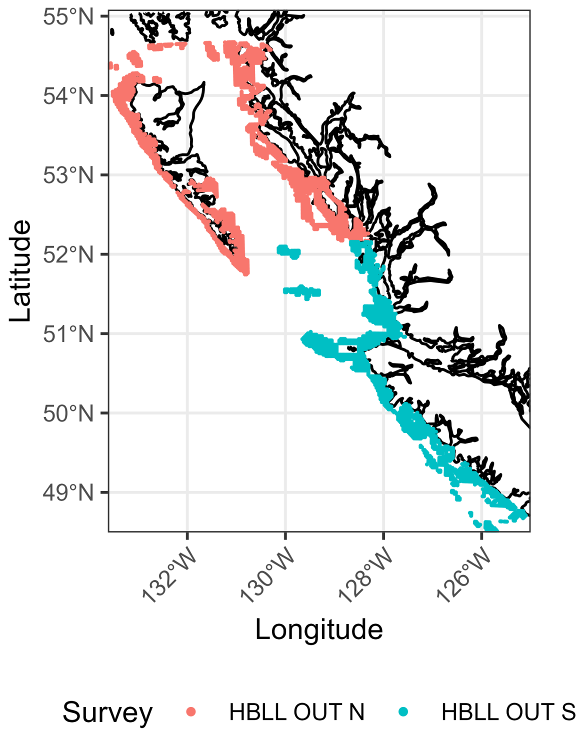

Figure B.2. Map of HBLL survey blocks indicating the northern and southern regions.

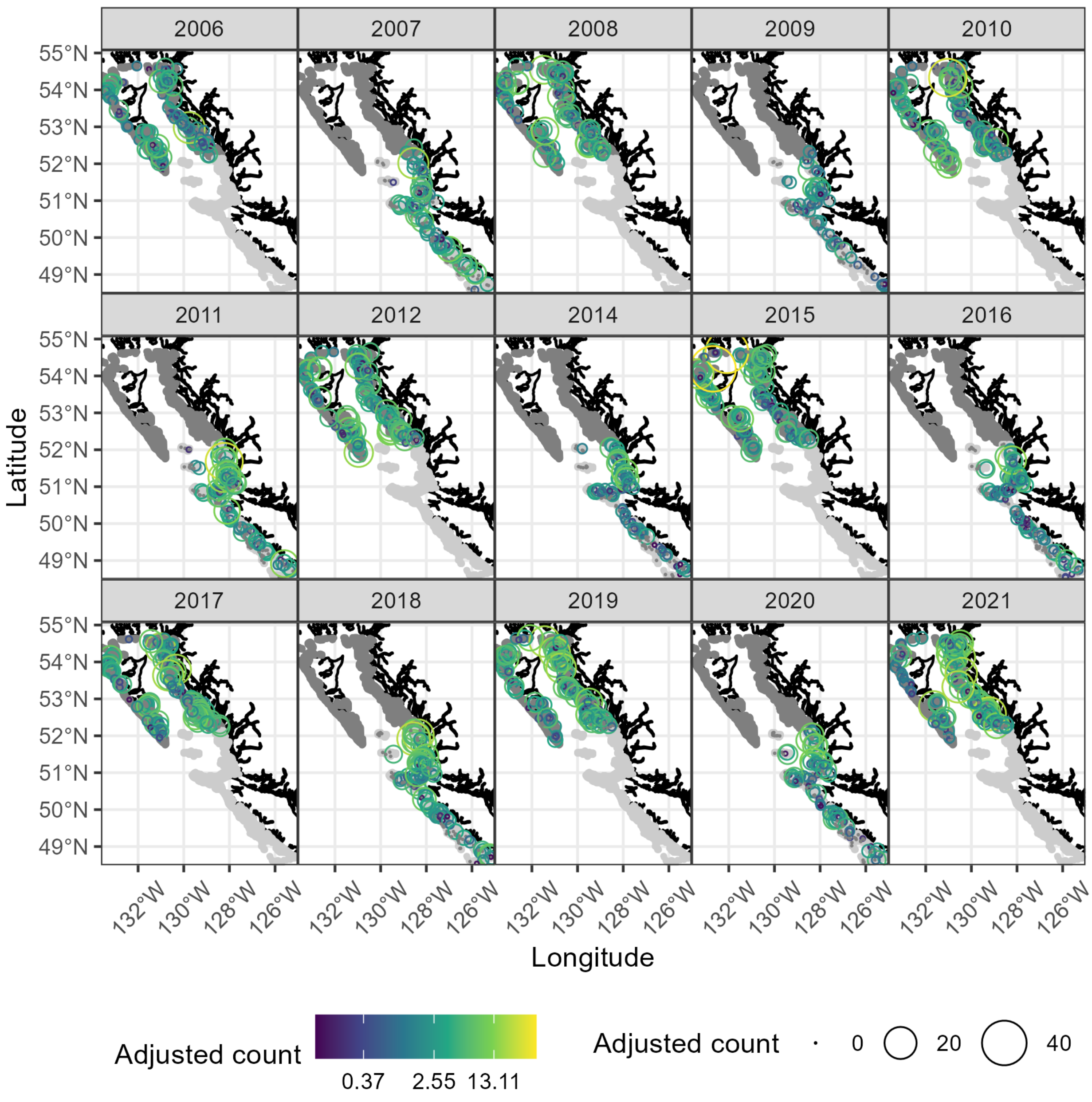

Figure B.3. Outside HBLL survey observations of Quillback Rockfish. Grey background shading indicates the northern and southern survey areas. The area of the circles represents the number of fish caught per hook after accounting for hook competition.

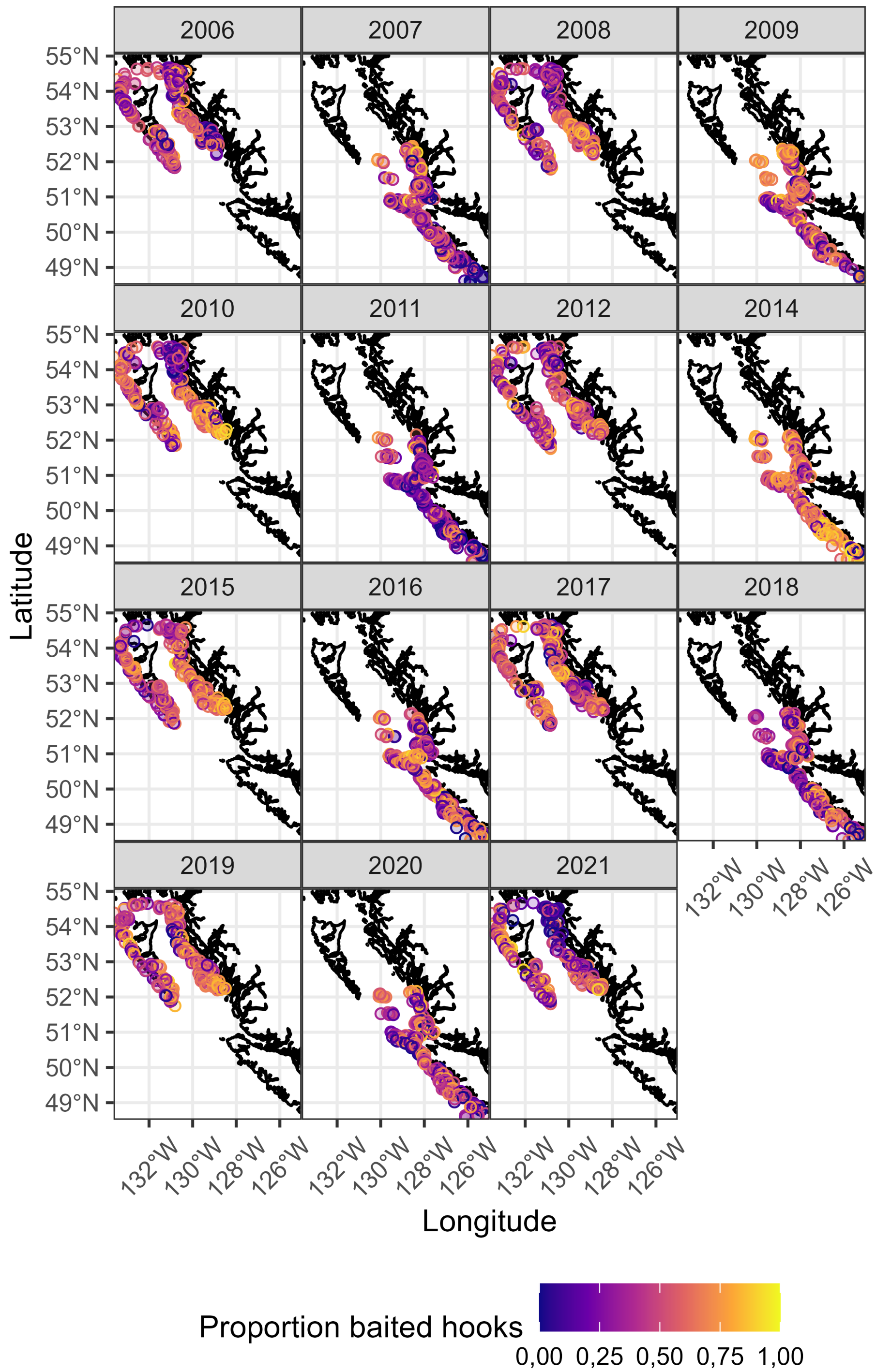

Figure B.4. Proportion baited hooks returned for the outside HBLL survey. Note the low values in the northern survey in 2019.

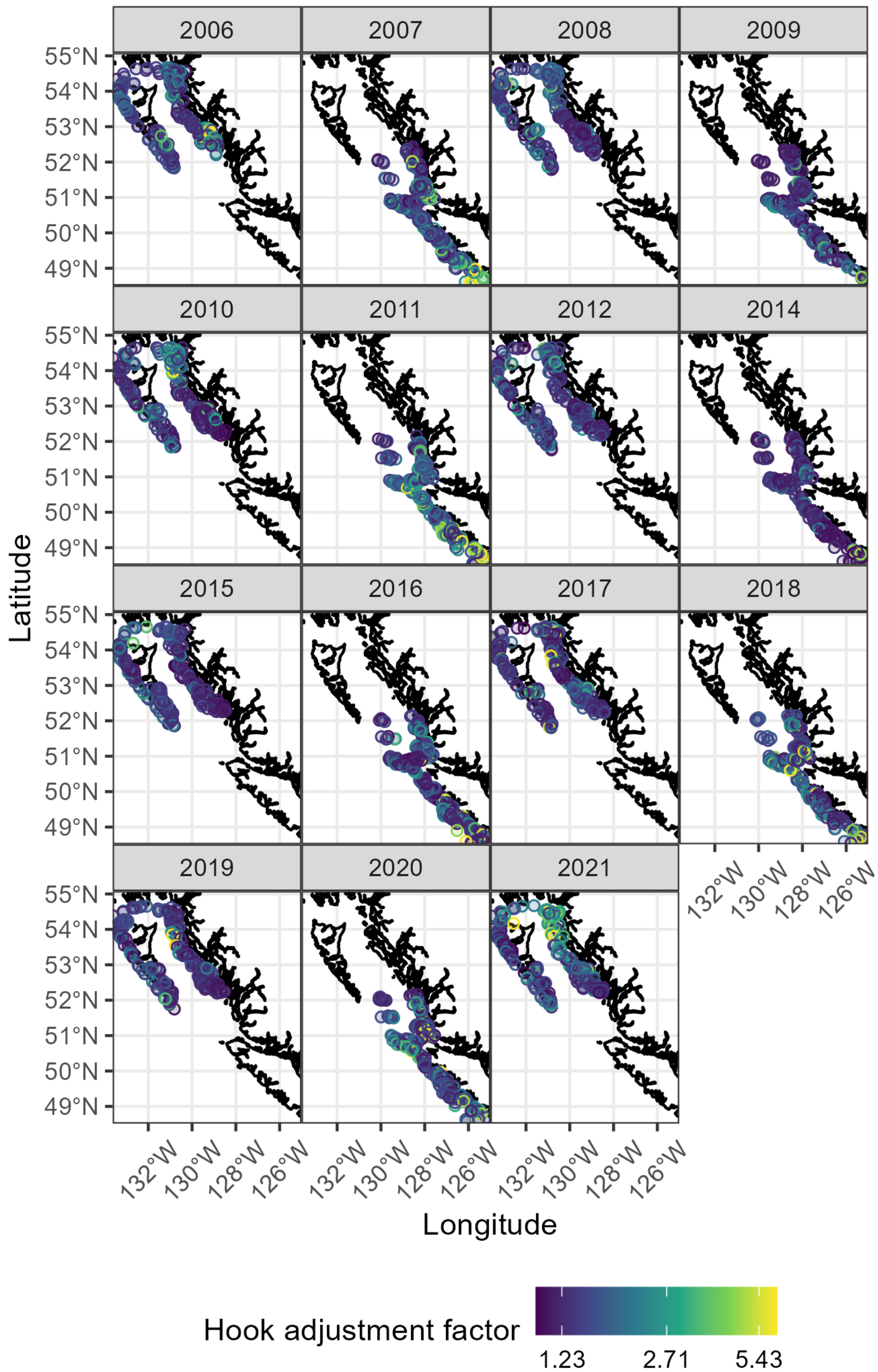

Figure B.5. Hook adjustment factor for the outside HBLL survey accounting for the number of hooks and the number of returned baited hooks.

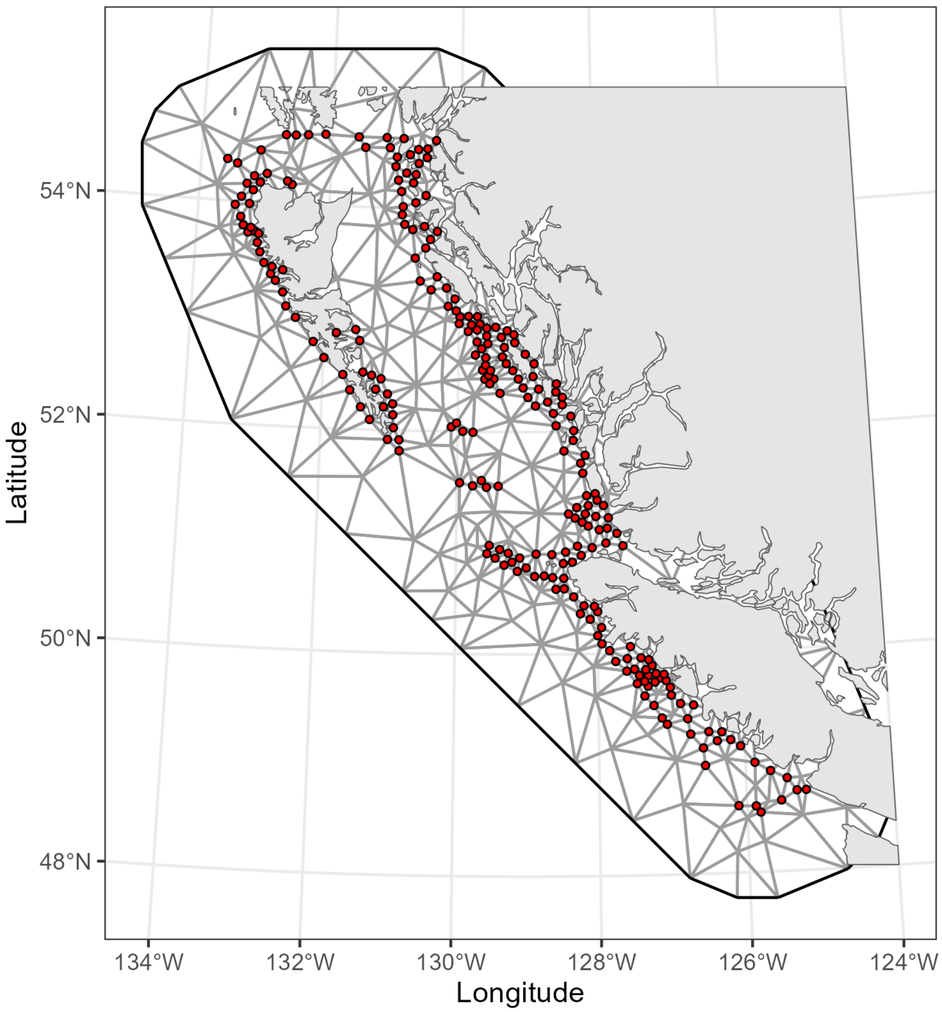

Figure B.6. Stochastic Partial Differential Equation (SPDE) mesh for the HBLL. The red dots represent the 250 knots made from k-means clustering of the spatial coordinates of the survey sets (across all years). These knots are then used to make the triangularization mesh used in the SPDE approximation and bilinear interpolation (grey lines). A greater number of knots will increase the accuracy of the approximation at the expense of computational time.

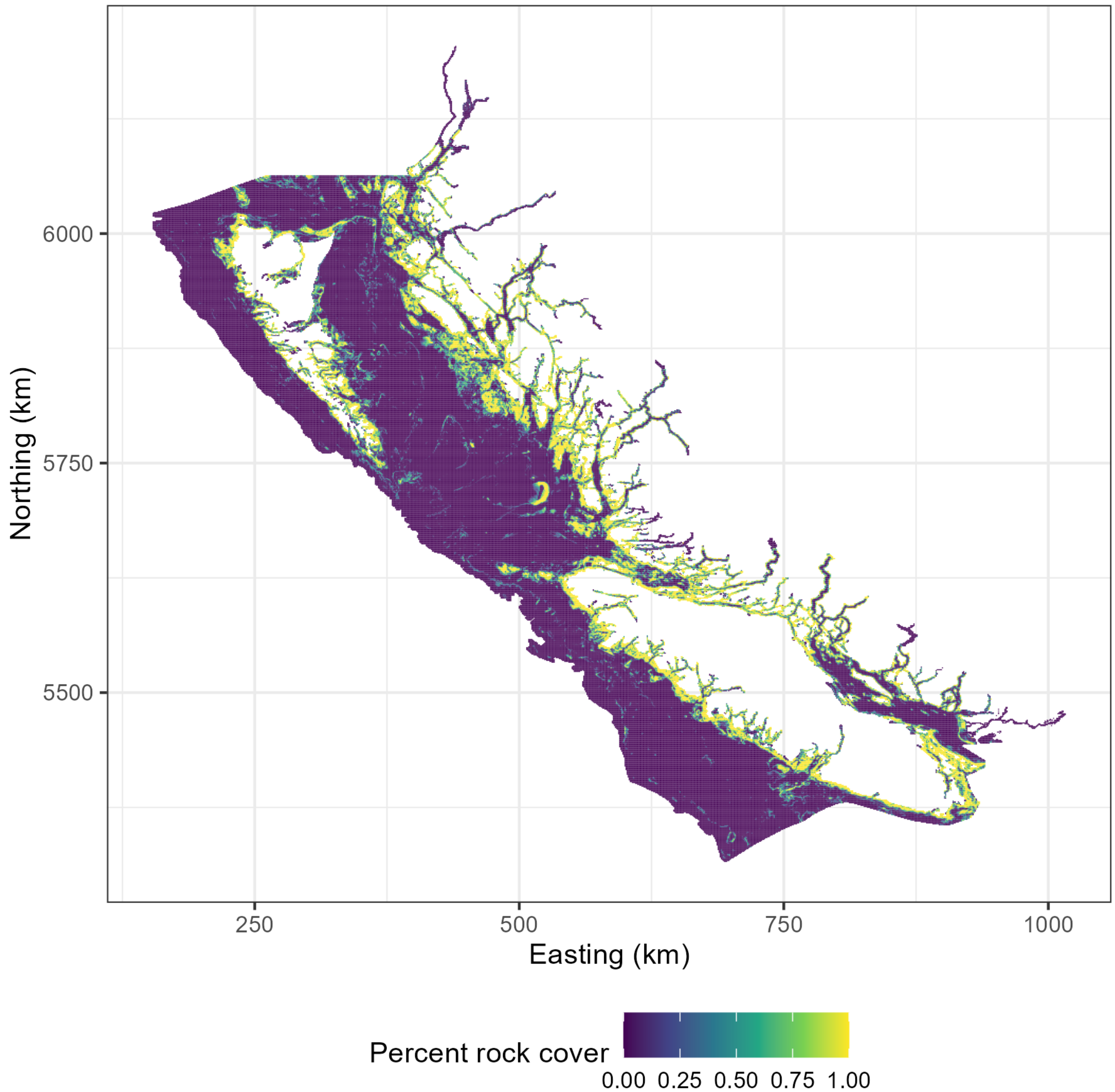

Figure B.7. Substrate map for the BC coast (Gregr et al. 2021). The substrate was predicted for each 100 x 100 m cell. Here, the percent rock cover is calculated as the proportion of cells identified as rock substrate within each 1 km x 1 km grid. UTM coordinates, which facilitates calculation of Euclidean distance between points, are presented here.

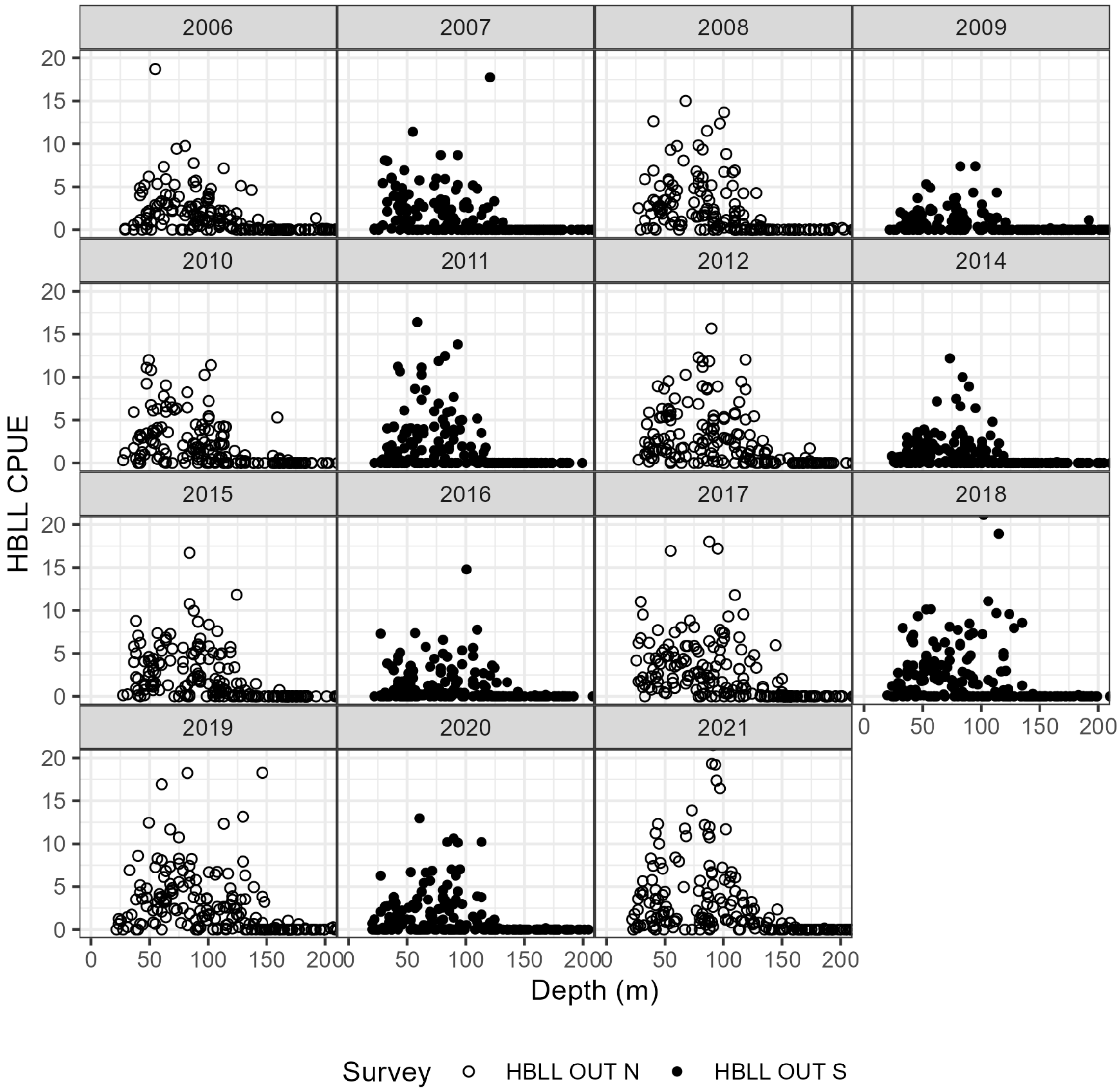

Figure B.8. Catch rates from individual sets in the outside HBLL survey as a function of depth.

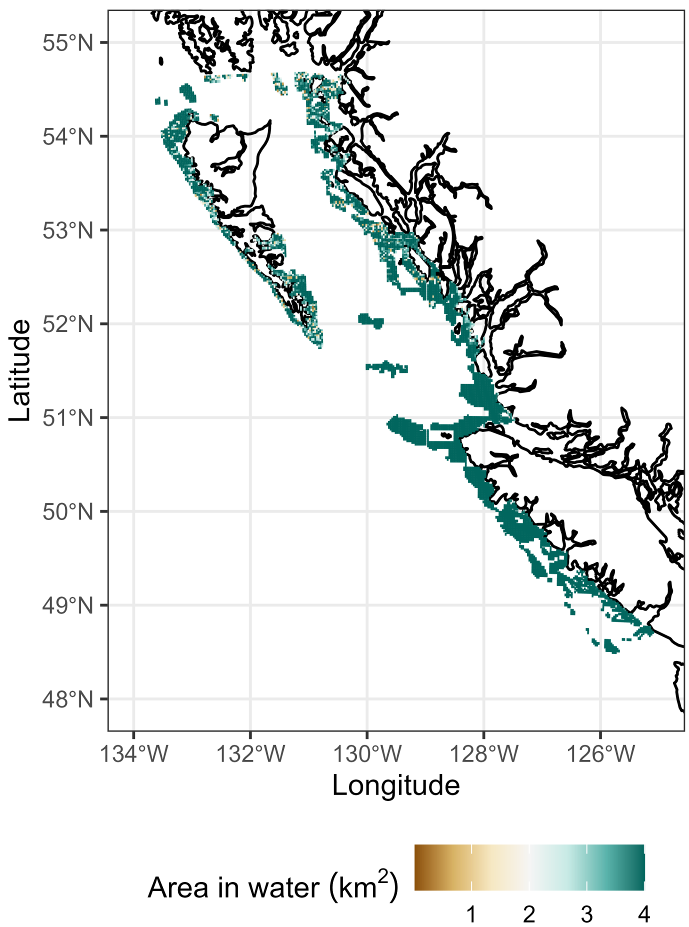

Figure B.9. Area per survey grid cell that is in water for the outside HBLL survey. The predicted count density for each grid cell is scaled up to the full survey domain based on these areas.

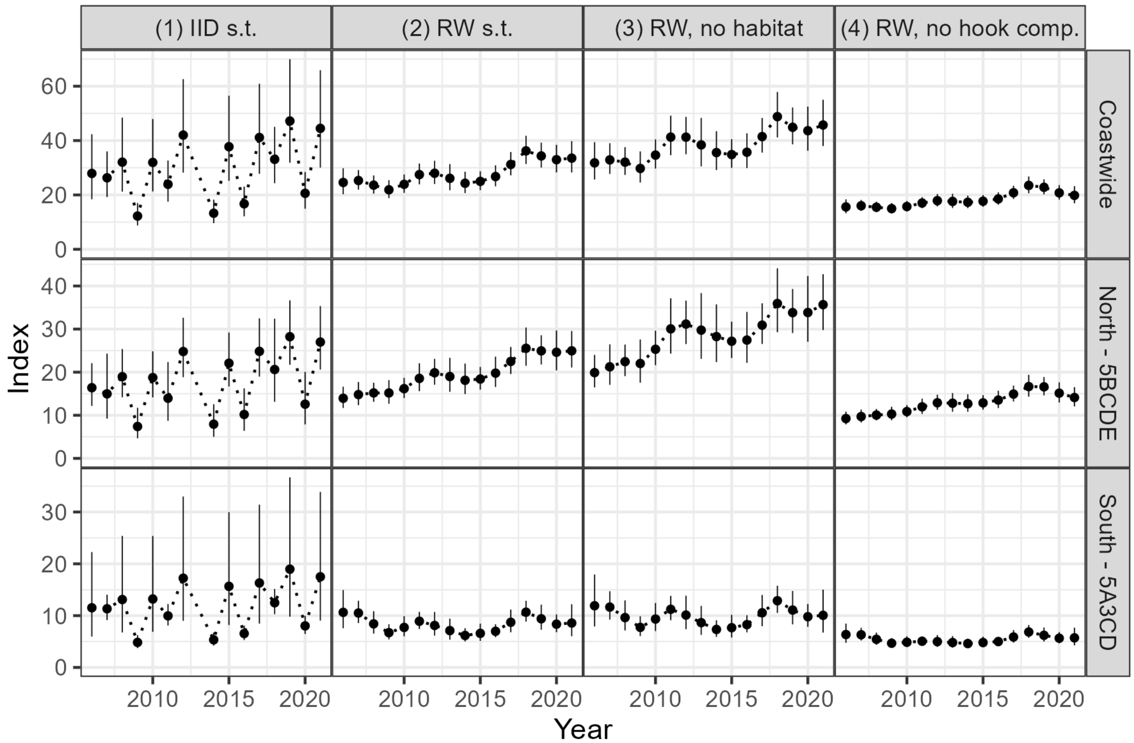

Figure B.10. Comparison of four indices of abundance (units of thousands of fish) from the outside HBLL survey: (1) Fixed year effects with habitat covariates, (2) Random walk in spatiotemporal random effects with habitat covariates, (3) Random walk with no habitat covariates, and (4) Random walk with no hook competition adjustment factor. Vertical lines span the 95% confidence interval. The preferred index series is from Model 2.

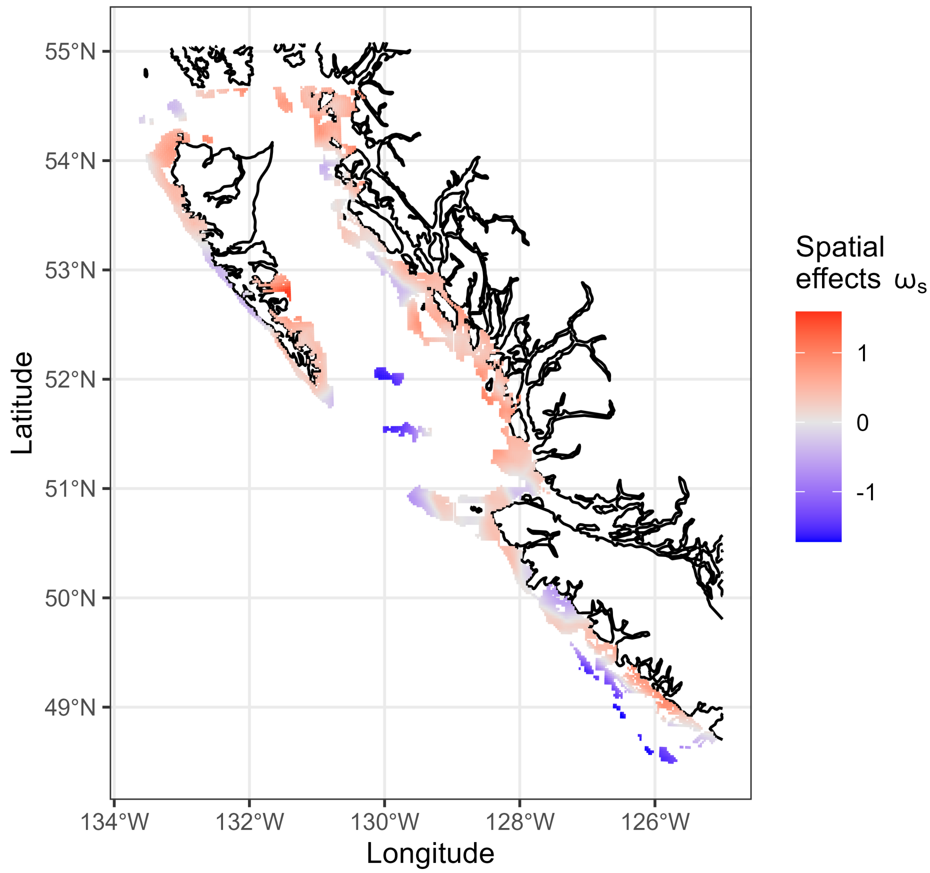

Figure B.11. Spatial random effects from GLMM Model 2. These are consistent spatially correlated differences in expected abundance through time. The values are shown in link (log) space.

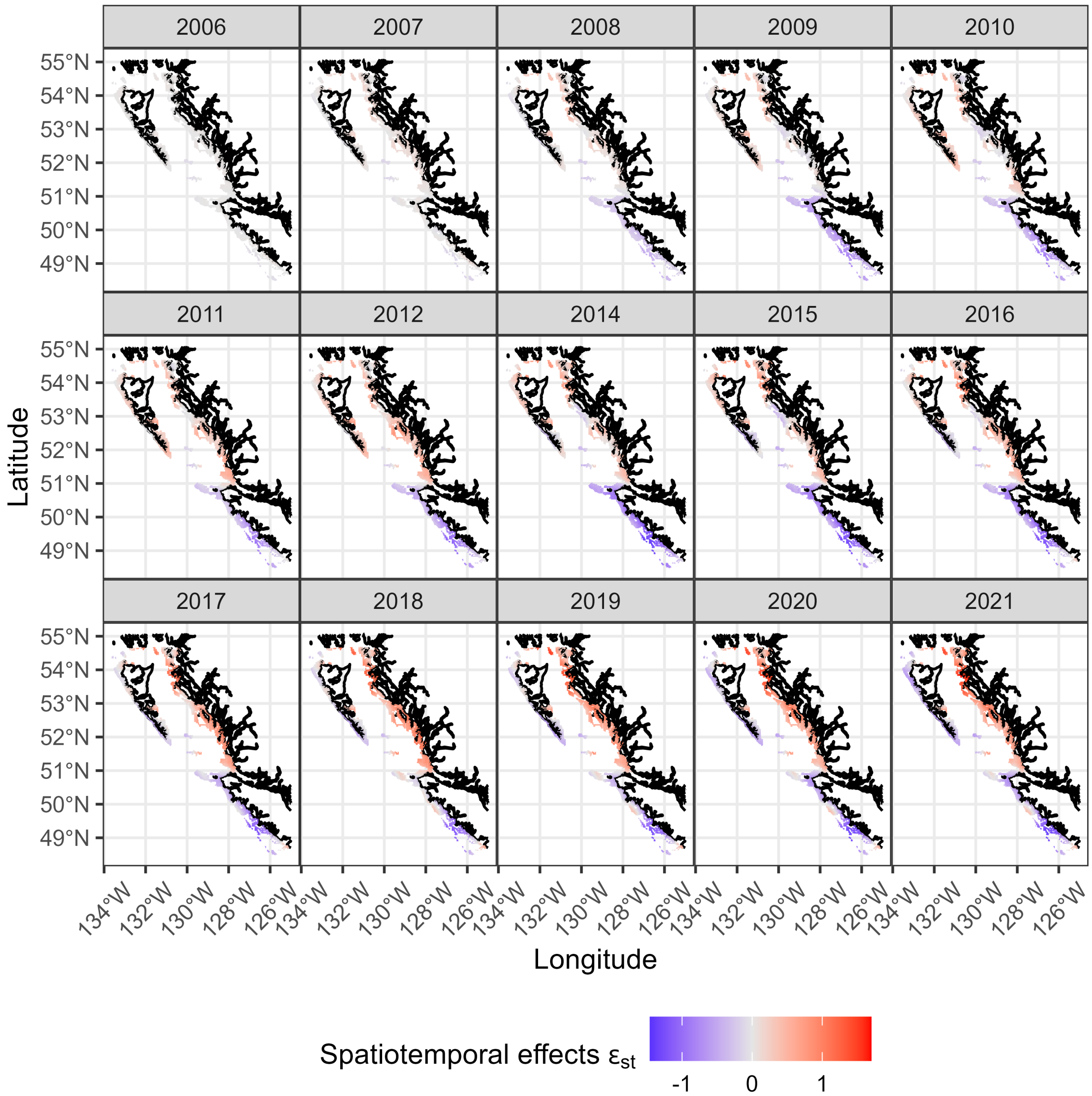

Figure B.12. Spatiotemporal random effects from GLMM Model 2. These are spatially correlated deviations that change through time. The variance in spatiotemporal random effects is higher than in the spatial random effects (previous figure).

Table B.1. Summary of the Outside HBLL Survey.

