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

Quang C. Huynh[1], Matthew R. Siegle[2], and Dana R. Haggarty[2]

[1]Blue Matter Science
2150 Bridgman Avenue
North Vancouver, British Columbia, V7P 2T9

[2]Pacific Biological Station
Fisheries and Oceans Canada, 3190 Hammond Bay Road
Nanaimo, British Columbia, V9T 6N7

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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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TABLE OF CONTENTS

ABSTRACT

The purpose of this project is to provide scientific advice to support management of Inside 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 the assumption of the natural mortality value for Inside Quillback Rockfish. Two additional robustness OMs were developed, with one developed by excluding a historical jig survey in Area 12, and another that modeled lower than average recruitment in the projection. The reference OMs indicated the stock was above the LRP (0.4 B_{MSY}) with at least 50% probability in 2021. The index from the jig survey is impactful on the historical stock trajectory, but is indicative of the declining stock trend that led to the rockfish conservation strategy in the early 2000s.

Two fixed catch MPs of 33 tonnes (the average catch during 2012-2019) and 41 tonnes (125% of the 2012-2019 mean) and eight index-based MPs (Iratio, GB_slope, and IDX with various tuning parameters) that adjust the catch based on the recent trend in the index of abundance from the inside hard-bottom longline (HBLL) survey were tested in the closed-loop simulations. In the reference set, all MPs passed the proposed satisficing criterion with the stock exceeding the LRP with at least 75% probability after one generation (24 years). The satisficing criterion was also met in both robustness operating models.

Visualizations present trade-offs in tabular and graphical formats to support the process of selecting the final MP. There is a trade-off between biomass and fishery catches after one generation with higher catches with Iratio management procedures compared to the others. Tradeoffs in short-term and long-term catch were evident in the short-term (7 years) and after one generation. The tradeoff was less evident over longer time scales (after one vs. three generations or after 24 vs. 72 years). MPs that advise high catches after one generation continue to do so after three 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 and HBLL mean weight to identify triggers for future re-assessment.

1. INTRODUCTION

The purpose of this project is to provide scientific advice to support management of the inside 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 Stock 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 inside stock of Quillback Rockfish (hereafter Inside Quillback Rockfish or IQB). These MPs are tested across multiple plausible states of nature, explicitly accounting for uncertainty in population biology, fleet dynamics, data process error, and management implementation process error. We identified the MP Framework to be the best approach for providing science advice for Inside 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").

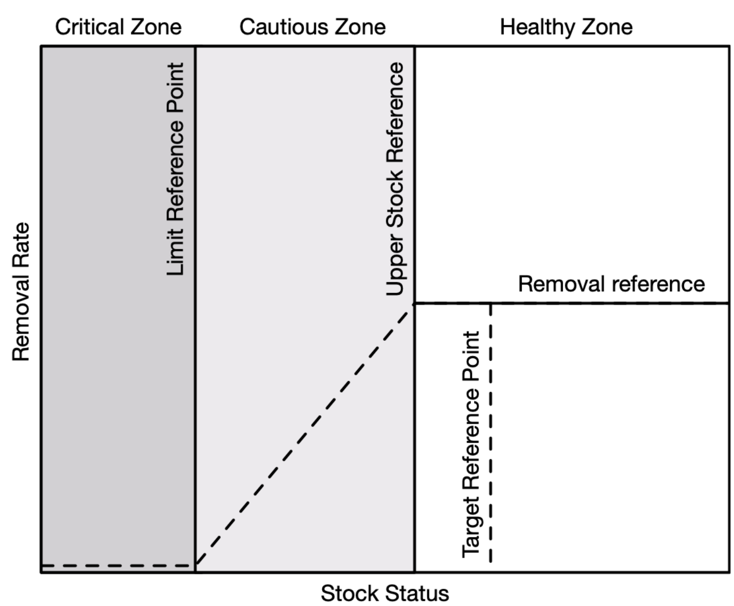

Figure 1. Illustration of the Precautionary Approach Framework. Based on DFO (2009).

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). Inside 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 G).

1.2. BACKGROUND

Quillback Rockfish is a long-lived species (up to 80 years for the Inside stock), commonly occurring in rocky marine habitats along the inner coast of British Columbia (BC) (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.

Inside Quillback Rockfish occur in Groundfish Management Area 4B in BC (Figure 2). The stock is proposed to be prescribed as a major fish stock in Batch 2, at which time its sustainable management will be legislated under the Fish Stocks Provisions in the *Fisheries Act* as described in the Guidelines for Implementing the Fish Stocks Provisions. In 2011, the median biomass of the Inside stock was assessed to be 2,668 tonnes (with a coefficient of variation of 0.60), with a 70% 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.

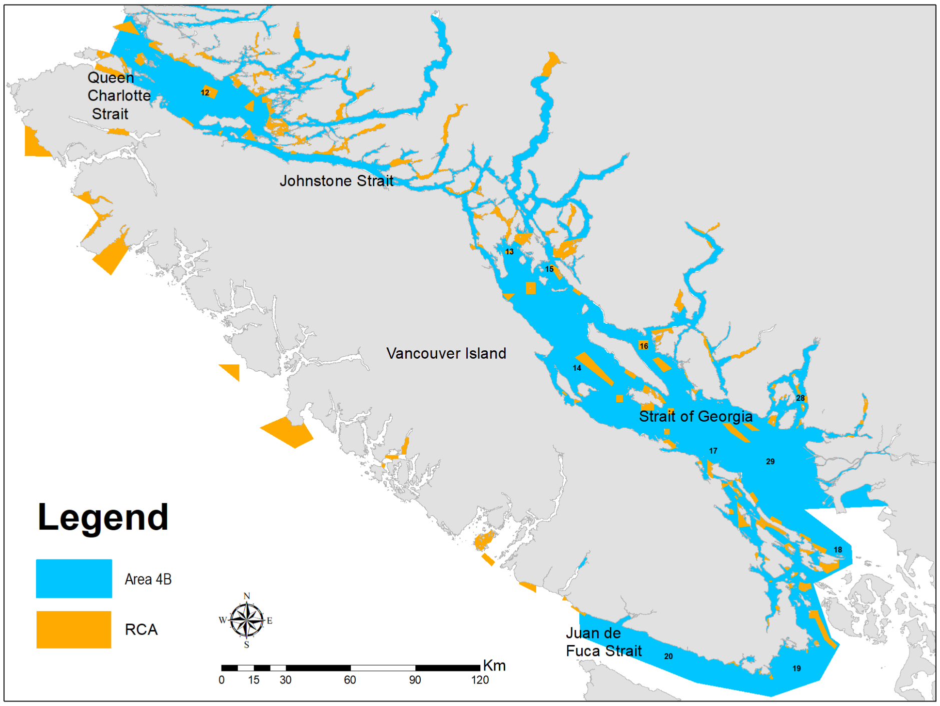

Figure 2. Map of Groundfish Management Area 4B showing rockfish conservation areas (RCAs) and the boundary for the Inside Quillback Rockfish Designatable Unit (DU).

1.3. MANAGEMENT STRATEGY EVALUATION (MSE)

Worldwide, the provision of scientific advice for managing fisheries has been moving towards 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). In 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 its use in the MPs (Punt et al. 2016; Carruthers and Hordyk 2018a; Anderson et al. 2021).

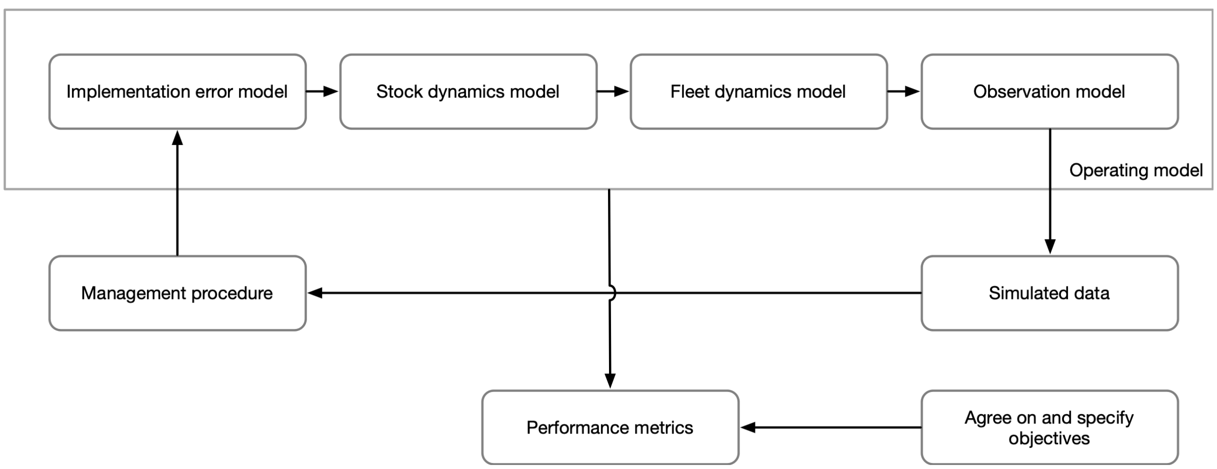

Figure 3. Illustration of the fisheries closed-loop simulation process from Anderson et al. (2021) following Punt et al. (2016). The management procedure may be based on a simple data rule (e.g., decrease the allowable catch x% if the survey index decreases y%) or it might be an estimation model combined 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 data-limited groundfish species. 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 Inside 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 limits for Inside 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)[1]. In large part, the openMSE software (Carruthers and Hordyk 2018a) has been designed to allow practitioners to follow these steps (Figure 4).

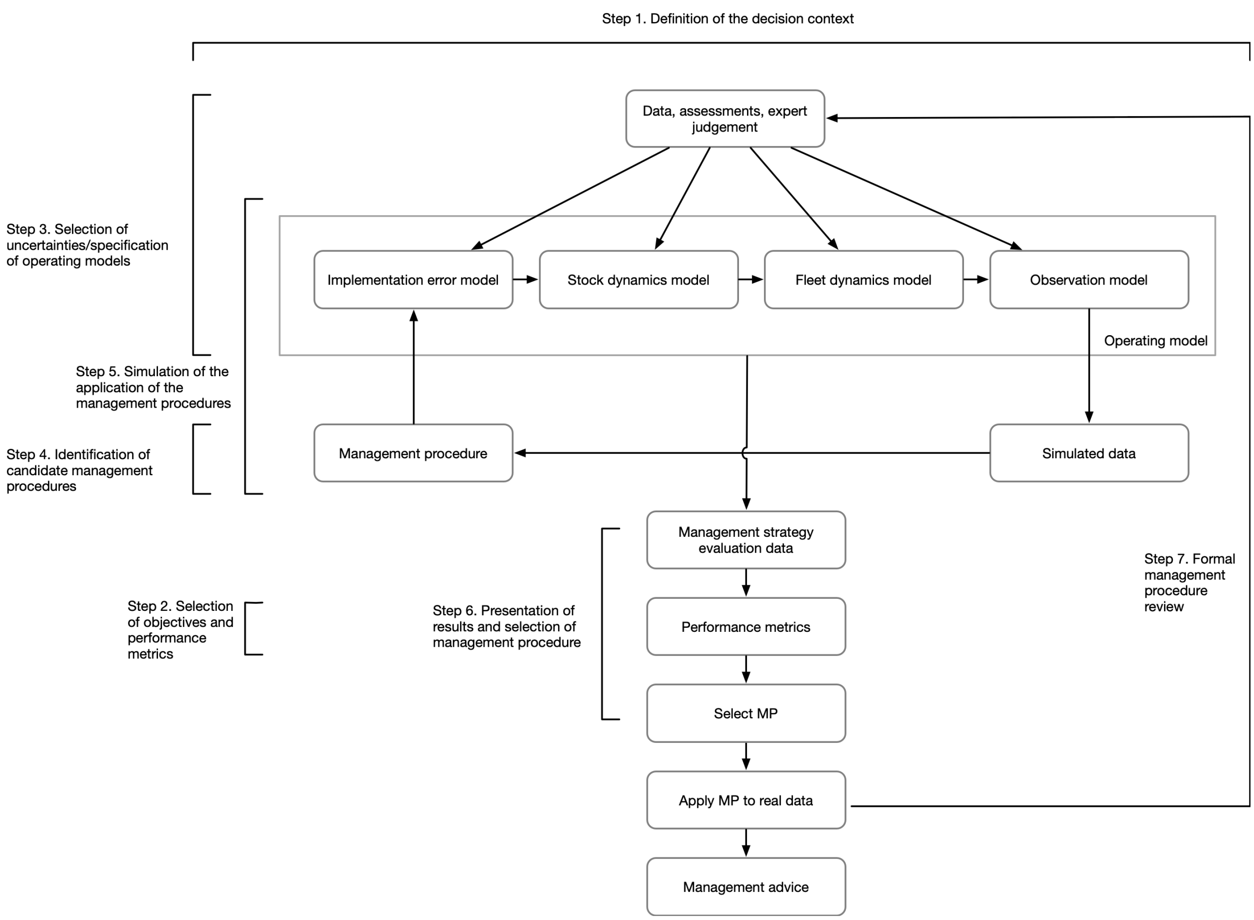

Figure 4. The steps of the MSE process following Punt et al. (2016) as implemented in openMSE, copied from Anderson et al. (2021) and adapted from Carruthers and Hordyk (2018a). This figure expands on Figure 3.

The six steps are as follows:

Step 1: Definition of the decision context.

Step 2: Selection of objectives and performance metrics.

[1]Cox and Benson. 2016. Roadmap to More Sustainable Pacific Herring Fisheries in Canada: A Step-by-Step Guide to the Management Strategy Evaluation Approach. Unpublished Report.

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 monitoring may be done through informal means, e.g., via feedback from fishers and survey information (e.g., Cox and Kronlund 2008), or through more formal statistical measures, where observed data are compared to predictions from the 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, Fisheries and Oceans Canada (DFO) hosted a series of workshops in early 2021, bringing together 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 Inside 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, were taken into account in the MP Framework results for Inside Quillback Rockfish. Other sustainability objectives were identified as topics suited for Groundfish management.

In the following sections, we describe our approach for identifying suitable management procedures for Inside 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, academia, and/or non-governmental organizations (NGOs).
- How will the final decision be made?

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

3. OBJECTIVES AND PERFORMANCE METRICS

Clear management and fishery objectives must be identified, along with the performance metrics that measure them. 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.

We present a set of objectives and associated performance metrics for Inside Quillback Rockfish. Haggarty et al. (2022) broadly delineated two types of objectives. Strategic objectives outline high level goals, while operational objectives which are fully quantified statements that 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 one generation).

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

For this analysis, we identified three broad strategic objectives pertinent for the MP Framework: (a) ensuring a sustainable stock into the future; (b) maintaining adequate and predictable fishing opportunities across all sectors; and (c) identifying a flexible management procedure approach to facilitate rapid assessment and new data into management responses (Haggarty et al. 2022). Additional policy objectives are guided by the PA Framework (DFO 2006, 2009) and the previous stock assessment (Yamanaka et al. 2011).

The proposed operational policy objective is to:

1. Maintain the stock above the LRP after one generation (24 years) with at least 75% probability of success.

Following general international practice, the desired probability of success was set at 75% to ensure there is high probability that the stock would be above the LRP in the simulated projections (Marentette et al. 2021). For more information on generation time, please see Appendix A, Section A.3.

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

2. Maintain the stock above the USR after one generation (24 years).
3. Maintain fishing mortality below that at maximum sustainable yield during one generation (24 years). To be compliant with the United Nations Fish Stocks Agreement (from which the PA Policy was developed), the removal reference should not exceed F_{MSY} (DFO 2006).
4. Maintain fishery access and catches both in the short-term (7 years) and in the long-term (1 generation and 3 generations). The one and three generation time periods correspond to 24 and 72 years, respectively. Catches over these time periods can be evaluated to ensure if there is inter-generational access to the fishery (Haggarty et al. 2022).

We did not assign target probabilities to Objectives 2-4 as they are provided for the purpose of evaluating trade-offs with Objective 1.

Operational objectives 1-3 broadly correspond to strategic objective (a) while objective 4 corresponds to strategic objective (b). Strategic objective (c) is incorporated into the MP Framework by identifying and testing management procedures that can update the catch advice on a biennial basis. Haggarty et al. (2022) also reported that both stability and flexibility in fishery catches were desirable from various participants of the objectives workshop. It was not apparent how to meet both stability and flexibility since they are opposing objectives. However, projections of catches under alternative management procedures can inform discussions on how flexible fishery catches could be in the future.

3.2. PERFORMANCE METRICS

We propose 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). In the closed-loop simulations, all reference points and performance metrics are calculated in the operating model. Raw performance metrics are calculated in each year of the projection and summarized according to the time-frame of interest:

1. **LRP 1GT**: P(B > 0.4 B_{MSY}) after 1 generation (in 2045, year 24 of the projection period)
2. **LRP ST**: P(B > 0.4 B_{MSY}) after 7 years (in 2028, year 7 of the projection period)
3. **USR 1GT**: P(B > 0.8 B_{MSY}) after 1 generation
4. **FMSY**: P(F < F_{MSY}) during the first generation (during 2022–2045, years 1–24 of the projection period)
5. **C ST**: Average catch during the short-term (during 2022–2028, years 1–7 of the projection period)
6. **C 1GT**: Average catch after 1 generation
7. **C 3GT**: Average catch after 3 generations (in 2093, years 1–72 of the projection period)

In cases where performance metrics are calculated over a range of years, the mean performance statistic was calculated across replicates and years for the defined time window (Anderson et al. 2021).

Two additional performance measures were calculated outside of those used directly in support of policy and fishery objectives. **LRP ST** calculates whether the stock is maintained above the LRP in the short-term (7 years). This time period is short-term relative to the generation time of Inside Quillback Rockfish, but may be of interest for groundfish management and fishery operations. 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 length is close to the age of 50% maturity, i.e., when a cohort starts to contribute to the spawning output of the population.

Since Inside Quillback Rockfish is a long-lived species, it may be difficult to observe trade-offs until there is sufficient turnover in the age structure of the population. Therefore, **C 3GT** was intended to facilitate comparison of short-term vs. long-term catch relative to the longevity of the species.

No catch threshold could be immediately 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, however, were developed that ensure continued access for the fishery (Section 5), a strategic objective identified in the Objectives Workshop (Haggarty et al. 2022).

4. OPERATING MODELS

Operating models 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).

Equations and parameters describing the four OM components are provided in detail in Appendix B of Carruthers and Hordyk (2018a) and Appendix A of Anderson et al. (2021). Uncertainty in many OM parameters is incorporated by sampling parameters from probability distributions. It is often not possible to incorporate all sources of uncertainty into a single operating model, so we developed multiple OMs that change the value (or distribution) of one or more parameters and/or data sources of interest (Section 4.2).

Best practice recommends calibrating or conditioning OMs with observed data so that historical observations can be reproduced. The SAMtool package (Huynh et al. 2022a) uses RCM (Rapid Conditioning Model), an efficient implementation of a statistical catch-at-age model that reconstructs the stock history that would be consistent with the observed data. The RCM is an update of the Stock Reduction Analysis (SRA) model described in Appendix B of Anderson et al. (2021). For Inside Quillback Rockfish, the estimated parameters are average unfished recruitment (R_0), annual recruitment deviates from the stock-recruitment relationship, selectivity parameters for each fishery and survey (age of 50 and 95% selectivity), and catchability coefficients for the indices of abundance. Year-specific fishing mortality for the fishery was calculated by internally solving the Baranov equation such that the predicted catch was equal to the observed catch.

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 is conditioned on historical observations using the RCM (see Appendix B of Anderson et al. 2021). The projection period covers the period from the first year after t_c to the final projection year t_N and is used to for closed-loop testing of management procedures and calculation of corresponding performance metrics.

OM development follows three steps:

1. Set parameter values and ranges in the OM;
2. Pass the OM parameters to the RCM, which conditions the historical dynamics of the operating model by fitting to historical catches, indices of abundance, and any available years of age and/or length composition data. This process results in conditioned estimates of model parameters and estimates of historical biomass and historical fishing mortality (in years t_1 to t_c) consistent with historical observations; and
3. Pass the conditioned parameter values back to the OM (now the “conditioned” OM) for use in the simulated projections, starting in year t_{c+1}.

Where possible, biological parameters were informed from survey biological samples from Area 4B, primarily collected on the inside hard bottom longline (HBLL) and jig surveys (Appendix A).

Other parameters, i.e., natural mortality and stock-recruit steepness, were informed by the scientific literature (Appendix D).

We conditioned the OMs with the RCM, using fishery (commercial and recreational) catch and composition data (Appendix C), age-composition data from research surveys (Appendix A), and indices of abundance developed from the inside HBLL survey and Jig Area 12 surveys (Appendix B). Results from conditioning the OMs are provided below in Section 4.3.

4.1. DATA SOURCES

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., depletion of the stock or range of natural mortality values), and a "robustness set", to capture a wider range of uncertainties that may be less plausible but should nonetheless be explored (Rademeyer et al. 2007). Anderson et al. (2021) recommended that reference set performance metrics should be averaged together (an ensemble approach to integrate across OM uncertainties) but that performance metrics from individual OM robustness set scenarios should 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).

Since natural mortality has not been directly estimated for Inside Quillback Rockfish, we established three reference set OMs which varied by the mean of the distribution for natural mortality (*M*, units of year^{-1}): (1) M = 0.067; (2) M = 0.055; and (3) M = 0.088 (Table 1). These means were based on various predictors that use maximum age to indirectly predict *M*.

We further established two robustness set OMs encompassing additional sources of uncertainty: (A) an OM that excludes the Jig Area 12 survey from the historical conditioning; and (B) an OM that assumes lower than average recruitment in the projection (Table 1).

Table 1. Inside Quillback Rockfish operating model scenarios.

Scenario name	Type
(1) M = 0.067	Reference
(2) M = 0.055	Reference
(3) M = 0.088	Reference
(A) No jig survey	Robustness
(B) Future 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). Parameter settings are provided in Appendix D.

Data sources are provided in Appendices A through C. Here, we here provide a brief description of OM (1) that was then 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 that was 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.

Biological samples from the commercial fishery were collected during 1984-2001. Age samples from 1996, 2000, and 2001, however, were excluded from model fitting. Initial fits showed a strong residual trend in the age composition when these data were included. These samples showed a leftward shift in the mode of the age distribution towards younger fish, but were collected from few fishing events (Table C.4). Mean weight in the commercial fishery (excluding these three years) was fairly constant over time and suggested that the age samples from these three years were outliers relative to the overall trend (Figure C.5).

Recreational catch was estimated from the creel survey (1982-2021), with linear interpolation needed to model the development of the recreational fishery after World War II (Appendix C). Dockside interviews also informed the length distribution of Inside Quillback Rockfish caught in the recreational fishery.

The Inside Quillback Rockfish stock is indexed by two fishery-independent surveys: the inside Hard Bottom Longline Survey (Appendix B, Section B.1) and the Jig Area 12 Survey (Appendix B, Section B.2). The HBLL survey informs population trends since 2003, while the Jig Area 12 Survey informs earlier population trends (1986–2004). Electronic records used to develop indices were not available for survey data collected in other Areas in recent years, i.e., 2004 and 2005 surveys in the Strait of Georgia, at the time of this analysis. While the Area 12 survey does not explicitly index all of Area 4B, similar reductions in catch rates have been observed from jig surveys in other statistical areas in Area 4B (Haggarty and King 2005, 2006). Therefore, it is believed that Area 12 index is representative of the population trends of the inside stock during the 1986–2004 period.

Age samples are also available from both surveys. No HBLL age samples were available from 2020 as the survey was cancelled due to the COVID-19 pandemic. Age samples from the 2021 HBLL survey were also not available for this analysis.

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

The steepness of the Beverton-Holt stock-recruit relationship was sampled from a probability distribution, with a mean of 0.67 and standard deviation of 0.17, based on a posterior estimate for Pacific rockfish species (Appendix D, Section D.1.3). Steepness is bounded between 0.2 – 1.0 while the sampled values ranged between 0.27–0.99.

During the projection period, only the HBLL index was assumed to be available for the MPs, as this survey is conducted annually. Use of a single index of abundance for deriving catch recommendations is consistent with many MPs, unless otherwise specified (Appendix E). Projected recruitment deviations were sampled in log space with standard deviation $\tau = 0.4$, with autocorrelation estimated post-hoc from the historical recruitment deviates in the RCM (Appendix A of Anderson et al. 2021).

Observation error in the projected index values was simulated with random deviates from a lognormal distribution with mean of one and standard deviation of approximately 0.10 based on the estimated standard error in the HBLL index.

Since natural mortality has not been directly estimated for Inside Quillback Rockfish, we incorporate alternative distributions of this parameter to develop three reference OMs.

4.2.1.1. (1) M = 0.067

Natural mortality (*M*) was sampled from a probability distribution, where $M \sim \text{Lognormal}(0.067, 0.08)$ (Appendix D, Section D.1.2). This mean value of *M* is based on the updated literature on predictors of natural mortality based on other life history traits, specifically, maximum observed age. The mean of 0.067 is based on the log-log regression of direct estimates of M and maximum observed age (Then et al. 2015).

4.2.1.2. (2) M = 0.055

In OM (2), natural mortality is lower than in (1), with $M \sim \text{Lognormal}(0.055, 0.06)$. 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 reflects the possibility that the stock could be less productive than assumed in the other scenarios.

4.2.1.3. (3) M = 0.088

In OM (3), natural mortality is higher than in (1), with $M \sim \text{Lognormal}(0.088, 0.11)$. This mean was obtained from nonlinear least squares regression from Then et al. (2015).

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) No jig survey

Since the Area 12 jig survey does not sample the entire stock, we tested model sensitivity to this index by removing it from the operating model in this scenario.

4.2.2.2. (B) Low recruitment

This scenario tests a scenario if environmental conditions were to contribute to lower than average recruitment of Inside 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 projected recruitment deviations (in normal space) is one. Here, the mean was set to 0.7 for OM (B) based on recent estimated recruitment deviations in the RCM from the reference operating models. This scenario is intended to evaluate how management procedures would perform in such circumstances. The historical dynamics here are identical to those in OM (1).

4.3. CONDITIONING THE OPERATING MODELS

After specifying the OM parameters (Appendix D), we conditioned the OMs using the RCM described in Appendix B of Anderson et al. (2021). The estimation model estimates historical recruitment and abundance, and fits to the indices of abundance and age/length composition. Fishery removals in the model are equal to the observed values.

RCM uses the multinomial distribution to fit to the age and length distribution data. Use of the multinomial distribution requires specification of the annual sample size. Increasing sample size implies an age distribution that is very precise and representative of the underlying population. However, no age composition data series was sampled with complete coverage of the Inside stock. Thus, the sample size for the multinomial likelihood function was specified as follows:

- The sample sizes for the HBLL survey were capped to maximum of 100 or the total number of age samples. This series used the highest sample sizes since the survey has the largest spatial coverage;
- The sample sizes for the Jig Area 12 survey were capped to maximum of 50 or the total number of age samples. While this survey had more annual age samples than the HBLL survey, the spatial coverage was much smaller;
- The sample sizes for the ages in the commercial fishery were set to the number of fishing events, and were set lower than those for the surveys since the sampling protocol here was less statistically rigorous; and
- The sample sizes of the lengths in the recreational fishery were set to the number of Pacific Fishery Management Areas (PFMAs) fished in the interviews.

RCM can model separate fisheries with separate selectivity. 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 RCM 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 (Appendix D.2). In this analysis, all index-based MPs utilize the inside HBLL survey.

The RCM was run for 200 replicates. Each replicate used a different value of *M* and *h* (sampled independently from the distributions shown in Appendix D). 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., $B_{1918} = B_0$. While this is unlikely to be true, as First Nations and others would have been catching Quillback Rockfish prior to 1918, these numbers are expected to be small enough not to impact the outcomes of the performance of MPs in the projection period.

4.3.1. OM conditioning results

The following sections describe the results of conditioning the OMs. 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 RCM was able to fit to the indices of abundance reasonably well (Figures 5 - 6) and convergence was achieved for all replicates in all OM scenarios. The estimated HBLL index fell within the observed confidence intervals in most years (Figure 5). The estimated trends are constant, if slightly decreasing, over 2003–2021. The model also follows the decline in the Jig Area 12 index inferred between the low value in 2004 relative to those in 1986-1991 (Figure 6).

The RCM also fit the survey age composition data reasonably well (Figures 7 - 13. The models capture the truncation of the age structure in the Jig Area 12 survey over time and the reduction in the abundance of fish 60 years and older (Figures 11 - 13). Similarly, the models capture the truncation of the age structure in the commercial fishery through the 1980s and 1990s (Figures 14 - 17). On the other hand, the recreational length composition data were more sparsely collected and the estimated distributions were unimodal over time (Figures 18 - 21).

Logistic-shaped selectivity functions were estimated for both surveys and fisheries (Figures 22 - 25). The age of 50% selectivity for the HBLL survey was approximately 13.5-14.0 years in the three reference operating models (Table 2). The Jig Area 12 survey and commercial fishery caught smaller fish with 50% selectivity at around six and eight years, respectively. Finally, 50% selectivity for the recreational fishery was estimated at approximately 12-13 years (when converted from length). Recreational selectivity was similar to that for the HBLL survey. Selectivity estimates differed in the robustness OM (A) relative to the reference OMs for the HBLL survey and commercial fishery. In particular, commercial selectivity was shifted rightward in OM (A) (Table 2).

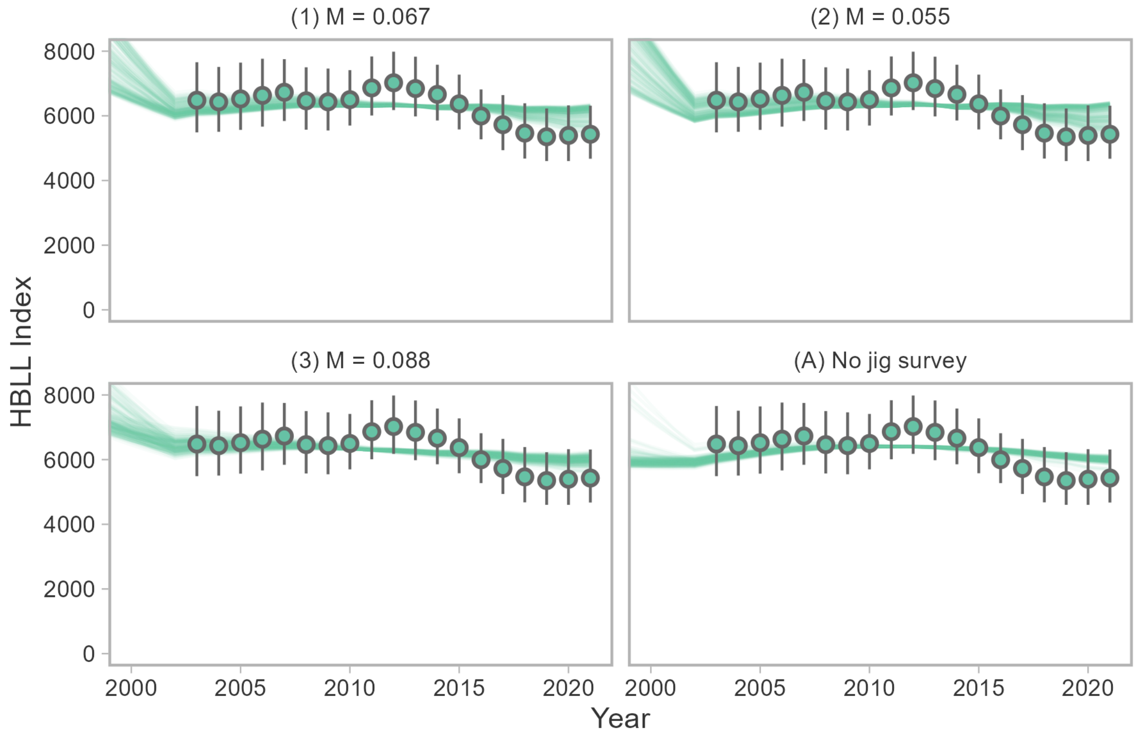

Figure 5. RCM model fits to the HBLL index by operating model. Thin, colored lines represent individual model fits across stochastic draws of natural mortality and steepness. Dots represent index mean and line segments represent 2 times the standard errors.

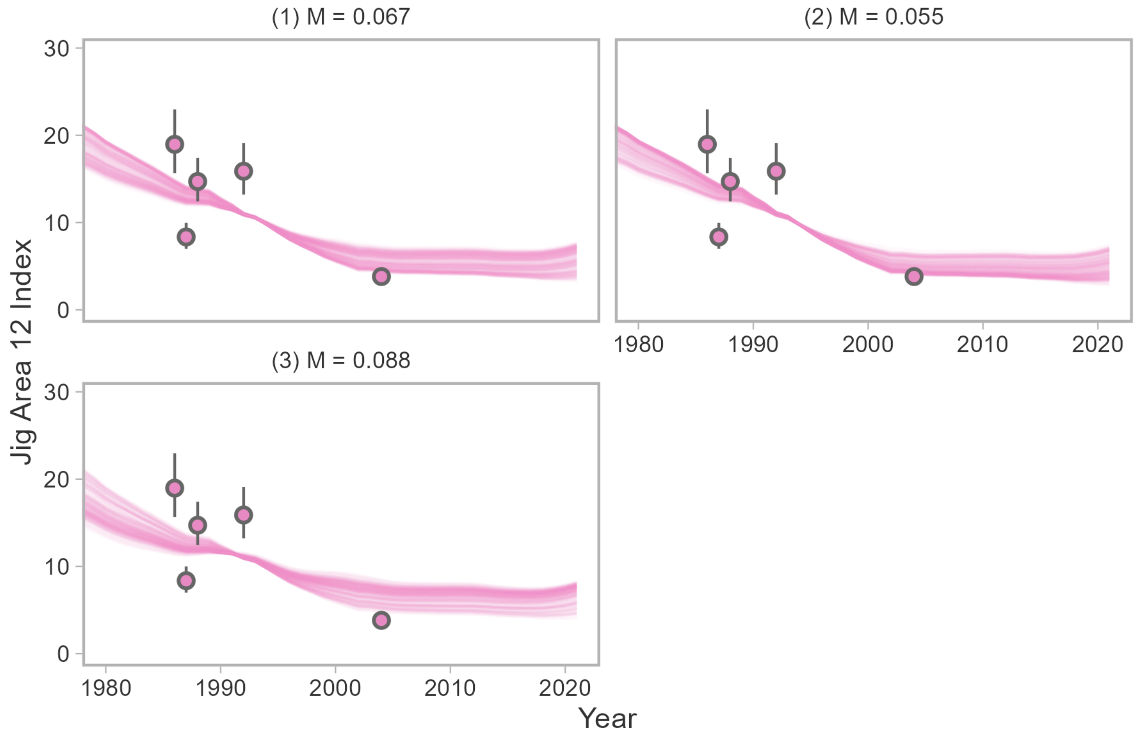

Figure 6. RCM model fits to the Jig Area 12 index by operating model. Thin, colored lines represent individual model fits across stochastic draws of natural mortality and steepness. Dots represent index mean and line segments represent 2 times the standard errors. This index was excluded from OM (A).

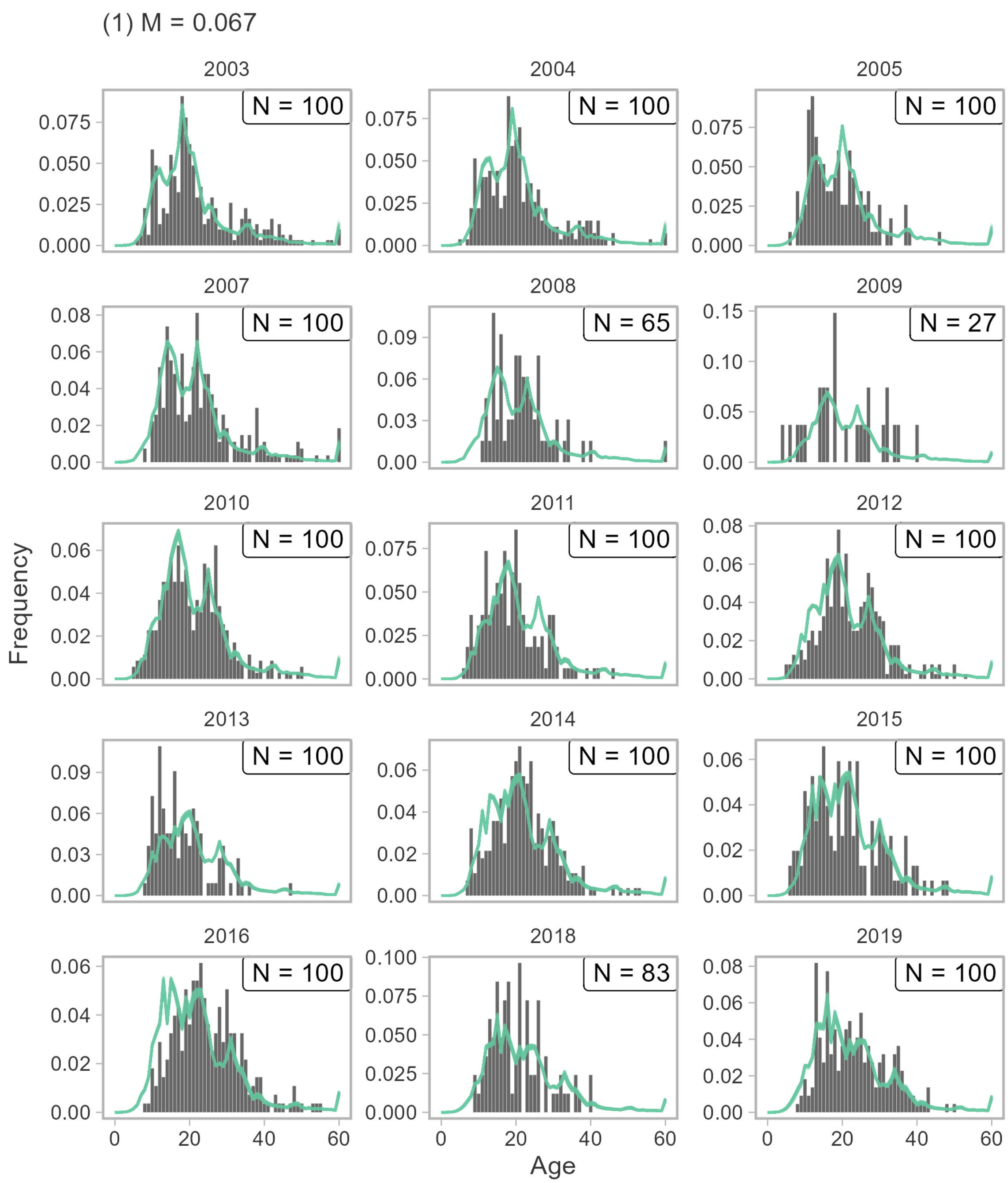

Figure 7. RCM model fits to the HBLL age composition data for OM Scenario (1), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples, capped at 100.

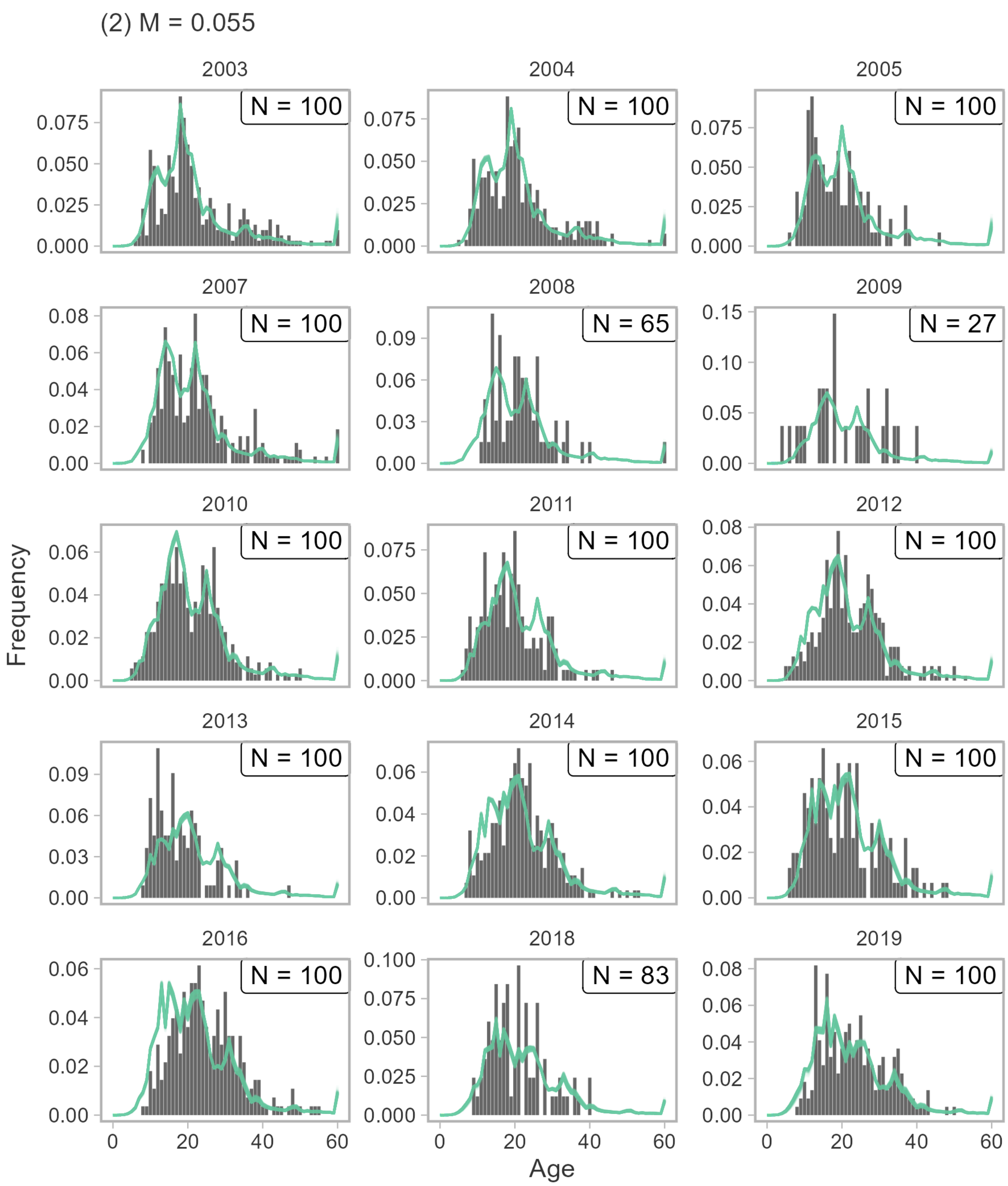

Figure 8. RCM model fits to the HBLL age composition data for OM Scenario (2), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples, capped at 100.

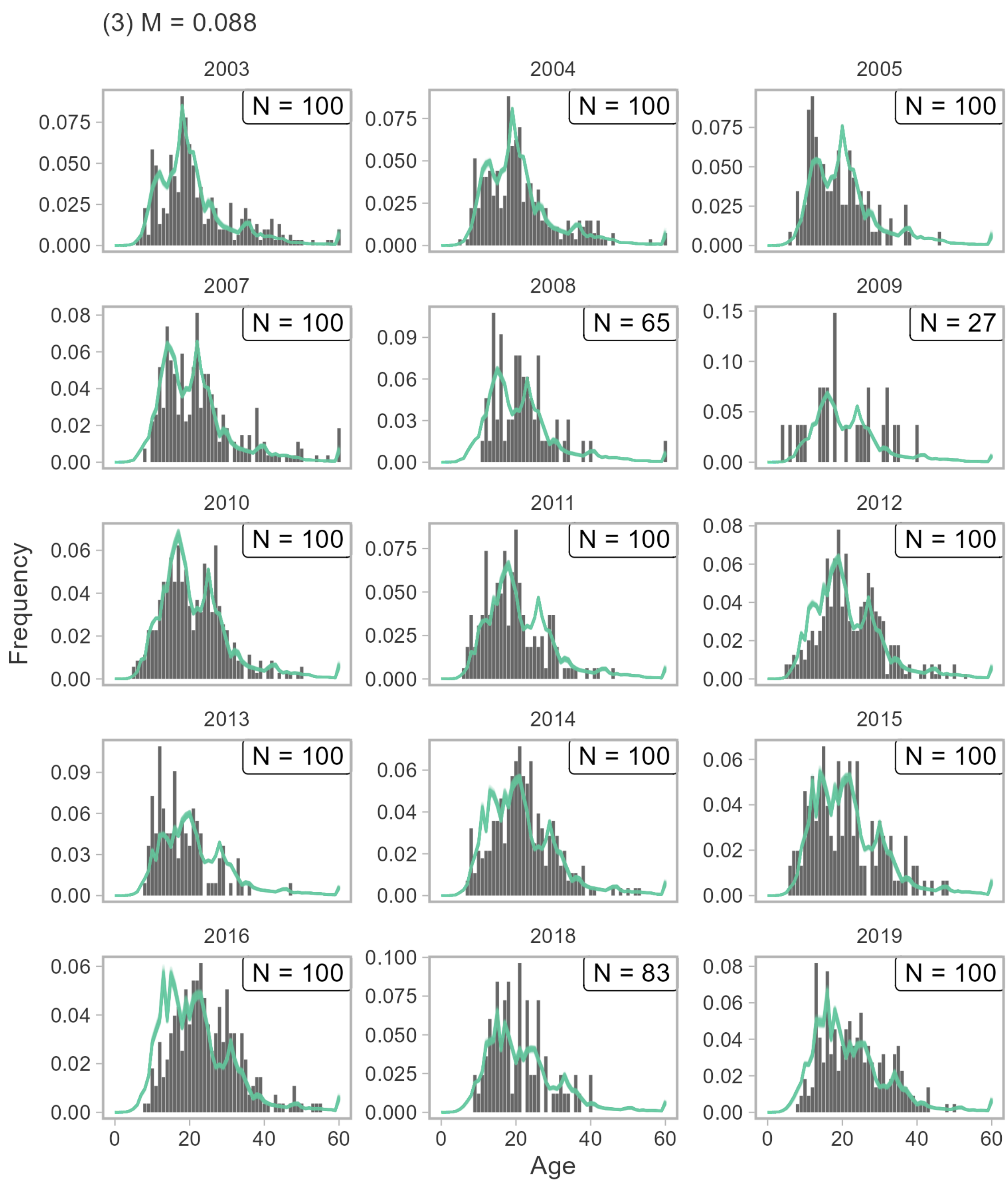

Figure 9. RCM model fits to the HBLL age composition data for OM Scenario (3), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples, capped at 100.

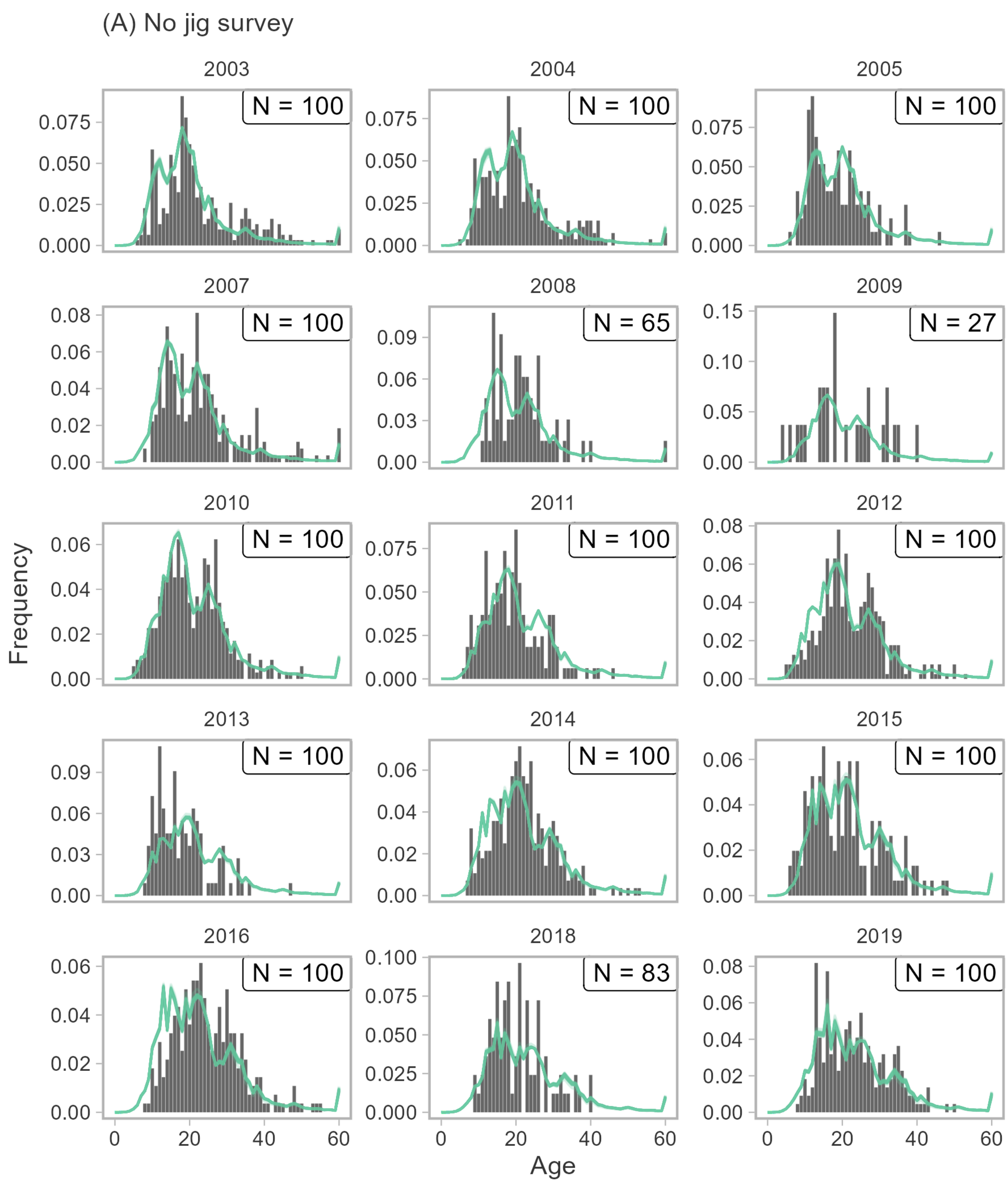

Figure 10. RCM model fits to the HBLL age composition data for OM Scenario (A), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples, capped at 100.

