Evaluation of potential rebuilding strategies for Outside Yelloweye Rockfish in British Columbia

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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

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This paper aims to provide advice on rebuilding Outside Yelloweye Rockfish (OYE) using a combination of stakeholder-manager-science consultations and closed-loop simulation modelling to test performance of a set of candidate management procedures (MPs) against specific quantitative objectives. The overall approach aims to expose the ecological and fishery consequences of specific analytical (e.g., data collection, assessment methods) and management choices (e.g., harvest control rules, target fishing mortality rates) for Yelloweye rebuilding. The key components of this work are: (i) development of two-stock hierarchical age-structured operating models for OYE that represent a range of hypotheses about natural mortality and exploitation history, (ii) testing MPs comprised of monitoring data, assessments, and harvest control rules (HCR) used to implement rebuilding policies, and (iii) evaluating performance measures that are used in determining the expected conservation performance of alternative MPs relative to stated rebuilding objectives.

Alternative data scenarios produced a wide range of estimated stock status, as well as biological and management parameters, from which 4 representative operating models (OMs) (using a 1960 or 1918 start year and alternative catch scenarios) were selected for simulation testing MPs. The 4 OMs ranged in current biomass from approximately 2,600 to 8,200 t in the North (groundfish management areas 5BCDE) and 1,900 to 4,400 t in the South (groundfish management areas 3CD5A). This range is considerably wider than the statistical uncertainty within any particular OM. No single factor clearly explains the range of biomasses because natural mortality, absolute catch levels, and historical recruitments all affect biomass and recruitment estimates either directly or indirectly. The 1960 start year generally has the higher unfished and current biomass, while the lower bound commercial catch scenario leads to the lower unfished and current biomass. None of the 4 OMs indicate that either OYE stock area has been fished to less than 20% of the unfished level or below 40% of B_{MSY} (Biomass at Maximum Sustainable Yield), as inferred in previous assessments. Model estimates of spawning biomass depletion relative to unfished levels range from 29–51% in the North, 21–43% in the South, and 27–48% coastwide. These correspond to 111–185% of B_{MSY} in the North, 75–154% in the South, and 96–173% coastwide.

The candidate MPs evaluated include three different assessment methods: i) a catch-at-age (CAA) assessment model, ii) a surplus production (SP) assessment model, and iii) an empirical rule (IDX) using survey index trends.

The three assessment methods were used in combination with different harvest control rules or implementation error scenarios to create a set of candidate MPs that were simulation tested for each of the 4 OMs for North and South areas independently. Performance statistics were evaluated using combined outputs across OMs via a 50%–16.67%–16.67%–16.67% weighting scheme. Simulations of MP performance for setting future OYE total allowable catches (TACs) generally showed robust, or potentially robust, performance to a wide range of OM scenarios. The CAA MPs were tuned to achieve a target fishing mortality rate that would provide relatively stable OYE biomass over the projection period and biomass in both the North and South areas. Management procedures based on SP models or survey index trends (IDX) produced a range of increases or stable trends in future OYE biomass. The IDX MPs were tuned to avoid biomass declines in the first 10 years, which produced long-term increases or stable trends in biomass with high inter-annual catch variability. Although the SP models generally led to biomass increases, they did so because of under-estimation biases and often showed erratic patterns in TACs. It is likely that undesirable properties of IDX and SP MPs could be improved via further tuning.

1   INTRODUCTION

The 2014 status assessment of the Outside population of Yelloweye Rockfish (OYE, *Sebastes ruberrimus*) in British Columbia (BC) indicated that the stock was in the Critical Zone defined by $B_{2014} < 0.4B_{MSY}$ (Biomass at Maximum Sustainable Yield), which triggered a rebuilding plan under the Sustainable Fisheries Framework (SFF) (DFO 2009, 2013; Yamanaka et al. 2018). Although Fisheries and Oceans Canada's (DFO) Guidance Document for the Development of Rebuilding Plans (DFO 2013) does not articulate specific components and objectives of rebuilding plans, it does require a high probability that management actions will lead to stock growth above the LRP within 1.5 to 2 generations. DFO (2013) also recommends that rebuilding plans be re-evaluated every 3 years. The rebuilding plan objective for OYE is to "achieve rebuilding throughout the outside stock's range and grow out of the critical zone within 15 years, with a 57% probability of success" (DFO 2018). Milestones were also established to "achieve a positive outside stock trajectory trend in each 10-year interval, such that the biomass at the end of each 10-year period is greater than the biomass at the beginning of the same 10-year period" and to "achieve catch reduction targets within three years." The estimated total OYE removals in 2014 of 287 t was subsequently decreased in 2016/17 to phase in a TAC of 100 t by 2018/2019.

The OYE Rebuilding Plan established after the 2015 stock assessment (see DFO 2018, Appendix 9) does not comply with DFO policy for two reasons. First, rebuilding objectives were defined using a 15-year rebuilding period, which is far shorter than 1.5 to 2 OYE generations (~57–76 years). Second, the rebuilding plan was not simulation-tested prior to implementation (DFO 2016). Thus, a more comprehensive analysis of the OYE rebuilding strategy is required than was originally anticipated under the 3-year SFF review cycle.

This paper aims to provide advice on rebuilding OYE using a combination of stakeholder-manager-science consultations and closed-loop simulation modelling to test performance of a set of candidate management procedures against specific quantitative objectives. The overall approach aims to expose the ecological and fishery consequences of specific analytical (e.g., data collection, assessment methods) and management choices (e.g., harvest control rules, target fishing mortality rates) (Smith 1994, Smith et al. 1999). We develop an analytical framework that can be modified for future analyses on other species, and explore the suitability of a revised set of rebuilding objectives for OYE. Shifting from a harvest management to rebuilding context does not change the elements included in the analysis, but may increase emphasis on conservation outcomes over fishery catch when considering management performance. The key components of this work are:

1. operating models for OYE that represent a range of hypotheses about natural mortality and exploitation history,

2. management procedures (MP) comprised of monitoring data, stock assessment model, and harvest control rules (HCR) used to implement rebuilding policies, and

3. performance measures that are used in determining the expected conservation performance of alternative MPs relative to stated rebuilding objectives.

Exploitation history is considered via scenarios of commercial and recreational catch developed by DFO in collaboration with the commercial and recreational fishing sectors prior to the 2014 stock assessment (Yamanaka et al. 2018) and updated to 2018 (Appendix B). Scientific uncertainty affects management procedures (ii) and performance measures (iii) via the choice of limit reference point (LRP) used to designate a stock as overfished and in need of rebuilding, as well as in assessments of stock status relative to the LRP (Milazzo 2012; NRC 2013). Although we do not fully understand the dynamics of OYE populations and fisheries, exploring alternative

scenarios and their consequences for rebuilding planning may provide important insights for management of OYE and other stocks considered to be at low abundance.

2 METHODS AND STUDY DESIGN

2.1 FISHERY REBUILDING OBJECTIVES

Objectives for OYE rebuilding emphasize biomass-based objectives over other important aspects such as catch and spatial distribution. The objectives are informed by the 2014 OYE assessment (Yamanaka et al. 2018) and have been revised by the steering committee for this project (see Appendix F), to ensure compliance with DFO rebuilding policy. The new primary objectives guiding the rebuilding evaluation are:

1. Grow the spawning stock biomass (SSB) out of the critical zone (i.e. above the LRP of $0.4B_{MSY}$), where B_{MSY} is the operating model biomass at MSY), with a very low (5%) probability of further decline, measured over 1.5 to 2.0 generations.

2. When the SSB is between $0.4B_{MSY}$ and $0.8\ B_{MSY}$, limit the probability of decline over the next 10 years from very low (5%) at the LRP to moderate (50%) at B_{MSY}. At intermediate stock status levels, define the tolerance for decline by linearly interpolating between these probabilities.

A preliminary objective for catch is to maximize the probability that annual catch levels remain above a minimum level of 100 t required to operate groundfish fisheries. Further collaborative work is required with First Nations and fishery stakeholders to fully specify conservation and fishery objectives for OYE.

In the sections below, we describe our approach to evaluating rebuilding management procedures for OYE that attempt to meet the preliminary objectives defined above. The evaluation follows a step-wise approach, which, for clarity, we state as the following algorithm (adapted from Cox et al. 2010) (Figure 1):

1. Define a range of alternative management procedures (MPs) defined by (i) **data** types and precision, (ii) **assessment methods** for establishing stock status, (iii) **harvest control rules** for setting base catch limits; and (iv) **meta-rules** for modifying base catch limits given pre-defined constraints and conditions as required. Meta-rules might involve time intervals and/or rules for revising the MPs, as well as "exceptional circumstances" that provide trigger points and subsequent actions when MPs are considered unreliable.

2. Specify an operating model (OM) to enable simulation of alternative plausible **scenarios** for OYE population responses to fishing and data generation mechanisms. This step involves first fitting the operating model to available data to estimate model parameters consistent with the stock history and structural assumptions of OM scenarios. Such a process is termed **conditioning**.

3. Project OYE stock dynamics and fishery harvesting forward from its current state for each management procedure under each alternative OM scenario. Each year and simulation replicate of the projection involves the following steps:

   a. Simulate the **data** available for stock assessment and append to existing data sets;

   b. Apply the **assessment method** to the data to estimate quantities required by the **harvest control rule**;

   c. Apply the **harvest control rule** to generate a catch limit;

d. Apply **meta-rules** such as constraints or averaging of catch limits across years;

e. Subtract the final catch limit from the simulated OYE population as represented by the operating model;

f. Return to Step 3a until final projection year

g. Repeat Step 3a–f for 100 independent replicate simulations

4. Calculate a set of quantitative **performance measures** based on the 100 simulation replicates that can be used to compare and rank MP performance against the fishery objectives.

Step 3a-e involves application of the operating model that was identified in Step 2, which maintains the state of the population over time and also generates the data that will be collected in the future. The operating model is described in detail in section 2.2 below. Data generated by the operating model are generally the fishery and survey data that are currently being accumulated by sampling programs, but these data could include new types for which cost-benefit analyses are required. A key feature of the evaluation process is that the assessment method applied in step 3b is blind to the operating model; that is, the assessment is only provided with data such as catch, survey indices of abundance, and catch-at-age. For OYE, this also involves not using fishery catch-at-age in the future since this data is no longer collected from fisheries. This closed-loop simulation strategy for testing harvest management procedures is well documented in the literature (e.g., see references in Cox and Kronlund 2008).

Each management procedure component in steps 3a–d requires a particular set of choices. For example, the data step could involve only a survey index of abundance, the assessment step could involve a model-based or data-based approach, and the harvest control rule may make adjustments for risk and uncertainty. The choices made will affect fishery performance and, therefore, are usually the main focus of management strategy evaluation (rather than focusing exclusively on statistical fitting of a single model). Details of OYE management procedure options, along with the choices involved in each, are provided in section 2.3 below. Performance measures used to compare management procedures are given at the end of the Methods in section 2.4.

2.2   OPERATING MODELS

This section develops the age-structured operating models used to assess current stock status and to evaluate potential rebuilding procedures for OYE. The age-structured model for OYE uses more extensive and recent data sets than previous assessments. We first provide a rationale for splitting OYE into North and South areas for assessment and rebuilding evaluation. Then, we present a two-area hierarchical modeling approach to parameterizing separate age-structured operating models for the two areas. The hierarchical approach is used in purely a statistical sense to share information about key model parameters across areas; otherwise, we assume no biological exchange (e.g., movement, spawning) between the two stock areas. State and parameter estimates from the hierarchical model are then input to separate age-structured operating models for evaluating rebuilding procedures. As in the hierarchical model, we assume no biological exchange between the North and South areas, which means the two operating models are completely independent in the projections, as are the candidate MPs.

2.2.1   Rationale for two OYE areas for assessment and rebuilding

Yelloweye are a long-lived (aged in BC to 121 years), slow-growing species with a late age-at-maturity (Love et al. 2002). Adults are habitat specialists, preferring demersal, rocky habitats, which have a discontinuous, patchy distribution on the B.C. coast. Genetic analysis has shown that two genetically distinct populations exist in BC: one on the outer coast (Outside), and one in

"inside" waters between Vancouver Island and the mainland (Inside) (Andrews et al. 2018, COSEWIC 2008, Siegle et al. 2013). The two populations are considered to be separate "designable units" by the Committee On the Status of Endangered Wildlife In Canada (COSEWIC). COSEWIC designated both populations of Yelloweye Rockfish as a Species of Special Concern in 2008 (COSEWIC 2008) and they were listed under the Species at Risk Act (SARA) in 2011. Readers are referred to the pre-COSEWIC document for additional background on Yelloweye Rockfish (Keppel and Olson 2019).

Fish stocks are defined for management purposes using a variety of characteristics, including species complexes that share habitat, distinctness of biological and/or life history traits, genetically distinct populations, and portions of stocks that exist within a given geographical area (Deriso et al. 1998; Spies et al. 2015). The TACs for the OYE population are distributed across 4 spatial units corresponding to groundfish management areas 3CD5A, 5B, 5CD, and 5E. Although these OYE management units were determined largely by the history of fisheries science and management in BC, most fishery participants believe there are spatial differences in OYE productivity that loosely map onto the management areas (Figure 2).

Previous stock assessments assumed a single panmictic OYE stock (Yamanaka et al. 2018). The consequent catch reductions from that assessment raised concern among industry stakeholders about how future catch should be allocated among the 4 management areas described above. In particular, stakeholders were concerned that (i) not enough catch would be allocated to northern areas, where OYE appeared to be relatively abundant and (ii) too much catch would be allocated to southern areas where OYE were less abundant and possibly declining. Concern (i) implies that low TACs on OYE in the north would interfere with other directed fisheries (e.g., Halibut), while concern (ii) implies that too high TACs in the south could exacerbate OYE declines, leading to even more restrictive coastwide TACs. Such a positive feedback could lead to future problems for both OYE and groundfish fisheries, in general. Indeed, subsequent analysis of spatial patterns in survey catch rate means and recent trends indicated that both observations were consistent with hard bottom survey data. Therefore, as part of the implementation planning for commercial fishery catch reductions following the 2014 OYE assessment, spatial allocation of future TACs were proposed (and subsequently adopted) via a collaborative process that considered historical catch allocation by areas, surveys in each area, and a desire by industry groups to ensure that TAC reductions required for OYE rebuilding were shared equitably among stakeholders[1].

Successful implementation of the spatial TAC allocation for OYE suggested that further spatial delineation of OYE into, at least, North and South components for biological assessment purposes could be warranted provided that assessment outputs are reliable at such spatial resolution. Finer resolution of age-composition data to 4 management areas is currently a limiting factor in delineating stocks further, at least for age-structured assessment modelling.