Year	Number of sets	Number of positive sets	Proportion positive
2006	188	109	0.58
2007	195	81	0.42
2008	187	102	0.55
2009	182	71	0.39
2010	191	111	0.58
2011	196	85	0.43
2012	195	125	0.64
2014	194	93	0.48
2015	195	118	0.61
2016	197	99	0.50
2017	197	121	0.61
2018	196	106	0.54
2019	195	128	0.66
2020	196	91	0.46
2021	197	127	0.64

Table B.2. Estimated parameters from the four spatiotemporal GLMMs for the outside HBLL survey. Asterisks indicate the fixed effects (habitat covariates and intercept terms) that were significant at the 5% level. All other parameters are nuisance parameters and significance was not evaluated. The range parameter is in units of km. sigma_O and sigma_E are the standard deviation of the spatial and spatiotemporal field, respectively. Fixed year effects in Model 1 are not reported here.

Term	Model 1	Model 2	Model 3	Model 4
depth_scaled, degree 1	-1.65*	-1.64*	NA	-1.63*
depth_scaled, degree 2	-0.98*	-0.98*	NA	-0.95*
drock_scaled	-0.21*	-0.2*	NA	-0.22*
dmix_scaled	-0.13*	-0.13*	NA	-0.13*
range	54	123	188.00	117
phi	5.23	5.35	6.45	5.35
sigma_O	0.94	1.17	8.47	1.25
tweedie_p	1.37	1.37	1.40	1.36
sigma_E	0.39	0.27	0.26	0.21
(Intercept)	NA	0.14	-5.09	-0.39

Table B.3. Estimated outside HBLL index from GLMM model 2 with the lognormal standard error in parentheses.

Year	Coastwide	North - 5BCDE	South - 5A3CD
2006	24.58 (0.10)	13.94 (0.09)	10.64 (0.17)
2007	25.30 (0.07)	14.80 (0.09)	10.51 (0.10)
2008	23.59 (0.07)	15.18 (0.07)	8.41 (0.13)
2009	21.89 (0.08)	15.17 (0.09)	6.71 (0.11)
2010	23.90 (0.07)	16.18 (0.07)	7.72 (0.13)
2011	27.47 (0.07)	18.55 (0.09)	8.92 (0.09)
2012	27.97 (0.08)	19.86 (0.08)	8.11 (0.14)
2013	26.10 (0.09)	18.99 (0.10)	7.12 (0.14)
2014	24.29 (0.08)	18.12 (0.10)	6.17 (0.10)
2015	24.98 (0.07)	18.40 (0.07)	6.58 (0.13)
2016	26.75 (0.07)	19.78 (0.09)	6.98 (0.09)
2017	31.20 (0.07)	22.49 (0.07)	8.71 (0.13)
2018	36.21 (0.07)	25.54 (0.09)	10.67 (0.10)
2019	34.34 (0.07)	24.94 (0.07)	9.39 (0.13)
2020	32.97 (0.08)	24.62 (0.10)	8.35 (0.10)
2021	33.53 (0.09)	24.95 (0.09)	8.58 (0.18)

B.2. IPHC SURVEY

The International Pacific Halibut Commission (IPHC) has conducted an annual fishery-independent setline survey (FISS) in BC coastal waters since 1995. The survey is intended to index population trends of Pacific halibut but incidentally catches rockfish species. The sampling design of the survey in BC waters has changed over time. Between 1995–1997, the survey had a spatially triangular station design (Figure B.13). In 1998, stations were re-organized and evenly spaced in northern BC (5ABCDE), then expanded down into West Coast Vancouver Island (WCVI, Areas 3CD) in 1999 (Figure B.14). In 2018, the new expansion stations were added to the survey. In 2020, only the stations in 5ABCDE (excluding WCVI) were sampled. A random subset of WCVI stations are sampled for 2021–2023 (Wilson et al. 2020), and it is likely that this sampling scheme will continue into 2025 (Webster and Wilson 2023).

The resolution at which rockfish catch is recorded in the IPHC FISS survey has varied depending on the availability of a third technician. In some years, catch is recorded on a hook-by-hook or set level, whereas in other years, only the catch in the first 20 hooks per skate is recorded (Anderson et al. 2019).

Unlike the HBLL survey, the IPHC survey frequently does not target rockfish habitat. Many stations have never caught Quillback Rockfish, with positive sets ranging between 5-20% annually (Figure B.14; Table B.4). Here, we develop an index from fixed stations that have caught for Quillback Rockfish in at least one year, as was done for the Outside Yelloweye Rockfish IPHC Index (Cox et al. 2020). The index started in 1998, excluding the sets that used the previous station design during 1995–1997. Expansion stations introduced since 2018 were also excluded (see Figure B.14).

We develop the index from bootstrapped mean catch rate (numbers caught per effective skate) from the individual set data in the `gfiphc` package (Edwards et al. 2022). The effective skate number determined by the number of observed hooks baited with Chum Salmon (Anderson et al. 2019). Two indices can be developed, either from catch from all hooks or from 20 hooks. With the 20 hooks subsample, there are fewer positive sets (Table B.4). The time series using catch per 20 hooks is longer but with lower precision than catch from all hooks (Doherty and Haggarty 2022).

Separate indices were developed for the North (5BCDE) and South (5A3CD) regions from the location of the fixed stations (Figure B.15). No index was calculated in 2000 and 2020 for the 5A3CD index because WCVI was not sampled.

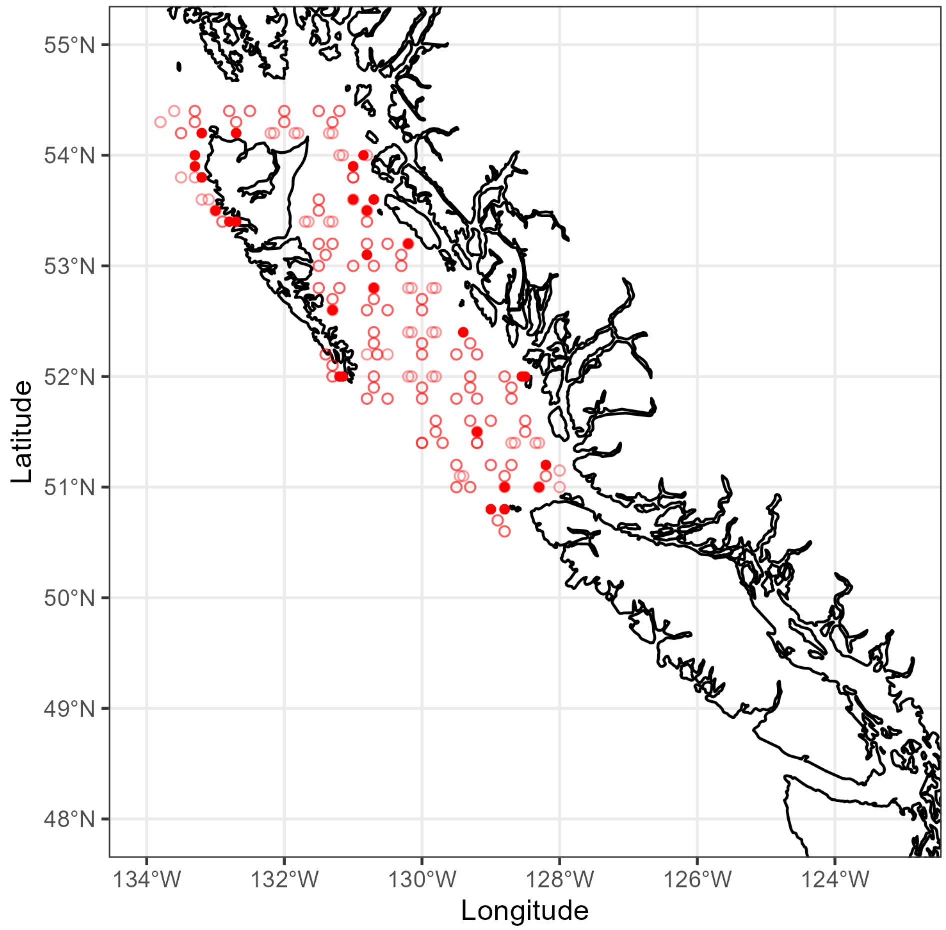

Figure B.13. Fixed stations of the IPHC survey during 1995-1997 (red circles). Empty circles indicate stations where no Quillback Rockfish was caught during this period.

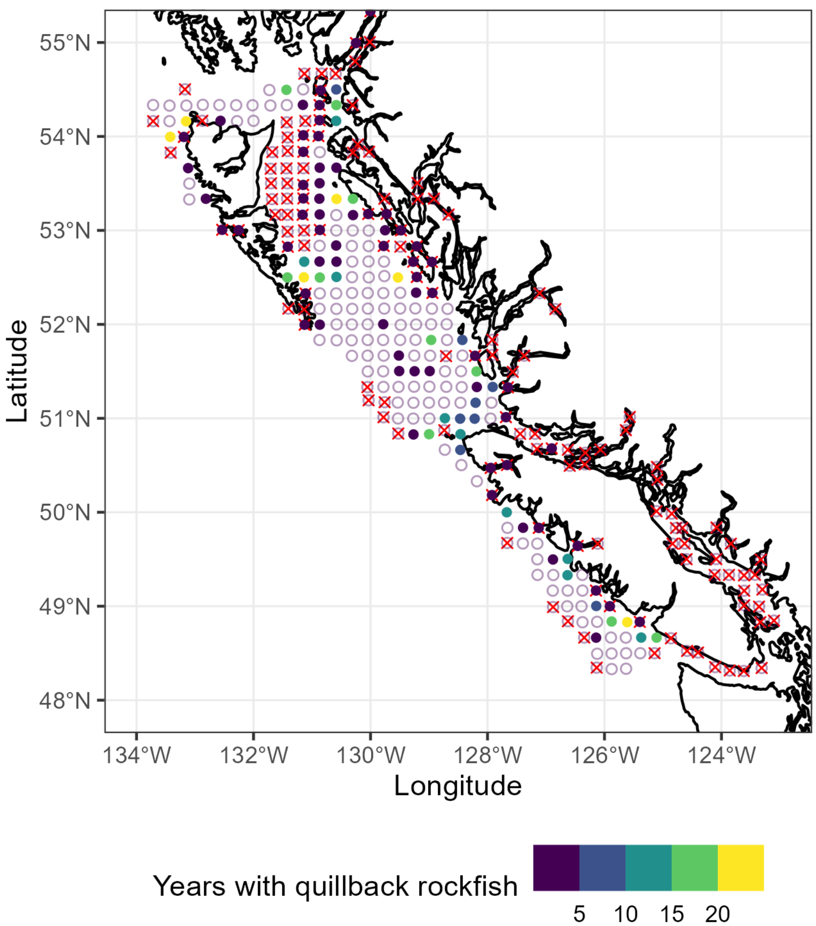

Figure B.14. Fixed stations of the IPHC survey since 1998 (circles). Red crosses indicate expansion stations introduced to the survey in 2018 but were not included for calculating the index of Quillback Rockfish. Colour bins for filled circles indicate the number of years when Quillback Rockfish were caught. Empty circles indicate stations where no Quillback Rockfish has been caught in the history of the survey.

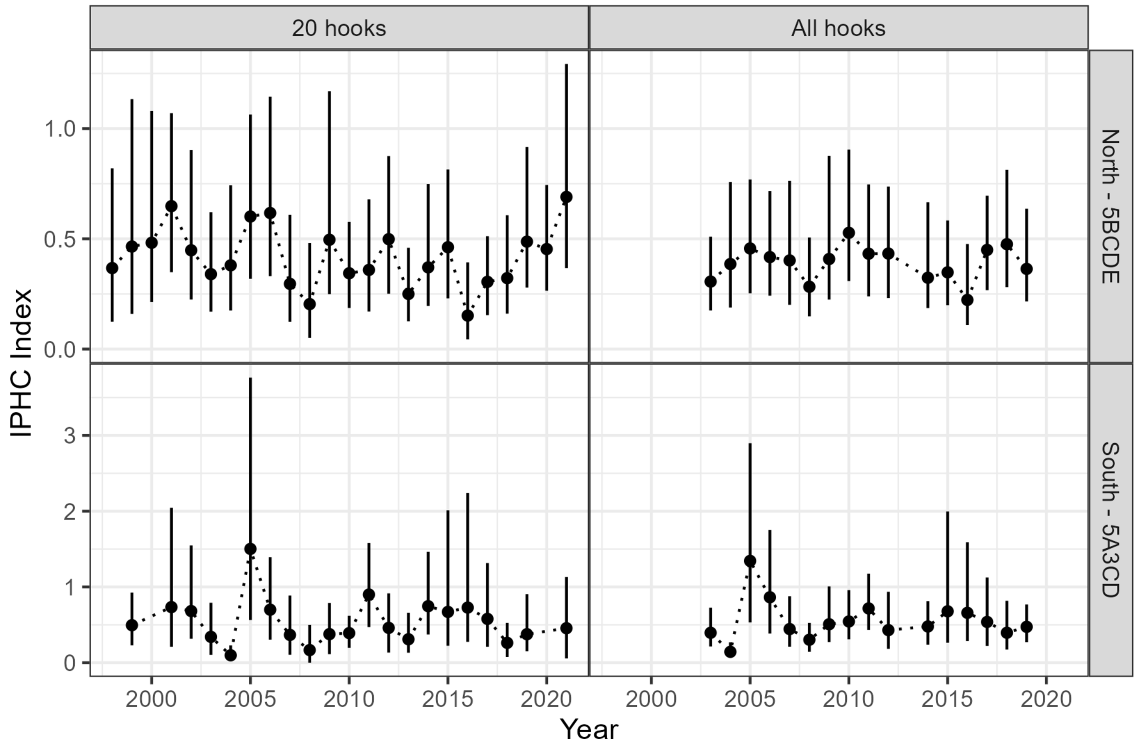

Figure B.15. Index of abundance (numbers per effective skate) from the IPHC survey. Vertical lines span the 95 percent confidence interval calculated from the standard error of the mean.

Table B.4. Summary of the IPHC FISS survey catch of Outside Quillback Rockfish.

Year	Number of sets	Proportion positive (all hooks)	Proportion positive (20 hooks)
1995	111	0.15	NA
1996	120	0.17	NA
1997	121	NA	0.09
1998	128	NA	0.05
1999	168	NA	0.08
2000	129	NA	0.09
2001	170	NA	0.09
2002	170	NA	0.11
2003	169	0.18	0.09
2004	167	0.14	0.08
2005	170	0.15	0.12
2006	169	0.17	0.12
2007	170	0.14	0.06
2008	167	0.14	0.04
2009	168	0.17	0.10
2010	170	0.19	0.12
2011	168	0.19	0.11
2012	170	0.13	0.09
2013	170	NA	0.09
2014	170	0.18	0.12
2015	170	0.18	0.10
2016	167	0.14	0.07
2017	165	0.16	0.09
2018	297	0.20	0.10
2019	165	0.20	0.13
2020	197	NA	0.17
2021	230	NA	0.14

Table B.5. Index of abundance (numbers per effective skate) and coefficient of variation in parentheses from the IPHC survey.

Year	Type	North - 5BCDE	South - 5A3CD
1998	20 hooks	0.37 (0.44)	NA
1999	20 hooks	0.47 (0.46)	0.49 (0.35)
2000	20 hooks	0.48 (0.41)	NA
2001	20 hooks	0.65 (0.28)	0.73 (0.53)
2002	20 hooks	0.45 (0.35)	0.68 (0.39)
2003	20 hooks	0.34 (0.33)	0.34 (0.46)
2004	20 hooks	0.38 (0.36)	0.10 (0.53)
2005	20 hooks	0.60 (0.31)	1.50 (0.46)
2006	20 hooks	0.62 (0.30)	0.70 (0.38)
2007	20 hooks	0.30 (0.39)	0.37 (0.50)
2008	20 hooks	0.20 (0.50)	0.17 (0.72)
2009	20 hooks	0.50 (0.39)	0.38 (0.43)
2010	20 hooks	0.34 (0.29)	0.39 (0.27)
2011	20 hooks	0.36 (0.34)	0.90 (0.30)
2012	20 hooks	0.50 (0.30)	0.46 (0.41)
2013	20 hooks	0.25 (0.31)	0.31 (0.41)
2014	20 hooks	0.37 (0.33)	0.75 (0.34)
2015	20 hooks	0.46 (0.31)	0.67 (0.55)
2016	20 hooks	0.15 (0.49)	0.73 (0.54)
2017	20 hooks	0.30 (0.29)	0.58 (0.45)
2018	20 hooks	0.32 (0.33)	0.26 (0.42)
2019	20 hooks	0.49 (0.30)	0.38 (0.44)
2020	20 hooks	0.45 (0.26)	NA
2021	20 hooks	0.69 (0.32)	0.46 (0.56)
2003	All hooks	0.31 (0.27)	0.39 (0.31)
2004	All hooks	0.39 (0.35)	0.14 (0.34)
2005	All hooks	0.46 (0.28)	1.34 (0.42)
2006	All hooks	0.42 (0.27)	0.86 (0.37)
2007	All hooks	0.40 (0.33)	0.44 (0.35)
2008	All hooks	0.28 (0.31)	0.30 (0.31)
2009	All hooks	0.41 (0.34)	0.51 (0.33)
2010	All hooks	0.53 (0.27)	0.54 (0.29)
2011	All hooks	0.43 (0.28)	0.72 (0.25)
2012	All hooks	0.43 (0.29)	0.43 (0.40)
2014	All hooks	0.32 (0.32)	0.48 (0.30)
2015	All hooks	0.35 (0.27)	0.68 (0.51)
2016	All hooks	0.22 (0.37)	0.66 (0.43)
2017	All hooks	0.45 (0.24)	0.54 (0.40)
2018	All hooks	0.48 (0.27)	0.39 (0.38)
2019	All hooks	0.36 (0.27)	0.47 (0.26)

B.3. SYNOPTIC TRAWL SURVEYS

DFO, in conjunction with the Canadian Groundfish Research and Conservation Society, implemented a set of bottom trawl surveys that together cover the continental shelf and upper slope of most of the trawlable habitat on the BC coast. The surveys follow a random depth stratified design and use the same bottom trawl fishing gear and fishing protocols (Sinclair et al. 2003). The surveys were designed to provide a synopsis of all species available to bottom trawl gear as opposed to focusing on specific species. Four synoptic (SYN) surveys cover Hecate Strait (HS), West Coast Vancouver Island (WCVI), Queen Charlotte Sound (QCS), and West Coast Haida Gwaii (WCHG). The Queen Charlotte Sound and West Coast Haida Gwaii surveys have been conducted on chartered commercial fishing vessels, while the Hecate Strait and West Coast Vancouver Island surveys have been conducted on the Canadian Coast Guard Service (CCGS) research vessel (RV) *WE Ricker* or chartered commercial fishing vessels when the *WE Ricker* was not available. These surveys are now conducted on the CCGS RV *Franklin*, the successor to the RV *Ricker*. Two of the synoptic surveys are conducted each year on an alternating basis so that each survey is conducted once every two years.

In three of the four areas, the trawl surveys catch very few, if any, Quillback Rockfish, except in Hecate Strait (Table B.6). No Quillback Rockfish has been caught in West Coast Haida Gwaii Trawl Survey as it largely fishes outside of the depth range of Quillback Rockfish (Figure B.16). The proportion of positive sets (between 20–30 percent) in Hecate Strait is relatively high compared to the other trawl surveys and the IPHC survey, likely because of the shallow depth distribution of the Hecate Strait. Set by set catch rates in Hecate Strait are shown in Figure B.17. Further description of the Hecate Strait trawl survey is provided in Wyeth et al. (2018).

We used this survey to develop a biomass index (Table B.6 and Figure B.18). The biomass estimate from the trawl survey is a designed-based estimate of trawl CPUE expanded by the area of the survey strata (see Appendix F.5 of Anderson et al. (2019)). Compared to the HBLL and IPHC surveys, the Hecate Strait trawl survey catches younger Quillback Rockfish (Appendix A).

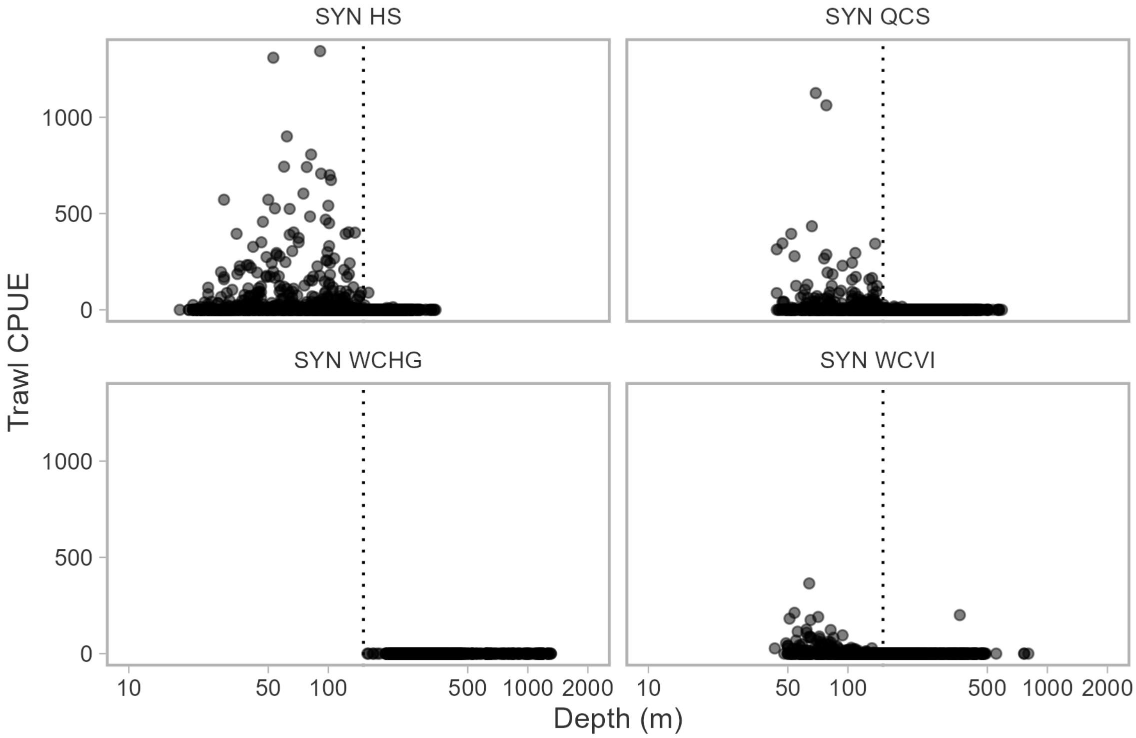

Figure B.16. Set-by-set CPUE (kg per square km) vs. depth (meters) in the four Synoptic trawl surveys. The x-axis is on the natural logarithmic scale and vertical dotted lines correspond to depth of 150 m.

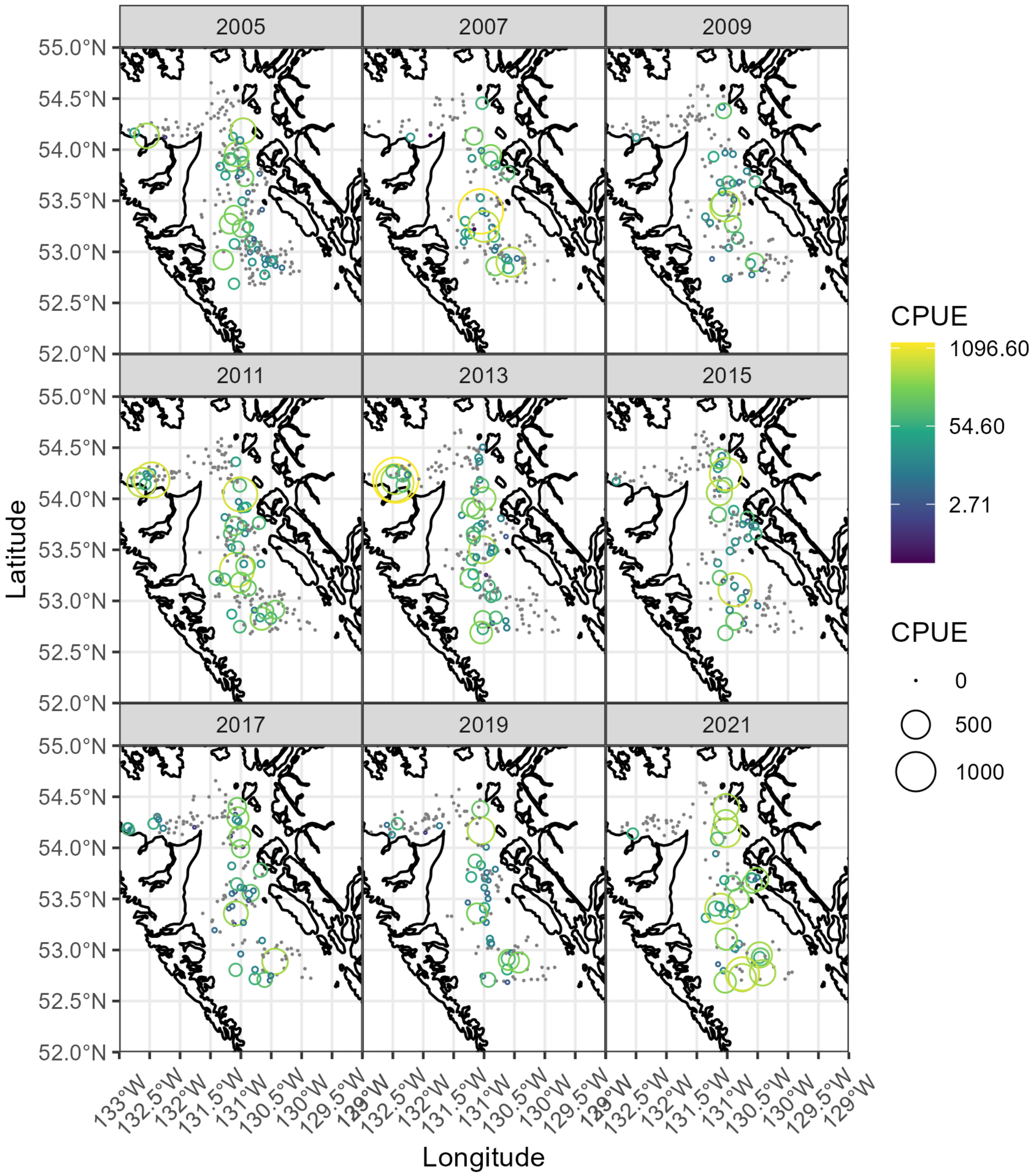

Figure B.17. Set-by-set CPUE (kg per square km) in the Synoptic Hecate Strait trawl survey. The size and colour of the circles are proportional to CPUE. Grey dots indicate sets with zero catch of Quillback Rockfish.

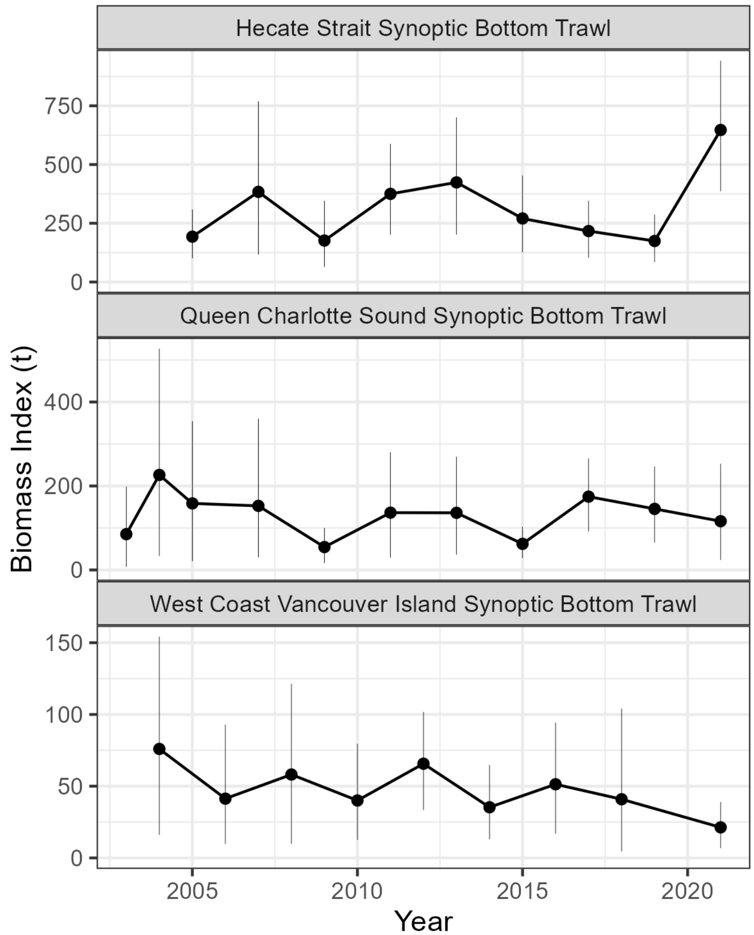

Figure B.18. Biomass indices from the synoptic trawl surveys, with bootstrapped means and 95% confidence intervals. Only the index from the Hecate Strait survey is used in this Research Document. For reference, indices from Queen Charlotte Sound and West Coast Vancouver Island are shown here. No Quillback Rockfish has been caught in West Coast Haida Gwaii.

Table B.6. Surveyed biomass of Outside Quillback Rockfish from the Synoptic Trawl surveys in Hecate Strait (SYN HS), Queen Charlotte Sound (SYN QCS), and West Coast Vancouver Island (SYN WCVI). No Quillback Rockfish has been caught in West Coast Haida Gwaii (SYN WCHG). The CV is the coefficient of variation of the index mean.

Survey	Year	Number of sets	Proportion positive	Biomass (t)	CV
SYN HS	2005	198	0.21	193	0.27
SYN HS	2007	132	0.23	384	0.44
SYN HS	2009	155	0.18	176	0.41
SYN HS	2011	184	0.22	375	0.26
SYN HS	2013	175	0.25	424	0.31
SYN HS	2015	148	0.22	270	0.31
SYN HS	2017	138	0.32	217	0.29
SYN HS	2019	135	0.25	175	0.30
SYN HS	2021	116	0.29	647	0.22
SYN QCS	2003	228	0.02	85	0.58
SYN QCS	2004	229	0.06	226	0.59
SYN QCS	2005	221	0.05	158	0.54
SYN QCS	2007	255	0.05	153	0.60
SYN QCS	2009	230	0.04	55	0.40
SYN QCS	2011	248	0.06	136	0.48
SYN QCS	2013	236	0.07	136	0.44
SYN QCS	2015	238	0.08	62	0.31
SYN QCS	2017	239	0.17	175	0.25
SYN QCS	2019	242	0.10	145	0.32
SYN QCS	2021	193	0.06	116	0.50
SYN WCHG	2006	107	0.00	NA	NA
SYN WCHG	2007	108	0.00	NA	NA
SYN WCHG	2008	117	0.00	NA	NA
SYN WCHG	2010	126	0.00	NA	NA
SYN WCHG	2012	128	0.00	NA	NA
SYN WCHG	2014	54	0.00	NA	NA
SYN WCHG	2016	110	0.00	NA	NA
SYN WCHG	2018	118	0.00	NA	NA
SYN WCHG	2020	96	0.00	NA	NA
SYN WCVI	2004	89	0.09	76	0.47
SYN WCVI	2006	164	0.05	41	0.52
SYN WCVI	2008	159	0.05	58	0.49
SYN WCVI	2010	136	0.07	40	0.45
SYN WCVI	2012	151	0.11	66	0.26
SYN WCVI	2014	146	0.06	35	0.37
SYN WCVI	2016	140	0.06	51	0.39
SYN WCVI	2018	190	0.04	41	0.73
SYN WCVI	2021	169	0.07	21	0.39

APPENDIX C. FISHERY DATA

Outside Quillback Rockfish is caught in commercial fisheries using hook-and-line and trawl gears, Food Social and Ceremonial (FSC) fisheries, and recreational fisheries. Management of Outside Quillback Rockfish fisheries began in 1986, with the introduction of the “ZN” category commercial licence and daily bag limits for recreational anglers. A chronology of management changes for commercial and recreational fisheries is shown in Tables C.12 and C.13.

C.1. COMMERCIAL DATA

C.1.1. CATCH

Rockfish catch data can be grouped into three time periods: historic (1918-1950), early electronic (1951–2005), and modern (2006 onwards). There are two major sources of uncertainty in the historical and early electronic periods for Outside Quillback Rockfish. The first uncertainty is that rockfish catch, other than Pacific Ocean Perch (*Sebastes alutus*), was reported as an aggregate (other rockfish, ORF) in the historic period. To reconstruct historical catches, an algorithm was developed by (Haigh and Yamanaka 2011, see their Section 1) that applies a ratio (γ) calculated from a period with credible landings data from dockside monitoring program (1997–2005) to generate a time series of catch by species, year, fishery sector, and management area (Table C.2). “Credible” landings data are taken from reference years where catch knowledge was considered high quality and stable, beginning in 1997 with the start of observer trawl coverage and the individual vessel quota system (Haigh and Yamanaka 2011).

The second major source of uncertainty is the magnitude of unreported catch that was released or discarded at sea, prior to the introduction of 100% observer coverage in 2006. The catch reconstruction of Haigh and Yamanaka (2011) assumes no discarding prior to 1986 for hook and line fisheries, when the ZN licence was instituted, and prior to 1953 for the trawl fishery (it is assumed all rockfish were kept). Discards are assumed to be fully reported in DFO databases since 2006 and the introduction of 100% observer coverage.

Non-retained Quillback Rockfish catch (releases or discards) was estimated for each fishery using the ratio of Quillback Rockfish (δ) discarded by a fishery to fishery-specific landed targets using observer logs from 2000–2004 for the hook and line fisheries and from 1999–2005 for the trawl fishery (Table C.3). The estimated historical unreported catch was then incorporated into the catch reconstruction for 1986–2005 for hook and line fisheries and 1954-1995 for the trawl fishery (Figure C.1). Ongoing quality control and updates to the groundfish catch database resulted in minor differences in the data over time (Maria Cornthwaite, DFO, Pacific Biological Station, pers. comm., March 9, 2020). Further refinements to the reconstruction algorithm resulted in significant changes to the estimated historical catch in intervening years (Norm Olsen, DFO, Pacific Biological Station, pers. comm., March 9, 2020).

For this analysis, we used the reconstructed catch data from 1918–2005, and switched to the nominal catch data in 2006 when full at-sea and dockside monitoring came into effect. Since 2006, the majority of the commercial catch is from Areas 5A, 5B, and 5C (Figure C.2).

For the trawl fishery, observer logs reported a very high discard rate (up to 400 percent; Table C.3). However, these discard rates were observed during a time period (1999–2005) when the fishery was not able to retain Quillback Rockfish. This prohibition did not exist prior to 1997. It is likely that the fishery operated differently prior to 1997 and there was no incentive to discard or mis-report Quillback Rockfish (B. Mose, pers. comm. 2022). Thus, we used trawl catches with zero discard in the reconstruction, i.e., $\delta = 0$. Such a discard rate is consistent with what is seen in other hook and line sectors that target non-rockfish species, e.g., Pacific Halibut and dogfish. Application of these high discard rates to the historical catch resulted in unlikely high trawl removals (as large as the hook and line catch).

C.1.2. BIOLOGICAL SAMPLES

Biological sampling in the commercial fishery, including handline, longline, and trawl gears, has historically been limited. Age samples are available from the handline and longline gears (Figure C.3). Only length samples are available from the trawl fishery (Figure C.4). Catch totals from the hook-and-line sectors are not readily identified by the gear used in the fishing trip, but historical sales slip and logbook records indicate higher rockfish catch using longline gear in Outside waters during the 1980s (Hand and Richards 1988; Hand et al. 1990).

Samples have been collected from a very small subset of the catch (limited to 1-2 fishing events for most years, Table C.1). A summary of the number of specimens collected and fishing events is provided in Table C.1. No age or length samples have been collected from the commercial fishery since 2010.

Since 2006, the Fishery Operations System (FOS), the repository for commercial groundfish catch data, reports the total weight and pieces (numbers) caught in individual fishing trips. This allows mean weight of the commercial catch to be calculated (2006–2021; Figure C.5 and Table C.6). Standard errors for the mean weight were calculated from bootstrapping catch records, stratified by year, gear, and area fished. Mean weight in the trawl fishery is higher (> 1 kg for most years) than in the hook and line fishery.