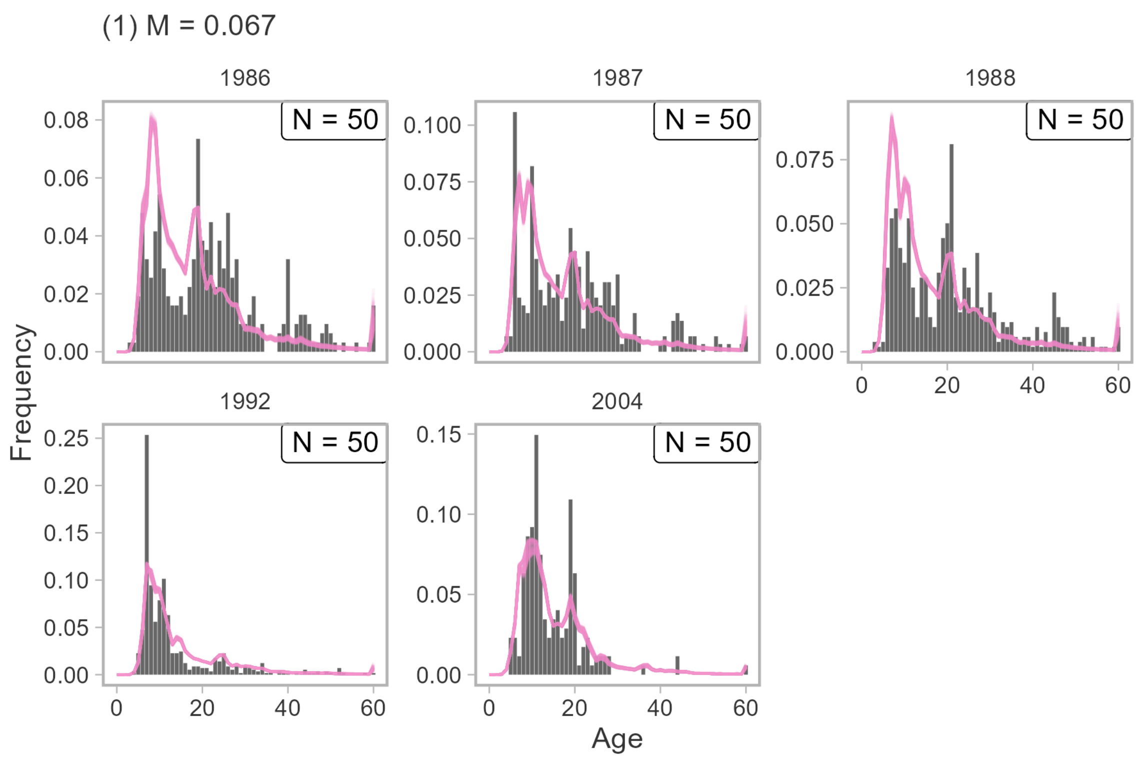

Figure 11. RCM model fits to the Jig Area 12 age composition data for OM Scenario (1), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples, capped at 50.

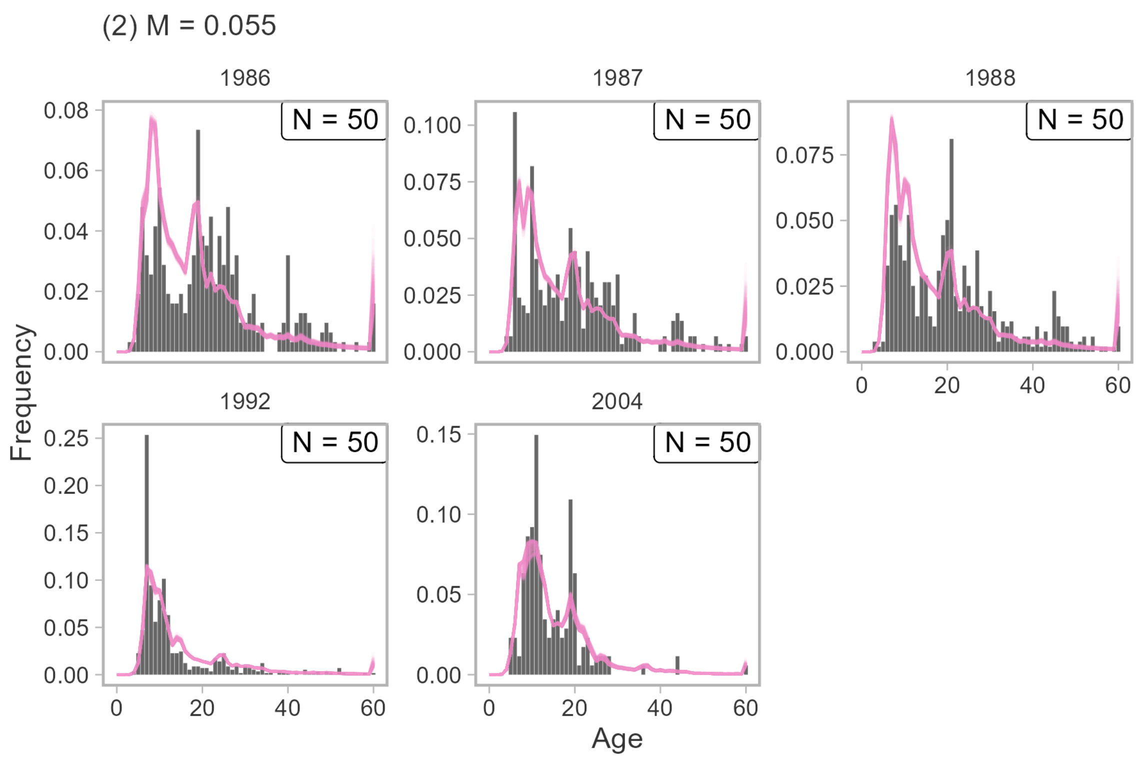

Figure 12. RCM model fits to the Jig Area 12 age composition data for OM Scenario (2), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples, capped at 50.

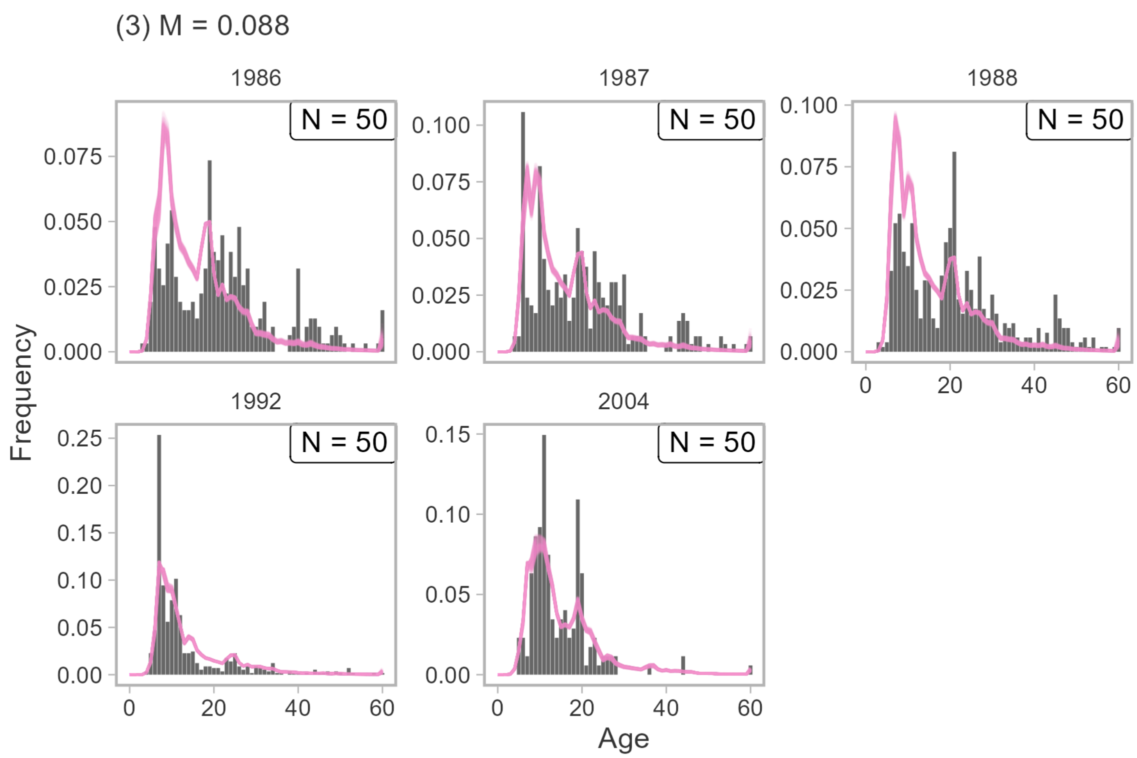

Figure 13. RCM model fits to the Jig Area 12 age composition data for OM Scenario (3), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of age samples, capped at 50.

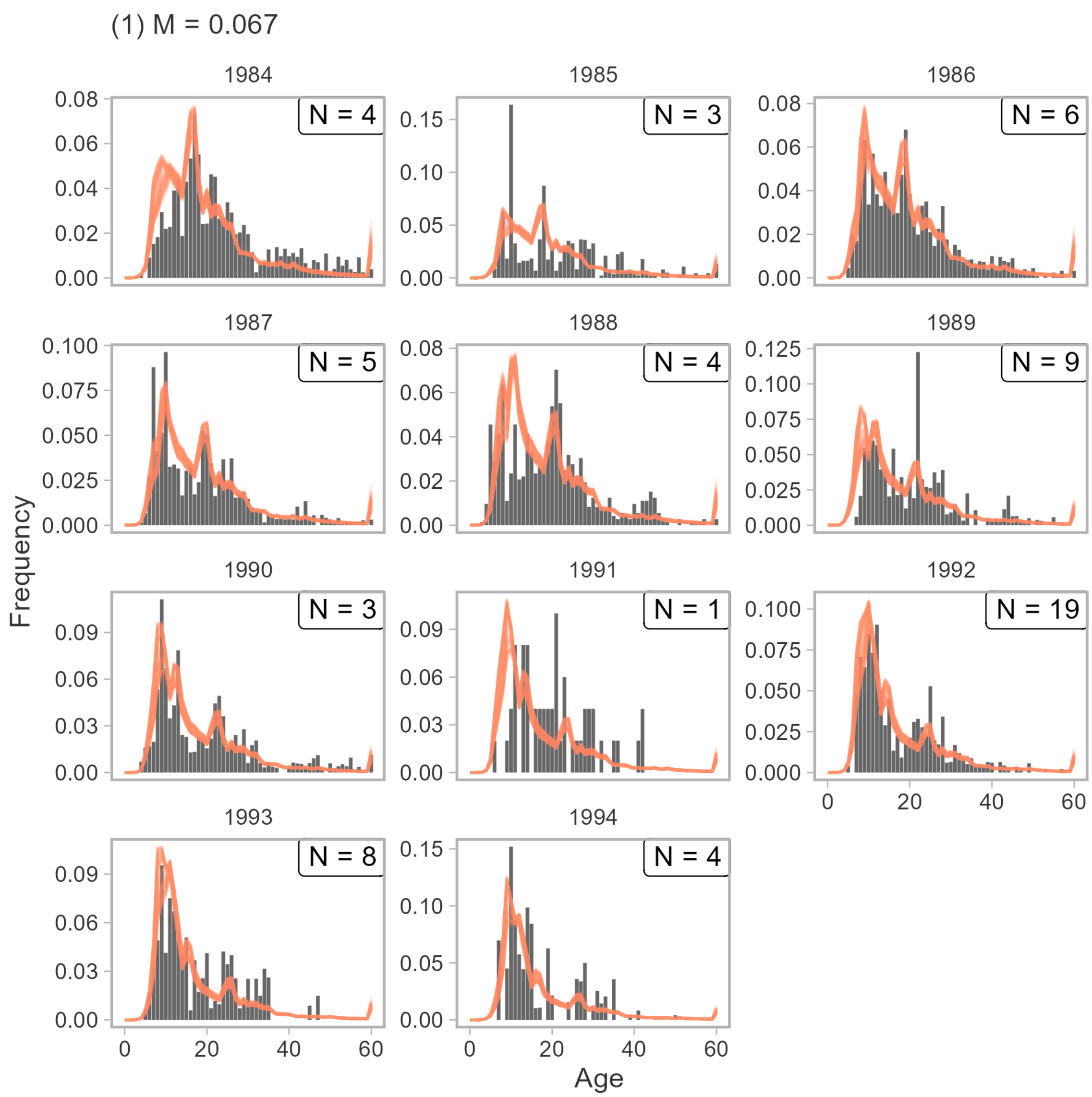

Figure 14. RCM model fits to the commercial fishery age composition data for OM Scenario (1), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of fishing events.

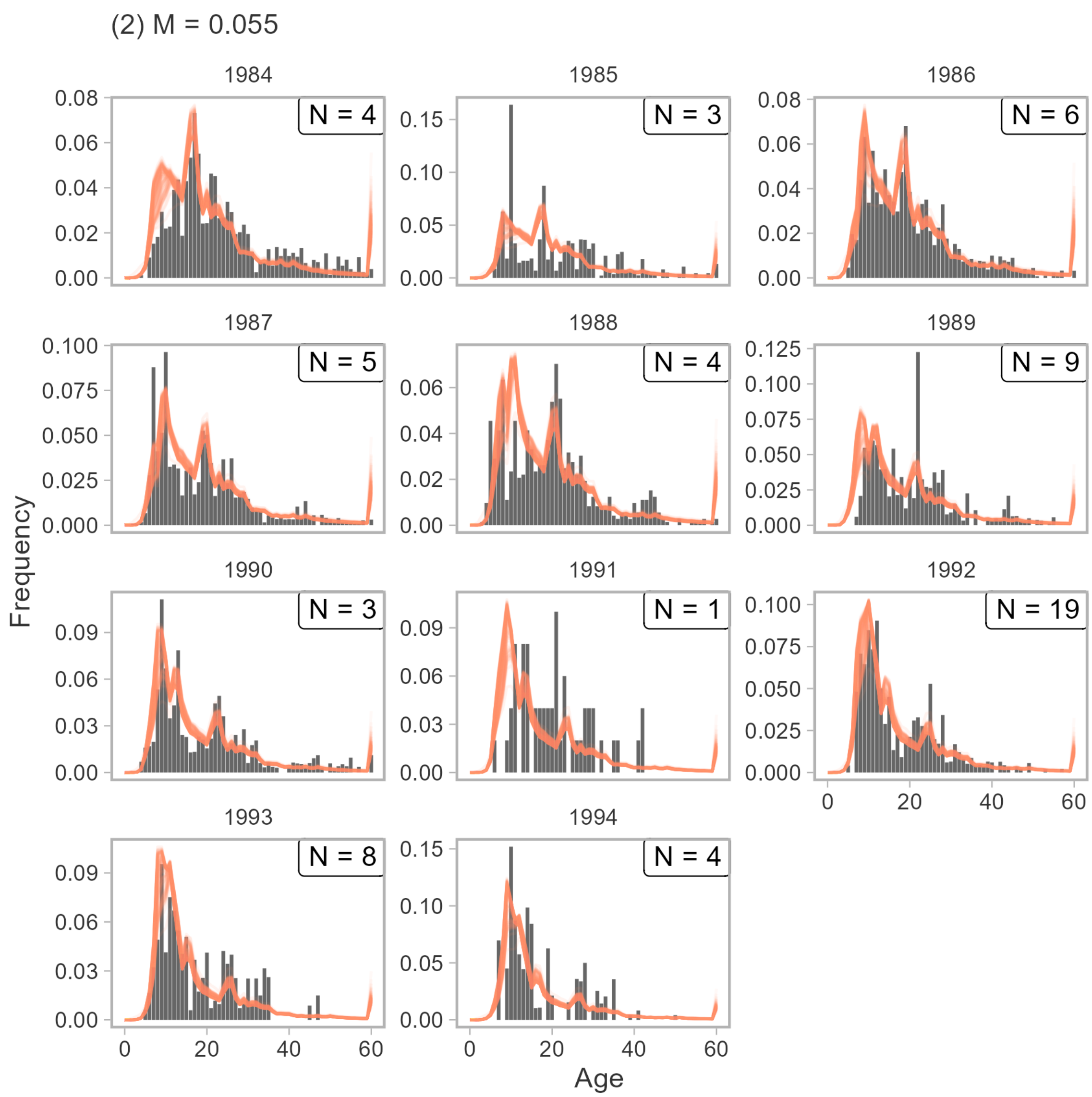

Figure 15. RCM model fits to the commercial fishery age composition data for OM Scenario (2), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of fishing events from which the age samples were collected.

(3) M = 0.088

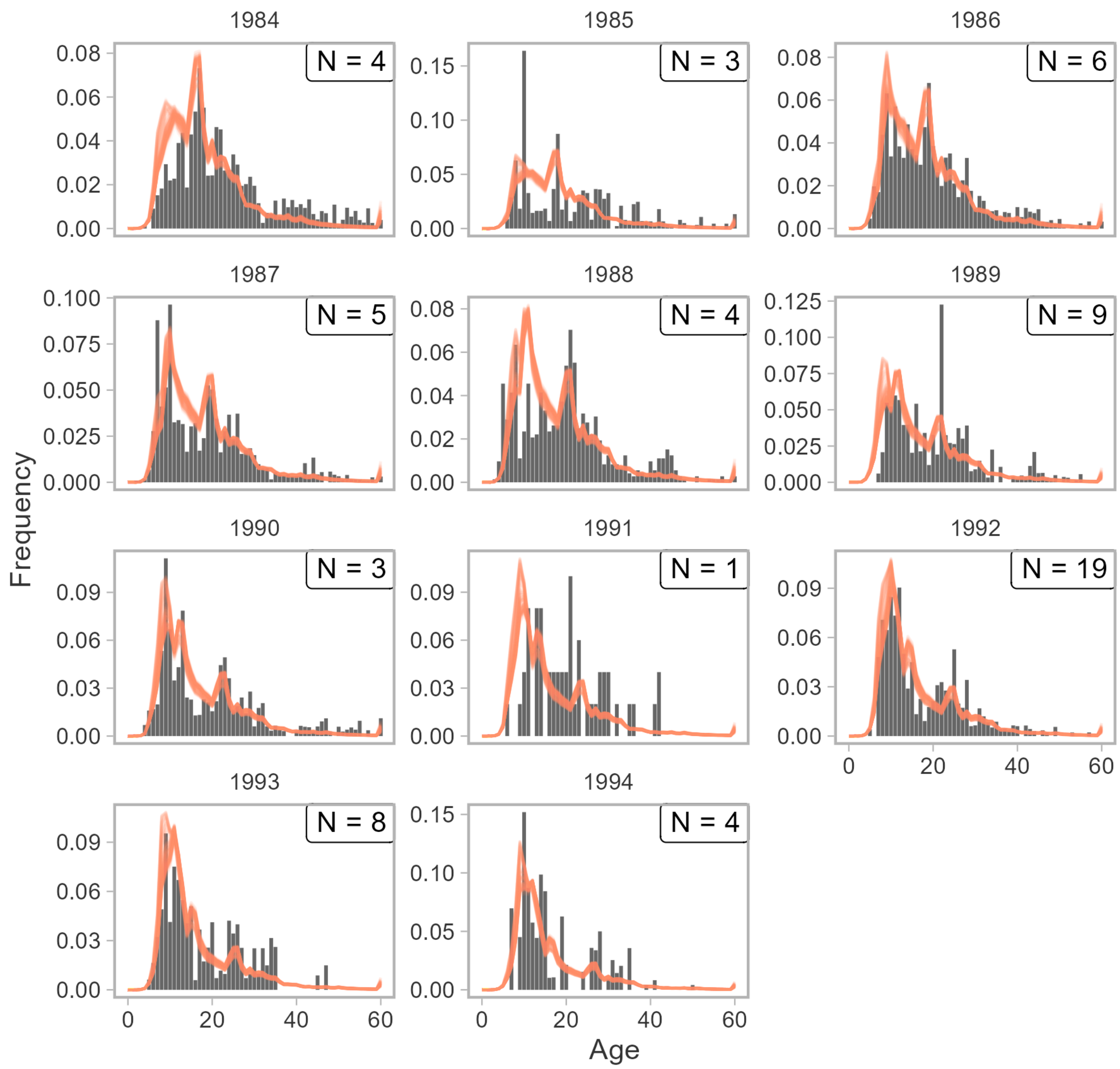

Figure 16. RCM model fits to the commercial fishery age composition data for OM Scenario (3), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of fishing events.

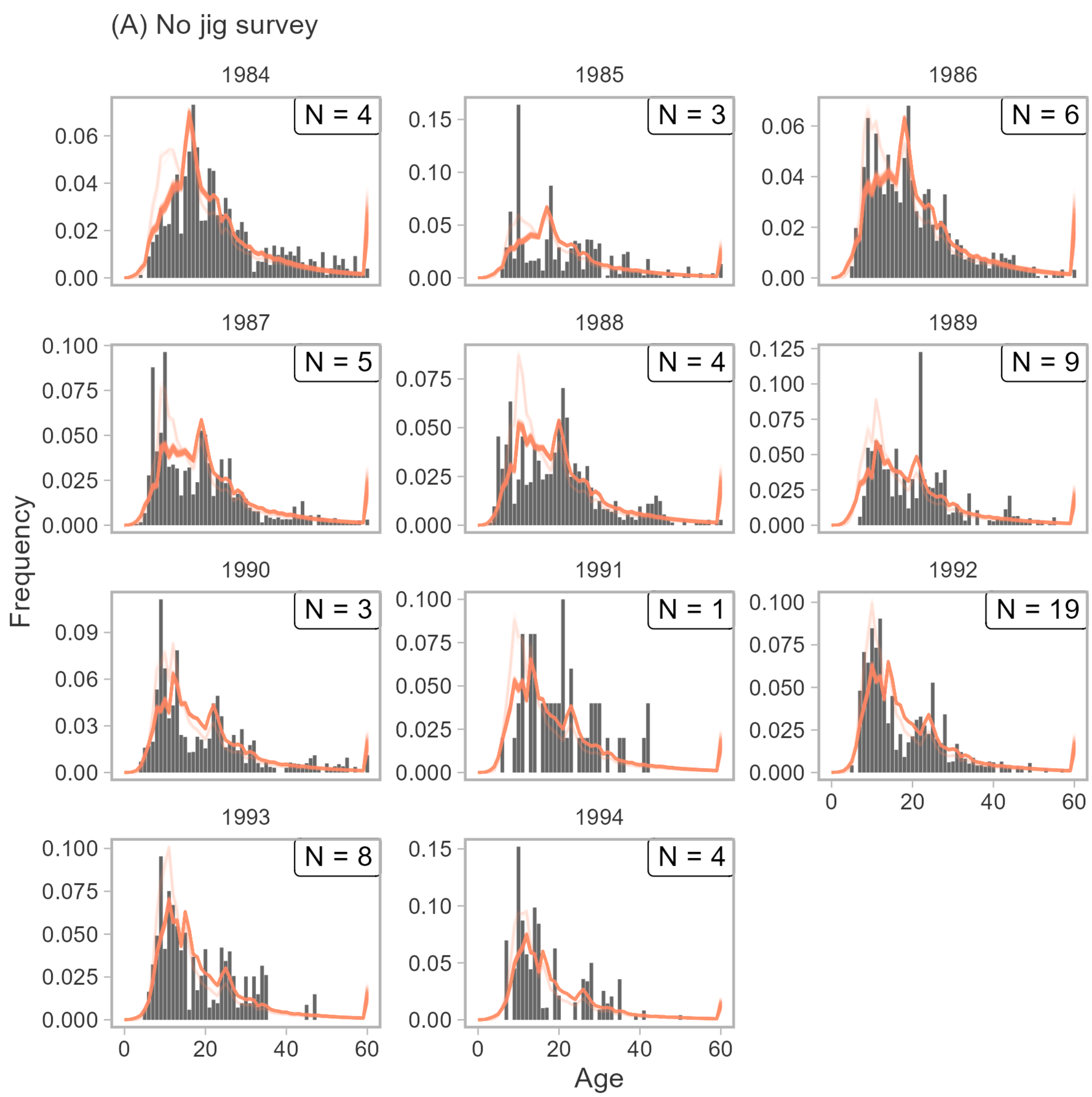

Figure 17. RCM model fits to the commercial fishery age composition data for OM Scenario (A), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of fishing events.

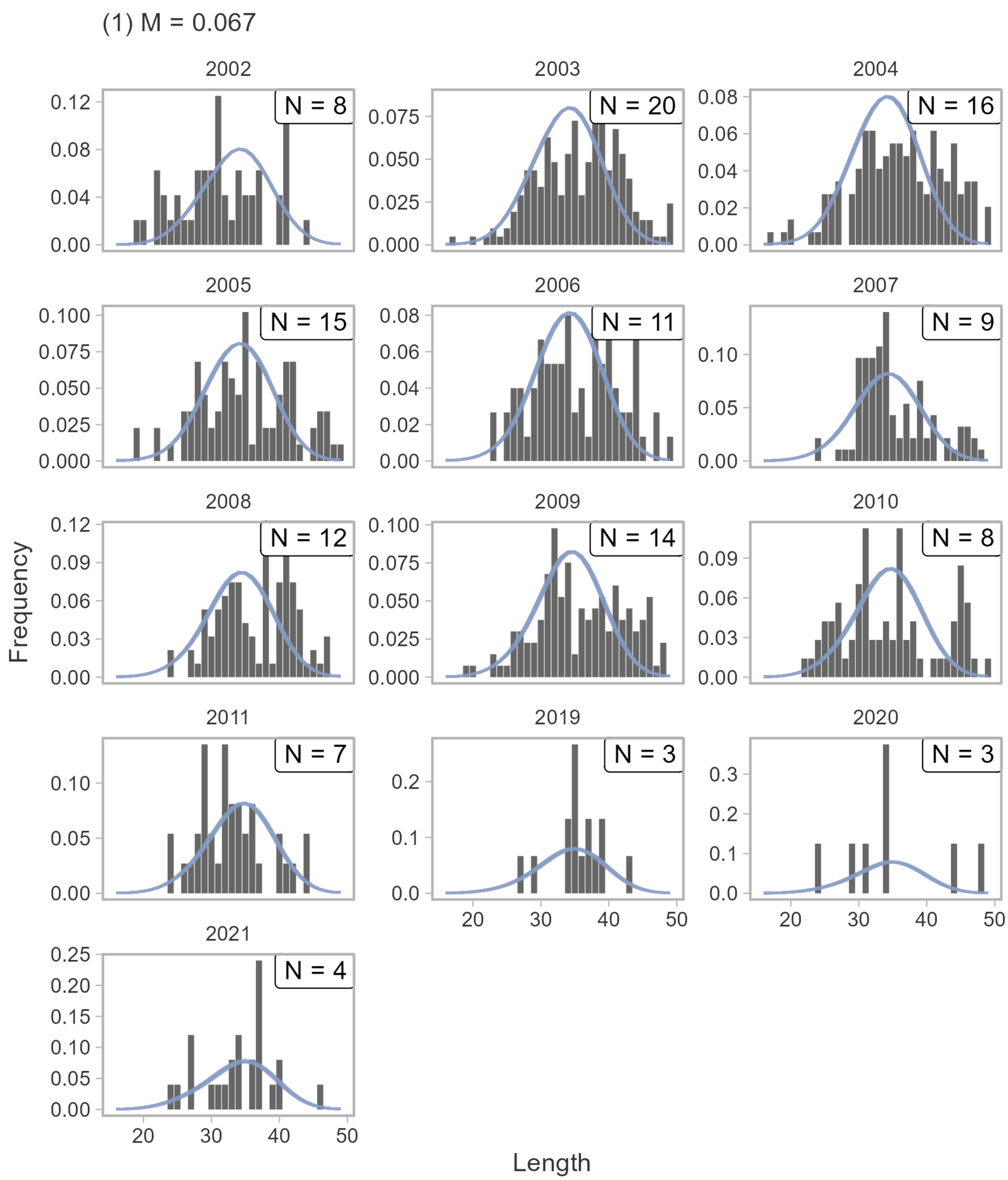

Figure 18. RCM model fits to the recreational fishery length composition data (centimeters) for OM Scenario (1), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of fishing events.

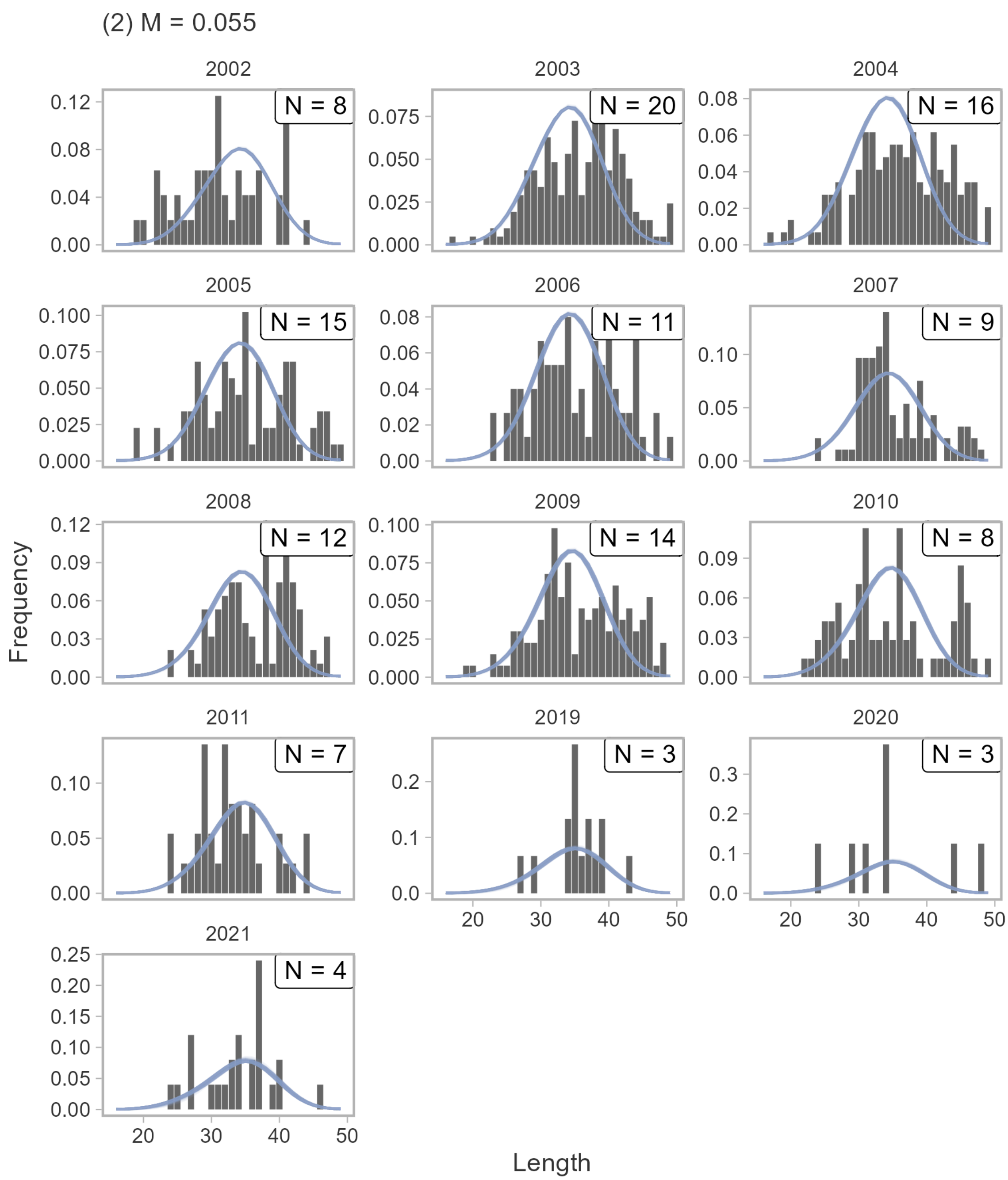

Figure 19. RCM model fits to the recreational fishery length composition data (centimeters) for OM Scenario (2), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of PFMAs from which the length samples were collected.

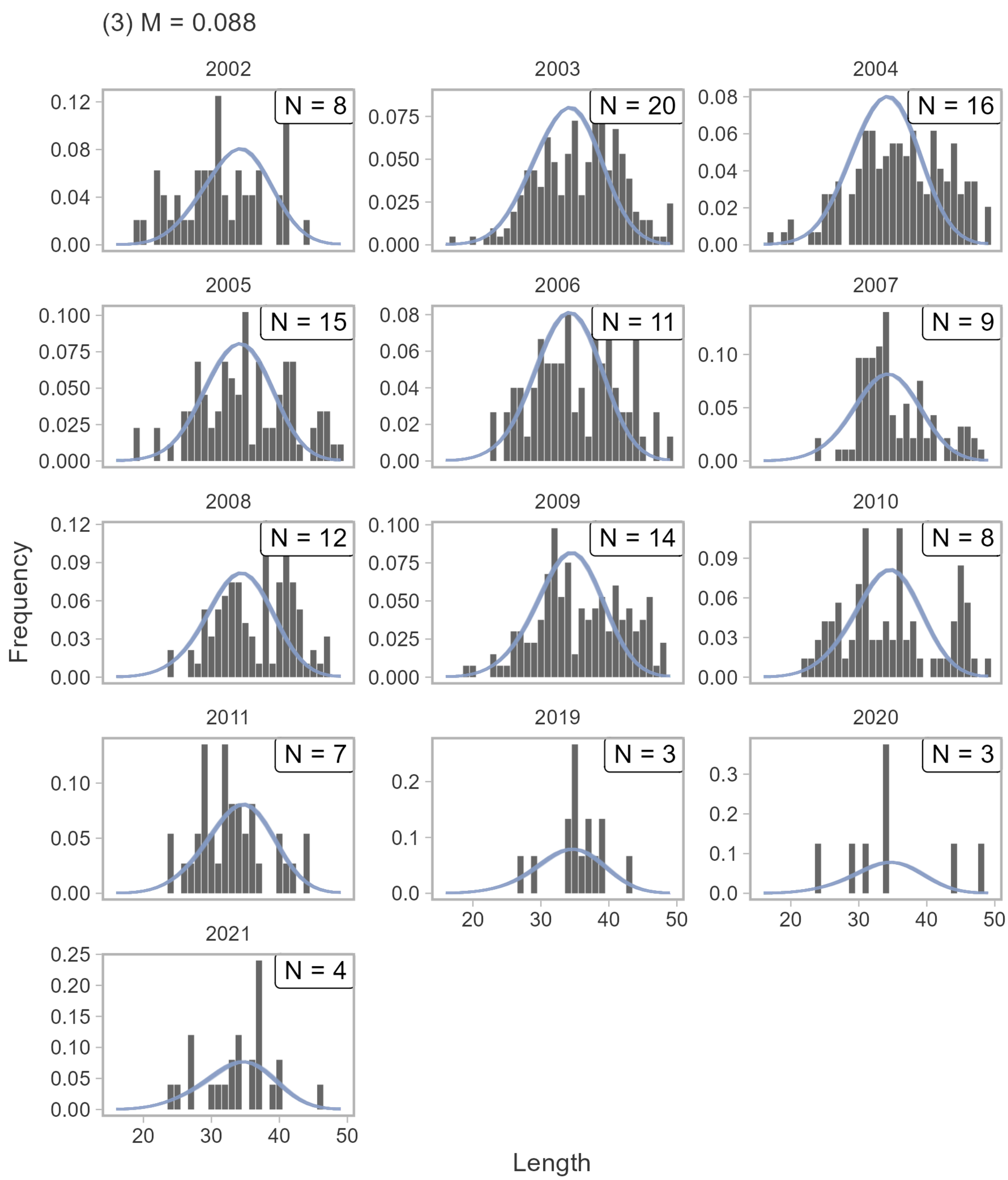

Figure 20. RCM model fits to the recreational fishery length composition data (centimeters) for OM Scenario (3), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of PFMAs from which the length samples were collected.

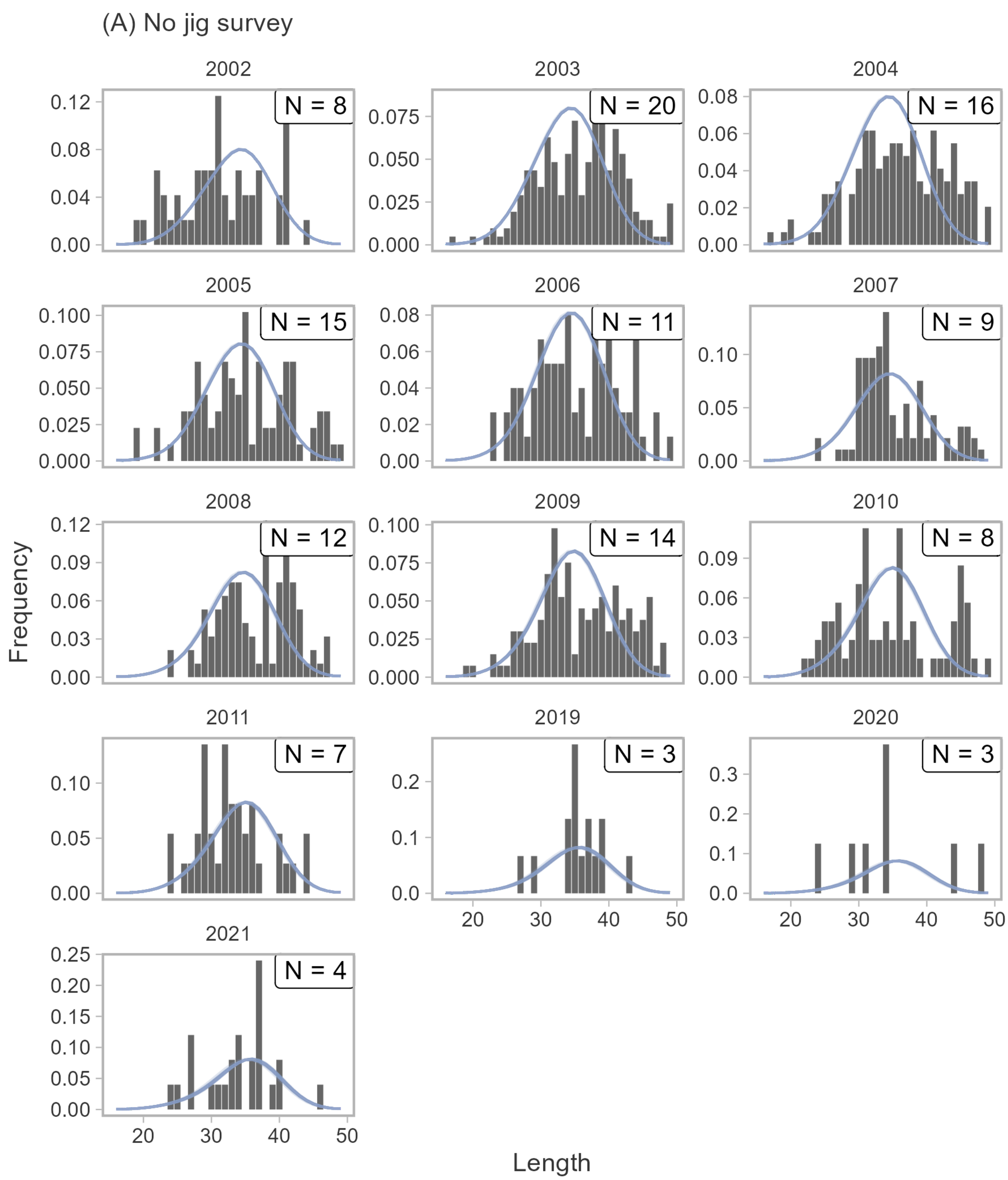

Figure 21. RCM model fits to the recreational fishery length composition data (centimeters) for OM Scenario (A), showing observed (bars) and estimated (lines) proportions. Sample sizes (N) are the number of PFMAs from which the length samples were collected.

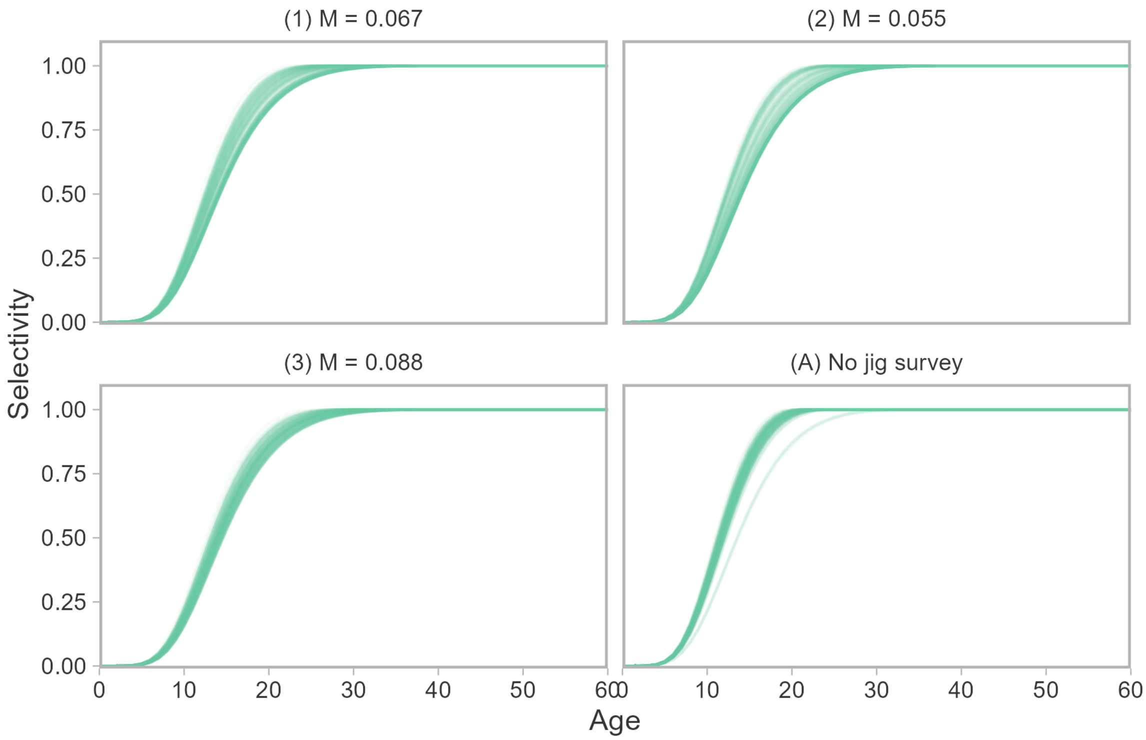

Figure 22. Selectivity at age for the HBLL survey estimated in the RCM for the four operating models.

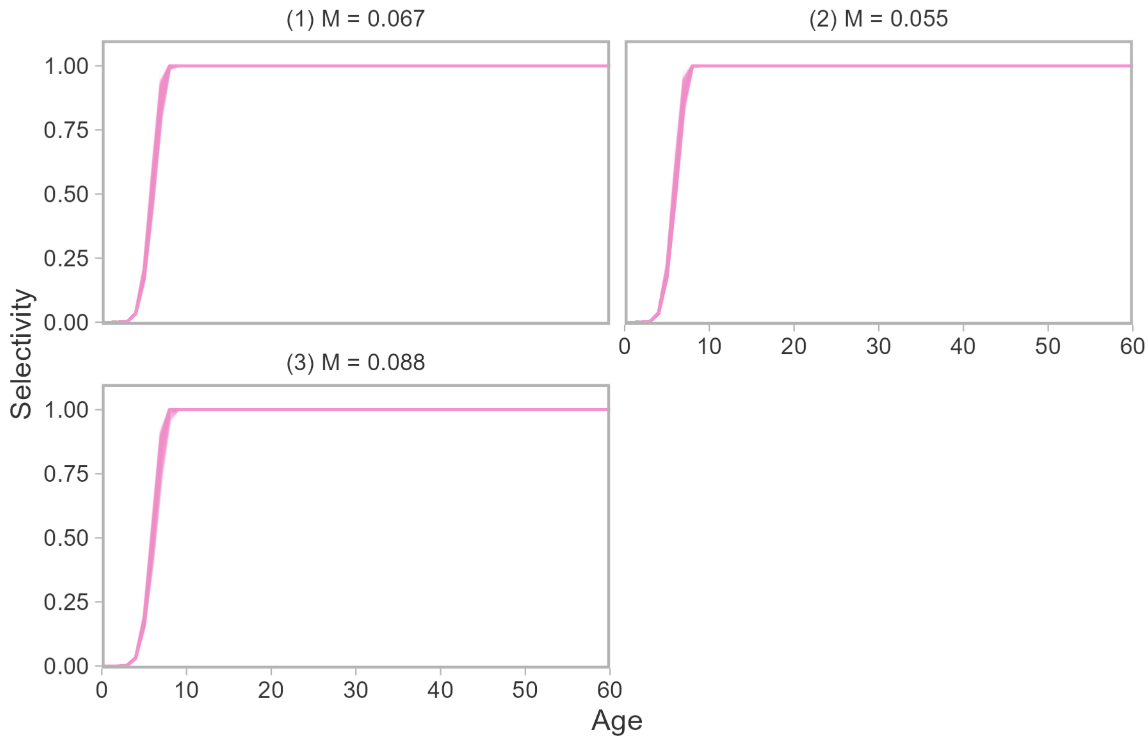

Figure 23. Selectivity at age for the Jig Area 12 survey estimated in the RCM for the four operating models. This survey was not used in OM (A).

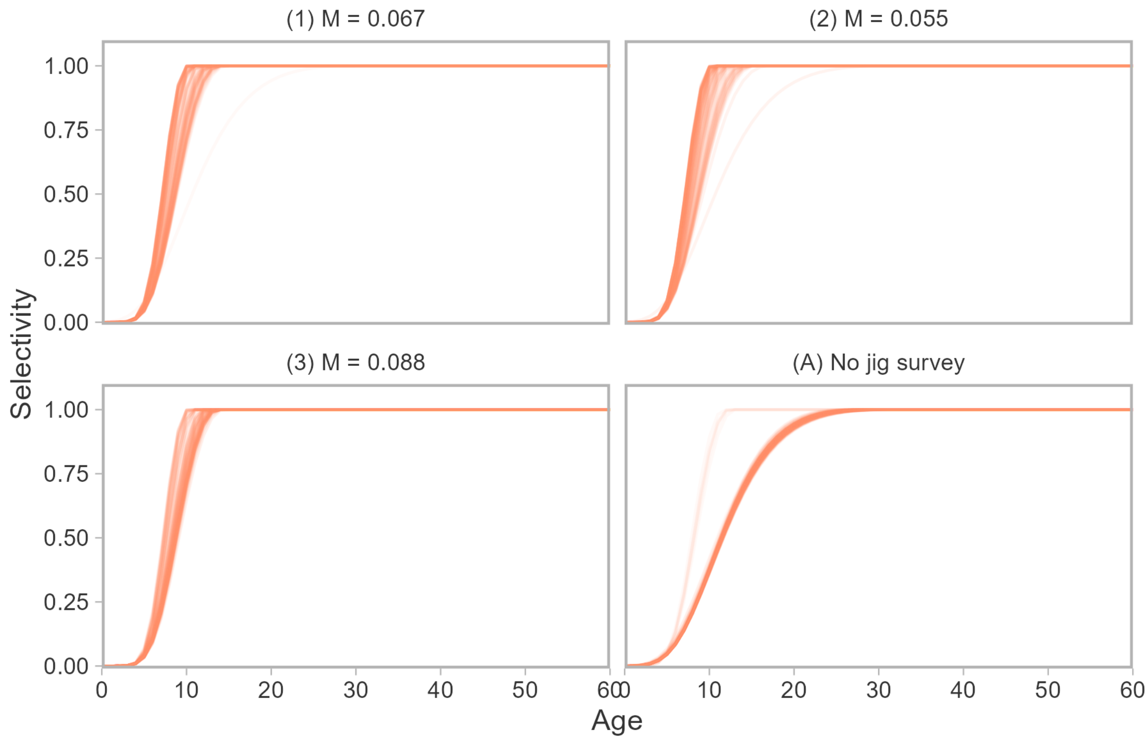

Figure 24. Selectivity at age for the commercial fishery estimated in the RCM for the four operating models.