2.2.2 Two-area hierarchical age-structured model

We developed a two-area, age-structured operating model (OM) for OYE in which North (5BCDE) and South (3CD5A) components were assumed to be independent, closed populations, but with shared population dynamics parameters. The two areas allowed us to represent the key spatial issues related to biomass sizes and population trends without having to model biological exchange between populations (i.e., there is no basis for assessing movement given lack of tagging). Modelling North and South components for OYE simultaneously simply allowed us to share information about uncertain parameters (i.e., natural

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[1] Landmark Fisheries Research 2016. Options for distributing Yelloweye Rockfish TAC among groundfish management areas for the 2016 fishing season. Unpublished report prepared for BC Seafood Alliance.

mortality, selectivity, productivity) between the two stocks. Current understanding of OYE life history is that movement rates are extremely low once fish settle to rocky bottom habitats, which means that the independence assumption is plausible, at least at the gross North-South scale.

The OM (Table 1–2) is written generically to represent two biologically independent stock areas indexed by $p = (1,2)$ for North and South, respectively. Equations describing equilibrium population characteristics and states are given in Table 2 (Eqs.1–6).

Fleets in the model consist of commercial fisheries using Hook-and-Line and Trawl, a recreational fishery, and three hook-and-line surveys including two hard-bottom, stratified-random rockfish surveys (Pacific Halibut Management Association [PHMA] North and PHMA South) and the fixed-grid International Pacific Halibut Commission (IPHC) Fishery Independent Setline Survey for Pacific Halibut (Appendix B). We model the catch in sequential, discrete fisheries (Eqs.C.1–C.8; Table 2) mainly for numerical convenience because this does not require solving a catch equation in continuous time for multiple fisheries. The discrete approach, which assumes that catches are known without error, speeds up both OM fitting and simulations of future catch-at-age assessments. OYE mortality and growth rates, as well as fishery exploitation rates are all low enough, on average, that continuous dynamics are probably unnecessary. Our sequential Pope's approximation (Pope 1972) to fishing mortality seems adequate to model fishery exploitation and total mortality rates when these peaked due to intensive fisheries in some years.

Population dynamics assume that North and South OYE area were in unfished equilibrium at the first model time step, which is 1918 in the base model. Recruitment to age-1 is modelled as a Beverton-Holt function parameterized via steepness and unfished biomass parameters. Stock-recruit steepness, which has the range (0.20, 1.0), represents the proportion of unfished equilibrium recruitment expected when the spawning stock biomass is reduced to 20% of the unfished level. Equation A.2 (Table 2) uses a more compact parameterization for presentation purposes, but the conversions are: $a = \frac{4hR_{0,p}}{B_{0,p}(1-h)}$ and $b = 5(h-1)/B_{0,p}(1-h)$, where h is the steepness parameter. Recruitment process errors are used to estimate age-1 recruitments that deviate from the underlying Beverton-Holt recruitment model. The log-deviations were assumed to be normally distributed (Table 3, PE.1) with mean zero and estimated standard deviation σ_R for both stocks. Recruitment deviations are estimated from 1952 to 2002; sensitivity analyses (not shown) indicated that using earlier years generated unrealistic scenarios that inflated biomass above B_0 in 1960s–1980s to explain high catches.

2.2.3 Data likelihoods

Equations L.1–L.5 (Table 3) give components of the total log-likelihood (L.6). We assume a log-normal error structure for the survey biomass indices (we do not use any commercial CPUE data as biomass indices for OYE). Surveys do have specific timings within a year as indicated by times $t_{1,f}$ and $t_{2,f}$ in the observation model likelihoods for fleet f ("fleet" is used generically to describe fisheries as well as surveys) (Table 3, L.1).

We used a logistic-normal distribution for the age-composition data (Schnute and Haigh 2007) because the variances are estimated and usually more realistic than indicated by multinomial sample sizes. For a given year t, stock area p, and fleet f, the compositional negative log-likelihood l is given by equations (L.2–L.6, Table 2), where $A^+ = 65$ yr is the plus group age. We applied a tail compression algorithm to reduce the sensitivity of the likelihood to age classes with data prevalence below 2% of the total observed sample size and to provide robustness against age classes with no data (Francis 2014). Expected age proportions were modified by an ageing error matrix described in Appendix B.2 (Cox et al. 2019).

We explored using standardized age-compositions for the Hook-and-Line fleet by area and year at the coastwide scale to attempt to account for biased sampling in different management areas and increase the number of years with age composition data for both North and South areas. (Appendix B.2). Therefore, to fit these data, we computed mixed-stock area catch and catch-at-age from the model assuming a common Hook-and-Line selectivity and catch (by stock area and age) proportional to stock area- and age-specific biomass (Eq M.1–M.2, Table 2). Sensitivity analyses (Appendix C) showed little difference in model fits using standardized or non-standardized age composition data so final OM fits used non-standardized coastwide age compositions.

2.2.4 Prior distributions on OYE parameters

We used several prior distributions to stabilize OM fitting and parameter estimates given the limited information about some parameters, as well as to reflect alternative OM scenarios. In particular, we used a Beta prior distribution for the stock-recruitment relationship steepness, Log-normal priors for natural mortality rates, and Jeffrey's priors on quantities such as initial biomass and process error variances that tend toward large values and may lead to over-parameterized models.

Hierarchical structuring model parameters can improve assessment models for data-poor stocks (Johnson and Cox 2018) provided that individual stocks are reasonably exchangeable replicates within a larger population or aggregate. For OYE, we assumed that the stock-recruitment steepness parameter followed a Beta distribution with aggregate-level parameters $\alpha = 17.5$ and $\beta = 7.5$, placing the mode of the prior distribution near $m_h = 0.7$ (PD.2, Table 2), which is typically assumed for rockfishes (Forrest et al. 2010, Gertseva et al. 2017). Stock-specific steepness for North and South areas were then modelled via logit-scale deviations from the aggregate-level value, i.e.

$$\text{logit } h_p = \text{logit } m_h + \epsilon_{h,p},$$

where deviations $\epsilon_{h,p}$ were modeled via a Normal prior with mean zero and standard deviation $\sigma_h = 0.01$ (PD.3).

Although natural mortality M_p is a key unknown parameter for fish population dynamics models, it is typically confounded with fishing mortality, productivity parameters, and the scale of the population. It is probably safe to assume, based on proximity alone, that natural mortality rates are similar across OYE populations in British Columbia. Therefore, we used a hierarchical prior on the aggregate-level natural mortality rate such that $\bar{M} = 0.0345, \sigma_M = 0.01$, which we derived via Hoenig's (1983) method (Figure 3). Similar to the approach for steepness, we then modeled area-specific natural mortality rates via area-specific deviations from the aggregate-level value, i.e.,

$$\log M_p = \log \bar{M} + \epsilon_p$$

where $\epsilon_p \sim N(0, \tau)$ and $\tau = 0.01$.

We used Inverse-Gamma priors on the observation error variance parameters for the surveys (PD.4). These were defined to have shape parameter $\alpha = 0.1$ and β_f scale parameters defined such that the implied modes (i.e., $\log(CV_f^2 + 1)$) occurred at approximately the average sampling-based coefficients of variation of 0.10, 0.12, 0.24 for PHMA_N, PHMA_S, and IPHC surveys, respectively. Sensitivity analyses (not shown) indicated that final estimates of observation error CVs were insensitive to values of $\alpha \in (0.1, 1.0, 10, 50)$.

We also used an Inverse-Gamma prior on the recruitment process error standard deviation σ_R with shape $\alpha = 1$ and scale $\beta = 2$ (PD.5) giving an implied mode of $\sigma_R = 0.67$.

We used Normal priors on the age-at-95% selectivity (a_{95}^{sel}), with means 19 yr (Trawl), 19 yr (Hook and Line), 25 yr (PHMA_N), 26 yr (PHMA_S), and 24 yr (IPHC) with CVs of 0.25 to bound initial OM fits within a reasonable range (PD.6). There are no age or length composition data for the recreational fleet so we fixed length-based selectivity parameters to $l_{50}^{sel} = 36.5$ cm (age-6.7) and $l_{95}^{sel} = 42.4$ cm (age-11.5) based on values estimated for the recreational fishery in Washington State (Gertseva et al. 2017).

Time-varying age-at-50% (a_{50}^{sel}) selectivity was used to obtain better fits to the IPHC survey data (PD.7), which is modelled using a random-walk with log-scale deviations, i.e.

$$\log a_{50,t+1,p}^{sel} = \log a_{50,t,p}^{sel} + \epsilon_{a_{50}^{sel},t,p}$$

where deviations $\epsilon_{a_{50}^{sel},t,p}$ were modeled via a Normal prior with mean zero and standard deviation $\sigma_{a_{50}^{sel}} = 0.04$ (PD.7).

The use of time-varying IPHC selectivity in the historical period is needed to account for negative trends in residuals for index fits, since the IPHC survey is a key index used in the projections (see section 2.4.1). Selectivity for all other fleets are estimated as constant over time.

2.3 OPERATING MODEL SCENARIOS

Preliminary meetings of the OYE Technical Committee identified the model start date (1918 or 1960), alternative historical catch series, and prior assumptions about natural mortality as the main axes of uncertainty that should be reflected in OYE operating models. Therefore, we derived 24 OMs from combinations of the two start dates, two commercial catch series, two recreational catch series, and 5 aggregate-level prior means for natural mortality (Appendix A). Each model was fitted to the same survey and age-composition datasets and then models were clustered into 4 representative groups according to the start year (1918 or 1960) and commercial catch series used (lower or upper bound), within which model fits and biological properties were similar. A final set of 4 individual OMs were selected from each representative group to represent the broad set of characteristics shown across the 24 OMs. These final 4 OMs were further classified into a "most plausible" base model (defined below) and three alternatives. We then weighted the base models 50% and the alternatives 16.67% for the purpose of evaluating rebuilding procedures and providing a single, concise summary of MP performance (as requested by GMU). Note that this weighting was used in the absence of a preferred weighting scheme for the OMs, but it could be changed in the final process of selecting a rebuilding MP, or alternative weighting schemes could be tested in future sensitivity analyses.

The commercial and recreational catch reconstructions go back to the year 1918; however, there is limited fishery-independent survey data or age-composition to inform the assessment prior to the 1990's. The last assessment found that stock biomass remained close to the unfished level until about 1960 (Yamanaka et al. 2018). Therefore, we tested the influence of the model start year by parameterizing operating models starting from 1918 or 1960.

Historically, Yelloweye Rockfish commercial catch was lumped together with other rockfish species and discards were not recorded. In 2011, DFO undertook an extensive process to reconstruct historical rockfish catch by attempting to account for unreported/misreported catch and discards at-sea. The resulting catch reconstruction, from 1918 to 2006, is considered the

best information available and was used in the previous Yelloweye Rockfish stock assessment. Since groundfish integration in 2006, there has been 100% monitoring of all commercial catch and discards, so that recent information is considered accurate. Thus, reconstructed historical commercial catch in the base OMs is considered an upper bound, as well as the most plausible record of historical catch.

Historical records for recreational catch of Yelloweye Rockfish do not exist and, while some areas of the coast have been monitored through creel surveys for the past few decades, over much of the time series rockfish species were either lumped together or remain uncertain because of species misidentification. A coastwide recreational catch reconstruction was developed for the last assessment (Yamanaka et al. 2018) and updated to 2018 (Appendix B.3). The lack of historical records precludes splitting the reconstructed recreational catch into North and South area; therefore, a method for assigning catch to each area was developed via consensus in the OYE Technical Committee. Catch was split evenly between the North and South areas based on the 2016–2017 recreational catch data, which indicated that approximately half the annual catch occurs in the North and half in the South (Table B.9). As with commercial catch, the reported recreational data was treated as a lower bound scenario, while the full reconstruction was treated as an upper bound catch scenario.

2.3.1 Base operating models

The base OMs for North (base_North) and South (base_South) reflect model configurations from Group 1 fits, which use a 1918 model start year and upper bound (reconstructed) commercial catch, as in the 2014 assessment, with the least informative prior (baseM) for aggregate-level natural mortality $\bar{M} = 0.0345/\text{yr}, \sigma_M = 0.01$ (Tables 4–5).

2.3.2 Alternative operating models

Three alternative OMs were chosen for each area in an attempt to cover the range of plausible OMs given the input data and assumptions about natural mortality.

The OM2 (Group 2) scenario uses (i) 1960 model start year, (ii) lower bound commercial catch series, and (iii) baseM prior mean for aggregate-level natural mortality $\bar{M} = 0.0345/\text{yr}, \sigma_M = 0.01$.

The OM3 (Group 3) scenario uses (i) 1960 model start year, (ii) reconstructed catch series, and (iii) prior mean for aggregate-level natural mortality $\bar{M} = 0.03/\text{yr}, \sigma_M = 0.0001$.

The OM4 (Group 4) scenario uses (i) 1918 start year, (ii) lower bound commercial catch, and (iii) base prior mean for natural mortality rate $\bar{M} = 0.0345/\text{yr}, \sigma_M = 0.01$.

As noted above, these particular combinations (OM1–OM4, Tables 4-5) are generally representative of the range of properties across the 14 OMs with coastwide MSY < 500 t, which include natural mortality estimates ranging from $\bar{M} = 0.031 - 0.044/\text{yr}$, but excluded the scenarios for $\bar{M} > 0.05/\text{yr}$. The base and alternative OMs selected were re-fit without any priors on selectivity.

2.4 MANAGEMENT PROCEDURES

2.4.1 Assessment data

The assessment components of candidate MPs use actual historical data for the pre-MP period (1960–2018) and simulated data for the evaluation period (2019–2076). For the projection period, we assume that annual catches are equal to the annual TACs and that catch is known exactly in the assessments regardless of the method (i.e., there is no under-utilization, unreported catch, or unreported discarding).

All of the assessment methods use abundance indices from PHMA and IPHC surveys (Appendix B). We simulate this data in the projections by generating independent and identically distributed (i.i.d.) log-residuals $\xi_{t,f} \sim N\left(-\tau_f^2/2, \tau_f^2\right)$ with survey-specific CVs equal to their operating model-specific estimates given in Table 4.

We used an auto-correlated random-walk on the IPHC age-at-50% selectivity (a_{50}^{sel}), bounded between the minimum ($a_{50,p}^{min}$) and maximum values ($a_{50,p}^{max}$) estimated from the historical period. This allows selectivity to vary from 2018–2076 and 2017–2076 in North and South, respectively, starting from the last year with IPHC age data, i.e.

$$a_{50,p,t} = a_{50,p}^{min} + \lambda_{p,t}(a_{50,p}^{max} - a_{50,p}^{min})$$

where $\lambda_{p,t}$ has the range (0,1). The auto-correlation coefficients range from 0.36-0.53 and 0.38-0.58 for the 4 OMs in the North and South, respectively.