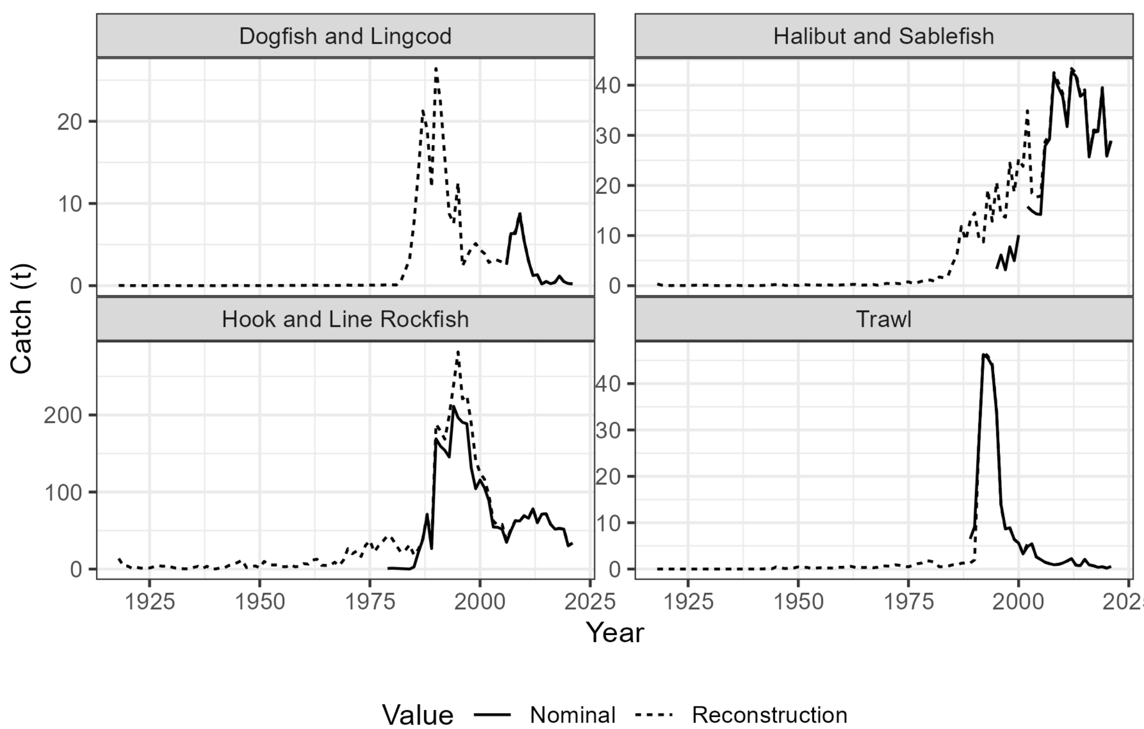

Figure C.1. Comparison of reconstructed and nominal commercial catch for Outside Quillback Rockfish.

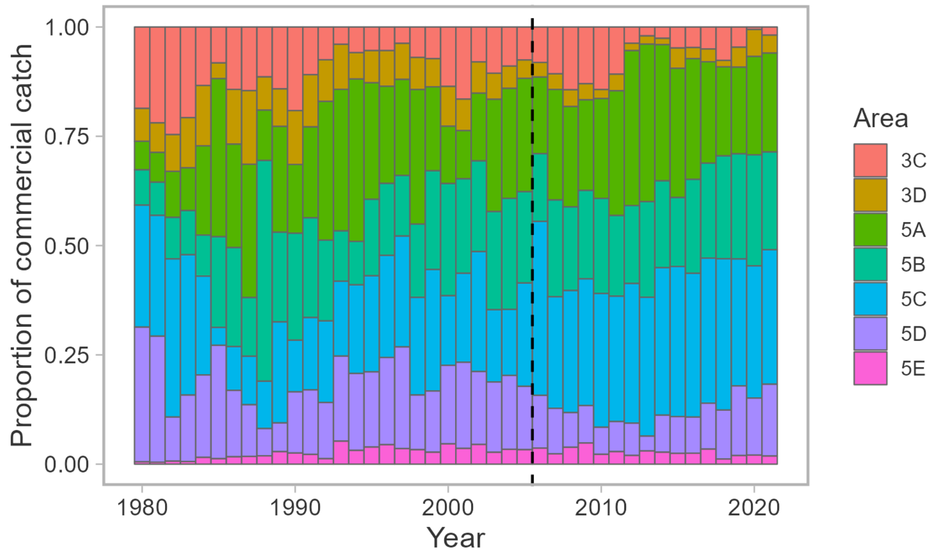

Figure C.2. Proportion of the commercial catch by area for Outside Quillback Rockfish since 1980. The dotted vertical line delineates year 2006 when full electronic monitoring was implemented for fishery catch. Proportions prior to 2006 were calculated from reconstructed catch.

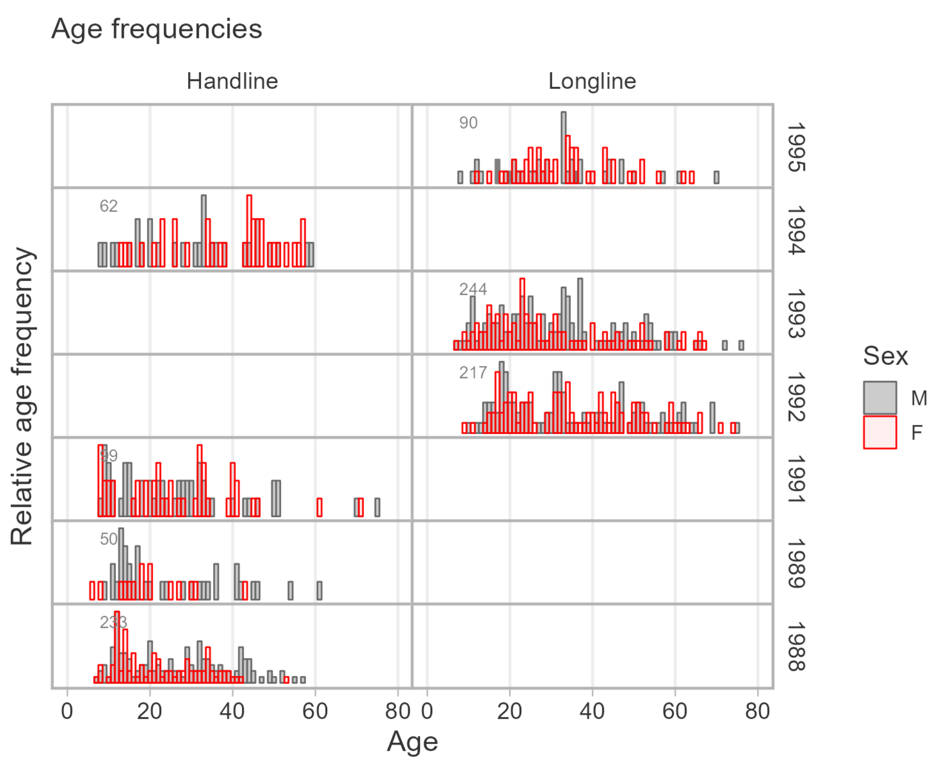

Figure C.3. Age frequency from the commercial hook-and-line fishery. Female fish are shown as red bars and male fish are shown behind as grey bars. The total number of fish aged for a given year is indicated along the top of each panel.

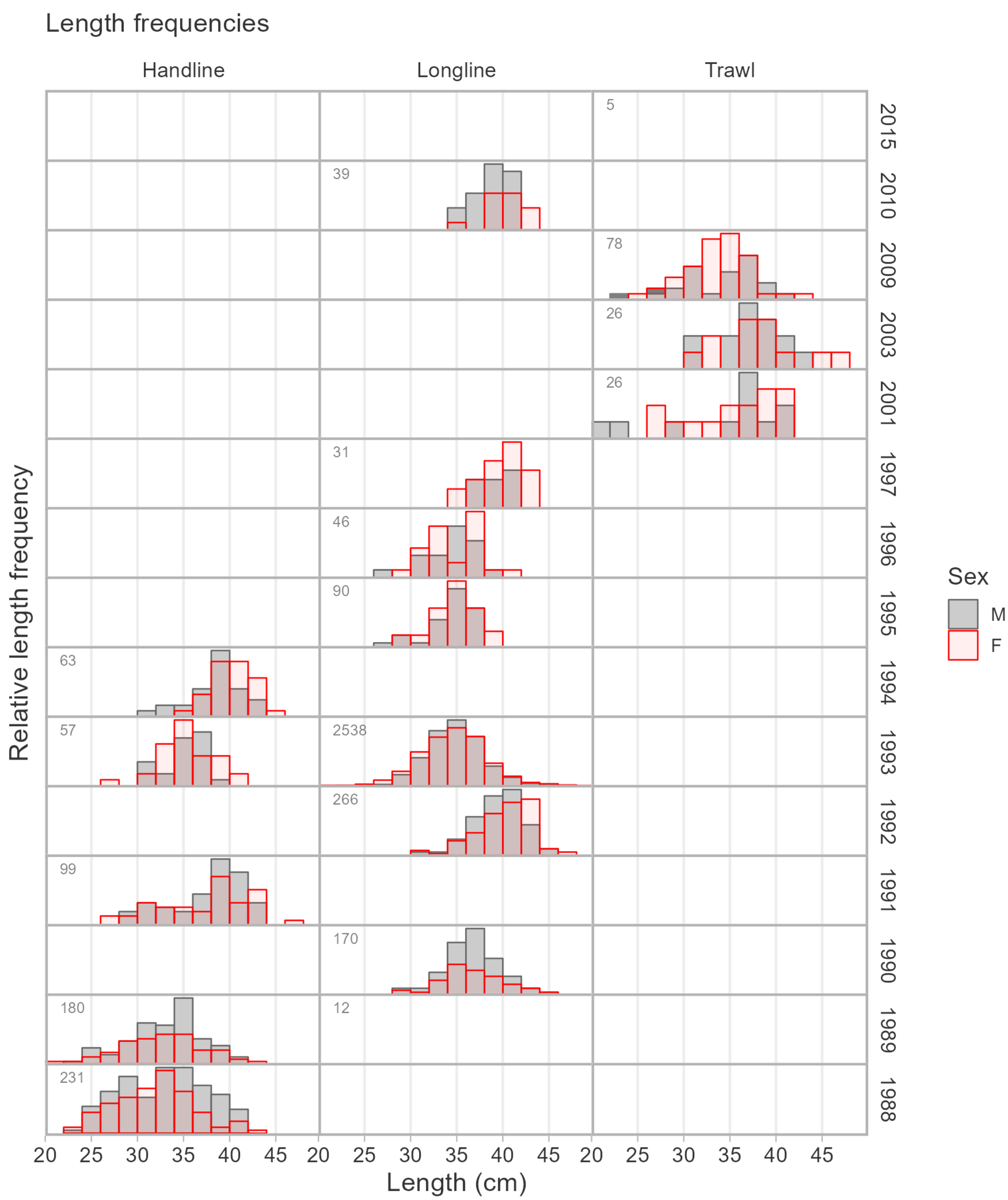

Figure C.4. Length frequency from the commercial fishery. Female fish are shown as red bars and male fish are shown behind as grey bars. The total number of fish samples for a given year is indicated along the top of each panel.

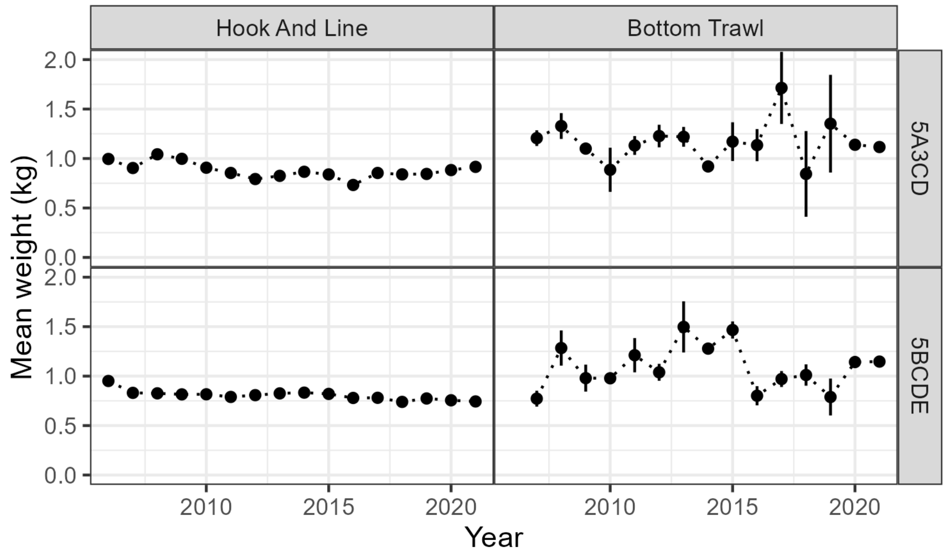

Figure C.5. Mean weight (kg) of Outside Quillback Rockfish caught in the commercial fishery, stratified by area and gear. Error bars show the 95% confidence interval using the standard error. Values were obtained by calculating the ratio of total weight and total pieces reported in the Fishery Operations System (FOS) database.

Table C.1. Outside Quillback Rockfish biological samples from the commercial fishery. Otoliths have been collected from all specimens but only a subset have been aged.

Gear	Year	Fishing events	Number of specimens	Lengths	Weights	Maturities	Ages
Handline	1988	1	233	231	232	233	233
Handline	1989	1	180	180	180	180	50
Handline	1991	2	99	99	99	99	99
Handline	1993	1	57	57	0	0	0
Handline	1994	1	63	63	1	63	62
Longline	1989	1	12	12	12	12	0
Longline	1990	1	170	170	0	170	0
Longline	1992	5	266	266	266	266	217
Longline	1993	36	2,539	2,538	444	492	244
Longline	1995	2	90	90	52	90	90
Longline	1996	1	46	46	0	46	0
Longline	1997	1	31	31	0	0	0
Longline	2010	1	39	39	39	0	0
Bottom Trawl	2001	1	26	26	0	0	0
Bottom Trawl	2003	1	26	26	0	0	0
Bottom Trawl	2009	1	78	78	0	0	0

Table C.2. Values of γ, the ratio of Quillback Rockfish to target catch or all catch, by fishery sector and area for the commercial catch reconstruction.

Area	Trawl	Halibut	Sablefish	Dogfish-Lingcod	H&L Rockfish
3C	0.0001	0.0341	0.0067	0.0464	0.1918
3D	0.0000	0.0174	0.0020	0.0305	0.0600
5A	0.0001	0.0298	0.0000	0.0624	0.1012
5B	0.0001	0.0164	0.0005	0.0857	0.1961
5C	0.0002	0.0479	0.0000	0.0562	0.3096
5D	0.0012	0.0459	0.0000	0.0805	0.3291
5E	0.0000	0.0112	0.0006	0.0037	0.0019

Table C.3. Values of δ, the discard to landed ratio of Quillback Rockfish, by fishery sector and area for the commercial catch reconstruction. The discard ratio was calculated from observer logs during 1996-2006 for the Trawl sector, and 2000-2004 for all other sectors.

Area	Trawl	Halibut	Sablefish	Dogfish-Lingcod	H&L Rockfish
3C	0.8785	0.0025	0	0.0009	0.0200
3D	1.4271	0.0003	0	0.0009	0.0192
5A	4.0528	0.0001	0	0.0002	0.0064
5B	4.1786	0.0001	0	0.0004	0.0088
5C	3.8639	0.0020	0	0.0005	0.0070
5D	2.9504	0.0011	0	0.0004	0.0134
5E	0.0000	0.0002	0	0.0002	0.0000

Table C.4. Commercial catch (tonnes) by area of Outside Quillback Rockfish in the Dogfish-Lingcod, Hook and Line Rockfish, Halibut, and Sablefish sectors. The table contains reconstructed (1918-2005) and nominal (2006-2021) values in tonnes.

Year	3C	3D	5A	5B	5C	5D	5E	Total
1918	1.3	0.3	0.1	4.4	2.7	5.2	0.0	14.0
1919	2.6	0.7	0.1	0.5	0.3	0.6	0.0	4.8
1920	1.5	0.4	0.1	0.7	0.5	0.9	0.0	4.1
1921	0.9	0.2	0.0	0.0	0.0	0.0	0.0	1.1
1922	1.9	0.5	0.1	0.0	0.0	0.0	0.0	2.5
1923	0.9	0.2	0.0	0.1	0.0	0.1	0.0	1.3
1924	0.8	0.2	0.0	0.2	0.1	0.2	0.0	1.5
1925	0.5	0.1	0.0	0.3	0.2	0.3	0.0	1.4
1926	1.0	0.2	0.0	0.6	0.4	0.8	0.0	3.0
1927	1.4	0.4	0.1	1.0	0.6	1.2	0.0	4.7
1928	1.3	0.3	0.0	0.7	0.4	0.9	0.0	3.6
1929	1.1	0.3	0.0	1.1	0.7	1.3	0.0	4.5
1930	0.8	0.2	0.0	0.6	0.4	0.7	0.0	2.7
1931	0.8	0.2	0.0	0.1	0.1	0.1	0.0	1.3
1932	0.4	0.1	0.0	0.1	0.0	0.1	0.0	0.7
1933	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.4
1934	0.3	0.1	0.0	0.1	0.0	0.1	0.0	0.6
1935	0.3	0.1	0.0	0.6	0.4	0.8	0.0	2.2
1936	0.7	0.2	0.0	1.0	0.6	1.2	0.0	3.7
1937	0.2	0.0	0.0	0.2	0.1	0.2	0.0	0.7
1938	2.8	0.7	0.1	0.1	0.0	0.1	0.0	3.8
1939	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.2
1940	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.2
1941	0.0	0.2	0.0	0.5	0.4	0.4	0.0	1.5
1942	0.1	0.5	0.0	0.4	0.3	0.4	0.0	1.7
1943	0.4	1.3	0.1	1.2	0.9	1.0	0.0	4.9
1944	0.5	1.7	0.2	1.7	1.2	1.4	0.0	6.7
1945	0.4	1.3	0.1	2.8	1.9	2.2	0.1	8.8
1946	0.3	1.2	0.1	4.1	2.9	3.3	0.1	12.0
1947	0.1	0.3	0.0	0.6	0.4	0.5	0.0	1.9
1948	0.1	0.5	0.1	0.9	0.7	0.8	0.0	3.1
1949	0.2	0.7	0.1	1.3	0.9	1.0	0.0	4.2
1950	0.1	0.3	0.0	0.5	0.4	0.4	0.0	1.7
1951	0.4	1.0	0.0	2.9	2.9	3.0	0.1	10.3
1952	0.1	0.7	0.1	2.6	1.1	1.5	0.1	6.2
1953	0.4	0.9	0.7	1.6	0.7	1.1	0.0	5.4
1954	0.4	1.1	0.3	1.6	0.5	1.6	0.0	5.5
1955	0.2	1.3	0.1	0.3	0.7	0.7	0.0	3.3
1956	0.7	1.2	0.2	0.7	0.2	0.1	0.0	3.1
1957	2.0	1.9	0.0	1.6	0.3	0.4	0.0	6.2
1958	0.6	1.8	0.0	0.4	0.1	0.1	0.0	3.0
1959	1.0	2.0	0.1	0.5	0.0	0.0	0.0	3.6
1960	1.1	2.2	0.6	0.8	1.6	1.0	0.0	7.3

Year	3C	3D	5A	5B	5C	5D	5E	Total
1961	1.1	2.9	0.4	1.4	0.5	0.4	0.0	6.7
1962	2.9	3.3	0.6	1.3	3.8	0.1	0.0	12.0
1963	1.9	2.1	0.7	5.7	1.8	0.8	0.1	13.1
1964	0.8	1.5	0.1	1.8	0.7	0.1	0.0	5.0
1965	0.7	1.3	0.1	0.8	1.7	0.3	0.0	4.9
1966	0.5	1.5	0.3	1.2	0.7	0.9	0.0	5.1
1967	1.1	2.1	0.2	1.0	2.6	2.3	0.0	9.3
1968	0.8	1.7	0.1	1.2	0.3	0.4	0.0	4.5
1969	1.8	1.7	0.7	3.5	3.9	0.2	0.0	11.8
1970	3.5	2.0	0.2	6.9	11.2	3.1	0.0	26.9
1971	2.2	0.6	0.7	4.4	9.1	3.3	0.0	20.3
1972	4.1	3.2	0.8	5.1	6.3	4.6	0.0	24.1
1973	2.9	1.3	1.0	1.8	5.5	4.2	0.0	16.7
1974	6.6	1.6	0.8	1.3	14.9	6.3	0.0	31.5
1975	5.1	1.4	0.7	4.2	20.1	6.2	0.0	37.7
1976	4.8	1.5	0.6	5.6	5.8	4.6	0.0	22.9
1977	6.1	1.7	3.4	5.7	9.9	4.5	0.0	31.3
1978	5.1	1.6	1.7	5.2	13.3	10.5	0.1	37.5
1979	9.2	3.3	3.8	4.4	15.3	8.5	0.2	44.7
1980	7.9	3.2	2.7	3.3	11.6	12.1	0.2	41.0
1981	7.2	2.2	2.2	2.3	8.7	8.8	0.1	31.5
1982	6.1	2.1	2.5	2.3	8.9	2.3	0.2	24.4
1983	5.8	3.2	2.6	2.8	8.9	4.1	0.2	27.6
1984	4.9	5.2	7.5	3.4	8.3	6.8	0.6	36.7
1985	2.5	1.1	11.1	6.3	1.0	7.8	0.4	30.2
1986	6.5	5.8	10.8	10.4	4.5	7.0	0.8	45.8
1987	10.5	12.4	21.9	9.7	7.9	8.5	1.3	72.2
1988	11.2	7.6	11.2	50.4	10.7	6.1	1.9	99.1
1989	7.8	4.8	13.4	11.3	12.8	3.6	1.6	55.3
1990	43.9	28.4	35.8	56.1	27.1	31.7	5.9	228.9
1991	25.3	25.4	47.6	51.2	35.9	20.5	5.3	211.2
1992	15.4	22.5	58.8	41.6	36.1	15.3	3.0	192.7
1993	10.2	27.7	73.3	28.7	42.0	30.8	14.4	227.1
1994	16.1	18.1	90.5	27.9	56.9	40.8	9.6	259.9
1995	14.4	24.6	78.5	58.9	72.7	52.2	13.6	314.9
1996	13.1	20.4	51.7	40.7	54.2	46.2	11.2	237.5
1997	9.3	20.7	51.9	33.6	62.2	55.8	8.9	242.4
1998	15.3	16.6	65.5	37.3	49.5	26.0	7.5	217.7
1999	12.0	11.0	31.3	37.8	46.4	22.0	4.7	165.2
2000	20.8	14.6	19.4	40.1	24.7	27.4	7.4	154.4
2001	24.1	10.6	15.1	31.4	29.3	28.6	5.3	144.4
2002	10.7	9.9	18.4	28.4	37.4	22.8	6.3	133.9
2003	8.9	5.3	20.9	19.1	13.6	13.7	2.4	83.9
2004	6.9	4.1	19.0	20.2	11.6	13.3	2.7	77.8
2005	5.9	3.4	20.2	16.4	18.9	11.1	2.7	78.6
2006	5.6	2.3	12.0	10.5	27.3	8.4	2.6	68.7

Year	3C	3D	5A	5B	5C	5D	5E	Total
2007	9.4	3.2	22.2	19.5	22.6	9.1	2.1	88.1
2008	16.1	4.3	25.6	21.2	31.5	8.8	4.4	111.9
2009	14.5	4.2	23.3	22.5	32.6	9.5	5.5	112.1
2010	16.3	2.4	25.6	24.6	35.0	6.9	2.6	113.4
2011	10.5	3.9	29.3	18.4	29.5	6.9	3.0	101.5
2012	4.2	2.1	43.5	22.1	40.0	8.9	2.5	123.3
2013	1.9	2.0	37.8	22.7	33.2	3.4	3.2	104.2
2014	2.8	1.6	34.4	21.9	36.9	9.3	3.0	109.9
2015	5.0	5.3	33.5	16.5	38.9	9.5	2.8	111.5
2016	3.7	2.2	23.5	18.0	28.0	7.0	2.1	84.5
2017	4.1	2.5	19.5	18.1	27.8	8.7	2.9	83.6
2018	6.5	1.3	17.3	19.9	29.4	9.4	1.0	84.8
2019	4.2	4.2	18.3	22.2	26.8	14.7	1.8	92.2
2020	0.3	3.5	12.8	14.5	17.2	7.4	1.2	56.9
2021	1.0	2.6	14.4	14.2	19.5	10.3	1.2	63.2

Table C.5. Commercial catch (tonnes) by area of Outside Quillback Rockfish in the Trawl sector. The table contains reconstructed (1918-2005) and nominal (2006-2021) values in tonnes. Here, the discard rate was assumed to be zero prior to 1996.

Year	3C	3D	5A	5B	5C	5D	5E	Total
1918	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1919	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1920	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1921	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1922	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1923	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1924	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1925	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1926	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1927	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1928	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1929	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1930	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1931	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1932	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1933	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1934	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1935	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1936	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1937	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1938	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1939	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1940	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1941	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1942	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.04
1943	0.03	0.00	0.03	0.02	0.00	0.03	0.00	0.11
1944	0.01	0.00	0.01	0.01	0.00	0.02	0.00	0.05
1945	0.12	0.00	0.12	0.10	0.00	0.12	0.00	0.46
1946	0.06	0.00	0.06	0.05	0.00	0.08	0.00	0.25
1947	0.03	0.00	0.03	0.03	0.00	0.03	0.00	0.12
1948	0.05	0.00	0.05	0.04	0.00	0.05	0.00	0.19
1949	0.06	0.00	0.06	0.05	0.00	0.07	0.00	0.24
1950	0.10	0.00	0.13	0.09	0.00	0.15	0.00	0.47
1951	0.09	0.00	0.09	0.09	0.00	0.10	0.00	0.37
1952	0.08	0.00	0.09	0.08	0.00	0.10	0.00	0.35
1953	0.04	0.00	0.04	0.03	0.00	0.04	0.00	0.15
1954	0.05	0.00	0.05	0.05	0.00	0.06	0.00	0.21
1955	0.05	0.00	0.08	0.04	0.00	0.11	0.00	0.28
1956	0.03	0.00	0.09	0.02	0.00	0.03	0.00	0.17
1957	0.04	0.00	0.04	0.04	0.00	0.11	0.00	0.23
1958	0.05	0.00	0.05	0.04	0.00	0.05	0.00	0.19
1959	0.12	0.00	0.07	0.06	0.00	0.11	0.00	0.36
1960	0.12	0.00	0.05	0.05	0.00	0.15	0.00	0.37

Year	3C	3D	5A	5B	5C	5D	5E	Total
1961	0.13	0.00	0.06	0.05	0.00	0.18	0.00	0.42
1962	0.15	0.00	0.09	0.08	0.00	0.26	0.00	0.58
1963	0.07	0.00	0.07	0.06	0.00	0.11	0.00	0.31
1964	0.06	0.00	0.09	0.05	0.00	0.14	0.00	0.34
1965	0.07	0.00	0.09	0.04	0.01	0.11	0.00	0.32
1966	0.07	0.00	0.19	0.05	0.00	0.09	0.00	0.40
1967	0.03	0.00	0.12	0.06	0.00	0.07	0.00	0.28
1968	0.06	0.00	0.19	0.07	0.00	0.06	0.00	0.38
1969	0.07	0.00	0.35	0.12	0.00	0.18	0.00	0.72
1970	0.07	0.00	0.22	0.09	0.00	0.27	0.00	0.65
1971	0.07	0.00	0.20	0.09	0.00	0.24	0.00	0.60
1972	0.04	0.00	0.24	0.13	0.00	0.50	0.00	0.91
1973	0.04	0.00	0.33	0.13	0.00	0.30	0.00	0.80
1974	0.02	0.00	0.17	0.08	0.00	0.38	0.00	0.65
1975	0.04	0.00	0.08	0.07	0.01	0.27	0.00	0.47
1976	0.02	0.00	0.05	0.12	0.02	0.63	0.00	0.84
1977	0.06	0.00	0.11	0.11	0.04	0.83	0.01	1.16
1978	0.02	0.00	0.15	0.17	0.06	0.88	0.01	1.29
1979	0.05	0.00	0.13	0.16	0.13	1.34	0.00	1.81
1980	0.04	0.00	0.06	0.18	0.35	1.07	0.00	1.70
1981	0.05	0.00	0.05	0.16	0.47	0.70	0.00	1.43
1982	0.04	0.00	0.12	0.07	0.08	0.17	0.00	0.48
1983	0.05	0.00	0.14	0.07	0.11	0.15	0.00	0.52
1984	0.07	0.00	0.12	0.13	0.12	0.20	0.00	0.64
1985	0.08	0.01	0.19	0.11	0.24	0.28	0.01	0.92
1986	0.19	0.02	0.27	0.12	0.17	0.07	0.01	0.85
1987	0.18	0.01	0.53	0.20	0.21	0.13	0.01	1.27
1988	0.25	0.01	0.37	0.35	0.17	0.17	0.01	1.33
1989	0.24	0.01	0.33	0.34	0.24	0.13	0.00	1.29
1990	0.21	0.01	0.52	0.33	0.27	0.63	0.01	1.98
1991	0.76	3.23	2.18	3.40	3.65	14.86	0.00	28.08
1992	2.54	0.26	17.21	2.67	8.63	15.51	0.00	46.82
1993	0.64	0.45	15.07	2.74	4.75	22.31	0.00	45.96
1994	1.80	0.25	22.41	2.26	4.74	12.68	0.00	44.14
1995	4.46	1.04	14.52	2.20	3.97	7.81	0.05	34.05
1996	0.45	0.13	4.01	0.63	4.48	3.85	0.02	13.57
1997	0.14	0.01	3.28	1.16	1.45	2.58	0.00	8.62
1998	0.44	0.06	4.25	0.69	1.08	2.36	0.00	8.88
1999	0.43	0.10	1.65	0.93	1.28	1.99	0.00	6.38
2000	0.97	0.00	1.58	0.95	0.70	1.37	0.01	5.58
2001	0.24	0.05	1.23	0.53	0.74	0.54	0.00	3.33
2002	0.46	0.09	3.14	0.49	0.81	0.44	0.00	5.43
2003	0.58	0.02	2.02	0.94	1.20	0.68	0.00	5.44
2004	0.32	0.01	1.22	0.25	0.57	0.24	0.00	2.61
2005	0.18	0.00	0.71	0.42	0.17	0.56	0.00	2.04
2006	0.07	0.02	0.28	0.38	0.62	0.10	0.00	1.47

Year	3C	3D	5A	5B	5C	5D	5E	Total
2007	0.16	0.00	0.34	0.29	0.21	0.16	0.00	1.16
2008	0.11	0.00	0.27	0.38	0.04	0.12	0.00	0.92
2009	0.20	0.01	0.11	0.37	0.17	0.14	0.00	1.00
2010	0.09	0.00	0.53	0.36	0.10	0.20	0.00	1.28
2011	0.65	0.00	0.14	0.64	0.12	0.18	0.00	1.73
2012	0.47	0.00	0.98	0.28	0.16	0.37	0.00	2.26
2013	0.21	0.00	0.05	0.24	0.20	0.13	0.00	0.83
2014	0.06	0.00	0.09	0.10	0.40	0.09	0.00	0.74
2015	0.45	0.00	0.06	1.42	0.07	0.07	0.00	2.07
2016	0.32	0.00	0.11	0.39	0.04	0.04	0.00	0.90
2017	0.15	0.00	0.04	0.21	0.17	0.14	0.00	0.71
2018	0.01	0.00	0.01	0.15	0.07	0.13	0.00	0.37
2019	0.07	0.00	0.10	0.13	0.08	0.10	0.00	0.48
2020	0.04	0.00	0.02	0.01	0.05	0.07	0.00	0.19
2021	0.14	0.00	0.08	0.04	0.10	0.18	0.00	0.54

Table C.6. Commercial fishery mean weight (kg) by gear and area of Outside Quillback Rockfish.

Year	Gear	Area	Mean weight	Standard error	CV
2006	Hook And Line	North - 5A3CD	1.00	0.0070	0.0070
2007	Hook And Line	North - 5A3CD	0.90	0.0049	0.0055
2008	Hook And Line	North - 5A3CD	1.04	0.0050	0.0048
2009	Hook And Line	North - 5A3CD	1.00	0.0058	0.0058
2010	Hook And Line	North - 5A3CD	0.91	0.0080	0.0088
2011	Hook And Line	North - 5A3CD	0.85	0.0055	0.0064
2012	Hook And Line	North - 5A3CD	0.79	0.0040	0.0051
2013	Hook And Line	North - 5A3CD	0.82	0.0041	0.0049
2014	Hook And Line	North - 5A3CD	0.87	0.0033	0.0039
2015	Hook And Line	North - 5A3CD	0.84	0.0040	0.0047
2016	Hook And Line	North - 5A3CD	0.73	0.0056	0.0076
2017	Hook And Line	North - 5A3CD	0.85	0.0079	0.0093
2018	Hook And Line	North - 5A3CD	0.84	0.0083	0.0098
2019	Hook And Line	North - 5A3CD	0.84	0.0112	0.0133
2020	Hook And Line	North - 5A3CD	0.88	0.0101	0.0114
2021	Hook And Line	North - 5A3CD	0.92	0.0135	0.0147
2006	Hook And Line	South - 5BCDE	0.95	0.0048	0.0051
2007	Hook And Line	South - 5BCDE	0.83	0.0040	0.0049
2008	Hook And Line	South - 5BCDE	0.83	0.0033	0.0039
2009	Hook And Line	South - 5BCDE	0.82	0.0031	0.0038
2010	Hook And Line	South - 5BCDE	0.82	0.0024	0.0030
2011	Hook And Line	South - 5BCDE	0.79	0.0031	0.0039
2012	Hook And Line	South - 5BCDE	0.81	0.0029	0.0035
2013	Hook And Line	South - 5BCDE	0.83	0.0036	0.0043
2014	Hook And Line	South - 5BCDE	0.83	0.0027	0.0032
2015	Hook And Line	South - 5BCDE	0.82	0.0031	0.0038
2016	Hook And Line	South - 5BCDE	0.78	0.0030	0.0039

Year	Gear	Area	Mean weight	Standard error	CV
2017	Hook And Line	South - 5BCDE	0.78	0.0032	0.0040
2018	Hook And Line	South - 5BCDE	0.74	0.0036	0.0049
2019	Hook And Line	South - 5BCDE	0.77	0.0023	0.0030
2020	Hook And Line	South - 5BCDE	0.76	0.0034	0.0045
2021	Hook And Line	South - 5BCDE	0.74	0.0031	0.0042
2007	Bottom Trawl	North - 5A3CD	1.21	0.0405	0.0336
2008	Bottom Trawl	North - 5A3CD	1.33	0.0665	0.0501
2009	Bottom Trawl	North - 5A3CD	1.10	0.0238	0.0216
2010	Bottom Trawl	North - 5A3CD	0.89	0.1139	0.1286
2011	Bottom Trawl	North - 5A3CD	1.13	0.0485	0.0429
2012	Bottom Trawl	North - 5A3CD	1.23	0.0581	0.0474
2013	Bottom Trawl	North - 5A3CD	1.22	0.0512	0.0419
2014	Bottom Trawl	North - 5A3CD	0.92	0.0126	0.0136
2015	Bottom Trawl	North - 5A3CD	1.17	0.0998	0.0853
2016	Bottom Trawl	North - 5A3CD	1.14	0.0828	0.0729
2017	Bottom Trawl	North - 5A3CD	1.71	0.1861	0.1086
2018	Bottom Trawl	North - 5A3CD	0.84	0.2211	0.2619
2019	Bottom Trawl	North - 5A3CD	1.35	0.2519	0.1863
2020	Bottom Trawl	North - 5A3CD	1.14	0.0080	0.0070
2021	Bottom Trawl	North - 5A3CD	1.12	0.0128	0.0115
2007	Bottom Trawl	South - 5BCDE	0.77	0.0409	0.0530
2008	Bottom Trawl	South - 5BCDE	1.28	0.0907	0.0706
2009	Bottom Trawl	South - 5BCDE	0.98	0.0695	0.0710
2010	Bottom Trawl	South - 5BCDE	0.98	0.0270	0.0276
2011	Bottom Trawl	South - 5BCDE	1.21	0.0882	0.0728
2012	Bottom Trawl	South - 5BCDE	1.04	0.0437	0.0421
2013	Bottom Trawl	South - 5BCDE	1.50	0.1318	0.0880
2014	Bottom Trawl	South - 5BCDE	1.28	0.0103	0.0081
2015	Bottom Trawl	South - 5BCDE	1.47	0.0440	0.0300
2016	Bottom Trawl	South - 5BCDE	0.80	0.0495	0.0617
2017	Bottom Trawl	South - 5BCDE	0.97	0.0411	0.0423
2018	Bottom Trawl	South - 5BCDE	1.01	0.0551	0.0545
2019	Bottom Trawl	South - 5BCDE	0.79	0.0950	0.1205
2020	Bottom Trawl	South - 5BCDE	1.14	0.0105	0.0092
2021	Bottom Trawl	South - 5BCDE	1.15	0.0103	0.0090

C.2. RECREATIONAL CATCH

Annual catch of outside Quillback Rockfish by the recreational fishery is estimated from two sources. The creel survey utilizes aerial surveys to estimate recreational effort with a dockside interview to document catch composition (DFO 2022c). Spatial coverage of the creel survey is limited to the South Coast (Statistical Areas 11, 21–27 corresponding to Groundfish Management Area 3C, 3D, and 5A) for Outside Quillback Rockfish (Lewis 2004). While the creel survey started in 1981, coverage was limited to Statistical Area 23 (Barkley Sound) until the 1990s. There is currently no coverage for the North and Central Coast.