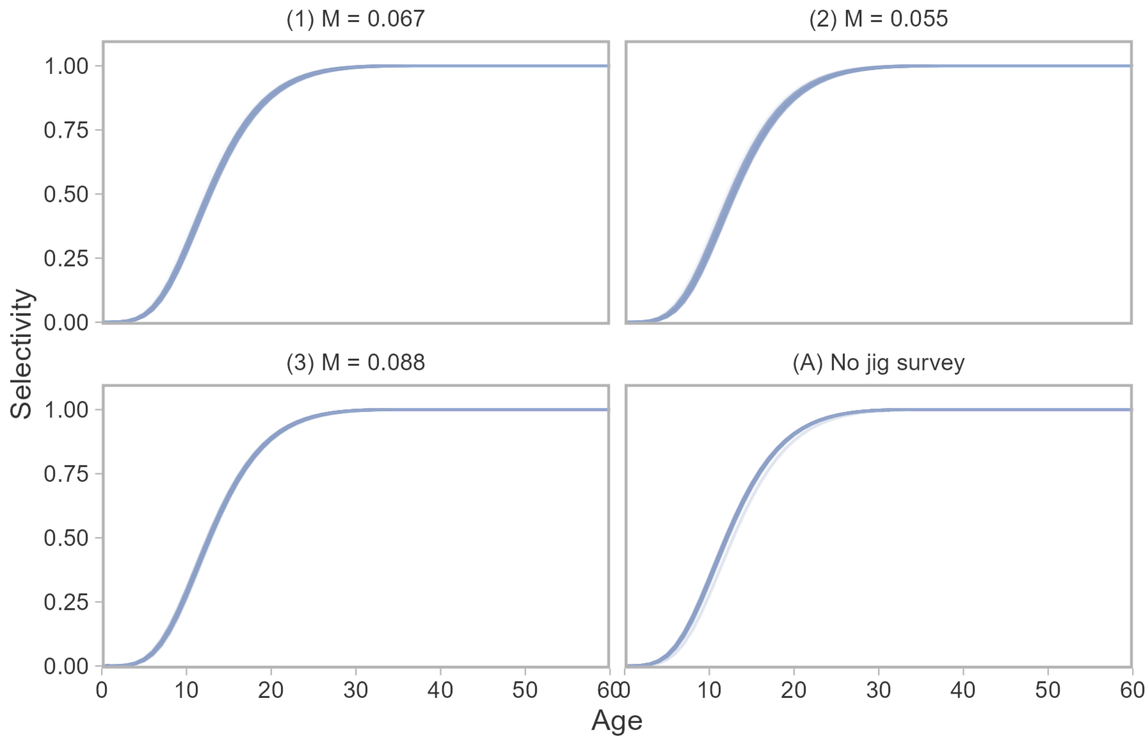

Figure 25. Selectivity at age for the recreational fishery estimated in the RCM for the four operating models. Length units were converted to age.

Table 2. Median estimates of the age of 50% selectivity (age of 95% selectivity in parentheses) in the RCM.

OM	HBLL	Jig Area 12	Commercial	Recreational
(1) M = 0.067	13.5 (22.9)	5.9 (7.6)	7.8 (10.5)	12.7 (23.3)
(2) M = 0.055	13.7 (23.7)	5.9 (7.6)	7.5 (10.0)	12.9 (23.7)
(3) M = 0.088	13.9 (23.8)	6.0 (7.6)	8.5 (11.5)	12.7 (23.0)
(A) No jig survey	11.6 (18.1)	NA (NA)	11.5 (20.7)	12.0 (22.4)

4.3.1.2. Historical estimates

In all operating models, the RCM estimated that the spawning biomass in 2021 was likely above the LRP (with greater than 50% probability, Figure 26 and Table 3). The probability was higher in the operating models with a higher natural mortality rate (OM 1 and 3) and when the Jig Area 12 index was excluded from the RCM (OM A). The operating model with mean M = 0.055 (the lowest mean in the reference set) produced the lowest probability of being above the LRP.

All models inferred similar trends in stock biomass over time, with biomass declines during the 1980s–2000 followed by more stable conditions since then (Figures 27 - 29). These declines were concurrent with high fishing mortality with the median F/F_{MSY} greater than 1 in operating models 1 and 2 (Figure 30). Since 2000, there have been steep declines in fishing mortality.

Comparison of OM (A) that excluded the Jig Area 12 survey shows that this survey is quite impactful on the historical stock trajectory for the reference operating models. The 2004 data point shows a substantial decline from the 1980s (Figure 6), concurrent with high catches during 1980–2000 and truncation in the age composition from the same survey (Figure 11). While no other data series spans the same time period as this survey, there is general agreement among managers and fishing representatives that this index is indicative of declining stock trends, which led to the development of the rockfish conservation strategy in the early 2000s to reduce catch and effort (Yamanaka and Logan 2010).

In 2021, the credible intervals of B/B_{MSY} and B/B_0 in all OM scenarios varied based on the value of natural mortality and steepness (Figures 31 and 32). Within each operating model, the status relative to the LRP and USR was primarily driven by the value of steepness (Figure 33). While population declines were estimated for Inside Quillback Rockfish (Appendix G), the stock was estimated to be above the LRP in all operating models.

With respect to unfished biomass, the stock was likely to be below 0.2 B_0 in OM 2 (Figure 32 and 34). The status of the stock relative to 0.2 and 0.4 B_0 is shown in Figure 34.

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., B_{MSY} is less than 0.5 B/B_0 (Figures 35 and 36).

Estimates of historical recruitment deviations were similar across OM scenarios (Figure 37). Estimated historical apical fishing mortality followed a similar trend with a large peak in the 1980s and 1990s, with larger values in scenarios with lower natural mortality and more depleted trajectories (Figure 38). These mortality rates appear to be within the range of values estimated from catch curves using the HBLL and Jig 12 age compositions (Appendix F).

The LRP is a low biomass state at which the age structure is expected to be severely truncated. The observed HBLL age composition was compared to the expected equilibrium age structure at the LRP. The observed age structure in the survey in 2019 and the estimated age structure in 2021 within the operating models contained more older fish (20+ years) than expected at the LRP (Figure 39). The mean age of the HBLL survey in 2019 was 23.3 years, larger than the equilibrium mean age at the LRP in our operating models (Table 4). While the LRP is defined with respect to biomass, the age structure analysis provides an additional insight on the conditions needed to identify the stock to be below the LRP. The age structure at the LRP would need to be severely truncated beyond what is currently observed in the HBLL survey.

Trends in the mean age can be used to evaluate truncation in the age structure over time. In equilibrium, mean age can be broadly indicative of mortality changes over time, i.e., a smaller mean age implies high mortality as fewer fish survive to old ages. However, other factors such as recruitment pulses or a switch in targeting can be conflated with high mortality when interpreting mean age trends. Nevertheless, the mean age in the HBLL survey was predicted to decrease during periods of high fishing mortality in the 1980s by the RCM (had the survey been running back then, Figure 40). This trend is most apparent in most operating models, excluding OM (3). The mean age has since stabilized and somewhat increased since then.

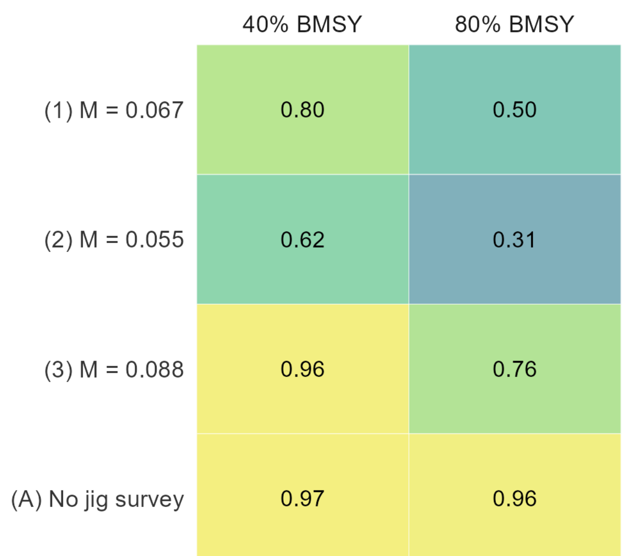

Figure 26. Probability that the 2021 spawning biomass is above the LRP and USR for the four operating models.

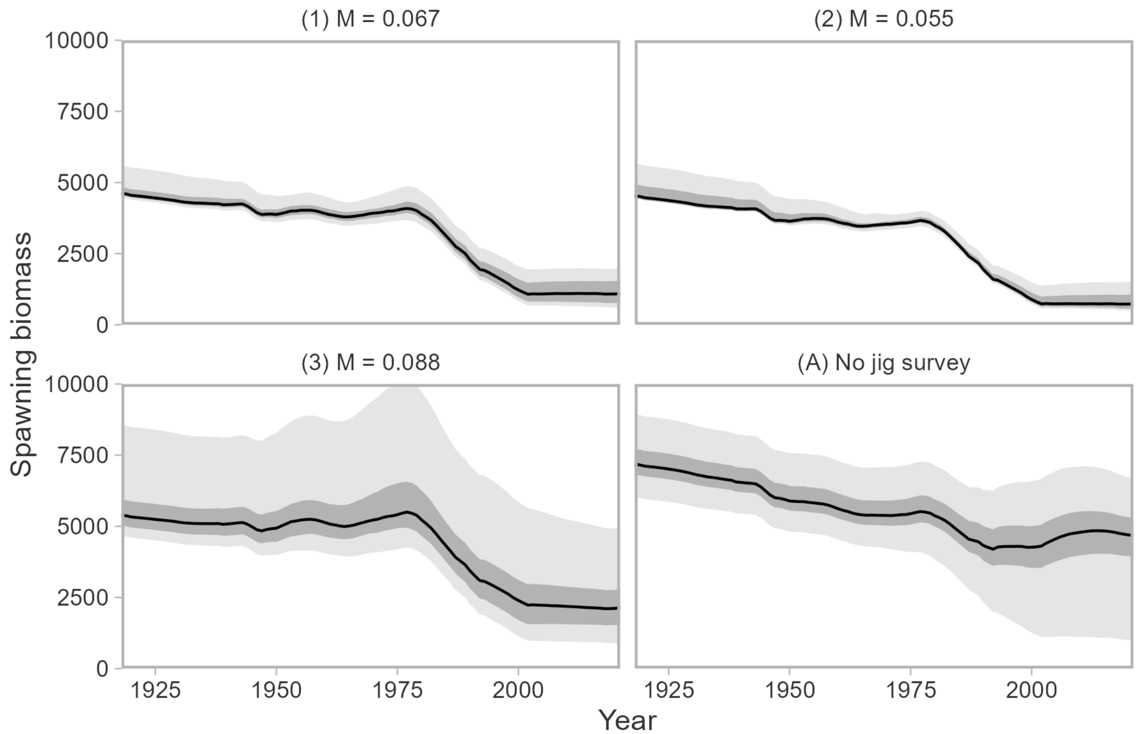

Figure 27. Historical spawning biomass estimates for reference and robustness set OMs. Solid lines represent medians, and dark and light grey shading represent 50% and 95% quantiles across replicates, respectively.

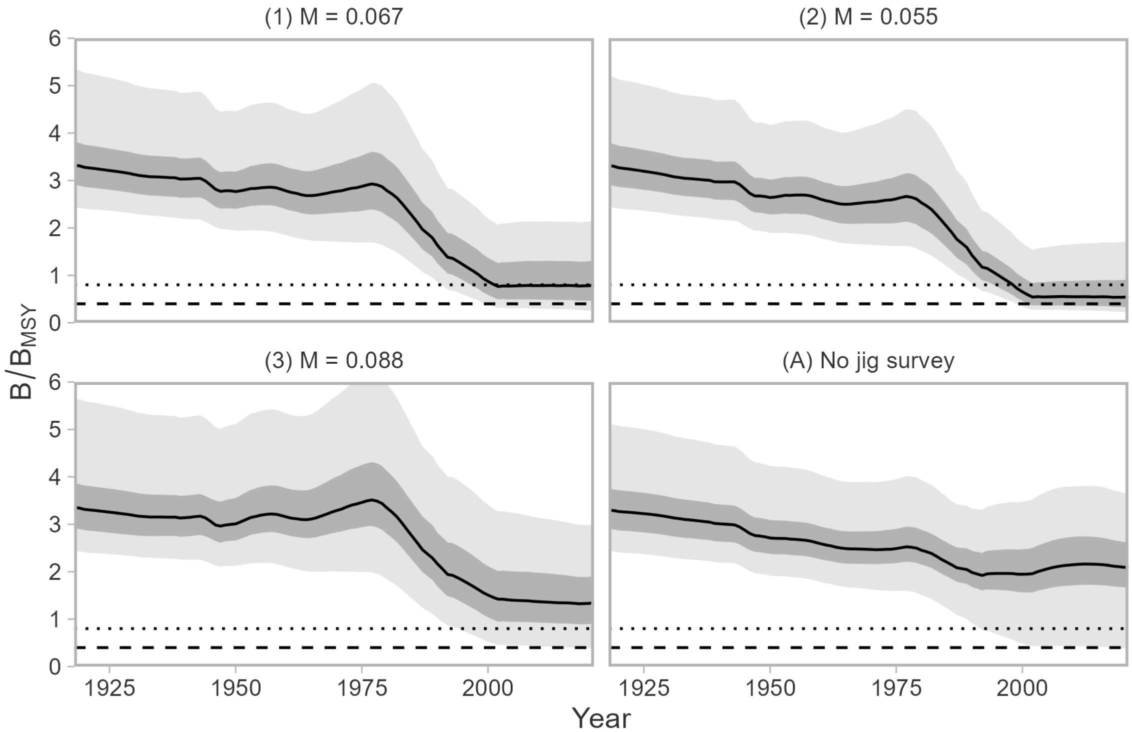

Figure 28. Spawning biomass relative to that at MSY (B/B_{MSY}*) trajectories for reference and robustness set OMs. Solid lines represent medians, and dark and light grey shading represent 50% and 95% quantiles across replicates, respectively. Dashed and dotted horizontal lines represent the LRP (0.4* B_{MSY}*) and USR (0.8* B_{MSY}*), respectively.*

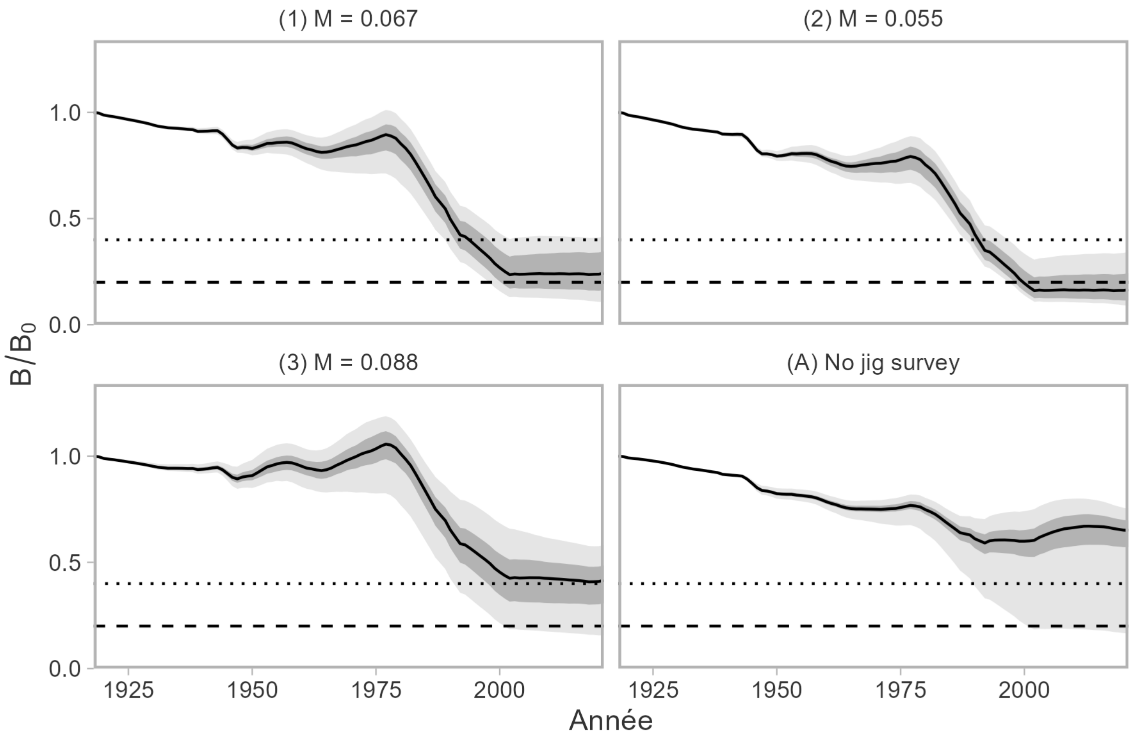

Figure 29. Spawning biomass relative to that at unfished conditions (B/B_0) *trajectories for reference and robustness set OMs. Solid lines represent medians, and dark and light grey shading represent 50% and 95% quantiles across replicates, respectively. Dashed and dotted horizontal lines represent 0.2* B_0 *and 0.4* B_0*, respectively.*

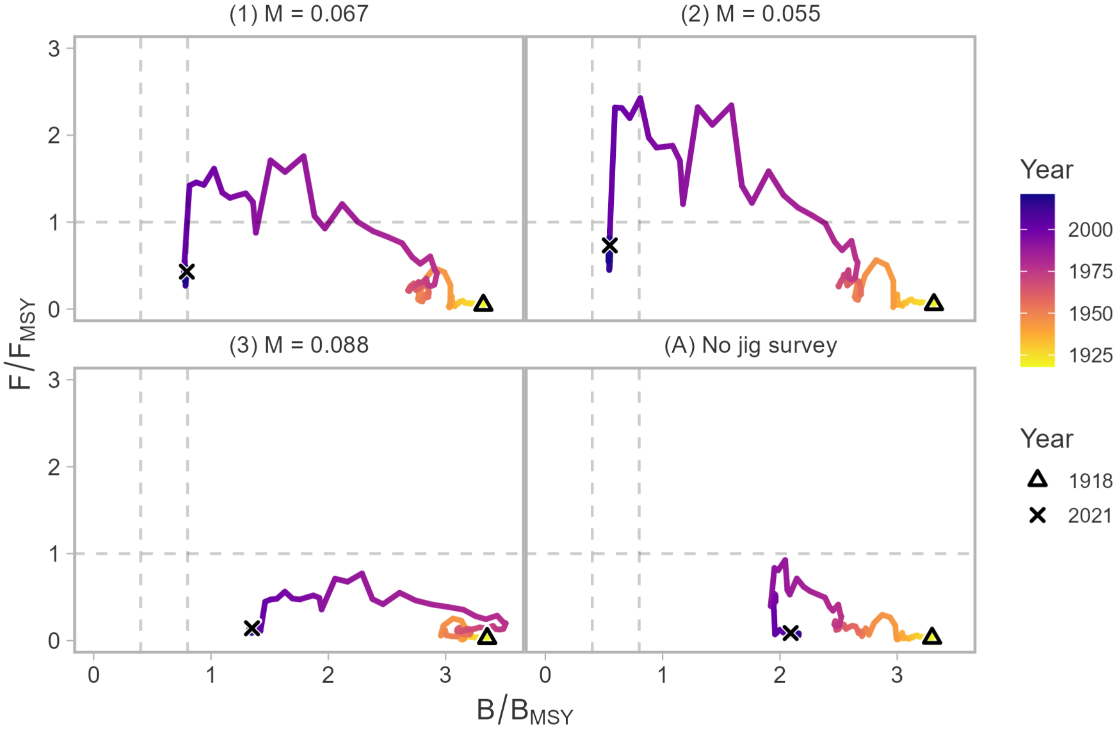

Figure 30. Kobe phase plot showing the median historical stock trajectory in terms of B/B_{MSY} *and* F/F_{MSY} *for the reference and robustness set OMs. Years are indicated by color and shapes indicate the start and end years of the historical period.*

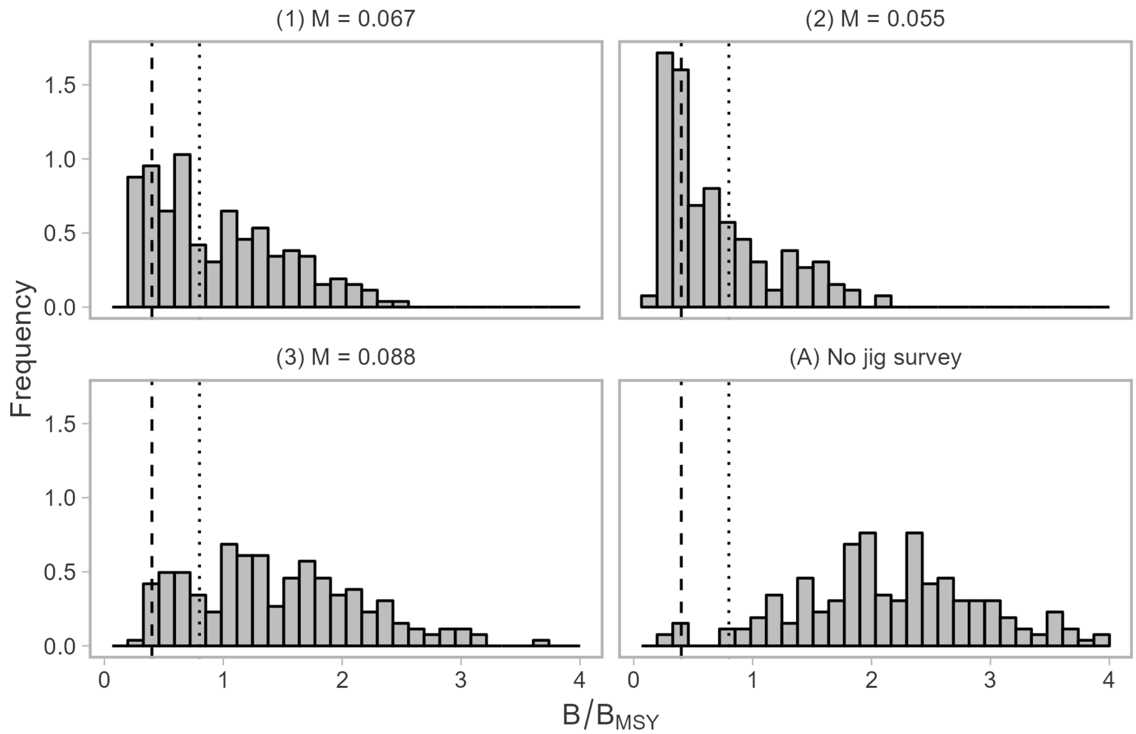

Figure 31. Histogram (200 simulations) of spawning biomass relative to that at MSY (B/B_{MSY}*) in 2021 within reference and robustness set OMs. Dashed and dotted vertical lines represent the LRP (0.4* B_{MSY}*) and USR (0.8* B_{MSY}*), respectively.*

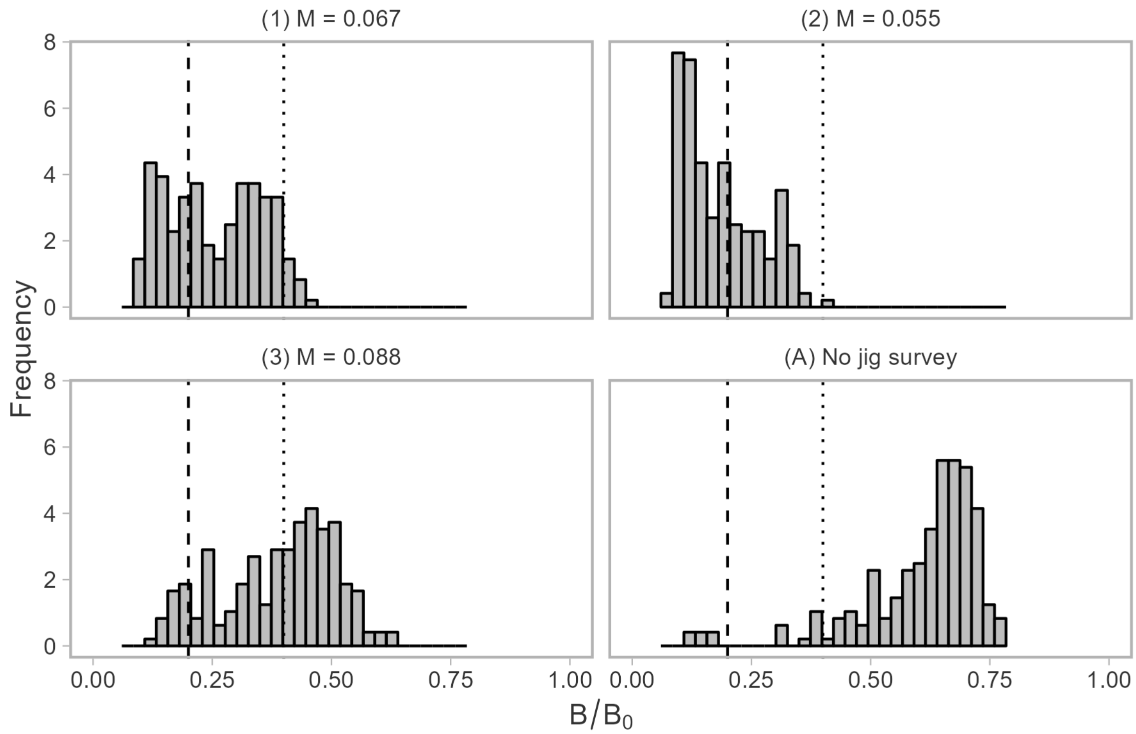

Figure 32. Histogram (200 simulations) of spawning biomass relative to unfished (B/B_0*) in 2021 within reference and robustness set OMs. Dashed and dotted vertical lines represent 0.2* B_0 *and 0.4* B_0*, respectively.*

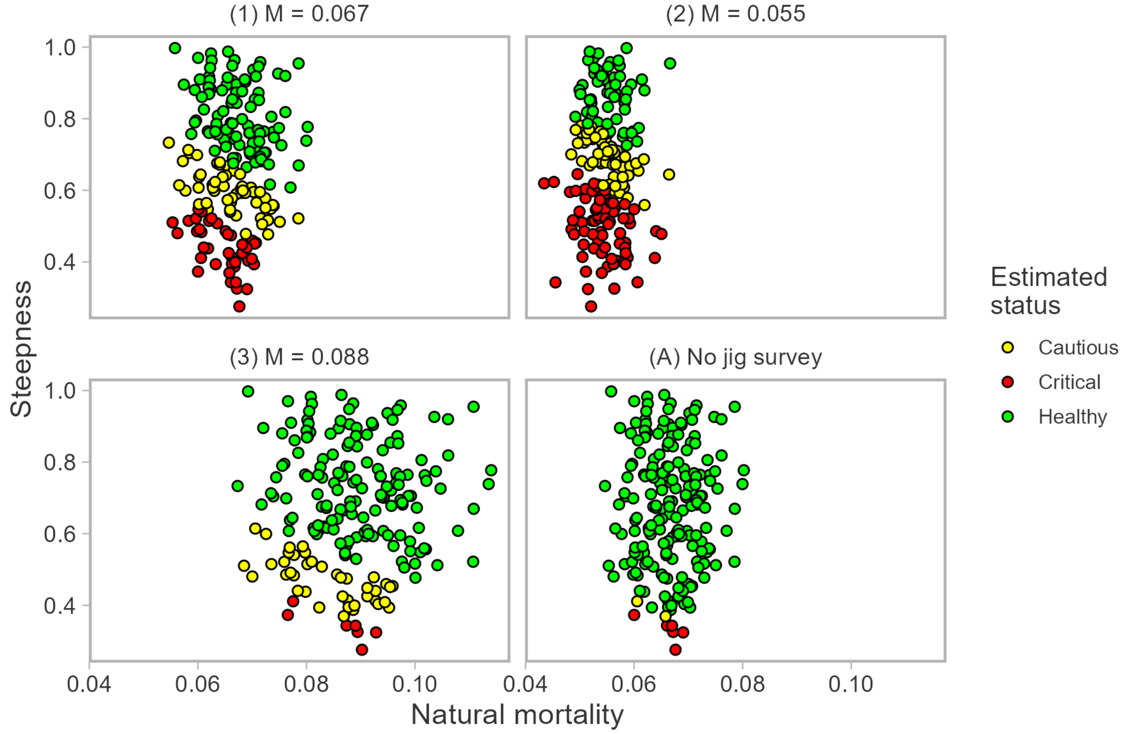

Figure 33. Scatterplot (200 simulations) of the natural mortality and steepness for the reference and robustness set OMs. Colors denote that the estimated status ("Healthy" for above the USR, "Cautious" for between the LRP and USR, and "Critical" for below the LRP) of the stock in 2021 relative to the LRP and USR corresponding to each sampled value of natural mortality and steepness.

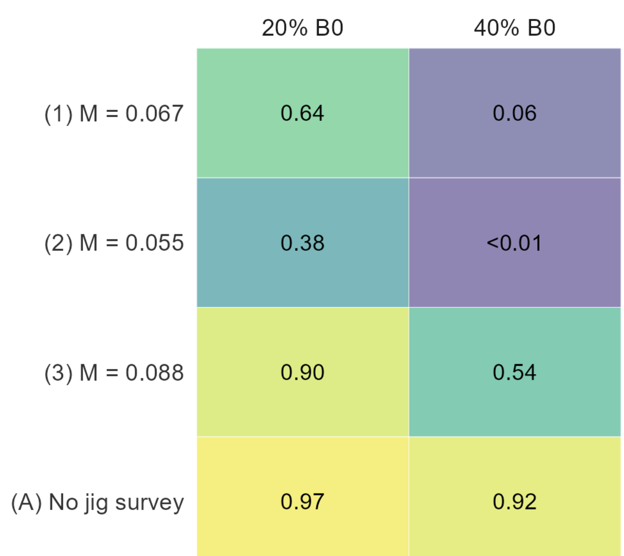

Figure 34. Probability that the 2021 spawning biomass is above 0.2 and 0.4 B_0 *for the four operating models.*

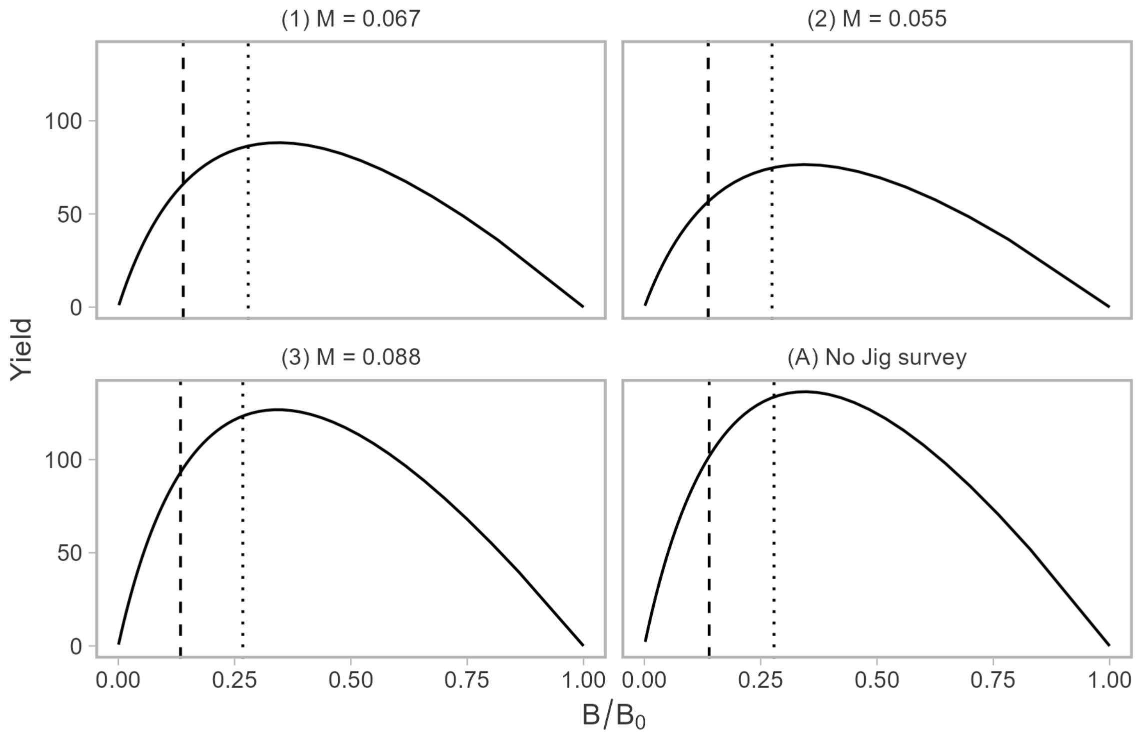

Figure 35. Yield curve as a function of depletion (B/B_0) using the mean value of natural mortality and steepness (h = 0.67). Dashed and dotted vertical lines represent the value of 0.4 B_{MSY} (LRP) and 0.8 B_{MSY} (USR), respectively. The location of the LRP and USR relative to B_0 is relatively consistent among all four operating models, with 0.4 B_{MSY} between 0.13 – 0.14 B_0 and 0.8 B_{MSY} between 0.26 – 0.28 B_0.

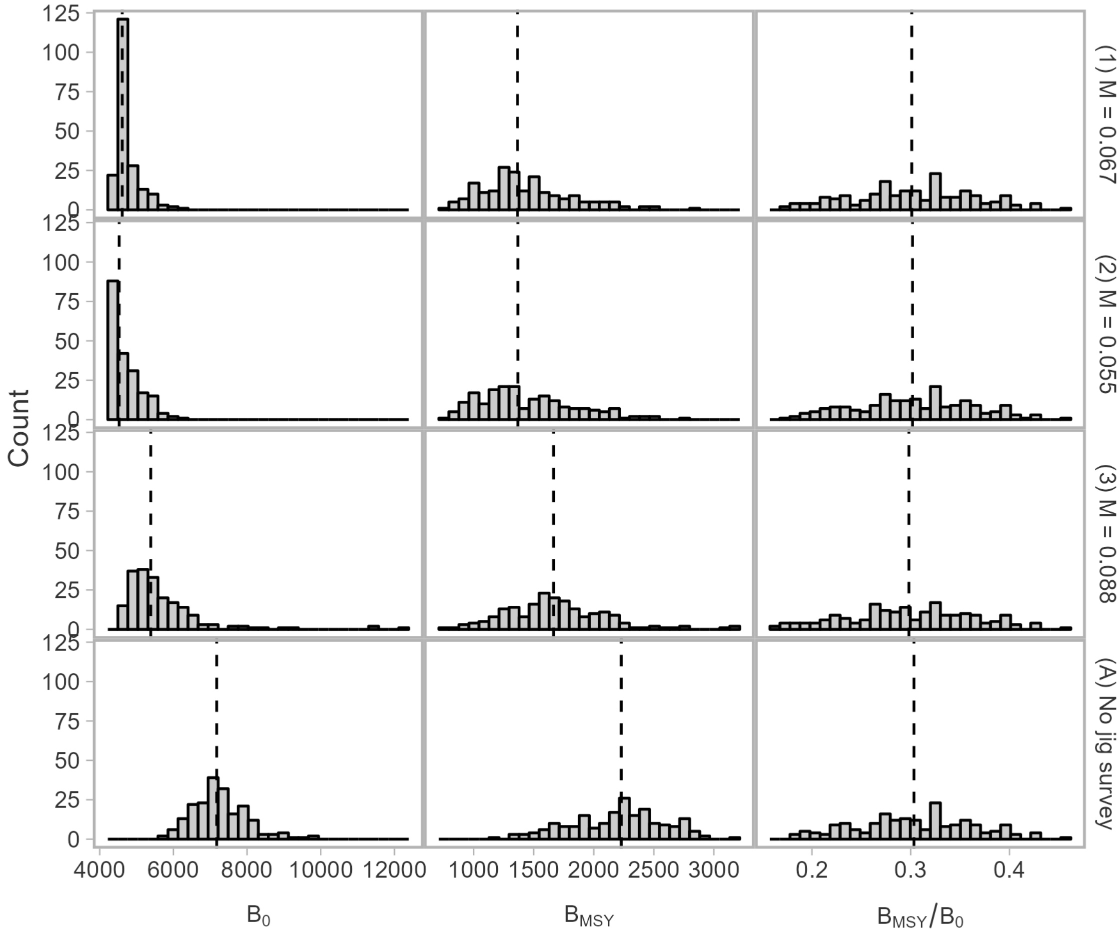

Figure 36. Histogram of B_{MSY}*,* B_0*, and the ratio of the two in the operating models across 200 simulation replicates. Within operating model, values vary based on natural mortality and steepness. The vertical dotted line indicate the median in each operating model.*

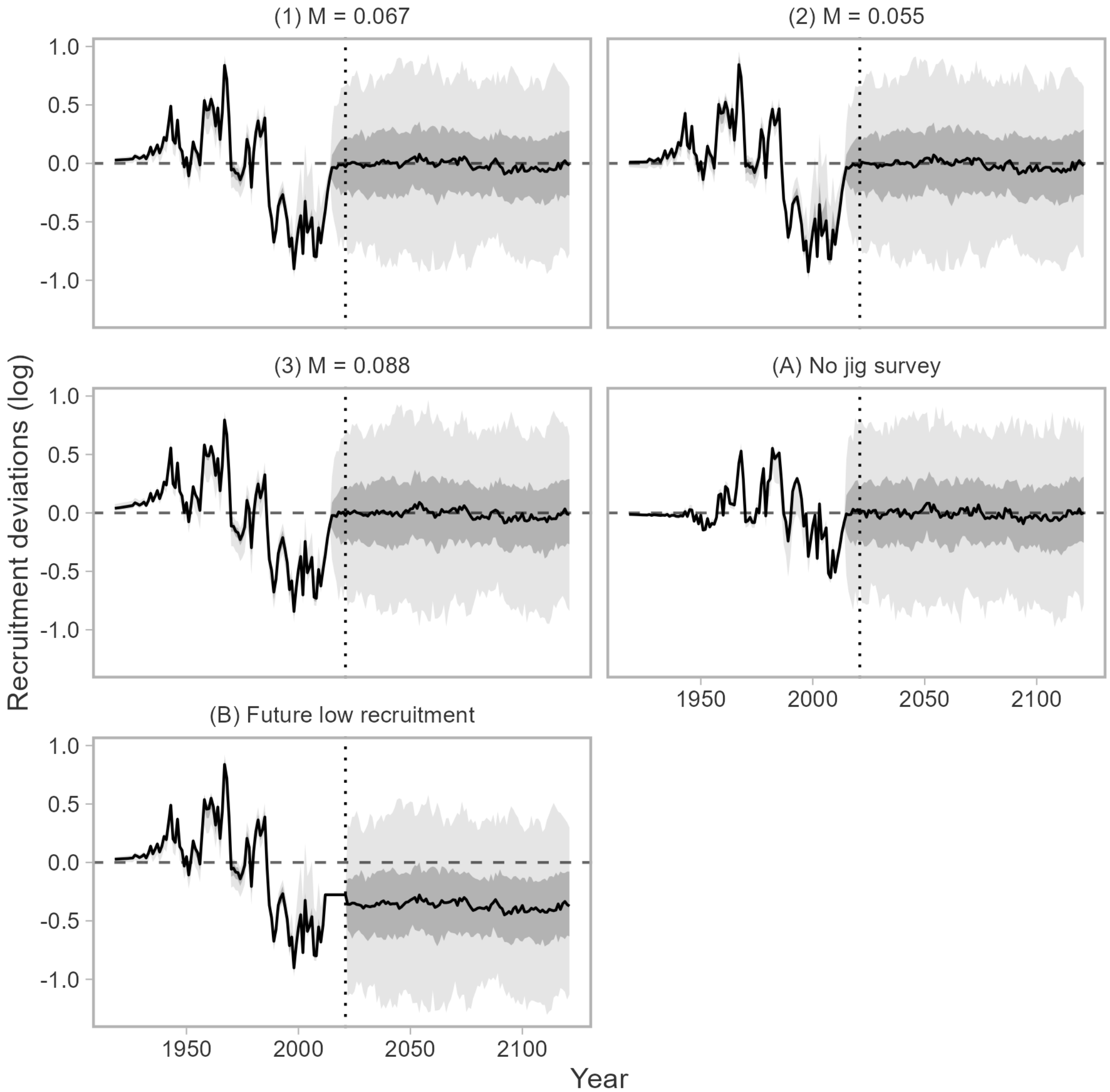

Figure 37. Log recruitment deviations (age 0) estimated by the RCM prior to 2021 (vertical dotted line) and sampled values for the projections. Solid lines represent medians, and dark and light grey shading represent 50% and 95% quantiles across replicates, respectively. Recruitment deviations were not estimated for the most recent 7 years of the historical period because these cohorts have not been observed due to the selectivity of the HBLL survey. For the operating model, the strength of these cohorts were sampled stochastically (standard deviation of 0.4) and shown here.

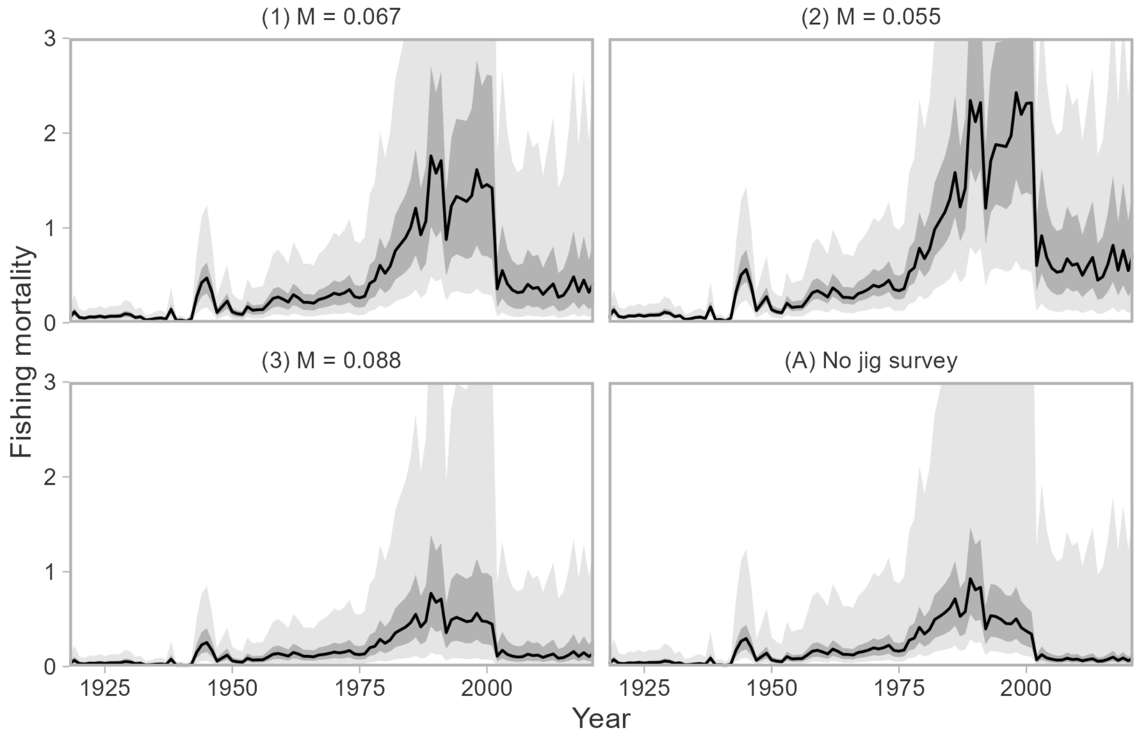

Figure 38. Apical fishing mortality (F_y) trajectories for reference and robustness set OMs. Apical fishing mortality is the maximum F_y experienced by fish of any age in a given year. Solid lines represent medians, and dark and light grey shading represent 50% and 95% quantiles across replicates, respectively.

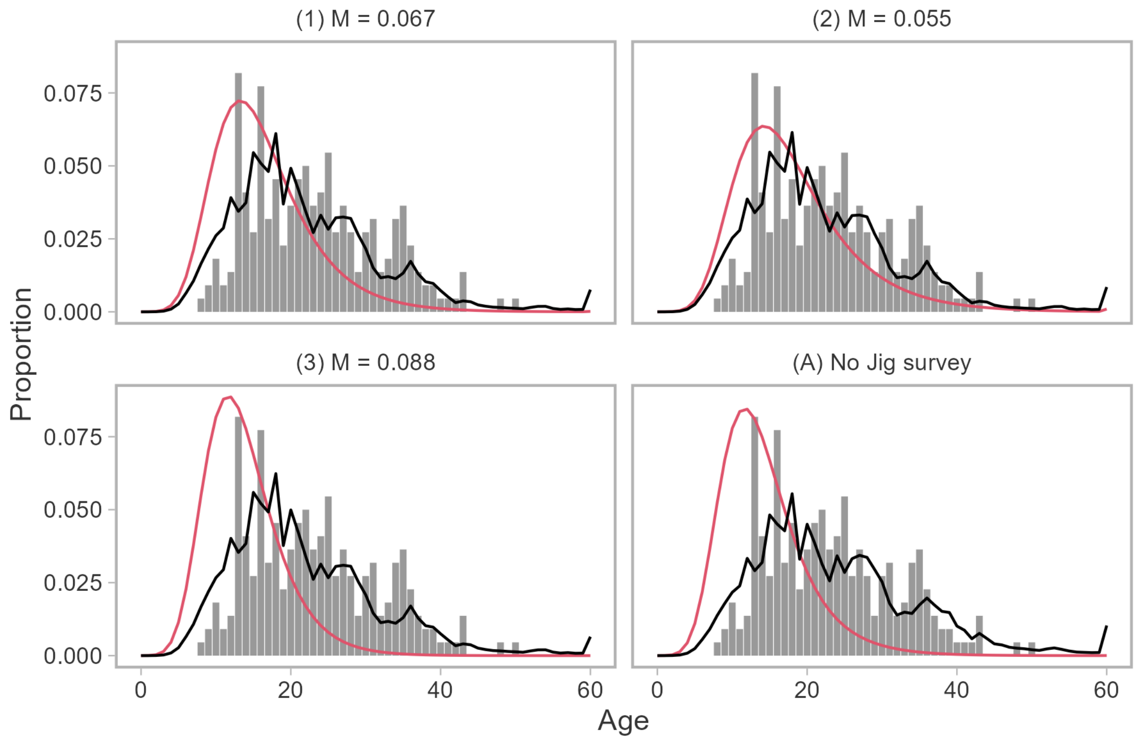

Figure 39. Age structure in the HBLL survey relative to the LRP. Bars represent observed proportions in 2019. The black line is the predicted age distribution in the survey in 2021 and the red line is the predicted equilibrium age distribution at the LRP.

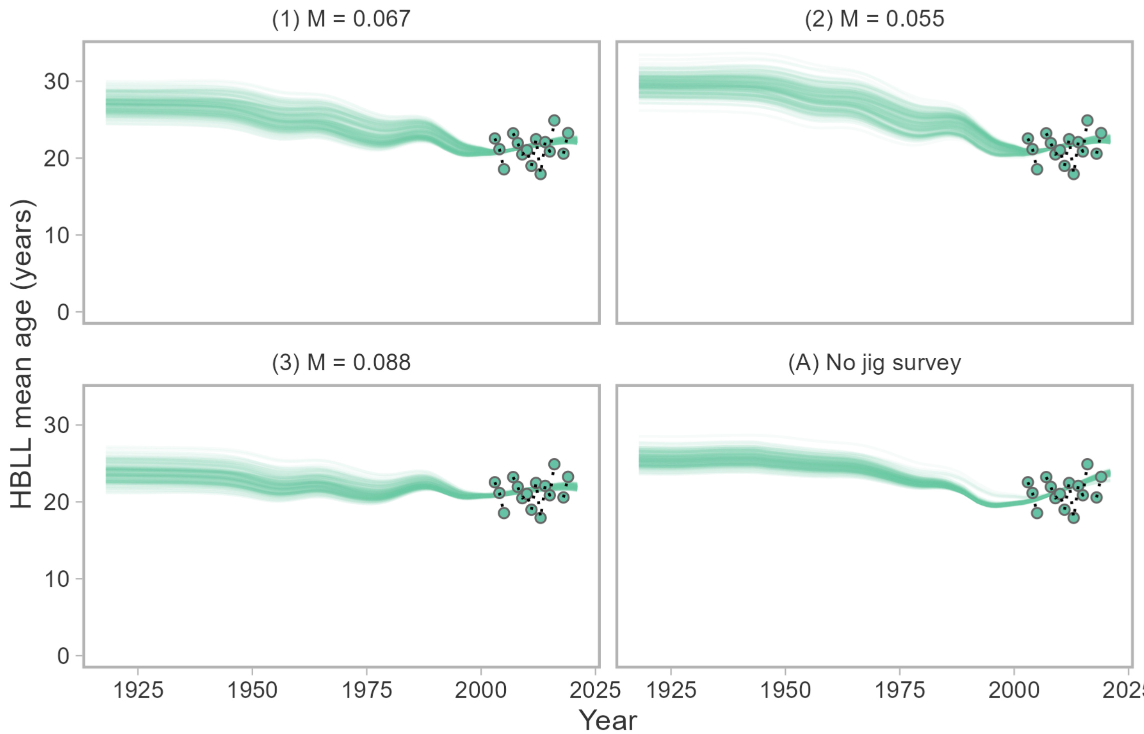

Figure 40. Mean age in the HBLL survey. Points indicate observed values calculated from biological samples, while lines indicate values predicted in the RCM in individual simulations. Note that the mean age was not used in the RCM to condition the operating model. Rather, the model was fitted to the age distribution, from which the mean age is derived. However, it can be easier to evaluate mean age trends instead of annual age composition over time.