The catch-at-age (CAA) assessment method also requires simulating future age-composition data in a similar way, but from the logistic-normal distribution. To simplify the following presentation, we ignore both fleet and time subscripts to just focus on generating an observed sample proportion for a single age-class: data generation for other age-classes is identical. First, generate a vector of i.i.d. residuals for each $a \in (1,2,\ldots A^+)$ via $\eta_a \sim N(0,\tau')$, where τ' is the operating model estimate of the residual standard deviation for age-composition data (these will be fleet- and OM-specific). For each age-class, generate a new observed proportion data point y_a via

$$y_a = \log p_a + \tau'\eta_a - \frac{1}{A^+}\sum_{a'=1}^{a'=A^+}[\log p_{a'} + \tau'\eta_{a'}]$$

where p_a is the true proportion of age-class a in the operating model population for that fleet and year. These simulated age-proportion vectors are then appended to the historical data sets and provided to the CAA assessment.

As noted above, age-composition data are only simulated in the projections for PHMA and IPHC surveys because such data are no longer collected from the fisheries. Therefore, age-composition provided to the CAA assessment for Hook-and-Line and Trawl fisheries are fixed to the historical data sets.

2.4.2 Assessment methods

This section provides specifications for three candidate methods for the assessment component of management procedures for OYE. A statistical catch-at-age model (with base label CAA in figures and tables) utilizes the most comprehensive catch, survey, age-composition, and life history data available. A Schaefer surplus production model (SP) provides a reduced approach to assessing OYE based only on catch and survey indices, which is consistent with previous OYE assessments. A tuned SP model ("tuning" is described below) has been used to set annual TACs for Canadian Sablefish for almost a decade. Finally, we also examined performance of an empirical (IDX) survey index trend estimator for tracking proportional changes in OYE biomass over time.

Catch-at-age model assessment: CAA

The CAA assessment model has nearly identical structure to the OYE operating model, so we do not replicate the model equations here. The CAA model has the following structural modifications:

1. North and South models are independent: there is no sharing of parameter information via joint priors;

2. There is no mixed-stock fishery;

3. The models are not fitted to future age-composition in the Hook-and-Line or Trawl fishery because that information is no longer collected;

4. The stock-recruitment steepness parameter uses a Beta distribution with parameters $\alpha = 74$ and $\beta = 26$, placing the mode of the prior distribution near $m_h = 0.74$ to match the base OM1 estimates of h;

5. The models use informative priors on survey catchability with means $\bar{q}_{PHMA\_N}^{North} = 3.8, \bar{q}_{PHMA\_QCS}^{North} = 3.6, \bar{q}_{IPHC}^{North} = 1.9, \bar{q}_{PHMA}^{South} = 5.8, \bar{q}_{IPHC}^{South} = 1.8$ all with standard deviation $\sigma_q = 0.05$, to closely match base OM estimates;

6. Uses a 1960 start year so that the same MP can be tested across different OMs using 1918 start years (base OM1 and OM4) and 1960 start years (OM2 and OM3).

7. Use the upper bound commercial and recreational catch time series from 1960–2018;

8. The recruitment process error SD is fixed at σ_R=0.4 to match reference OM estimates.

Note that catchability priors in modification (5) are only to match the base OM1, so they will probably generate biases when tested against other OMs. The CAA model uses a Newton-Raphson solver to derive U^{MSY} (optimal proportional harvest rate) and B^{MSY} estimates from the equilibrium equations, where all OMs use the same life history information except selectivity (which are re-estimated annually in CAA models). These derived quantities are needed for the harvest control rule component of management procedures.

Schaefer surplus production model assessment: SP

The Schaefer surplus production (SP) model attempts to estimate annual stock biomass and harvest control rule parameters U^{MSY} and B^{MSY}. Model notation and equations are listed in Tables 6 and 7, respectively. The SP model derives inferences about management parameters from time-series observations of total catch and survey biomass indices. The SP assessment does not take into account age-composition changes over time or selectivity differences among fleets, even though both are included in the operating models.

Production models pool the effects of recruitment, growth, and natural mortality into a single production function to model biomass in each year B_{t+1} based on four components: (i) the predicted stock present in the previous year B_t, (ii) an average production function $f(B_t)$ that depends on biomass, (iii) total catch C_t, and (iv) a random deviation ω_t from the average production relationship (Punt 2003). These components can be written into a production model of the form

$$B_{t+1} = (B_t + rB_t(1 - B_t/K) - C_t)e^{\omega_t},$$

where B_t (tonnes) and C_t (tonnes) are the stock biomass at the start of year t and catch biomass during year t, respectively. Parameters *r* and *K* are the usual intrinsic population growth rate and carrying capacity for a logistic growth model. The catch is assumed to be taken instantaneously and after production. The random production anomaly term ω_t is assumed independent of stock biomass and may represent deviations from the average production relationship. We assume i.i.d. production deviations (Eq. E2.1, Table 7) regardless of how they might arise.

The Schaefer form assumes that fish production is a symmetric, dome-shaped function of existing stock biomass so that $U^{MSY} = r/2$ and $Y^{MSY} = rK/4$ define the optimum exploitation rate and maximum sustainable yield, respectively. The maximum sustainable yield biomass level is $B^{MSY} = K/2$. We re-parameterized Equation 1 so that two management parameters, U^{MSY} and Y^{MSY} are estimated directly, since it is somewhat easier to derive prior assumptions about them. The resulting production model is given by equation Eq. 2.6.

Indices of relative abundance for fleets $g \in (1,2,\dots G)$ are used in estimating production model parameters via a linear observation model of the form

(2) $I_{t,g} = q_g B_t e^{\xi_{t,g}}$,

where q_g is a constant catchability coefficient and $\xi_{t,g}$ is a normally-distributed random observation error in year t for fleet index g.

SP model likelihoods

Different assumptions about how to allocate random deviations in the data to the stock dynamics (ω_t) or the observations ($\xi_{t,g}$) give different production model estimators. Assigning the total model error to the observations leads to an observation error estimator in which the stock dynamics are assumed to be non-random and exactly equal to that predicted by Equation 1 with $\omega_t = 0$ for all values of t. Thus, observation error models ignore inter-annual changes in stock biomass that may occur via un-modelled processes like natural mortality, immigration, emigration, or environmental influences on production. On the other hand, assigning all random error to the underlying stock dynamics by setting $\xi_{t,g} = 0$ in the observation model (Equation 2 above) for all values of t and g leads to a process error estimator in which the observations are assumed to be exact, i.e., $I_{t,g} = q_g B_t$, and thus any change in the survey index is directly proportional to changes in true stock biomass. For the process error estimator, the variance and individual terms ω_t must be estimated.

Inferences about the dynamics of fish stocks depend upon uncertainty in both the observations and the underlying population dynamics processes. Admitting both observation and process errors in the stock assessment model leads to errors-in-variables estimators in which some proportion ρ of the total error variance is assigned to the observations and the remainder $1 - \rho$ is assigned to process deviations in the underlying stock dynamics. Formally, errors-in-variables estimators define the total error variance, κ^2, as

(3) $\kappa^2 = \tau^2 + \sigma^2$.

If the observation error proportion $\rho^2 = \tau^2/(\tau^2 + \sigma^2)$ is assumed known, the individual variance components can then be expressed as

(4) $\tau^2 = \rho\kappa^2$, $\sigma^2 = (1 - \rho)\kappa^2$,

for observation and process errors, respectively. For our SP model, ρ is treated as a control or tuning parameter in the estimation procedure. As ρ approaches 0, the emphasis on process error will tend to allow for relatively large random changes in the estimated stock biomass from year to year, provided, of course, that possibly multiple abundance indices suggest the same direction and magnitude of change. Conversely, values of ρ near 1 will cause the model biomass to change deterministically in response to changes in fishery impacts; that is, the stock will only increase if catches are less than the deterministic surplus production. Preliminary simulations indicated that $\rho = 0.33$ was needed to prevent SP assessments from making large jumps in biomass scale periodically, which happens because OYE time series are short and there is little indication in survey data about long-term stock depletion and, therefore, stock size. The final negative log-likelihood function is given by Eq. 2.10.

Prior distributions

We used informative prior distributions on U^{MSY} and Y^{MSY} to tune the behaviour of the production model. Priors were both based on the Normal distribution with means ($\mu_{North}^{U} = 0.053$, $\mu_{South}^{U} = 0.052, \mu_{North}^{Y} = 210, \mu_{South}^{Y} = 160$) and standard deviations ($\sigma^{U} = 0.001, \sigma^{Y} = 0.02$), respectively. Specifying informative priors for the assessment model component of management procedures is similar to the approach taken in the International Whaling Commission's Catch Limit Algorithm (Cooke 1999) and Canadian Sablefish (Cox et al. 2011, 2019). Informative priors constrain the behaviour of SP models such that they perform reasonably well against the set of operating models under consideration. In other words, tuned SP models are not meant to be ideal stand-alone statistical estimators (like a single, best assessment would); instead, they are tuned to provide specific performance in harvest strategy simulations. Their reliability in setting annual TACs in practice is determined by the choice of operating models, which represent the total state of knowledge about a fishery resource. If this knowledge is reasonably comprehensive, then a tuned SP model may be a good choice for use in MPs provided that it is re-tuned periodically to reflect changes in knowledge (i.e., operating model updates).

Empirical survey index trend estimator: IDX

The empirical assessment method is a simple biomass trend estimator derived from a weighted combination of PHMA and IPHC survey indices. The trend-based approach assumes that survey catchabilities remain constant over time, but otherwise are unknown.

An OYE weighted biomass trend index ($\Delta \hat{B}_t$) is estimated as the weighted proportional change in stock biomass from the most recent survey indices, e.g., $\left(I_{f,t_{2,f}}, I_{f,t_{1,f}}\right)$, where the weights are the inverse-variances, $w_f = 1/\log(\tau_f^2 + 1)$, and

$$\Delta \hat{B}_t = \sum_{f=1}^{f=n} w_f \left(\frac{I_{f,t_{2,f}} - I_{f,t_{1,f}}}{I_{f,t_{1,f}}}\right) \Bigg/ \sum_{j=1}^{j=n} w_j$$

Time subscripts $t_{2,f}$ and $t_{1,f}$ give the most recent (subscript "2") and second most recent (subscript "1") index values for survey f. These times for estimated trends depend on the survey because PHMA surveys occur every other year, while IPHC surveys occur every year. Therefore, the PHMA survey indices are re-used in off years, while a new IPHC survey index is used every year.

The North area uses PHMA North, PHMA QCS, and IPHC North with corresponding CVs of 0.10, 0.24, and 0.28, respectively, while the South area uses PHMA South and IPHC South with corresponding CVs of 0.13 and 0.28, respectively. See Appendix B for background on survey indices.

2.4.3 Harvest control rules

Model-based management procedures (CAA and SP) use assessment model estimates of stock status (B_t/B_{MSY}) relative to lower/upper control points to determine the target fishing mortality via the familiar hockey stick harvest control rule (HCR, Figure 4). When stock status is estimated below the lower control point ($0.4B_{MSY}$) the target exploitation rate equals zero and, when stock status is above the upper control point ($0.8B_{MSY}$), the target exploitation rate is equal to some reference removal rate (e.g., maximum fishing mortality or exploitation rate).

Management procedures involving the SP model use the SP estimate of U^{MSY} as the reference removal rate, while the CAA procedures use tuned fishing mortality rates (*Ftune*) to achieve objective 2 (i.e., *P(B₂₀₂₉<B₂₀₂₀) ≤ 50%*) for weighted performance across OMs for CAA MPs. The TAC in the first year (2020) is the weighted equilibrium yield at Ftune derived from the 4 OMs (Figure 5) to maintain equilibrium biomass near 2018 levels (Table 8). A tuned F was used because initial simulations showed that all CAA-based MPs reduced OYE biomass in both North and South by fishing at an F$_{MSY}$ removal reference value. This behaviour is normal given that all the CAA models (as well as all the OMs) estimate OYE stock status to be above B$_{MSY}$. The tuned F was, therefore, chosen such that equilibrium biomass would be near the 2018 level (Table 7, Figure 5). That way, the model would generally aim to maintain the stock near 2018 levels until further advice is given on target stock levels for OYE.

A tuned F was not required for the SP-based management procedures because that model tends to under-estimate stock biomass and U^{MSY}; therefore, fishing at this rate leads to increasing stock sizes.

Simulated assessments are performed every 2 years in the projections and use constant catch in between assessment years. The CAA MP uses the weighted target TAC in 2020 (Table 7), while the SP MP applies the HCR (Figure 4) in year 2020.

The IDX MPs set TACs by adjusting the previous year's TAC according to the estimated proportional change in stock biomass (described above), such that

$$TAC_t = \begin{cases} TAC^{Floor} & \Delta\hat{B}_t \leq \delta_{min} \\ \left(1 + m_{down}\Delta\hat{B}_t\right)TAC_{t-1} & \delta_{min} < \Delta\hat{B}_t \leq 0 \\ \left(1 + m_{up}\Delta\hat{B}_t\right)TAC_{t-1} & 0 < \Delta\hat{B}_t \leq 0.25 \\ (1.25)TAC_{t-1} & \Delta\hat{B}_t > 0.25 \end{cases}$$

where m_{down} and m_{up} are the up/down slopes for adjusting catch and δ_{min} = -50% is the most negative drop allowed in the weighted indices before closing commercial and recreational fisheries for that year (Figure 4). The up/down slopes range from 0.9–1.0 and 1.0–1.1 for m_{up} and m_{down}, respectively, and were tuned for different IDX MPs to avoid biomass declines in first 10-years (i.e. objective 2). The maximum TAC increase is capped at 25% and the floor (TAC^{Floor}) is set according to the coastwide catch allocated for FSC fisheries (18.9 t) and research surveys (15.8 t) in the 2019 IFMP. The FSC allocation is split evenly between North and South areas in each year, whereas survey catches are allocated to the North or South in proportion to PHMA survey blocks fished in each area. The IDX MP uses the weighted target TAC (Table 7) for the first projection year (2020).

Alternative versions of the IDX MP included (i) δ_{min} = -100% (idx_dec100), (ii) TAC^{Floor}_{North}= 62 t and TAC^{Floor}_{South}= 38 t (idxFlr), and (iii) 100 t as the TAC for the first year in 2020 (idx_2020).

We applied an additional smoothing step to output TACs from IDX and CAA based MPs to limit inter-annual variation in TACs caused by high survey index variability (IDX) and a short-term jump from existing TACs for OYE to those implied by the CAA-based MP (i.e., which aims to stabilize biomass near current levels). Preliminary simulations showed that TACs generated from CAA-based MPs make a large jump in the first projection year and, therefore, a smoother provides an option for a more gradual transition to those TAC levels.

The smoother takes the form,

$$TAC_t^{Smuv} = \lambda TAC_t + (1 - \lambda)TAC_{t-1}^{Smuv}$$

Where we used $\lambda = 0.50$ in the current simulations (this can be set to any value in (0,1) depending on the desired degree of smoothing).

The smoother-based CAA MPs (caaSmuv) allows for a higher target F than the non-smoother MP (caa) and phases-in the weighted target TACs of 175 t and 116 t in the North and South, respectively, over 2 years (2020 and 2021). The non-smoothed CAA and all IDX MPs implement target TACs of 166 t and 107 t in North and South, respectively, immediately in 2020.