In 2012, DFO established a coast-wide, internet-based survey of tidal water licence holders (iRec), which collects Quillback Rockfish data for the entire Outside region (DFO 2015). The iRec survey includes catch estimates reported by anglers, with catch rate expansions by year and area to account for non-respondent license holders. Due to its more comprehensive coverage of Outside Quillback Rockfish catch, iRec was preferred over the creel survey for recreational catch (Tables C.7-C.8).

The spatial distribution of catch and recreational effort is reported in Figures C.6 and C.7, respectively.

Most rockfish catch in iRec is identified to the species level, although a sizable amount of catch is reported in the “Other and unknown rockfish” category, some of which is ostensibly Quillback Rockfish. The proportion of Quillback to other rockfish, identified at the species level, was calculated in each year and area and then applied to the “Other and unknown rockfish” catch to calculate the constituent Quillback catch in this broader category for the corresponding stratum (Table C.9).

Released and kept rockfish are recorded in the iRec survey. A majority proportion, i.e., greater than 50 percent, of Outside Quillback Rockfish are released for most years and management areas (Figure C.8). Release rates appear to be higher in the South Coast (3CD) than in the North and Central Coasts (5ABCDE). It is assumed that all released Quillback Rockfish die, for example, due to barotrauma. Since 2019, use of descender devices for released rockfish has been mandatory for non-retained rockfish (Table C.13). Compliance rates are not known. Quillback Rockfish are believed to have high survival rates following deep-water release (Haggarty 2019).

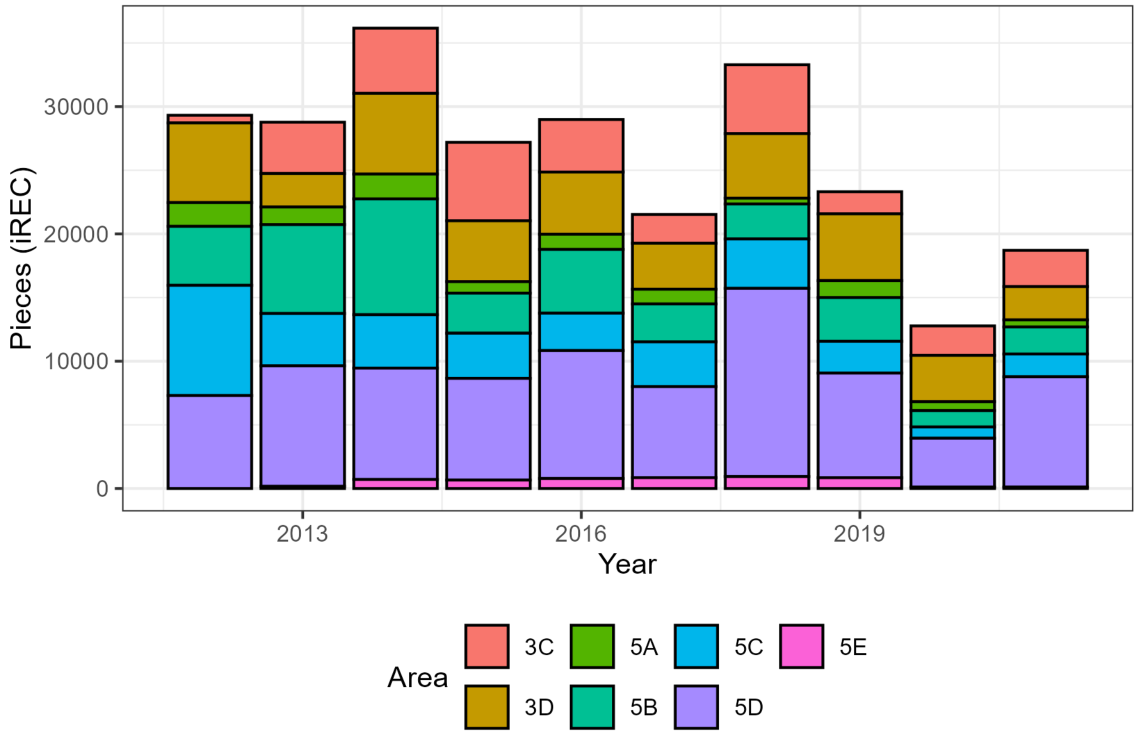

Figure C.6. Distribution of recreational fishery catch since 2012 from the iRec survey.

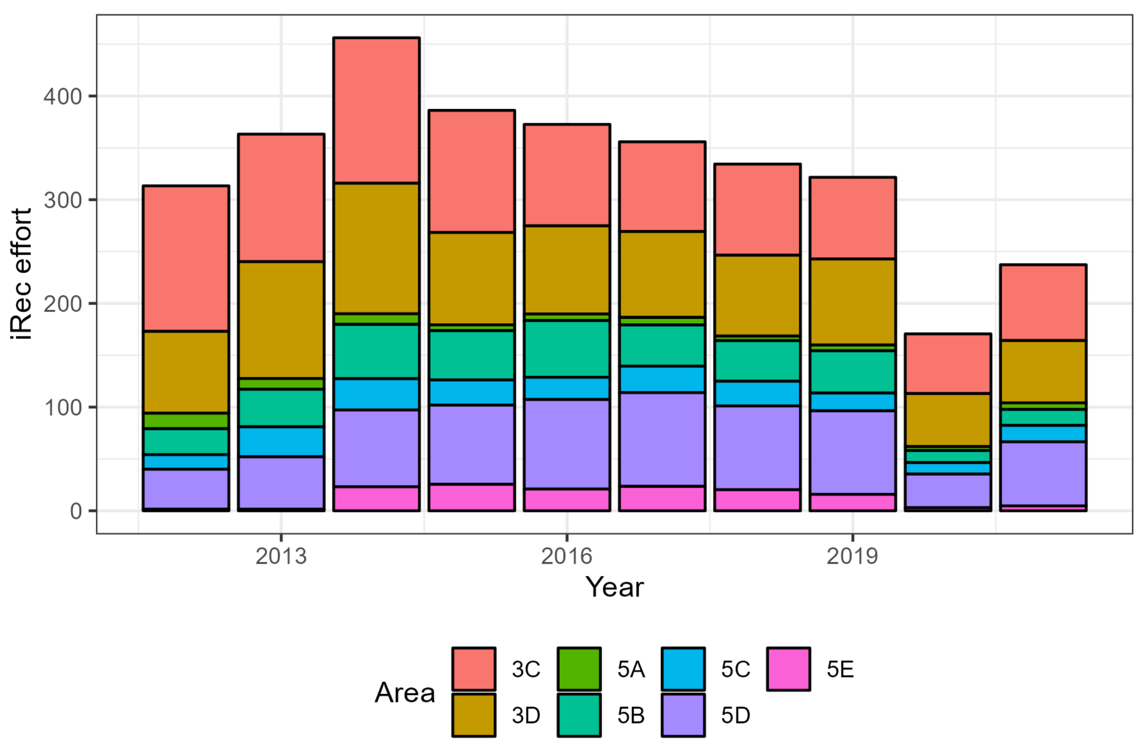

Figure C.7. Distribution of recreational fishery effort (thousands of angler days) since 2012 from the iRec survey.

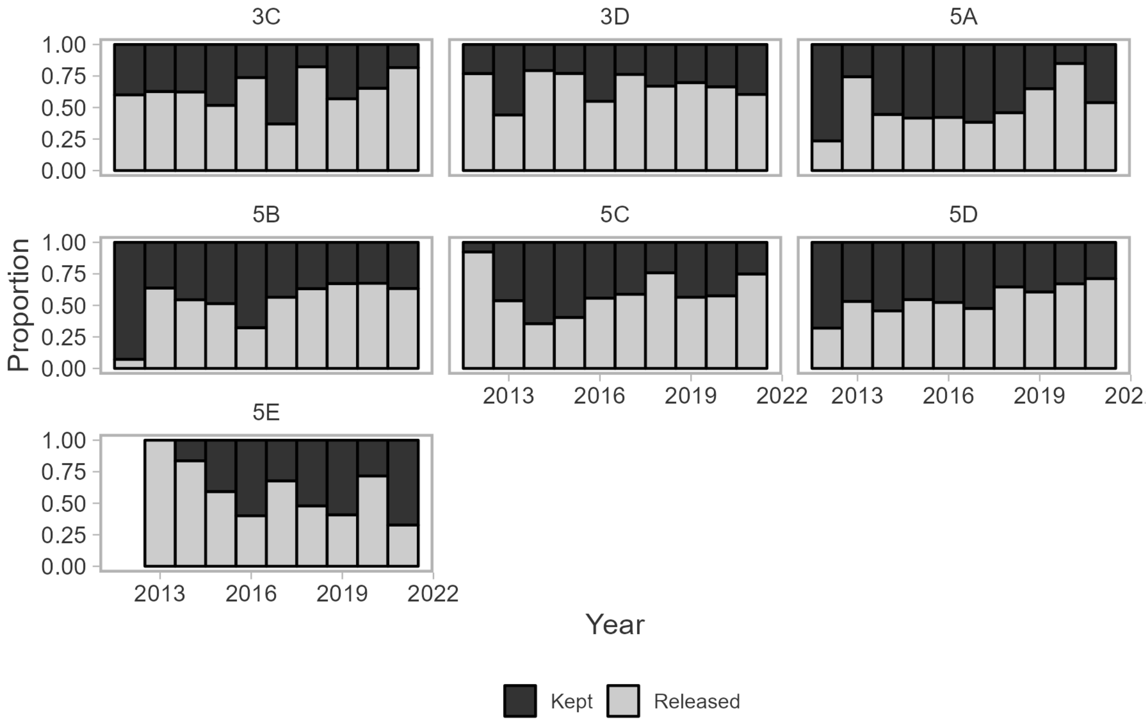

Figure C.8. Recreational release and retention (kept) rates, by year and fishing area, of Outside Quillback Rockfish as reported in the iRec survey.

Table C.7. Outside Quillback Rockfish catch (pieces) from the Internet Recreational Effort and Catch reporting program. Values include catch identified to the species level as well as a portion of catch reported in the "Other and unknown rockfish" category.

Year	3C	3D	5A	5B	5C	5D	5E	Total
2012	604	6,257	1,866	4,633	8,659	7,303	0	29,322
2013	4,034	2,630	1,382	6,981	4,115	9,466	169	28,777
2014	5,124	6,337	1,951	9,100	4,195	8,746	709	36,162
2015	6,164	4,781	904	3,145	3,547	7,991	662	27,194
2016	4,127	4,888	1,190	5,008	2,940	10,050	784	28,987
2017	2,262	3,611	1,154	2,979	3,517	7,153	851	21,527
2018	5,409	5,076	451	2,750	3,879	14,784	938	33,287
2019	1,738	5,245	1,330	3,439	2,494	8,219	847	23,312
2020	2,314	3,642	699	1,284	885	3,840	110	12,774
2021	2,848	2,615	556	2,122	1,794	8,664	111	18,710

Table C.8. Recreational catch reported in tonnes, with a conversion of 0.94 kg/piece based on the biological samples collected from the creel survey in inside waters between 2000 and 2008. This table is intended to facilitate comparison with commercial catch.

Year	3C	3D	5A	5B	5C	5D	5E	Total
2012	0.57	5.88	1.75	4.36	8.14	6.86	0.00	27.56
2013	3.79	2.47	1.30	6.56	3.87	8.90	0.16	27.05
2014	4.82	5.96	1.83	8.55	3.94	8.22	0.67	33.99
2015	5.79	4.49	0.85	2.96	3.33	7.51	0.62	25.56
2016	3.88	4.59	1.12	4.71	2.76	9.45	0.74	27.25
2017	2.13	3.39	1.08	2.80	3.31	6.72	0.80	20.24
2018	5.08	4.77	0.42	2.58	3.65	13.90	0.88	31.29
2019	1.63	4.93	1.25	3.23	2.34	7.73	0.80	21.91
2020	2.18	3.42	0.66	1.21	0.83	3.61	0.10	12.01
2021	2.68	2.46	0.52	1.99	1.69	8.14	0.10	17.59

Table C.9. Proportion of Quillback Rockfish reported in the Internet Recreational Effort and Catch reporting program from rockfish identified at the species level (including Black, Bocaccio, Canary, China, Copper, Tiger, Vermilion, Yelloweye, and Yellowtail Rockfish).

Year	3C	3D	5A	5B	5C	5D	5E
2012	0.02	0.16	0.17	0.28	0.70	0.35	0.00
2013	0.11	0.04	0.23	0.31	0.36	0.29	0.08
2014	0.10	0.09	0.31	0.24	0.30	0.20	0.04
2015	0.13	0.09	0.19	0.17	0.27	0.21	0.03
2016	0.09	0.10	0.18	0.18	0.26	0.24	0.05
2017	0.06	0.06	0.25	0.12	0.26	0.21	0.04
2018	0.15	0.08	0.17	0.15	0.35	0.32	0.05
2019	0.09	0.11	0.21	0.17	0.34	0.25	0.09
2020	0.11	0.10	0.19	0.19	0.14	0.19	0.26
2021	0.10	0.08	0.14	0.25	0.20	0.22	0.05

Table C.10. Recreational effort (angling by boat, thousands of angler days) from the Internet Recreational Effort and Catch reporting program.

Year	3C	3D	5A	5B	5C	5D	5E	Total
2012	140.4	78.9	15.0	24.9	14.1	38.5	1.6	313.4
2013	123.0	112.7	10.4	36.2	28.9	50.6	1.5	363.3
2014	140.3	125.9	10.2	52.4	30.2	74.0	23.2	456.2
2015	117.8	89.1	5.6	47.5	24.3	76.3	25.5	386.1
2016	97.9	85.0	6.3	54.7	21.4	86.4	20.9	372.6
2017	86.5	82.8	7.3	39.8	25.5	90.4	23.5	355.8
2018	87.9	78.0	4.4	39.1	23.9	80.8	20.3	334.4
2019	78.7	83.0	5.6	40.7	17.1	80.6	15.9	321.6
2020	57.6	51.2	3.8	11.6	11.1	32.4	3.0	170.7
2021	73.1	60.1	6.4	15.4	15.9	61.8	4.7	237.4

C.3. FOOD, SOCIAL, AND CEREMONIAL CATCH (FSC)

Quillback Rockfish are an important traditional food source for coastal First Nations in BC (Frid et al. 2016; McGreer and Frid 2017). Total FSC catch of Quillback Rockfish is not available for either the historic or contemporary time period, and the available data is not resolved to the species level (M. Fetterly, DFO Policy Treaty Support, pers. comm., November 7, 2019 and A. Rushton, DFO South Coast Fisheries Management, pers. comm., February 7, 2020). FSC catch was not accounted for in the previous stock assessment (Yamanaka et al. 2011).

The only available FSC data are from the commercial dockside monitoring program (DMP) since 2007 (Table C.11). These data were collected from "dual fishing" trips, which occur when Indigenous fishers choose to keep some of the catch obtained during a commercial fishing trip for FSC purposes. Both commercial and FSC catch are monitored during the offload. Between 0.05 and 1.9 tonnes was landed on dual fishing trips in this time period. The FSC catch from these dual trips is included in the annual totals for commercial catch within the groundfish sector databases. The DMP catch data can only be resolved to the trip level rather than the set level, so some of the dual fishing data may be from inside waters, i.e., include the catch of Inside Quillback Rockfish. If more than 70% of the total landed catch (from all species) was from the outside waters, then the catch were included for the Outside stock. For those trips with total catch comprised between 30 - 70% outside, we added 50% of that catch to the total catch for each year.

There is limited information available to assist with quantifying FSC catch of Outside Quillback Rockfish. Without more detailed information, it is not possible to reliably estimate any impact of FSC catch on the results of this analysis. Greater collaboration with First Nations could help address some of these data issues, and building mutually beneficial relationships with First Nations should be a priority for DFO to resolve uncertainties with FSC catch information.

Table C.11. FSC catch (t) of Outside Quillback Rockfish as a proportion of total commercial catch reported to dockside observers from either dual fishing trips or all fishing trips.

Year	FSC	Commercial (dual)	Total (dual)	Total (all)	Percent FSC (dual)	Percent FSC (all)
2007	3.930	5.408	9.338	85.635	0.421	0.046
2008	2.675	4.861	7.537	105.943	0.355	0.025
2009	2.741	6.030	8.771	110.027	0.313	0.025
2010	3.067	4.503	7.570	110.440	0.405	0.028
2011	3.379	3.356	6.734	99.643	0.502	0.034
2012	4.974	4.991	9.966	118.183	0.499	0.042
2013	2.955	5.428	8.383	103.346	0.352	0.029
2014	2.040	5.341	7.380	108.279	0.276	0.019
2015	2.221	5.897	8.117	108.390	0.274	0.020
2016	1.174	0.021	1.195	82.841	0.983	0.014
2017	1.673	0.880	2.553	80.185	0.655	0.021
2018	1.801	1.002	2.803	87.572	0.642	0.021
2019	2.536	5.405	7.941	92.742	0.319	0.027
2020	2.202	2.065	4.267	57.949	0.516	0.038
2021	0.913	1.074	1.988	60.412	0.460	0.015
2022	2.666	1.376	4.041	54.232	0.660	0.049

C.4. CHRONOLOGY OF MANAGEMENT CHANGES

Table C.12. History of management changes for the commercial Rockfish fishery in coastwide and outside waters from 1986 to 2019.

Year	Area	Management Action
1986	Coastwide	Introduced a category ZN licence for the directed hook-and-line rockfish fishery with a voluntary logbook program
1990	Outside	Provisional 650-metric-ton quota
1990	Outside	Portions closed, area 7
1990	Outside	Jan 1 to Apr 30 closed west coast of Vancouver Island
1991	Coastwide	Area licensing, 1,591 outside
1991	Outside	Rotational closure was initiated in area 7
1991	Coastwide	Limited-entry licensing program was announced
1993	Outside	Limited-entry licensing with 183 eligible outside licences
1993	Coastwide	TAC quota management for Red Snapper and other rockfish by five management regions
1993	Coastwide	Region and time closures
1994	Coastwide	User-pay logbook program
1994	Coastwide	Trip limits for trawl species
1994	Coastwide	Incidental catch allowances
1995	Coastwide	User-pay dockside monitoring program
1995	Coastwide	Aggregate species quota management for Yelloweye Rockfish, Quillback Rockfish, Copper Rockfish, China Rockfish, and Tiger Rockfish
1995	Coastwide	Monthly fishing periods, monthly fishing period limits, annual landing options, and annual trip limits
1995	Coastwide	Relinquishment of period limit overages
1996	Coastwide	Change to species quotas, aggregate 1-2 TAC (quillback rockfish, copper rockfish, china rockfish, and tiger rockfish)
1997	Coastwide	Initiate 5 percent quota allocation for research purposes
1998–1999	Outside	92 percent of commercial rockfish TAC allocated to the hook-and-line sector, 8 percent to trawl sector
1999–2000	Coastwide	10 percent at-sea observer coverage
1999–2000	Coastwide	Quillback rockfish, copper rockfish, china rockfish, tiger rockfish TAC reduced by 25 percent

Year	Area	Management Action
1999–2000	Coastwide	Selected area closures: rockfish protection areas, closed fishing areas to commercial groundfish hook-and-line gear types
2000–2001	Coastwide	Allocation of rockfish species between the Pacific Halibut and hook-and-line sectors
2001–2002	Outside	Licence option elections before fishing season, monthly fishing period limits
2002–2003	Outside	50 percent reduction of inshore rockfish TAC from 1997-1998
2002–2003	Coastwide	Expansion of catch monitoring programs
2002–2003	Coastwide	Introduced 1 percent interim areas of restricted fishing, closed to all commercial groundfish fisheries
2004–2005	Coastwide	RCAs expanded to 8 percent of rockfish habitats
2005–2006	Coastwide	Introduce groundfish licence integration pilot program: 100 percent catch monitoring
2006–2007	Outside	RCAs expanded to 15 percent of rockfish habitats
2006–2007	Coastwide	Introduce groundfish integrated fishery management program
2010	Outside	Implemented Gwaii Haanas National Marine Conservation Area interim management plan and zoning plan
2012	Coastwide	Introduce trawl fishery boundaries in consultation with industry
2017	Outside	Implemented Hecate Strait/Queen Charlotte Strait glass sponge reef closures

Table C.13. History of management changes for the recreational Rockfish fishery from 1986 to 2019.

Year	Area	Management Action
1986	Coastwide	8 rockfish daily bag limit per person implemented
2002	Haida Gwaii, North and Central Coast	Inshore Rockfish Conservation Strategy - Daily limit reduced to 5 rockfish in Areas 1 to 10, 101 to 111 and 130 to 142.
2002	South Coast (WCVI)	Inshore Rockfish Conservation Strategy - Daily limit reduced to 3 rockfish in Areas 11, 21 to 27 and 121 to 127 and Subareas 20-1 to 20-4.
2002–2007	Coastwide	Rockfish Conservation Areas (RCAs) established - RCAs closed to fin fish harvest in recreational fishery.
2017	Haida Gwaii, North and Central Coast	Daily rockfish limit reduced to 3. Clearly defined closed times (November 16 to March 31).
2017	South Coast (WCVI)	Daily rockfish limit reduced to 2 in Areas 11, 21 to 27, 111, 121 to 127 and Subareas 20-1 to 20-4. Clearly defined closed times (November 16 to March 31).
2018	Outside	3 Rockfish daily, only 1 of which may be a China, Tiger or Quillback Rockfish; possession limits are twice the daily limit. Season length April 1 - November 15
2019	Coastwide	Condition of licence: "Anglers in vessels shall immediately return all rockfish that are not being retained to the water and to a similar depth from which they were caught by use of an inverted weighted barbless hook or other purpose-built descender device".

APPENDIX D. OPERATING MODEL DEFINITION

D.1. OVERVIEW

This appendix complements Section 4 of the main text.

Here we describe the specification of Stock Synthesis 3 (SS3) model, version 3-30-19-01, used to condition the age-structured operating model. The most important inputs are specified in the `data.ss` and `control.ss` input files. The description below follows the general format of these files.

The maximum age in the model is 70 years, which is a plusgroup consisting of the abundance of all animals of age 70 and above. The historical period of the spanned from 1918–2021 (104 years). The bin width of the length data was 1 cm.

A single-sex, two-area model was used, with area 1 representing the North (5BCDE) and area 2 representing the South (5A3CD). There is a single stock-recruit relationship for the Outside population, i.e., the coastwide recruitment is predicted by the coastwide spawning population. The proportion of the recruitment that settles into either area is then estimated. Subsequently, there is no animal movement between areas.

The dynamics equations summarizing the structure of the SS3 model is in Table D.1. The likelihoods and priors used to fit the SS3 models are in Table D.2.

After obtaining the MPD (maximum posterior density) fit, Markov chain Monte Carlo (MCMC) posterior samples were obtained by running the No U-Turn Sampling algorithm with `Stan` via the `adnuts` R package (Monnahan and Kristensen 2018; Stan Development Team 2023). A total of 1,000 MCMC iterations obtained from two chains, each run for 3,500 MCMC iterations with a warmup of 1,000 and thin rate of 5.

The operating model was created in MSEtool version 3-6-0 and replicated the structure of the SS3 model. A custom function was used to import the SS3 output into an openMSE operating model, using the multiMSE feature, containing two populations and a single fishery. The single fishery preserved the historical F-at-age estimated in SS3 and the selectivity in the projection period was based on the F-at-age in the terminal historical year, i.e., 2021. The two populations corresponded to the two areas in SS3 and the operating model had the coastwide stock recruit function. A schematic of the conversion between the two software packages is provided in Figure D.1.

A subset of 200 MCMC iterations were used to generate 200 simulations for the operating model (after further thinning for every 5th iteration). The function was validated by comparing an initial SS3 model fit with zero fishing and no process error in the forecast module. Identical spawning biomass was seen in the openMSE operating model projected with the zero fishing management procedure.

Model files are available in the Zenodo archive. A summary table of model parameters is provided in Table D.7.

Table D.1. Summary of SS3 model equations used to condition operating models for Outside Quillback Rockfish. The stock dynamics were then replicated in MSEtool for closed-loop projections. Variables $a = 0, 1, ..., A$ $(A = 70)$ indexes age, $y = 1918, 1919, ..., 2021$ indexes year, f indexes fishery, s indexes survey, $r = 1, 2$ indexes area, M is natural mortality, m_a is maturity at age, w_a is weight at age, h is steepness, R_0 is unfished recruitment and q is index catchability.

Variable	Equation	Number
Unfished survival (equilibrium)	$l_a = \begin{cases} \exp(-Ma) & a = 0, 1, \ldots, A-1 \\ \exp(-Ma)/(1-\exp(-M)) & a = A \end{cases}$	1
Coastwide spawning biomass	$B_y = \sum_r \sum_a N_{y,a} m_a w_a$	2
Coastwide recruitment	$R_y = \frac{\alpha B_y}{1+\beta B_y} \exp(\delta_y)$	3
Stock recruit α	$\alpha = \frac{4h}{(1-h)\phi_0}$	4
Stock recruit β	$\beta = \frac{5h-1}{(1-h)\phi_0 R_0}$	5
Unfished spawning biomass per recruit	$\phi_0 = \sum_a l_a m_a w_a$	6
Area-specific recruitment	$R_{y,r} = R_y \frac{\exp(\varepsilon_{y,r})}{\sum_r \exp(\varepsilon_{y,r})}$	7
Recruitment distribution between areas	$\varepsilon_{y,r} = \begin{cases} 0 & r = 1 \\ \varepsilon^{\text{base}} + \tilde{\varepsilon}_y & r = 2 \end{cases}$	8
Selectivity (fishery or survey)	$v_{a,f} = \begin{cases} \exp\left[-\left(\frac{a-\mu_f}{\sigma_f}\right)^2\right], & \text{if } a \le \mu_f \\ 1, & \text{otherwise} \end{cases}$	9
Fishing mortality	$F_{y,a,r} = \sum_f v_{a,f} F_{y,f,r}$	10
Survival (non-equilibrium)	$s_{y,a,r} = \exp(-F_{y,a,r} - M)$	11
Initial stock abundance (in 1918)	$N_{y,a,r} = R_0 l_a \frac{\exp(\varepsilon_{y,r})}{\sum_r \exp(\varepsilon_{y,r})}$	12
Stock abundance	$N_{y,a,r} = \begin{cases} R_{y,a,r} & a = 0 \\ N_{y-1,a-1,r} s_{y,a,r} & a = 1, 2, \ldots, A-1 \\ N_{y-1,a-1,r} s_{y,a,r} + N_{y-1,A,r} s_{y,A,r} & a = A \end{cases}$	13
Fishery catch at age (abundance)	$C_{y,a,f,r} = \frac{v_{a,f} F_{y,f,r}}{F_{y,a,r}+M} N_{y,a,r}(1 - s_{y,a,r})$	14
Total fishery catch (abundance)	$Y^N_{y,f,r} = \sum_a C_{y,a,f,r}$	15
Total fishery catch (weight)	$Y^W_{y,f,r} = \sum_a C_{y,a,f,r} w_a$	16
Annual catch at age proportion	$p_{y,a,f,r} = C_{y,a,f,r} / Y^N_{y,f,r}$	17
Fishery mean weight	$\bar{w}_{y,f,r} = Y^W_{y,f,r} / Y^N_{y,f,r}$	18

Variable	Equation	Number
Index (abundance)	$I^N_{y,r,s} = q^N_{r,s} \sum_a N_{y,a,r} v_{a,s}$	19
Index (weight)	$I^W_{y,r,s} = q^W_{r,s} \sum_a N_{y,a,r} v_{a,s} w_a$	20

Table D.2. Summary of SS3 likelihood and prior equations used to condition operating models to data. Variables a indexes age, y indexes year, f indexes fishery or survey, s indexes survey, and r indexes area. The circumflex symbol denotes an estimate.

Component	Distribution	Equation	Number
Index	Lognormal	$L_1 = \sum_r \sum_s \sum_y -\lambda^I_{r,s} \times 0.5 \left(\frac{\log(I_{y,r,s}/\hat{I}_{y,r,s})}{\sigma^I_{y,r,s}}\right)^2$	1
Fishery age composition	Multinomial	$L_2 = \sum_r \sum_a \sum_y \sum_f N_{r,y,f} p_{y,a,f,r} \log(\hat{p}_{y,a,f,r})$	2
Fishery mean weight	T-distribution with $\nu = 1000$ degrees of freedom	$L_3 = \sum_r \sum_y \sum_f -\lambda^{\bar{w}}_{f,r} \times 0.5(\nu+1) \log\left(1 + \left[\frac{\bar{w}_{y,f,r} - \hat{\bar{w}}_{y,f,r}}{\sigma^{\hat{w}}_{y,f,r}}\right]^2\right)$	3
Coastwide recruitment deviation	Normal	$P_\delta = \frac{1}{\tau^2} \sum_y \hat{\delta}^2_y, \tau = 0.4$	4
Recruitment distribution	Normal	$P_\varepsilon = \frac{1}{\tau^2} \sum_y \hat{\varepsilon}^2_y$	5
Prior for selectivity parameter μ_f	Normal	$P_\mu = \sum_f \left(\frac{\hat{\mu}_f - m^\mu_f}{\mathrm{SD}^\mu_f}\right)^2$	6
Prior for selectivity parameter σ_f	Normal	$P_\sigma = \sum_f \left(\frac{\log(\hat{\sigma}_f) - m^\sigma_f}{\mathrm{SD}^\sigma_f}\right)^2$	7
Total log-prior	NA	$P = P_\mu + P_\sigma + P_\delta + P_\varepsilon$	8
Total log-likelihood	NA	$\Lambda = L_1 + L_2 + L_3$	9
Log-posterior function	NA	$f = \Lambda + P$	10

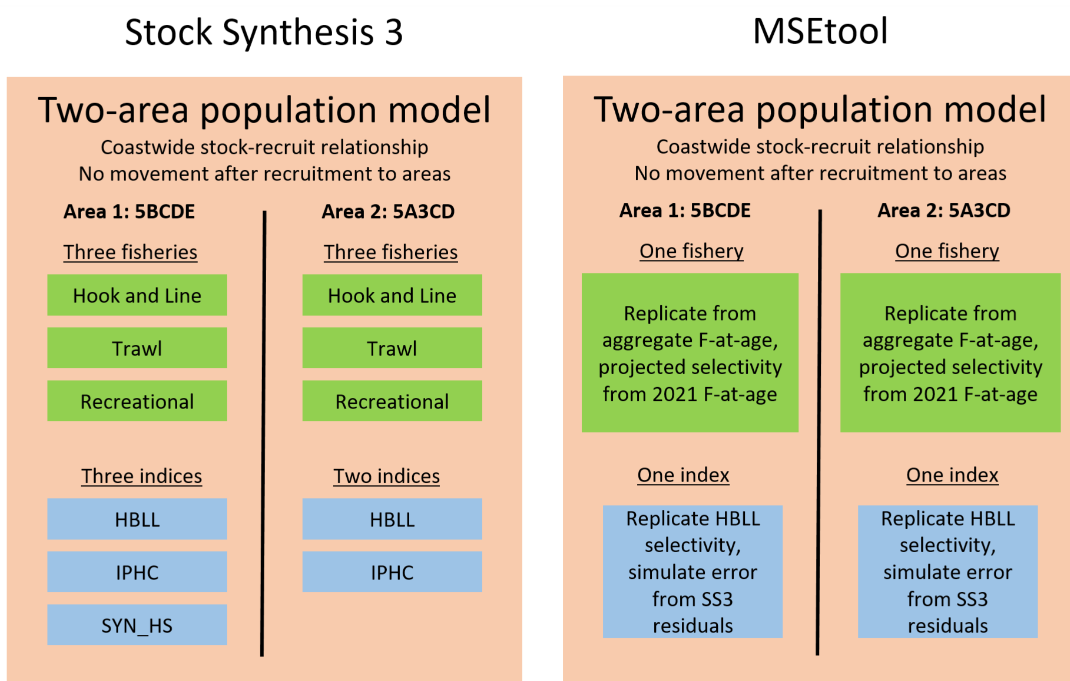

Figure D.1. A schematic that summarizes the overall structure and population dynamics of the Stock Synthesis 3 (SS3) model for Outside Quillback Rockfish. For the closed-loop simulation, the structure of the operating model in the MSEtool package replicated the population structure of the SS3 model. However, the three-fishery structure was simplified into a single aggregate fishery and only the HBLL index was modeled in MSEtool.

D.2. STOCK SYNTHESIS DATA FILE

The `data.ss` file is used to specify the data that will be fitted in the model.

D.2.1. CATCH

Here the historical commercial and recreational catches are provided. Six fisheries were separately modeled, including the hook-and-line commercial fishery, commercial trawl fishery, and recreational fishery for each of the two areas.

The commercial fishery catch series was based on the reconstruction algorithm from 1918–2005 and the nominal catch from 2006 and onwards, as presented in Appendix C.

The recreational fishery catch series from 2012 and onwards used the iRec catch, as presented in Appendix C. Historical recreational catch prior to 2012 was reconstructed based on trends in fishing effort developed through interviews with the owners of a recreational fishing resort (Yamanaka et al. 2011; Stanley et al. 2012). Following Langseth et al. (2021), linear interpolation was used for 1945-2011 to characterize the development of the recreational fishery after World War II. The same trend was used for both areas and scaled so that the catch at the end of the interpolation series was equal to the 2012 iRec catch (Figure D.2).

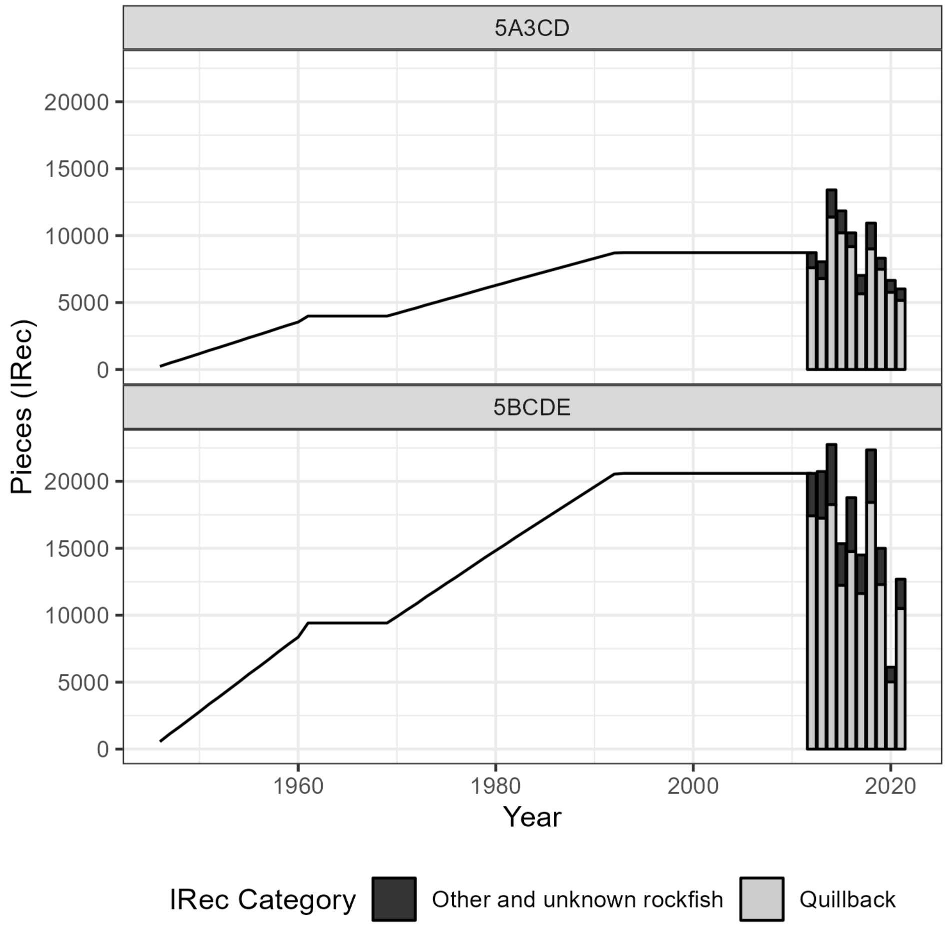

Figure D.2. Recreational fishery catch time series used in the conditioning model. Bars denote iRec catch after 2012, with colours indicating the category where catch is recorded at the species or group level. Catches prior to 2012 are based on interpolation to describe the development of the recreational fishery and increase in recreational effort since 1945.

D.2.2. INDICES OF ABUNDANCE

Five indices of abundance were included in the conditioning model, include those from the HBLL and IPHC surveys for both areas, as well as the Synoptic Hecate Strait trawl survey that is assigned to Area 1 of the model (Appendix B).

The IPHC index developed from the catch from 20 hooks per skate was used since it had the longer time series.

The lognormal likelihood was used for the indices.

D.2.3. LENGTH COMPOSITION

The model included length composition from only the commercial trawl fishery (Figure C.4).

The multinomial likelihood was used for the length composition.

D.2.4. MEAN WEIGHT

The model included mean weight from the commercial hook and line and trawl fisheries (Figure C.5).

The t-distribution likelihood was used for the mean weight, with $\nu = 1000$ degrees of freedom used to approximate the normal distribution.