Table 3. *Estimates of MSY and unfished reference points, natural mortality (M), steepness (h), spawning biomass (B) and fishing mortality (F) in 2021, and corresponding ratios. The LRP and USR are 0.4* B_{MSY} *and 0.8* B_{MSY}*, respectively. Parameter values report the median from 200 simulations, while status probabilities are calculated across 200 samples. The Reference OM column reports the median with equal weighting across the three reference operating models (designated by numbers).*

variable	(1) M = 0.067	(2) M = 0.055	(3) M = 0.088	(A) No jig survey	Reference
B_0	4611.000	4528.000	5386.000	7176.000	4797.000
R_0	711.200	505.500	1431.000	1094.000	713.600
h	0.675	0.675	0.675	0.675	0.675
M	0.066	0.055	0.088	0.066	0.066
B_{2021}	1100.000	740.500	2143.000	4683.000	1221.000
F_{2021}	0.037	0.055	0.019	0.009	0.033
B_{MSY}	1365.000	1368.000	1665.000	2229.000	1485.000
F_{MSY}	0.086	0.074	0.125	0.100	0.093
MSY	102.400	88.010	163.900	171.300	104.900
LRP	545.900	547.100	666.000	891.600	594.200
USR	1092.000	1094.000	1332.000	1783.000	1188.000
LRP/B_0	0.120	0.121	0.119	0.121	0.120
USR/B_0	0.241	0.242	0.238	0.243	0.240
$B_{2021}/B_{\mathrm{MSY}}$	0.795	0.549	1.350	2.091	0.882
$P(B_{2021} > LRP)$	0.795	0.620	0.965	0.970	0.795
$P(B_{2021} > USR)$	0.495	0.310	0.765	0.960	0.495
$P(B_{2021} > B_{\mathrm{MSY}})$	0.445	0.220	0.715	0.935	0.445
$F_{2021}/F_{\mathrm{MSY}}$	0.431	0.732	0.142	0.087	0.377
$P(F_{2021} < F_{\mathrm{MSY}})$	0.780	0.590	0.950	0.970	0.780

Table 4. Predicted mean age in 2021 and at the LRP (in equilibrium) for the HBLL survey in the operating models. The observed mean age in 2019 was 23.3 years.

Operating model	2021 Predicted	LRP
(1) M = 0.067	21.9	16.3
(2) M = 0.055	22.0	18.1
(3) M = 0.088	21.8	13.7
(A) No jig survey	23.7	14.2

4.3.2. Additional diagnostics

Two diagnostic procedures, model reweighting and likelihood profiling, were utilized to evaluate the RCM fits.

Additional models were fitted by adjusting either the standard error of the index series or the sample size for the age and length composition data. This follows general practice of iterative re-fitting of statistical catch-at-age models so that the statistical properties, e.g., variance, of the predicted age composition are consistent with the input nuisance parameters specified for the multinomial distribution (McAllister and Ianelli 1997; Francis 2011). These model reweighting procedures balance the likelihoods of the two datasets (indices and age composition) for estimation.

Following the notation of Punt (2017), indices for each survey were re-weighted by updating the standard deviation to the standard deviation σ^* of the residuals from the previous fit,

$$\sigma^* = \sqrt{\frac{\sum_y [\log(I_y/\hat{I}_y)]^2}{Y}} \tag{1}$$

where I_y and $\hat{I}_y$ are the observed and predicted index, respectively, and Y is the number of index data points for each survey.

Two composition re-weighting procedures were explored. The McAllister-Ianelli method updates the annual sample size N_y^* of each fishery or survey based on the harmonic mean of the ratio of the input sample size N_y and the effective size E_y calculated from the previous model fit:

$$N_y^* = N_y \left[\frac{1}{Y} \sum_y \left(\frac{E_y}{N_y} \right)^{-1} \right]^{-1} \tag{2}$$

$$E_y = \frac{\sum_a \hat{p}_{y,a}(1 - \hat{p}_{y,a})}{\sum_a (p_{y,a} - \hat{p}_{y,a})^2} \tag{3}$$

where $p_{y,a}$ is the proportion in year y and age a.

The Francis reweighting method updates the input sample size based on the residual variance of the mean age μ_y in the composition data,

$$N_y^* = N_y \left(\frac{\sum_y (z_y - \bar{z}_y)}{Y - 1} \right)^{-1} \tag{4}$$

$$z_y = \frac{\mu_y - \hat{\mu}_y}{\sqrt{\sum_a \hat{p}_{y,a}(a - \hat{\mu}_y)^2 / N_y}} \tag{5}$$

The residuals in operating model 1 substantially downweighted the Jig Area 12 index, with $\sigma^* = 0.069$ and 0.324 for the HBLL and Jig Area 12 index, respectively, and in effect replicated operating model A (Figure 41). It was also determined that the model was robust to the alternative input sample sizes. Both McAllister-Ianelli and Francis procedures produced slightly higher, but similar biomass estimates similar to the original model fit.

Likelihood profiling evaluated the change in the RCM fit to alternative values of natural mortality (Figure 42). The total likelihood in the model indicated a minimum near 0.04. However, various data series inform either lower or higher values of *M*. The Jig Area 12 survey (both the index and age data) pulls the model towards lower values of *M*, such as in OM (2), while the HBLL age data pulls the model towards higher values, such as in OM (3). The shallower curvature of the likelihoods for the fishery composition data indicated these data to be less informative on *M* compared to the survey data.

Overall, the set of reference operating models appear to span a substantial range of *M* values inferred among the various data components.

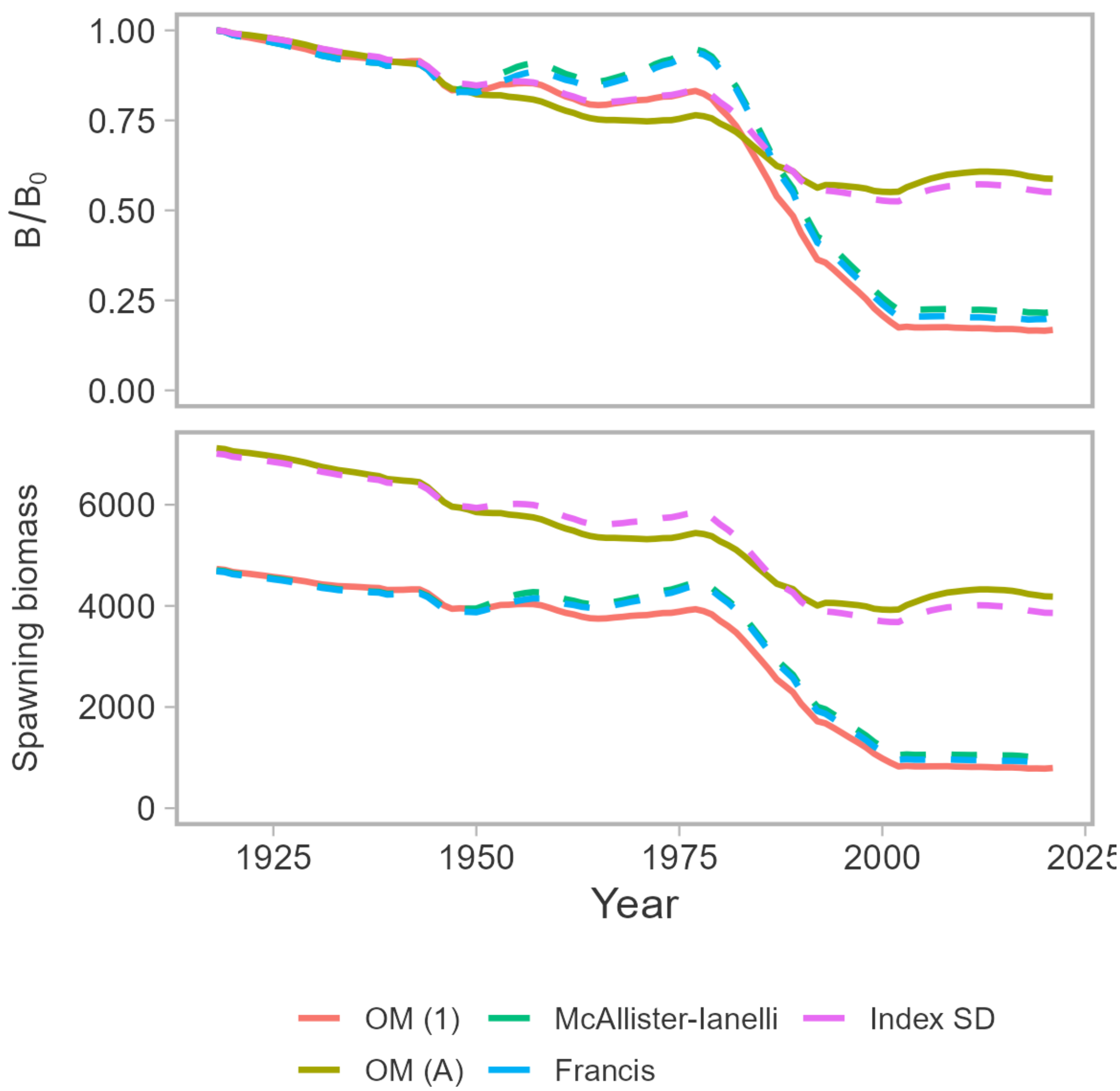

Figure 41. Estimates of spawning depletion and biomass from two operating models (solid lines) and models after reweighting (dotted lines) either the indices of abundance or the age composition (using either the McAllister-Ianelli or Francis methods).

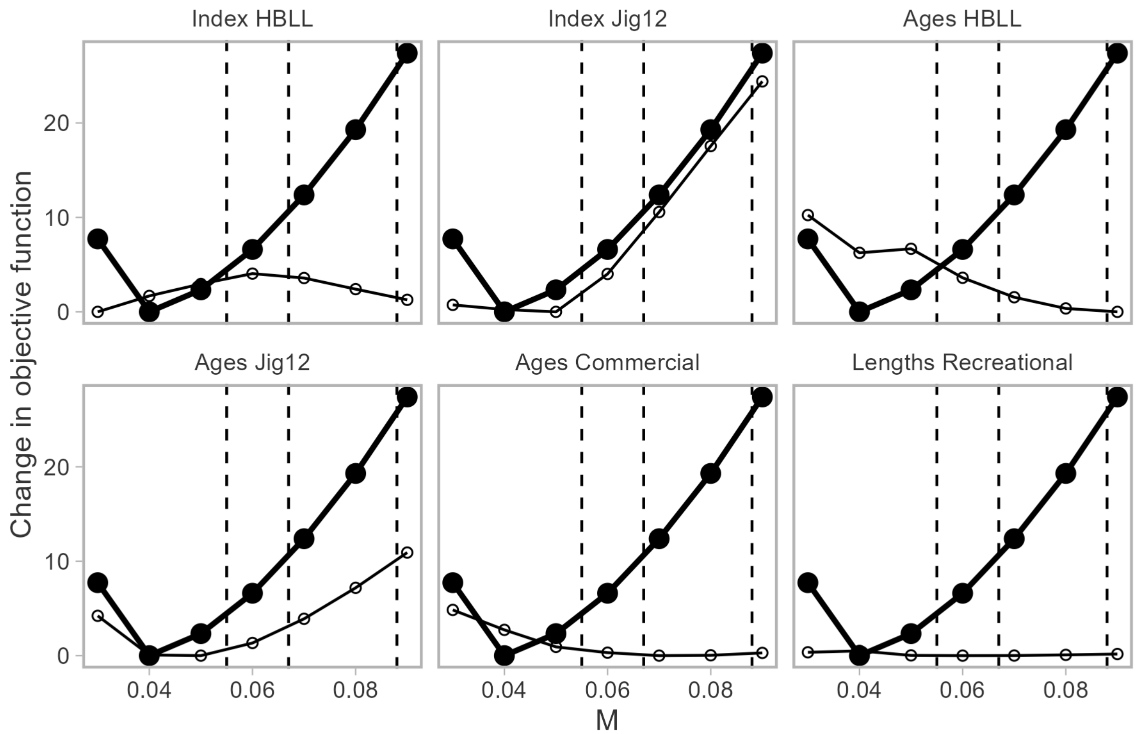

Figure 42. Likelihood profile where the change in the objective function (relative to the minimum) is plotted against alternative values of natural mortality (M). The dark, line is the total objective function in the model and is identical in all panels. Open circles and thin lines show the likelihood component for each data type in the corresponding panel. The vertical dotted lines represent the three values used in the reference set of operating models.

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. In comparison, the current commercial fishery TAC for Inside Quillback Rockfish is 24 tonnes (t).

Management procedures that were considered for the Inside Quillback Rockfish are detailed in Appendix E. 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.

We considered two constant-catch MPs of 33 t and 41 t. Thirty-three tonnes is the average catch during 2012–2019 and is intended to reflect status quo conditions. This 7-year time period starts from the previous assessment and excludes 2020 and 2021 due to the effects of the pandemic on fishery operations. Forty-one tonnes corresponds to 125% of the 2012–2019 average.

5.2. INDEX-BASED MANAGEMENT PROCEDURES

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

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. All index-based MPs set a minimum catch floor of 0.5 t, the approximate catch required for scientific surveys. 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 (NFref)
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 “no fishing” reference MP provides information on maximum possible stock levels and the rate of population growth in the absence of fishing. “FMSYref” can not 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. This management procedure is mainly used to compare MPs within a single operating model.

Table 5. Candidate management procedures.

Management procedure	MP type
CC_33	Constant catch
CC_41	Constant catch
IDX	Index ratio
IDX_smooth	Index ratio
Iratio_23	Index ratio
Iratio_55	Index ratio
GB_slope_5y_lam1	Index slope
GB_slope_5y_lam05	Index slope
GB_slope_10y_lam1	Index slope
GB_slope_10y_lam05	Index slope
NFref	Reference
FMSYref	Reference

6. APPLICATION OF MANAGEMENT PROCEDURES

We ran the closed-loop simulations across 200 stochastic replicates using MSEtool version 3-6-2 and the simulation random seed set to 1. During the projections, the catch was assumed to be known without error and the simulated fishery removals were equal to the catch advice specified in the management procedures. The error in the index of abundance were random deviates with the standard deviation and autocorrelation calculated from the residuals in the RCM (Figure D.9).

The length of the projection period was set at 72 years (3 generations for Inside Quillback Rockfish). The LRP 1GT performance metric stabilized such that the ranking of management procedures and satisficing threshold did not change after 150 simulations (Figure 43).

6.1. PERFORMANCE MEASURES

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). We set the following criterion to determine which MPs are satisficed: **LRP 1GT** > 0.75.

Almost all management procedures met the satisficing criterion, except for the 41 t constant catch MP in OM (2) (Figures 44 and 45). However, this MP did meet the satisficing criterion when the performance measure was averaged across the reference operating models (Figure 46).

With respect to the short-term LRP performance metric (**LRP ST**), the stock is likely (greater than 50% probability) to remain above the LRP with all management procedures and all operating model. The probability was less than 75 percent only in OM (2).

With respect to the LRP, USR, and FMSY performance measures, MP performance was better when the natural mortality rate was higher (Figure 44). For all management procedures, the stock was likely (greater than 50% probability) to remain above the USR after 1 generation.

Performance of MPs was higher in OM (A) than in OM (1) because the stock was in a better state at the beginning of the projection and larger in OM (A). On the other hand, performance was slightly worse in OM (B) than in OM (1) due to the lower productivity (lower recruitment) in the former operating model. However, these management procedures still met the satisficing criterion despite the lower recruitment modeled in projections for OM (B).

Looking at the performance measures averaged across reference OMs, the Iratio_55 MP generated the lowest short-term catch, and the highest catch after 1 generation (Figures 46 and 47). On the other hand, the 41 t constant catch MP (CC_41) provided the highest short-term catch. The four GB_slope MPs differed in tuning parameters, but slightly higher catches after 1 generation were generated with $\lambda = 1$ compared to $\lambda = 0.5$ (λ is the ratio of the change in the catch advice relative to that in the index). The performance of most index-based MPs (IDX, GB_slope, and Iratio MPs) with respect to **LRP 1GT** and **C ST** was in between that for the 31 t and 41 t constant catch MP. All index-based MPs generated higher catch after 1 generation compared to the 33 t constant catch MP.

Looking at the performance measures averaged across reference OMs, Iratio MPs generated lower catch than in GB_slope, IDX, and the constant catch MPs (Figures 46 and 47). Iratio_55 generated lower short-term catch than Iratio_23. The four GB_slope MPs differed in tuning parameters, but slightly lower catches were generated with $\lambda = 1$ compared $\lambda = 0.5$ (λ is the ratio of the change in the catch advice relative to that in the index). The IDX, GB_slope, and CC_33

MPs performed very similarly with respect to **LRP 1GT**, **C ST**, and **C 1GT**. There is a tradeoff between **LRP 1GT** and **C 1GT** across the candidate MPs (Figure 49).

We observed a trade-off between **LRP 1GT** and **C 1GT** across the candidate MPs (Figure 49). While CC_33 generated the lowest catch and high probability above the LRP, the Iratio MPs generated the highest catch and lowest LRP probabilities. All other MPs appeared to be clustered in between the two ends of the tradeoff frontier. Overall, all MPs had similar **C ST** (short-term catch) but the two Iratio MPs generated the highest catch after 1 generation (**C 1GT** performance measure, Figure 50).

Catch tradeoffs diminished when comparing over 3 generations (Figure 51). MPs that generate higher catch after 1 generation continue to do so after 3 generations. Most MPs generate slightly higher catch after 3 generations since they lie left of the one-to-one line.

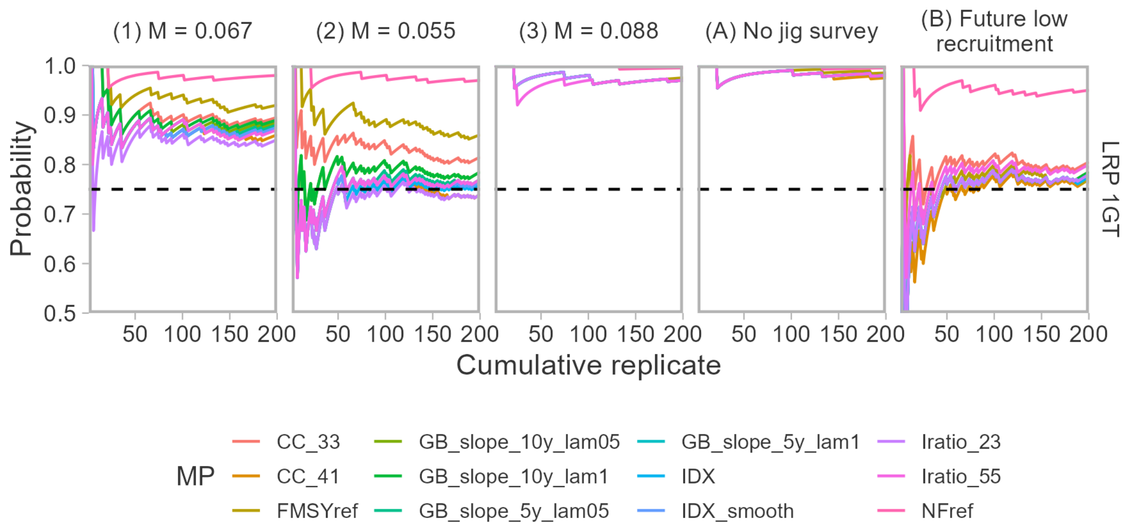

Figure 43. Evaluating the order and satisficing of management procedures with respect to the LRP 1GT performance metric against the number of simulation replicates. Colours represent individual MPs. The horizontal dotted line denotes the 75 percent satisficing threshold. Lines that do not cross by the final replicates indicate that rank order among replicates has converged, i.e., identification of satisficed MPs do not change with additional replicates.

(1) M = 0.067

	LRP 1GT	LRP ST	USR 1GT	FMSY	C ST	C 1GT
NFref *	0.98	0.93	0.87	1.00	0.00	0.00
FMSYref *	0.92	0.86	0.47	0.59	100.00	91.00
CC_33	0.90	0.84	0.75	0.84	33.00	33.00
GB_slope_10y_lam1	0.89	0.83	0.75	0.81	35.00	43.00
GB_slope_10y_lam05	0.88	0.83	0.75	0.81	36.00	39.00
GB_slope_5y_lam1	0.88	0.82	0.75	0.80	37.00	46.00
GB_slope_5y_lam05	0.88	0.82	0.75	0.80	37.00	41.00
IDX_smooth	0.88	0.82	0.74	0.80	37.00	42.00
IDX	0.88	0.82	0.74	0.79	38.00	47.00
Iratio_55	0.87	0.84	0.70	0.77	29.00	91.00
CC_41	0.86	0.82	0.74	0.79	41.00	41.00
Iratio_23	0.85	0.82	0.72	0.76	38.00	65.00

(2) M = 0.055

	LRP 1GT	LRP ST	USR 1GT	FMSY	C ST	C 1GT
NFref *	0.97	0.82	0.79	1.00	0.00	0.00
FMSYref *	0.86	0.72	0.35	0.52	66.00	67.00
CC_33	0.82	0.70	0.61	0.71	33.00	33.00
GB_slope_10y_lam1	0.78	0.70	0.57	0.68	35.00	42.00
GB_slope_10y_lam05	0.78	0.69	0.57	0.68	36.00	39.00
GB_slope_5y_lam1	0.76	0.69	0.55	0.64	36.00	45.00
GB_slope_5y_lam05	0.77	0.69	0.56	0.66	36.00	40.00
IDX_smooth	0.76	0.69	0.56	0.64	37.00	41.00
IDX	0.76	0.69	0.55	0.62	37.00	46.00
Iratio_55	0.77	0.72	0.46	0.59	29.00	83.00
CC_41	0.74	0.67	0.56	0.62	41.00	40.00
Iratio_23	0.74	0.69	0.50	0.56	37.00	60.00

(3) M = 0.088

	LRP 1GT	LRP ST	USR 1GT	FMSY	C ST	C 1GT
NFref *	1.00	1.00	0.97	1.00	0.00	0.00
FMSYref *	0.98	0.98	0.60	0.75	250.00	170.00
CC_33	0.97	0.98	0.92	0.96	33.00	33.00
GB_slope_10y_lam1	0.97	0.98	0.90	0.96	35.00	43.00
GB_slope_10y_lam05	0.97	0.97	0.90	0.96	36.00	39.00
GB_slope_5y_lam1	0.97	0.97	0.90	0.95	37.00	46.00
GB_slope_5y_lam05	0.97	0.97	0.90	0.95	37.00	41.00
IDX_smooth	0.97	0.97	0.90	0.95	37.00	42.00
IDX	0.97	0.97	0.90	0.95	38.00	48.00
Iratio_55	0.97	0.98	0.87	0.96	29.00	90.00
CC_41	0.97	0.96	0.90	0.95	41.00	41.00
Iratio_23	0.97	0.97	0.88	0.94	38.00	65.00

Figure 44. Performance measures of all MPs in individual reference set operating models. MPs are ordered by decreasing performance metric values from top to bottom starting with the left-most performance metric (LRP 1GT) and using columns from left to right to break any ties. The colour shading reflects the range in probabilities and catch values for individual performance metrics across the reference and robustness sets to illuminate contrast in MP performance. Italicized MPs with asterisks indicate reference MPs. Only the average catch during the short-term and after one generation (24 years) are presented here. The FMSY performance metric for the FMSYref MP is subject to rounding error (F/FMSY numerically equivalent to 1), see Figure 52 for the F/FMSY trajectory.

	(A) No jig survey						(B) Future low recruitment					
	LRP 1GT	LRP ST	USR 1GT	FMSY	C ST	C 1GT	LRP 1GT	LRP ST	USR 1GT	FMSY	C ST	C 1GT
*NFref **	1.00	0.98	0.97	1.00	0.00	0.00	0.95	0.88	0.78	1.00	0.00	0.00
*FMSYref **	0.98	0.98	0.86	0.62	350.00	180.00	0.77	0.79	0.10	0.52	100.00	63.00
CC_33	0.98	0.97	0.96	0.97	33.00	33.00	0.80	0.79	0.64	0.79	33.00	33.00
GB_slope_10y_lam1	0.98	0.97	0.96	0.97	35.00	38.00	0.78	0.79	0.62	0.78	35.00	37.00
GB_slope_10y_lam05	0.98	0.97	0.96	0.97	35.00	37.00	0.78	0.79	0.63	0.78	35.00	36.00
GB_slope_5y_lam1	0.98	0.97	0.96	0.97	36.00	40.00	0.78	0.79	0.62	0.77	36.00	39.00
GB_slope_5y_lam05	0.98	0.97	0.96	0.97	36.00	38.00	0.78	0.79	0.62	0.77	36.00	37.00
IDX_smooth	0.98	0.97	0.96	0.97	37.00	39.00	0.78	0.79	0.62	0.77	37.00	38.00
IDX	0.98	0.97	0.96	0.97	37.00	42.00	0.78	0.79	0.62	0.76	37.00	40.00
Iratio_55	0.98	0.97	0.97	0.97	28.00	51.00	0.80	0.80	0.60	0.81	28.00	50.00
CC_41	0.98	0.97	0.96	0.97	41.00	41.00	0.76	0.78	0.60	0.74	41.00	40.00
Iratio_23	0.98	0.97	0.96	0.97	37.00	49.00	0.78	0.79	0.61	0.76	37.00	44.00

Figure 45. Performance measures of all MPs in individual robustness set operating models. MPs are listed in the same order as in Figure 44. The colour shading reflects the range in probabilities and catch values for individual performance metrics across the reference and robustness sets to illuminate contrast in MP performance. Italicized MPs with asterisks indicate reference MPs. Only the average catch during the short-term and after one generation (24 years) are presented here. The FMSY performance metric for the FMSYref MP is subject to rounding error (F/FMSY numerically equivalent to 1), see Figure 52 for the F/FMSY trajectory.

	LRP 1GT	LRP ST	USR 1GT	FMSY	C ST	C 1GT
*NFref **	0.98	0.92	0.88	1.00	0.00	0.00
*FMSYref **	0.92	0.85	0.47	0.62	138.67	109.33
CC_33	0.90	0.84	0.76	0.84	33.00	33.00
GB_slope_10y_lam1	0.88	0.84	0.74	0.82	35.00	42.67
GB_slope_10y_lam05	0.88	0.83	0.74	0.82	36.00	39.00
GB_slope_5y_lam05	0.87	0.83	0.74	0.80	36.67	40.67
Iratio_55	0.87	0.85	0.68	0.77	29.00	88.00
IDX_smooth	0.87	0.83	0.73	0.80	37.00	41.67
GB_slope_5y_lam1	0.87	0.83	0.73	0.80	36.67	45.67
IDX	0.87	0.83	0.73	0.79	37.67	47.00
CC_41	0.86	0.82	0.73	0.79	41.00	40.67
Iratio_23	0.85	0.83	0.70	0.75	37.67	63.33

Figure 46. Average performance of all MPs 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 1GT) and using columns from left to right to break any ties. The colour shading reflects the range in probabilities and catch values within each performance metric to illuminate contrast in MP performance. Italicized MPs with asterisks indicate reference MPs. Only the average catch during the short-term and after one generation (24 years) are presented here. The FMSY performance metric for the FMSYref MP is subject to rounding error (F/FMSY numerically equivalent to 1), see Figure 52 for the F/FMSY trajectory across operating models.

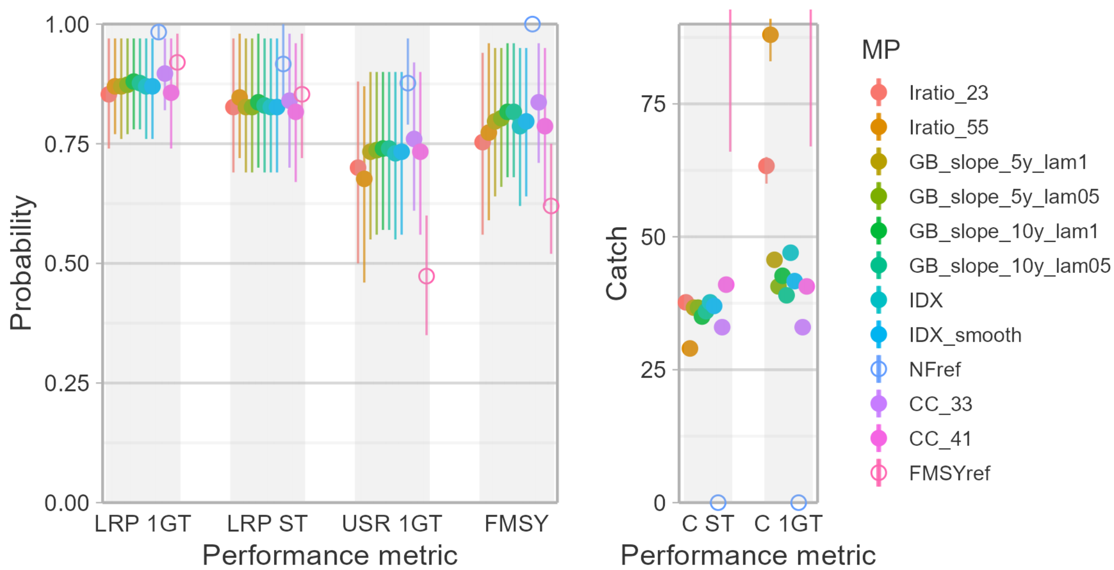

Figure 47. Dot-and-line plot of performance metrics averaged across the reference operating models. Dots represent average performance metric values and thin lines represent the range of values across operating models. Reference MPs are indicated by open circles, while candidate MPs are indicated by closed circles. The average catch (tonnes) for FMSYref is outside the range of the plot and is not shown.

	LRP 1GT	C 1GT	C 3GT
NFref *	0.98	0.00	0.00
FMSYref *	0.92	109.33	116.67
CC_33	0.90	33.00	31.67
GB_slope_10y_lam1	0.88	42.67	50.67
GB_slope_10y_lam05	0.88	39.00	41.33
GB_slope_5y_lam05	0.87	40.67	42.33
Iratio_55	0.87	88.00	85.33
IDX	0.87	47.00	55.33
GB_slope_5y_lam1	0.87	45.67	52.33
IDX_smooth	0.87	41.67	45.00
CC_41	0.86	40.67	37.00
Iratio_23	0.85	63.33	75.33

Figure 48. Catch performance measures (average catch after 1 and 3 generations) for all MPs 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 1GT) and using columns from left to right to break any ties. The colour shading reflects the range in probabilities and catch values within each performance metric to illuminate contrast in MP performance.. Italicized MPs with asterisks indicate reference MPs.

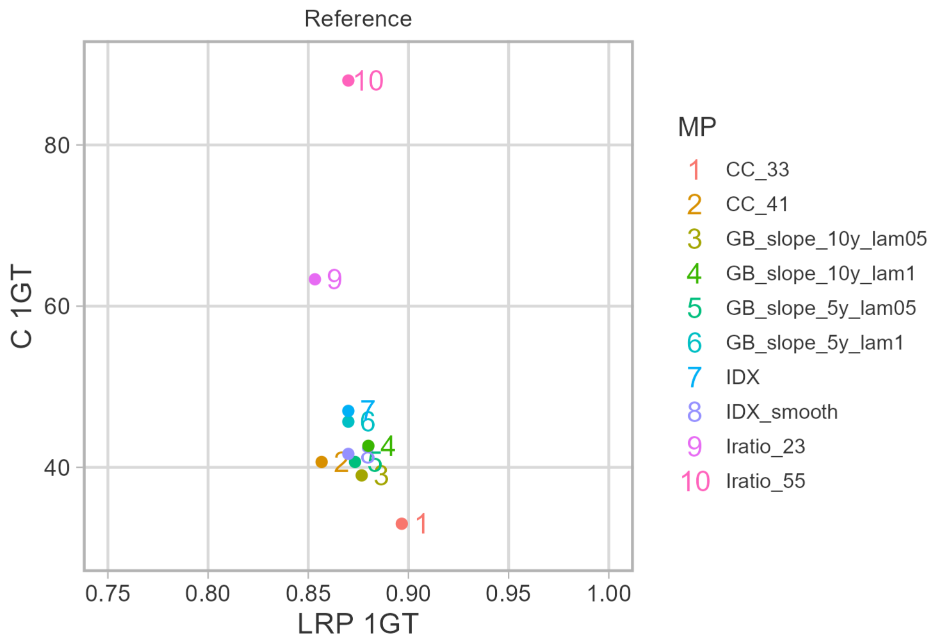

Figure 49. Trade-off between LRP 1GT and C 1GT performance metrics (averaged across the OM reference set) among the candidate management procedures.

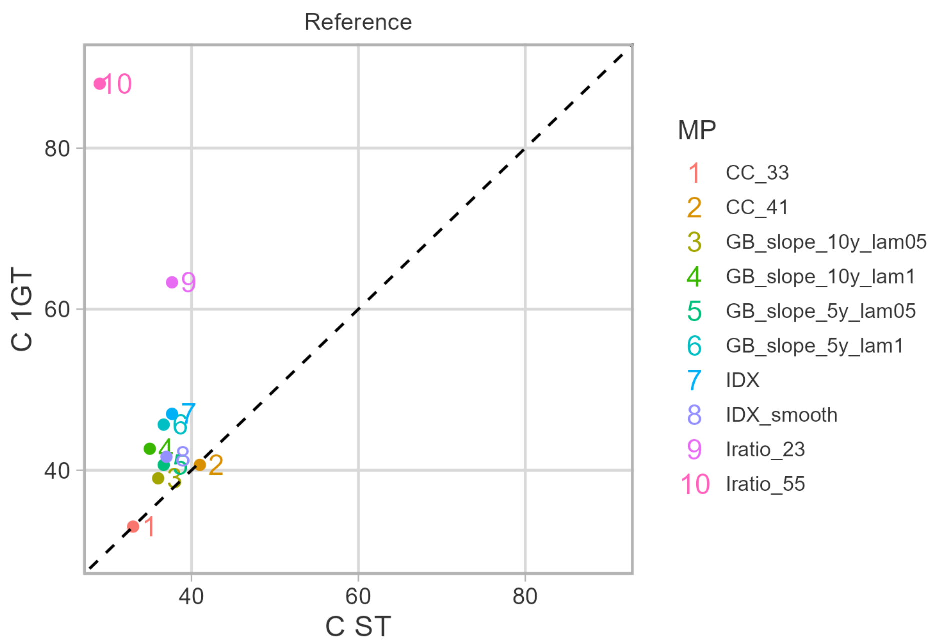

Figure 50. Trade-off between C 1GT and C ST performance metrics (averaged across the OM reference set) among the candidate management procedures.

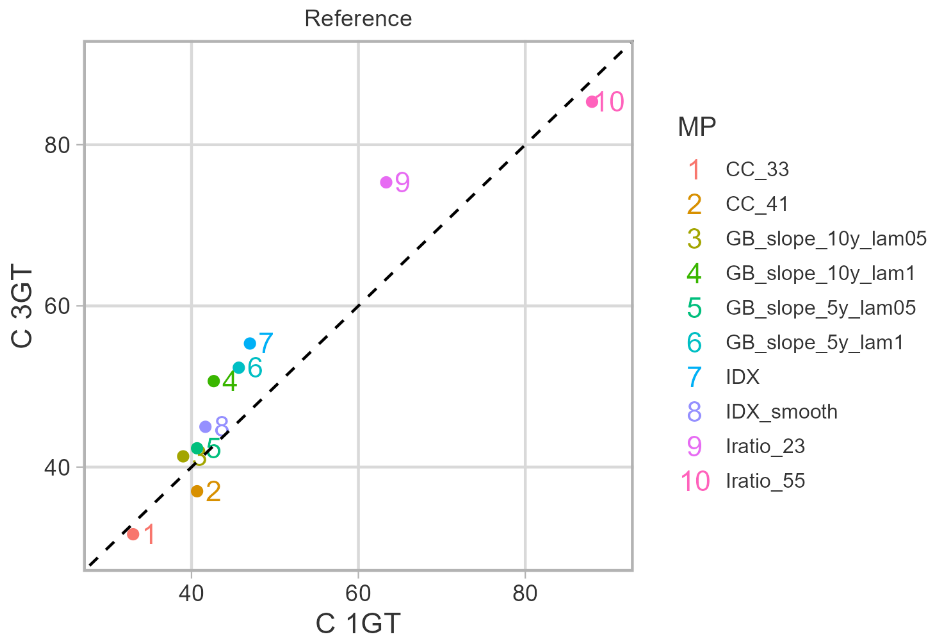

Figure 51. Trade-off between C 1GT and C 3GT performance metrics (averaged across the OM reference set) among the candidate management procedures.

6.2. PROJECTION TRAJECTORIES

The timeseries trajectories of B/B_{MSY} and catch in the first generation (24 years) of the projection demonstrate performance of various MPs in the operating models.

While there is broad range in the confidence interval for B/B_{MSY} at the beginning of the projection, all candidate MPs (excluding the reference MPs) maintained the stock at similar levels to 2021 or achieved continuous stock growth over the first generation of the projection period (Figures 52 and 53). Stock decline was only observed with the FMSYref MP in operating models where the stock was above B_{MSY} at the start of the projections. The rate of stock growth was dependent on individual operating model, with the most responsive changes in the stock observed when the natural mortality rate was high (OM 3).

The catches in the FMSYref MP show the fishery removals when the state of nature (available biomass and value of F_{MSY}) is known perfectly and there is perfect implementation of fishing at F_{MSY}. As such, they represent the highest hypothetical catches while meeting the requirements of the PA Policy. These catches are higher than those in the other management procedures. In effect, the difference in catch between FMSYref and the candidate management procedures is the cost of our imperfect knowledge of the size and productivity of the stock.

Simulated catches in the projections were within the magnitude of historical values since 2000, except for the high catches simulated in the FMSYref MP (Figures 52 and 53). Among the index-based MPs, there was more catch variability in the Iratio MPs compared to the more stable GB_slope and IDX MPs.

Kobe trajectory plots report the B/B_{MSY} and F/F_{MSY} at the end of the first generation (i.e., after 24 years) (Figures 54 and 55). Trajectories for most candidate management procedures move rightward, i.e., towards higher biomass with no significant increases in fishing mortality. The notable exceptions were the Iratio MPs as catches increased towards the end of the first generation (particularly in OM 2 with low natural mortality). The FMSYref MP had the opposite behavior of the candidate MPs where the stock was fished down when $B > B_{MSY}$.

Annual probabilities that the stock is above the LRP and USR in the simulation are reported in Figures 56 and 57. Probabilities for all management procedures in all operating models were increasing or held high over time except in the FMSYref MP, where the probability above the USR declined in the low recruitment scenario.

The range in the simulated HBLL index, based on the projected abundance, the estimated selectivity in the RCM, and expected sampling error, is reported in Figure 58. Values of the index either stayed within the historical range or increased in all management procedures (except with the FMSYref MP). Within the index-based and constant catch MPs, the largest increases are seen in the reference set. The index increased the least in the robustness scenarios for opposite reasons. In OM (A) the stock is in a good state and there is little possible increase in the population, while in OM (B), low recruitment prevents significant increases to the stock size.

The mean age and mean weight are also simulated for the HBLL index as indicators of values expected to be observed in the future if the assumptions of the projections are appropriate (Figures 59 and 60). Application of candidate MPs is expected to maintain the mean age and mean weight in the HBLL survey to within a similar range to historical values (since 2003). Less contrast in the mean age and mean weight was observed compared to the index of abundance. The mean age and mean weight stayed relatively stable within range of historical values, although the values were highest in OM (A). The simulated index and mean size appreciably decreased only in the FMSYref MP.

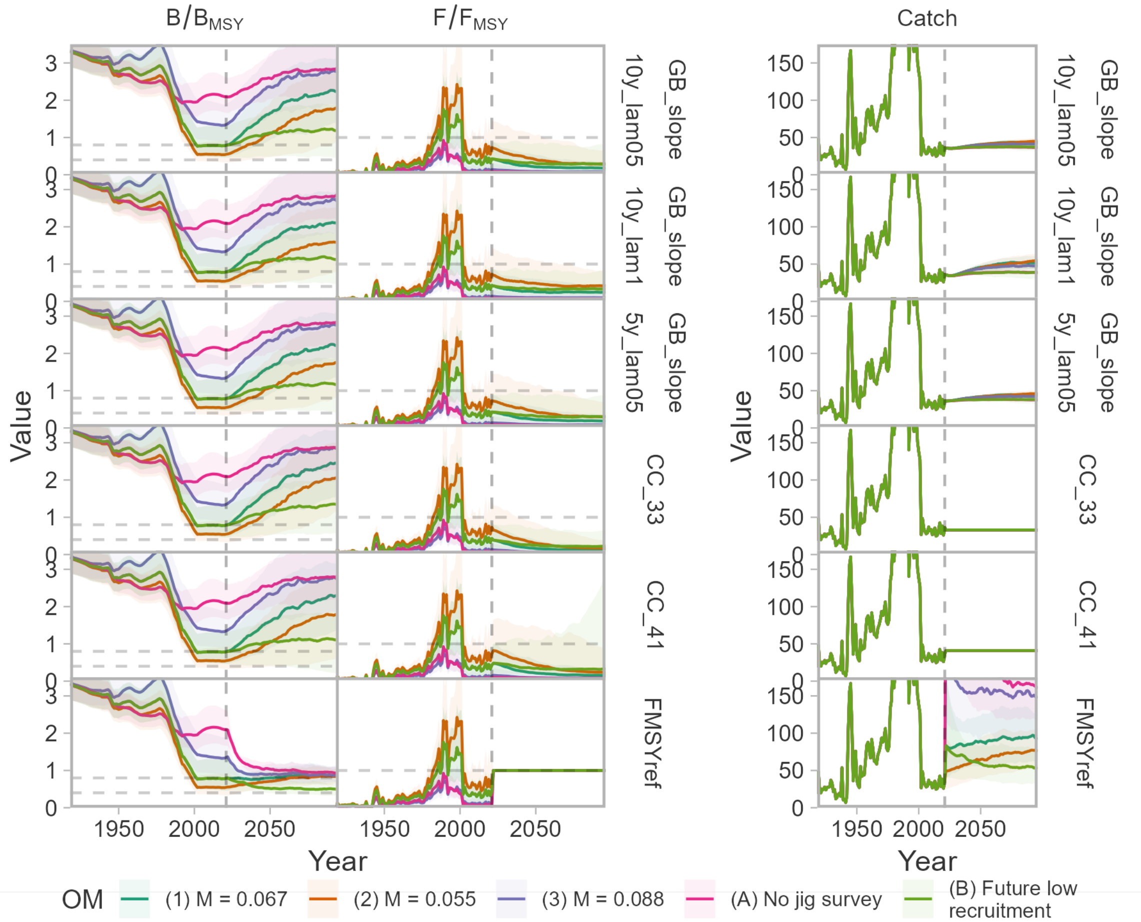

Figure 52. Historical and projected time series of B/B_{MSY} (left column, with horizontal grey lines denoting $0.4B_{MSY}$ and $0.8B_{MSY}$), F/F_{MSY}, (middle column, with horizontal grey line denoting $F/F_{MSY} = 1$) and catch (tonnes, right column) by operating model (colours) and management procedure (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 identical among rows. The catch exceeded 150 tonnes during 1980-2000, as well as in the FMSYref management procedure, and truncated in the right column. The projection period shows the resulting trajectories from implementation of the management procedures.

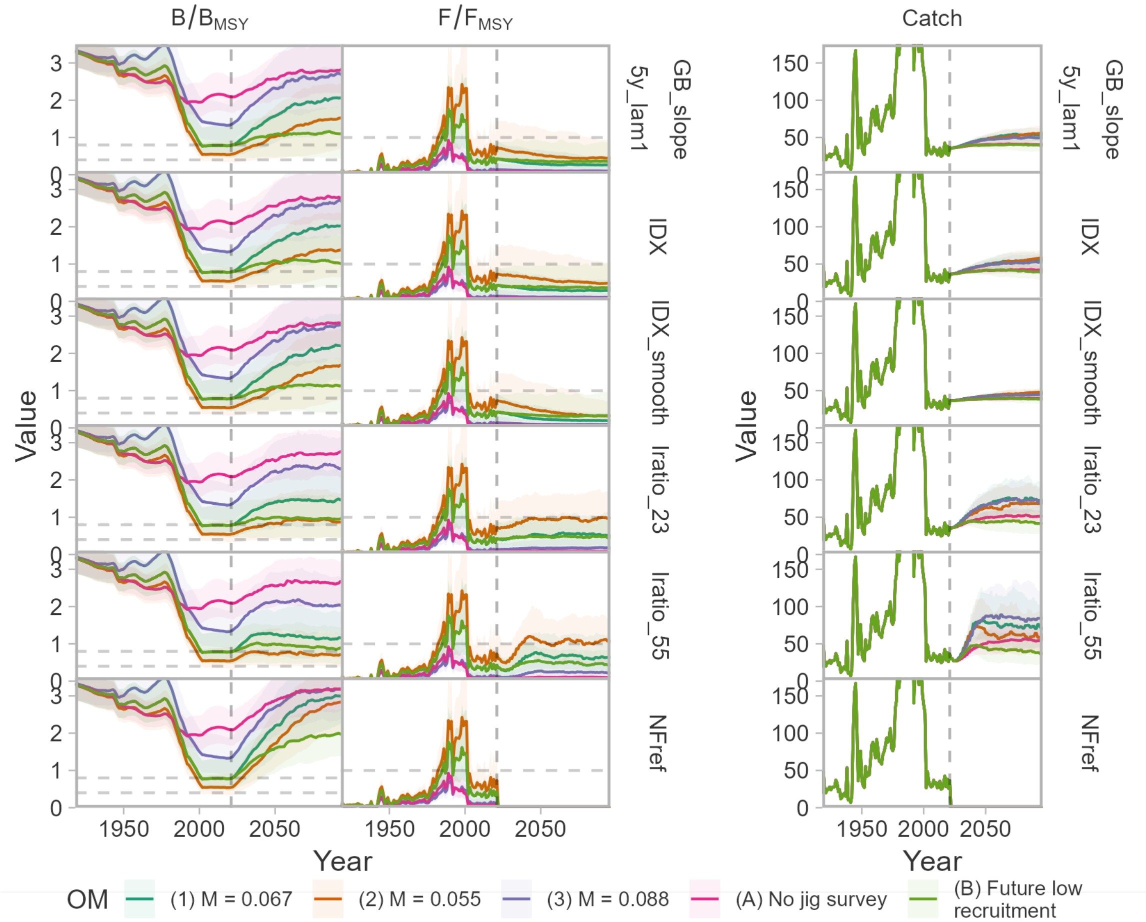

Figure 53. Historical and projected time series of B/B_{MSY} (left column, with horizontal grey lines denoting $0.4B_{MSY}$ and $0.8B_{MSY}$), F/F_{MSY}, (middle column, with horizontal grey line denoting $F/F_{MSY} = 1$) and catch (tonnes, right column) by operating model (colours) and management procedure (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 identical among rows. The historical catch exceeded 150 tonnes during 1980-2000 and truncated in the right column. The projection period shows the resulting trajectories from implementation of the management procedures.