We also tested overage errors for FSC and recreational catch that set realized harvest for FSC (idx_2xFSC, caa_2xFSC, sp_2xFSC) or recreational fisheries (idx_2xRec, caa_2xRec, sp_2xRec) to double the TAC allocation for those sectors. These MPs assume that the catch overages are reported so that the assessment-based MPs get the correct catch totals.

The TACs for 2019 are fixed at 74.2 t in the North and 41.5 t in the South for all MPs, based on projected catches for 2019 (Table 9). The allocation of annual TACs in projection years among fishing fleets is described in Table 10.

2.5 PERFORMANCE MEASURES

Evaluating management procedures by simulation requires quantitative performance indicators for each fishery objective. Stock status indicators are all measured using the true operating model spawning stock biomass and, where necessary 1.5 OYE generations (57 years) calculated using the base OM natural mortality estimates of $M = 0.038 - 0.039$/yr (Table 5). We use the average age of the unfished spawning stock to calculate a generation time (G) of 38 years for OYE (Cox et al. 2011[2]), i.e.

$$G = \frac{\sum_{a=1}^{A} a S_a m_a}{\sum_{a=1}^{A} S_a m_a}$$

where maturity at age (m_a) is defined in equation EQ.1 (Table 2) and survivorship at-age (S_a) is defined in equations E.2-E.3 (Table 2).

Conservation Objective 1 can be stated probabilistically as $P(B_{2076} > LRP) \geq 0.95$, which we simply compare to the proportion of 100 simulation replicates for which the condition is true; that is, operating model spawning biomass in Year 2076 is greater than $0.4B_{MSY}$.

Performance statistics for the biomass-based rebuilding Objective 2, as well as other quantities that may be of interest are listed in (Table 11). Each statistic is calculated for a simulation replicate and then expected MP performance is summarized via the median of the 100 replicate statistics. Performance measures are calculated separately for the 4 OMs for each stock and then weighted to generate one weighted-performance table for North and South stock areas. Performance measures from each individual OM are provided for reference in Appendix D.

3   RESULTS

3.1   OPERATING MODEL CONDITIONING

Alternative data scenarios produced a wide range of estimated stock status, as well as biological and management parameters (Appendix A, Table A.2) from the 24 operating model scenarios. Some of these were implausible given the history of the fishery and biology of the

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[2] Cox, S.P., Kronlund, A.R., and Lacko, L. 2011. Management procedures for the multi-fleet sablefish (*Anoplopoma fimbria*) fishery in British Columbia, Canada. Centre for Scientific Advice Working Paper P2010-05. 166 pp.

species and were subsequently excluded from further consideration. Examples of implausible OM choices include configurations that estimated coastwide MSY > 500 t, current spawning biomasses larger than 20,000 t in either area (occurs for M > 0.04/yr), and biomasses well above B_0 in the 1960–1990 period to explain high catches in the 1980s–90s. The remaining OMs fell clustered into 4 general groups with similar data inputs and estimated parameters. We selected one model from each of the 4 groups for a given stock area to represent the suite of OM behaviour (see Appendix A for all individual OM summaries and selection process).

3.1.1 OM fits to biomass indices

Biomass index time-series are all short relative to the longevity and fishing history of OYE; therefore, we do not have a long-term survey trend by which to assess the overall depletion of OYE that appears to have occurred during the 1980–2000 period. Fits to survey data, therefore, mostly capture the survey means for PHMA data sets and possibly some recent declines in the North for the IPHC survey (Figure 6). Although the fits look somewhat noisy, the estimated survey index CVs are mostly reasonable, in the 20–30% range, except for South-IPHC, which is estimated 36%. The higher CV and relatively strong residual pattern for this index occurs because the base OM for OYE South shows increasing biomass over the 2006–2018 period even though the IPHC survey suggests a decline since about 2005 (Figure 6, South-IPHC). We account for the high CV in projections and the negative auto-correlation in IPHC indices by using a random-walk on time-varying IPHC selectivity (See details in section 2.4.1).

3.1.2 OM fits to age-composition

Age-composition data for OYE show broad distributions of abundance across age-classes, with all having a main group of fish in the 20–35 year age-classes and a strong accumulator class at age-65+ (Figure 7, see Appendix D for all age-composition fits). The OM North model fit the PHMA survey age-composition data reasonably well with estimated observation error standard deviations (sd) 0.66–0.88 for the two subareas, while the OM South model fits were lower precision ranging from 0.94–0.99 (Table 4). These differences probably arise from much higher sample sizes in the North (489–2826 per year) compared to the South (144–560 per year).

Fits to IPHC age-composition data (sds 1.03–1.54) were not as good as to the PHMA data sets, probably because IPHC surveys catch fewer OYE, on average, in both the North (183–916 per year) and South (98–319 per year); therefore, annual data sets are sometimes noisy and sparse when spread over 65 age classes. These IPHC surveys are not specifically designed to sample OYE, so poorer fits are not surprising. Indeed, similar differences are observed between *ad hoc* fixed-station and stratified random surveys for Canadian Sablefish, where the latter provide age-composition data that are more precisely fitted by Sablefish models (Cox et al. 2011, Cox et al. 2019).

The single age-composition from 1999 for the Trawl fishery in the North area was also fitted reasonably well with estimated sd 0.47–0.53. Good precision (0.32–0.34) was also obtained via the combination of North and South base OMs for fitting the mixed-stock longline (Hook-and-Line) age-composition in the coastwide data set.

None of the OMs fit observed proportions in the age-65+ group particularly well (Figure 7). In fact, the models are all positively biased, on average, for this age-class. For these data sets, fish in the age-65+ class were born prior to 1954, which is around the first year (1952) for which we estimated annual recruitment. Therefore, most age-65+ fish are assumed to come from the deterministic unfished recruitment level. The 1952-year class, in particular, would have been 52–55 years old when age-composition was first sampled in IPHC and PHMA surveys and, at these ages, are only present at low prevalence in the compositions for 10-13 years before

entering the age-65+ class. The lack of fit, particularly for the PHMA data, should be explored in future assessments, possibly by re-examining stochastic recruitments prior to 1952, although preliminary analyses were not promising because an expanded set of recruitment deviations (e.g., to 1945) leads to a suspiciously large pulse of biomass just prior to the intense fisheries of the 1980s–90s.

Estimated selectivity-at-age shows recruitment to Hook-and-Line fisheries generally beginning at about age 12–13 years (25% of maximum selectivity) with full selectivity (>95%) by age-21 (Figure 8). The Trawl fishery shows later selectivity, although this is based on one age-composition data set and Trawl actually catches relatively few OYE. The recreational fishery selectivity shows much earlier selectivity (25% near age-5 and 95% near age-12 years), but mainly reflects the prior assumption based on estimates from Washington State fisheries. Fish recruit to PHMA and IPHC surveys considerably later than both longline and recreational fisheries at about 18–21 years (25%) and are fully selected between age-31 and age-32.

OYE maturation (Appendix Figure B.11) occurs after recruitment to recreational fisheries and before recruitment to Hook-and-Line fisheries. This suggests uncertainty about recreational catch and commercial hook and line selectivity should be addressed via age-composition sampling because future fishery sustainability will probably depend on both the TAC level and allocation between commercial longline and recreational fleets.

Estimated biomass, recruitment, and fishing mortality

The base operating models for North and South stocks both show a steep decline in biomass from 1980 to 2000, corresponding to the period of peak catches (Figure 9). Estimated recruitments between 1952 and 2002 in the North show several strong year classes during the 1950–60s followed by another strong year class in the early 1980s. The South shows 3 strong year-classes separated by long periods of below average recruitment. The specific timing of what appears to be a 1952 year-class is not particularly reliable since sensitivity analyses on the start year showed that this event corresponds to first year that recruitments are estimated. In other words, estimating recruitment process errors beginning in 1950 will show a strong year-class in 1950. On the other hand, the later recruitment events around 1980 and early 2000s are insensitive to the start year of recruitment process errors. Fishing mortality peaked at approximately 10% and 17% in the North and South, respectively, which was mostly catch from the hook and line fleet.

Neither stock was depleted enough to provide strongly informative variation in spawning stock size necessary to estimate stock-recruitment steepness (Figure 10). Posterior-prior variance ratios were 0.73 (base OM), 1.0 (OM2), 1.0 (OM3), and 0.89 (OM4), indicating the data contribute some information to the stock-recruitment relationship for the base OM and OM4, and none for OM2 and OM3.

3.1.3 Current OYE status, parameter estimates, and biological reference points

The 4 OMs range in current biomass from approximately 2,600 to 8,200 t in the North, 1,900 to 4,400 t in the South, and 4,500–12,600 t coastwide (Figure 11, Table 5). This range is considerably wider than the statistical uncertainty within any particular OM. No single factor clearly explains the range of biomasses because natural mortality, absolute catch levels, and historical recruitments all affect biomass and recruitment estimates either directly or indirectly. The 1960 start year generally has the higher unfished and current biomass, while the lower bound commercial catch leads to the lower unfished and current biomass.

None of the 4 OMs indicate that either OYE stock area has been fished to less than 20% of the unfished level or below 40% of BMSY, as inferred in previous assessments (Figure 11). Model

estimates of spawning biomass depletion relative to unfished levels range from 29–51% in the North, 21–43% in the South, and 27–48% coastwide (Table 5). These correspond to 111–185% of B_{MSY} in the North, 75-154% in the South, and 96-173% coastwide. The weighted coastwide estimates of stock status provided in the last row of Table 5 are relevant for COSEWIC standards.

The base OMs, which receive 50% of the total OM weight in MP projections, estimate current spawning biomasses of 4,500 t and 3,300 t in the North and South, respectively, which correspond to 31% and 30% of unfished and 123% and 118% of B_{MSY}.

Estimated values of F_{MSY} and MSY from the base OMs are 0.053/yr and 210 t, respectively, for the North and 0.052/yr and 160 t, respectively, for the South. Despite being consistent with DFO's precautionary approach to fisheries (DFO 2009), using these F_{MSY} values as default reference fishing mortality rates in harvest control rules will lead to OM stock declines (i.e., toward B_{MSY}) in the future. Such declines would be inconsistent with our original intent to evaluate rebuilding policies; that is, short-term declines would not be consistent with rebuilding Objective 2, which aims to limit the probability of short-term decline. Therefore, we tuned fishing mortality rates for CAA and up/down slopes for IDX MPs that, on average, aimed to avoid stock biomass declines and maintain a stable biomass over the next 10 years (Figure 4, Table 7).

3.1.4 Comparison to 2014 coastwide surplus production model

As expected, the yield curve for the catch-at-age base OM is both asymmetric around B_{MSY} and shifted to the left due to a lower B_0 in comparison to the surplus production yield curve (redrawn from Yamanaka et al. 2018) from the previous assessment (Figure 12). This shift is large enough that B_{MSY} for the catch-at-age base OM occurs at the LRP of the 2014 surplus production model. Despite differences in shapes of the curves, there is little difference in estimates of MSY (370 t for CAA base OM, 349 t for 2014 assessment).

The 2014 biomass estimates from the catch-at-age base OM and 2014 assessment are 7.4 kt and 4.6 kt, respectively.

3.2 MANAGEMENT PROCEDURE EVALUATION

We simulated each candidate MP under each of the 4 OMs for North and South areas independently and then combined outputs across OMs via the 50%–16.67%–16.67%–16.67% weighting scheme. Here, we first provide example simulation replicates of North and South OMs under each of the model-based assessment approaches, mainly to show bias, variability, and retrospective behaviour of each model. Recall that, although the assessment methods are tuned to the base OMs (e.g., using priors derived from the base OMs), they must perform well across all the OMs to provide adequate weighted performance. For example, some of the model-based procedures will be biased low because they use the lower bound catch series compared to the base OMs, which use the larger reconstructed catches.

We then present the spawning biomass, catch, fishing mortality, and recruitments corresponding to the above single simulation replicates under three MPs using: (i) a CAA assessment every 2 years (caa), (ii) a surplus production assessment every 2 years (sp), and (iii) an empirical survey-based trend (idx) estimate every year.

Finally, we provide weighted OM projection envelopes of spawning biomass depletion and catch to show the expected distributions of spawning biomass depletion and catch for MPs based on sp, caa, caaSmuv, idx, and idxSmuv assessment and smoothing methods. Similar envelopes specific to each OM and area are provided in Appendix D.

3.2.1 MP performance

Simulated assessment method behavior

The SP assessment method under-estimates both the spawning and exploitable biomass components of base OM, OM2, and OM3, although the bias is greater for the North compared to the South and also greater for the OM2 (lower bound catch and 1960 start year) data scenario (Figure 13). The SP model is almost unbiased under OM4 that uses lower bound catch and a 1918 start year, which combine to produce the lowest absolute biomass. The SP model also shows high inter-annual variability in the estimates, partially because of the assumed high process error component (33%) of the total estimated error. Note also that there are occasional outlier SP model estimates, which correspond to models that failed to converge under 3 repeated attempts (with some jittering of start parameters each time). We limit the impact of these on TACs by using estimates corresponding to the most recent converged model. Smoothing TACs also helps limit these effects in the simulations. In any case, the SP behavior could be described as somewhat erratic, and could probably benefit from further tuning to constrain parameter estimates, although tuning might not reduce the bias.

The CAA model assessments are far less erratic than the SP models for the same simulation (Figure 14). In general, CAA models are less biased because they are structurally very similar to the OMs. Under the base models, in particular, CAA assessments show relatively good behavior and little retrospective pattern, while both bias and retrospective patterns increase for the alternative, mis-specified OMs. As with the SP model, under-estimation bias is greatest for the OM2 scenario (lower bound catch and 1960 start year) especially in the North, while the CAA model over-estimates biomass for the smallest stock OM4.

Although the SP and CAA models produce similar estimates of MSY and BMSY, the relationship of B_{MSY} relative to B_0 as well as current stock size relative to B_{MSY} are very different (Figure 15).

MP behavior under alternative assessment methods

The alternative assessment methods generate contrasting spawning biomass and catch outcomes in the North when embedded within the MPs (Figure 16). The SP model, which tends to under-estimate biomass and optimal fishing mortality, sets low TACs that lead to strong increases in spawning stock biomass in base OM, OM2, and OM3 scenarios (Appendix D). The CAA MP maintains the spawning biomass near the current 2018 level, as planned, because the model is mostly unbiased and the reference F (Ftune) was chosen to maintain a steady spawning biomass. The IDX approach also maintains spawning biomass near 2018 levels for the first 20 years, after which the stock slowly increases, because the up/down slopes for the IDX HCR (Figure 4) were tuned to avoid declines over the first 10 years. Catch levels under the IDX approach also fluctuate considerably from year-to-year.

Spawning biomass and catch differences were smaller under the alternative assessment approaches in the South (Figure 17). The SP model is less biased in this area and, therefore, leads to more similar catch and spawning biomass projections as the CAA MP. Inter-annual variability in catch remains higher because of the variation in SP model parameter estimates. Unlike the stable biomass in the North, the IDX approach produced a rapid increase in spawning biomass in the South, with decreasing TACs towards the end of the simulation.