D.2.5. AGE COMPOSITION

The model included age composition from commercial hook and line fishery (Figure C.3) and the HBLL, IPHC, and Synoptic Hecate Strait surveys (Figures A.1 and A.2).

It was not possible to identify the gear corresponding to the historical catch series in the hook and line sectors. Quillback Rockfish is caught from both longline and handline gears (Hand and Richards 1988; Hand et al. 1990). The ZN rockfish sector, which comprises the majority of the hook and line catch, targets smaller rockfish based on market preferences (A. Grout and J. Belveal, pers. comm. 2023). Therefore, ages from handlines, which appear to catch younger fish than in longlines, were used to represent the hook and line fishery.

The multinomial likelihood was used for the age composition.

D.3. STOCK SYNTHESIS CONTROL FILE

The `control.ss` file describes the configuration of the age-structured model.

D.3.1. NATURAL MORTALITY

The instantaneous natural mortality rate *M* is a core uncertainty for this stock, as for many stocks that do not have direct estimates of this parameter. Indirect estimates using meta-analysis were obtained from relationships between direct estimates of *M* and maximum observed age across various fish taxa.

The seminal paper of Hoenig (1983) developed a prediction equation based on direct estimates of *M* and the maximum observed age ($a_{\max}$ of various taxa. Use of log-log regression is preferred over nonlinear least squares regression to control for heteroschedasticity. As reported in Hamel (2015), the estimate of natural mortality is

$$\log(M_{\text{Hoenig}}) = 1.48 - \log(a_{\max}) \quad \text{(D.1)}$$

Then et al. (2015) updated the *M* estimator by updating the dataset used in Hoenig (1983). Several equations are presented depending on the regression used. Again using log-log regression of the dependent and independent variables, natural mortality is estimated as

$$\log(M_{\text{Then-log-log}}) = 1.717 - 1.01 \times \log(a_{\max}) \tag{D.2}$$

With the maximum observed age of 95 years for Outside Quillback Rockfish, we have two estimates for *M*:

$$M_{\text{Hoenig}} = 0.046 \tag{D.3}$$
$$M_{\text{Then-log-log}} = 0.056 \tag{D.4}$$
$$\tag{D.5}$$

The Then-log-log estimate (M = 0.056) is the preferred value, based on the latest available information and the use of log-log regression.

D.3.2. LENGTH AT AGE

Length-at-age was estimated for both males and females combined, as no sexual dimorphism has been observed for this stock.

Mean asymptotic length.

The value of 39.2 cm was estimated from length and age data (see Appendix A).

von Bertalanffy growth coefficient (K).

The value of 0.11 was estimated from length and age data.

von Bertalanffy theoretical age at length zero.

The value of -3.23 was estimated from length and age data.

The corresponding L_1 parameter, defined as the length at age 1 (14.6 cm), was provided to the model from these three length-at-age parameters.

D.3.3. MATURITY

Maturity ogive.

Maturity was directly input as an age-based function. Female maturity-at-age was estimated using maturity and age data (Appendix A). Since the minimum observed age of a mature fish was 5 years, it assumed that all fish at younger ages were immature.

```
# Maximum age in the model is 70 years
age <- 0:70

# Estimated from binomial GLM with cauchit link
intercept <- -4.44198 - 0.11046
slope <- 0.44489 + 0.03816

linear_predictors <- intercept + slope * age

maturity_age <- ifelse(age <= 4, 0, stats::pcauchy(linear_predictors))
```

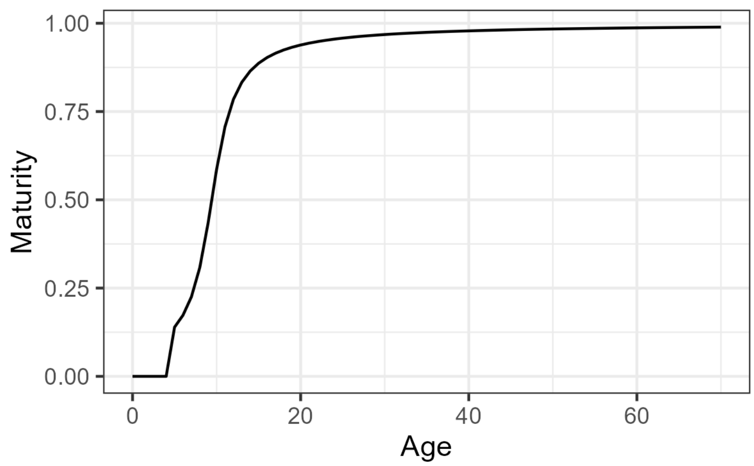

Figure D.3. Maturity-at-age. The minimum observed age of maturity was 4 years and it assumed that younger ages were all immature.

D.3.4. LENGTH-WEIGHT

The length-weight relationship was estimated for both males and females combined, as no sexual dimorphism has been observed for this stock.

Length-weight parameter alpha

The value of 1.38×10^{-5} was estimated from length and weight data (see Appendix A).

Length-weight parameter beta

The value of 3.11 was estimated from length and weight data.

D.3.5. STOCK-RECRUITMENT RELATIONSHIP

The Beverton-Holt stock-recruit relationship was used for Outside Quillback Rockfish. The recruitment R in year y and area $r = 1, 2$ is calculated from the coastwide spawning biomass B_y as

$$R_{y,r} = \frac{(4R_0 h)B_y}{R_0\phi_0(1-h) + (5h-1)B_y} \exp(\delta_y) \frac{\exp(\varepsilon_{y,r})}{\sum_r \exp(\varepsilon_{y,r})} \tag{D.6}$$

where R_0 is the unfished recruitment, h is steepness, ϕ_0 is unfished spawning biomass per recruit, δ_y is the lognormal recruitment deviation of coastwide recruitment from the Beverton-Holt equation, and $\varepsilon_{y,r}$ is a softmax vector that assigns the proportion of coastwide recruitment into each area.

D.3.6. AVERAGE UNFISHED RECRUITMENT (R0)

This is the primary parameter, in units of thousands of fish, that informs the size of the coastwide population. This parameter was estimated. There was a broad uniform prior for the $\log(R_0)$ with lower bound of 3 and upper bound of 12.

D.3.7. STEEPNESS

Steepness of the stock-recruit relationship (*h*) is the reduction in average recruitment at 20 percent of unfished biomass. For the Beverton-Holt stock-recruit relationship, steepness is bounded between 0.2 and 1.0. A steepness of 1 implies infinite density-dependence, i.e., recruitment is independent of spawning output or egg production.

This parameter is another core uncertainty for most stocks. Forrest et al. (2010) did a meta-analysis of Pacific rockfish in British Columbia and U.S. West Coast and estimated a posterior mean of 0.67 of the Beverton-Holt steepness parameter. This information was subsequently used in Yamanaka et al. (2011). Here, we fix the steepness value to 0.67.

An alternative operating model was developed with a lower steepness value of 0.50.

D.3.8. RECRUITMENT STANDARD DEVIATION

Process error, the standard deviation of lognormal recruitment deviations.

Recruitment deviations from the Beverton-Holt stock-recruit equation were estimated for 1940–2021, with a prior standard deviation of 0.4:

$$\delta_y \sim N(0, \sigma_R = 0.4) \quad \text{(D.7)}$$

D.3.9. RECRUITMENT DISTRIBUTION

Distribution of recruitment between areas.

Since recruitment distribution is a multinomial logistic vector, the parameter was set to zero for area $r = 1$ and estimated for the second area as:

$$\varepsilon_{y,r=2} = \varepsilon_{r=2}^{\text{base}} + \tilde{\varepsilon}_y \tag{D.8}$$

Parameter $\varepsilon_{r=2}^{\text{base}}$ is a fixed effect that describes the recruitment distribution in an equilibrium state, estimated with a normal prior with mean 0 and standard deviation of 2.

For 1940–2021, a year-specific distribution was estimated through an additive deviation parameter $\tilde{\varepsilon}_y$. For earlier years, $\tilde{\varepsilon}_y = 0$. These deviations were constrained by a prior distribution with standard deviation of 0.4:

$$\tilde{\varepsilon}_y \sim N(0, \sigma = 0.4) \tag{D.9}$$

D.3.10. FISHING MORTALITY

Fishing mortality was specified to be continuous over annual time steps (using the Baranov equation). The model was configured to solve for the fishing mortality such that the predicted catch is equal to observed catch.

D.3.11. INDEX CATCHABILITY

The catchability coefficient scales the population into the units of the indices of abundance.

For the HBLL index, catchability was specified to be identical between the north and south. In this way, the abundance estimate in the index between areas will also inform the the relative population size, i.e., a higher index in the North implies a larger stock than in the South.

For the IPHC and Synoptic Hecate Strait indices, catchability was a floating independent parameter, i.e., the parameter was solved analytically and the coefficient for each survey is independent of the magnitude of other surveys.

D.3.12. SELECTIVITY

Selectivity for the commercial hook and line and trawl fisheries and the survey were estimated using the double-normal function in SS3. Functionally, the selectivity at age v_a for a fishery or survey is

$$v_a = \begin{cases} \exp\left[-\left(\frac{a-\mu}{\sigma}\right)^2\right], & \text{if } a \leq \mu \\ 1, & \text{otherwise} \end{cases}, \tag{D.10}$$

A simple two-parameter configuration was created with a Gaussian ascending limb and flat-top selectivity for the oldest age classes. Selectivity was mirrored for fisheries and surveys that operate in both areas. The location and width of the ascending limb is controlled by the μ and σ parameters.

For the trawl fishery, selectivity was estimated in units of length and the equivalent age-based selectivity was subsequently reported.

Gaussian priors were developed from the shape of the age (or length) composition. The prior mean for μ was the mode of the distribution and the prior mean of $\log(\sigma)$ was half the distance between the mode and the smallest observed age class (Table D.3). The prior standard deviation was calculated so that the coefficient of variation was 0.3.

Since no age or size samples were available from the recreational fishery, the selectivity estimated for the inside Quillback Rockfish, from lengths reported in creel survey interviews, was used here (Huynh et al. 2024). A logistic function was used with the age of 50 and 95 percent selectivity at 12.7 and 23.3 years, respectively.

D.3.13. DATA WEIGHTING

The McAllister and Ianelli method (McAllister and Ianelli 1997) was employed to reduced the sample size of the age compositions in the multinomial likelihood for the HBLL and IPHC surveys. The multiplicative re-weighting factors were 0.3, 0.7, 0.8, and 0.5 for the ages from the HBLL North, HBLL South, IPHC North, and IPHC South indices, respectively. These values were identified during the initial model fitting for operating model 1 and used for all operating model conditioning.

No re-weighting was done for the composition data in the Hecate Strait survey and commercial fisheries, since there were few years of samples that would not dominate the likelihood.

Additional likelihood weighting factors $\lambda = 0.01$ were added for the hook and line fishery mean weights. In effect, the mean weights were downweighted relative to the age composition. The standard error of the mean weights were very low for the hook and line fishery (Table C.6). With $\lambda = 1$ (the default), the model fit the fishery mean weight well at the expense of poor fit to survey age composition. Since the value of the mean weight data was to determine the relative selectivity between hook and line and trawl fisheries, it was decided to downweight the hook and line mean weight to ensure a reasonable fit to the survey age data.

D.4. MCMC DIAGNOSTICS

Convergence of the two MCMC chains was confirmed via visual evaluation. Wormplots indicated there was little autocorrelation between successive MCMC samples (Figure D.4). The MC standard error was low (less than 0.1 for all parameters) and the $\hat{R}$ statistic was close to 1 for all parameters. Posterior distributions were approximately Gaussian shaped (Figure D.5).

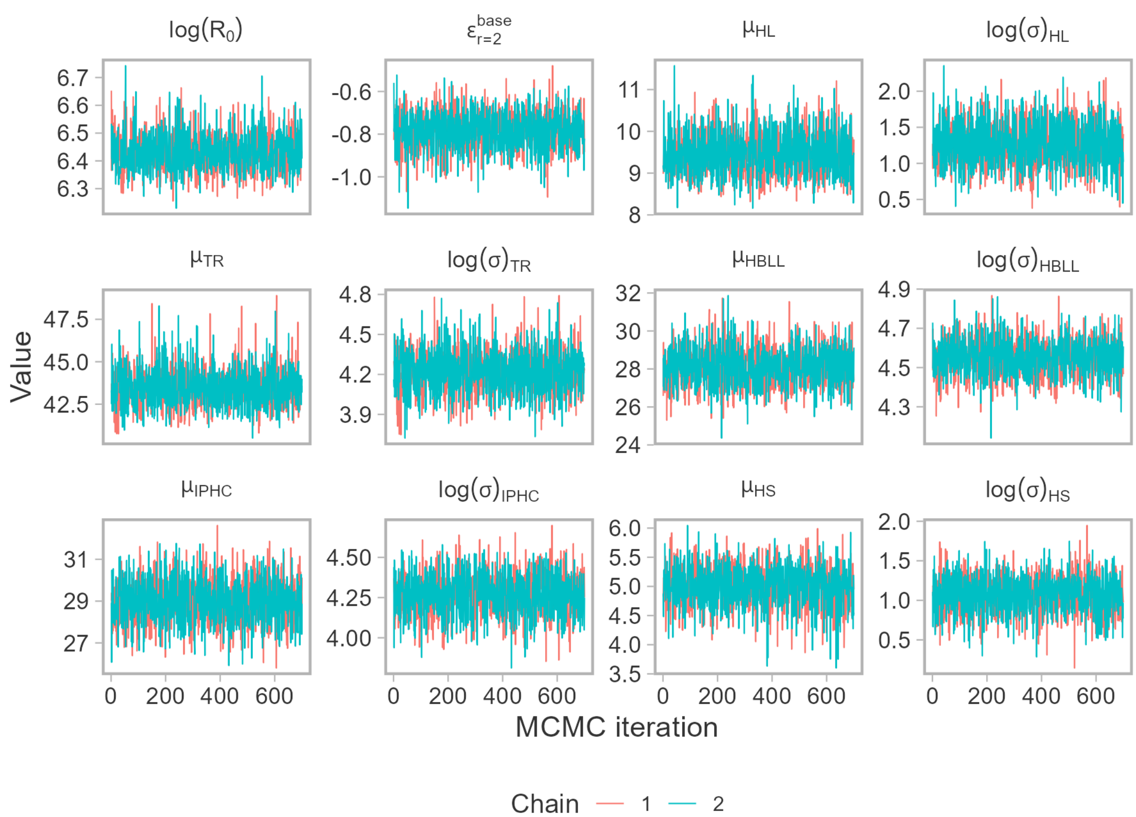

Figure D.4. Wormplots of SS3 parameters in the MCMC simulation for operating model 1. Description of parameters are available in Table D.3. Recruitment deviation parameters are not reported here.

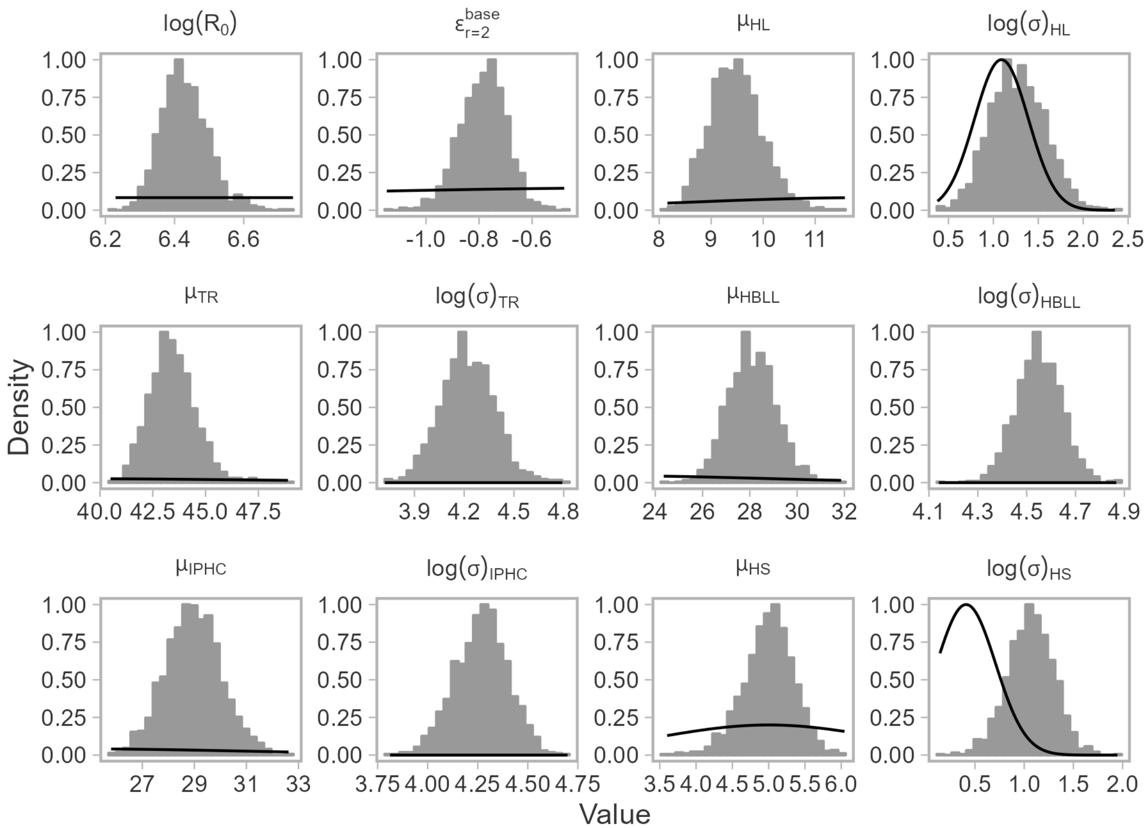

Figure D.5. Prior (black line) and posterior (grey bars) density of SS3 parameters for operating model 1. Description of parameters and distributions are available in Table D.3. The x-axis limits are determined by the posterior distribution. Flat black lines indicate that the posterior density is far from the prior density. Recruitment deviation parameters are not reported here.

Table D.3. Parameter priors and posterior means from the SS3 model for Outside Quillback Rockfish. Posterior values are reported for operating model 1. Recruitment deviation parameters are not reported here. A uniform prior was used for unfished recruitment and a normal prior used for all other parameters.

Parameter	Description	Prior	Posterior mean	Posterior SD
$\log(R_0)$	Unfished recruitment	U(3.00, 12.0)	6.43	0.07
$\varepsilon_{r=2}^{\text{base}}$	Recruitment distribution	N(0.00, 2.0)	-0.79	0.09
μ_{HL}	Full selectivity - Hook and Line	N(12.00, 3.6)	9.48	0.50
$\log(\sigma)_{\text{HL}}$	Selectivity width - Hook and Line	N(1.10, 0.3)	1.27	0.30
μ_{TR}	Full selectivity - Trawl	N(37.00, 11.1)	43.46	1.11
$\log(\sigma)_{\text{TR}}$	Selectivity width - Trawl	N(1.80, 0.3)	4.22	0.16
μ_{HBLL}	Full selectivity - HBLL	N(22.00, 6.6)	28.11	1.00
$\log(\sigma)_{\text{HBLL}}$	Selectivity width - HBLL	N(2.10, 0.3)	4.55	0.09
μ_{IPHC}	Full selectivity - IPHC	N(24.00, 7.2)	28.95	1.06
$\log(\sigma)_{\text{IPHC}}$	Selectivity width - IPHC	N(1.90, 0.3)	4.27	0.13
μ_{HS}	Full selectivity - Hecate Strait	N(5.00, 1.5)	5.00	0.34
$\log(\sigma)_{\text{HS}}$	Selectivity width - Hecate Strait	N(0.41, 0.3)	1.07	0.23

D.5. ADDITIONAL OPERATING MODEL PARAMETERS

Additional observation parameters (for simulated data in the projections) and implementation parameters are described below.

D.5.1. COBS

Observation error in the catch expressed as a SD.

This parameter (σ_C) sets the standard deviation of the simulated catch for the projection period. The openMSE operating model can generate σ_C based on the residuals between the predicted and observed catch. Since SS3 was conditioned on observed catch, the predicted catch will match the observed catch and thus, $\sigma_C < 0.01$.

D.5.2. CBIAS

Bias in the catch.

This parameter controls the bias, expressed as the ratio of simulated observed to true catches, i.e., under/overreporting, for the projection period. Since SS3 was conditioned on observed catch, the ratio is 1.

D.5.3. IOBS

Observation error in the relative abundance indices expressed as a SD.

This parameter sets the standard deviation in simulated survey indices for the projection period. We sampled the observation error using the standard deviation and autocorrelation of residuals in the HBLL index for each posterior sample (Figure D.6).

D.5.4. BETA

A parameter controlling hyperstability/hyperdepletion where values below 1 lead to hyperstability (an index that decreases more slowly than true abundance) and values above 1 lead to hyperdepletion (an index that decreases more rapidly than true abundance). Uniform distribution.

We set the hyperstability/hyperdepletion parameter $\beta = 1$ to imply no hyperstability or hyperdepletion.

D.5.5. TACFRAC

Mean fraction of TAC taken. Uniform distribution.

We assumed no implementation error between the catch advice in the management procedure and the subsequent fishery removal in the operating model, i.e., TACFrac = 1.

Persistent implementation error is not believed to occur in the commercial fishery. The magnitude of unreported FSC catch is not known at this time. Since 2007, FSC catch from dual fishing trips is approximately 1–5 percent of commercial catch. If the FSC catch from non-dual fishing trips is of similar magnitude, then there could be implementation error of 1–5 percent. Due to the low magnitude, no implementation error was modeled in this analysis.

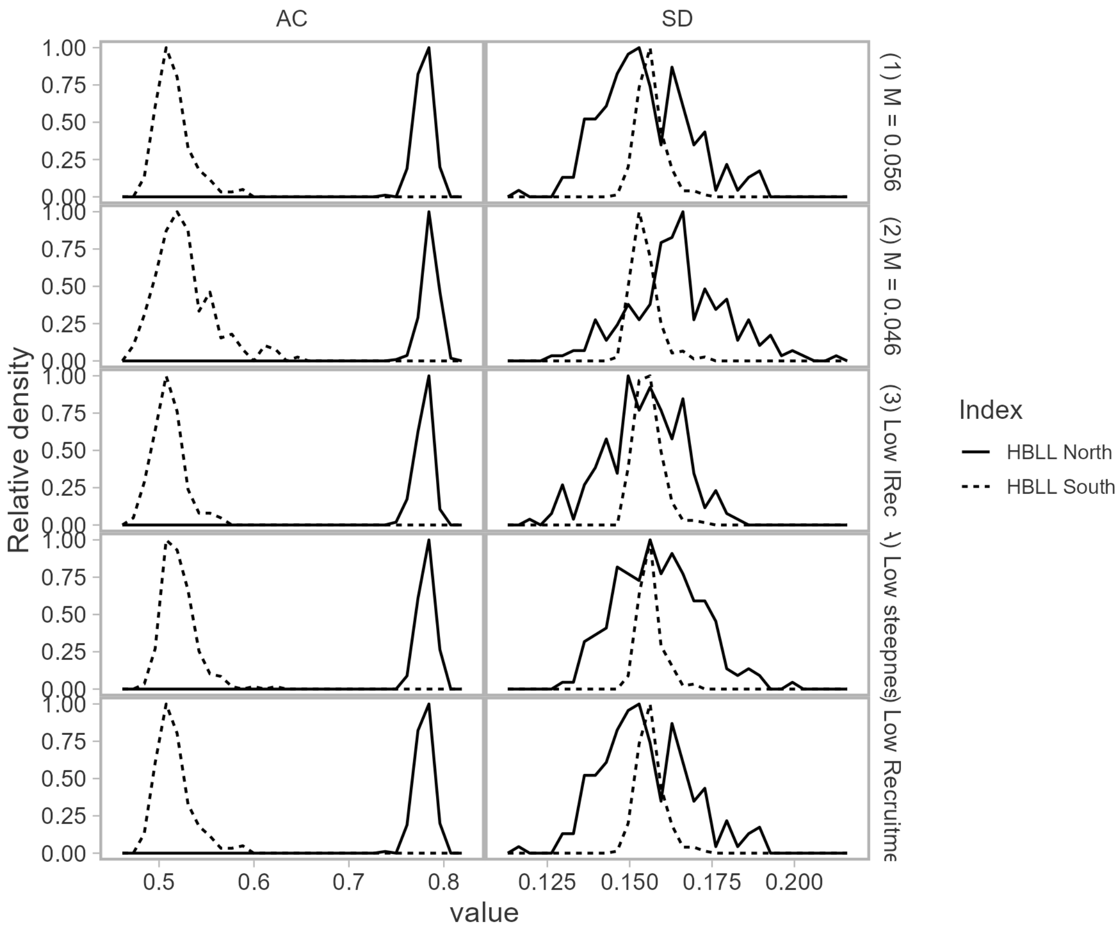

Figure D.6. Autocorrelation (AC) and standard deviation (SD) of the observation error in the simulated HBLL index of the projection period. Values were calculated from the residuals of the index in 200 posterior samples of the SS3 model.

D.6. ADDITIONAL STOCK SYNTHESIS MODEL FITS

This section describes additional model fits used to explore the model to facilitate review, but ultimately were not included in the reference or robustness set for further consideration.

The influence of the various indices on stock trends was explored through alternative fits that excluded either the IPHC or Hecate Strait index, along with the accompanying age compositions. Excluding one of these indices did not appear to change the fit to the others (Figure D.7). An additional fit included a likelihood weighting factor $\lambda^I = 5$ for the HBLL North index which improved the fit to that index series. The model estimated higher biomass in that area as a result of higher than average recruitment into the North. However, differences in reference points, based on the average stock recruit relationship, appeared to be trivial because the weighting factor primarily affected estimation in the recruitment deviation parameters.

Attempts were made to estimate natural mortality and steepness within the model rather than fixing these parameters. A lognormal prior $M \sim \mathrm{Lognormal}\left(\log(0.056), 0.08\right)$ for natural mortality was developered where the standard deviation was the standard error of the intercept term from the meta-analysis in Then et al. (2015). For steepness, a beta prior with mean of 0.67 and standard deviation of 0.17, following the posterior estimate from Forrest et al. (2010) was used. The model estimated that the stock was much larger and lightly fished during its history, i.e., B/B_{2021} = 0.91, with a natural mortality of 0.08 (Figures D.8 and D.9). Due to the high steepness value, estimated at 0.84, the shape of the yield curve was extremely skewed with the optimum at very low stock levels, i.e., B_{MSY} = 0.22 B_0 (Figure D.10).

This model was not further considered as the yield curve and historical depletion estimate was not considered to be plausible. However, the review group did request that this model be given further consideration in the future as a robustness scenario in the evaluation of management procedures.

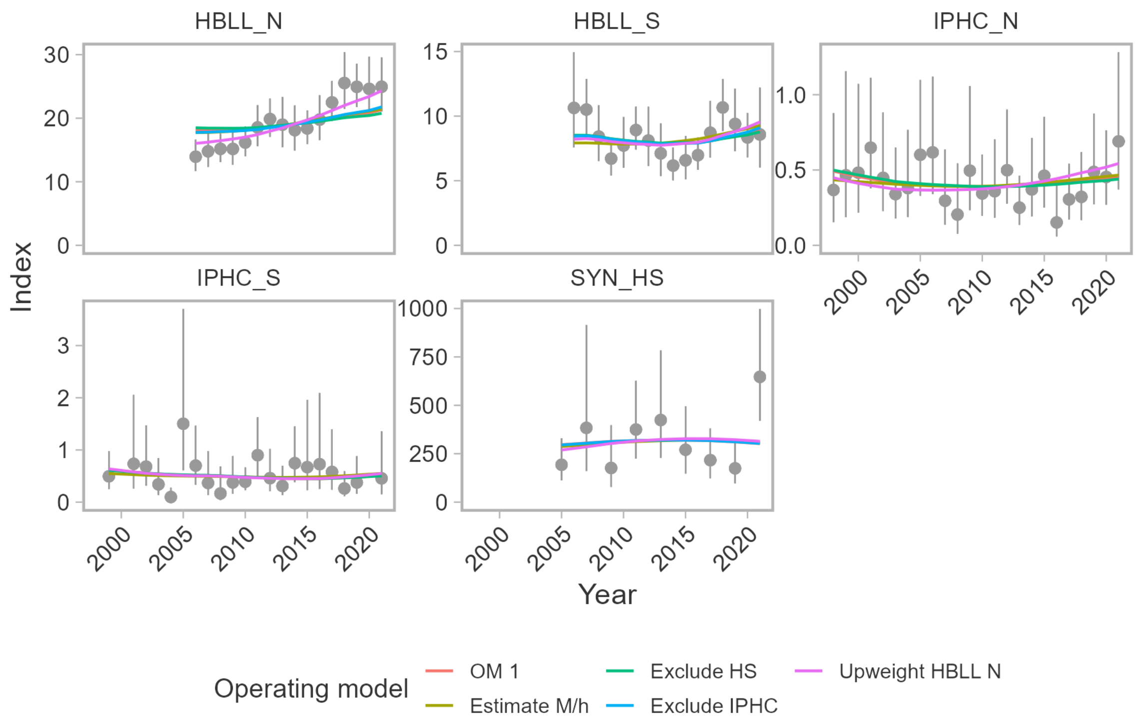

Figure D.7. Comparison to fits to indices of abundance from additional SS3 model fits.

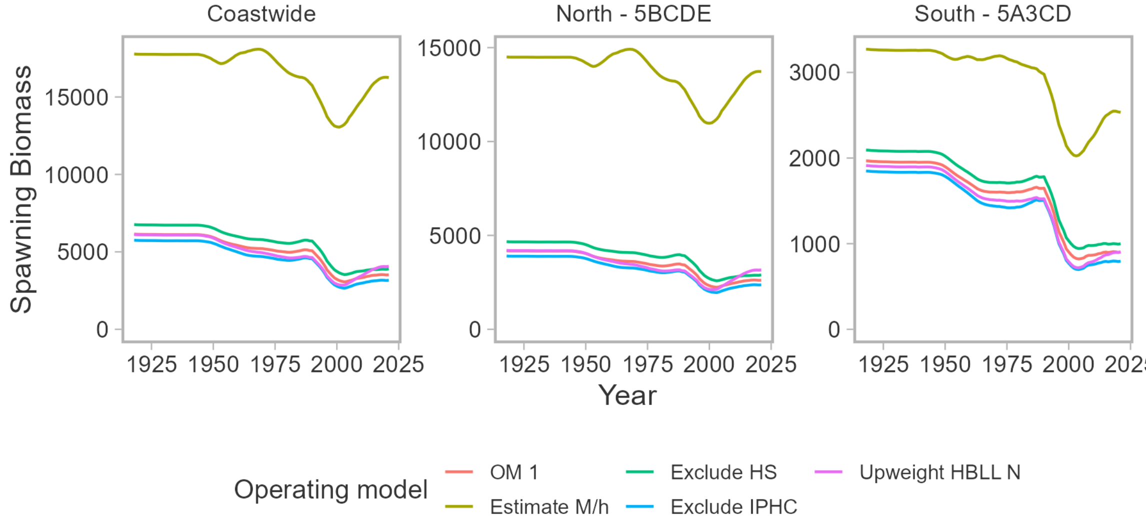

Figure D.8. Comparison of spawning biomass estimated from additional SS3 model fits.

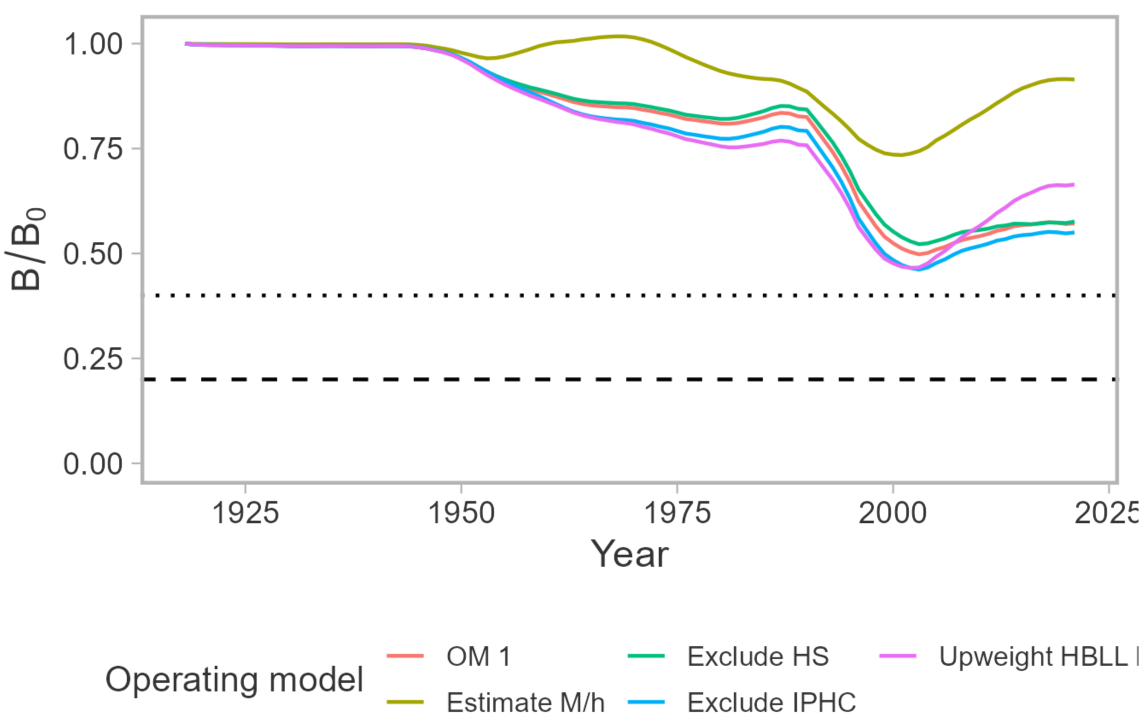

Figure D.9. Comparison of spawning depletion estimated from additional SS3 model fits.

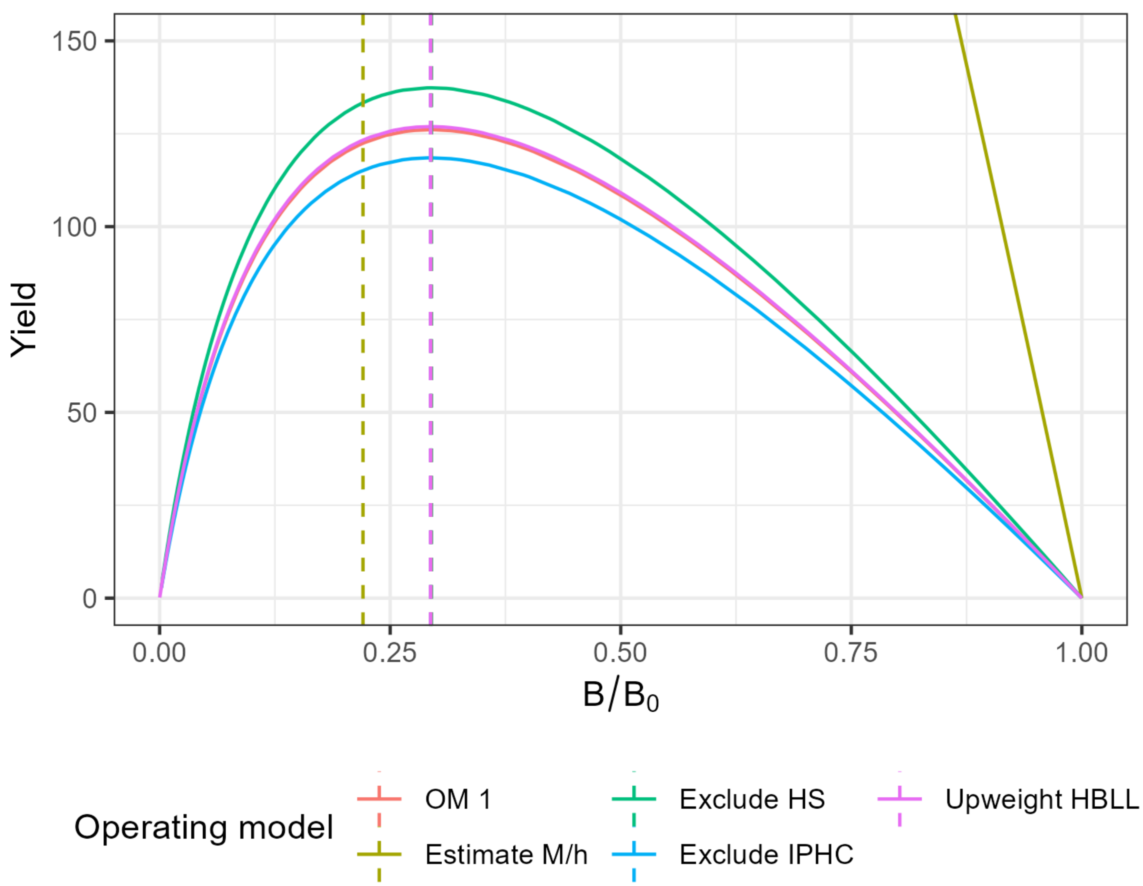

Figure D.10. Comparison of yield curves estimated from additional SS3 model fits. Vertical, dotted lines indicate the depletion where the yield curve is at the maximum. For the operating model that estimated M and h, the maximum sustainable yield is 665 t.