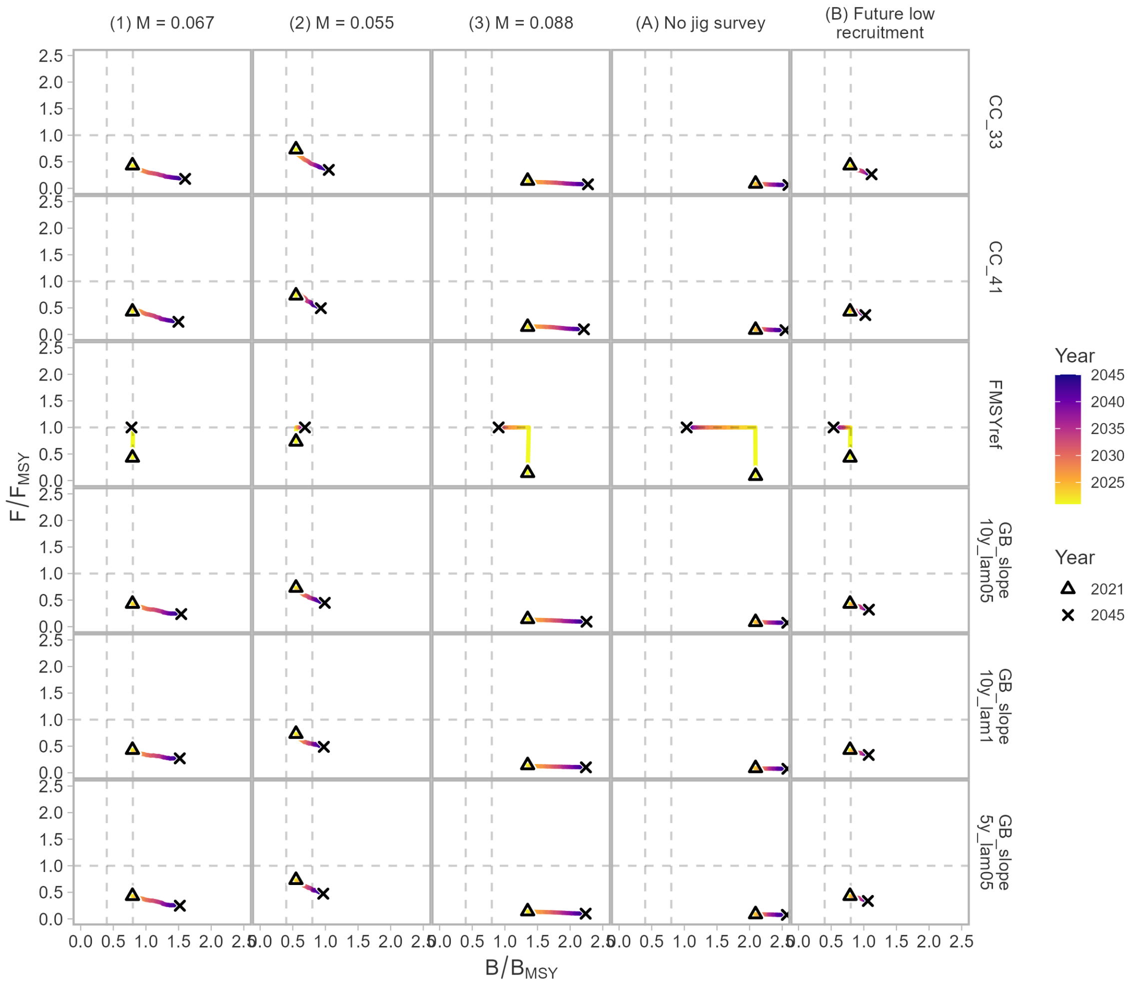

Figure 54. Kobe phase plot of median F/F_{MSY} *and* B/B_{MSY} *from application of management procedures (set 1 of 2 figures) over 1 generation. Coloured lines indicate the year of the projection and shapes denote the beginning and end years.*

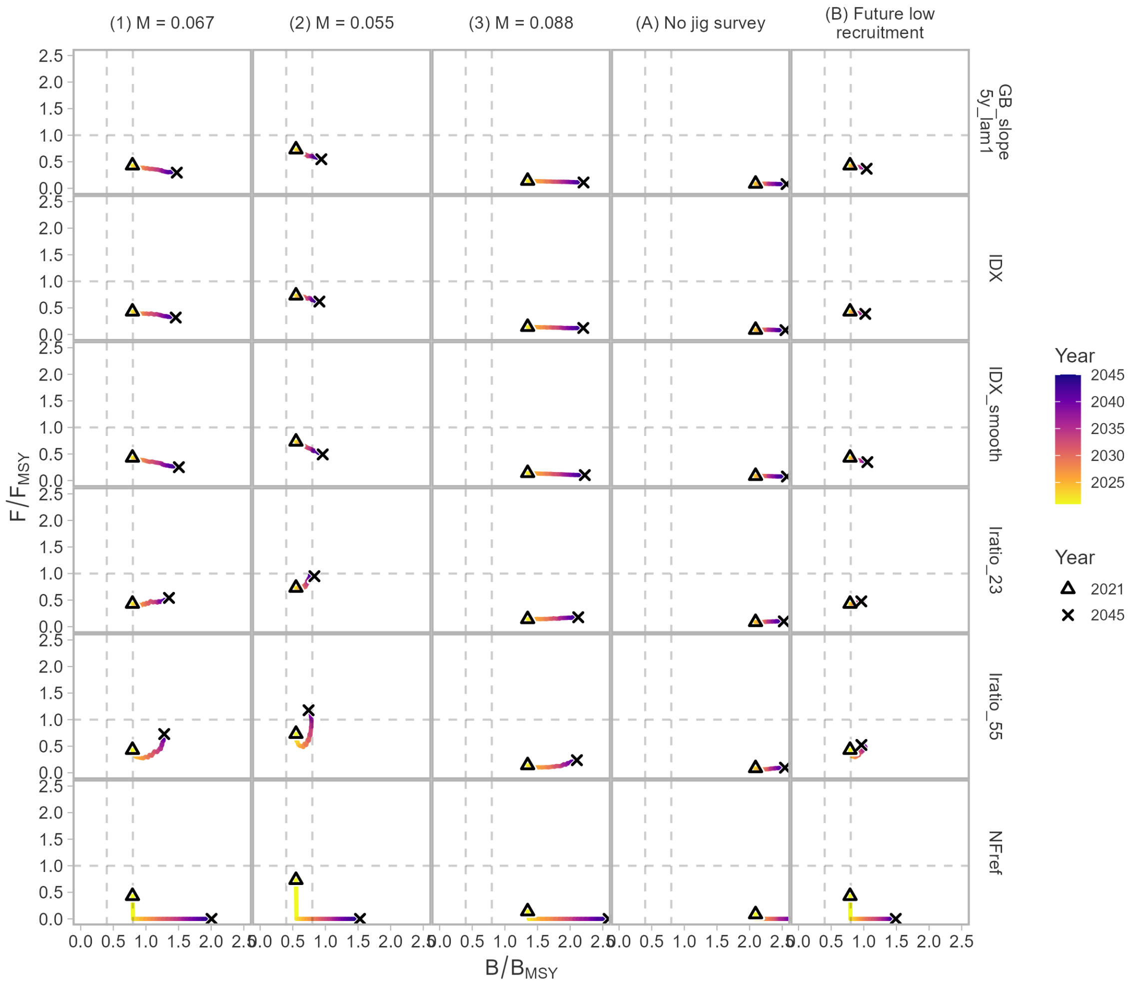

Figure 55. Kobe phase plot of median F/F_{MSY} *and* B/B_{MSY} *from application of management procedures (set 2 of 2 figures) over 1 generation. Coloured lines indicate the year of the projection and shapes denote the beginning and end years.*

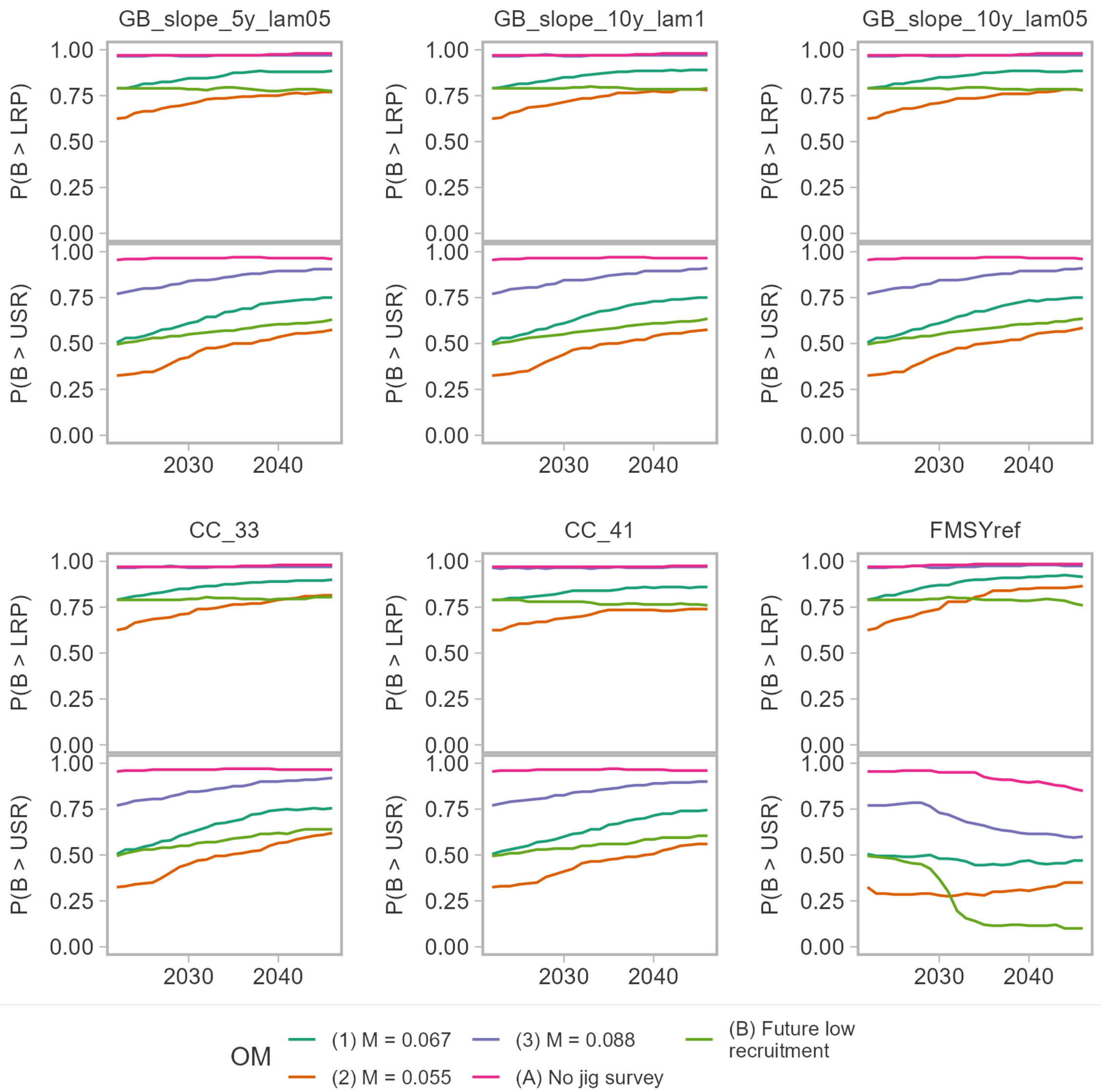

Figure 56. Annual probability that the stock is above the LRP and USR during the first generation of the projections (set 1 of 2 figures). Values are presented by management procedure (panels) and operating model (colours).

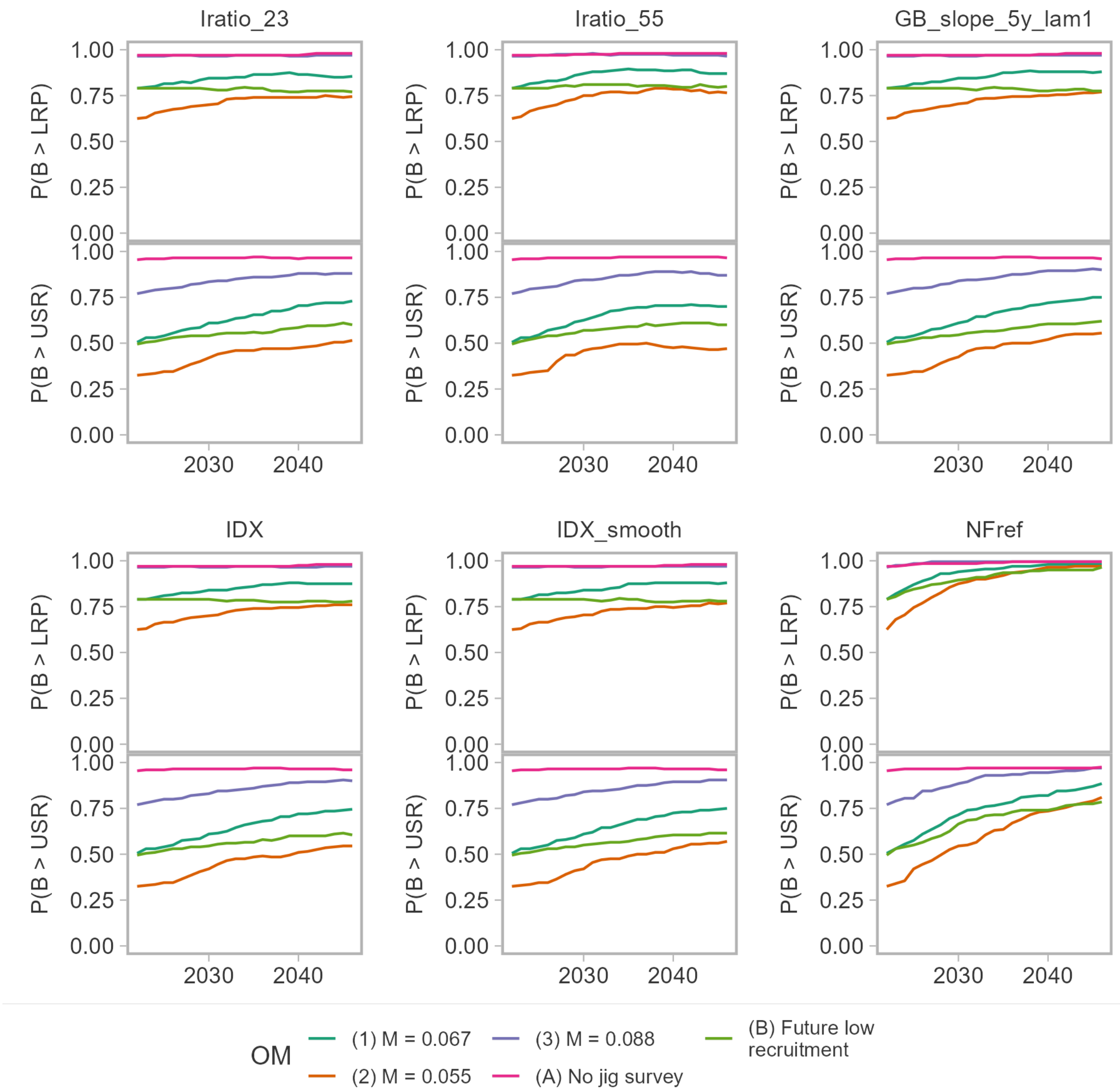

Figure 57. Annual probability that the stock is above the LRP and USR during the first generation of the projections (set 2 of 2 figures). Values are presented by management procedure (panels) and operating model (colours).

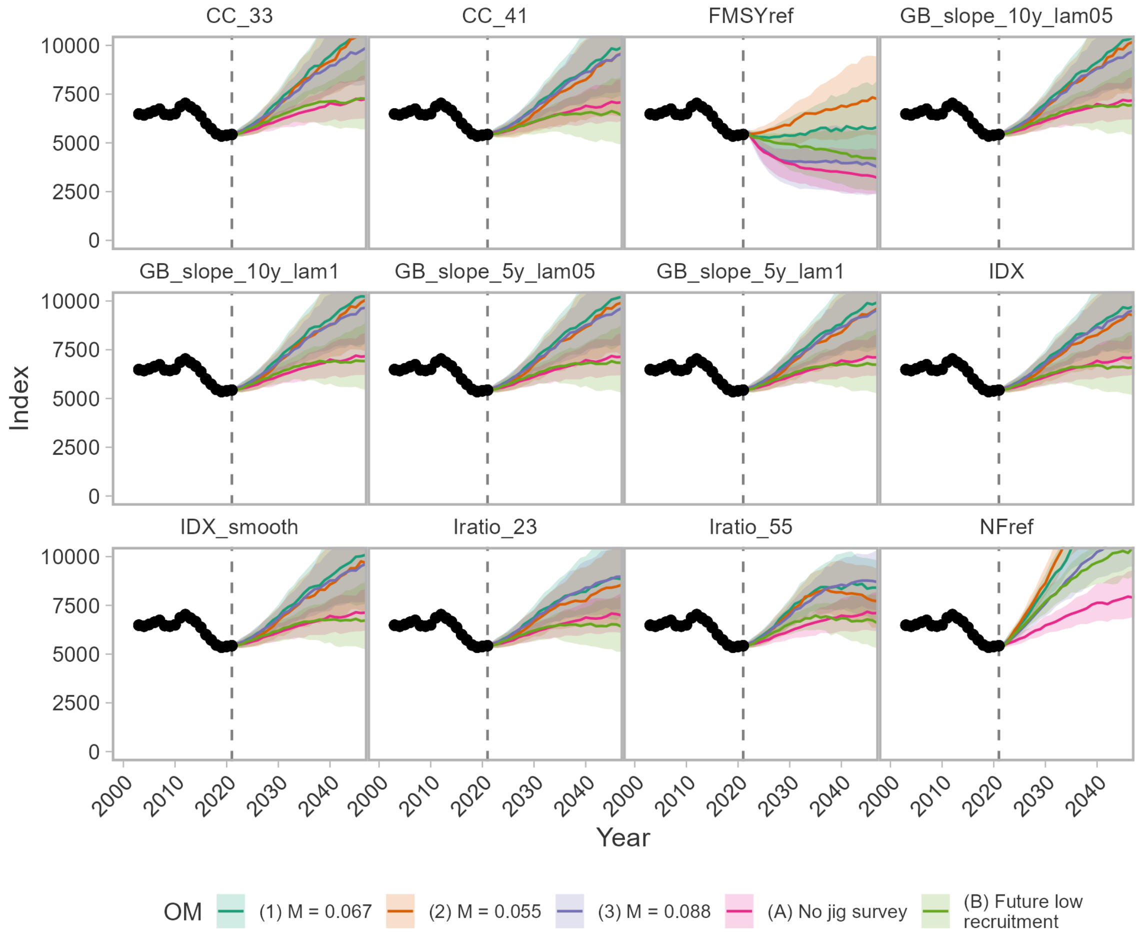

Figure 58. The HBLL index of abundance from the historical and projected (one generation) time periods for each management procedure (by panel) in the five operating models (colours). Coloured ribbons indicate the 95% coverage interval of simulated values in the projection period in each individual operating model. The black line indicates the mean historical values obtained from the spatial generalized linear mixed model (GLMM) fit to the survey data. The vertical dashed line indicates the last year of the historical period.

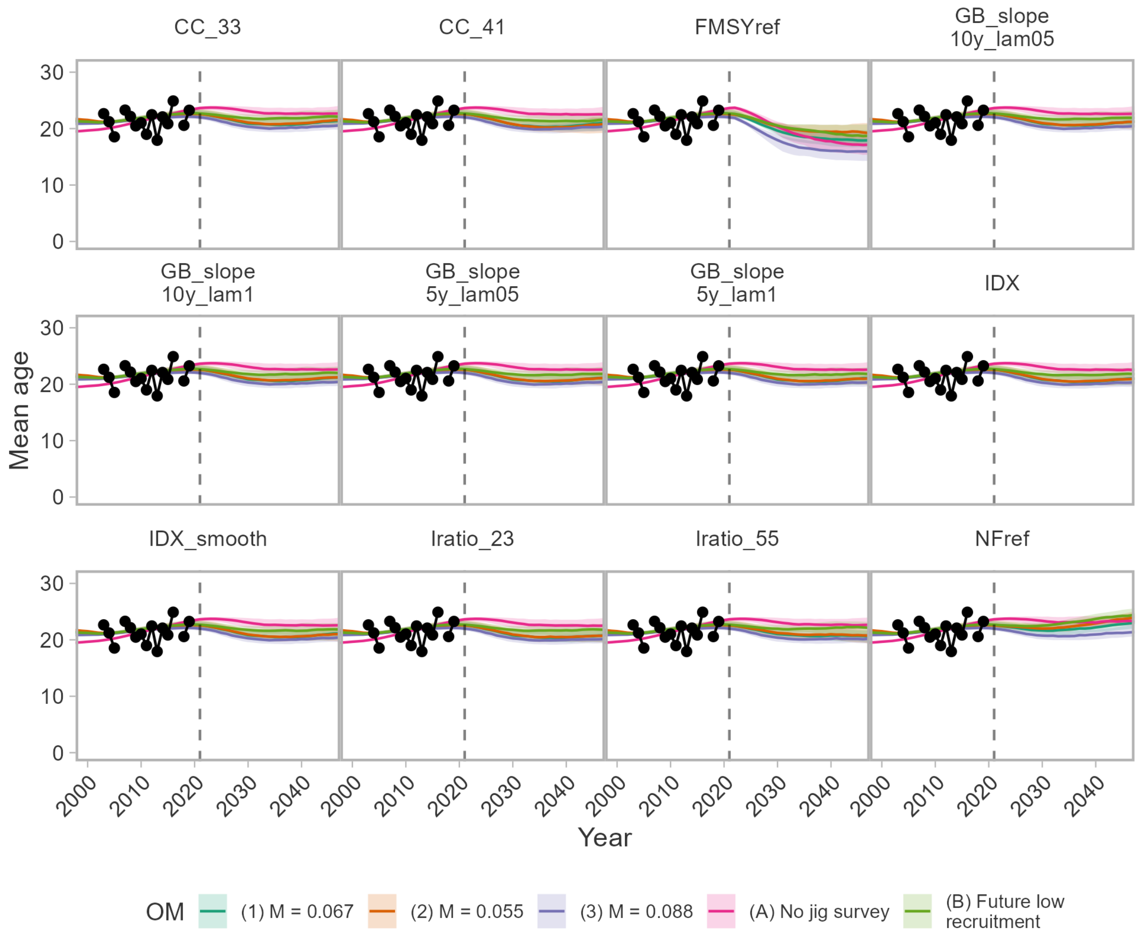

Figure 59. The mean age from the HBLL index of abundance from the historical and projected (one generation) time periods for each management procedure (by panel) in the five operating models (colours). Coloured ribbons indicate the 95% coverage interval of simulated values in the projection period in each individual operating model. The black points indicate the historical values obtained from the age samples in the survey. The vertical dashed line indicates the last year of the historical period. No sampling error was included in the mean age calculation.

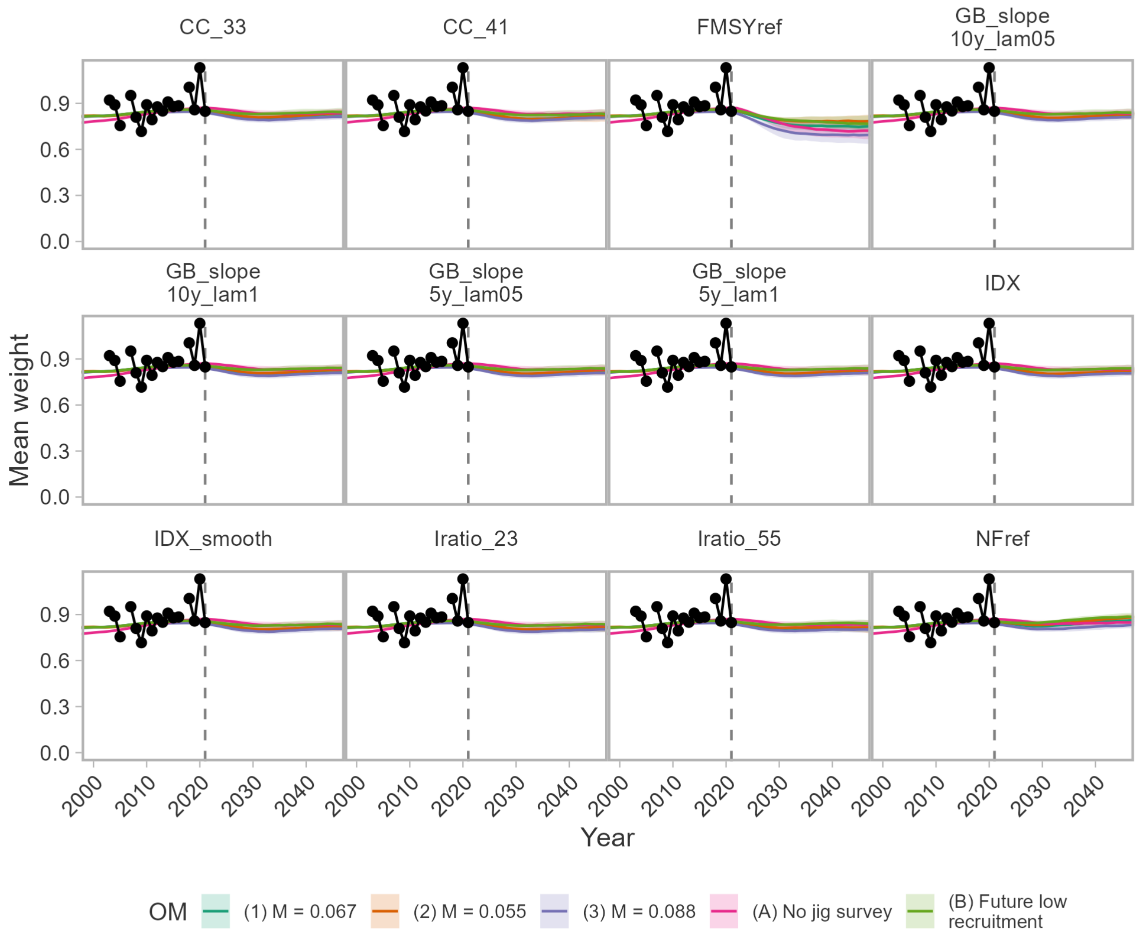

Figure 60. The mean weight from the HBLL index of abundance from the historical and projected (one generation) time periods for each management procedure (by panel) in the five operating models (colours). Coloured ribbons indicate the 95% coverage interval of simulated values in the projection period in each individual operating model. The black points indicate the historical values obtained from the size samples in the survey. The vertical dashed line indicates the last year of the historical period. No sampling error was included in the mean weight calculation.

7. DISCUSSION

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

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. We identified LRP 1GT > 0.75, averaged across the OM reference set scenarios, as the primary criterion to identify management procedures that would meet policy requirements. All MPs achieved this policy performance metric with at least 75% probability, averaged across the reference set and in individual robustness operating models. This result was achieved primarily because the stock was estimated to be above the LRP in 2021. In all operating models, catches were set to levels such that the stock did not 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.

In addition to projected stock trajectories, we presented a number of visualizations to show trade-offs among policy and catch objectives (see also Anderson et al. 2021). The visualizations present trade-offs in different tabular and graphical formats, intended to support the process of selecting the final MP to guide harvest policy.

While all the MPs met the LRP 1GT satisficing probability under the OM reference set scenarios, there was a trade-off between this probability and the mean catch. Final selection of the MP will have to balance the probability of meeting this criterion with fishery objectives, such as ensuring that there are sufficient opportunities to catch Inside Quillback Rockfish (Haggarty et al. 2022). Several management procedures, particularly the index-based MPs, generated 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 decreasing trend in the HBLL index in the most recent ten years (2012–2022). By definition, constant catch management procedures can help meet objectives depending on the magnitude of the catch. In the long-term, there is an observed tradeoff in catch, i.e., lower catches in the short-term for higher catches three generations later.

7.1. NATURAL MORTALITY

The reference set was intended to explore robustness of management procedures to alternative hypotheses regarding natural mortality in Inside 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.

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 0.02 to 0.25 year^{-1}, 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. Other Quillback Rockfish assessments, such as those on the U.S. West Coast, have also used M values in the lower range (Langseth et al. 2021).

Natural mortality can be directly estimated from multiple years of tag returns, but estimation can be confounded if the tag shedding rate and tag reporting rate are unknown. Alternatively, catch curve estimates from age samples in an unfished population can provide estimates of M. To some extent, this was done for Inside Quillback Rockfish, with estimates in the range of values used in the reference operating models (Schnute and Haigh 2007, see Appendix F for additional discussion). Overall, the reference operating models covered credible values of natural mortality for this stock.

Natural mortality rates can change over time, for example, due to changes in predator population abundance in the Strait of Georgia. 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). Lingcod in the Strait of Georgia also suffered major population declines and were thought to have been fished down to 2% of historic levels in 1990, but the population has increased since (Holt et al. 2016).

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 the Strait of Georgia and BC overall. 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). Approximately 42% of the population can be found in the Strait of Georgia. The most recent Stellar Sea Lion assessment in BC estimates population abundance of 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.), 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 128 RCAs in Area 4B (Figure 2) that protect an estimated 267 square kilometres of rockfish habitat, amounting to 19% of available rockfish habitat in inside waters (Dunham et al. 2020). Remotely Operated Vehicle (ROV) surveys of RCAs in inside waters found that there was no difference in the abundance or size of Yelloweye Rockfish inside RCAs at the time of study (3-7 years after RCA establishment) (Haggarty et al. 2016). Additional data collected on a 2018 ROV survey have also shown little difference between RCA and non-RCA sites (D. Haggarty, unpublished data). The results from this survey, however, were not available in time to be included in this project.

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). The RCAs in the inside waters have now been in place for 16 to 18 years, so we might expect to find 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

The MP Framework was developed with the intention of using reference points implicitly in the science advice, in contrast to a conventional stock assessment, where stock status is explicitly reported and decision tables are presented. Such tables present probabilities of breaching reference points (e.g., probability of the stock falling below the LRP) over a range of future catch levels. Consideration of risk occurs at the final step of the decision-making process.

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 (DFO 2009). To meet the requirements of the Fish Stocks Provisions, best use of the MP Framework for BC groundfish should consider whether the conditioned operating models are sufficient for identifying status. These operating models should be classified in the reference set. Operating models can also be developed with the primary intention of testing management procedures and studying their behavior across various scenarios rather than identifying status. These operating models should be in the robustness set. On the other hand, operating models for very data-limited species, e.g., those with few data, such as size or age data or representative indices of abundance, may not be defensible for identifying status, in which case, there would be no operating models in the reference set. The MP Framework was developed for a data-limited context, but it can accommodate the data spectrum more elegantly than a piecemeal approach of stock assessment models.

For Inside Quillback Rockfish, we identified three operating models for the reference set that differed in the natural mortality rate. The first OM used a "base" mean value for M based on the most recent scientific information available for predicting the parameter, with alternative means including a continuity scenario from the 2011 assessment in the other two OMs. The status of the stock in 2021 relative to the LRP was robust to the value of M (with distribution means ranging from 0.055 to 0.088). The stock was more likely than not above the LRP, with probabilities of being above the LRP differing based on M.

Averaging across the three reference OMs results in a 79% probability that the stock in 2021 is above the LRP. There is a 52% corresponding probability, averaged across the three reference OMs, that the stock is above the USR.

COSEWIC Metric A measures the decline across a three generation time span. When the three reference OMs are averaged, our analysis shows that there is a high probability that the population has declined by 30% and 50% (with 99% and 86% percent probability, respectively), and a lower probability (48 percent) that the population had declined more than 70% in 2021 (Appendix G).

7.4. ENVIRONMENTAL CONSIDERATIONS

In anticipation of Inside Quillback Rockfish to be included in the second batch of major stocks prescribed to the Fish Stock 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). Furthermore, incorporating environmental effects into assessments may bias advice depending on how well the environment-productivity relationship is understood (Haltuch et al. 2019).

Here, we do not directly model any individual environmental variable (e.g., temperature or 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 a low recruitment scenario. In this way, we assume that any number of 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.

7.5. HISTORICAL CATCH

The other major source of uncertainty in our analyses is the magnitude of historical catch. 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. The reconstructed catches were used in the previous stock assessment (Yamanaka et al. 2011). Reconstruction remains the best available time series of historical catches and there was no further guidance on whether they were underestimates or overestimates. We therefore followed the same approach to reconstructing historical recreational catch data and estimating current recreational catch data as Yamanaka et al. (2011).

Biological samples have not been collected from the commercial fishery since 2001. 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 over time. 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 (Haggarty et al. 2021), FSC catch is not explicitly included and remains uncertain for the Inside Quillback Rockfish. 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. Dual fishing trips mostly occur in the northern part of the inside waters. Similarly, some FSC effort will also be captured in the creel survey effort data because FSC fishing that occurs from small vessels will appear like a recreational fishing boat and be counted on DFO creel survey overflights and will enter into the estimate of recreational effort.

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 Area 4B. 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 OM(s) 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 and mean weight as 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. (2022b) 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).

Since management procedures were implemented biennially in the projections, we recommend re-evaluation of the performance of the selected MP at least once every two years. This is the minimum time period needed to process survey data to update the HBLL index. Furthermore, the Groundfish data synopsis (Anderson et al. 2019), which provides a snapshot of population and fishing trends for major BC groundfish stocks, is updated every two years, and is a useful tool for tracking and reporting on all groundfish survey indices. While continued processing of ages from biological samples is desirable, other commitments for the DFO ageing lab may make this infeasible for periods of time. Thus, an alternative such as mean weight was proposed here.

7.7. FUTURE RESEARCH

This section provides a summary of future research recommendations that can inform the next assessment of Inside Quillback Rockfish.

General research topics:

- Repeat Dogfish calibration survey to link the index series between years that use different hook types
- Repeat Jig Area 12 survey to update the index series since 2004
- Ensure the set data from jig surveys in other statistical areas in inside waters are available for developing indices of abundance
- Explore the potential to develop a fishery index from recreational catch per unit effort (CPUE)
- Explore the relationship between recreational catch and input controls. Recreational catch is managed through input controls, i.e., seasonal closures and retention limits, while candidate management procedures currently provides advice in terms of total catch.

Future modeling topics:

- Incorporate uncertainty in reconstructed catch by sampling from a distribution for operating model conditioning
- Explore catch implementation error to account for unreported catch, for example, if there is potential for large FSC catch that are not caught during dual fishing trips (note: annual FSC

catch from dual fishing has been estimated to be less than 0.5 t while the recent average total commercial catch has been 33 t).

- Identify modeling approaches that can incorporate marine spatial planning into stock assessment
- Develop operating models that have alternative steepness scenarios
- Explore alternative operating model weighting schemes
- Explore operating model scenarios with time-varying natural mortality and compare indicators, e.g., indices of abundance, to determine if this scenario can be differentiated from changes in mean recruitment
- Develop F-based MPs that determine the catch advice from a target harvest rate and an estimate of abundance. Such MPs can be empirical, for example, the abundance estimate is developed from the catch and index and the harvest rate is tuned to obtain good performance, or model-based, where a separate model is fitted and a harvest control rule is implemented. Each model-based MP specifies a unique configuration of the estimation model and harvest control rule. MPs with surplus production models have been evaluated but may not perform well due to the longevity of rockfish species (Haggarty et al. 2021). Delay difference models and statistical catch-at-age models may be more suitable alternatives.

8. ACKNOWLEDGEMENTS

We are grateful to Robert Tadey (Groundfish Management Unit) for helpful discussions and guidance regarding the Fish Stocks Provisions, and to Sean Anderson and Rowan Haigh for helpful discussion on technical aspects of the analysis. We also thank Dave Renwall for his suggestion to look into the commercial fishery mean weight in the FOS database.

Rowan Haigh also provided advice on the historical catch reconstruction algorithm and Maria Cornthwaite provided data on dual fishing.

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APPENDIX A. BIOLOGICAL DATA

Groundfish management uses Area 4B to define the Inside Quillback Rockfish stock.

A.1. AGE AND GROWTH

The maximum observed age for Inside Quillback Rockfish is 80 years, which was collected in 2003 from the hard-bottom longline (HBLL) survey. Age data for Inside Quillback Rockfish, derived from the break and burn or break and bake methods, are available from various surveys in Groundfish Management Area 4B from 1986-2019. Age samples were obtained from biological samples from jig surveys beginning in 1986. After 2003, age samples predominantly come from directed HBLL surveys. Additional samples of young Quillback Rockfish (4 years old and under) were collected from the Strait of Georgia Lingcod Young-of-year Bottom Trawl survey in 2005. Proportions-at-age are shown by year and sex in Figure A.1.

Inside Quillback Rockfish grow up to 64 cm in length for males and 61 cm for females (Figure A.2). The maximum recorded weight is 2.1 kg for males and 2.8 kg for females. Length-weight model fits and plots for all available survey data in area 4B are shown in Figure A.3. It is assumed that all ages and growth measurements are independent of subarea.

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:

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

where σ 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 inside Quillback Rockfish are shown in Figure A.4. 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:

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

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).

A.2. MATURITY

To estimate maturity at age, biological samples from all surveys within area 4B 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.5. 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.6). 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.6. Maturity frequency by each month is shown in the bubble plot in Figure A.7 for all fish in all surveys within area 4B for 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.

A.3. GENERATION TIME

This analysis updated the generation time of inside Quillback Rockfish to 24 years. The previous stock assessment estimated the generation time as 28.5 years, but this was based on the natural mortality of M = 0.057 (Yamanaka et al. 2011). Since then, new meta-analyses have updated the relationship between natural mortality and maximum observed age (Then et al. 2015), (Hamel 2015). Based on an updated value of M = 0.067 and 50% female maturity at 8.7 years, the generation time of 24 years (age at 50% maturity + 1/M) is used here.

See Appendix D for further discussion of natural mortality for Inside Quillback Rockfish.

A.4. SUMMARY TABLE OF BIOLOGICAL DATA

Table A.1. Inside Quillback Rockfish biological data.

Year	Specimens	Lengths	Weights	Maturities	Ages	Age specimens collected
1984	4	4	4	4	0	4
1985	94	92	92	93	0	94
1986	591	575	578	590	464	591
1987	434	427	428	434	418	434
1988	943	918	743	942	636	943
1991	38	37	23	21	0	38
1992	449	439	302	449	448	449
1993	590	585	193	199	177	590
1998	344	343	133	344	342	344
2003	372	358	359	329	308	372
2004	283	272	271	279	272	283
2005	152	145	144	147	152	152
2007	372	372	372	372	271	372
2008	70	66	61	62	65	70
2009	27	27	26	26	27	27
2010	441	438	438	438	353	441
2011	296	290	290	292	163	296
2012	769	756	755	755	397	769
2013	198	195	198	194	110	198
2014	610	604	604	605	287	610
2015	243	237	237	236	152	243
2016	596	595	596	595	304	596
2018	128	128	128	128	111	128
2019	447	440	440	440	220	447
2020	36	36	36	36	0	36
2021	778	775	775	747	0	778

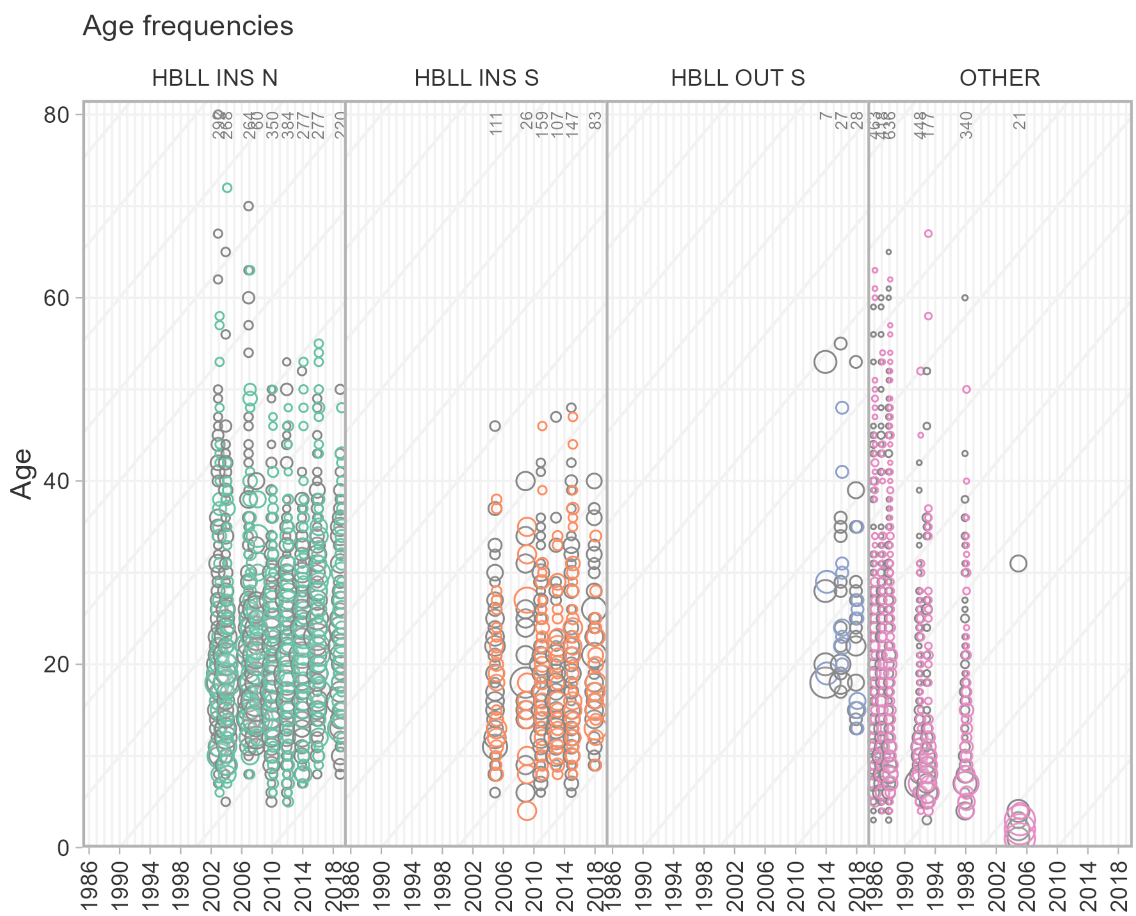

Figure A.1. Age-frequency plot for Inside Quillback Rockfish from all available surveys in Area 4B: hard-bottom longline surveys (northern and southern) in inside waters (HBLL INS N/S), hard-bottom longline surveys in outside waters (a small portion of area 4B was included in this survey in 2014 and 2016; HBLL OUT S), and "OTHER" surveys including jig surveys in the 1980s and 1990s and a bottom trawl survey in 2005. Female fish are shown as coloured circles and male fish are shown behind as light grey circles. The total number of fish aged for a given survey and year is indicated along the top of the panels. Diagonal lines are shown at five-year intervals to facilitate tracing cohorts through time.

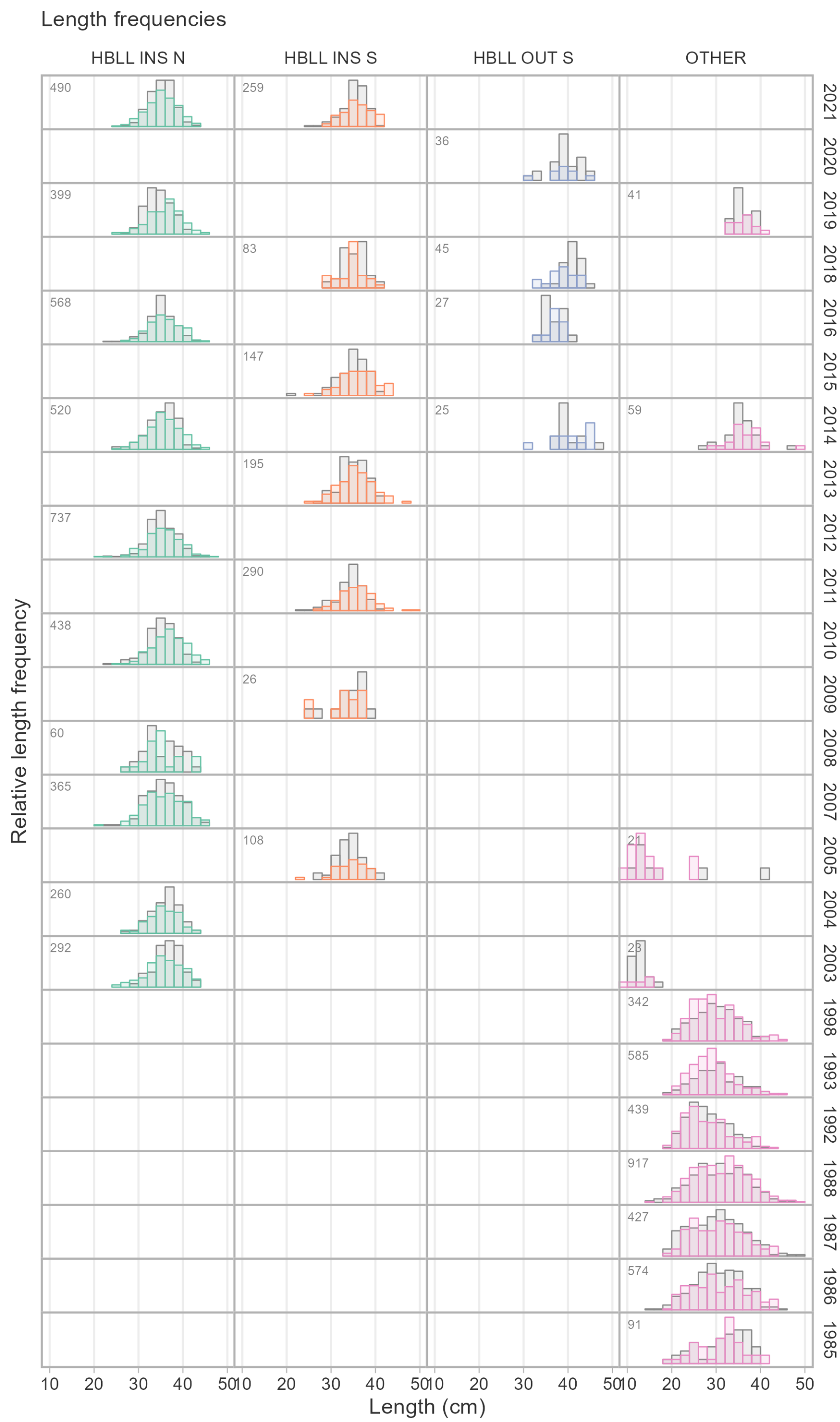

Figure A.2. Length-frequency plot for Inside Quillback Rockfish from all available surveys in Area 4B: hard-bottom longline surveys (northern and southern) in inside waters (HBLL INS N/S), hard-bottom longline surveys in outside waters (a small portion of area 4B was included in this survey in 2014 and 2016; HBLL OUT S), and "OTHER" surveys including jig surveys prior to 1998, bottom trawl survey in 2005, and the Strait of Georgia Dogfish Survey in 2014 and 2019. Female fish are shown as coloured bars and male fish are shown behind as light grey bars. The total number of fish measured for a given survey and year is indicated in the top left corner of each panel.

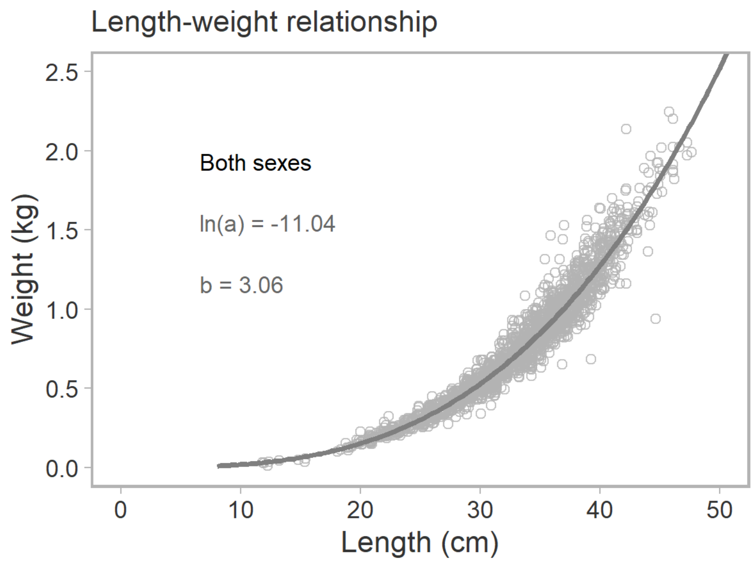

Figure A.3. Length-weight model fits and plots for inside Quillback Rockfish (all survey samples in area 4B). Circles represent individual fish and the solid black line indicates the fitted line. Text reports the parameter estimates of the weight-at-length relationship. A single set of parameters was estimated from both sexes.

Figure A.4. Length-age model fits and plots for inside 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. These figures include all survey samples.

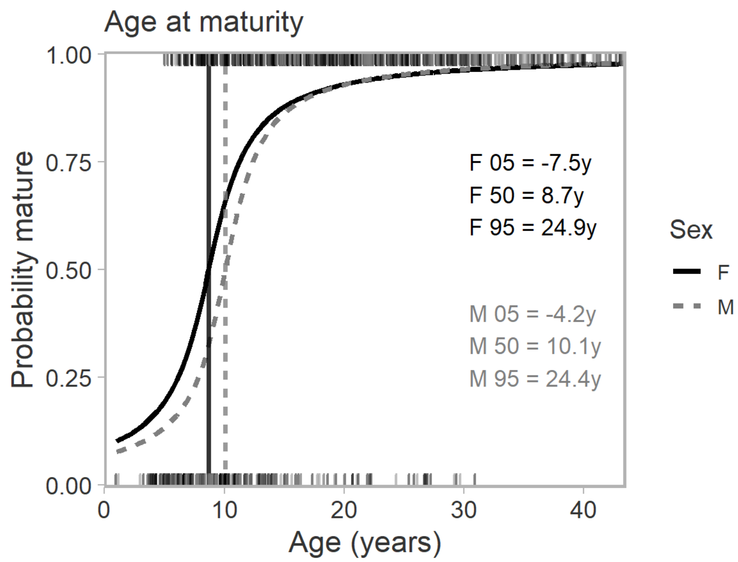

Figure A.5. Age-at-maturity ogive plots for inside Quillback Rockfish. The solid black lines represent fits to the female fish and the dashed grey lines represent fits to the male fish. The vertical lines indicate the estimated age at 50% maturity. Text on the panels indicates the estimated age at 5, 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.

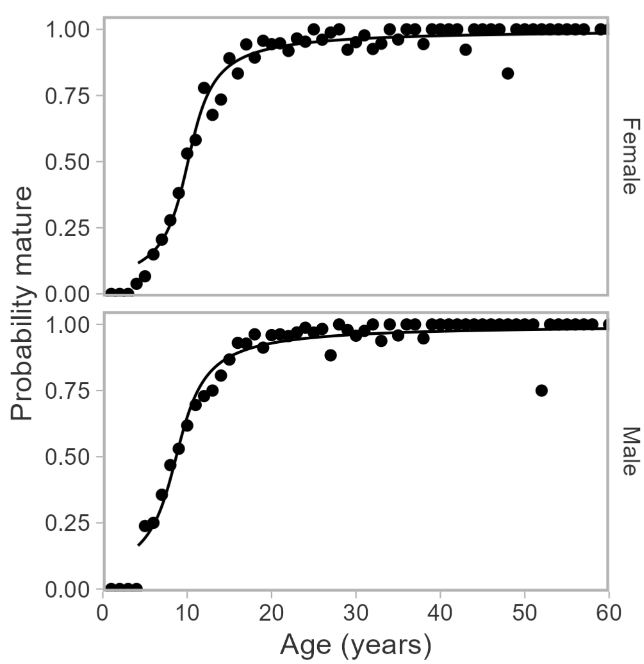

Figure A.6. Predicted and observed proportions mature-at-age.