3.2.2 Weighted projections under selected MPs: North

Surplus production model MPs

Similar to the single simulation replicate behavior (Figures 16–17), the weighted spawning biomass under the SP MP increases to 40–70% of the unfished biomass over the 57-year projection period in the North (Figure 18, sp). Annual TACs generally track the increasing biomass, although in the later years, more frequent SP model failures lead to unstable TAC behavior. This occurs because of the structural difference in productivity between the OMs and the SP model. The SP model under-estimates available production and therefore becomes unstable under long-term stock increases while catch levels exceeding production. Process errors in production probably offset discrepancies in the short-term, but these are constrained to have approximately mean-zero in the long-term, which will create increasingly harsh penalties in the overall likelihood. Allowing for greater adaptive potential in SP model parameters or random-walk productivity could improve estimation performance over the long-term, although short-term behavior may become more erratic via fluctuating parameter estimates while time-series remain short (Cox et al. 2019).

Doubling the recreational catch over-and-above the TACs determined by the SP MP (sp_2xRec) had little effect on conservation performance of the SP MP because the TACs are already set low relative to stock productivity. Therefore, the extra catch just increases average catch statistics (Table 12)

Catch-age model MPs

Weighted spawning biomass depletion for CAA MPs reflects the tuned reference fishing mortality rate plan to maintain a relatively constant biomass near the present level (Figure 18, caa). Over the 57-year projection period, the weighted median final biomass is $0.36B_0$ with a 48% probability of decline in the first 10 projection years (Table 12).

TACs increase from the projected 74 t in 2019 to the weighted TAC of 166 t in 2020, after which TACs are set according to the CAA MP rule every 2 years under the tuned reference F of 0.035/yr. Weighted average catches are 193 t over the first 10 years (2020–2029) and decrease slightly over the remainder of projection period as the bias in the CAA assessment model is reduced (Figure 17).

Adding a smoother to the CAA MP (caaSmuv) produces slightly less catch in the first 5 projection years in comparison to the unsmoothed CAA MP (caa), because catch is increased more slowly to 124 t in 2020 and the target TAC of 175 t in 2021 (Table 12). The smoother allows a higher tuned reference F of 0.039/yr to achieve the same probability of decline over the first 10 projection years as the unsmoothed CAA MP (caa). Otherwise, smoothing had little effect on long-term biomass or TAC distributions, probably because TACs output from this approach are relatively smooth already (Figure 18, caaSmuv). TACs make a large initial jump for both CAA MPs corresponding to the difference between current TACs (mainly selected from an SP-based assessment) and the higher estimated biomass and stock status in the age-structured OMs. The spawning biomass envelopes also show that the CAA MP does relatively well despite biomass being largely over-estimated under OM4, which is represented here in 16.67% of the simulation envelopes (probably the lower edge).

Doubling the FSC catch over-and-above that determined by the MPs increased the probability of short-term decline from 48% for the base CAA MP to 57% for the CAA with 2xFSC catch. Similar doubling of the recreational catch had a bigger impact (72% short-term decline probability) because of higher catches by the recreational sector and younger age-at-recruitment. As noted above, uncertainty about recreational selectivity may be worth resolving.

Empirical survey trend MPs

The base empirical survey trend IDX MP (idx) produced a 43% probability of decline in the first 10 years and an increase in weighted spawning biomass at the end of the 57-year projection (Figure 17, idx). Unlike the CAA MPs, smoothing had a strong effect of reducing inter-annual variability in TACs at the cost of a lower average TAC over the first 10 years. The lower TACs, in turn, reduced the probability of decline over the first 10 years to 26% and led to increasing catches over the 57-year projection period. In contrast, the base IDX MP without the smoother (idx) had decreasing catches over the projection period, probably because it uses a more conservative HCR (i.e., slow up, fast down) with a steeper down slope (m_{down}=1.1) than up slope (m_{up}= 0.9, Figure 4b).

Doubling FSC and recreational catch had similar effects on survey trend based IDX MPs, although the impact of the recreational catch increase was even more substantial (88% short-term decline probability). The idx_dec100 and idxFlr MPs were no different from the base IDX MP.

3.2.3 Weighted projections under selected MPs: South

Surplus production model MPs

Similar to the North, the SP MP (sp) produces increasing spawning biomass and TACs over the 57-year projection period. The lower level of bias in SP models for the South results in more stable model behavior, which avoids convergence failures and fishery closures (Figure 19, sp). Low biomass estimates by the SP model in the first few years results in a relatively high 56% and 44% probabilities that the TAC will be less than 38 t (minimum catch for fisheries to operate) in the first 5 or 10 years, respectively (Table 13).

Doubling the recreational catch over-and-above the TACs determined by the SP MP in the South also had little effect on conservation performance of the SP MPs because the TACs are already set low relative to stock productivity in the OMs. Therefore, the extra catch just increases average catch statistics (Table 13, sp_2xRec)

Catch-age model MPs

Performance of the CAA MP in the South is similar to behavior in the North, except that TACs in the first few projection years increase much more (Figure 19, caa, caa_Smuv). The CAA MP generates higher TACs in first 10 projection years, increasing from 41.5 t in 2019 to 107 t weighted target TAC in 2020, and then increasing to 141–182 t range from 2021–2029 under the tuned reference F of 0.036/yr. After the first 10 years, the catch is reduced as the CAA assessment model revises biomass estimates downwards closer to OM biomass, with most TACs ranging from 100–163 t for the remainder of the projection for weighted OMs. The weighted spawning stock is steady throughout the projections despite the swings in TACs.

Applying the 50% smoother (caaSmuv) produces slightly lower catch in the short-term in comparison to the unsmoothed CAA MP (caa), as catch is increased more slowly to 79 t in 2020 and reaching the target TAC of 116 t in 2021. Otherwise, the CAA smoother has little effect on the long-term performance beyond 5 years, since the smoother MP allows for a higher tuned fishing mortality of 0.039/yr that leads to similar probability of declines and median catch in the first 10 years (Table 13).

Doubling the FSC catch over-and-above that determined by the base CAA MPs increased the probability of short-term decline from 45% for the base CAA MP to 58% for the CAA with 2xFSC catch and 88% for doubling the recreational catch.

Empirical survey trend MPs

The empirical survey trend IDX MP performance in the South was different from behavior in the North (Figure 19, idx). Specifically, the IDX MPs in the South both produced increasing trends in weighted spawning biomass with less than 5% weighted probability of decline and over the first 10 years.

The median TAC for the base IDX MP (idx) was 104 t for the first 10 years with only a 2% probability of TACs less than the 38 t that allows fisheries to operate (Table 13). The 107 t weighted target TAC is used in 2020, after which the IDX MP generates highly variable catches that mostly range from 48–167 t over next 9 years. Adding a 50% smoother (idxSmuv) reduces the catch variability by (i) phasing in the higher TACs over the first two years with catch of 74 t in 2020 and 107 t in 2020, and (ii) applying the 50% smoother between annual TACs that leads to most catches in the 83–134 t range.

Doubling FSC catch in the South had much smaller impacts on performance compared to the North, increasing short-term decline probability from 5% under the base IDX MP to 19% under 2xFSC catch. Doubling the recreational catch had similar large impacts in the South as it did in the North, increasing short-term decline probability from 11% under the base IDX MP to 81% under 2xRec catch. The idx_dec100 and idxFlr MPs were no different from the base IDX MP.

4   DISCUSSION

This paper presents an approach to evaluating rebuilding plans for OYE. We developed a hierarchical age-structured approach to conditioning OYE operating models based on several scenarios for uncertain data and parameters. We then chose a subset of these operating models for testing expected performance of rebuilding procedures for setting future OYE catch limits.

All operating model scenarios suggest that OYE stock status in the North and South areas are well outside the Critical Zone defined in Canadian fisheries policy. Nearly all models imply that OYE are currently in the Healthy Zone above B_{MSY}, even though biomass declined rapidly by 49–71% in the North and 57–79% in the South over the past two OYE generations. Although these declines are consistent with COSEWIC's Special Concern status, the risk of extinction is very low at the present time, and practically negligible under future feedback management procedures.

It is not surprising that our hierarchical age-structured approach provides a different status assessment compared to the previous assessment that used a coastwide surplus production model. The age-structured approach allows for offset timing of OYE recruitment to fisheries, surveys, and the spawning stock, while also differing considerably in the shape of the production relationship to spawning biomass. These factors combine to imply various delays in biomass response to fishing and age-1 recruitment that SP modelling approaches potentially over-simplify. Indeed, the SP approaches were generally biased low in simulations of MP performance and were only unbiased for the OM4 scenario (lower bound catch with 1918 start year), where the range of biomass and production probably appear between the two approaches.

Simulations of MP performance for setting future OYE TACs generally showed robust, or potentially robust, performance to a wide range of OM scenarios. The CAA MPs used tuned fishing mortality rates to provide relatively stable OYE biomass over the projection period and biomass in both the North and South responded accordingly. Management procedures based on SP models or survey index trends (IDX) produced a range of increases or stable trends in future OYE biomass. The IDX MPs were tuned to avoid biomass declines in the first 10 years, which produced long-term increases or stable trends in biomass with high interannual catch

variability. Although the SP models generally led to biomass increases, they did so because of under-estimation biases and often showed erratic patterns in TACs. It is likely that undesirable properties of IDX and SP MPs could be improved via further tuning.

4.1   LIMITATIONS AND FUTURE RESEARCH

This paper presents a management-oriented approach that was initially intended to develop rebuilding plans for OYE. In identifying and conditioning operating models for OYE, we found that the stock is probably not in need of rebuilding; however, as with any assessment, this conclusion has some limitations.

4.1.1   OYE operating model conditioning

First, even though we used surveys and age-composition data, the amount and quality of this data remains limited relative to the longevity of OYE and time span over which groundfish fisheries have operated in B.C. This means that certain parameter assumptions – via prior distributions – could have considerable influence on the results. Prior assumptions on variance parameters are rarely consequential and we did not find much sensitivity to those. However, we did find that informative priors on high natural mortality rates, or weakly informative priors, in general, lead to high estimated natural mortality and unrealistically high biomass estimates. There is not much additional information in the way of unfished age-composition or tagging data to estimate M for OYE, which means that natural mortality scenarios will continue to be necessary for OYE assessments and MP evaluation.

Second, the operating models show some lack of fit, particularly over-estimating the age-65+ class in the age-composition and under-estimating the downward trend in the IPHC_South survey index. Some of this could be due to the self-weighting we allowed in the overall model likelihood; that is, we did not attempt iterative re-weighting of survey and age-composition data. Such procedures are needed where multinomial likelihoods are used for composition data because the variances implied by the sample sizes are usually unrealistically small; therefore, multinomial data components may dominate the overall fitting procedure. Sensitivity analyses indicated age-composition likelihoods needed to be down-weighted to 25% to improve fits to the IPHC South survey index, which led to worse fits for survey age-compositions (Appendix C). Future iterations of OYE operating model development should investigate the relative contributions of different data types to the parameter estimates. On the other hand, the IPHC survey is designed for Pacific Halibut and, therefore, a lack of OYE considerations could lead to systematic trends in the survey that do not accurately reflect changes in OYE abundance (See analyses on IPHC index in Appendix B.2).

Third, estimated growth curves appear positively biased for young ages (age-1 to age-6), which could lead to over-estimation of exploitable biomass and under-estimation of fishing mortality. This may be minor given that these fish are not recruited for several years to either exploitable or spawning components and by that time, the growth model is a bit more accurate.

An important consideration for future research would involve more detailed testing of the OMs for OYE to specifically include simulation testing for bias and precision properties. This would help establish the robustness of conclusions drawn about MP performance as well.

4.1.2   OYE operating model selection

Our approach to selecting 4 OMs to represent each stock area was intended to capture the typical expected behaviour within combinations of data inputs, natural mortality assumptions, and catch series. In general, this method appeared to reasonably capture the range of uncertainty; however, two OMs for the South (Group 2 M.03_1960_lbComm, Group 1

baseM_1960_str2018_lbRec, Appendix Table A.2) had lower depletion (0.59B$_{Msy}$) than any of the OMs included in the final 4 OM set. We did not specifically evaluate MPs under these two lower depletion scenarios because they used lower bound catch time series thought to be less plausible than the upper bound catch scenarios and a strong prior on M ($\bar{M} = 0.03/\text{yr}, \sigma_M = 0.0001$) for the Group 2 scenario (See Appendix A). In addition, their inclusion was not requested by the Technical Team or the GMU, nor was it clear how this result would be integrated into the weighted performance output. Challenges assessing MP robustness to specific, and less plausible OMs are common to management strategy evaluation. Future work could examine approaches to integrating robustness trials into formal operating model selection and weighting.

4.1.3 MP simulations

Most MP evaluation studies make strong assumptions about the implementation of management procedures. In this study, we assumed that TACs are fully taken (no under-utilization), catch and discards are fully reported, assessments are performed exactly as in the simulations, etc. Although none of these assumptions can be assured, periodic OM updates and re-evaluating MPs provide checks and course corrections over time that probably minimize impacts of these types of errors.

Incorrect assumptions about data are another matter and, therefore, future research should evaluate data simulated from the OMs. Inevitably, simulated data are better behaved than real data, especially age-composition and non-directed surveys, both of which are relevant to OYE MPs. Time trends in survey catchability are certainly possible, especially for the fixed-grid IPHC survey. As noted above, the IPHC_South index shows a negative trend in residuals implying a systematic deviation from the OMs. In the first few years of the projections, an auto-correlated simulated index should, on average, be more similar to the last observed index value than one generated from the OM. So, a series of large negative residuals leading up to the end of the historical period should lead to negative residuals, on average, in the first few projection years. We accounted for negative auto-correlation in indices by incorporating a random-walk on time-varying IPHC selectivity in the projections, otherwise OMs would tend to generate positively biased indices, which would affect MP performance. Empirical (IDX) MPs would be affected most since they use this data directly, while the CAA models will be affected the least. Model-based assessments would be less sensitive to auto-correlated biomass indices because the underlying biomass dynamics model and catch provides a constraint on expected trends. Further, the model-based approaches have flexibility in estimating larger observation error variances to account for residual trends, whereas the empirical methods assume survey variances are fixed and known. Nevertheless, future work could examine and quantify the range of CAA model robustness, as well as examine the impacts on empirical MPs of different assumptions for dealing with negative residuals in the southern IPHC index.

Better understanding the age-composition data would also be helpful in evaluating potential benefits of re-starting sampling programs for commercial fisheries and especially starting new sampling of recreational sector catch. Given management changes in BC fisheries since the 1980s (Appendix E) and the proportion of Yelloweye catch from different sectors (e.g., Halibut, Lingcod, Rockfish), there may be changes in commercial hook and line selectivity over time. Due to limited age-composition data from 1986-2001, we did not evaluate time-varying selectivity blocks for the hook and line fleet in this study; however, new age or length samples from the commercial sector would provide insight on any changes in selectivity since 2001. Current estimates of recreational and FSC catch are also highly uncertain, but also highly influential to MP performance. It was suggested by DFO that these be treated as lower bounds

on potential catch from these sectors. Simulated MP performance was less sensitive to FSC overages compared to recreational, but both increased the probability of short-term decline.