D.7. TABLE OF STOCK SYNTHESIS PARAMETERS

Table D.4. Parameters reported from SS3 for operating model 1. The other operating models were obtained by re-fitting the model after adjusting the parameter value corresponding to natural mortality, steepness, or the recreational catch multipliers in the control file.

Parameter	Estimated?	Value	Standard Error	Description
NatM_uniform_Fem_GP_1	Fixed	0.056	NA	Natural mortality, derived from literature
L_at_Amin_Fem_GP_1	Fixed	14.580	NA	Mean length at age 1, estimated from data
L_at_Amax_Fem_GP_1	Fixed	39.200	NA	Mean length at age 999, i.e., L_∞, estimated from data
VonBert_K_Fem_GP_1	Fixed	0.110	NA	Von Bertalanffy K parameter, estimated from data
CV_young_Fem_GP_1	Fixed	0.090	NA	Variability in length at age 1, estimated from data
CV_old_Fem_GP_1	Fixed	0.090	NA	Variability in length at age 999, estimated from data
Wtlen_1_Fem_GP_1	Fixed	0.000	NA	Length-weight scalar (a), estimated from data
Wtlen_2_Fem_GP_1	Fixed	3.110	NA	Length-weight exponent (b), estimated from data
Mat50%_Fem_GP_1	Fixed	0.000	NA	Not used - maturity at age (estimated from data) directly specified
Mat_slope_Fem_GP_1	Fixed	0.000	NA	Not used - maturity at age (estimated from data) directly specified
Eggs/kg_inter_Fem_GP_1	Fixed	1.000	NA	Fecundity proportional to weight
Eggs/kg_slope_wt_Fem_GP_1	Fixed	0.000	NA	Fecundity proportional to weight
RecrDist_GP_1_area_1_month_1	Fixed	0.000	NA	Recruitment distribution for area 1
RecrDist_GP_1_area_2_month_1	Yes	-0.754	0.078	Recruitment distribution for area 2 relative to 1, $\varepsilon^{\text{base}}$
CohortGrowDev	Fixed	1.000	NA	Internal SS3 parameter
Catch_Mult:_5_Recreational_N	Fixed	1.000	NA	Catch multiplier for recreational fishery in area 1
Catch_Mult:_6_Recreational_S	Fixed	1.000	NA	Catch multiplier for recreational fishery in area 2
FracFemale_GP_1	Fixed	0.500	NA	Not used
RecrDist_GP_1_area_2_month_1_dev_se	Fixed	0.400	NA	Standard deviation in annual recruitment distribution
RecrDist_GP_1_area_2_month_1_dev_autocorr	Fixed	0.000	NA	Not used
SR_LN(R0)	Yes	6.421	0.061	Natural logarithm of unfished recruitment
SR_BH_steep	Fixed	0.670	NA	Steepness, derived from literature
SR_sigmaR	Fixed	0.400	NA	Standard deviation in annual recruitment deviates
SR_regime	Fixed	0.000	NA	Not used
SR_autocorr	Fixed	0.000	NA	Not used
Main_RecrDev_1940	Yes	-0.625	0.299	Recruitment deviation
Main_RecrDev_1941	Yes	-0.477	0.285	Recruitment deviation
Main_RecrDev_1942	Yes	-0.763	0.299	Recruitment deviation
Main_RecrDev_1943	Yes	-0.434	0.273	Recruitment deviation
Main_RecrDev_1944	Yes	-0.229	0.252	Recruitment deviation
Main_RecrDev_1945	Yes	-0.261	0.249	Recruitment deviation
Main_RecrDev_1946	Yes	0.081	0.218	Recruitment deviation
Main_RecrDev_1947	Yes	-0.067	0.229	Recruitment deviation
Main_RecrDev_1948	Yes	-0.113	0.225	Recruitment deviation
Main_RecrDev_1949	Yes	0.071	0.205	Recruitment deviation
Main_RecrDev_1950	Yes	-0.049	0.210	Recruitment deviation
Main_RecrDev_1951	Yes	-0.236	0.220	Recruitment deviation
Main_RecrDev_1952	Yes	-0.267	0.218	Recruitment deviation
Main_RecrDev_1953	Yes	-0.180	0.206	Recruitment deviation

Parameter	Estimated?	Value	Standard Error	Description
Main_RecrDev_1954	Yes	0.081	0.185	Recruitment deviation
Main_RecrDev_1955	Yes	-0.117	0.194	Recruitment deviation
Main_RecrDev_1956	Yes	0.172	0.169	Recruitment deviation
Main_RecrDev_1957	Yes	-0.192	0.192	Recruitment deviation
Main_RecrDev_1958	Yes	0.029	0.171	Recruitment deviation
Main_RecrDev_1959	Yes	0.327	0.149	Recruitment deviation
Main_RecrDev_1960	Yes	-0.195	0.180	Recruitment deviation
Main_RecrDev_1961	Yes	0.111	0.156	Recruitment deviation
Main_RecrDev_1962	Yes	0.000	0.161	Recruitment deviation
Main_RecrDev_1963	Yes	-0.084	0.159	Recruitment deviation
Main_RecrDev_1964	Yes	-0.216	0.165	Recruitment deviation
Main_RecrDev_1965	Yes	-0.102	0.153	Recruitment deviation
Main_RecrDev_1966	Yes	-0.017	0.142	Recruitment deviation
Main_RecrDev_1967	Yes	0.079	0.135	Recruitment deviation
Main_RecrDev_1968	Yes	0.096	0.131	Recruitment deviation
Main_RecrDev_1969	Yes	0.014	0.131	Recruitment deviation
Main_RecrDev_1970	Yes	0.158	0.119	Recruitment deviation
Main_RecrDev_1971	Yes	0.065	0.121	Recruitment deviation
Main_RecrDev_1972	Yes	0.119	0.114	Recruitment deviation
Main_RecrDev_1973	Yes	0.128	0.110	Recruitment deviation
Main_RecrDev_1974	Yes	0.338	0.098	Recruitment deviation
Main_RecrDev_1975	Yes	0.304	0.097	Recruitment deviation
Main_RecrDev_1976	Yes	0.530	0.085	Recruitment deviation
Main_RecrDev_1977	Yes	0.466	0.085	Recruitment deviation
Main_RecrDev_1978	Yes	0.171	0.094	Recruitment deviation
Main_RecrDev_1979	Yes	-0.045	0.101	Recruitment deviation
Main_RecrDev_1980	Yes	0.084	0.095	Recruitment deviation
Main_RecrDev_1981	Yes	0.229	0.090	Recruitment deviation
Main_RecrDev_1982	Yes	0.218	0.089	Recruitment deviation
Main_RecrDev_1983	Yes	0.204	0.089	Recruitment deviation
Main_RecrDev_1984	Yes	0.199	0.088	Recruitment deviation
Main_RecrDev_1985	Yes	-0.095	0.099	Recruitment deviation
Main_RecrDev_1986	Yes	-0.074	0.097	Recruitment deviation
Main_RecrDev_1987	Yes	0.015	0.093	Recruitment deviation
Main_RecrDev_1988	Yes	0.065	0.091	Recruitment deviation
Main_RecrDev_1989	Yes	0.080	0.091	Recruitment deviation
Main_RecrDev_1990	Yes	-0.091	0.098	Recruitment deviation
Main_RecrDev_1991	Yes	-0.340	0.111	Recruitment deviation
Main_RecrDev_1992	Yes	0.252	0.089	Recruitment deviation
Main_RecrDev_1993	Yes	0.179	0.095	Recruitment deviation
Main_RecrDev_1994	Yes	0.242	0.095	Recruitment deviation
Main_RecrDev_1995	Yes	0.427	0.090	Recruitment deviation
Main_RecrDev_1996	Yes	0.282	0.097	Recruitment deviation
Main_RecrDev_1997	Yes	0.335	0.100	Recruitment deviation
Main_RecrDev_1998	Yes	0.108	0.113	Recruitment deviation
Main_RecrDev_1999	Yes	0.042	0.121	Recruitment deviation
Main_RecrDev_2000	Yes	0.785	0.094	Recruitment deviation
Main_RecrDev_2001	Yes	-0.301	0.166	Recruitment deviation
Main_RecrDev_2002	Yes	0.414	0.145	Recruitment deviation
Main_RecrDev_2003	Yes	0.733	0.142	Recruitment deviation
Main_RecrDev_2004	Yes	0.574	0.167	Recruitment deviation
Main_RecrDev_2005	Yes	-0.050	0.229	Recruitment deviation
Main_RecrDev_2006	Yes	0.448	0.210	Recruitment deviation
Main_RecrDev_2007	Yes	0.194	0.257	Recruitment deviation
Main_RecrDev_2008	Yes	-0.117	0.310	Recruitment deviation
Main_RecrDev_2009	Yes	0.184	0.310	Recruitment deviation
Main_RecrDev_2010	Yes	0.118	0.325	Recruitment deviation
Main_RecrDev_2011	Yes	-0.196	0.329	Recruitment deviation
Main_RecrDev_2012	Yes	0.036	0.305	Recruitment deviation

Parameter	Estimated?	Value	Standard Error	Description
Main_RecrDev_2013	Yes	-0.242	0.312	Recruitment deviation
Main_RecrDev_2014	Yes	-0.314	0.313	Recruitment deviation
Main_RecrDev_2015	Yes	-0.410	0.321	Recruitment deviation
Main_RecrDev_2016	Yes	-0.724	0.339	Recruitment deviation
Main_RecrDev_2017	Yes	-0.640	0.350	Recruitment deviation
Main_RecrDev_2018	Yes	-0.477	0.372	Recruitment deviation
Main_RecrDev_2019	Yes	-0.372	0.390	Recruitment deviation
Main_RecrDev_2020	Yes	-0.340	0.396	Recruitment deviation
Main_RecrDev_2021	Yes	-0.337	0.397	Recruitment deviation
ForeRecr_2022	Yes	0.000	0.400	Recruitment deviation
LnQ_base_HBLL_N(7)	Yes	-4.156	0.186	Catchability of HBLL N index
LnQ_base_HBLL_S(8)	Fixed	-3.884	NA	Not used - HBLL S catchability follows HBLL N
LnQ_base_IPHC_N(9)	Fixed	-7.801	NA	Not used - IPHC N catchability calculated analytically
LnQ_base_IPHC_S(10)	Fixed	-6.502	NA	Not used - IPHC S catchability calculated analytically
LnQ_base_SYN_HS(11)	Fixed	-2.342	NA	Not used - SYN HS catchability calculated analytically
Size_DblN_peak_Trawl_N(3)	Yes	43.465	1.074	μ selectivity parameter
Size_DblN_top_logit_Trawl_N(3)	Fixed	50.000	NA	Flat-top selectivity if length $\geq \mu$
Size_DblN_ascend_se_Trawl_N(3)	Yes	4.222	0.159	σ selectivity parameter
Size_DblN_descend_se_Trawl_N(3)	Fixed	10.000	NA	Not used, flat-top selectivity if length $\geq \mu$
Size_DblN_start_logit_Trawl_N(3)	Fixed	-999.000	NA	Selectivity goes to zero at the left
Size_DblN_end_logit_Trawl_N(3)	Fixed	-999.000	NA	Not used, flat-top selectivity if length $\geq \mu$
Age_DblN_peak_HookLine_N(1)	Yes	9.527	0.448	μ selectivity parameter
Age_DblN_top_logit_HookLine_N(1)	Fixed	50.000	NA	Flat-top selectivity if age $\geq \mu$
Age_DblN_ascend_se_HookLine_N(1)	Yes	1.268	0.285	σ selectivity parameter
Age_DblN_descend_se_HookLine_N(1)	Fixed	10.000	NA	Not used, flat-top selectivity if age $\geq \mu$
Age_DblN_start_logit_HookLine_N(1)	Fixed	-999.000	NA	Selectivity goes to zero at the left
Age_DblN_end_logit_HookLine_N(1)	Fixed	-999.000	NA	Not used, flat-top selectivity if age $\geq \mu$
Age_inflection_Recreational_N(5)	Fixed	12.700	NA	Age of 50 percent selectivity (logistic function), estimated from inside stock
Age_95%width_Recreational_N(5)	Fixed	10.600	NA	Difference between 95 and 50 percent selectivity, estimated from inside stock
Age_DblN_peak_HBLL_N(7)	Yes	28.375	0.961	μ selectivity parameter
Age_DblN_top_logit_HBLL_N(7)	Fixed	50.000	NA	Flat-top selectivity if age $\geq \mu$
Age_DblN_ascend_se_HBLL_N(7)	Yes	4.571	0.087	σ selectivity parameter
Age_DblN_descend_se_HBLL_N(7)	Fixed	10.000	NA	Not used, flat-top selectivity if age $\geq \mu$
Age_DblN_start_logit_HBLL_N(7)	Fixed	-999.000	NA	Selectivity goes to zero at the left
Age_DblN_end_logit_HBLL_N(7)	Fixed	-999.000	NA	Not used, flat-top selectivity if age $\geq \mu$
Age_DblN_peak_IPHC_N(9)	Yes	29.053	1.053	μ selectivity parameter
Age_DblN_top_logit_IPHC_N(9)	Fixed	50.000	NA	Flat-top selectivity if age $\geq \mu$
Age_DblN_ascend_se_IPHC_N(9)	Yes	4.276	0.128	σ selectivity parameter
Age_DblN_descend_se_IPHC_N(9)	Fixed	10.000	NA	Not used, flat-top selectivity if age $\geq \mu$
Age_DblN_start_logit_IPHC_N(9)	Fixed	-999.000	NA	Selectivity goes to zero at the left
Age_DblN_end_logit_IPHC_N(9)	Fixed	-999.000	NA	Not used, flat-top selectivity if age $\geq \mu$
Age_DblN_peak_SYN_HS(11)	Yes	5.075	0.259	μ selectivity parameter
Age_DblN_top_logit_SYN_HS(11)	Fixed	10.000	NA	Flat-top selectivity if age $\geq \mu$
Age_DblN_ascend_se_SYN_HS(11)	Yes	1.108	0.192	σ selectivity parameter
Age_DblN_descend_se_SYN_HS(11)	Fixed	10.000	NA	Not used, flat-top selectivity if age $\geq \mu$
Age_DblN_start_logit_SYN_HS(11)	Fixed	-999.000	NA	Selectivity goes to zero at the left
Age_DblN_end_logit_SYN_HS(11)	Fixed	-999.000	NA	Not used, flat-top selectivity if age $\geq \mu$
RecrDist_GP_1_area_2_month_1_DEVadd_1940	Yes	0.289	0.963	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1941	Yes	0.014	0.937	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$

Parameter	Estimated?	Value	Standard Error	Description
RecrDist_GP_1_area_2_month_1_DEVadd_1942	Yes	0.155	0.976	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1943	Yes	0.221	0.917	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1944	Yes	-0.239	0.885	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1945	Yes	-0.451	0.887	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1946	Yes	-0.439	0.827	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1947	Yes	0.474	0.827	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1948	Yes	-0.219	0.842	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1949	Yes	-0.739	0.816	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1950	Yes	-0.674	0.828	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1951	Yes	-0.449	0.846	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1952	Yes	-0.551	0.848	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1953	Yes	-0.673	0.829	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1954	Yes	-0.053	0.758	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1955	Yes	-0.313	0.793	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1956	Yes	-0.645	0.742	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1957	Yes	0.210	0.777	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1958	Yes	-0.451	0.745	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1959	Yes	0.080	0.662	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1960	Yes	0.106	0.754	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1961	Yes	0.329	0.677	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1962	Yes	1.036	0.673	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1963	Yes	-0.207	0.712	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1964	Yes	0.354	0.711	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1965	Yes	0.179	0.682	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1966	Yes	-0.550	0.678	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1967	Yes	0.562	0.612	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1968	Yes	0.806	0.592	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1969	Yes	0.623	0.600	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1970	Yes	-0.039	0.580	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$

Parameter	Estimated?	Value	Standard Error	Description
RecrDist_GP_1_area_2_month_1_DEVadd_1971	Yes	0.404	0.572	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1972	Yes	0.058	0.560	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1973	Yes	-0.014	0.548	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1974	Yes	0.125	0.494	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1975	Yes	-0.124	0.496	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1976	Yes	-0.456	0.456	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1977	Yes	0.243	0.436	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1978	Yes	0.472	0.468	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1979	Yes	0.777	0.489	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1980	Yes	0.570	0.466	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1981	Yes	0.893	0.431	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1982	Yes	1.436	0.419	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1983	Yes	1.501	0.414	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1984	Yes	0.491	0.419	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1985	Yes	0.773	0.457	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1986	Yes	0.002	0.460	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1987	Yes	0.125	0.435	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1988	Yes	-0.507	0.434	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1989	Yes	-0.605	0.431	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1990	Yes	-0.522	0.456	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1991	Yes	-0.665	0.506	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1992	Yes	-0.928	0.414	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1993	Yes	-1.428	0.447	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1994	Yes	-0.960	0.432	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1995	Yes	-0.669	0.407	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1996	Yes	0.639	0.426	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1997	Yes	-0.595	0.451	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1998	Yes	0.344	0.495	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_1999	Yes	0.664	0.527	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$

Parameter	Estimated?	Value	Standard Error	Description
RecrDist_GP_1_area_2_month_1_DEVadd_2000	Yes	-1.849	0.488	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2001	Yes	0.452	0.677	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2002	Yes	0.512	0.591	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2003	Yes	0.412	0.576	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2004	Yes	-0.180	0.659	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2005	Yes	0.137	0.804	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2006	Yes	-0.328	0.750	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2007	Yes	-0.166	0.818	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2008	Yes	-0.723	0.887	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2009	Yes	-0.841	0.851	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2010	Yes	-1.275	0.868	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2011	Yes	-0.587	0.908	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2012	Yes	-0.481	0.877	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2013	Yes	0.543	0.922	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2014	Yes	-0.342	0.948	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2015	Yes	-0.107	0.973	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2016	Yes	0.271	1.022	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2017	Yes	0.228	1.019	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2018	Yes	0.091	1.007	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2019	Yes	0.010	1.001	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2020	Yes	0.002	1.000	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$
RecrDist_GP_1_area_2_month_1_DEVadd_2021	Yes	0.000	1.000	Annual deviation in recruitment distribution $\tilde{\varepsilon}_y$

APPENDIX E. MANAGEMENT PROCEDURES

Here we present the management procedures (MPs) that were evaluated in the current study. See Anderson et al. (2021) for a list of MPs explored in the MP Framework.

All management procedures specify the catch advice, inclusive of commercial, recreational, and FSC catch, in the North (5BCDE) and South (5A3CD) separately.

E.1. CONSTANT-CATCH MANAGEMENT PROCEDURES

We evaluated three constant catch MPs:

- RecentCatch: Constant annual catch of 81.6 tonnes in the North (5BCDE), 44 tonnes in the South (5A3CD)
- 125RecentCatch: Constant annual catch at 125 percent of the RecentCatch MP, i.e., 102 and 55 tonnes for the North and South, respectively
- 75RecentCatch: Constant annual catch at 75 percent of the RecentCatch MP, i.e., 61.2 and 33 tonnes for the North and South, respectively

The catch values for the RecentCatch management procedure are based on the mean annual catch during 2012–2019. Recreational catch from the iRec survey was converted from pieces to weight using the mean weight of 0.94 kg/piece observed from the creel survey (Yamanaka et al. 2011). This management procedure is intended to reflect status quo conditions. Catches in 2020 and 2021 were excluded from the average catch calculation due to the extrinsic effects of the COVID-19 pandemic on the fishery (Tables C.4, C.7). The second and third constant catch MP use 125 percent and 75 percent, respectively, of the 2012–2019 average.

By definition, constant catch MPs are not updated during the projection.

E.2. INDEX-BASED MANAGEMENT PROCEDURES

We evaluated index-ratio and index-slope management procedures described below. For all index-based MPs, the catch recommendation is updated biennially, i.e., every second year, based on the anticipated turnaround time for the HBLL survey and associated data processing needed to update the index. In the projections, the catch recommendation is fixed in between updates.

E.3. INDEX-RATIO MPS

Index-ratio MPs base their catch recommendation C^*_y in year y on the product of the previous year's catch C_{y-1} and the ratio of the average recent change in the population (α):

$$C^*_y = \alpha_y \times C_{y-1}, \tag{E.1}$$

To calculate α, the index in a recent time period (e.g., the most recent two years) is compared to the mean in the preceding time period. Therefore, the reference population index is a moving window average. For example,

$$\alpha_y = \frac{I_{y-1} + I_{y-2}}{2} \bigg/ \frac{I_{y-3} + I_{y-4} + I_{y-5}}{3}\ , \tag{E.2}$$

where α is the ratio of the mean index in the most recent two years and the mean index in years 3–5 before the current year.

We evaluated two configurations of the index-ratio MPs, which differ in the time window used to calculate α:

- Iratio_23: ratio of the latest 2 years to the previous 3 years
- Iratio_55: ratio of the latest 5 years to the previous 5 years

A demonstration of the Iratio MPs to calculate α in the HBLL index is in Figure E.1.

E.4. INDEX-SLOPE MPS

Index-slope MPs fit a linear regression of population index data compared to time and make a catch recommendation based on the slope of the regression. They are closely related to index-ratio MPs.

E.4.1. GB_SLOPE: GEROMONT AND BUTTERWORTH INDEX SLOPE

This MP adjusts the catch recommendation based on previous catch and the trend in a relative abundance index to aim for stable catch rates (Geromont and Butterworth 2015). The catch recommendation is calculated as:

$$C^*_y = C_{y-1}(1 + \lambda\beta^I_y) \tag{E.3}$$

$$0.8 \leq (1 + \lambda\beta^I_y) \leq 1.2 \tag{E.4}$$

where C_{y-1} is catch from the previous year, β^I_y is the slope of a linear regression of the ln abundance index over the last n years (default of $n = 5$), and λ is a fixed control parameter between 0 and 1 that adjusts how quickly TAC is adjusted based on the slope of the index. The default λ value is 1 in DLMtool. The catch advice is constrained to limit the rate at which the catch can be adjusted up or down between 80 - 120 percent of the catch in the previous year.

We evaluated four configurations of GB_slope, each applied biennially:

- GB_slope_5y_lam1: $\lambda = 1$ and β^I_y is calculated from the index in the preceding 5 years
- GB_slope_5y_lam05: $\lambda = 0.5$ and β^I_y is calculated from the preceding 5 years
- GB_slope_10y_lam1: $\lambda = 1$ and β^I_y is calculated from the preceding 10 years
- GB_slope_10y_lam05: $\lambda = 0.5$ and β^I_y is calculated from the preceding 10 years

A demonstration of index slope calculation to the HBLL index is in Figure E.2. Illustrations of the GB_slope MPs are also provided in Anderson et al. (2021) (their Appendix D).

E.4.2. IDX: INDEX-BASED MP FROM COX ET AL. (2020)

This MP was evaluated in the rebuilding plan for Outside Yelloweye Rockfish in BC (Cox et al. 2020). The IDX MP assigns the catch recommendation as:

$$C^*_y = \begin{cases} 0.2\bar{C}, & \text{if } \Delta I_y \leq \delta_{\min} \\ (1 + \Delta I_y)C^*_{y-1}, & \text{if } \delta_{\min} < \Delta I_y \leq \delta_{\max} \\ (1 + \delta_{\max})C^*_{y-1}, & \text{if } \Delta I_y > \delta_{\max} \end{cases}, \tag{E.5}$$

where $\delta_{\min}$ is the most negative drop allowed in the relative biomass index before a major reduction in the fishery is recommended, where catch is reduced to the 20% of the mean in the most recent 5 years. ΔI_y is the change in the index over time defined as:

$$\Delta I_y = \frac{I_y}{I_{y-n}} - 1, \quad \text{(E.6)}$$

where I_y refers to a population index value in year y and n determines the reference year. We set $\delta_{\min} = -0.5$ as in Cox et al. (2020). The maximum increase in the catch recommendation is capped at $\delta_{\max} = 0.25$ by default. This means that the catch cannot increase by more than 25%, implementing a "slow up" behaviour of the MP. Parameters $\delta_{\min}$ and $\delta_{\max}$ can be adjusted as necessary to tune the behaviour of the MP.

A variant, IDX_smooth, adds a smoother to the catch advice recommended in IDX:

$$C_y^{*\mathrm{IDX\_smooth}} = \lambda \cdot C_y^{*\mathrm{IDX}} + (1 - \lambda) C_{y-1}^{*}, \quad \text{(E.7)}$$

where λ controls the degree of smoothing and can range between 0 and 1. Cox et al. (2020) used $\lambda = 0.5$, which in effect splits the difference between the upcoming proposed catch recommendation and the one previously recommended.

We evaluated the IDX and IDX_smooth MPs, applied biennially:

- IDX : with $\Delta I_y = \frac{I_y}{I_{y-1}} - 1$
- IDX_smooth : with $\Delta I_y = \frac{I_y}{I_{y-1}} - 1$ and $\lambda = 0.5$

Illustrations of the IDX MPs are provided in Figure E.3 and in Anderson et al. (2021) (their Appendix D).

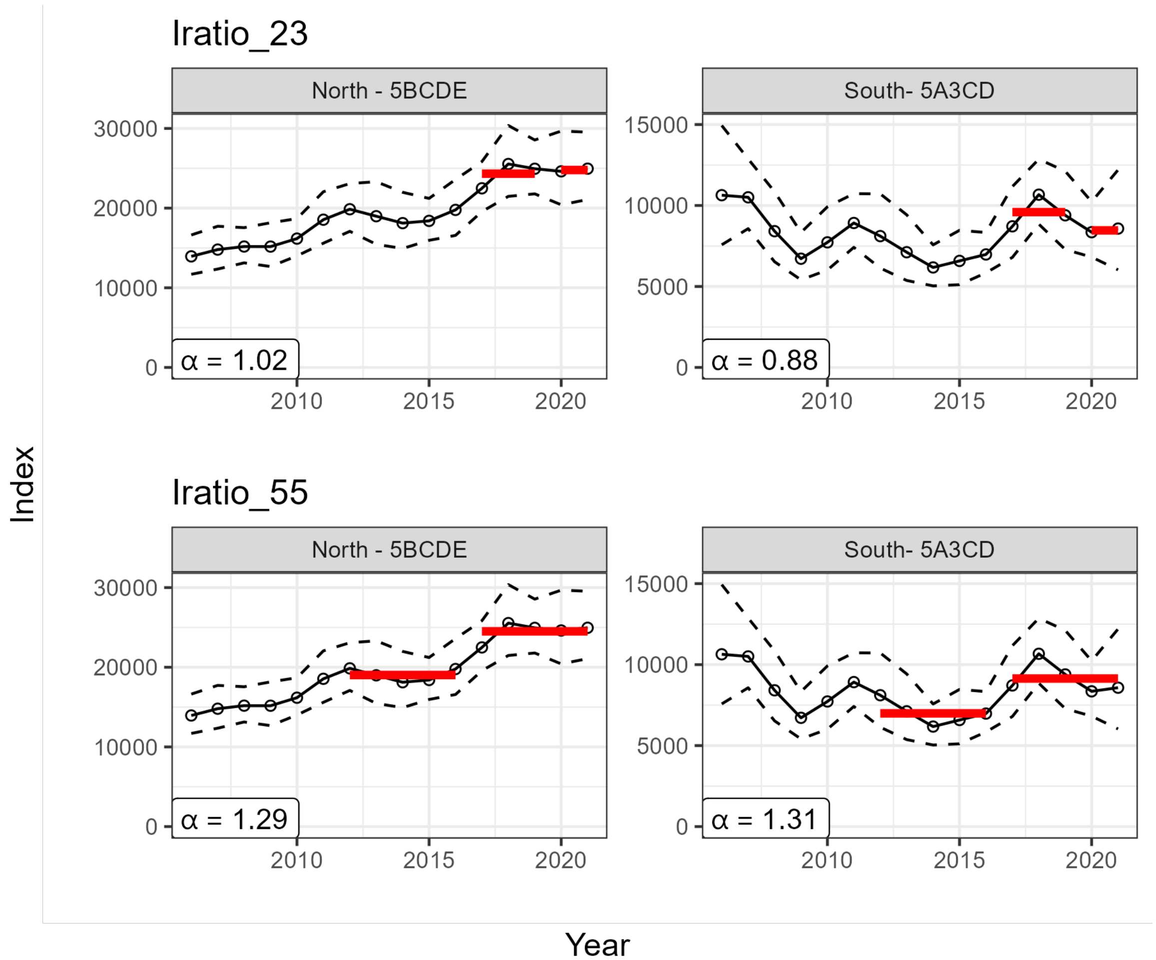

Figure E.1. Application of the two Iratio management procedures to the HBLL index. In 2022, $\alpha = 1.02$ *and* 0.88 *for the North and South, respectively, with Iratio_23 based on the ratio of the mean index in 2020-2021 relative to that in 2017–2019 (top row). With Iratio_55,* $\alpha = 1.29$ *and* 1.31 *for the North and South, respectively, using the mean index in 2017-2021 relative to that in 2012–2016 (bottom row). Red lines indicate the mean of the index during the corresponding time period.*

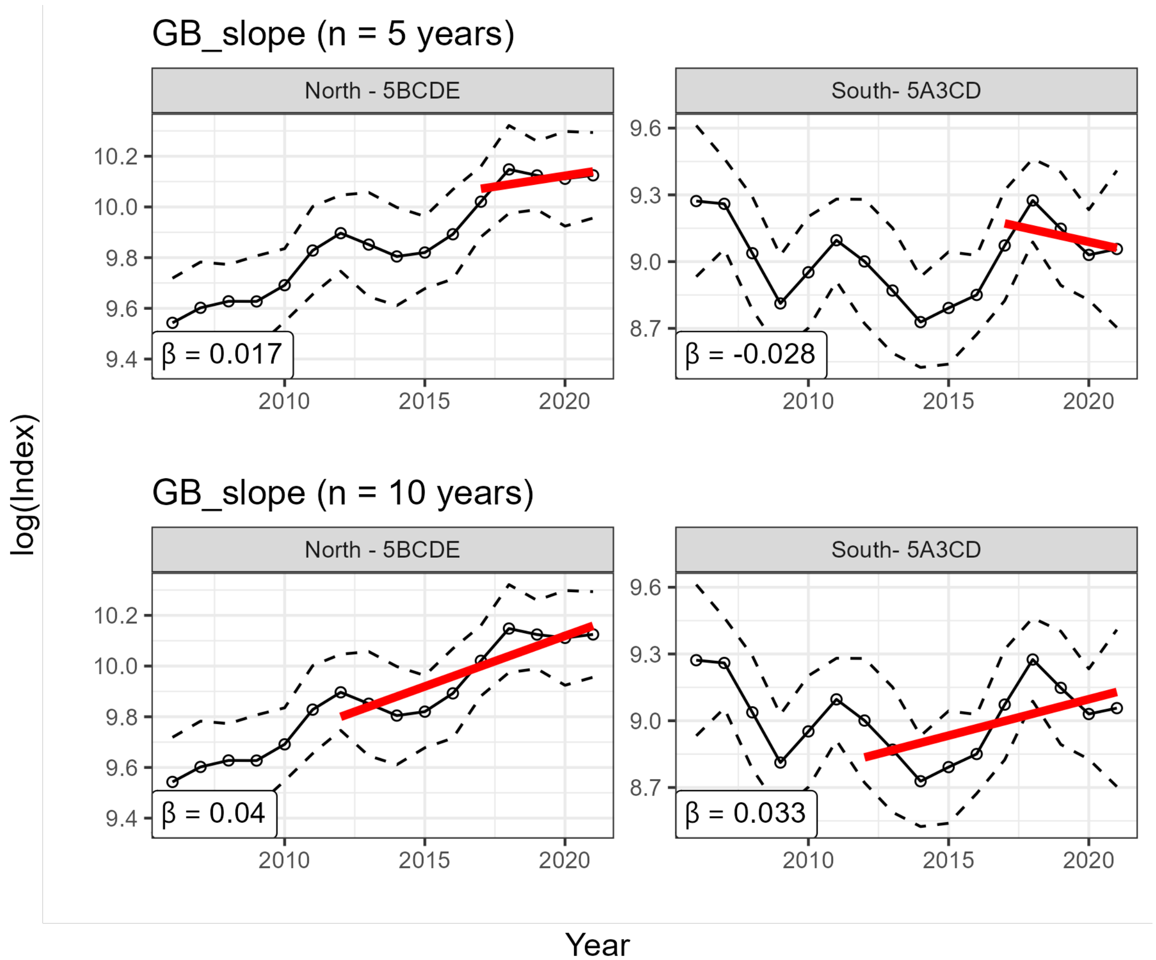

Figure E.2. Calculation of the index-slope in the GB_slope management procedure to the HBLL index. In 2022, $\beta^I = 0.017$ and -0.028 in the North and South, respectively, based on the slope of the log of the index during 2017–2021 (n = 5 years, top row), while $\beta^I = 0.04$ and 0.033 North and South, respectively, from the index over 2012–2021 (n = 10 years, bottom row). The change in the catch advice is $1 + \lambda\beta^I$. Red lines indicate the predicted index from a linear regression over the corresponding time period used to estimate β^I.

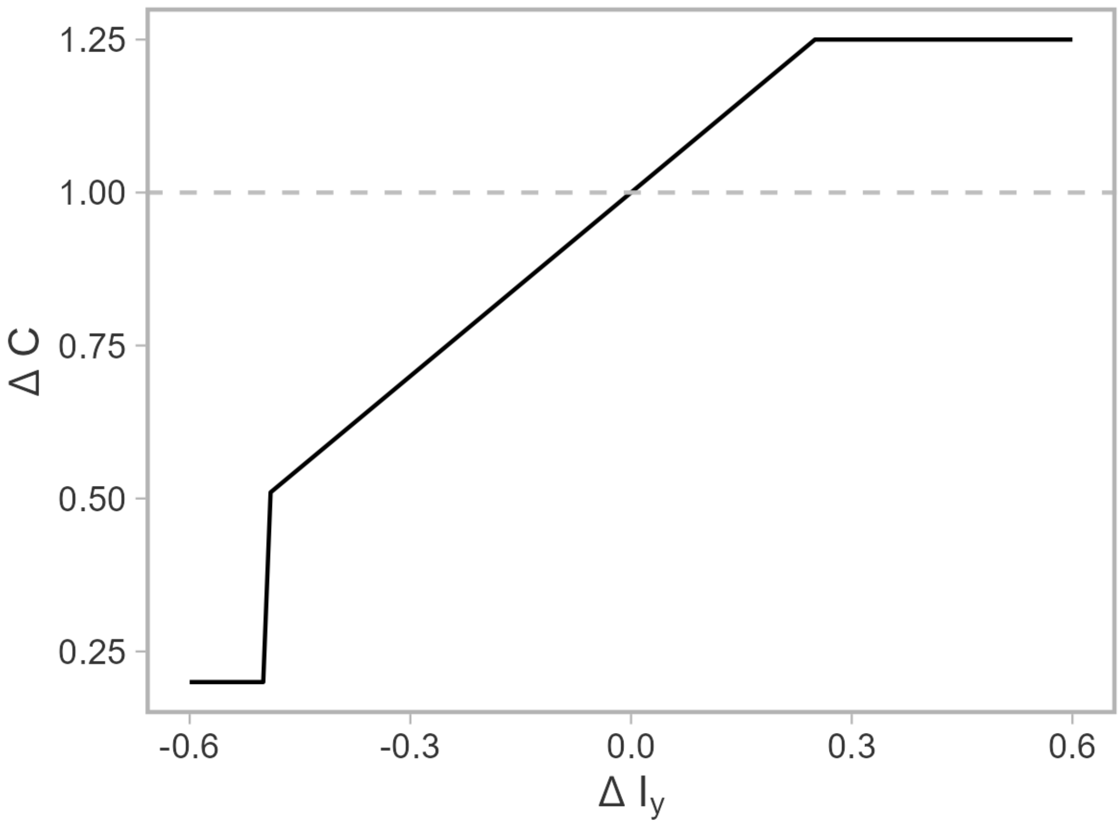

Figure E.3. Calculation of the change in catch advice, ΔC, in the IDX management procedure based on the change in the index ΔI_y. The maximum possible increase in the catch advice is 25 percent between updates of the management procedure, while a greater than 50 percent reduction in the index results in a stepwise reduction in the catch advice (to 20 percent of recent catch).

APPENDIX F. CLOSED-LOOP PROJECTIONS

This appendix complements Section 6 of the main text and shows the results from the closed-loop projections of the management procedures.