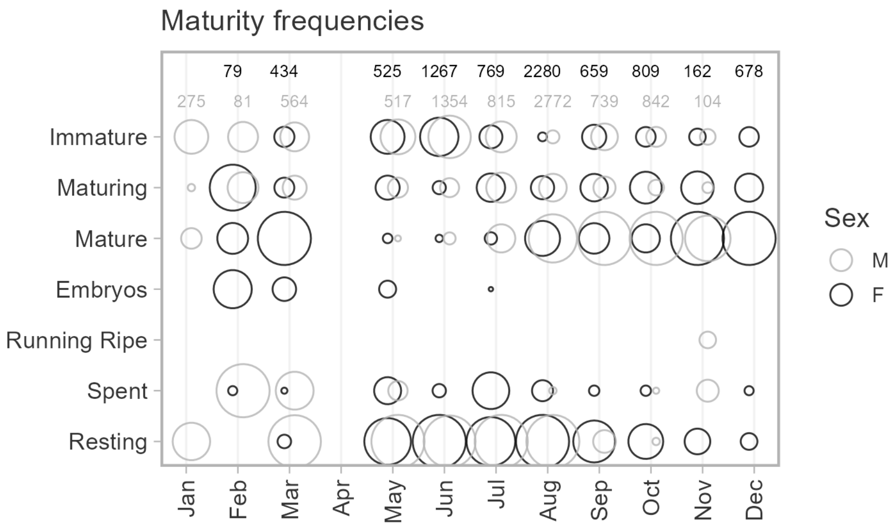

Figure A.7. Maturity frequency-by-month for inside Quillback Rockfish. The area of each circle corresponds to the number of fish specimens in a given maturity category for the given month. Female fish are indicated by black circles and male fish are indicated by light grey circles behind. The total number of fish specimens for each month are indicated by the numbers at the top of the plot.

APPENDIX B. FISHERY-INDEPENDENT SURVEY DATA

We conditioned the operating models using indices of abundance from the inside Hard Bottom Longline (HBLL) survey and the Jig Area 12 survey. Survey design and modelling of indices for each survey are described here.

B.1. INSIDE HBLL SURVEY INDEX

The Inside HBLL survey for the Strait of Georgia management area (4B) has been providing catch-rate indices and associated biological data for inshore rockfish assessment since 2003 (Lochead and Yamanaka 2007). The survey has a depth-stratified random design consisting of 2 km by 2 km survey blocks, and has always taken place on the CCGS *Neocaligus* vessel. The survey uses size 13/0 snap-type circle hooks and squid bait with 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 Lochead and Yamanaka (2004) and Williams and Haggarty (2022).

The survey area is divided into northern and southern regions (Figure B.1), which are fished in alternating years. The border between the two regions occurs approximately at the northern ends of Pacific Fishery Management Areas (PFMAs) 14 and 15 (Figure 2). However, several irregularities have occurred (Figure B.2):

- The survey did not take place in 2006, 2017 and 2020.
- The duration of the survey has varied annually, and has led to inconsistencies in the geographic extent surveyed between years.
- Desolation Sound (PFMA 15) is allocated as part of the southern region, but was sampled as part of the northern region in 2003, 2008, and 2019, and not sampled in 2009 and 2018. Catch rates of Quillback Rockfish are frequently high in Desolation Sound and in the northern region in general (PFMA 15; Figure 2). Therefore, we expect the lack of sampling in 2009 and 2018 to have an effect on survey estimates from the southern survey.
- The full southern survey was not completed in 2009 where only 38 blocks were fished in the southern Strait of Georgia, and only between Nanaimo and Victoria. This is in contrast to normal years when approximately 70 blocks are fished as far north as Campbell River. Catch rates of most rockfish species caught on this survey tend to decline from the north to the south, so this trend could also have a major effect on the survey index in that year.
- Sampling coverage in 2021 spanned both the northern and southern regions because there was no survey in 2020 (Williams and Haggarty 2022).

We applied a geostatistical spatiotemporal model to standardize of the HBLL index (e.g., Shelton et al. 2014; Thorson et al. 2015; Anderson et al. 2019) to account for the irregular implementation of the survey design (Section B.1.2). Previous work indicated that this approach can stitch together the north and south survey regions with relatively little bias to generate an index for the entire inside 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). The Inside HBLL survey catch is mostly comprised of 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, to the HBLL survey data. 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, $N^{(0)}_{i,t}$:

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

The adjustment factor depends on the proportion of observed hooks that are returned with bait still on them, $P_{i,t}$ (Figure B.3):

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

As $P_{i,t} \to 0$, $A_{i,t} \to \infty$, the expected number $N^{(0)}_{i,t} \to \infty$. Therefore, in cases where zero hooks were returned with bait, we set the number of baited hooks to one. See Anderson et al. (2019) (their Appendix G, Section G.5) for further details on the hook competition correction. The catch rate adjusted for hook competition (Figure B.4) 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 $O_{s,t}$ (fixed effect with 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 ($N^{\mathrm{hooks}}_{i,t}$):

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

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., $\mathrm{Var}(y_{s,t}) = \phi\mu^p_{s,t}$, which provides more flexibility in fitting over the Poisson and negative binomial distributions.

We assumed that the spatial random effects (ω_s) were drawn from 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 with which spatial correlation decays with distance.

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

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

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 $\boldsymbol{\Sigma}_\epsilon$:

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

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:

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

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

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

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

The spatial random effects accounted for spatial factors that were constant across time, for example, depth and substrate type. The spatiotemporal random effects 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 is independent and identically distributed (IID) and can constrain the change in the index from year to year. This feature would be desirable to constrain the change in the index from year to year because demographically, total abundance cannot rapidly fluctuate for a long-lived species.

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.5). 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.5).

Three spatiotemporal GLMMs were fitted, depending on 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 were also explicitly included in the GLMM to explain survey catch rates. Therefore, the random effects incorporate processes that affect distribution but are not accounted for by depth and substrate.
- Model 2: Spatiotemporal effects were estimated as a random walk. Habitat variables remained as fixed effects, with the year effect implicitly included in the random walk.
- Model 3: Spatiotemporal effects were estimated as a random walk and no habitat fixed effects. In this way, the random effects implicitly incorporate all processes that affect animal distribution.

Habitat variables include the set depth and distance to rock substrate and mixed substrate, chosen based on previous analyses (Carrasquilla-Henao et al. 2021). Substrate geospatial data for Area 4B were obtained from (Gregr et al. 2021) (Figure B.6). Depth for each set and survey block was measured *in-situ* by the survey vessel. 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 effect sizes were similar in magnitude.

From the fitted models, we projected predictions from the model to the full survey domain using the covariance projection matrix and the bilinear interpolation mesh provided by INLA (Lindgren et al. 2011; Rue et al. 2016) (Figures B.5 and B.7).

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

$$I_t = \sum_{j=1}^{n_j} w_j \cdot \exp\left(\boldsymbol{X}_{j,t}\boldsymbol{\beta} + \boldsymbol{\omega_j} + \boldsymbol{\epsilon_{j,t}}\right), \tag{B.12}$$

where j references a grid cell within the survey domain and w_j represents the area of that grid cell (Figure B.7). 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 generalized 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.

The resulting standardized population index accounts for the irregular sampling of the survey domain and hook competition and “stitches” the northern and southern regions into a single population index.

B.1.3. Model comparison

Overall trends in the estimated index are similar among the three spatiotemporal GLMMs (Figure B.8). Between Models 1 and 2, the magnitude in the index are similar but the inclusion of the random walk smooths out the trend over time. For both, habitat covariates were significant at $\alpha = 0.05$, with higher abundance expected at deeper depths and closer to rock and mixed substrate (Table B.1). However, Model 1 has a residual effect where the index is higher in years when the northern area was sampled. In effect, the model is spuriously assigning spatial effects as year effects.

Compared to Model 2, Model 3 is similar in trend although the confidence interval is smaller and the magnitude is smaller. In Model 2, the depth covariate is used to predict abundance over the survey domain, including waters exceeding 600 m depth, e.g., Johnston Strait and Bute Inlet (Figure B.9). However, the survey only samples up to depths of 150 m. The index was generated by extrapolating the depth effect beyond the depths sampled by the survey. As a result, the index developed from Model 2 has a larger confidence interval than from Model 3.

While Model 2 has a lower AIC score than Model 3 with $\Delta\mathrm{AIC}$ = 75.7, Model 3 is the preferred model for generating the index over the survey domain (Table B.2). Conceptually, the random effects should implicitly incorporate the habitat effects (up to 150 m depth) and avoids the problem of extrapolating well beyond the range of a fixed parameter.

For Model 3, spatial relative abundance is shown in Figure B.10. The spatial random effects show a north-south decreasing gradient consistent with the observed data (Figure B.11). The spatiotemporal time series show a gradual change consistent with the random walk (Figure B.12).

B.1.4. Self-simulation of the spatiotemporal GLMM

One method of evaluating the performance of a complex model is to perform self-simulation, where a model is used to generate simulated observations. The model is re-fitted to these simulated datasets. A well-performing model should be able to estimate the parameters used to generate the simulated datasets with minimal bias and high precision. Otherwise, poor performance could be indicative of poor model structure, e.g., overparameterization.

Simulated observations were generated from Model 3 by sampling from the Tweedie distribution conditional on the estimated dispersion parameters and spatial and spatiotemporal random effects (Equations B.3-B.4, Table B.1). The locations of the sampling sites are preserved in the simulation. A total of 100 simulation sets were generated. Both Model 1 and Model 3 were then fitted for each set of simulated observations, and the index generated by predicting the relative abundance across the grid cells in the survey domain (Equation B.12).

Overall, the simulated indices of abundance retain the character and trend of the indices seen in Figure B.8. When year effects are specified as fixed effects in estimation Model 1, the index alternates between high and low values. This appears to be a residual pattern from sampling of the northern and southern regions of Area 4B in alternating years. On the other hand, the random walk specification of the spatiotemporal effects in estimation Model 3 generates a smoother index trend from year-to-year (Figure B.13). Thus, it appears that Model 3 is a suitable model for developing the inside HBLL index.

B.2. JIG SURVEY, AREA 12

Hook and line jig fishing surveys were initiated in 1984 to support biological sampling and assessment of inshore rockfish. Jig surveys have sampled the following Pacific Fisheries Management Areas (PFMAs) in Johnstone Strait:

- PFMA 12 in 1986, 1987, 1988, 1992, and 2004
- PFMA 13 in 1986, 1987, and 1988

Jig surveys in Johnstone Strait followed a standardized protocol (Yamanaka and Lacko 2008). Ten sites were fished at three depth intervals (5-40 m, 41-70 m, and 71-100 m) on two separate days. Each fishing set comprised of three anglers fishing for 20 minutes in duration, with hooks baited with frozen herring. Data from these surveys were considered to be valuable for informing stock trends over the 1980-2000 time period.

PFMAs 15 and 16 in the Strait of Georgia have also been sampled in 1984, 1985, 1986, and 2004 (Haggarty and King 2005). Additional jig surveys have sampled PFMAs 17, 18, and 19 in the southern Strait of Georgia as part of a research program targeting Lingcod. (Haggarty and King 2006).

The focus was to develop an index based on the jig survey in PFMA 12, because this survey was designed to target rockfish and had a longer time series than in PFMA 13. Additionally, electronic records for recent years, i.e., 2004 and 2005 surveys in the Strait of Georgia, were not readily available in other PFMAs at the time of the analysis.

Catch per unit effort of the Area 12 survey was calculated as the number of fish caught per hour fishing. The annual mean and coefficient of variation was calculated by bootstrapping (Figure B.14 and Table B.3). The index shows a decline in 2004 relative to 1986-1992, due to the reduction in catch rates (there are fewer sets with high CPUE, Figure B.15).

While the Jig Area 12 index is limited spatially and does not explicitly index all of 4B, similar reductions in catch rates have been observed from jig surveys in other PFMAs within 4B (Haggarty and King 2005, 2006). Therefore, it is believed that this index can be representative of the population trends of the inside stock going back to the 1980s.

B.3. OTHER SURVEYS

B.3.1. Strait of Georgia Dogfish longline survey

The Dogfish longline survey is a depth-stratified longline survey that uses snap on gear with 300 size 14/0 circle hooks baited with Pacific Herring and a two-hour soak time (King et al. 2012). The survey began in 1986 and sampling has also occurred in 1989, 2005, 2008, 2011, 2014, and 2019. Dogfish survey samples nine locations in the Strait of Georgia that were historically fished by the commercial Dogfish fishery (King et al. 2012). For most of the time series, set-by-set catch of rockfish has been recorded (Figure B.16). Beginning in 2019, hook-by-hook data for all captured species were collected on board, along with biological data for rockfish.

The Dogfish survey is not designed to index rockfish, so there are several important differences between the inside HBLL and Dogfish survey designs. Perhaps the most significant difference is that the HBLL specifically targets habitats suitable for rockfish, i.e. hard bottom, whereas the Dogfish survey visits sites that were important in the commercial fishery that have mainly soft sediment bottoms. The Dogfish survey also uses slightly larger circle hooks than the HBLL survey (14/0 vs. 13/0); herring bait instead of squid; fishes 300 hooks per set instead of 225; and the hooks are spaced 1.8m apart instead of 2.4m. Encounter rates with Quillback Rockfish were low, with the proportion of positive sets below 0.25 for Quillback Rockfish (Table B.4). In addition, no calibration could be made to compare catch rates when a different in hook type was implemented after 2004 because no Quillback Rockfish were caught.

For these reasons, the Dogfish survey was not considered to be suitable survey to index the Quillback Rockfish population. A design-based index was developed and presented here (see Anderson et al. 2019), but was not further considered (Figure B.17, Table B.4).

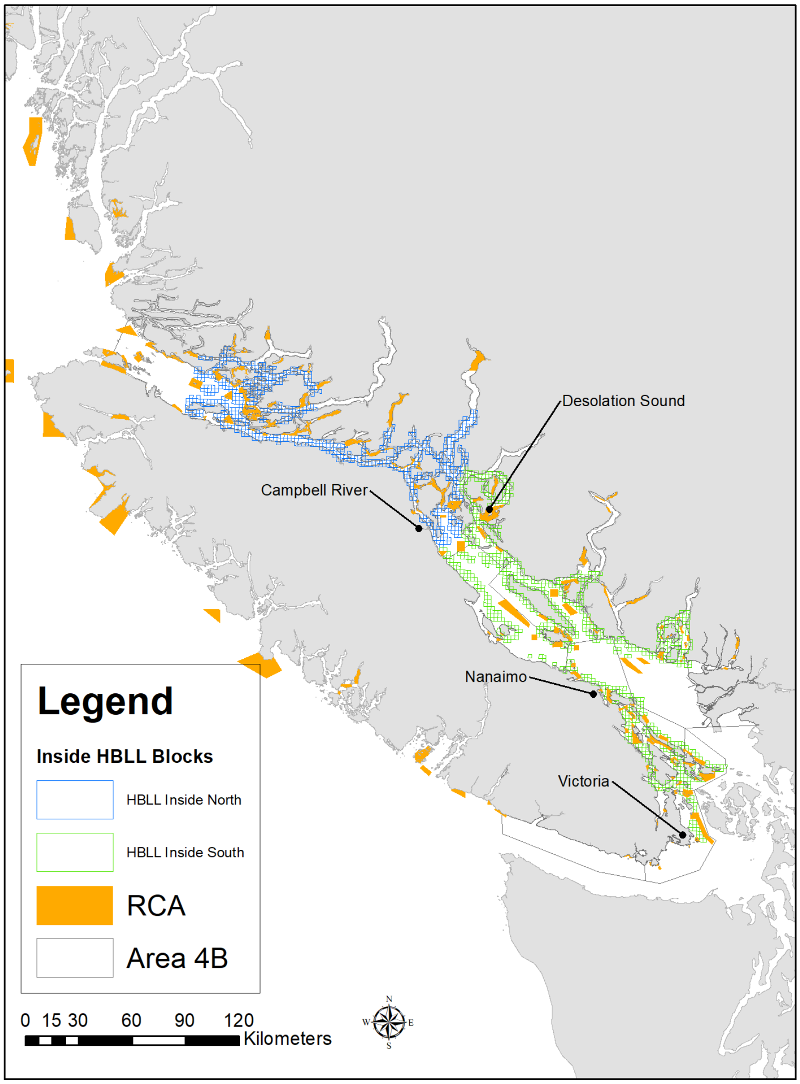

Figure B.1. Map of HBLL survey blocks indicating the northern (blue) and southern (green) regions. Rockfish Conservation Areas (RCAs, orange blocks) are also shown.

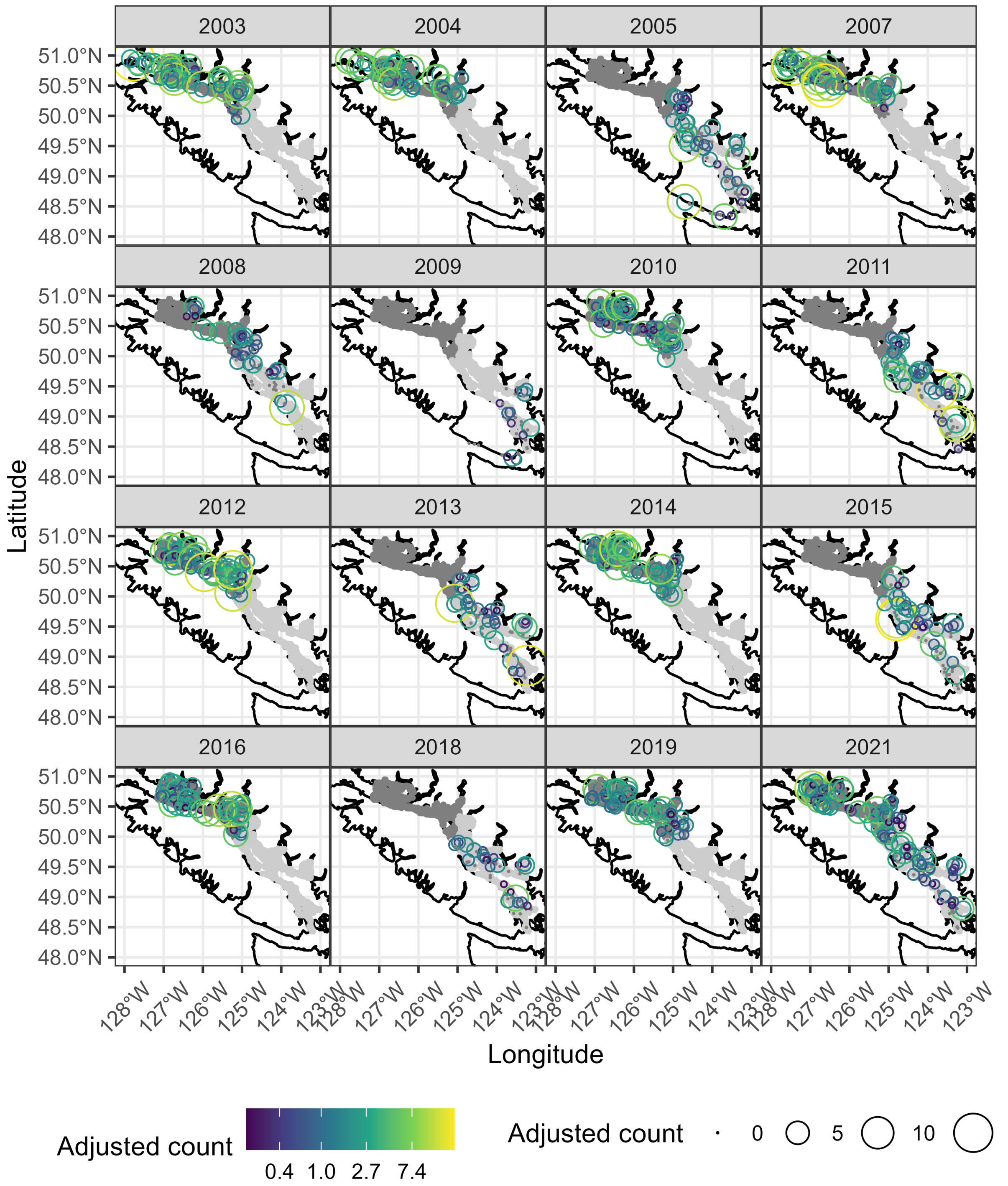

Figure B.2. Inside HBLL survey observations of Quillback Rockfish. Gray background shading indicates the northern and southern survey areas. The area of the circles represents the number of fish caught per hook after accounting for hook competition.

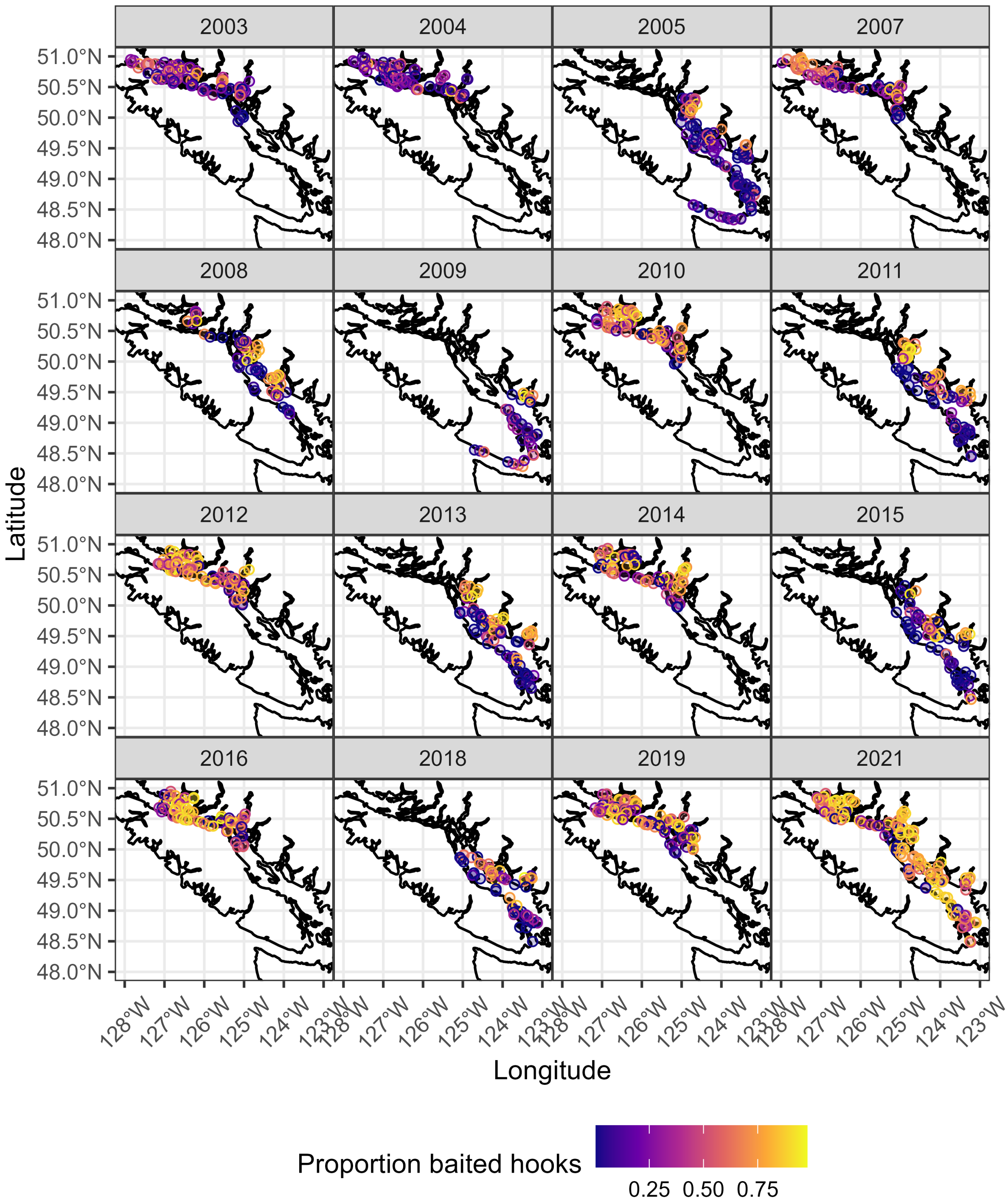

Figure B.3. Proportion baited hooks returned for the inside HBLL survey. Note the substantial difference between the northern and southern areas and the change in the north between 2003–2007 and subsequent years.

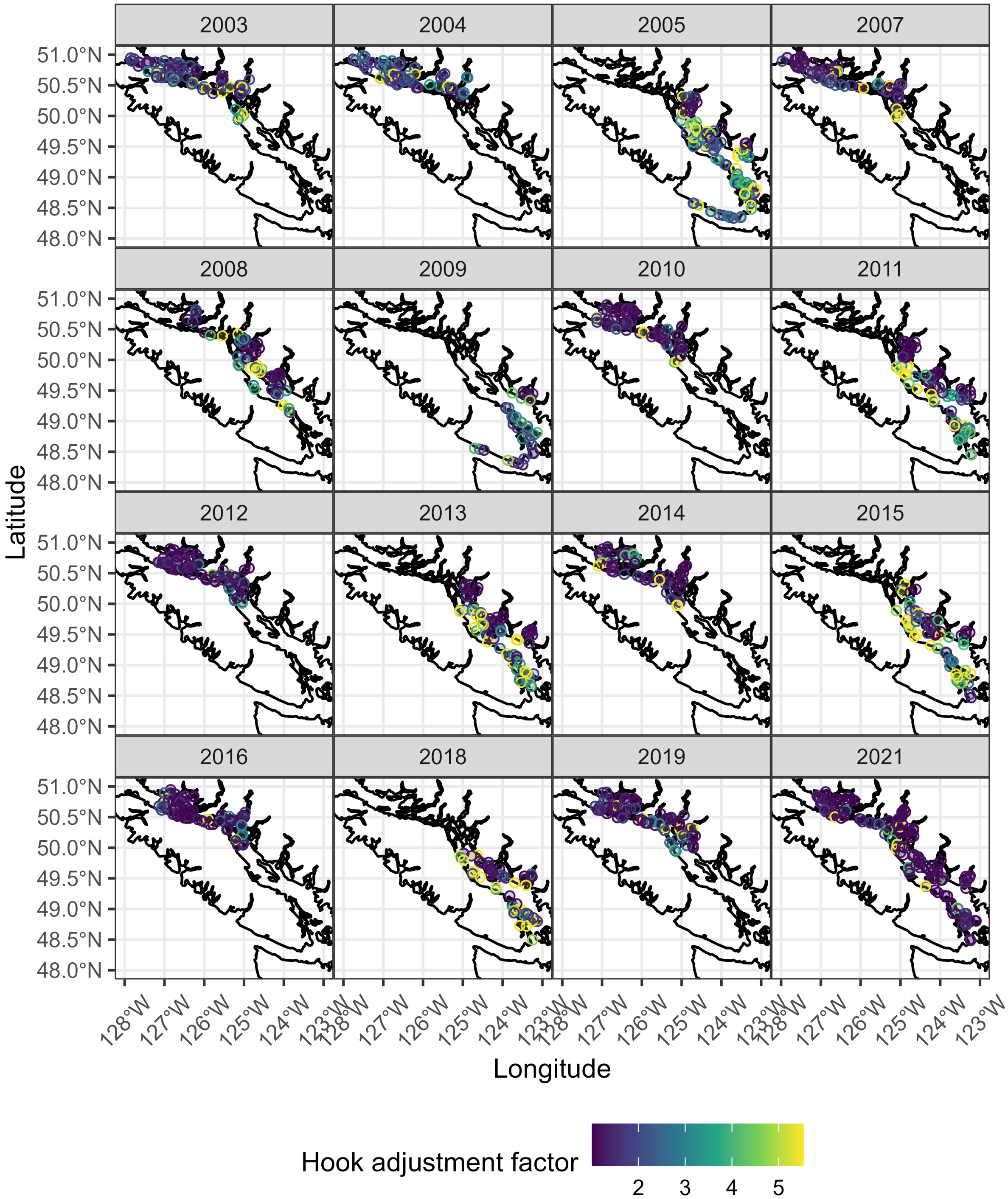

Figure B.4. Hook adjustment factor for the inside HBLL survey accounting for the number of hooks and the number of returned baited hooks.

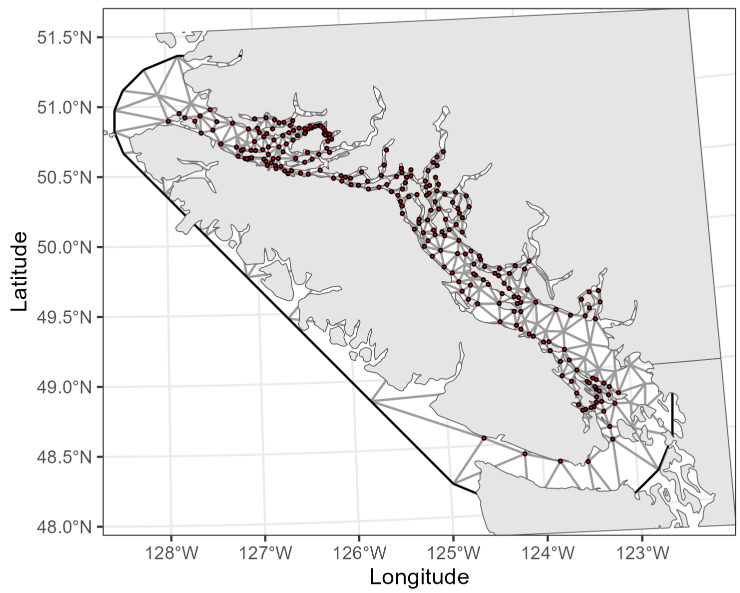

Figure B.5. Stochastic Partial Differential Equation (SPDE) mesh for the HBLL. The red dots represent the 250 knots made from k-means clustering of the spatial coordinates of the survey sets (across all years). These knots are then used to make the triangularization mesh used in the SPDE approximation and bilinear interpolation (grey lines). A greater number of knots will increase the accuracy of the approximation at the expense of computational time.

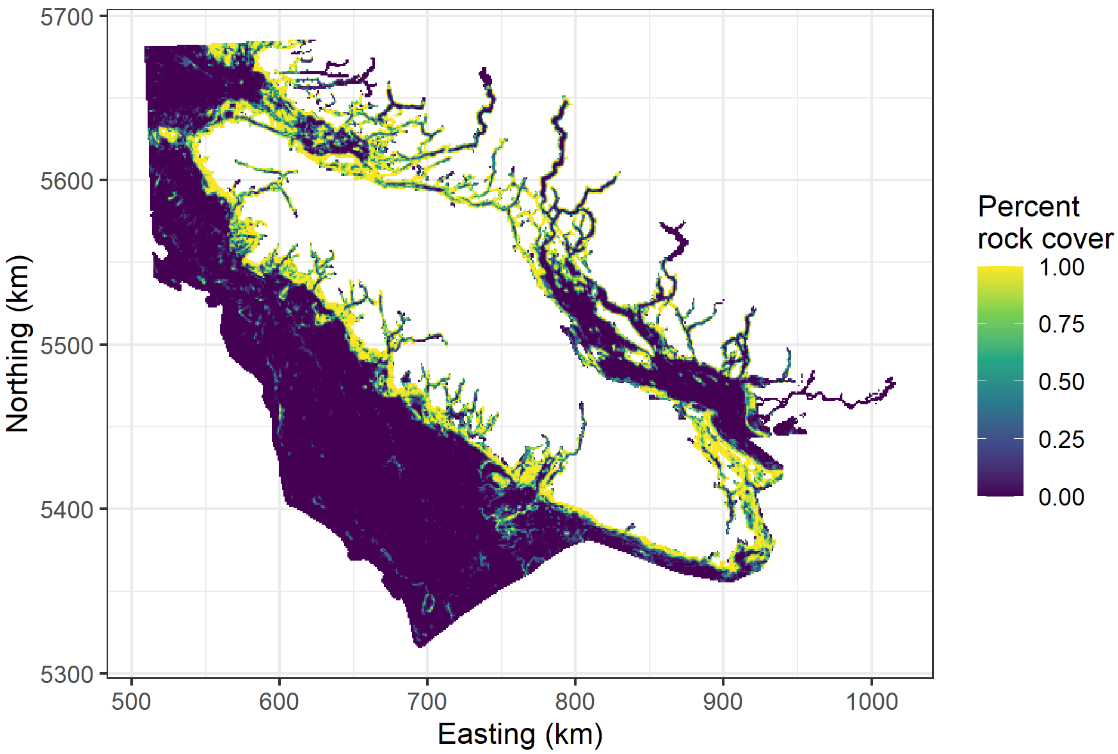

Figure B.6. Substrate map for Area 4B and surrounding areas (Gregr et al. 2021). The substrate was predicted for each 100 x 100 m cell. Here, the percent rock cover is calculated as the proportion of cells identified as rock substrate within each 1 km x 1 km grid. UTM coordinates, which facilitates calculation of Euclidean distance between points, are presented here.

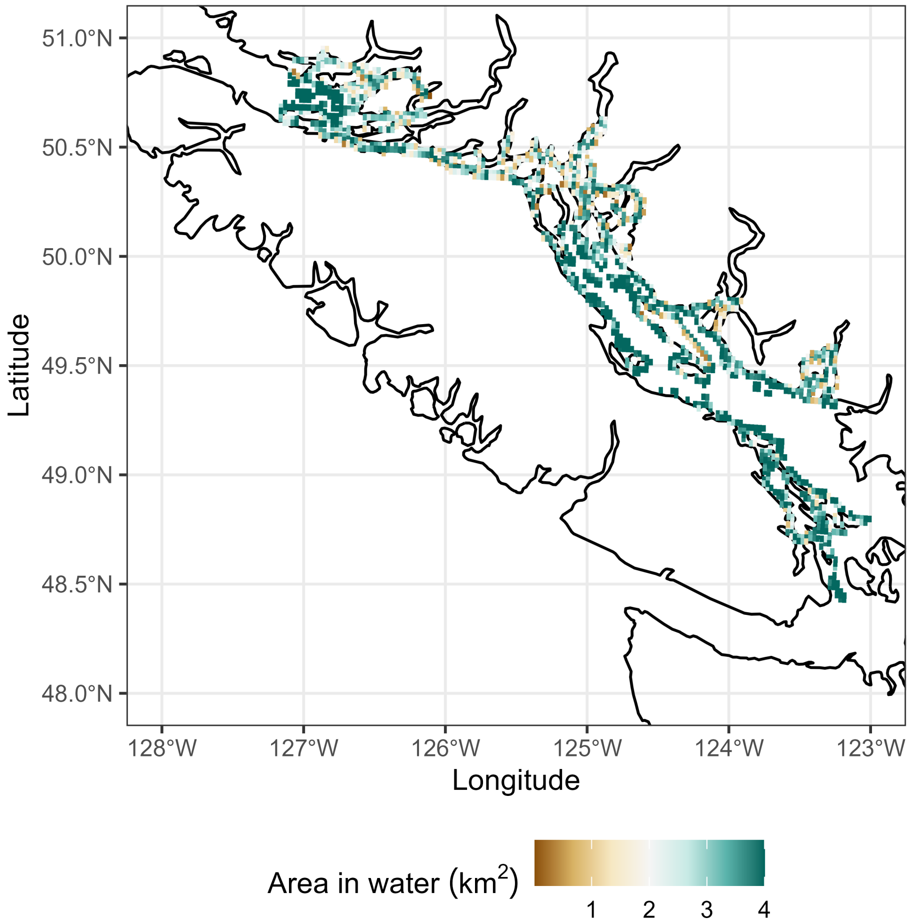

Figure B.7. Area per survey grid cell that is in water for the inside HBLL survey. The predicted count density for each grid cell is scaled up to the full survey domain based on these areas.

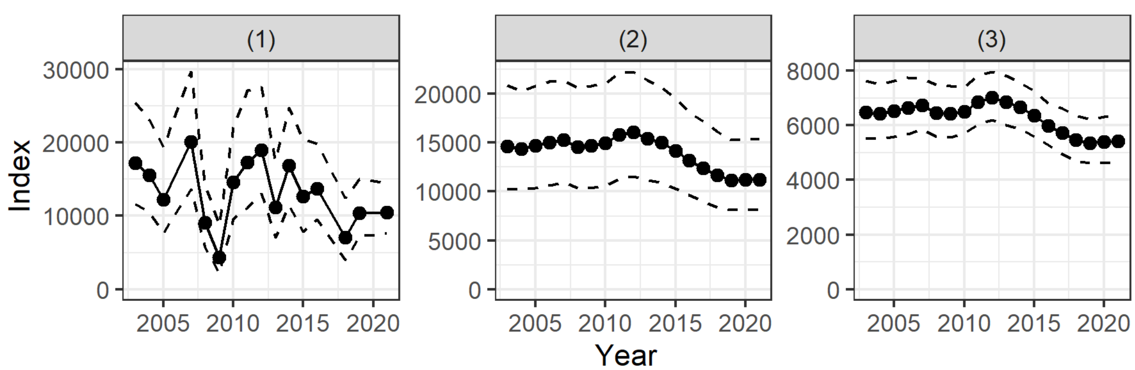

Figure B.8. Comparison of three indices of abundance from the inside HBLL survey: (1) Separate year effects with habitat covariates, (2) Random walk in spatiotemporal random effects with habitat covariates, and (3) Random walk with no habitat covariates. Dotted lines indicate the 95% confidence interval.

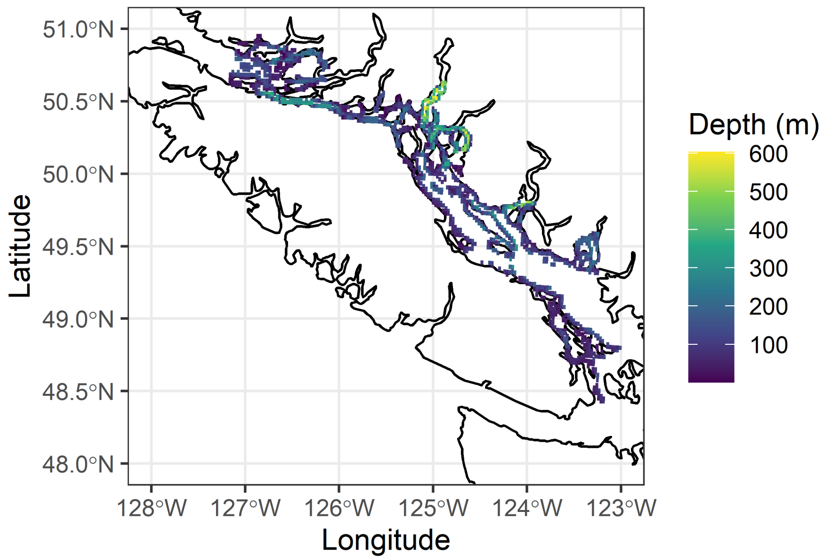

Figure B.9. Depth (m) of the HBLL survey domain used to predict abundance for the index.

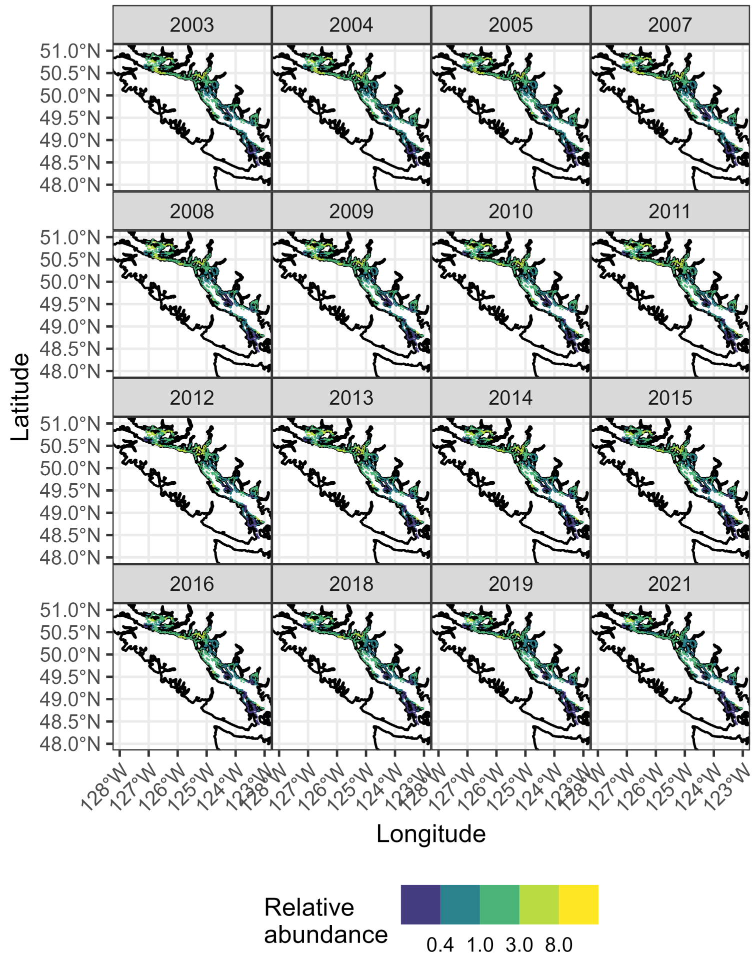

Figure B.10. Predicted relative density in space and time for the inside HBLL survey from GLMM Model 3.

Table B.1. Estimated parameters from the three spatiotemporal GLMMs for the inside 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.

Term	Model 1	Model 2	Model 3
depth_scaled	0.26*	0.27*	NA
drock_scaled	-0.08*	-0.09*	NA
dmix_scaled	-0.13*	-0.13*	NA
range	0.2	0.36	0.29
phi	2.48	2.53	2.59
sigma_O	0.84	0.86	1.00
sigma_E	0.38	0.24	0.23
tweedie_p	1.28	1.29	1.30
(Intercept)	NA	0.21	0.15

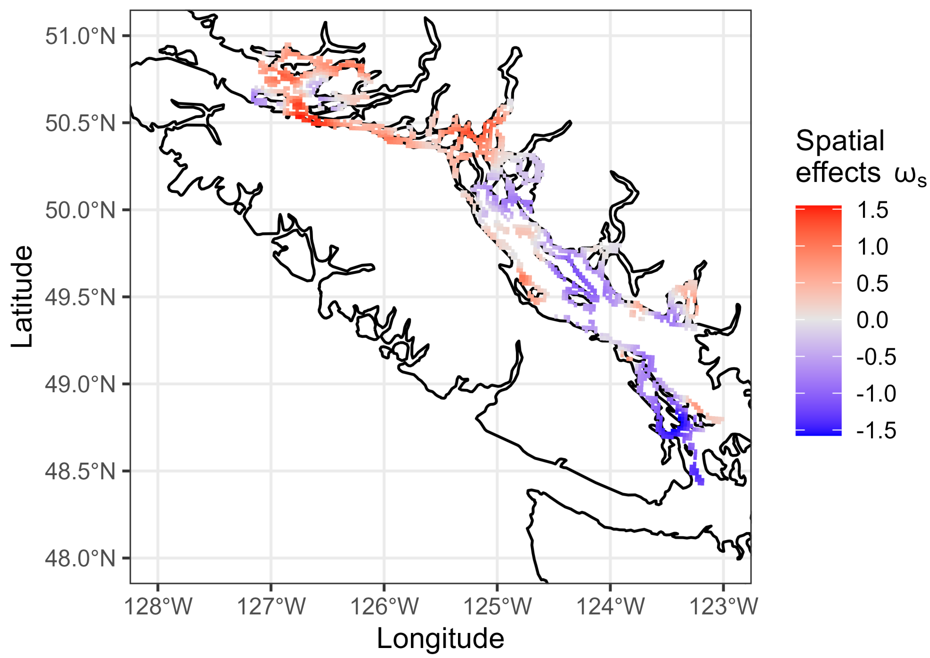

Figure B.11. Spatial random effects from GLMM Model 3. These are consistent spatially correlated differences in expected abundance through time. The values are shown in link (log) space.

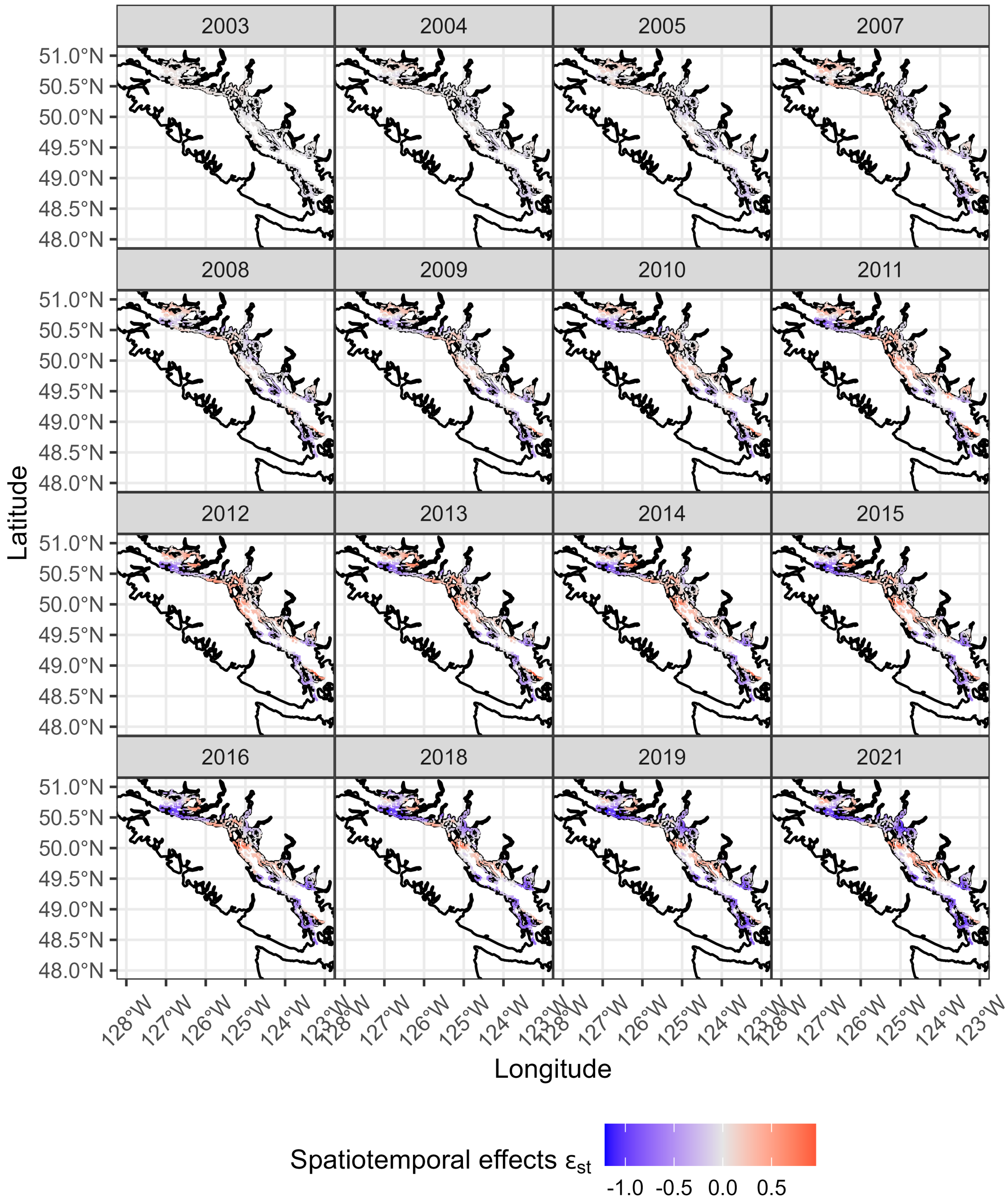

Figure B.12. Spatiotemporal random effects from GLMM Model 3. These are spatially correlated deviations that change through time. The variance in spatiotemporal random effects is slightly smaller than in the spatial random effects (previous figure).