4.1.4 Management implications

We identified several potential MPs that could promote rebuilding or stabilization of OYE biomass in both North and South areas. However, it is not possible at this time to recommend a specific MP for each area without further guidance from OYE managers, First Nations, and fishery stakeholders. Specifically, the original objectives provided above do not apply to any of OM scenarios we selected. In all 4 OM scenarios, OYE do not meet the conditions needed for rebuilding because they are above $0.4B_{MSY}$. A specific biomass target (e.g., B_{MSY} or some multiple) would be a basic requirement because MPs could then be tuned to meet the target objective with some probability. Until further advice is given on target stock levels for OYE, the current biomass (i.e., 2018 level) can be considered an interim biomass target, which we used to tune MPs to achieve stable biomass over the first 10 projection years (i.e., objective 2). This paper suggests there is opportunity to design a strategic management plan for rockfish that includes both entry/exit from rebuilding plans. Avoiding low biomass states in the future appears feasible for a range of MPs, while still providing fishing opportunities in other groundfish fisheries.

5   ACKNOWLEDGEMENTS

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7   TABLES

Table 1. Notation for the operating models and catch-at-age assessment model.

Indices

Symbol	Description
f	Fleet/survey index where $f = 1, ..., F$ and F=6
p	Stock index, where $p=1,2$ for North and South
a	Age-class in years where $a = 1, ..., A^+$ and $A^+=65$
a'	Age-class with ageing-error matrix adjustment

Observations

Symbol	Description
$C_{p,f,t}$	Catch biomass removed for stock p, by fleet f, during year t
$I_{t,g}$	Stock relative abundance observation for year t and survey f
$A_{a,p,f,t}$	Numbers at age a for stock p, by fleet f, during year t, from catch-at-age samples
$y_{a,p,f,t}$	observed proportion of age-class a, for stock p, by fleet f, during year t

Model parameters

Symbol	Description
$B_{0,p}$	Unfished spawning biomass (t)
$q_{p,f}$	Catchability coefficient for stock p and fleet f
$a^{sel}_{50,p,f}, a^{sel}_{95,p,f}$	age at 50% and 95% selectivity for stock p and fleet f
$a^{mat}_{50}, a^{mat}_{95}$	age at 50% and 95% maturity
M_p	Instantaneous natural mortality for stock p (yr^{-1})
h_p	Recruitment function steepness for stock p
$\tau_{f,p}$	observation error in survey indices for survey f and stock p
$\tau_{age,f,p}$	observation error in proportions-at-age for fleet f and stock p
σ_R	Standard error of log-recruitment deviations
$\omega_{R,p,t}$	log-recruitment deviations for stock p in year t
$\epsilon_{h,p}$	logit-scale deviations for recruitment steepness for stock p

Derived variables

Symbol	Description
m_a	proportion mature-at-age
$S_{a,p}$	Unfished equilibrium survivorship at age-a for stock p
ϕ_p	Unfished equilibrium spawning biomass per recruit for stock p
$R_{0,p}$	Unfished recruitment for stock p
$N_{a,p}^{eq}$	Unfished equilibrium numbers of fish at-age a for stock p
$s_{a,p,f}$	Selectivity-at-age a for stock p and fleet f
w_a	weight-at-age a
a_p, b_p	Beverton-Holt recruitment parameters for stock p

State variables

Symbol	Description
$N_{a,p,f,t}$	Numbers at-age a, for stock p, by fleet f, in year t
$B_{a,p,f,t}$	Biomass at-age a, for stock p, by fleet f, in year t
$R_{p,t}$	Recruitment for stock p, in year t
$p_{a,f,t}$	Proportion of fish in age-class a, by fleet f, in year t

Table 2. Age-structured operating model.

Unfished Equilibrium States

Equation Number	Equations
(EQ.1)	$m_a = \begin{cases} \left(1 + e^{-log19\frac{a-a_{50}^{mat}}{a_{50}^{mat}-a_{95}^{mat}}}\right)^{-1} & a > 8 \\ 0 & a \le 8 \end{cases}$
(EQ.2)	$S_{a,p} = e^{-(a-1)M_p}$
(EQ.3)	$S_{A,p} = \dfrac{e^{-(A-1)M_p}}{1-e^{-M_p}}$
(EQ.4)	$\phi_p = \sum_a S_{a,p} \cdot w_a \cdot m_a$
(EQ.5)	$R_{0,p} = B_{0,p} / \phi_p$
(EQ.6)	$N_{a,p}^{eq} = R_0 \cdot S_{a,p}$

Catch from discrete fisheries

Equation Number	Equations
(C.1)	$N_{a,p,t+t_{f^-}} = N_{a,p,t+t_{f-1}} \cdot e^{-1(t_f-t_{f-1})M_p}$
(C.2)	$s_{a,p,f} = \left(1 + e^{-\log 19\frac{a-a_{p,50}^{sel}}{a_{p,95}^{sel}-a_{p,50}^{sel}}}\right)^{-1}$
(C.3)	$N_{a,p,f,t} = N_{a,p,t+t_{f^-}} \cdot s_{a,p,f}$
(C.4)	$B_{a,p,f,t} = N_{a,p,f,t} \cdot w_a$
(C.5)	$B_{p,f,t} = \sum_a B_{a,p,f,t}$
(C.6)	$C'_{a,p,f,t} = C_{p,f,t} \cdot \dfrac{B_{a,p,f,t}}{\sum_{a'} B_{a',p,f,t}}$
(C.7)	$C_{a,p,f,t} = C'_{a,p,f,t} / w_a$
(C.8)	$N_{a,p,t+t_f} = e^{-(t_f-t_{f-1})M_p} \cdot N_{a,p,t+t_{f-1}} - C_{a,p,f,t}$

Annual Numbers-at-age

Equation Number	Equations
(A.1)	$B_{p,t} = e^{-(1-t_F)M_p} \cdot \sum_a N_{a,p,t+t_F} \cdot w_a \cdot m_a$
(A.2)	$R_{p,t+1} = \dfrac{a_p B_{p,t}}{1 + b_p B_{p,t}} \cdot e^{\omega_{R,p,t}}$
(A.3)	$N_{a,p,t+1} = \begin{cases} R_{p,t+1} & a = 1 \\ e^{-(1-t_F)M_p} \cdot N_{a-1,p,t+t_F} & 2 \le a \le A-1 \\ e^{-(1-t_F)M_p} \cdot \left(N_{a-1,p,t+t_F} + N_{a,p,t+t_F} \right) & a = A. \end{cases}$

Mixed-stock catch and catch-at-age

Equation Number	Equations
(M.1)	$\hat{C}_{p,f,t} = \dfrac{\hat{B}_{p,f,t}}{\sum_p \hat{B}_{p,f,t}} C_{f,t}$
(M.2)	$\hat{C}_{a,p,f,t} = \dfrac{\hat{B}_{a,p,f,t}}{\sum_p \hat{B}_{a,p,f,t}} C_{a,f,t}$

Table 3. Statistical models for age-structured operating model.

Eq. No	Equation
(L.1)	$$\mathcal{L}(\Theta \mid \vec{I}_{p,f,t}) = \prod_{t=t_{1,f}}^{t_{2,f}} \frac{1}{\sqrt{2\pi\sigma^2}} \cdot e^{-\frac{\left(\log\left(\frac{I_{p,f,t}}{q_{p,f}B_{p,f,t}}\right)\right)^2}{2\tau_f^2}}$$
(L.2)	$$y_a = A_{a,p,f,t} \Big/ \sum_{a'} A_{a',p,f,t}$$
(L.3)	$$p_a = C'_{a,p,f,t} \Big/ \sum_{a'} C'_{a',p,f,t}$$
(L.4)	$$\tilde{y} = \left(\prod_a y_a\right)^{1/A^+}$$
(L.5)	$$\tilde{p} = \left(\prod_a p_a\right)^{1/A^+}$$
(L.6)	$$l(p,\tau_{age,f} \mid y) = (A^+ - 1)\cdot \log\tau_{age,f,p} + \frac{1}{2\tau_{age,f,p}^2}\sum_{a=1}^{A^+}\left(\log\frac{y_a}{\tilde{y}} - \log\frac{p_a}{\tilde{p}}\right)^2$$
(PE.1)	$$\omega_{R,p,t} \sim N(0,\sigma_{R,p})$$
(PE.2)	$$\omega_{M,p,t} \sim N(0,\sigma_{M,p})$$
(PD.1)	$$\log q_{f,p} \sim N(\log m_q, s_q)$$
(PD.2)	$$h \sim \beta(17.5, 7.5)$$
(PD.3)	$$\epsilon_{h,p} \sim N(0,\sigma_h)$$
(PD.4)	$$\tau_{f,p}^2 \sim IG(100, 101\cdot m_{\tau,f})$$
(PD.5)	$$\sigma_R^2 \sim IG(1,2)$$
(PD.6)	$$a_{95}^{sel} \sim N(\bar{a}_f^{sel95}, 0.25\bar{a}_f^{sel95})$$
(PD.7)	$$\epsilon_{a_{50}^{sel},t,p} \sim N(0,\sigma_{a_{50}^{sel}})$$

Table 4. Estimated observation model standard errors for different operating models.

OM	Biomass index observation errors					Age composition observation errors						
	PHMA_N	PHMA_QCS	PHMA_S	IPHC_N	IPHC_S	PHMA_N	PHMA_QCS	PHMA_S	IPHC_N	IPHC_S	Longline Mixed	Trawl
base_North	0.20	0.30	-	0.24	-	0.66	0.85	-	1.03	-	0.32	0.53
OM2_North	0.19	0.30	-	0.28	-	0.70	0.86	-	1.07	-	0.32	0.47
OM3_North	0.19	0.30	-	0.25	-	0.74	0.88	-	1.16	-	0.34	0.47
OM4_North	0.24	0.32	-	0.26	-	0.66	0.85	-	1.03	-	0.32	0.53
base_South	-	-	0.26	-	0.36	-	-	0.95	-	1.38	0.32	-
OM2_South	-	-	0.26	-	0.39	-	-	0.94	-	1.46	0.32	-
OM3_South	-	-	0.25	-	0.35	-	-	0.99	-	1.54	0.34	-
OM4_South	-	-	0.24	-	0.33	-	-	0.95	-	1.38	0.32	-

Table 5. Biological parameter and management reference point estimates for reference operating models and alternative operating models, by area. Biomass and MSY units in kt. The posterior-prior variance ratio (ψ_M) is provided for Natural Mortality.

North

OM	Unfished Biomass (kt)		Natural Mortality		Reference Points				Current Status			
	B_0	95% CI	M	95% CI	B_{MSY}	LRP	F_{MSY}	MSY	B_{2018}	B_{2018}/B_0	B_{2018}/B_{MSY}	P(B_{2018}>LRP)
base	14.2	13.1 - 15.4	0.039	0.037 - 0.040	3.6	1.4	0.053	0.21	4.5	0.31	1.23	100.0%
2	16.0	11.8 - 21.8	0.044	0.043 - 0.046	4.4	1.8	0.052	0.26	8.2	0.51	1.85	100.0%
3	17.4	15.6 - 19.5	0.034	0.034 - 0.035	4.8	1.9	0.042	0.22	5.3	0.30	1.11	99.9%
4	8.8	8 - 9.7	0.039	0.037 - 0.040	2.3	0.9	0.051	0.13	2.6	0.29	1.12	100.0%
wtd	14.1	12.4 - 16.2	0.039	0.038 - 0.040	3.7	1.5	0.051	0.21	4.9	0.35	1.33	100.0%

South

OM	Unfished Biomass (kt)		Natural Mortality		Reference Points				Current Status			
	B_0	95% CI	M	95% CI	B_{MSY}	LRP	F_{MSY}	MSY	B_{2018}	B_{2018}/B_0	B_{2018}/B_{MSY}	P(B_{2018}>LRP)
base	10.8	10 - 11.7	0.038	0.036 - 0.039	2.8	1.1	0.052	0.16	3.3	0.30	1.18	100.0%
2	10.3	8.7 - 12.2	0.041	0.040 - 0.043	2.9	1.2	0.048	0.15	4.4	0.43	1.54	100.0%
3	11.6	10.8 - 12.5	0.031	0.031 - 0.032	3.2	1.3	0.038	0.13	2.4	0.21	0.75	91.8%
4	7.5	6.7 - 8.5	0.038	0.036 - 0.039	2.0	0.8	0.050	0.11	1.9	0.26	0.98	94.6%
wtd	10.3	9.4 - 11.4	0.037	0.036 - 0.038	2.8	1.1	0.049	0.14	3.1	0.30	1.13	98.0%

Coastwide

OM	Unfished Biomass (kt)		Natural Mortality		Reference Points				Current Status			
	B_0	95% CI	M	95% CI	B_{MSY}	LRP	F_{MSY}	MSY	B_{2018}	B_{2018}/B_0	B_{2018}/B_{MSY}	P(B_{2018}>LRP)
base	25.0	23.1 - 27.1	0.039	0.037 - 0.040	6.4	2.6	0.053	0.37	7.8	0.31	1.22	100.0%
2	26.3	20.5 - 34.0	0.043	0.042 - 0.045	7.3	2.9	0.050	0.41	12.6	0.48	1.73	100.0%
3	29.0	26.4 - 32.0	0.033	0.033 - 0.034	8.0	3.2	0.040	0.35	7.7	0.27	0.96	99.8%
4	16.3	14.7 - 18.2	0.039	0.037 - 0.040	4.3	1.7	0.051	0.24	4.5	0.28	1.05	99.7%
wtd	24.4	21.8 - 27.6	0.039	0.037 - 0.039	6.5	2.6	0.050	0.35	8.0	0.33	1.24	100.0%

Table 6. Notation for the surplus production stock assessment model.

Symbol	Description
	Indices and index ranges
T	Year in which stock assessment is performed
t	Year, where $t = 1, \ldots, T$
g	Survey index where $g = 1, \ldots, G$
n_g	Number of non-missing observations for the index g
i	Index for non-missing survey observations $i = 1, \ldots, n_g$
	Data
$C_{t,g}$	Catch biomass removed during year t by gear type g
$I_{t,g}$	Stock relative abundance observation for year t
	Leading model parameters
Y^{MSY}	Maximum sustainable yield
U^{MSY}	Optimal exploitation rate
	Nuisance parameters
q_g	Catchability coefficient for abundance index g
κ^2	Total error variance
ρ	Observation error proportion of total variance (assumed known)
	State variables
B_t	Biomass at the beginning of year t
	Derived reference points
B^{MSY}	Maximum sustainable yield biomass level
	Prior distributions
$N\left(\mu^Y, \sigma^Y\right)$	Normal prior on Y^{MSY}
$N\left(\mu^U, \sigma^U\right)$	Normal prior on U^{MSY}
	Error distributions
$\xi_{t,g} \sim N\left(0, \rho\kappa^2\right)$	Observation error in year t for index g
$\omega_t \sim N\left(0, (1-\rho)\kappa^2\right)$	Process error in year t

Table 7. Mixed-error surplus production model used for annual stock assessment in SP MPs.