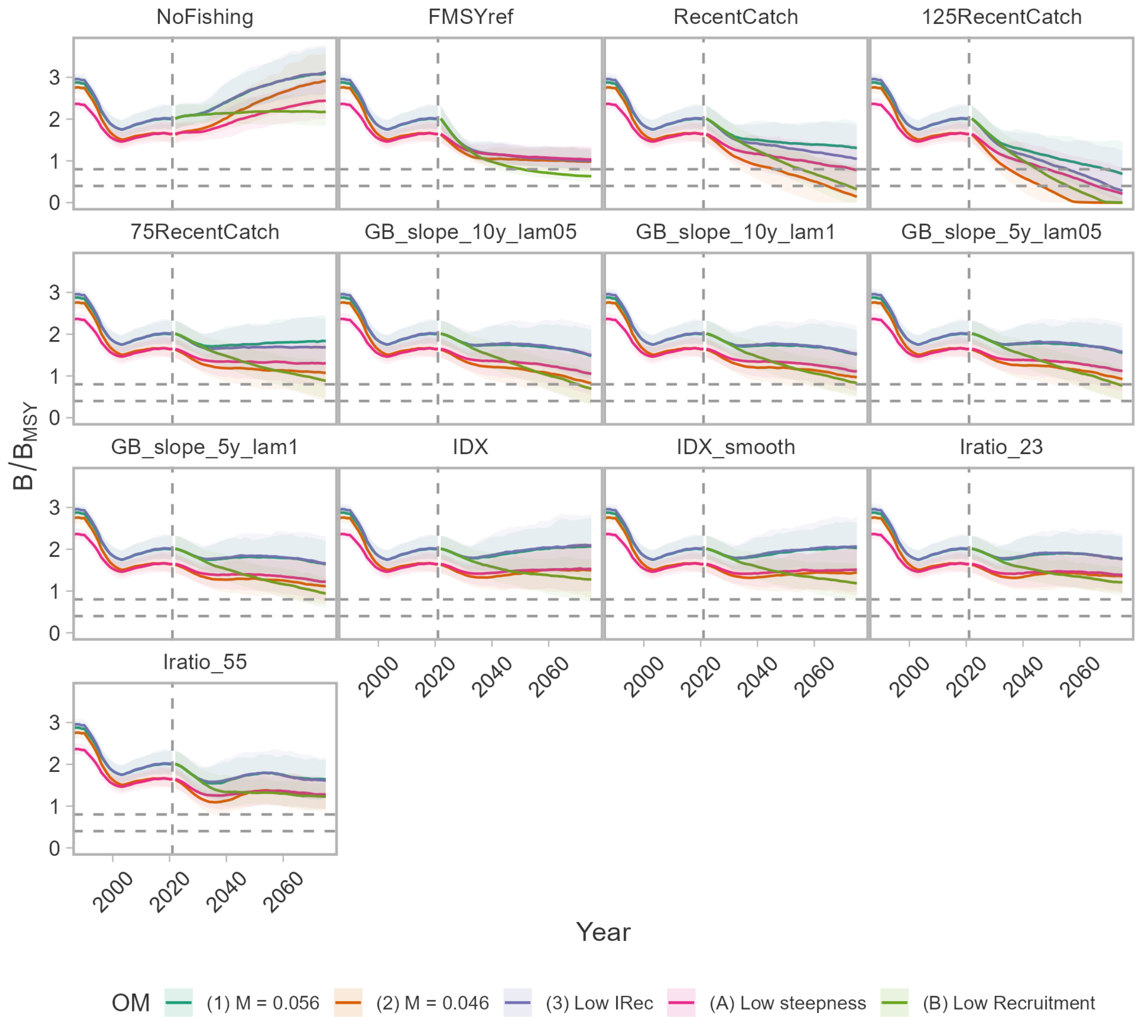

Figure F.1. Projected values of B/B_{MSY} *from application of management procedures over 2 generations. Solid lines plot the annual median value by operating model (colours) and shaded regions denote the 95 coverage interval across 200 simulations. Horizontal grey lines within each panel denote 0.4 and 0.8* B_{MSY}*. The end of the historical period is 2021 (vertical grey line).*

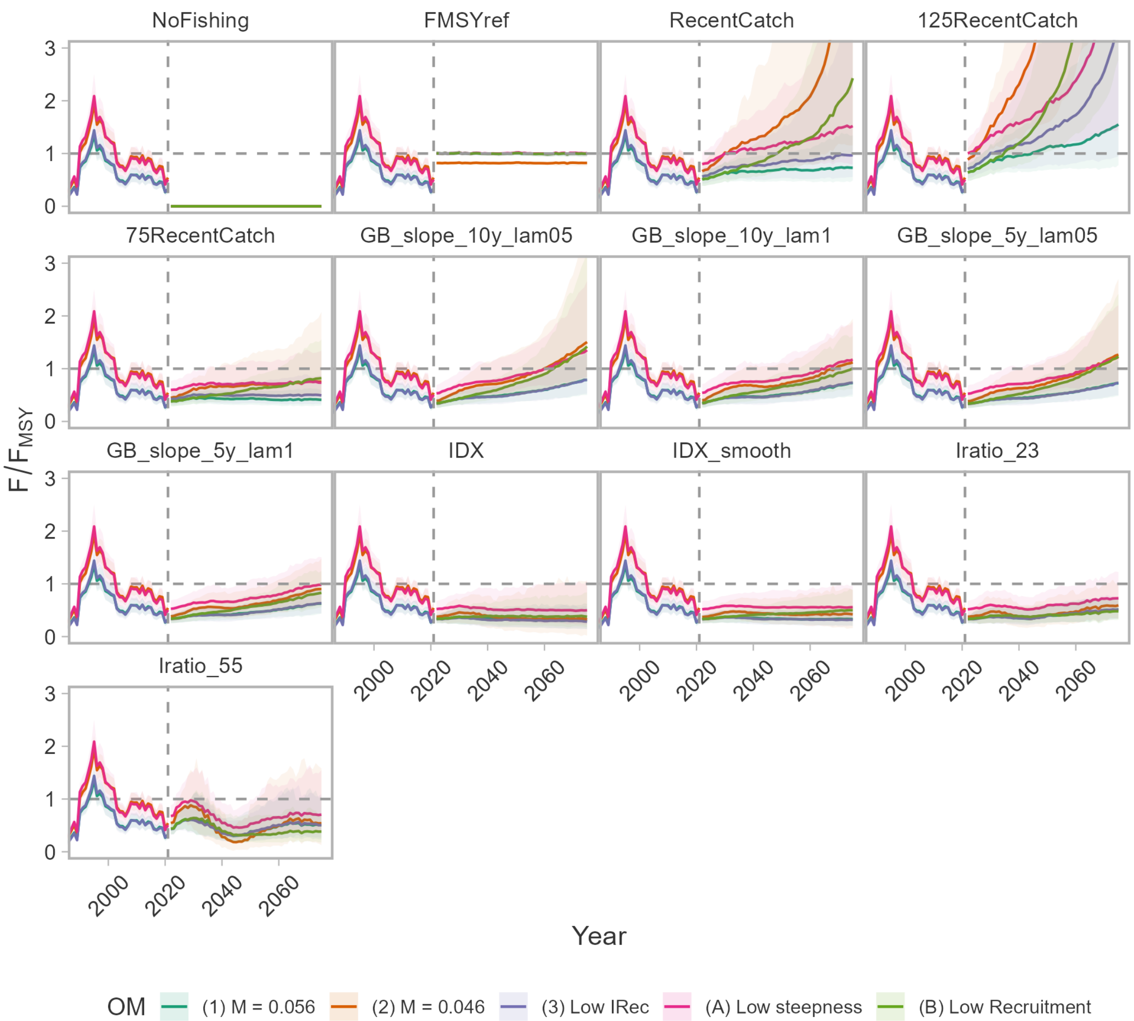

Figure F.2. Projected values of F/F_{MSY} *from application of management procedures over 2 generations. Solid lines plot the annual median value by operating model (colours) and shaded regions denote the 95 coverage interval across 200 simulations. Horizontal grey lines within each panel denote* $F/F_{MSY} = 1$*. The end of the historical period is 2021 (vertical grey line).*

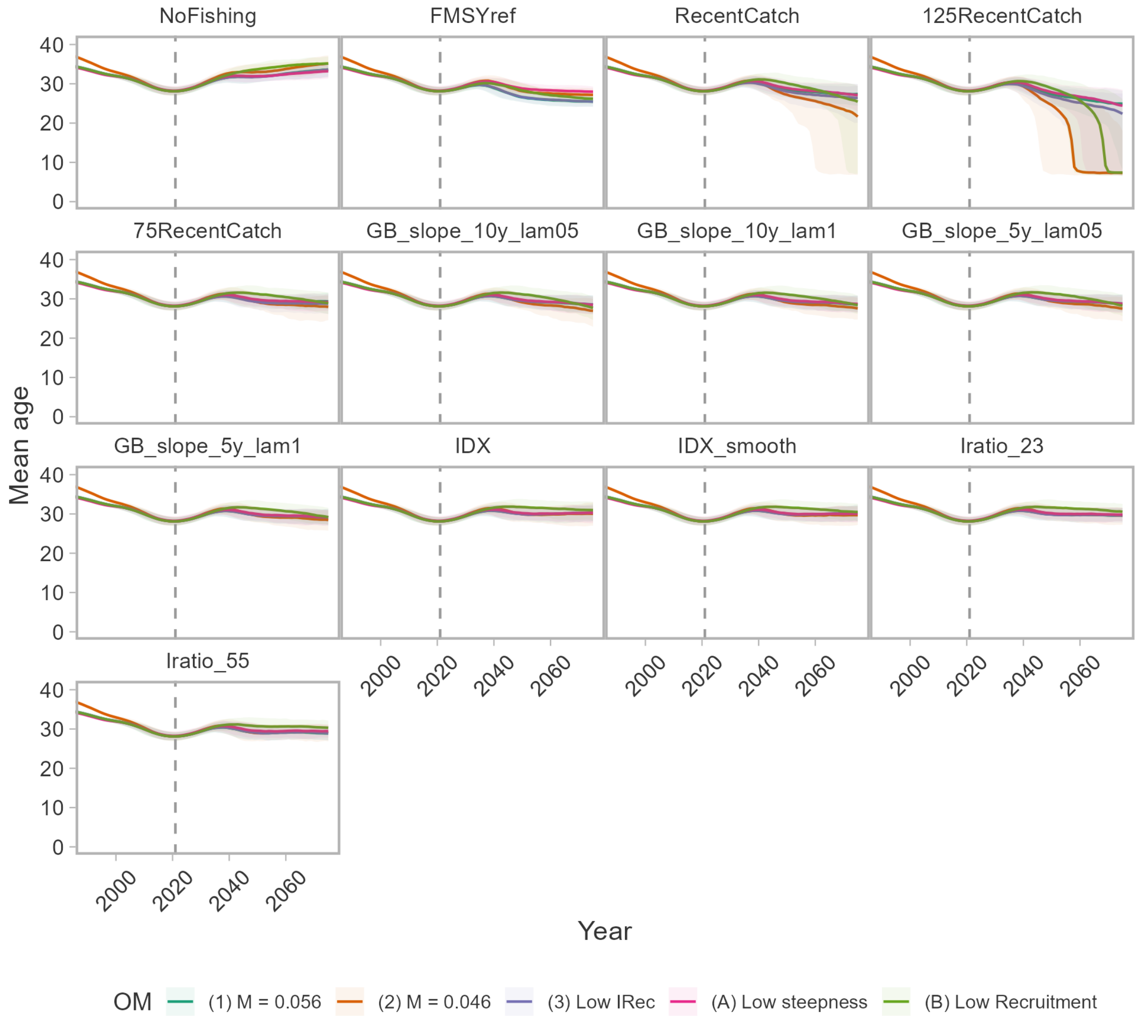

Figure F.3. Historical and projected mean age predicted from the HBLL index from application of management procedures over 2 generations. Solid lines plot the annual median value by operating model (colours) and shaded regions denote the 95 coverage interval across 200 simulations. The end of the historical period is 2021 (vertical grey line).

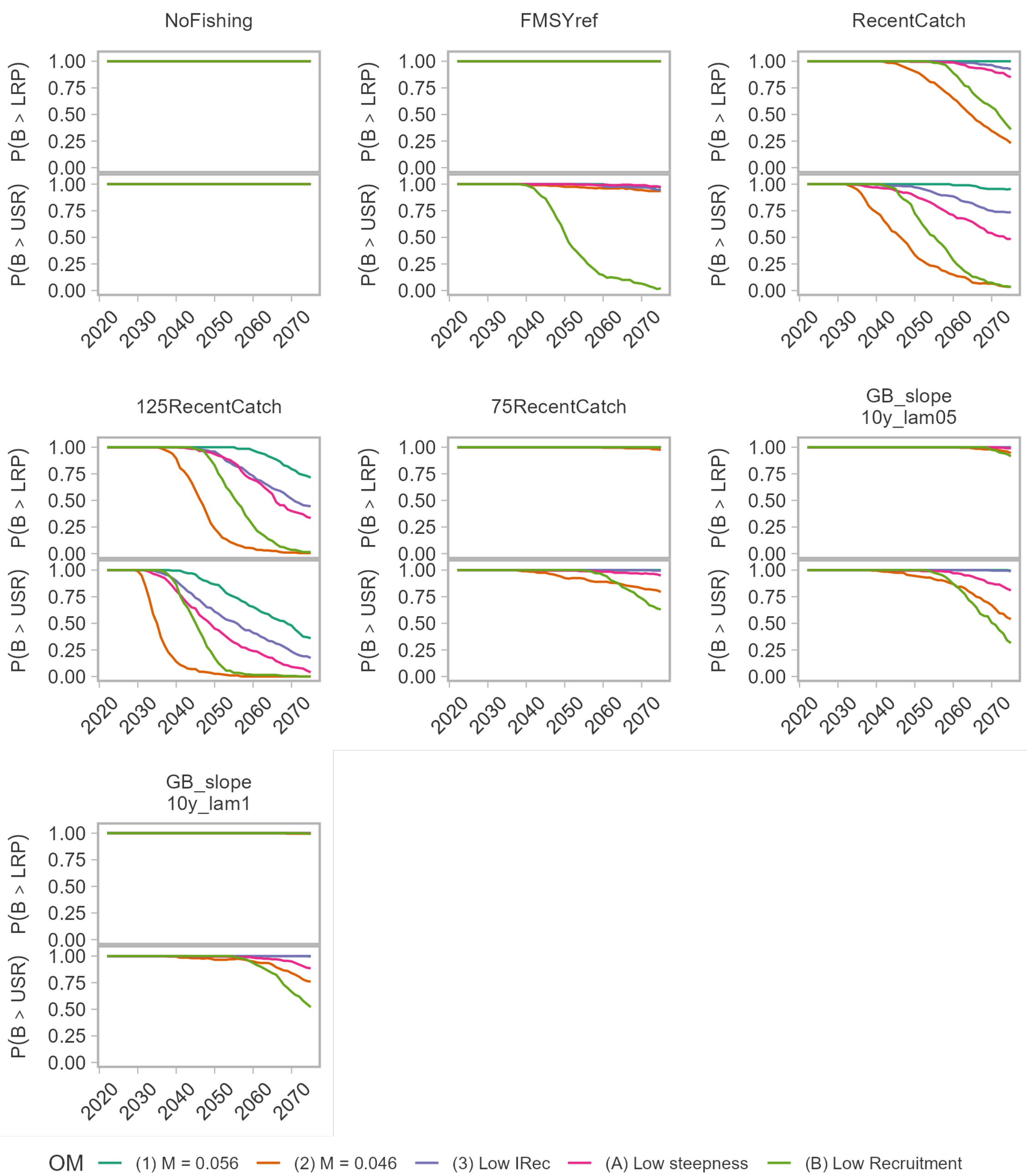

Figure F.4. Annual probabilities that the stock is above 0.4 and 0.8 B/B$_{MSY}$ *from application of management procedures (set 1 of 2 figures) over 2 generations.*

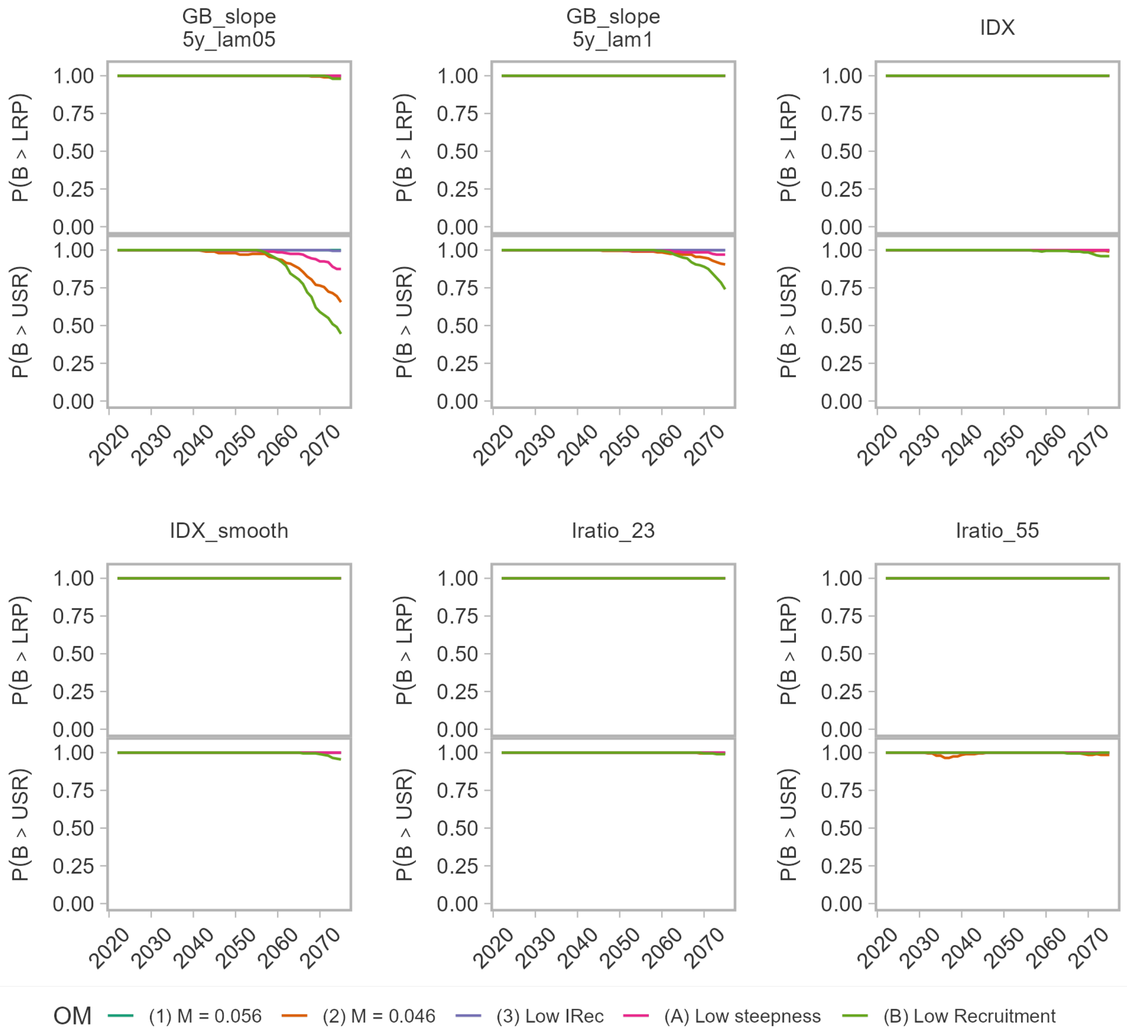

Figure F.5. Annual probabilities that the stock is above 0.4 and 0.8 B/B_{MSY} *from application of management procedures (set 2 of 2 figures) over 2 generations.*

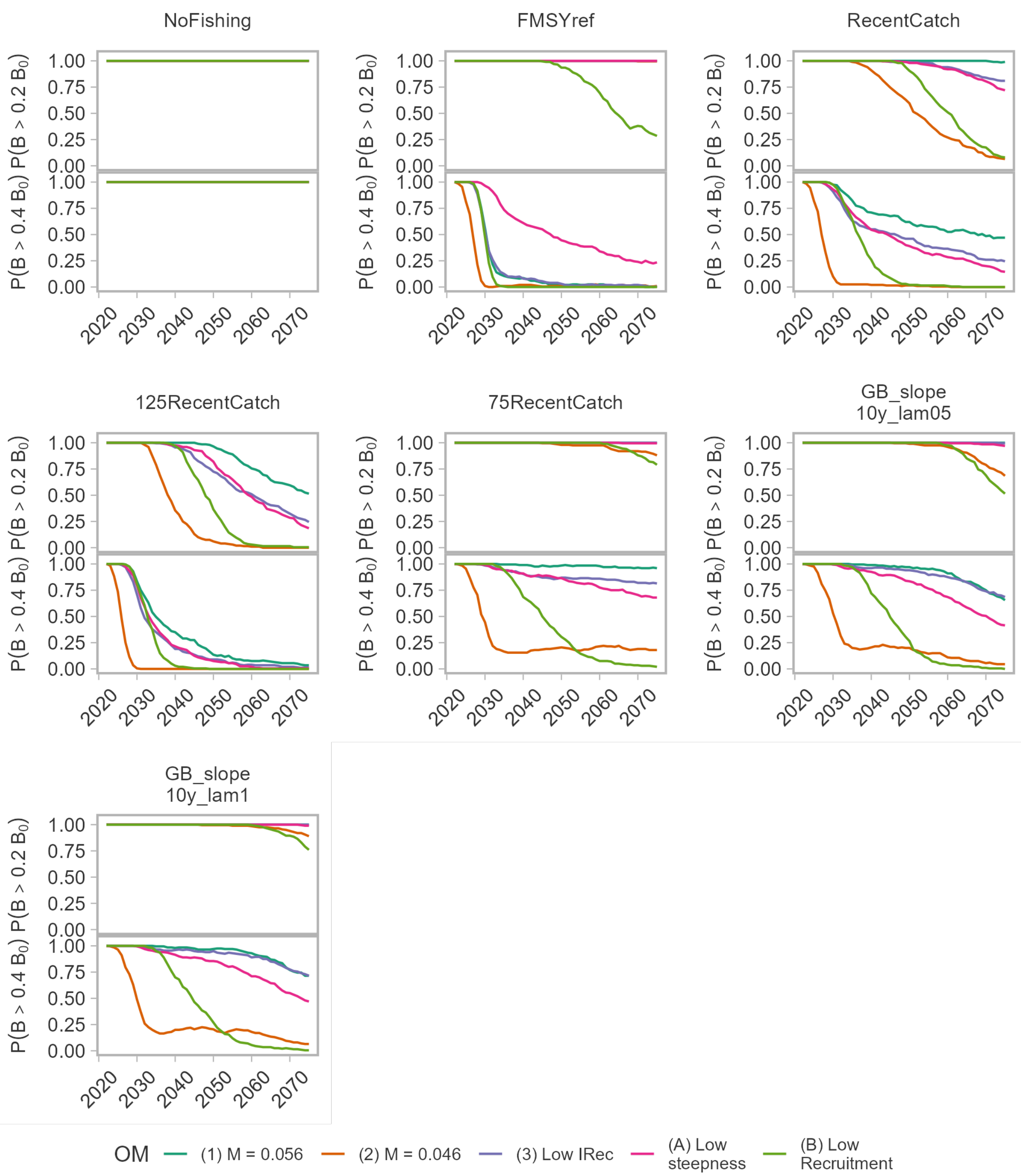

Figure F.6. Annual probabilities that the stock is above 0.2 and 0.4 B/B_0 *from application of management procedures (set 1 of 2 figures) over 2 generations.*

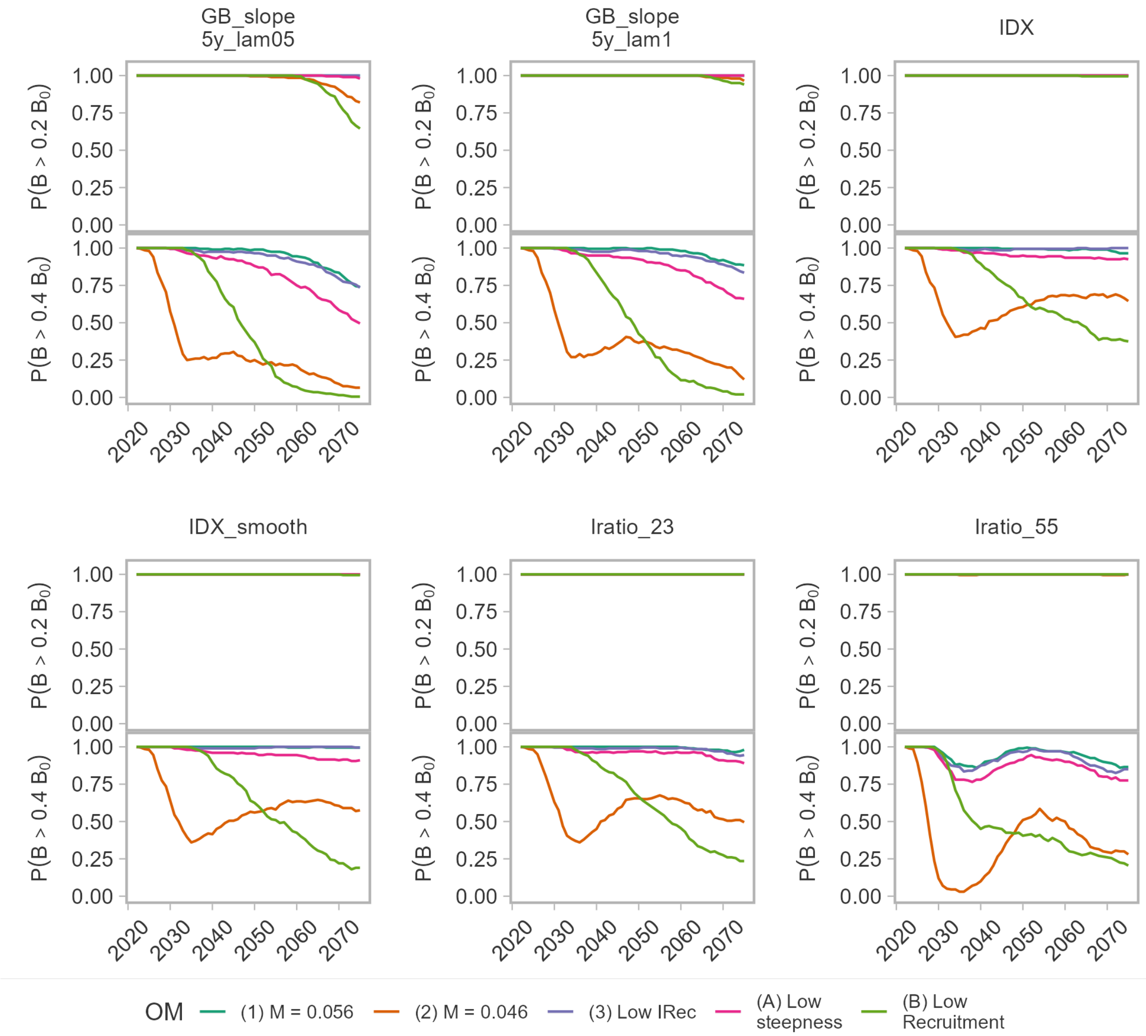

Figure F.7. Annual probabilities that the stock is above 0.2 and 0.4 B/B_0 *from application of management procedures (set 2 of 2 figures) over 2 generations.*

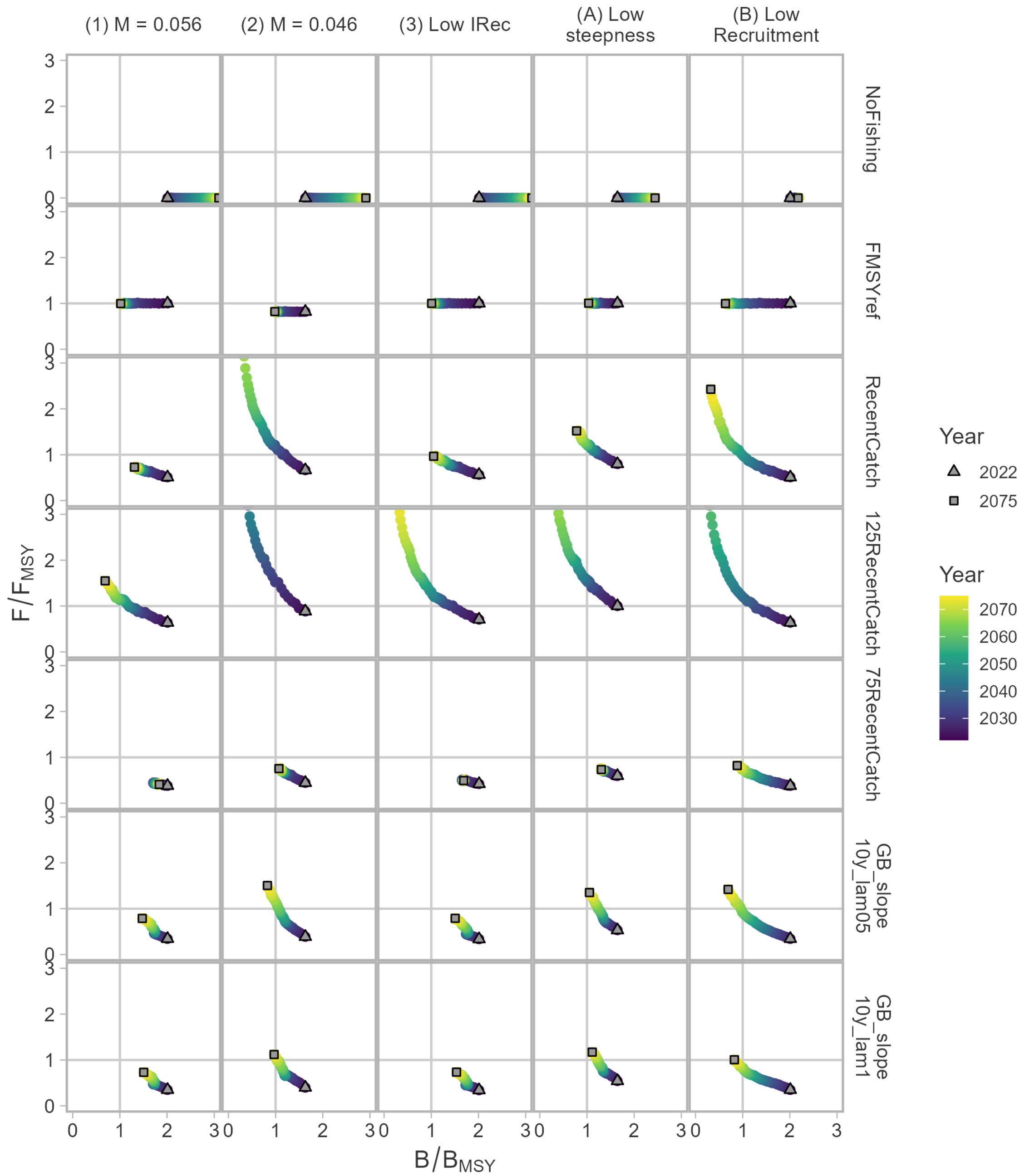

Figure F.8. Kobe phase plot of median F/F$_{MSY}$ *and* B/B$_{MSY}$ *from application of management procedures (set 1 of 2 figures) over 2 generations. Coloured lines indicate the year of the projection and shapes denote the beginning and end years of the projection.*

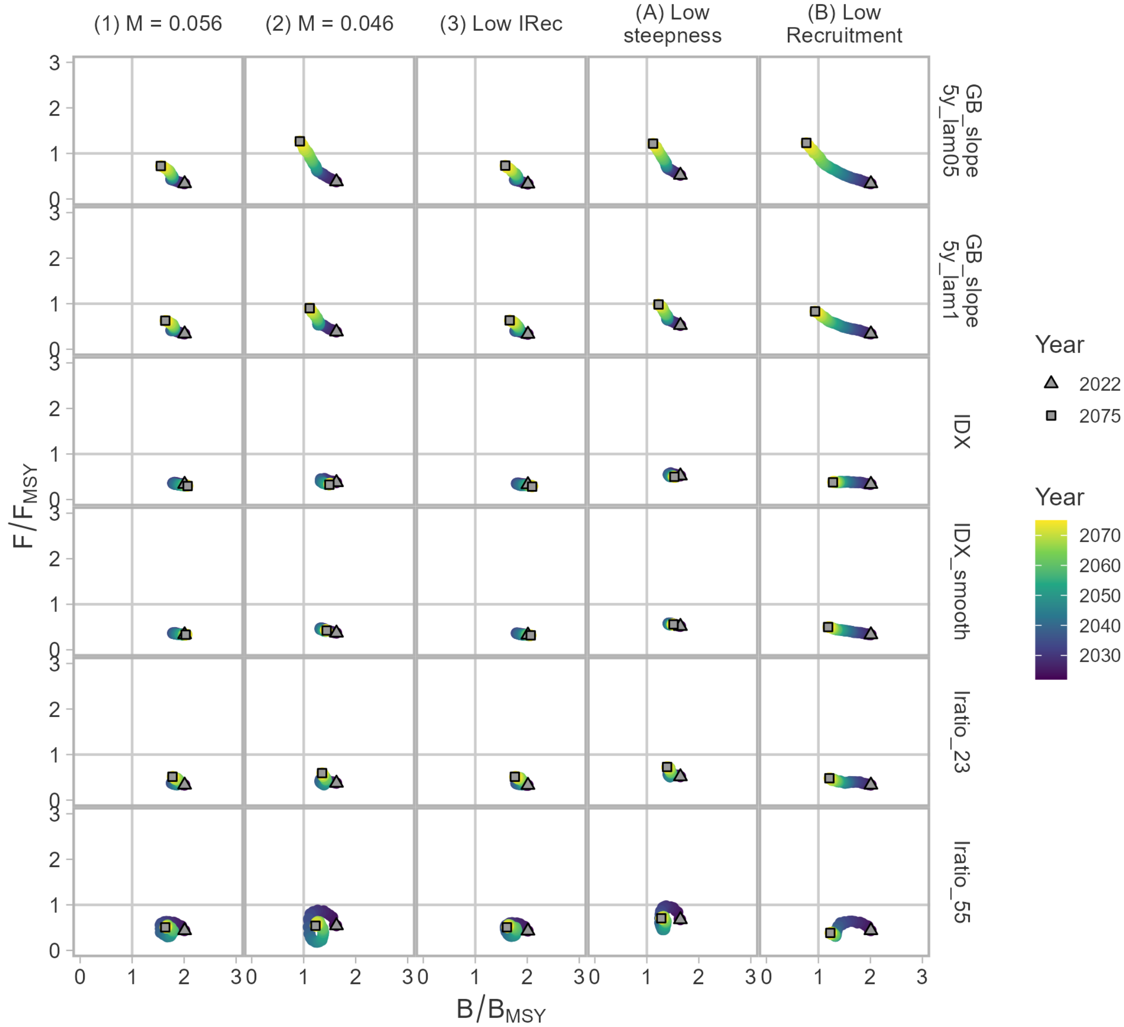

Figure F.9. Kobe phase plot of median F/F$_{MSY}$ and B/B$_{MSY}$ from application of management procedures (set 2 of 2 figures) over 2 generations. Coloured lines indicate the year of the projection and shapes denote the beginning and end years of the projection.

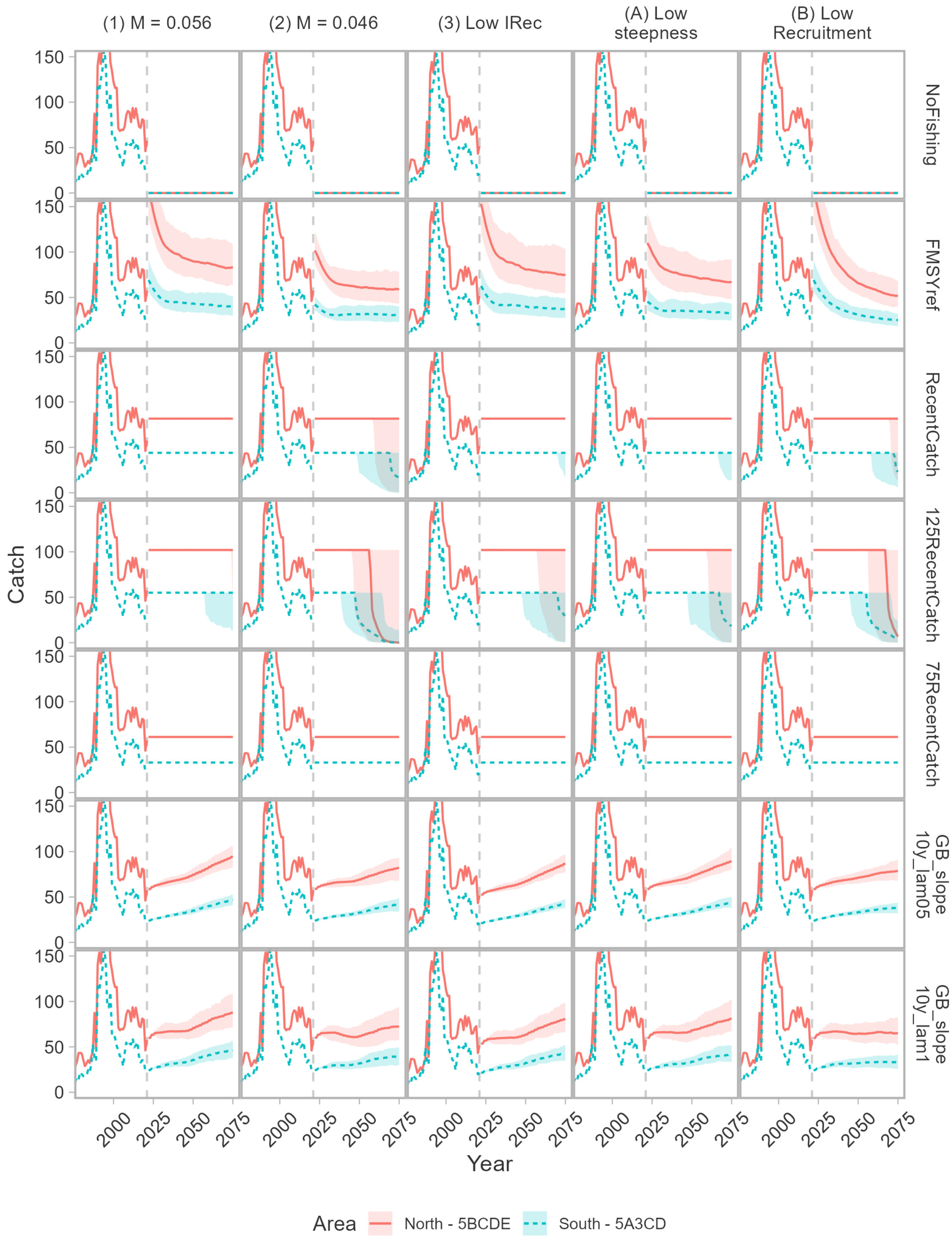

Figure F.10. Projected catches (all removals) by area from application of management procedures (set 1 of 2 figures) over 2 generations. Solid lines plot the annual median value and dotted lines denote the 95 coverage interval across 200 simulations. The end of the historical period is 2021 (vertical grey line).