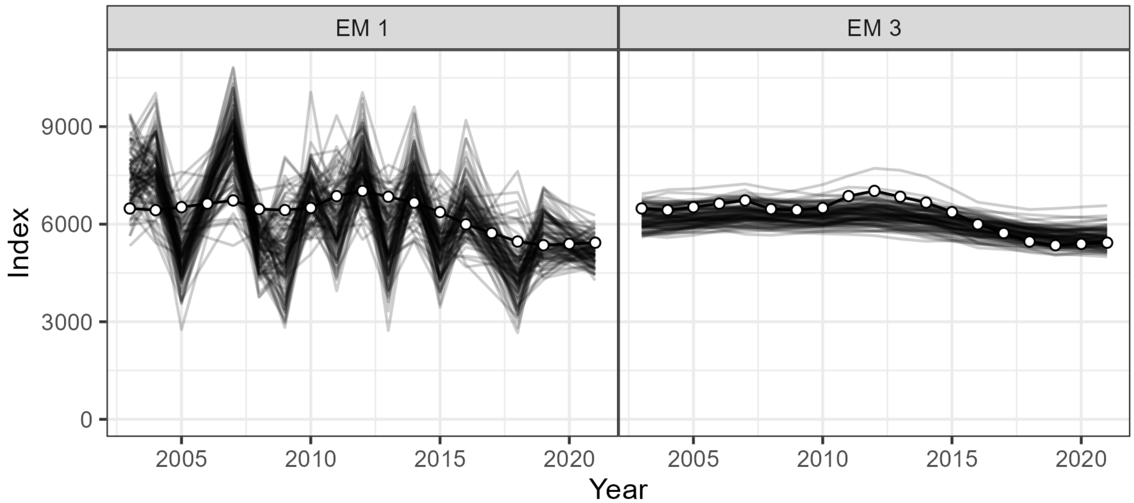

Figure B.13. Self-simulation of GLMM Model 3. One-hundred data sets were simulated from the model, and Model 2 and 3 were used to fit to those simulated values and generate the corresponding index. Light, black lines indicate the simulated indices from either estimation model (EM) 1 or 3. White points indicate the index developed Model 3 fitted to the real data.

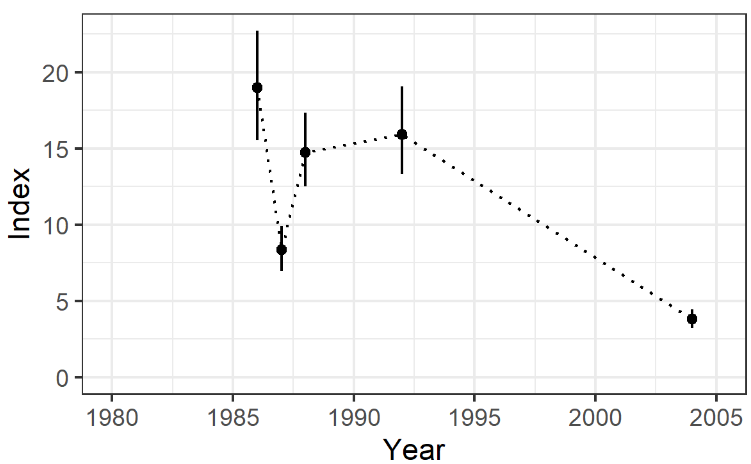

Figure B.14. Quillback Rockfish index from the Area 12 jig survey. Dots represent the mean catch per unit effort (fish per hour of fishing) and vertical line segments represent 95% confidence intervals from bootstrapping.

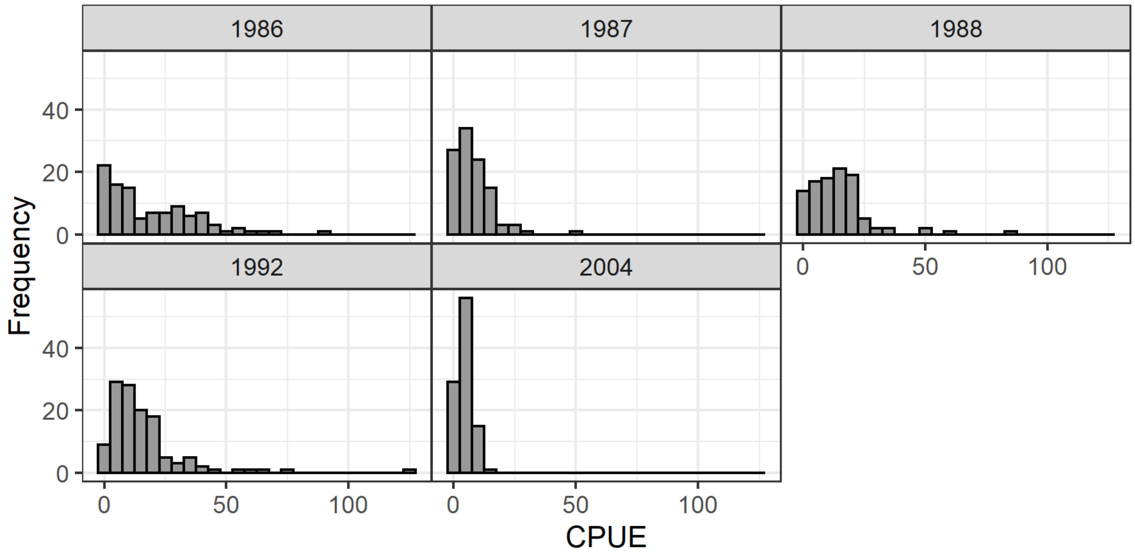

Figure B.15. Histogram of Quillback Rockfish CPUE (individual sets) from the Area 12 jig survey.

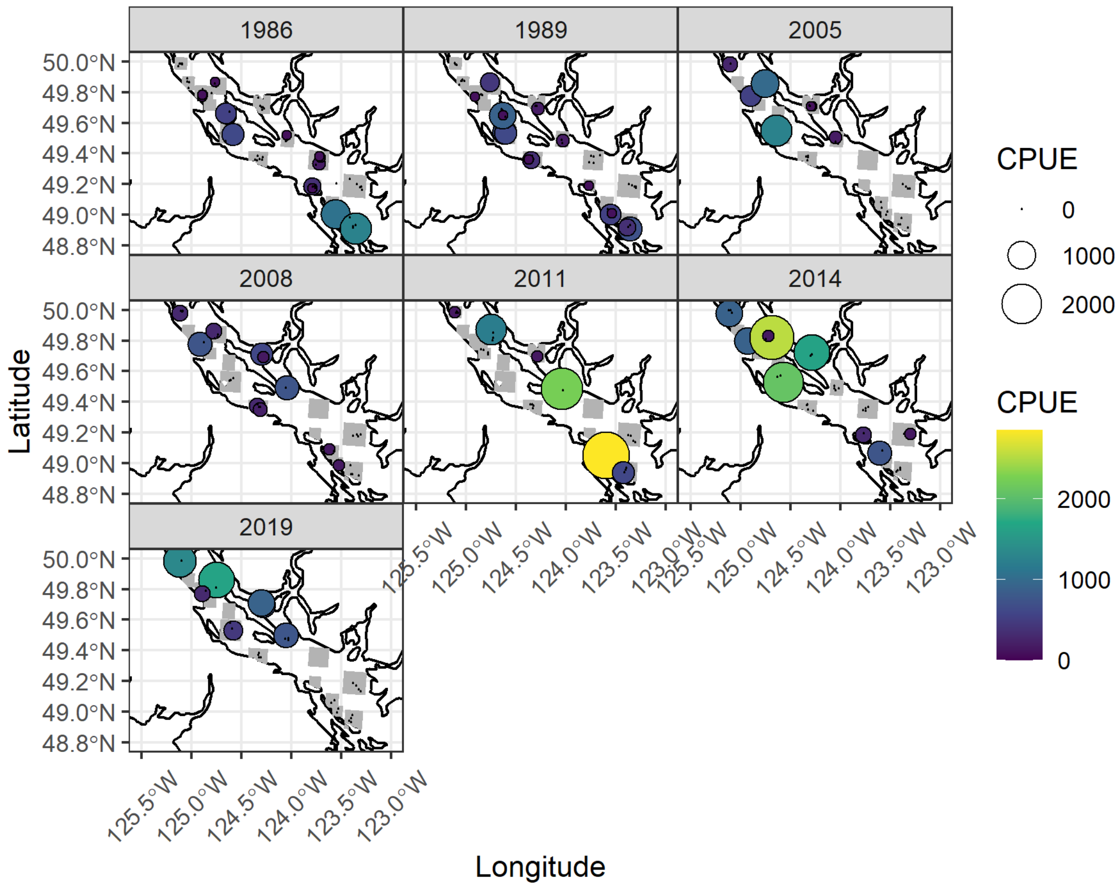

Figure B.16. Quillback Rockfish CPUE, numbers caught per area swept (km^2) per hook, in the Dogfish Survey. The values are shown as area of circles and color. Grey rectangles illustrate the assumed survey domain.

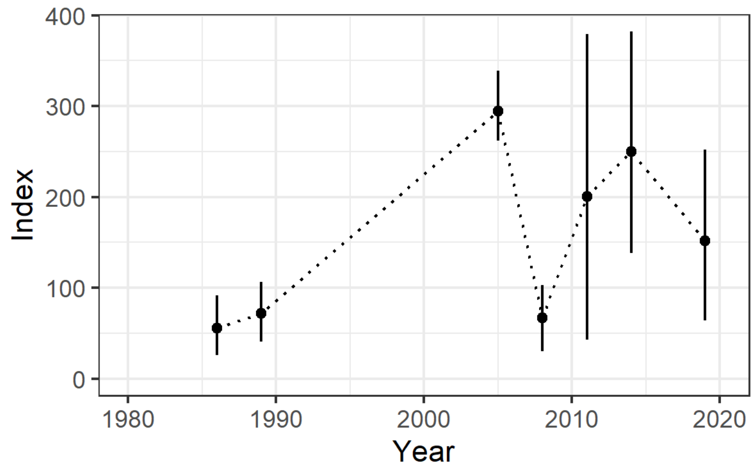

Figure B.17. Quillback Rockfish index from the Dogfish survey. Dots represent area-stratified means and vertical line segments represent 95% confidence intervals from bootstrapping.

Table B.2. Index of Inside Quillback Rockfish from the Inside HBLL Survey.

Year	Number of sets	Number of positive sets	Proportion positive	Index	Std. Dev.
2003	74	56	0.76	6,483	0.083
2004	63	50	0.79	6,431	0.078
2005	95	47	0.49	6,523	0.079
2007	60	44	0.73	6,729	0.071
2008	57	38	0.67	6,465	0.074
2009	36	13	0.36	6,434	0.074
2010	64	55	0.86	6,500	0.066
2011	69	46	0.67	6,863	0.066
2012	76	63	0.83	7,022	0.064
2013	66	37	0.56	6,844	0.067
2014	61	53	0.87	6,663	0.064
2015	60	35	0.58	6,371	0.066
2016	71	61	0.86	5,996	0.064
2018	55	26	0.47	5,466	0.078
2019	80	62	0.78	5,353	0.076
2021	138	104	0.75	5,431	0.075

Table B.3. Index of Inside Quillback Rockfish from the Area 12 jig survey.

Year	Number of sets	Number of positive sets	Proportion positive	Index	Std. Err.
1986	104	82	0.79	18.97	0.10
1987	108	87	0.81	8.36	0.09
1988	102	97	0.95	14.71	0.08
1992	125	116	0.93	15.89	0.09
2004	101	72	0.71	3.82	0.08

Table B.4. Index of Inside Quillback Rockfish from the Strait of George Dogfish Survey.

Year	Number of sets	Number of positive sets	Proportion positive	Index	CV
1986	77	16	0.21	55.56	0.30
1989	69	17	0.25	71.98	0.24
2005	40	7	0.17	294.21	0.07
2008	45	10	0.22	66.59	0.28
2011	35	6	0.17	200.11	0.44
2014	46	9	0.20	250.24	0.25
2019	39	7	0.18	151.97	0.32

APPENDIX C. FISHERY DATA

Inside Quillback Rockfish is caught in hook and line commercial fisheries, Food Social and Ceremonial (FSC) fisheries, and recreational fisheries. Management of Inside 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.8 and C.9.

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 Inside 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 ($/gamma$) calculated from a period with credible landings data from the hook and line dockside monitoring program (1997–2005) to generate a time series of catch by species, year, fishery sector, and management area (Table C.1). "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, when the ZN licence was instituted. Prior to that 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 data from 2000–2004 hook and line observer logs (Table C.2). The estimated historical unreported catch was then incorporated into the catch reconstruction, giving a final annual total (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 (greater than 75 percent) is from Statistical Areas 12 and 13 in Johnstone Strait (Figure C.3).

C.1.2. Biological samples

A biological sampling program for the commercial rockfish handline fishery was initiated in 1984 as landings increased and the fishery expanded northward into Statistical Areas 12 and 13 (Cass et al. 1986). Since Quillback Rockfish are sold live, samples were purchased from the fishery. It was frequently not possible to further identify the location and gear used to catch the fish.

Age samples were collected in 1984–1994, 1996, and 2000–2001 and presented in Figure C.4, since almost all commercial catch are from this gear (Figure C.2). A summary of the number of specimens collected and fishing events is provided in Table C.4.

No age samples have been collected from the commercial fishery since 2001. Since 2003, 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). The time series can be extended by calculating the mean weight from the biological sampling, although this is based on a subset of the catch. Mean weight has consistently fluctuated around 0.8-0.9 kg for most years without trend. The mean weight was slightly lower for 1996, 2000, and 2001, although the biological samples were collected from notably few fishing events (less than 5, Table C.4).

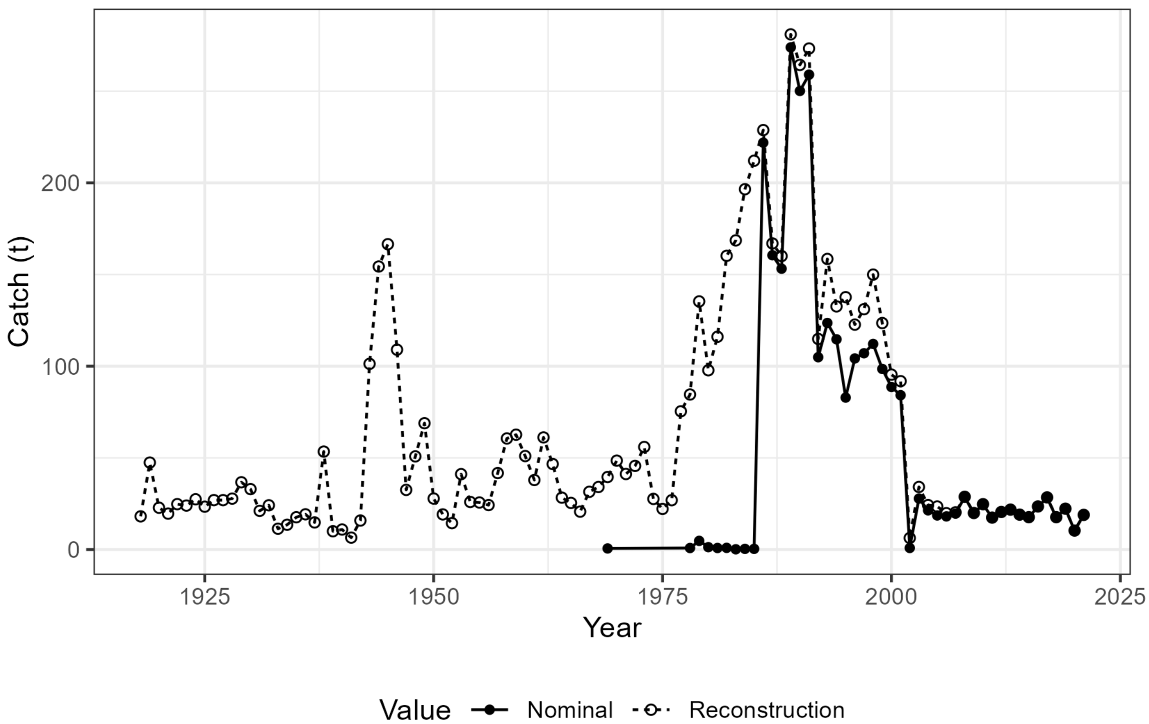

Figure C.1. Comparison of reconstructed and nominal commercial catch for Inside Quillback Rockfish.

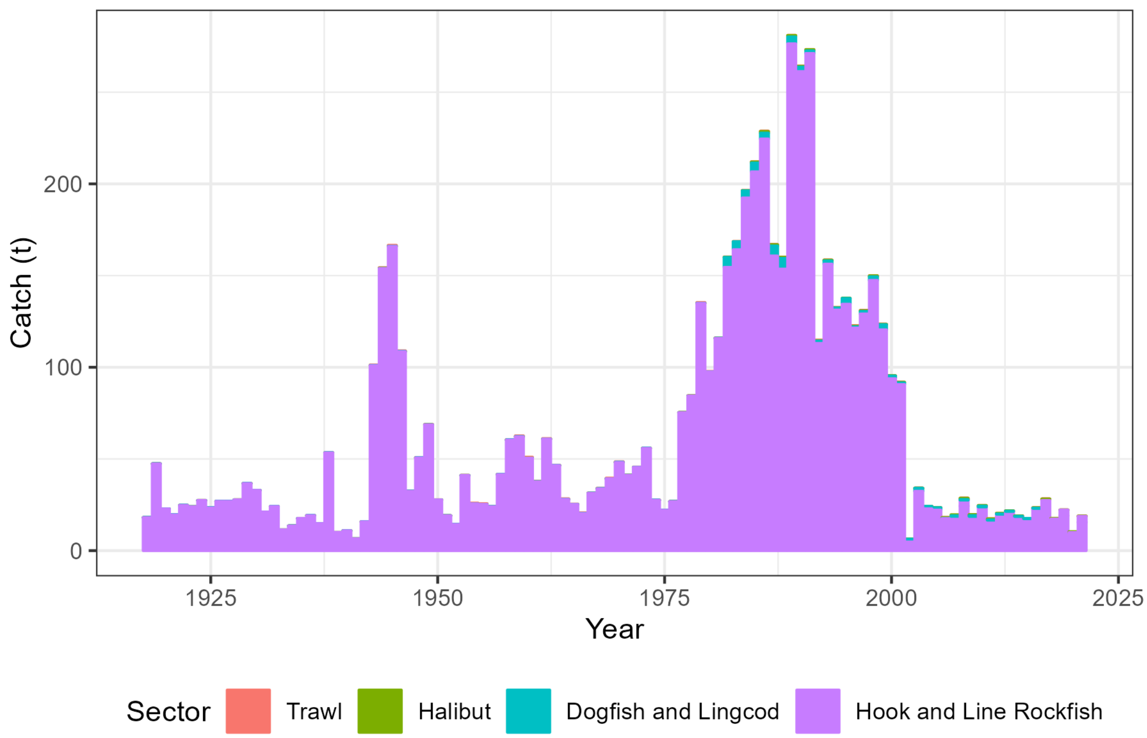

Figure C.2. Commercial catch by sector for Inside Quillback Rockfish. This figure contains reconstructed (1918–2005) and nominal (2006–2021) catch estimates in tonnes.

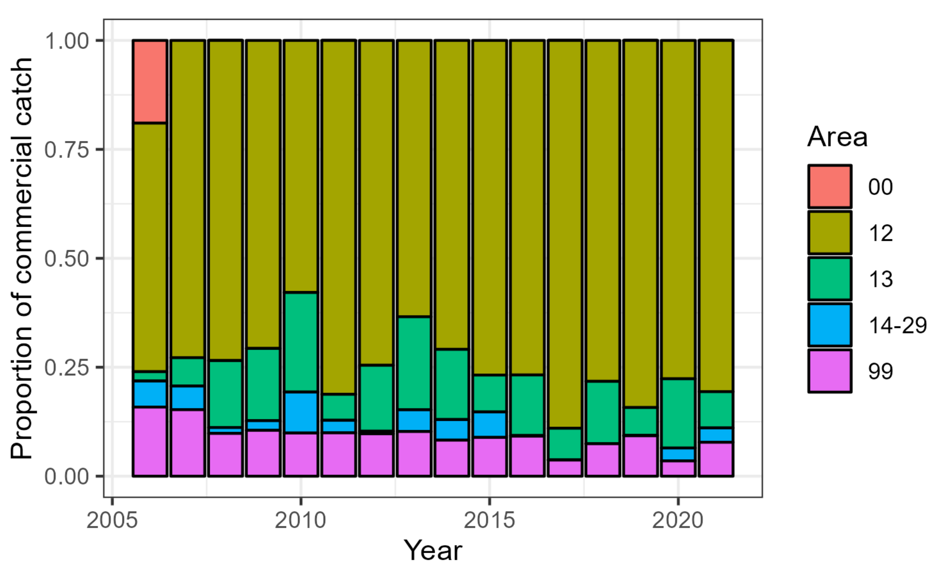

Figure C.3. Proportion of the commercial catch by area for Inside Quillback Rockfish. Codes 00 and 99 indicate that the Statistical Area of the catch was not known.

Age frequencies

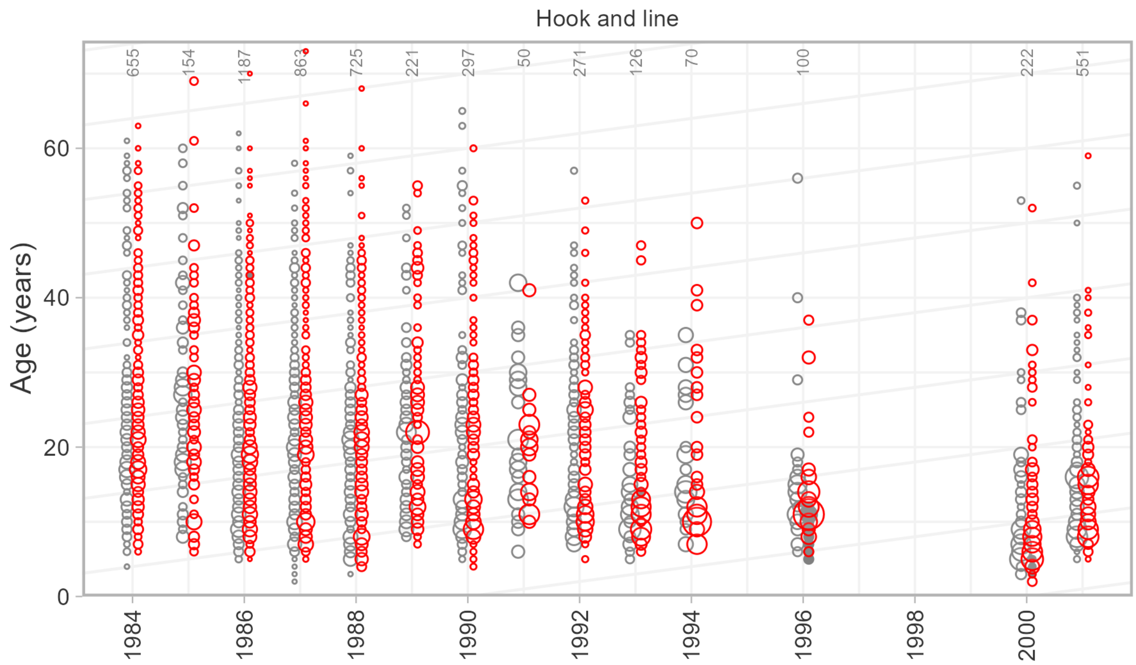

Figure C.4. Age samples from the commercial hook-and-line fishery (1984–2001). Female fish are shown as coloured circles and male fish are shown behind as light grey circles. The total number of fish aged for a given year is indicated along the top of the bubble plot. Diagonal lines are shown at five-year intervals to facilitate tracing cohorts through time.

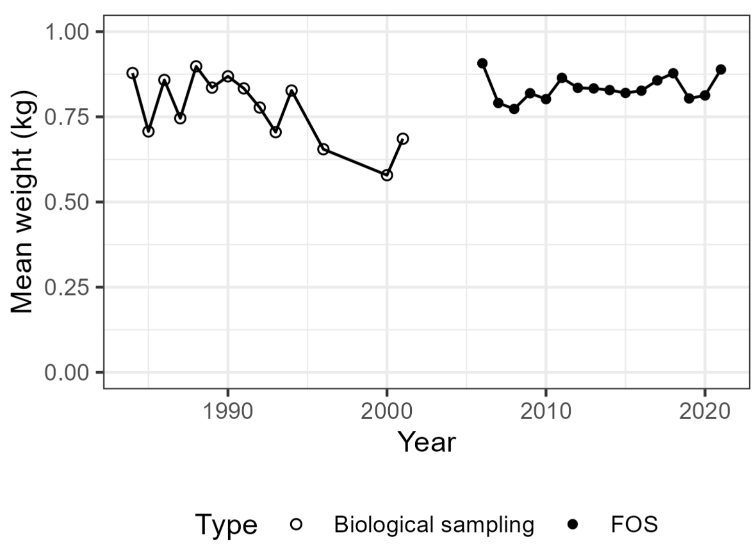

Figure C.5. Mean weight (kg) of Inside Quillback Rockfish caught in the commercial fishery. Mean weight prior to 2006 was calculated from individual weights collected from biological sampling. Values in 2006 and afterwards were obtained by calculating the ratio of total weight and total pieces reported in the Fishery Operations System (FOS) database.

Table C.1. Values of gamma, the ratio of Quillback Rockfish to other rockfish, by fishery sector in Area 4B used for the commercial catch reconstruction.

Sector	Ratio
Trawl	0.001437
Halibut	0.037001
Dogfish and Lingcod	0.089213
Hook and Line Rockfish	0.552418

Table C.2. Values of delta, the discard to landed ratio of Quillback Rockfish, by fishery sector in Area 4B used for the commercial catch reconstruction.

Sector	Ratio
Trawl	1.000000
Halibut	0.001337
Dogfish and Lingcod	0.001004
Hook and Line Rockfish	0.003769

Table C.3. Commercial catch by sector for Inside Quillback Rockfish. The table contains reconstructed (1918–2005) and nominal (2006–2021) catch estimates in tonnes.

Year	Trawl	Halibut	Dogfish and Lingcod	Hook and Line Rockfish	Total
1918	0.01	0.00	0.01	18.08	18.10
1919	0.01	0.01	0.03	47.38	47.43
1920	0.01	0.00	0.01	22.78	22.81
1921	0.01	0.00	0.01	19.56	19.58
1922	0.01	0.00	0.02	24.73	24.76
1923	0.01	0.00	0.02	23.95	23.97
1924	0.01	0.00	0.02	27.39	27.42
1925	0.01	0.00	0.02	23.35	23.37
1926	0.01	0.00	0.02	26.92	26.95
1927	0.01	0.00	0.02	26.92	26.94
1928	0.01	0.00	0.02	27.74	27.77
1929	0.01	0.00	0.02	36.66	36.69
1930	0.01	0.00	0.02	32.92	32.95
1931	0.01	0.00	0.01	21.08	21.10
1932	0.01	0.00	0.02	24.11	24.13
1933	0.00	0.00	0.01	11.34	11.35
1934	0.00	0.00	0.01	13.51	13.52
1935	0.01	0.00	0.01	17.60	17.62
1936	0.01	0.00	0.01	19.19	19.21
1937	0.00	0.00	0.01	14.76	14.78
1938	0.02	0.01	0.03	53.37	53.43
1939	0.03	0.00	0.01	9.93	9.97
1940	0.03	0.00	0.01	10.87	10.91

Year	Trawl	Halibut	Dogfish and Lingcod	Hook and Line Rockfish	Total
1941	0.02	0.00	0.00	6.47	6.50
1942	0.04	0.00	0.01	15.76	15.82
1943	0.28	0.01	0.06	100.92	101.28
1944	0.43	0.02	0.10	153.80	154.35
1945	0.51	0.02	0.11	165.89	166.52
1946	0.33	0.01	0.07	108.57	108.99
1947	0.11	0.00	0.02	32.40	32.53
1948	0.15	0.01	0.03	50.62	50.81
1949	0.20	0.01	0.04	68.64	68.89
1950	0.09	0.00	0.02	27.69	27.81
1951	0.06	0.00	0.01	19.08	19.15
1952	0.05	0.00	0.01	14.34	14.40
1953	0.08	0.00	0.03	41.01	41.12
1954	0.35	0.00	0.02	25.58	25.94
1955	0.37	0.00	0.02	25.25	25.65
1956	0.20	0.00	0.02	24.02	24.24
1957	0.12	0.00	0.03	41.55	41.70
1958	0.15	0.01	0.04	60.37	60.57
1959	0.46	0.01	0.04	62.13	62.63
1960	0.51	0.01	0.03	50.43	50.97
1961	0.30	0.00	0.02	37.59	37.91
1962	0.27	0.01	0.04	60.83	61.15
1963	0.15	0.01	0.03	46.46	46.64
1964	0.32	0.00	0.02	27.96	28.30
1965	0.18	0.00	0.02	25.22	25.42
1966	0.39	0.00	0.01	20.26	20.66
1967	0.14	0.00	0.02	31.32	31.48
1968	0.28	0.00	0.02	33.80	34.11
1969	0.28	0.00	0.03	39.24	39.55
1970	0.29	0.01	0.03	48.16	48.49
1971	0.10	0.00	0.03	41.06	41.19
1972	0.13	0.01	0.03	45.45	45.61
1973	0.07	0.01	0.04	55.81	55.93
1974	0.06	0.00	0.02	27.53	27.62
1975	0.08	0.00	0.01	22.05	22.15
1976	0.10	0.00	0.02	26.79	26.91
1977	0.09	0.01	0.05	75.25	75.39
1978	0.17	0.01	0.05	84.32	84.55
1979	0.36	0.01	0.09	134.86	135.32
1980	0.19	0.01	0.06	97.50	97.77
1981	0.16	0.01	0.07	115.80	116.05
1982	0.12	0.12	5.41	154.52	160.18
1983	0.08	0.04	4.32	164.15	168.59

Year	Trawl	Halibut	Dogfish and Lingcod	Hook and Line Rockfish	Total
1984	0.12	0.15	3.89	192.36	196.51
1985	0.08	0.53	4.83	206.61	212.05
1986	0.14	0.91	3.21	224.51	228.76
1987	0.04	0.74	5.43	160.72	166.94
1988	0.03	0.60	5.86	153.55	160.04
1989	0.01	0.82	3.75	276.40	280.97
1990	0.14	0.46	2.43	261.27	264.29
1991	0.03	0.65	1.44	271.14	273.27
1992	0.33	0.24	1.30	113.00	114.86
1993	0.02	0.39	1.81	156.25	158.47
1994	0.06	0.19	1.13	131.21	132.60
1995	0.00	0.05	3.17	134.41	137.63
1996	0.21	0.35	0.69	121.40	122.65
1997	0.18	0.43	1.36	129.09	131.06
1998	0.04	0.51	2.00	147.39	149.94
1999	0.01	0.24	2.83	120.43	123.51
2000	0.01	0.13	1.45	93.79	95.39
2001	0.01	0.31	0.94	90.58	91.83
2002	0.01	0.01	1.52	4.76	6.29
2003	0.02	0.03	1.70	32.38	34.13
2004	0.01	0.04	1.36	22.84	24.25
2005	0.01	0.03	1.31	22.12	23.47
2006	0.01	0.42	0.14	17.50	18.06
2007	0.00	0.53	0.38	18.69	19.60
2008	0.02	0.68	0.34	27.58	28.61
2009	0.01	0.53	0.51	18.64	19.69
2010	0.00	0.29	0.49	23.84	24.63
2011	0.00	0.65	0.06	16.65	17.35
2012	0.01	0.38	0.12	19.91	20.43
2013	0.01	0.16	0.19	21.39	21.75
2014	0.02	0.23	0.08	18.67	19.00
2015	0.01	0.09	0.05	17.42	17.58
2016	0.00	0.24	0.01	23.17	23.43
2017	0.00	0.82	0.00	27.37	28.20
2018	0.00	0.36	0.00	17.26	17.62
2019	0.00	0.02	0.00	22.19	22.21
2020	0.00	0.46	0.00	9.92	10.37
2021	0.00	0.18	0.00	18.70	18.88

Table C.4. Inside Quillback Rockfish age samples from the commercial hook and line fishery.

Year	Number of fishing events	Specimens	Ages	Age specimens collected
1984	4	807	655	807
1985	3	1,069	154	1,069
1986	6	1,413	1,187	1,413
1987	5	1,283	863	1,283
1988	4	725	725	725
1989	15	840	221	840
1990	3	399	297	399
1991	1	50	50	50
1992	32	785	271	785
1993	8	577	126	577
1994	7	248	70	248
1996	3	160	100	160
2000	4	222	222	222
2001	2	551	551	551

C.2. RECREATIONAL DATA

In 2012, DFO established a coast-wide, internet-based survey of tidal water licence holders (iREC), which collects Quillback Rockfish data (DFO 2015). However, the iREC data were not included in this analysis because the results of the survey calibration were not available at the time of the analysis (Robichaud and Haggarty 2022).

C.2.1. Catch

Annual catch (1982–2021) of inside Quillback Rockfish by the recreational fishery is estimated by the Strait of Georgia (SOG) and the Northern Vancouver Island (NVI) creel surveys in all PFMAs (Figure 2). The surveys cover PFMAs 12–20, 28, and 29 (Zetterberg and Carter 2010). Historical recreational catch prior to 1982 was reconstructed for the previous assessment based on trends in fishing effort developed through interviews with the owners of a recreational fishing resort (Yamanaka et al. 2011). Following Langseth et al. (2021), linear interpolation was used for 1945-1981 to characterize the development of the recreational fishery after World War II (Figure C.6).

Rockfish catch has been recorded in areas 13–19, 28, and 29 since 1982 but was not enumerated by species until 2000. In PFMA 12, rockfish have been counted by species since 2000, with no records prior to 2000 (Zetterberg and Carter 2010).

We followed the same method as in Yamanaka et al. (2011) to estimate the recreational catch of Inside Quillback Rockfish from 1982 to 1999. First, for all PFMAs other than PFMA 12, the average proportion of Quillback Rockfish to total rockfish catch was calculated for each PFMA in 2000 and 2001. The average proportions were then used to derive estimates of Quillback Rockfish catch from the total rockfish catch by PFMA between 1982–1999. The previous assessment assumed that the proportion of Quillback Rockfish catch in PFMA 12, out of the total Quillback catch in the Strait of Georgia (SOG), would remain relatively constant over time. Therefore, to estimate catch of Quillback Rockfish in PFMA 12 for the years 1982–1999, the proportion of Quillback Rockfish caught in PFMA 12, out of the total Quillback Rockfish caught in the SOG in 2000 and 2001, was calculated. The average proportion over 2000 and 2001 was then multiplied by the total Quillback Rockfish catch estimated for the rest of the SOG (sum of areas 13–19, 28 and 29) to estimate Quillback Rockfish catch in PFMA 12 by year. To be consistent with the previous assessment, an adjustment of 1.09 was applied to total annual effort to account for lack of records in PFMA 12, where effort was not recorded prior to 2000. We converted rockfish pieces to weight by multiplying by 0.94 kg, which was the average weight of Quillback sampled in the creel surveys between 2000 and 2008 (Table C.5). It is assumed that all released Quillback Rockfish die, for example, due to barotrauma.

Despite the availability of recent creel survey data, we did not develop a CPUE index for the recreational fishery. The creel survey is focused on characterizing the salmon fishery, and there has also been a shift towards active avoidance of rockfish in recreational fisheries with the implementation of management measures designed for rockfish conservation (Table C.9). As a result, there is concern that the CPUE for the recreational fishery would not be responsive to changes in abundance and would be misleading for assessment purposes.

The distribution of catch and effort among Statistical Areas in 4B since 2011 is reported in Figure C.7.

C.2.2. Biological samples

In addition to the aerial survey of effort count, the creel survey has a dockside interview component. Surveyors are stationed at boat ramps and marinas to interview returning anglers. Groundfish species are biologically sampled, with rockfish identified to species and the fork length measured (Zetterberg and Carter 2010).

Length composition from the creel survey are presented in Figure C.8 and Table C.6.

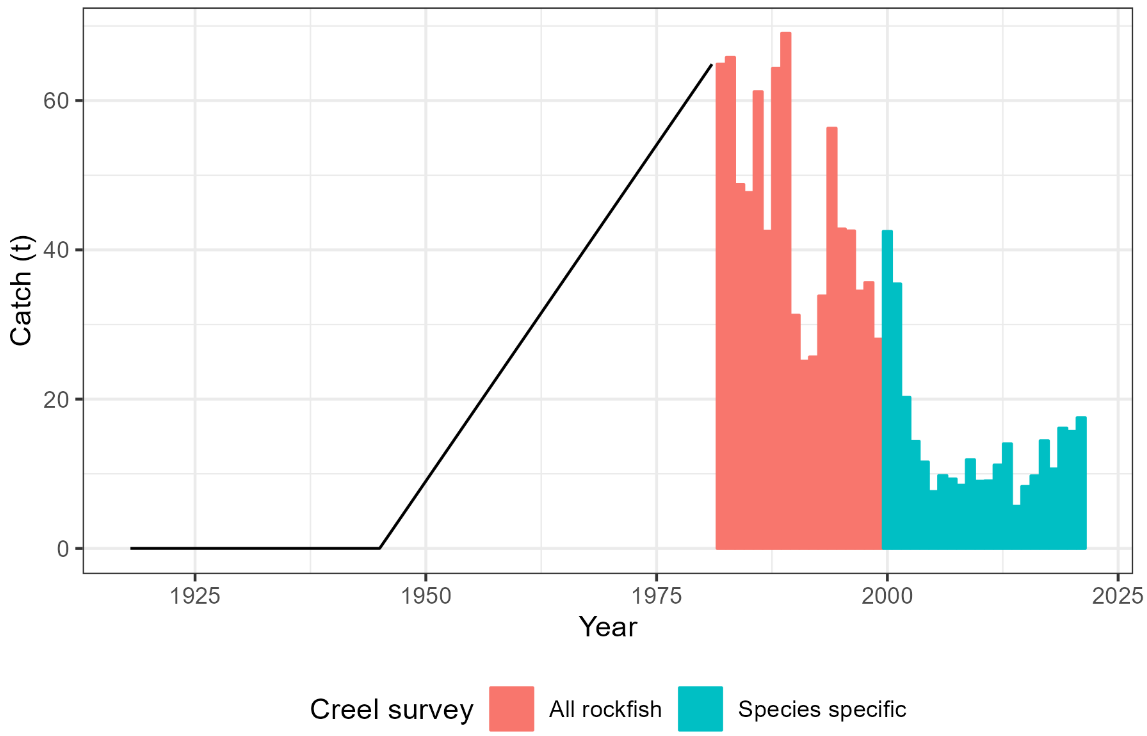

Figure C.6. Recreational catch for Inside Quillback Rockfish. The black line indicates reconstructed catch and the bars are creel survey data. The time series is a combination of interpolation (1918–1981), catch parsed from total rockfish catch in creel surveys (1982–1999), and catch from species specific creel surveys (1982–2021).

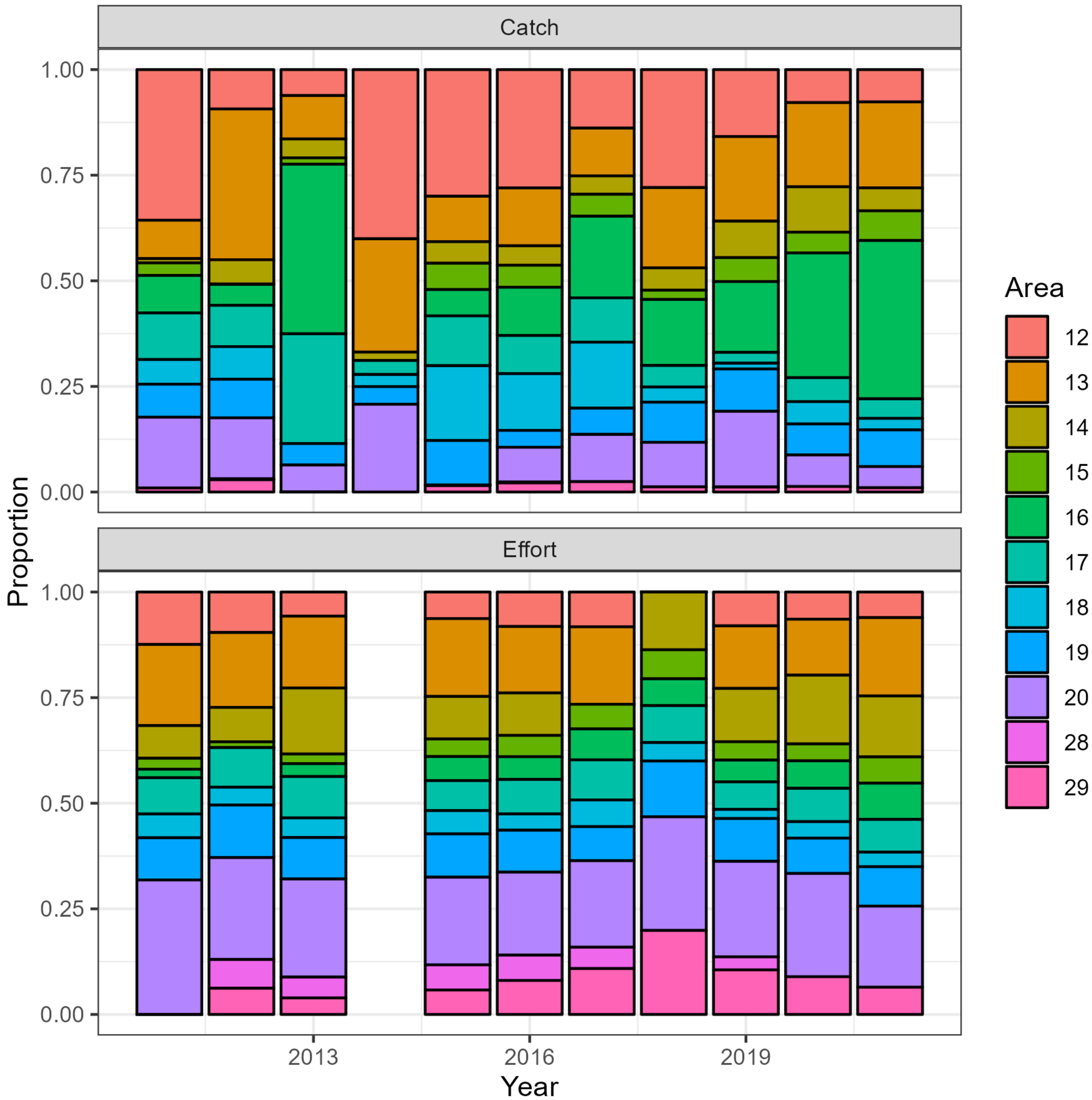

Figure C.7. Distribution of recreational fishery catch and effort within Area 4B. Note that the creel survey has missing strata.

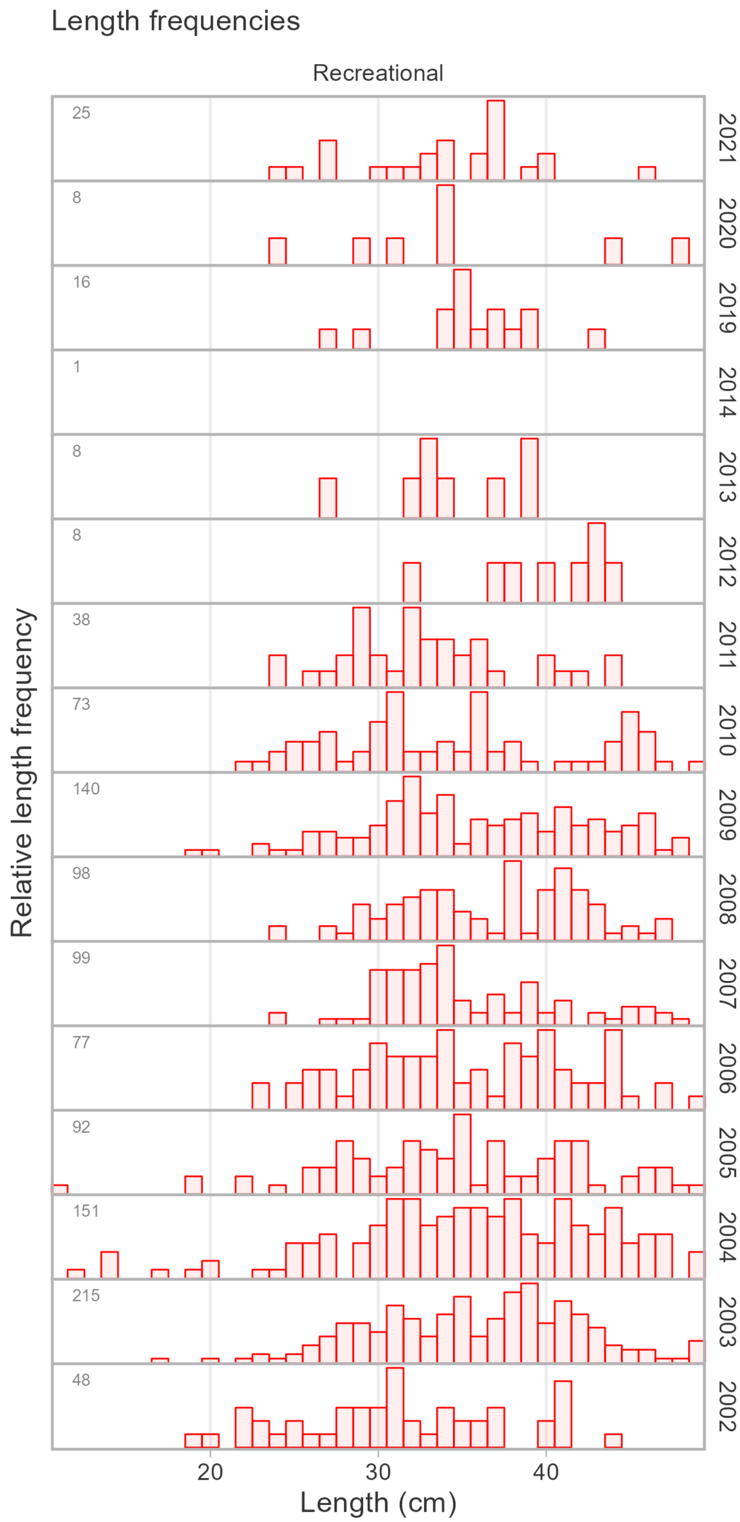

Figure C.8. Recreational length measurements for Inside Quillback Rockfish obtained from the dockside interview of the creel survey. The annual number of measurements is provided in the top left corner of each panel.

Table C.5. Recreational catch for Inside Quillback Rockfish from the creel survey. Catch in pieces is parsed from total rockfish catch in creel surveys (1982-1999), and catch from species specific creel surveys (1982–2021). Catch in tonnes is calculated using the mean weight of 0.94 kg per piece. Effort is in units of 10,000 boat trips.

Year	Pieces	Tonnes	Effort
1982	69,025	64.88	60.97
1983	69,990	65.79	58.18
1984	51,888	48.78	70.97
1985	50,723	47.68	68.51
1986	65,102	61.20	63.54
1987	45,229	42.52	64.27
1988	68,430	64.32	71.44
1989	73,446	69.04	65.76
1990	33,251	31.26	52.71
1991	26,708	25.11	22.53
1992	27,295	25.66	43.70
1993	35,985	33.83	54.28
1994	59,897	56.30	48.04
1995	45,542	42.81	35.28
1996	45,262	42.55	31.47
1997	36,688	34.49	29.74
1998	37,900	35.63	18.19
1999	29,838	28.05	17.81
2000	45,191	42.48	20.19
2001	37,708	35.45	21.46
2002	21,532	20.24	22.80
2003	15,280	14.36	19.72
2004	12,322	11.58	15.40
2005	8,111	7.62	12.28
2006	10,387	9.76	13.13
2007	9,909	9.31	13.42
2008	9,016	8.48	11.31
2009	12,637	11.88	12.63
2010	9,578	9.00	10.30
2011	9,637	9.06	13.29
2012	11,892	11.18	13.46
2013	14,905	14.01	16.45
2014	6,007	5.65	13.23
2015	8,833	8.30	19.33
2016	10,348	9.73	16.66
2017	15,352	14.43	19.02
2018	11,332	10.65	19.22
2019	17,148	16.12	13.99
2020	16,676	15.68	13.68
2021	18,638	17.52	14.19

Table C.6. Summary of length samples for Inside Quillback Rockfish from the creel survey angler interviews. Areas fished include PFMAs 10-21, 23-29.

Year	Number of landed sites	Number of PFMAs	Number of lengths
2002	12	8	48
2003	35	15	215
2004	29	12	151
2005	21	13	92
2006	21	9	77
2007	19	8	99
2008	23	10	98
2009	21	9	140
2010	11	8	73
2011	8	7	38
2012	2	2	8
2013	4	4	8
2014	1	1	1
2019	4	3	16
2020	4	3	8
2021	5	4	25

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), including in the inside waters of 4B. Specific to the southern part of our study area, the Coast Salish people have seen their relationship to marine resources eroded due to the development of commercial and recreational fisheries, as well as policy and political decisions (Ayers et al. 2012). 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) between 2007 and 2017 (Table C.7). 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 outside of area 4B, i.e., include the catch of Outside Quillback Rockfish. In order to deal with this, if more than 70% of the total landed catch (from all species) was from the inside waters, the catch was included in the commercial catch data for 4B. If more than 70% of the total landed catch was from the outside waters, they were excluded. For those trips with total catch comprised of <70% inside, we added 50% of that catch to the total catch for each year. Most of the dual fishing trips took place in the northern part of the study area because this is also where most of the commercial fishing for Quillback Rockfish in 4B currently takes place.

In the southern part of the study area, there is little commercial activity from Indigenous fishers. FSC catch in the Strait of Georgia is primarily from small recreational boats (Haggarty et al. 2021). Some FSC effort from small boats will be captured in the recreational data from the creel survey program. Although FSC fishers are not constrained by recreational catch limits or closures, their boats will be counted on the aerial portion of the creel survey, and therefore contribute to the expanded recreational catch estimates. The proportion of FSC fishers encountered by the dockside creel monitor was not, however, readily available in the recreational database (KREST) (Haggarty et al. 2021).