Model parameters

E2.1 $\quad \Theta = \left(U', Y', \{ \omega_t \}_{t=1}^{t=T-1} \right)$

Parameter transformations

E2.2 $\quad U^{\mathrm{MSY}} = \exp(U')$

E2.3 $\quad Y^{\mathrm{MSY}} = \exp(Y')$

Biomass dynamics model

E2.4 $\quad B_1 = 2 Y^{\mathrm{MSY}} / U^{\mathrm{MSY}}$

E2.5 $\quad B^{\mathrm{MSY}} = Y^{\mathrm{MSY}} / U^{\mathrm{MSY}}$

E2.6 $\quad B_{t+1} = \begin{cases} \left(B_t + 2 U^{\mathrm{MSY}} B_t \left(1 - \dfrac{B_t}{2 B^{\mathrm{MSY}}} \right) - \displaystyle\sum_{g=1}^{G} C_{t,g} \right) e^{\omega_t} & 1 \le t \le T-1 \\[4ex] B_t + 2 U^{\mathrm{MSY}} \left(1 - \dfrac{B_t}{2 B^{\mathrm{MSY}}} \right) - \displaystyle\sum_{g=1}^{G} C_{t,g} & t = T \end{cases}$

Residuals

E2.7 $\quad \xi_{t,g} = \log_e \left(I_{t,g} / B_t \right)$

Conditional maximum likelihood estimates

E2.8 $\quad \widehat{\log q}_g = \dfrac{1}{n_g} \sum_{1}^{n_g} \xi_{i,g}$

E2.9 $\quad \hat{\kappa}^2 = \dfrac{1}{n. + T - 1} \left(\dfrac{1}{\rho} \sum_{g=1}^{G} \sum_{i=1}^{n_g} (\xi_{i,g} - \widehat{\log q}_g)^2 + \dfrac{1}{1-\rho} \sum_{t=1}^{T-1} \omega_t^2 \right)$

Negative log-likelihood and objective function

E2.10 $\quad \ell(\mathbf{I}|\Theta) = \dfrac{n. + T - 1}{2} \left(\log_e \dfrac{1}{\rho} \sum_{g=1}^{G} \sum_{i=1}^{n_g} (\xi_{i,g} - \widehat{\log q}_g)^2 + \dfrac{1}{1-\rho} \sum_{t=1}^{T-1} \omega_t^2 \right)$

E2.11 $\quad G(\Theta|\mathbf{I}) \propto \ell(\mathbf{I}|\Theta) + \dfrac{1}{2(\sigma^Y)^2} \left(Y^{\mathrm{MSY}} - \mu^Y \right)^2 + \dfrac{1}{2(\sigma^U)^2} \left(U^{\mathrm{MSY}} - \mu^U \right)^2$

Table 8. Tuned reference fishing mortality (Ftune) and weighted (wtd) 2020 TACs used for catch-age model (CAA, CAASMUV) and index-based (IDX) MPs, by area.

North

MP	OM	Ftune	TAC (t)	B_{2018} (kt)	Fmsy	Weights (%)
CAA, IDX, IDXSMUV						
	1	0.035	151	4.5	0.053	50.00
	2	0.035	276	8.2	0.052	16.67
	3	0.035	179	5.3	0.042	16.67
	4	0.035	87	2.6	0.051	16.67
	wtd	0.035	166			
CAASMUV						
	1	0.037	159	4.5	0.053	50.00
	2	0.037	291	8.2	0.052	16.67
	3	0.037	189	5.3	0.042	16.67
	4	0.037	92	2.6	0.051	16.67
	wtd	0.037	175			

South

MP	OM	Ftune	TAC (t)	B_{2018} (kt)	Fmsy	Weights (%)
CAA, IDX, IDXSMUV						
	1	0.036	113	3.3	0.052	50.00
	2	0.036	153	4.4	0.048	16.67
	3	0.036	84	2.4	0.038	16.67
	4	0.036	67	1.9	0.050	16.67
	wtd	0.036	107			
CAASMUV						
	1	0.039	122	3.3	0.052	50.00
	2	0.039	166	4.4	0.048	16.67
	3	0.039	91	2.4	0.038	16.67
	4	0.039	73	1.9	0.050	16.67
	wtd	0.039	116			

Table 9. Projected Yelloweye catch estimates for 2019 by sector used in simulations. The north/south allocation for commercial hook and line fleet is based on TAC allocations by to area 5BCDE and 3CD5A in 2019. North/South allocation for FSC, IPHC survey, trawl and salmon troll are assumed 50/50.

| Sector | Projected Catch for 2019 (t) | | | North/South Allocation% | Source |
	North	South	Coastwide		
FSC	9.45	9.45	18.9	50/50	2019 IFMP TAC
PHMA Survey	9.30	0.00	9.3	100/0	2017 PHMA Survey Catch
IPHC Survey	2.10	2.10	4.2	50/50	2018 IPHC Survey Catch
Hook and Line	38.25	13.78	52.0	74/26	70% quota (incl. 2018 overages)
Trawl	0.65	0.65	1.3	50/50	2019 IFMP TAC
Salmon troll	0.25	0.25	0.5	50/50	2019 IFMP TAC
Recreational	14.20	15.30	29.5	48/52	2018 Recreational catch
Total	74.2	41.5	115.7	64/36	

Table 10. Proportional allocation of annual surplus TAC (after removal of 18.9 t for FSC and 15.8 t for surveys) used in simulations for the 3 fishing fleets in the operating models. Recreational TAC is not allocated spatially in IFMP and is assumed to be allocated evenly among North and South for simulation work.

| Fisheries | 2019/2020 TAC Allocation | | | TAC projection allocations (excl. FSC/Research) | |
	Coastwide	North	South	North %	South %
Hook and Line	49.6	36.3	13.3	82.1	64.5
Recreational	13.9	6.95	6.95	15.7	33.7
Trawl	1.3	0.97	0.36	2.2	1.7
Total	64.8	44.22	20.61	100.0	100.0

Table 11. Performance statistics calculated for simulation replicates for primary rebuilding objectives (first 2 rows), long-term depletion, and catch. The B denotes spawning stock biomass and statistics are calculated for either long-term (57 years), medium-term (10 years), or short-term projection periods (5 years). Note that fishery objectives for long-term depletion targets and catch have not yet been developed. The indicator function I(x is TRUE) = 1 or I(x is FALSE) = 0, and the $Q_2()$ function calculates the median performance statistic across i replicates.

Performance Measure	Description	Period	Definition
Objective 1 $P(B_{2076} > LRP)$	Proportion of replicates where B_{2076} exceeds the LRP of $0.4B_{MSY}$	*57 yrs:* t_1 =2020 t_2 =2076	$P(B > LRP) = \dfrac{1}{100}\sum_{i=1}^{100} I(B_{2076} < LRP)$
Objective 2 $P(B_{2029} < B_{2020})$	Proportion of replicates where biomass at end of period is less than biomass at beginning of period	*10 yrs:* t_1 =2020 t_2 =2029	$P(B_{2029} < B_{2020}) = \dfrac{1}{100}\sum_{i=1}^{100} I(B_{2029} < B_{2020})$
Final Depletion $\widetilde{B_{2076}/B_0}$ $\widetilde{B_{2076}/B_{MSY}}$	Median biomass depletion across replicates relative to unfished biomass and B_{MSY} at end of projection period	*57 yrs:* t_1 =2020 t_2 =2076	$\widetilde{B_{2076}/B_0} = Q_2\left(\dfrac{B_{2076,i}}{B_{0,i}}\right)$ $\widetilde{B_{2076}/B_{MSY}} = Q_2\left(\dfrac{B_{2076,i}}{B_{0,i}}\right)$
Minimum Catch $P(C_t>minC_p)$	Proportion of projection years where catch is greater than 64 t in the North and 36 t for the South, considered minimum totals for viable fisheries	*5 yrs:* t_1 =2020 \ t_2 =2024	$P(C_t > minC_p) = \dfrac{\sum_{i=1}^{100}\sum_{t_1}^{t_2} I(C_{i,t} > minC_p)}{100(t_2 - t_1 + 1)}$
Average Catch $\tilde{C}$	Median of average annual landed catch across replicates	10 yrs: $t1$ =2020 $t2$ =2029	$\tilde{C} = Q_2\left(\dfrac{1}{t_2 - t_1 + 1}\sum_{t_1}^{t_2} C_{t,i}\right)$
Catch Variability $\widetilde{AAV}$	Median of average annual absolute change in the landed catch across replicates		$\widetilde{AAV} = Q2\left(\sum_{t=t_1}^{t_2} |C_{t,i} - C_{t-1,i}| \Big/ \sum_{t=t_1}^{t_2} C_{t,i}\right)$

Table 12. Weighted-average management procedure performance over 4 operating model scenarios for the North. See Table 7 for operating model weights.

MP	Conservation Objectives		Other Performance Measures									
	1	2	Long-term depletion		Short-term Catch (5 years)			Medium-term Catch (10 years)			2020 Catch (t)	
	$P(B_{2076}>LRP)$	$P(B_{2029}<B_{2020})$	B_{2076}/B_0	B_{2076}/B_{MSY}	$P(C_t>62t)$	Median (t)	AAV	$P(C_t>62t)$	Median (t)	AAV	TAC	Catch
sp	1	0	0.55	1.89	0.20	43	45	0.34	54	39	38	38
sp_2xRec	1	0	0.52	1.79	0.25	46	48	0.38	60	42	38	41
caa	1	0.48	0.36	1.25	1.00	190	13	1.00	193	7	166	166
caaSmuv	1	0.48	0.35	1.21	1.00	181	15	1.00	195	7	124	124
caa_2xFSC	1	0.57	0.35	1.21	1.00	199	13	1.00	201	7	166	175
caa_2xRec	1	0.72	0.33	1.14	1.00	216	14	1.00	218	8	166	190
idx	1	0.43	0.43	1.48	1.00	185	22	0.99	184	19	166	166
idxSmuv	1	0.26	0.33	1.13	1.00	162	16	1.00	168	12	120	120
idx_2xFSC	1	0.65	0.40	1.38	1.00	210	21	1.00	207	19	166	175
idx_2xRec	1	0.88	0.36	1.24	1.00	256	24	1.00	250	21	166	190
idx_2020	1	0.00	0.46	1.59	0.94	96	14	0.94	105	15	85	85
idx_dec100	1	0.43	0.43	1.48	1.00	185	22	0.99	184	19	166	166
idxFlr	1	0.44	0.42	1.46	1.00	185	22	1.00	184	19	166	166

Table 13. Weighted-average management procedure performance over 4 operating model scenarios for the South. See Table 7 for operating model weights.