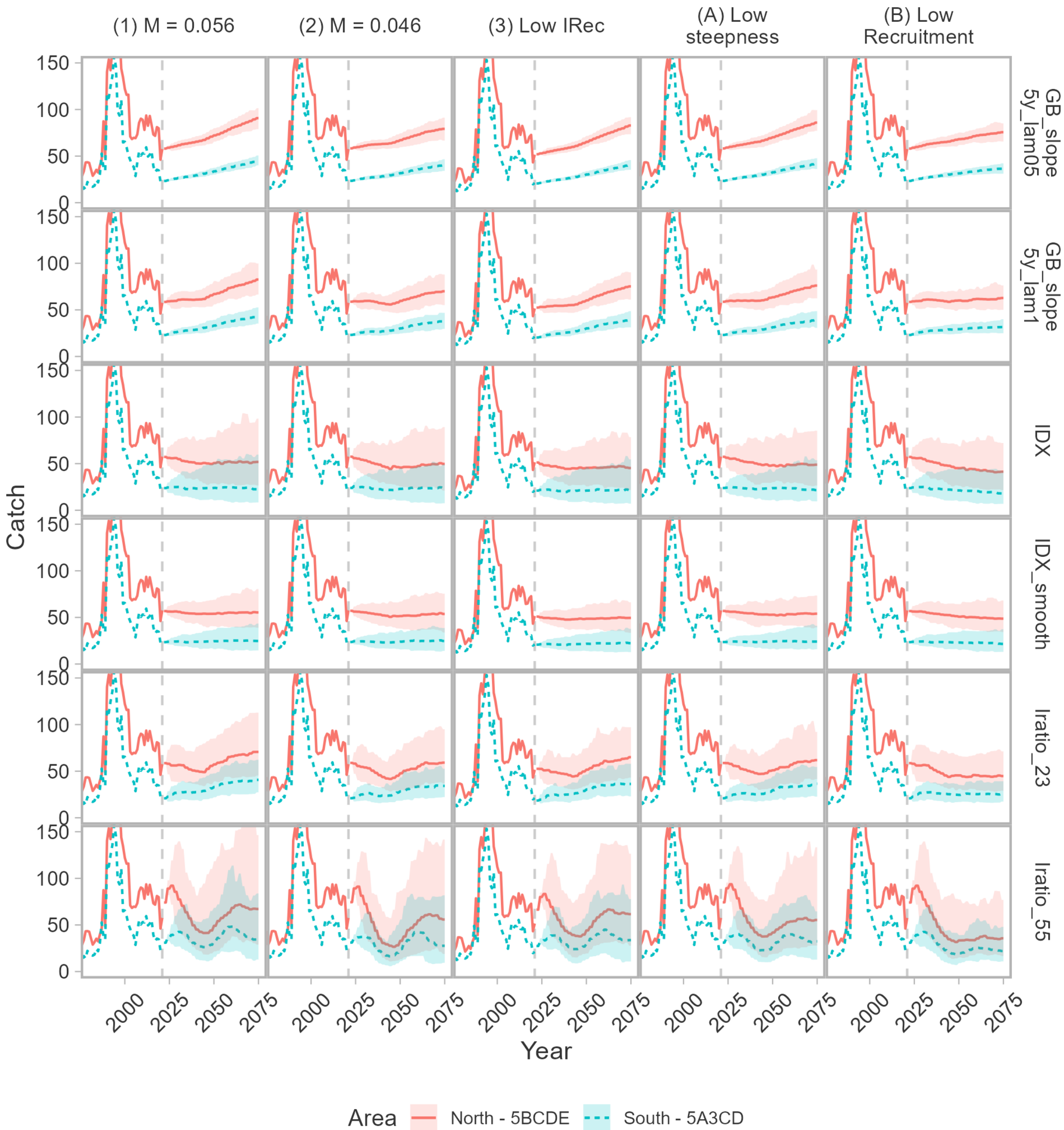

Figure F.11. Projected catches (all removals) by area from application of management procedures (set 2 of 2 figures) over 2 generations. Solid lines plot the annual median value and dotted lines denote the 95 coverage interval across 200 simulations. The end of the historical period is 2021 (vertical grey line).

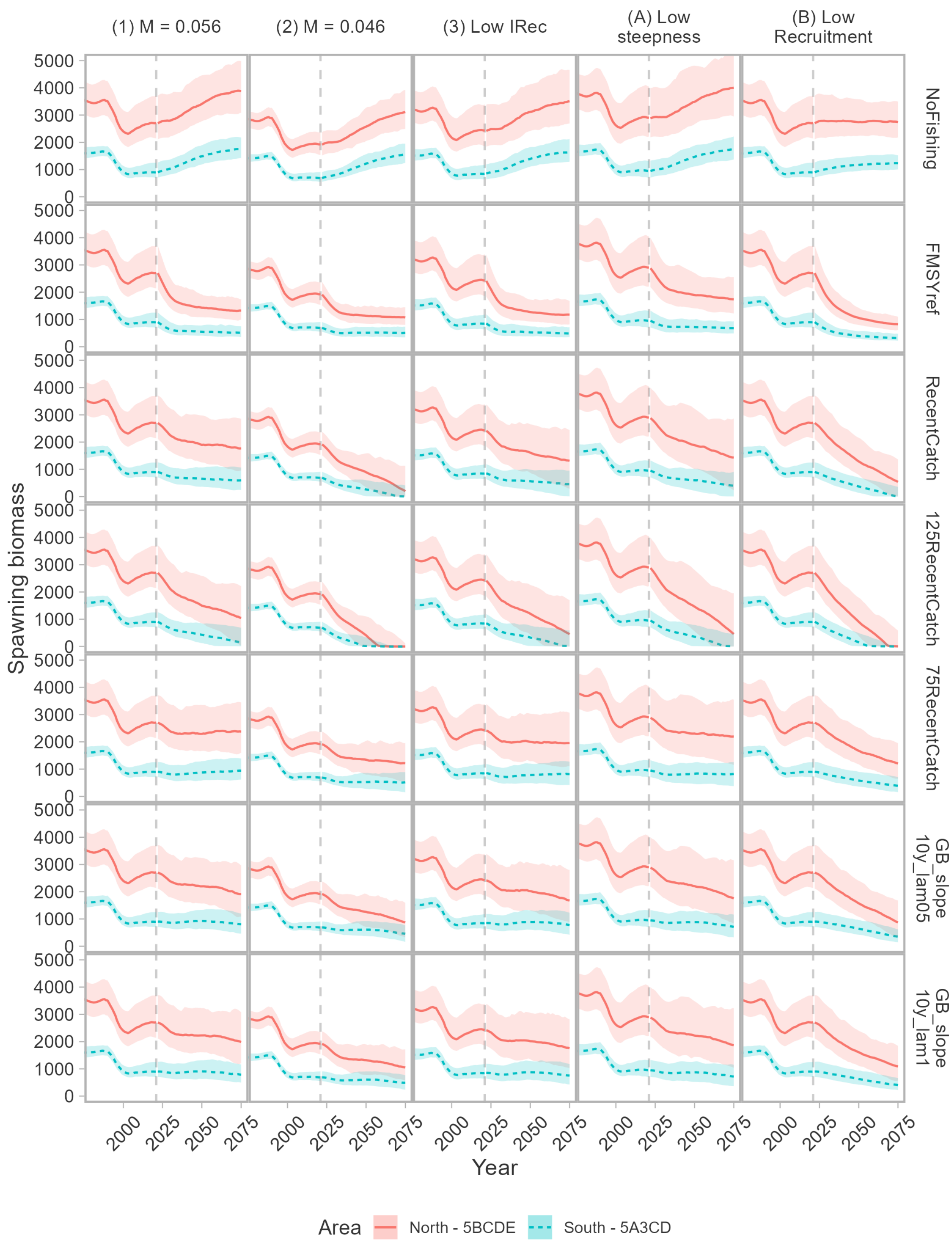

Figure F.12. Projected spawning biomass by area from application of management procedures (set 1 of 2 figures) over 2 generations. Solid lines plot the annual median value and dotted lines denote the 95 coverage interval across 200 simulations. The end of the historical period is 2021 (vertical grey line).

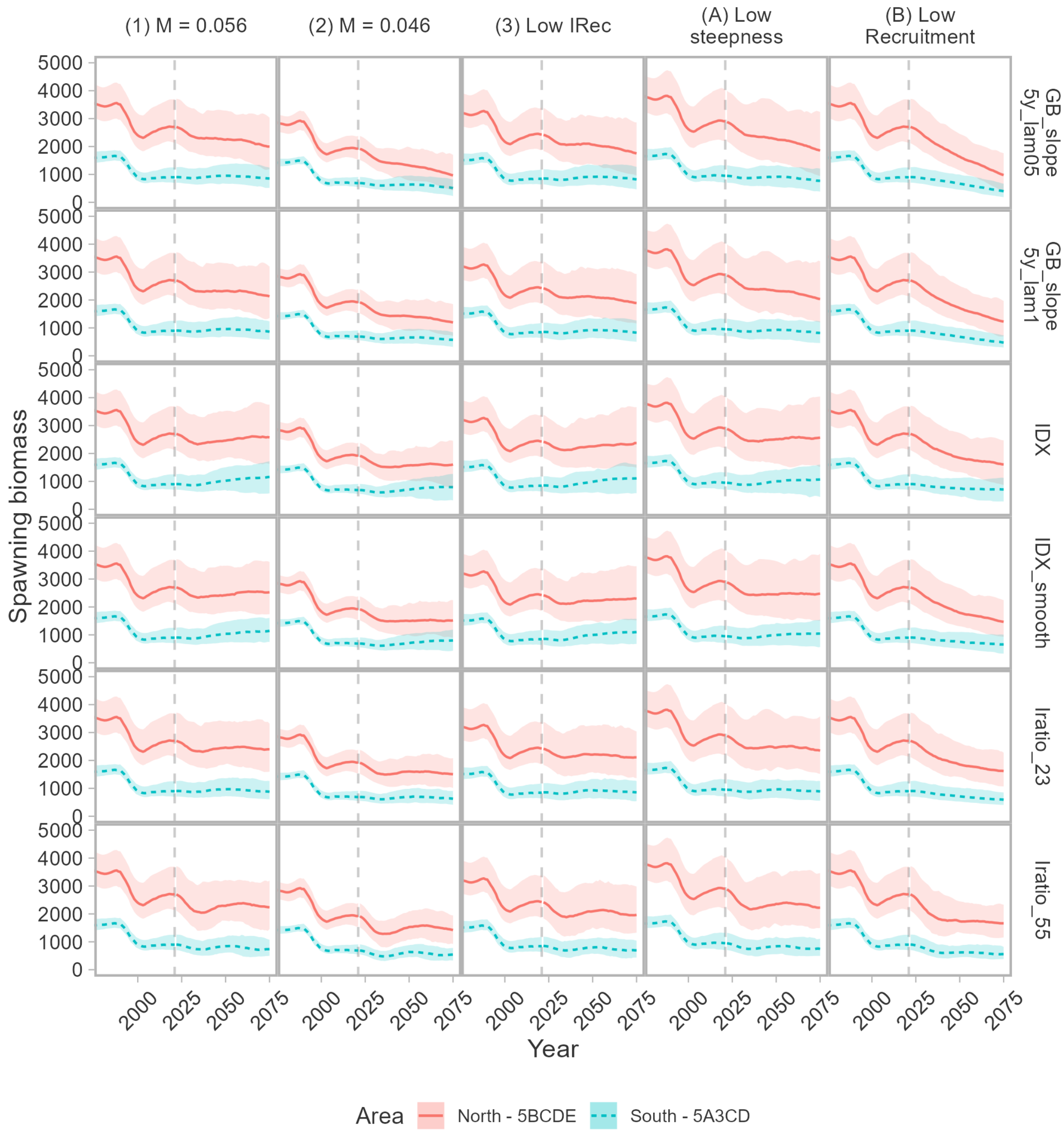

Figure F.13. Projected spawning biomass by area from application of management procedures (set 2 of 2 figures) over 2 generations. Solid lines plot the annual median value and dotted lines denote the 95 coverage interval across 200 simulations. The end of the historical period is 2021 (vertical grey line).

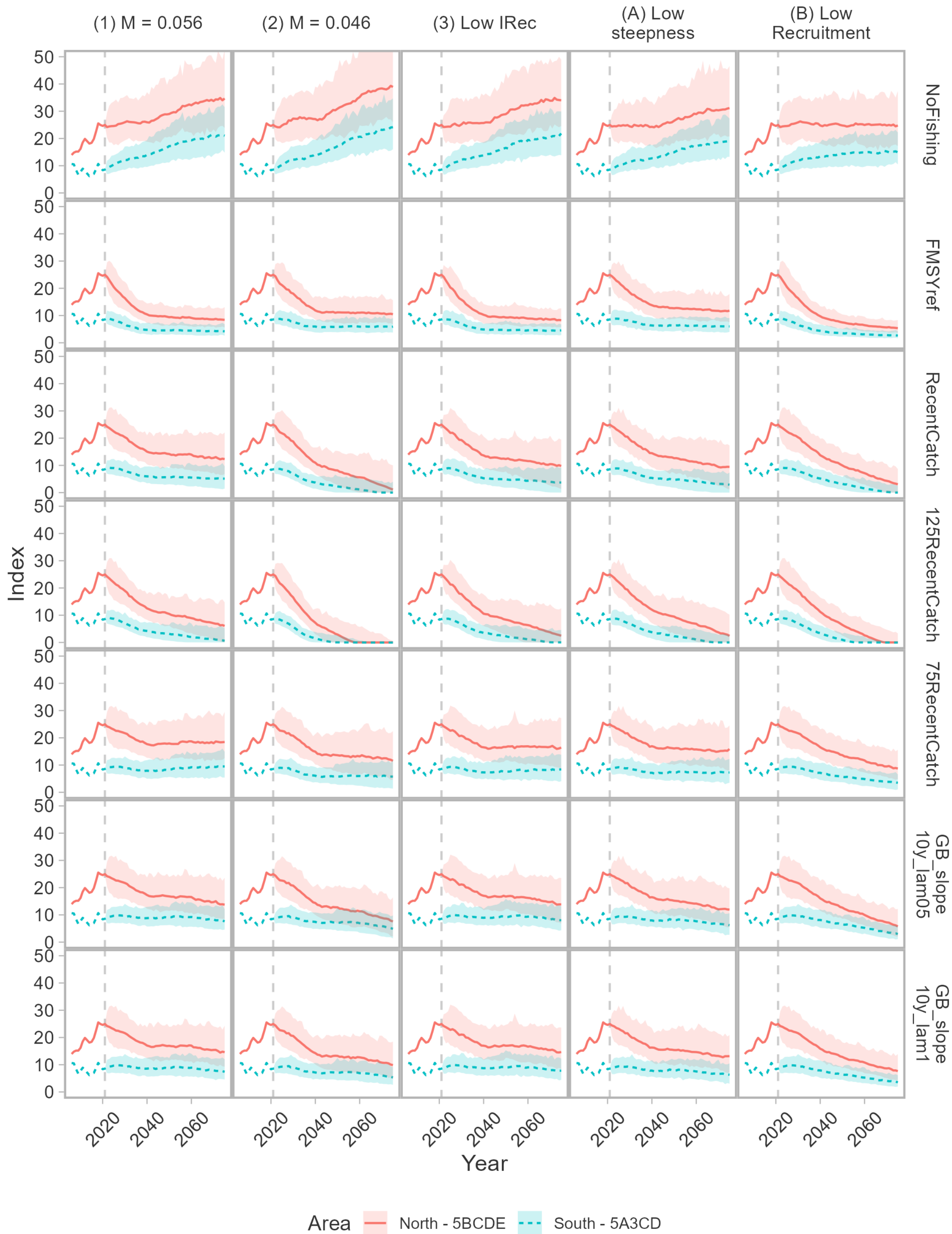

Figure F.14. Projected HBLL index by area from application of management procedures (set 1 of 2 figures) over 2 generations. Solid lines plot the annual median value and dotted lines denote the 95 coverage interval across 200 simulations. The end of the historical period is 2021 (vertical grey line).

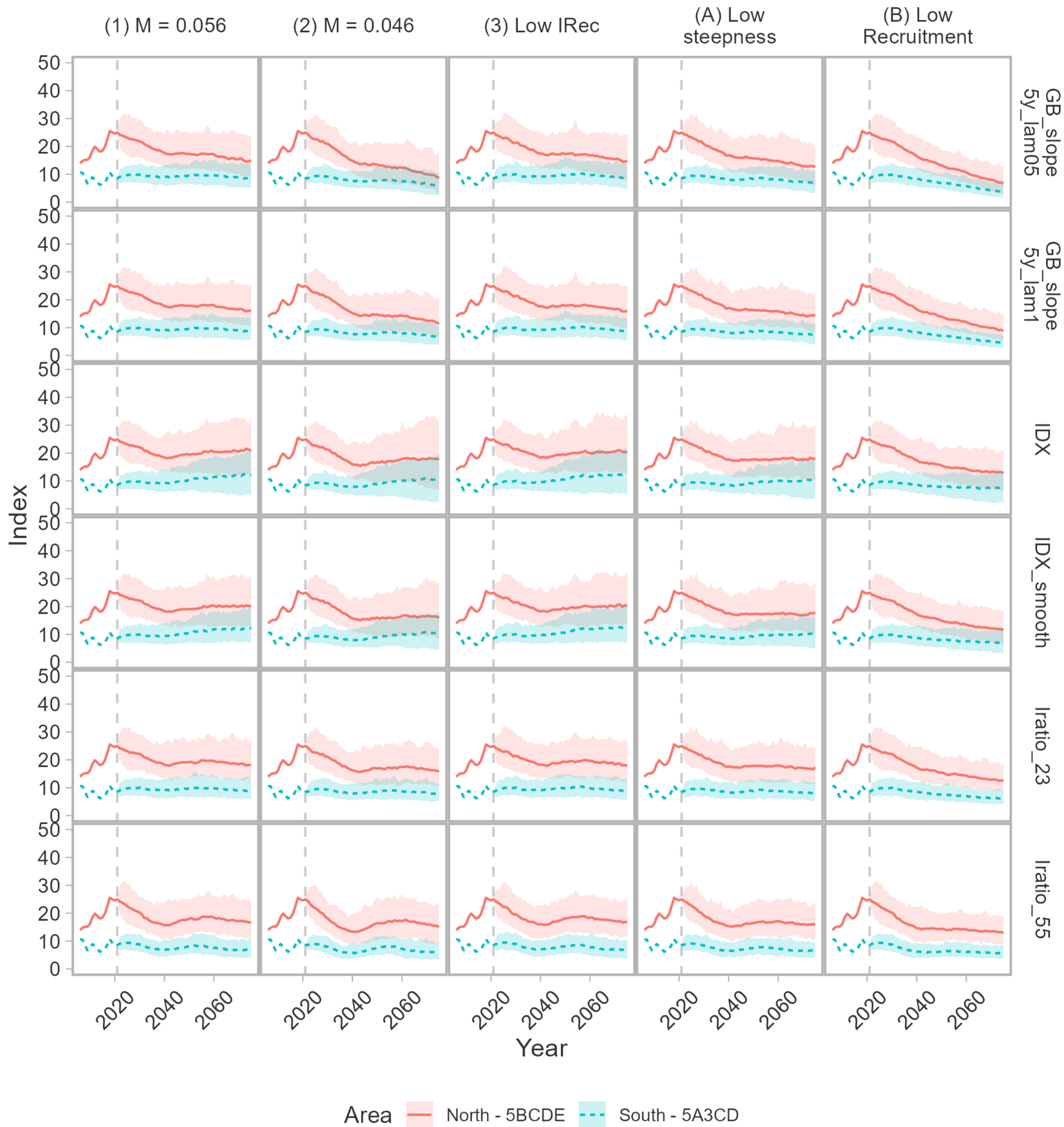

Figure F.15. Projected HBLL index by area from application of management procedures (set 2 of 2 figures) over 2 generations. Solid lines plot the annual median value and dotted lines denote the 95 coverage interval across 200 simulations. The end of the historical period is 2021 (vertical grey line).

APPENDIX G. CATCH CURVE ANALYSIS

Catch curve analysis has frequently been used to estimate total mortality (Z) from age-structured data. Abundance declines with age due to mortality, and the slope of a regression line from the log-transformed numbers versus age provides an estimate of Z (Ricker 1975). Higher mortality rates are inferred from steeper declines in age composition, i.e., truncated age structure.

Application of the catch curve requires filtering out young age classes on the ascending limb of the age structure as they are not completely selected and do not provide information on mortality. Age classes with zero observations are not included in the regression as the natural logarithm of zero is undefined. Older age classes (on the right side of the age composition) may also be excluded due to low and zero counts that may influence the slope of the regression line. Following the recommendations in Smith et al. (2012), the modal age was the first age included in the regression, no right truncation was utilized, and a weighted regression was used to estimate mortality. Following an initial fit (without weights), the predicted log-abundance at age were then used as weights for the corresponding age classes in a subsequent fit. While Smith et al. (2012) were concerned about its ad hoc nature, iterative weighting appeared to stabilize estimates of Z, which were robust regardless of the right truncation method used.

Estimates of Z from the catch curve regression on the 2006–2020 age samples of the outside HBLL survey are reported in Figures G.1 and G.2. Higher estimates of between 0.08–0.10 were observed during 2006–2010. Since 2010, mortality estimates are lower, with Z between 0.05–0.07 and without trend particular trend.

The shape of the age distribution changes between the two time periods, which affects the age classes included in the catch curve. The mode of the age distribution during 2006–2010 is approximately 30 years while the mode after 2010 is 20 years. It is not clear why the mode changes after 2010, but it may be indicative changes in abundance of 15–30 year old age classes due to high fishing mortality of those cohorts in previous years or due to changes in recruitment strength.

From the IPHC survey, the Z estimates from 2003–2004 are lower, i.e., around 0.02–0.04, followed by higher estimates between 0.05–0.07 since then (Figures G.3 and G.4).

Catch curves assume equilibrium conditions with constant mortality and recruitment over time. Caution is warranted when using catch curves in a dynamic system and interpreting current mortality rates. These mortality estimates were based on biological samples aged between 20–70+ years and various changes in the effort in the fisheries for Outside Quillback Rockfish have occurred. As with any equilibrium method, catch curves are informative on historical mortality rates rather than conditions at the time the samples were collected (Hilborn and Walters 1992).

Violations of equilibrium conditions can result in spurious conclusions. For example, a large, young cohort can result in a overestimate of mortality because the cohort steepens the regression line. However, no large cohorts were immediately apparent in the age data of Outside Quillback Rockfish.

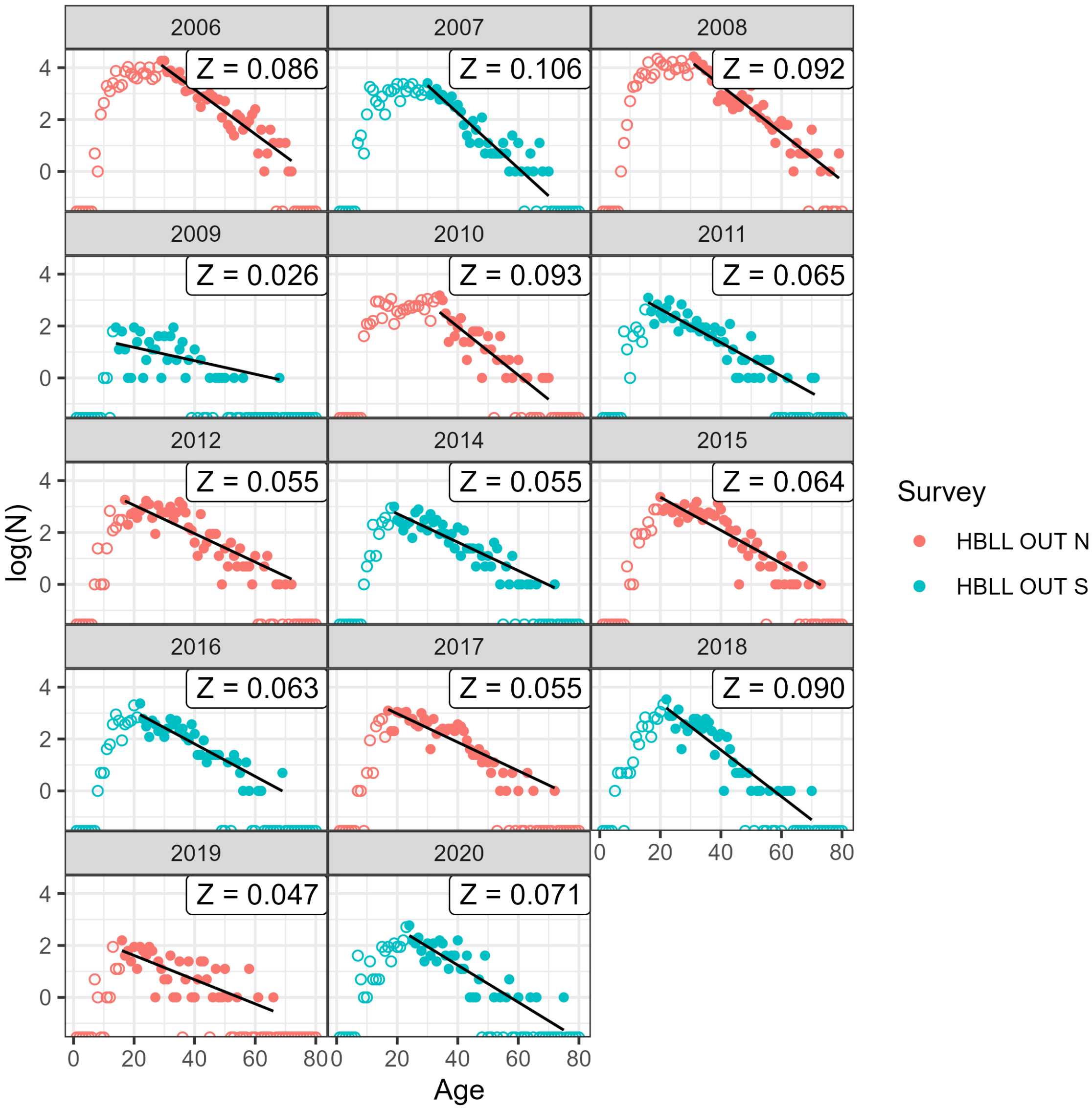

Figure G.1. Estimates of total mortality (Z) using catch curve analysis on the age samples from the outside HBLL survey, where N *is the numbers at age. Filled and empty circles indicate the data points included and excluded, respectively, from the catch curve regression. Lines show the predicted numbers of age from the catch curve under equilibrium assumptions. The magnitude of the slope of the line provides the estimate of Z.*

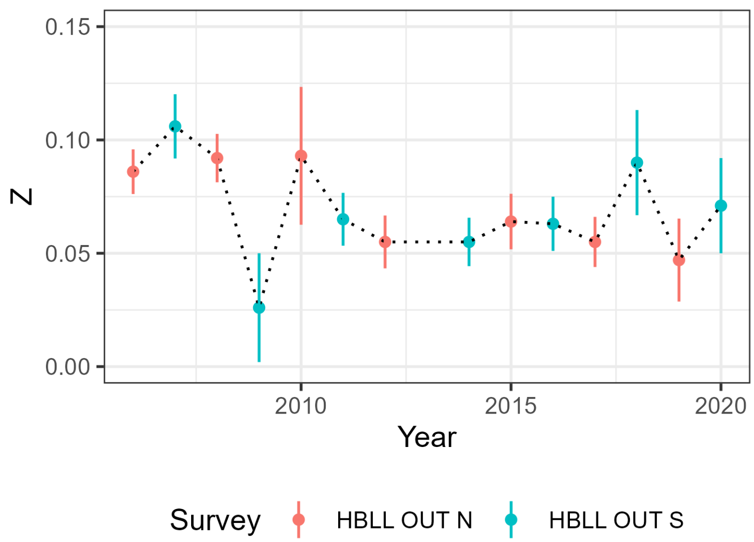

Figure G.2. Total mortality (Z) over time from the catch curves from the outside HBLL survey age samples. Vertical lines span the 95% confidence interval using the standard error of the slope estimated in the catch curve regression.

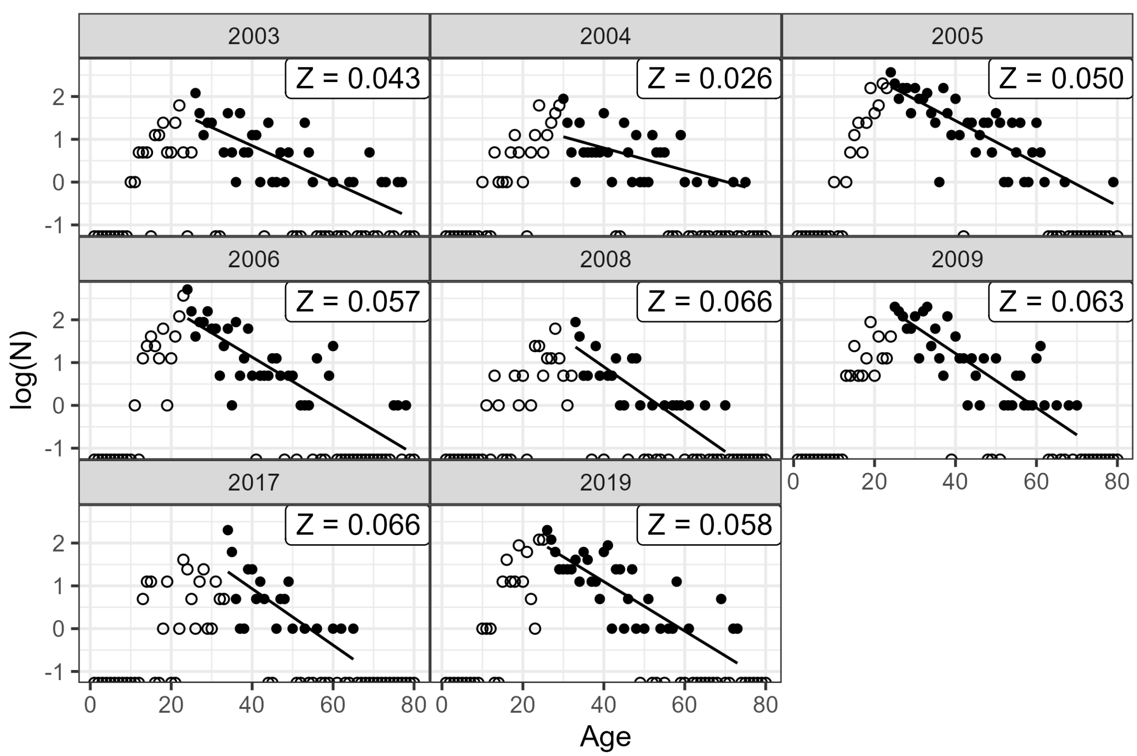

Figure G.3. Estimates of total mortality (Z) using catch curve analysis on the age samples from the IPHC survey, where N *is the numbers at age. Filled and empty circles indicate the data points included and excluded, respectively, from the catch curve regression. Lines show the predicted numbers of age from the catch curve under equilibrium assumptions. The magnitude of the slope of the line provides the estimate of Z.*

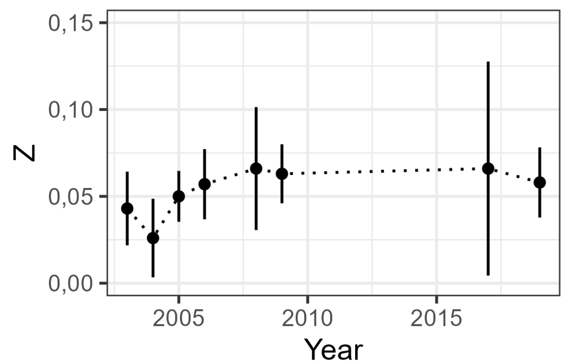

Figure G.4. Total mortality (Z) over time from the catch curves from the IPHC survey age samples. Vertical lines span the 95% confidence interval using the standard error of the slope estimated in the catch curve regression.

APPENDIX H. COSEWIC CONSIDERATIONS

Quillback Rockfish stock has been listed under the *Species at Risk Act* (SARA) as Threatened (COSEWIC 2009), and is anticipated to be reassessed by COSEWIC. COSEWIC and DFO have different criteria for assessing the status of marine fish stocks. DFO focuses on current status relative to some reference state or threshold, while COSEWIC criteria (based on IUCN Red List categories) are focused on the probability of decline over past generations and the probability of continued declines in the future (COSEWIC 2015). COSEWIC applies a set of quantitative assessment criteria and guidelines to develop and assign a status to the stock in question. To inform the reassessment of Quillback Rockfish, we report results for two of COSEWIC's quantitative assessment criteria that may be applicable to this stock, Metric A.

H.1. COSEWIC METRIC A

COSEWIC Metric A measures the probability that the stock has declined by 70%, 50% and 30% after three generations, where one generation for Outside Quillback Rockfish is defined to be 27 years (Appendix A.3). These probability thresholds are used to assign status designations of endangered, threatened, and species of special concern respectively, although other factors, such as cause of decline, are also considered (COSEWIC 2015).

To inform the COSEWIC re-assessment of Outside Quillback Rockfish, we report the following for each operating model (Figure H.1):

1. P70 - Probability that, on average, the spawning stock biomass (B) in 2021 declined below 70% of B_{1941} over three generations, where generation time is 24 years and probability is calculated as $P[1 - B_{2021}/B_{1941} > 0.7]$.
2. P50 - Probability that, on average, the stock declined below 50% of B_{1941} over three generations.
3. P30 - Probability that, on average, the stock declined below 30% of B_{1941} over three generations.

	P70	P50	P30
(1) M = 0.056	<0.01	0.01	0.99
(2) M = 0.046	<0.01	0.62	>0.99
(3) Low IRec	<0.01	<0.01	0.98
(A) Low steepness	<0.01	0.01	0.98

Figure H.1. Results for COSEWIC metric A, the probability that the spawning stock biomass in 2021 was below 70%, 50%, and 30% of B_{1941} *(over three generations) for each operating model scenario. One generation is defined to be 27 years.*

APPENDIX I. TECHNICAL WORKING GROUP MEMBERS

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Christine Macinnis	DFO Fisheries Management
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APPENDIX J. COMPUTATIONAL ENVIRONMENT

This version of the document was generated on 2024-11-28 11:51:38.868369 with R version 4.4.1 (2024-06-14 ucrt) (R Core Team 2023) and R package versions:

Package	Version	Date
bookdown	0.40	2024-07-02
cowplot	1.1.3	2024-01-22
csasdown	0.1.7	2024-10-31
DLMtool	6.0.6	2022-06-20
dplyr	1.1.4	2023-11-17
gfdata	0.1.3	2024-09-16
gfplot	0.2.1	2024-08-09
ggmse	0.0.2.9000	2024-09-16
ggplot2	3.5.1	2024-04-23
knitr	1.48	2024-07-07
MSEtool	3.7.2	2024-09-23
purrr	1.0.2	2023-08-10
rmarkdown	2.27	2024-05-17
tidyr	1.3.1	2024-01-24
TMB	1.9.14	2024-07-03

This document was compiled with the R package csasdown (Anderson et al. 2022a).