There is limited information available to assist with quantifying FSC catch of Inside 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.7. FSC catch (tonnes) of Inside Quillback Rockfish as a proportion of the commercial catch reported to dockside observers during dual fishing trips.

Year	FSC	Commercial	Total	Percent FSC
2007	0.0300639	0.0219991	0.0520631	57.745252
2008	0.2044784	1.2942510	1.4987294	13.643448
2009	0.0697894	0.4259029	0.4956922	14.079171
2010	0.1555269	1.0130592	1.1685862	13.308983
2011	0.2311495	0.9785161	1.2096656	19.108543
2012	0.2087013	1.7218072	1.9305085	10.810690
2013	0.0897927	1.6680092	1.7578019	5.108237
2014	0.0408957	1.0858763	1.1267720	3.629454
2017	0.0113352	0.1130891	0.1244243	9.110131

C.4. CHRONOLOGY OF MANAGEMENT CHANGES

Table C.8. History of management changes for the commercial Rockfish fishery in area 4B 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
1986	Inside	Feb 15 to Apr 15 closure
1987	Inside	Jan 1 to Apr 15 closure
1987	Inside	Provisional 75-metric-ton quota, area 12
1988	Inside	Year-round commercial closure, area 13 Discovery Pass
1988	Inside	Jan 1 to Apr 30 closure
1990	Inside	Jan 1 to Apr 30 and Nov 1 to Dec 31 closure
1991	Coastwide	Area licensing, 592 inside
1991	Inside	Trawl closure
1991	Inside	Live rockfish fishery only
1991	Inside	Jan 1 to May 14 closure, with no incidental rockfish catch allowances
1991	Inside	2-3-d opening in area 13 Discovery Pass
1991	Coastwide	Limited-entry licensing program was announced
1992	Inside	Limited-entry licensing with 74 eligible inside 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

Year	Area	Management Action
1998–1999	Inside	100 percent of commercial rockfish TAC allocated to the hook-and-line 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
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	Inside	Limited amount of at-sea observer coverage
2002–2003	Inside	75 percent reduction of inshore rockfish TAC from 2001
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	Inside	RCAs expanded to 28 percent of rockfish habitats
2005–2006	Coastwide	Introduce groundfish licence integration pilot program: 100 percent catch monitoring
2006–2007	Coastwide	Introduce groundfish integrated fishery management program
2012	Coastwide	Introduce trawl fishery boundaries in consultation with industry
2015	Inside	Implemented Strait of Georgia and Howe Sound glass sponge reef closures

Table C.9. 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
1992	Strait of Georgia	Daily limit reduced to 5 rockfish per person in Areas 12 to 19, 28 and 29 and Subareas 20-4 and 20-7.
2002	4B	Inshore Rockfish Conservation Strategy - Daily limit reduced to 1 rockfish in Areas 12 to 19, 28 and 29 and Subareas 20-5 to 20-7.
2002–2007	Coastwide	Rockfish Conservation Areas (RCAs) established - RCAs closed to fin fish harvest in recreational fishery.
2006	4B	Inshore rockfish recreational fishery closed in Areas 13 to 19, 28 and 29 from October 1.
2007	4B	Inshore rockfish recreational fishery closed October 1-May 31 in Areas 13 to 19 and Subarea 29-5. Areas 28 and 29 (except Subarea 29-5) remain closed until further notice.
2008–2016	4B	Inshore rockfish recreational fishery open May 1-September 30 in Areas 13 to 19, and Subareas 20-5 to 20-7 and 29-5. Areas 28 and 29 (except Subarea 29-5) remain closed.
2017	4B	Areas 13 to 19 and Subareas 12-1 to 12-13, 12-15 to 12-48, 20-5 to 20-7 and 29-5 open June 1 to September 30. Area 28 and 29 (except for Subarea 29-5) remain closed.
2019	4B	1 Rockfish daily; possession limits are twice the daily limit. Season length May 1-October 1.
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

Here we describe the specification of the initial OM before conditioning with the RCM. The operating model is described in Appendix A of Anderson et al. (2021).

D.1. STOCK SLOT DESCRIPTIONS

D.1.1. Maxage

The maximum age of the age structure of the model.

The maximum observed age of Inside Quillback Rockfish is 80 years (DFO, Pacific Region Groundfish Data Unit 2022). Here we set a maximum age of 60 years, noting that the maximum age class is treated as a plus group consisting of all fish older than 60 years.

```
display_om(oms, "maxage")
#> [1] 60
```

D.1.2. M

Natural mortality rate.

The rate of natural mortality *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 meta-analytic relationships published in the literature.

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 heteroscedasticity. As reported in Hamel (2015), the estimate of natural mortality is

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

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. Natural mortality is estimated as

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

and

$$M_{\text{Then-nls}} = 4.899 \times a_{\mathrm{max}}^{-0.916} \tag{D.3}$$

using log-log regression and direct non-linear least squares (NLS) of the untransformed variables, respectively.

Using the maximum age of 80 years for Inside Quillback Rockfish, we developed three prior distributions for *M*:

$$M_{\mathrm{Hoenig}} \sim \mathrm{Lognormal}(0.055, 0.06) \tag{D.4}$$
$$M_{\text{Then-log-log}} \sim \mathrm{Lognormal}(0.067, 0.08) \tag{D.5}$$
$$M_{\text{Then-nls}} \sim \mathrm{Lognormal}(0.088, 0.11) \tag{D.6}$$

where the mean is the given the equations above and the standard deviation is taken from the standard error of the intercept term in the regression.

The Then-log-log estimate is the preferred value, based on the latest available information and the use of log-log regression, followed by the Hoenig and Then-nls estimates. Accordingly, the three reference operating models are organized in this order and robustness operating models use the Then-log-log (mean M = 0.067) estimate. We incorporated uncertainty using a Monte Carlo approach by sampling *M* from these prior distributions. From these three distributions, the range in *M* was 0.04–0.11 (Figure D.1).

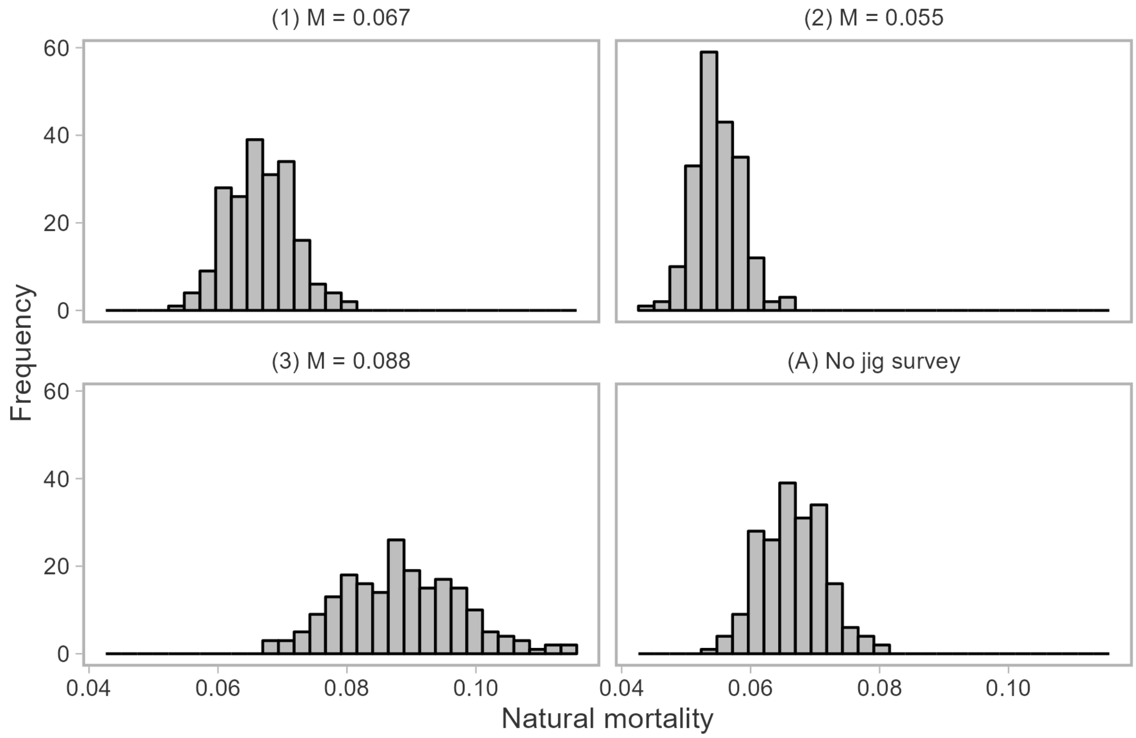

*Figure D.1. Distributions of natural mortality (*M*) used in the OM scenarios. Values in operating model (A) are identical to those in (1).*

D.1.3. h

Steepness of the stock-recruit relationship.

Steepness (*h*) is another core uncertainty for most stocks. For Pacific rockfish in British Columbia and U.S. West Coast, Forrest et al. (2010) estimated a posterior mean of 0.67 and standard deviation of 0.17 of the Beverton-Holt steepness parameter. This distribution was subsequently used in Yamanaka et al. (2011). We incorporated uncertainty using a Monte Carlo approach, by sampling *h* from a probability distribution, where $X \sim \mathrm{Beta}(\alpha = 2.56, \beta = 1.80)$, which was then transformed to $h = 0.8X + 0.2$. The sampled distribution was identical for all operating models and gave steepness values between 0.28–0.99, which is a broad range of coverage.

Process error, the CV of lognormal recruitment deviations.

We used a value of 0.4, as estimated in the base model for the Outside Yelloweye Rockfish rebuilding plan (Cox et al. 2020).

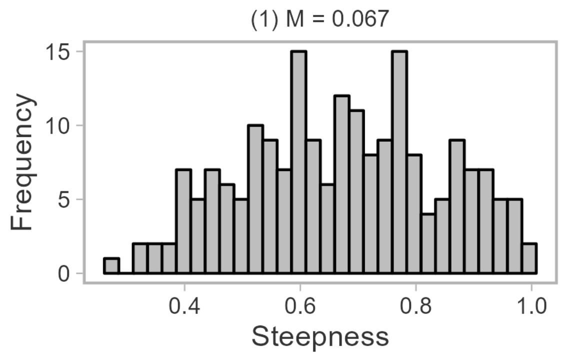

Figure D.2. Distributions of steepness (h) used in the OM scenarios. All OMs used the same h samples.

D.1.4. Perr

```
display_om(oms, "Perr")
#> [1] 0.4 0.4
```

D.1.5. Linf

Mean asymptotic length.

This value was estimated from length and age data from the survey data collected in Area 4B (see Appendix A). This parameter was estimated for both males and females combined, as no sexual dimorphism has been observed for this stock.

```
display_om(oms, "Linf")
#> [1] 39.1 39.1
```

D.1.6. K

von Bertalanffy growth parameter.

This value was estimated from length and age data from the survey data collected in Area 4B (see Appendix A). This parameter was estimated for both males and females combined, as no sexual dimorphism has been observed for this stock.

```
display_om(oms, "K")
#> [1] 0.1 0.1
```

D.1.7. t0

von Bertalanffy theoretical age at length zero.

This value was estimated from length and age data from the survey data collected in Area 4B (see Appendix A). This parameter was estimated for both males and females combined, as no sexual dimorphism has been observed for this stock.

```
display_om(oms, "t0")
#> [1] -3.38 -3.38
```

D.1.8. Maturity

Maturity ogive.

Maturity was directly input as an age-based function. Therefore the default operating slots L50 and L50_95 were not used. Female maturity-at-age was estimated using maturity and age data from the survey data collected in Area 4B (Appendix A). The minimum observed age of maturity was 5 years and it assumed that younger ages were all immature.

```
# Maximum age in the model is 60 years
age <- 0:60

# Parameters estimated from binomial GLM with cauchit link
intercept <- -4.448074 + 1.04861607
slope <- 0.44060084 - 0.04981391
linear_predictors <- intercept + slope * age

Mat_age <- ifelse(age < 5, 0, pcauchy(linear_predictors))
```

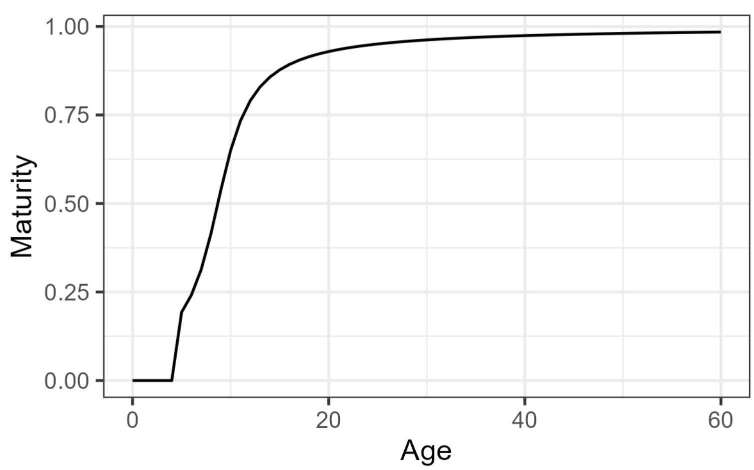

Figure D.3. Maturity-at-age in the operating model. The minimum observed age of maturity was 5 years and it assumed that younger ages were all immature.

D.1.9. a

Length-weight parameter alpha.

This value was estimated from length and weight data from the survey data collected in Area 4B (see Appendix A). This parameter was estimated for both males and females combined, as no sexual dimorphism has been observed for this stock.

```
display_om(oms, "a")
#> [1] 0.00001588715
```

D.1.10. b

Length-weight parameter beta.

This value was estimated from length and weight data from the survey data collected in Area 4B (see Appendix A). This parameter was estimated for both males and females combined, as no sexual dimorphism has been observed for this stock.

```
display_om(oms, "b")
#> [1] 3.06
```

D.2. FLEET SLOT DESCRIPTIONS

D.2.1. CurrentYr

The final calendar year of the historical simulations (t_c).

```
display_om(oms, "CurrentYr")
#> [1] 2021
```

D.2.2. nyears

The number of years for the historical period.

The time series of historical catch data $t_1 = 1918$ to $t_c = 2021$ was used to define the historical period of the operating model.

```
display_om(oms, "nyears")
#> [1] 104
```

D.2.3. Selectivity

Selectivity for the commercial and recreational fisheries and the survey were directly input as age-based logistic functions, as estimated in the RCM. Therefore the default MSEtool slots describing selectivity-at-length were not used.

The selectivity at age for all simulations is plotted in Figures D.4 – D.7. The median age at 50% and 95 percent selectivity for each operating model is reported in Tables D.1 and D.2, respectively. Estimates are consistent among the three reference operating models. When the jig survey is excluded from the RCM in the robustness operating model (A), the selectivity shifts rightward for the commercial fishery.

For the projection period ($t > t_c$), only a single fishery is modeled. In analyses with more than one fishery, the aggregate selectivity-at-age is weighted by the fishing mortality of the individual fishing fleets, based on normalized SRA estimates of relative fishing mortality by age and year $F_{a,y}$ (see Appendix A of Anderson et al. (2021)). The closed-loop simulation projections assume that the relative selectivities across fleets remains constant, as estimated by the RCM in the final historical year (t_c) (Figure D.8).

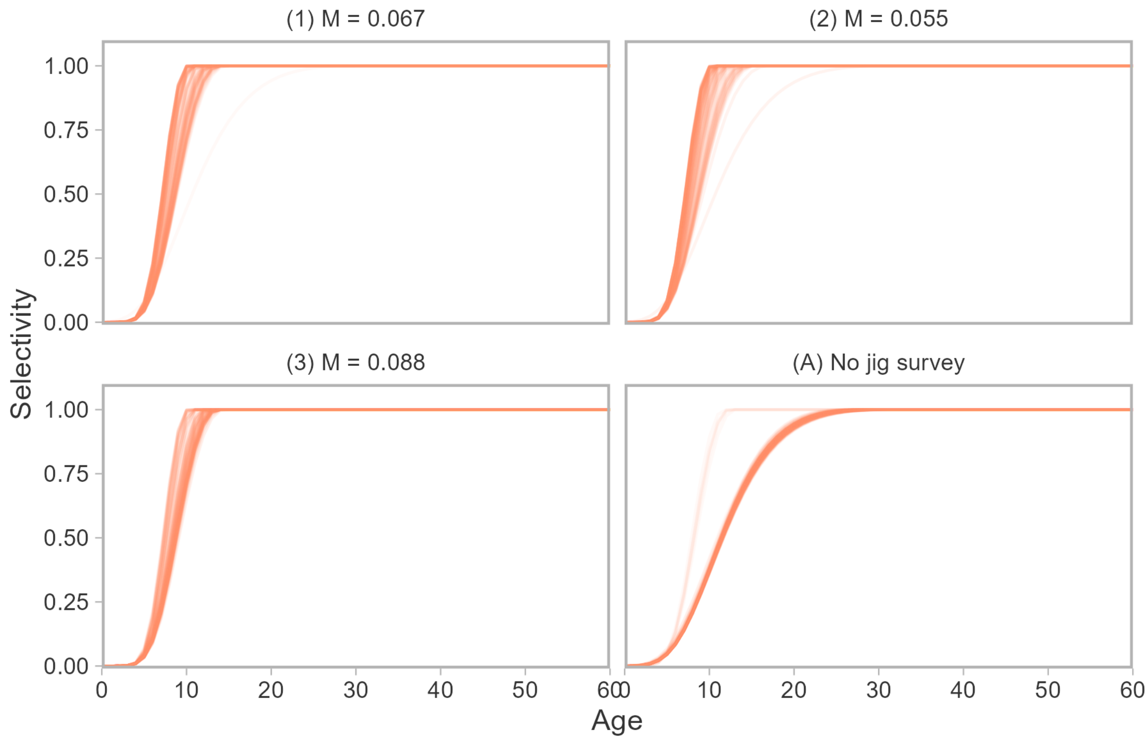

Figure D.4. Selectivity-at-age estimated for the commercial fishery.

Table D.1. Median values of the age of 50 percent selectivity estimated in the RCM for the fisheries and surveys.

OM	Commercial	Recreational	HBLL	Jig Area 12
(1) M = 0.067	7.8	12.7	13.5	5.9
(2) M = 0.055	7.5	12.9	13.7	5.9
(3) M = 0.088	8.5	12.7	13.9	6.0
(A) No jig survey	11.5	12.0	11.6	NA

Table D.2. Median values of the age of 95 percent selectivity estimated in the RCM for the fisheries and surveys.

OM	Commercial	Recreational	HBLL	Jig Area 12
(1) M = 0.067	10.5	23.3	22.9	7.6
(2) M = 0.055	10.0	23.7	23.7	7.6
(3) M = 0.088	11.5	23.0	23.8	7.6
(A) No jig survey	20.7	22.4	18.1	NA

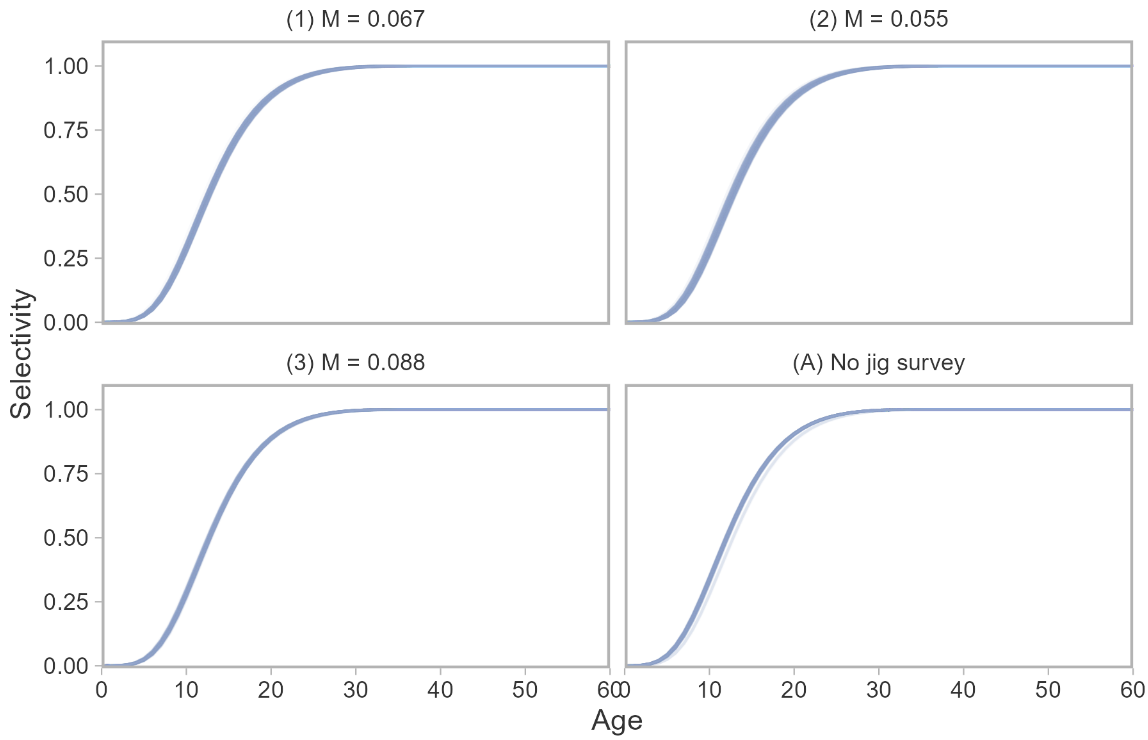

Figure D.5. Selectivity-at-age estimated for the recreational fishery.

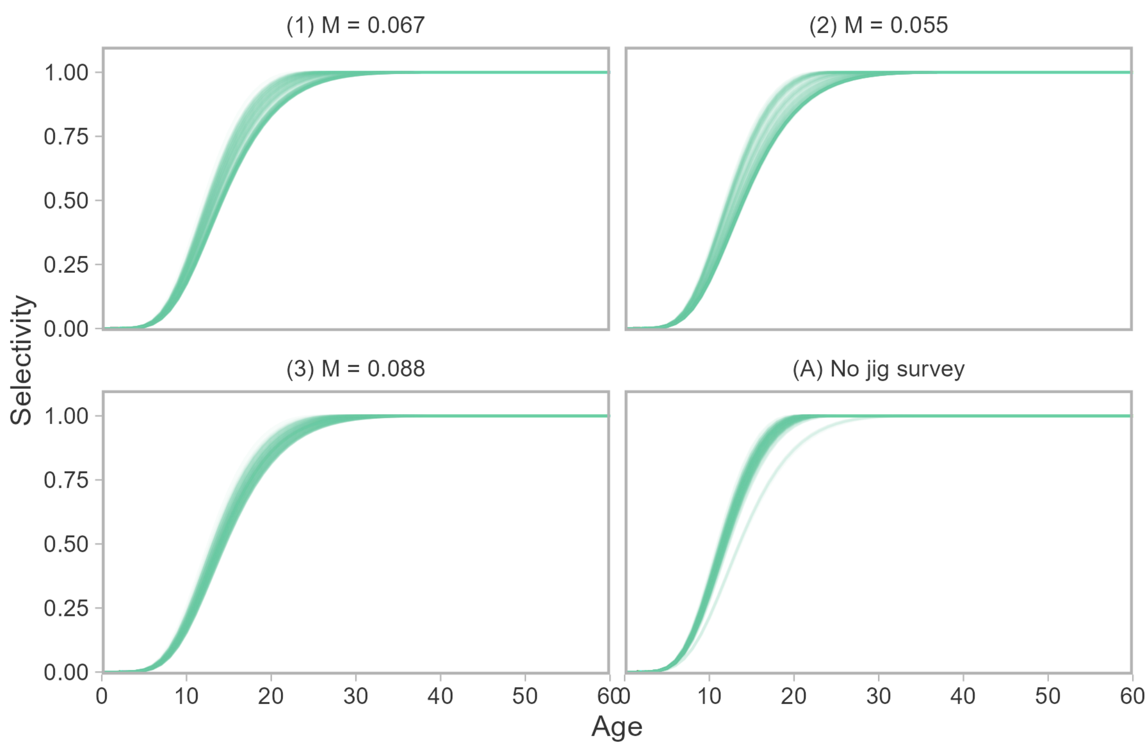

Figure D.6. Selectivity-at-age estimated for the HBLL survey.

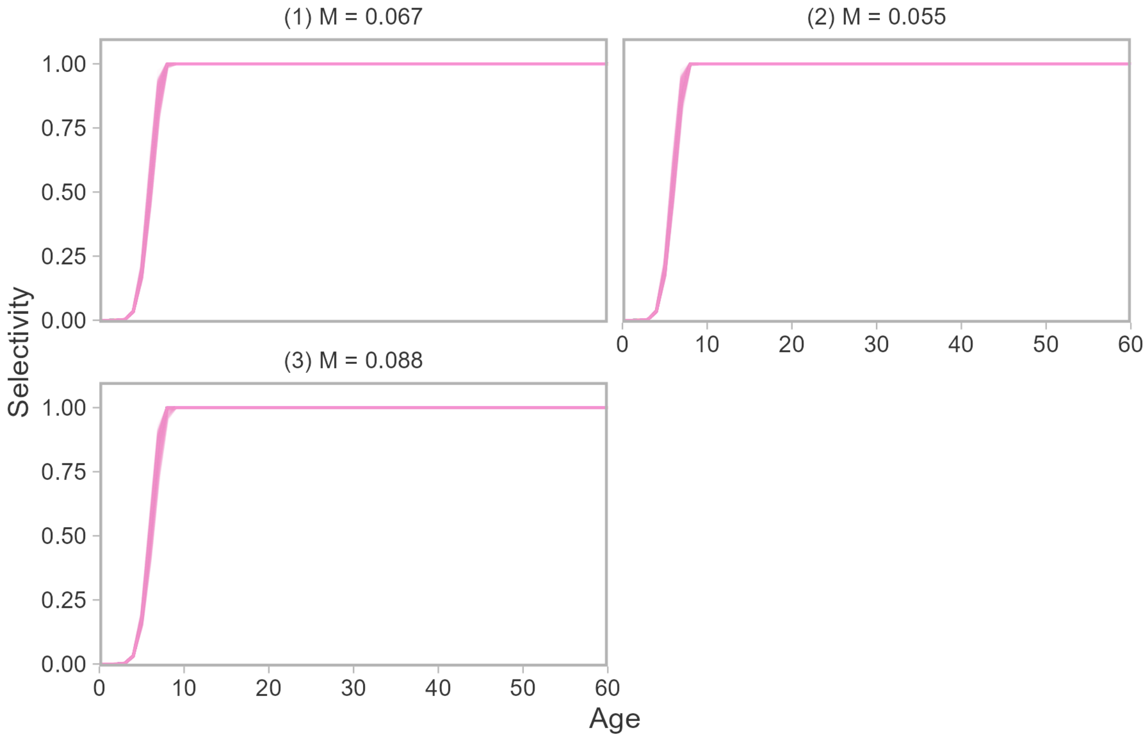

Figure D.7. Selectivity-at-age estimated for the Jig Area 12 survey. Operating model (A) was conditioned without this survey.

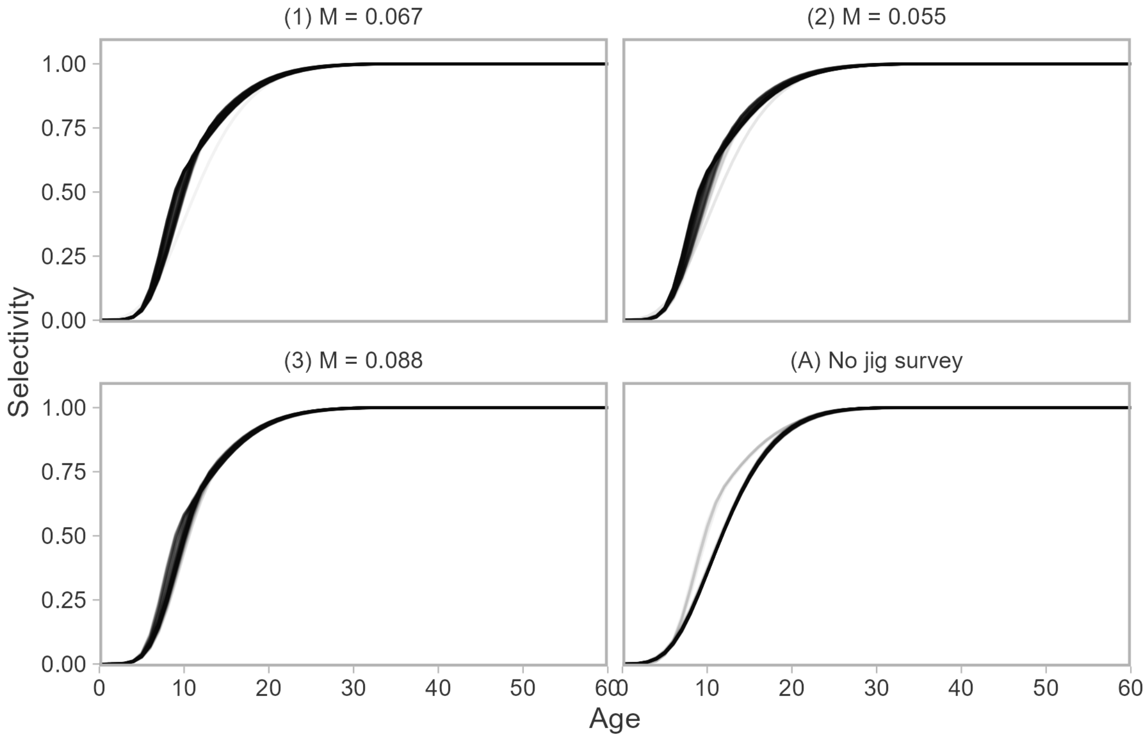

Figure D.8. Effective selectivity-at-age, based on those estimated for commercial and recreational fisheries, in years $t \geq t_c$ of the OM projections.

D.3. OBS SLOT DESCRIPTIONS

D.3.1. 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 MSEtool operating model can generate σ_C based on the residuals between the predicted and observed catch. Since the RCM conditions the OM on observed catch, the predicted catch will match the observed catch and thus, $\sigma_C < 0.01$.

D.3.2. 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 the RCM conditions the OM on observed catch, the ratio is 1.

D.3.3. 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. This parameter was bypassed by providing the historical HBLL index to the operating model. The autocorrelation and standard deviation in the observation error deviates are calculated within simulations which is functionally identical to those in the residuals of the RCM fits.

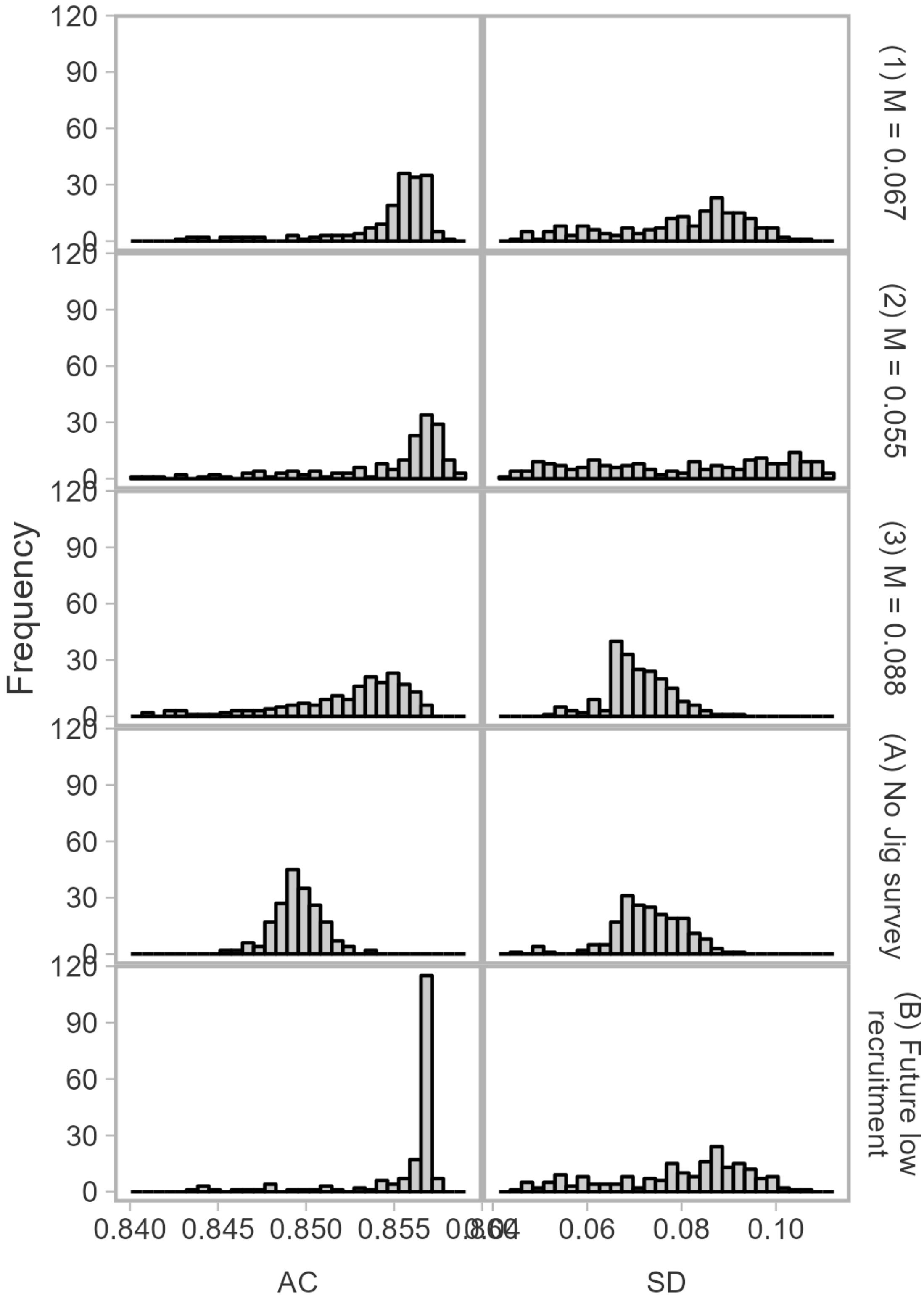

Figure D.9. Histogram of autocorrelation (AC) and standard deviation (SD) of the observation error in the simulated HBLL index of the projection period. Values were calculated from the residuals of the index in 200 RCM fits.

D.3.4. 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.4. IMP SLOT DESCRIPTIONS

D.4.1. TACFrac

Mean fraction of TAC taken. Uniform distribution.

We assumed no implementation error, i.e., TACFrac = 1.

```
display_om(oms, "TACFrac")
#> [1] 1 1
```

D.4.2. TACSD

Log-normal CV in the fraction of TAC taken. Uniform distribution.

We assumed no implementation error, i.e., TACSD = 0.

```
display_om(oms, "TACSD")
#> [1] 0 0
```

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.

E.1. CONSTANT-CATCH MANAGEMENT PROCEDURES

We evaluated two constant catch MPs:

- CC_33: Constant annual catch of 33 t
- CC_41: Constant annual catch of 41 t

Thirty-three (33) tonnes is the average catch during 2012–2019 and 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.3, C.5). For the second constant catch MP, 41 tonnes as calculated as 125% of 2012–2019 average.

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.

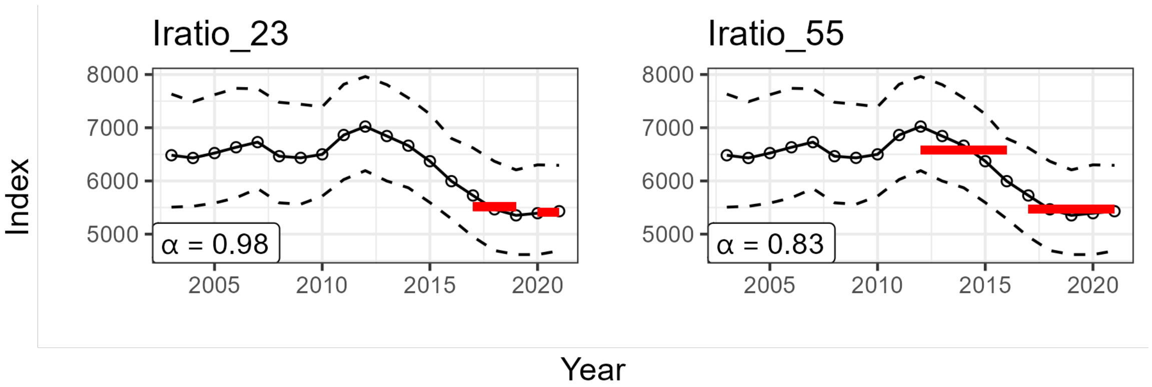

Figure E.1. Application of the two Iratio management procedures to the HBLL index. In 2022, $\alpha = 0.98$ with Iratio_23 based on the ratio of the mean index in 2020-2021 relative to that in 2017–2019 (left). With Iratio_55, $\alpha = 0.83$ using the ratio of the mean index in 2017-2021 relative to that in 2012–2016 (right). Red lines indicate the mean of the index during the corresponding time period.

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:

$$C_y^* = C_{y-1}(1 + \lambda\beta_y^I) \quad \text{(E.3)}$$

$$0.8 \leq (1 + \lambda\beta_y^I) \leq 1.2 \quad \text{(E.4)}$$

where C_{y-1} is catch from the previous year, β_y^I 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_y^I is calculated from the index in the preceding 5 years
- GB_slope_5y_lam05: $\lambda = 0.5$ and β_y^I is calculated from the preceding 5 years
- GB_slope_10y_lam1: $\lambda = 1$ and β_y^I is calculated from the preceding 10 years
- GB_slope_10y_lam05: $\lambda = 0.5$ and β_y^I is calculated from the preceding 10 years

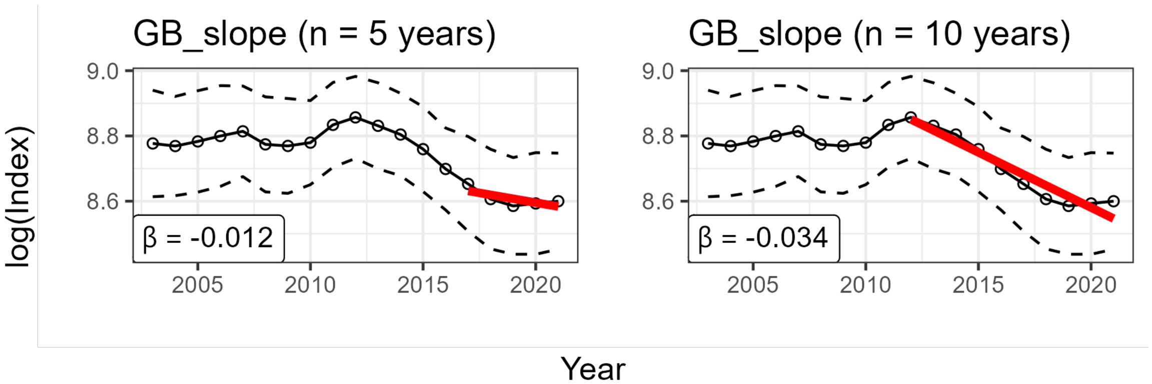

Figure E.2. Calculation of the index-slope in the GB_slope management procedure to the HBLL index. In 2022, $\beta^I = -0.012$ based on the slope of the log of the index during 2017–2021 (n = 5 years, left), while $\beta^I = -0.034$ using the index over 2012–2021 (n = 10 years, right). The change in 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.

E.4.2. IDX: Index-based MP from Cox et al. 2020

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).

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:

$$\Delta I_y = \frac{I_y}{I_{y-n}} - 1, \tag{E.6}$$

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:

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

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 Anderson et al. (2021) (their Appendix D).

APPENDIX F. 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 2003–2019 age samples from the inside HBLL survey are reported in Figures F.1 and F.2. Overall, estimates of *Z* have been approximately 0.1 with no strong trend. These estimates are consistent those from catch curves for Inside Quillback Rockfish with age data collected from the jig surveys. From 2003–2004 jig samples, the estimate of *Z* was approximately 0.09–0.11, an increase from 0.06–0.07 using age samples collected in 1986–1992 (Tables 7–8 of COSEWIC (2009); Schnute and Haigh (2007)).

Broadly speaking, catch curves can inform the general magnitude of total mortality inferred from descending limb of the age composition. Caution is warranted when using catch curves in a dynamic system and interpreting year-specific mortality rates. Catch curves assume equilibrium conditions with constant mortality and recruitment over time. While no large cohorts were apparent in the age data, these mortality estimates were based on biological samples aged between 20–60+ years and various changes in the fishing effort have occurred during this timespan. As a result, catch curves, as with any equilibrium method, are informative on historical mortality rates rather than conditions at the time the samples were collected (Hilborn and Walters 1992).

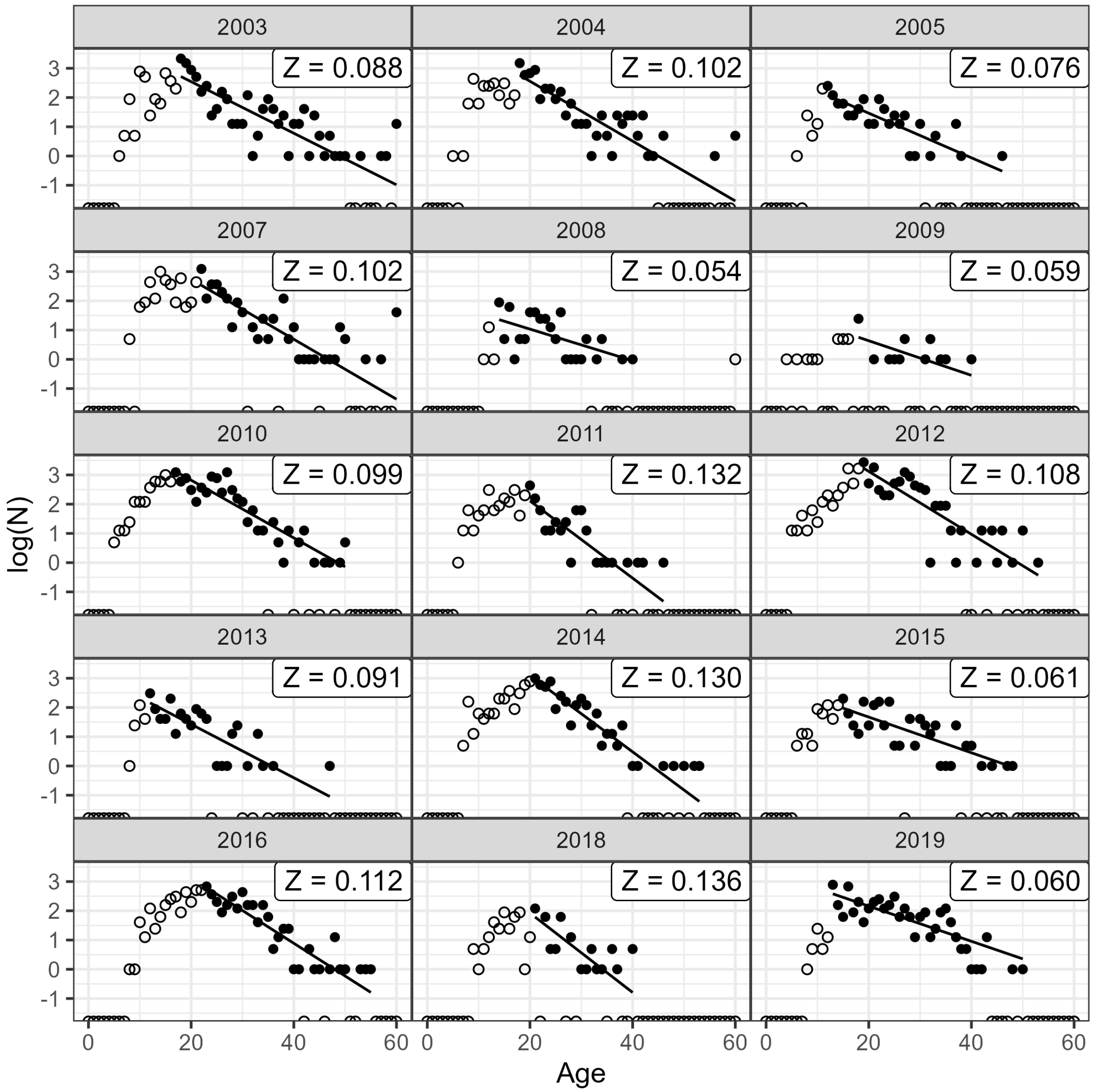

Figure F.1. Estimates of total mortality (Z) using catch curve analysis on the age samples from the inside HBLL survey, where N *is the numbers at age. Filled and empty circles indicate the data points included and excluded, respectively, from the catch curve regression. Lines show the predicted numbers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

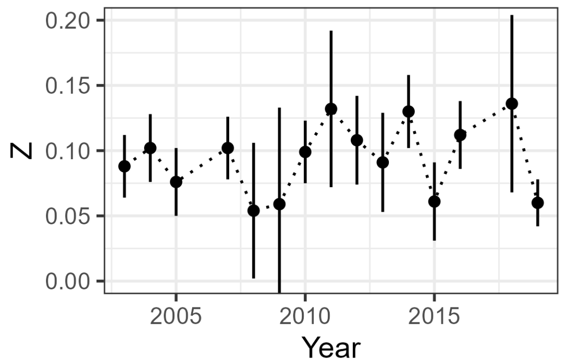

Figure F.2. Total mortality (Z) over time from the catch curves from the inside HBLL survey age samples. Vertical lines span the 95% confidence interval using the standard error of the slope estimated in the catch curve regression.

APPENDIX G. 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 the International Union for the Conservation of Nature (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 Inside Yelloweye Rockfish, we report results for two of COSEWIC's quantitative assessment criteria that may be applicable to this stock, Metric A.

G.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 Inside Quillback Rockfish is defined to be 24 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 Inside Quillback Rockfish, we report the following for each OM (Figure G.1):

1. P70 - Probability that, on average, the spawning stock biomass (B) in 2021 declined below 70% of B_{1950} over three generations, where generation time is 24 years and probability is calculated as $P[1 - B_{2021}/B_{1950} > 0.7]$.
2. P50 - Probability that, on average, the stock declined below 50% of B_{1950} over three generations.
3. P30 - Probability that, on average, the stock declined below 30% of B_{1950} over three generations.

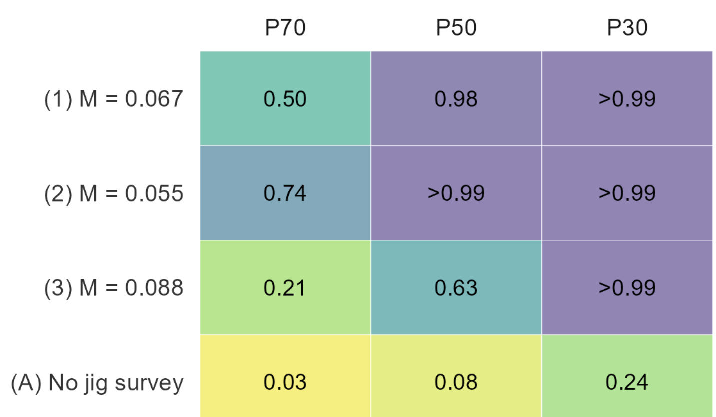

Figure G.1. Results for COSEWIC metric A, the probability that the spawning stock biomass in 2021 was below 70%, 50%, and 30% of B_{1950} (over three generations) for each operating model scenario. One generation is defined to be 24 years. OM (B) is not included here because its historical period is identical to that in OM (1).

APPENDIX H. COMPUTATIONAL ENVIRONMENT

Table H.1. This version of the document was generated on 2024-03-21 12:35:15.048498 with R version 4.3.2 (2023-10-31 ucrt) (R Core Team 2022) and the following R packages.

Package	Version	Date
bookdown	0.37	2023-12-01
cowplot	1.1.1	2020-12-30
csasdown	0.1.5	2024-03-21
DLMtool	6.0.6	2022-06-20
dplyr	1.1.4	2023-11-17
gfdata	0.1.2	2023-04-25
gfplot	0.2.1	2023-09-07
ggmse	0.0.2.9000	2023-10-31
ggplot2	3.4.4	2023-10-12
knitr	1.42	2023-01-25
MSEtool	3.7.1.9999	2024-03-14
purrr	1.0.1	2023-01-10
rmarkdown	2.24	2023-08-14
SAMtool	1.6.4	2024-02-14
tidyr	1.3.0	2023-01-24
TMB	1.9.10	2023-12-12

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

The specific versions of the primary packages used to generate this report can be viewed at:

<https://github.com/Blue-Matter/MSEtool/>
<https://github.com/Blue-Matter/SAMtool/>
<https://github.com/Blue-Matter/DLMtool/>
<https://github.com/pbs-assess/gfdata/>
<https://github.com/pbs-assess/gfplot/>
<https://github.com/pbs-assess/ggmse/>
<https://github.com/pbs-assess/csasdown/>

or installed via:

```
# install.packages('remotes')
remotes::install_github("Blue-Matter/MSEtool")
remotes::install_github("Blue-Matter/SAMtool")
remotes::install_github("Blue-Matter/DLMtool")
remotes::install_github("pbs-assess/gfdata")
remotes::install_github("pbs-assess/gfplot")
remotes::install_github("pbs-assess/ggmse")
remotes::install_github("pbs-assess/csasdown")
```