MP	Conservation Objectives		Other Performance Measures									
	1	2	Long-term depletion		Short-term Catch (5 years)			Medium-term Catch (10 years)			2020 Catch (t)	
	$P(B_{2076}>LRP)$	$P(B_{2029}<B_{2020})$	B_{2076}/B_0	B_{2076}/B_{MSY}	$P(C_t>38t)$	Median (t)	AAV	$P(C_t>38t)$	Median (t)	AAV	TAC	Catch
sp	1	0	0.42	1.45	0.44	38	33	0.65	56	30	32	32
sp_2xRec	1	0	0.36	1.21	0.50	44	43	0.70	68	37	32	34
caa	1	0.45	0.31	1.07	1.00	146	16	1.00	154	8	107	107
caaSmuv	1	0.47	0.29	1.01	1.00	138	19	1.00	156	9	79	79
caa_2xFSC	1	0.58	0.30	1.01	1.00	154	15	1.00	162	8	107	116
caa_2xRec	1	0.88	0.25	0.86	1.00	187	18	1.00	193	10	107	136
idx	1	0.05	0.56	1.9	1.00	103	27	0.98	104	23	107	107
idxSmuv	1	0.03	0.45	1.56	1.00	100	19	1.00	105	14	74	74
idx_2xFSC	1	0.19	0.50	1.73	1.00	125	23	0.99	126	21	107	116
idx_2xRec	1	0.81	0.42	1.45	1.00	191	25	0.98	193	24	107	136
idx_2020	1	0	0.63	2.15	0.88	51	18	0.87	53	18	52	52
idx_dec100	1	0.05	0.56	1.9	1.00	103	27	0.98	104	23	107	107
idxFlr	1	0.05	0.53	1.79	1.00	103	27	1.00	104	23	107	107
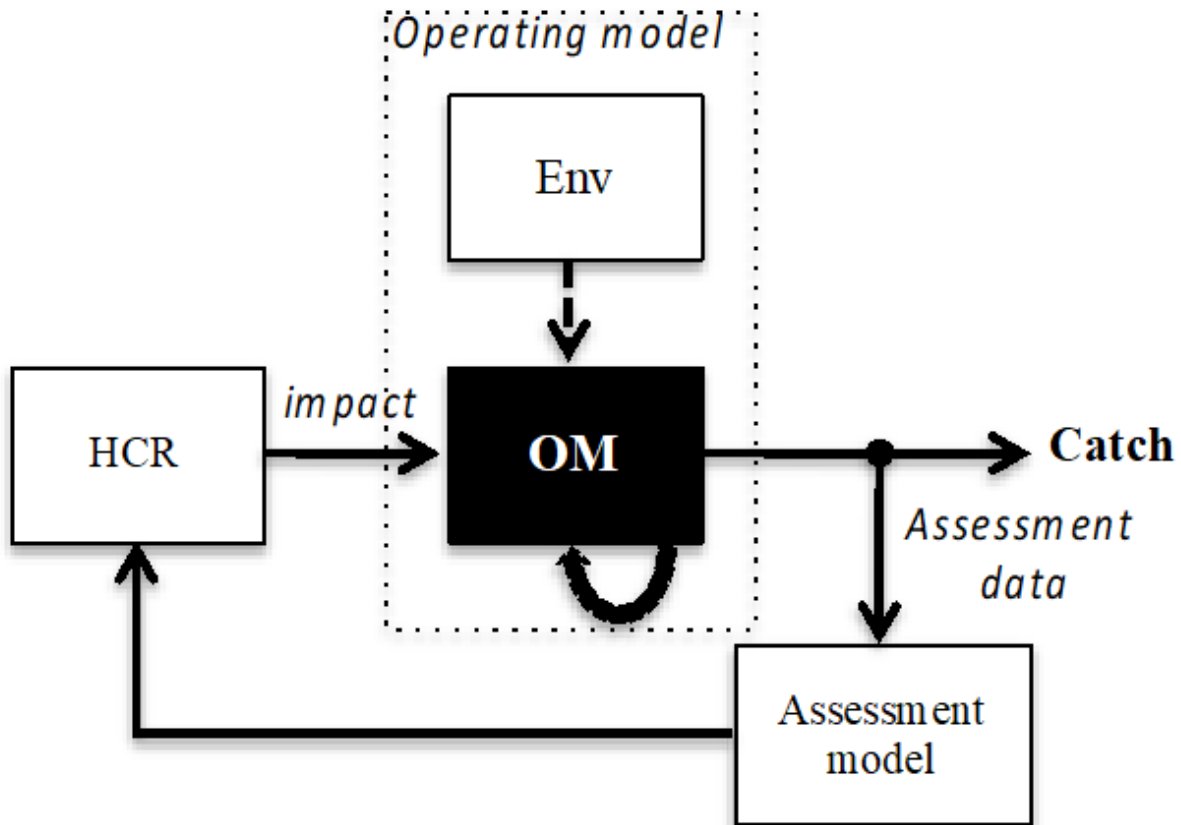
Figure 1. Schematic of the closed loop simulation approach taken here comprises operating model (OM) scenarios that represent alternative hypotheses of OYE biology, ecology, exploitation history and environmental conditions (Env) that are fit to historic data (dotted box). The operating model scenarios are used to simulate future estimates of the data which are fit after applying a Harvest Control Rule (HCR) to set the catch under each management procedure at each annual time step. The simulation repeats until the end of the projection period. The assessment model is run at each time step to evaluate management performance against the objectives (adapted from Cox et al. 2010).
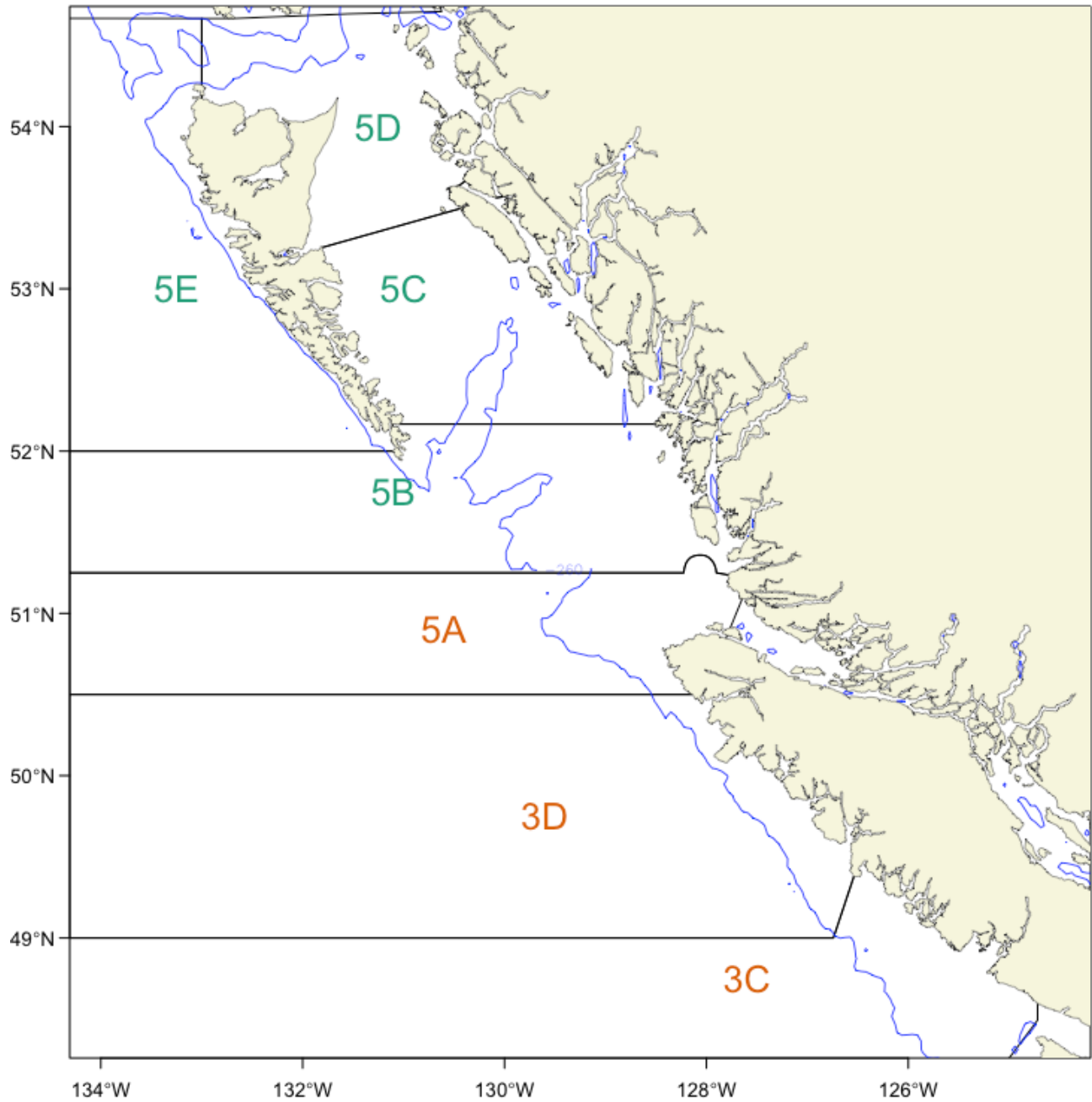
Figure 2. Map of BC groundfish major management areas used to bound the North Outside Yelloweye Stock in areas 5BCDE (green) and the South Outside Yelloweye Stock in areas 3CD5A (orange). Contour line shown for 260 m at the deep end of the depth range for Yelloweye habitats.
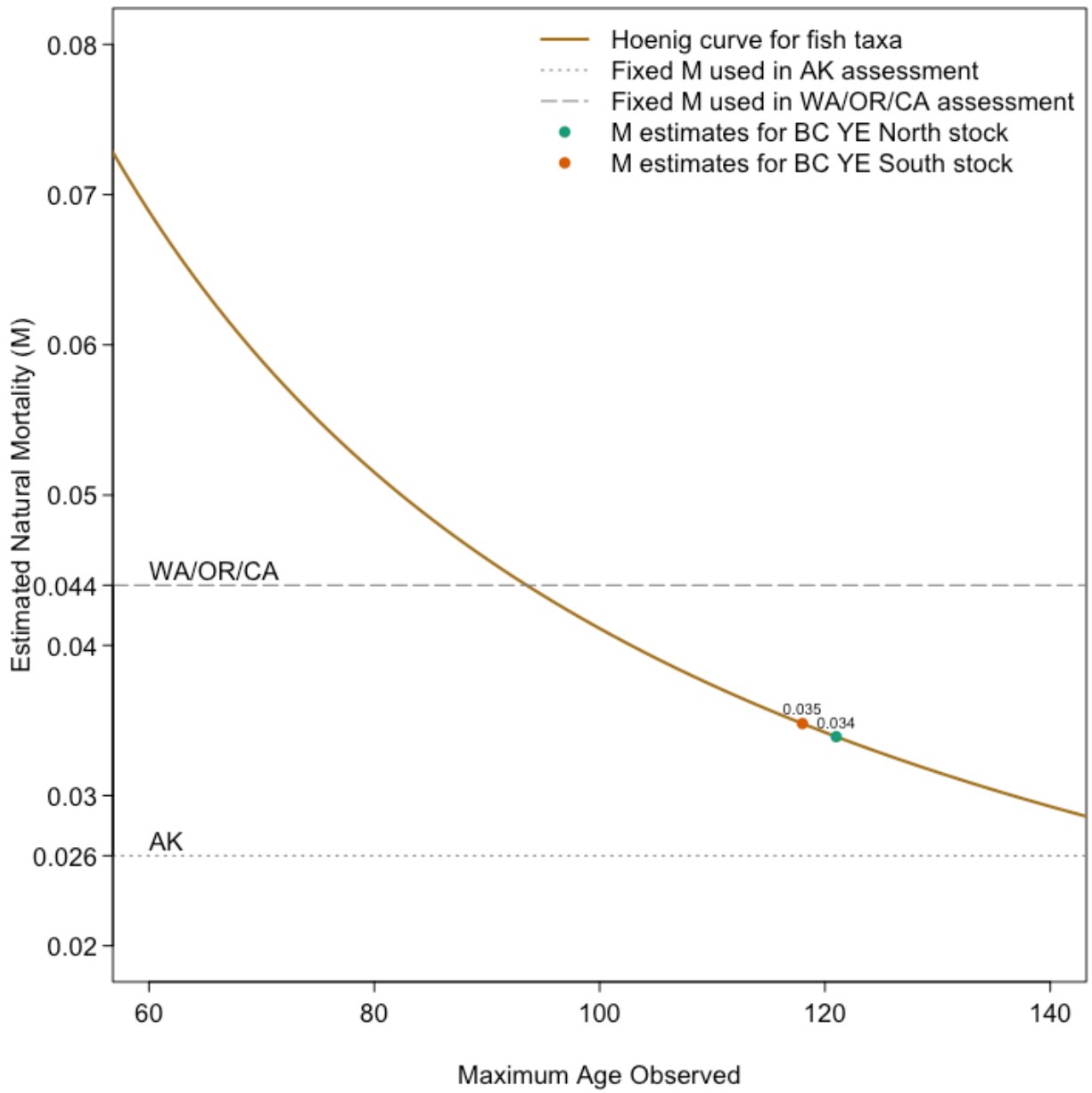
Figure 3. Estimates of natural mortality (M) for North and South Yelloweye Rockfish stocks in BC from Hoenig (1983) fish taxa curve. Dashed and dotted lines indicated M values used in most recent assessments in Washington/Oregon/California and Alaska, respectively.
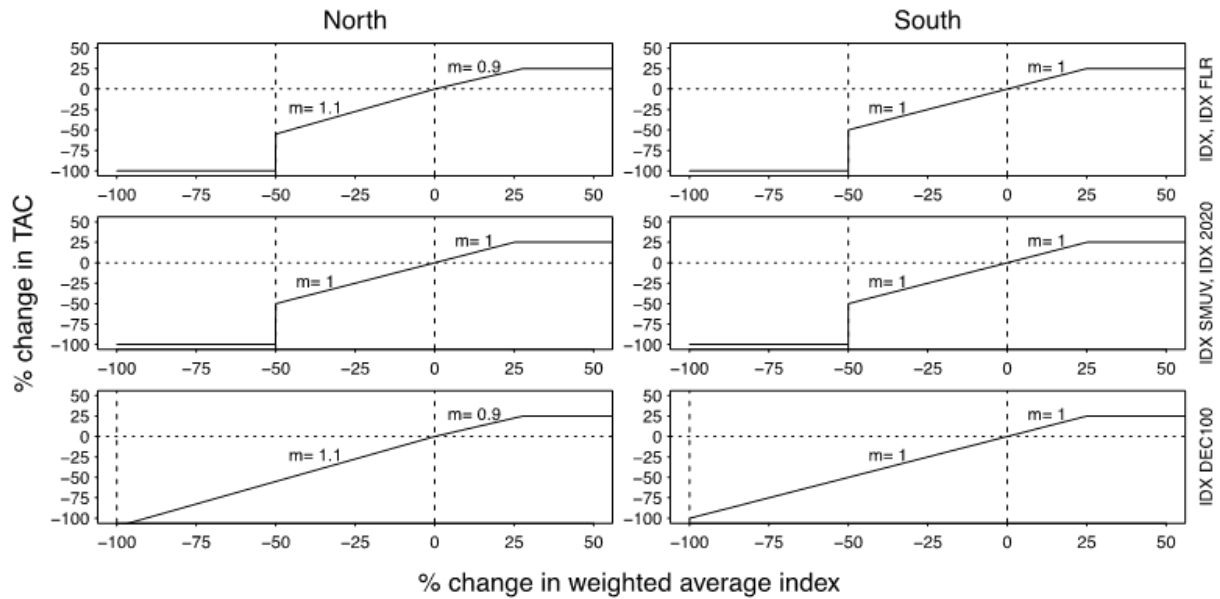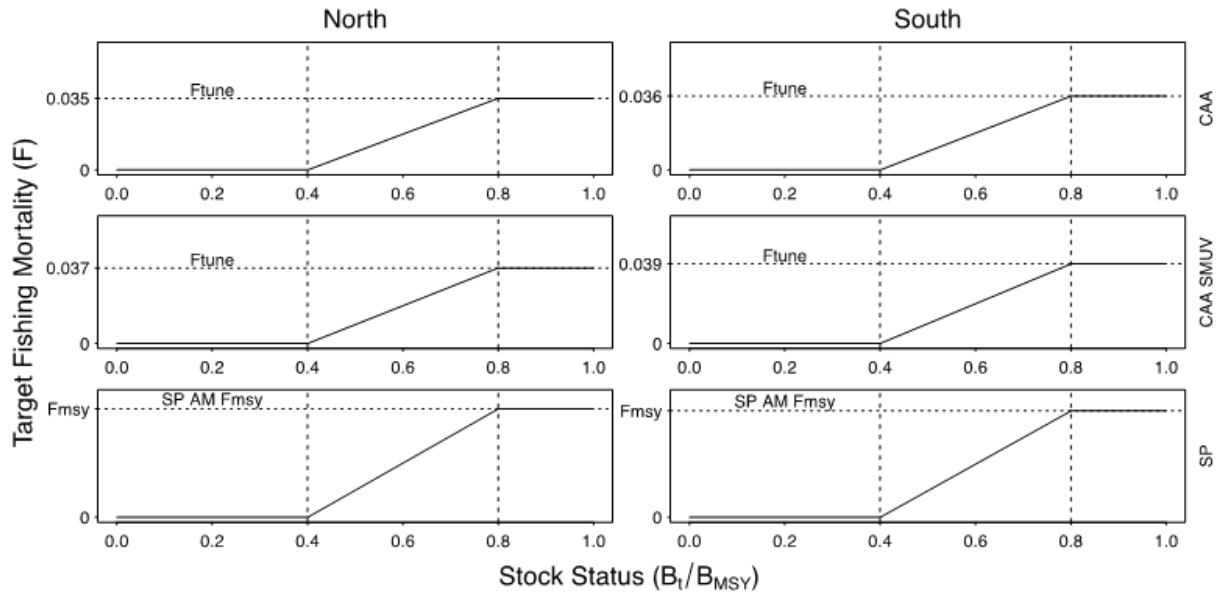
Figure 4. a) Harvest control rules for CAA (top row), CAA SMUV (middle row), SP (bottom row) and b) index (IDX, IDX_FLR, IDX_SMUV, IDX_2020, IDX_DEC100) MPs for North and South stock areas. The CAA MPs use a target F (Ftune) tuned to provide relatively stable OYE biomass over the projection period and the SP MPs use the assessment estimate of Fmsy (SP AM Fmsy) as the maximum removal rate. Index-based rules (IDX) use different up/down slopes (m) to determine the TAC change in proportion to changes in the survey index.
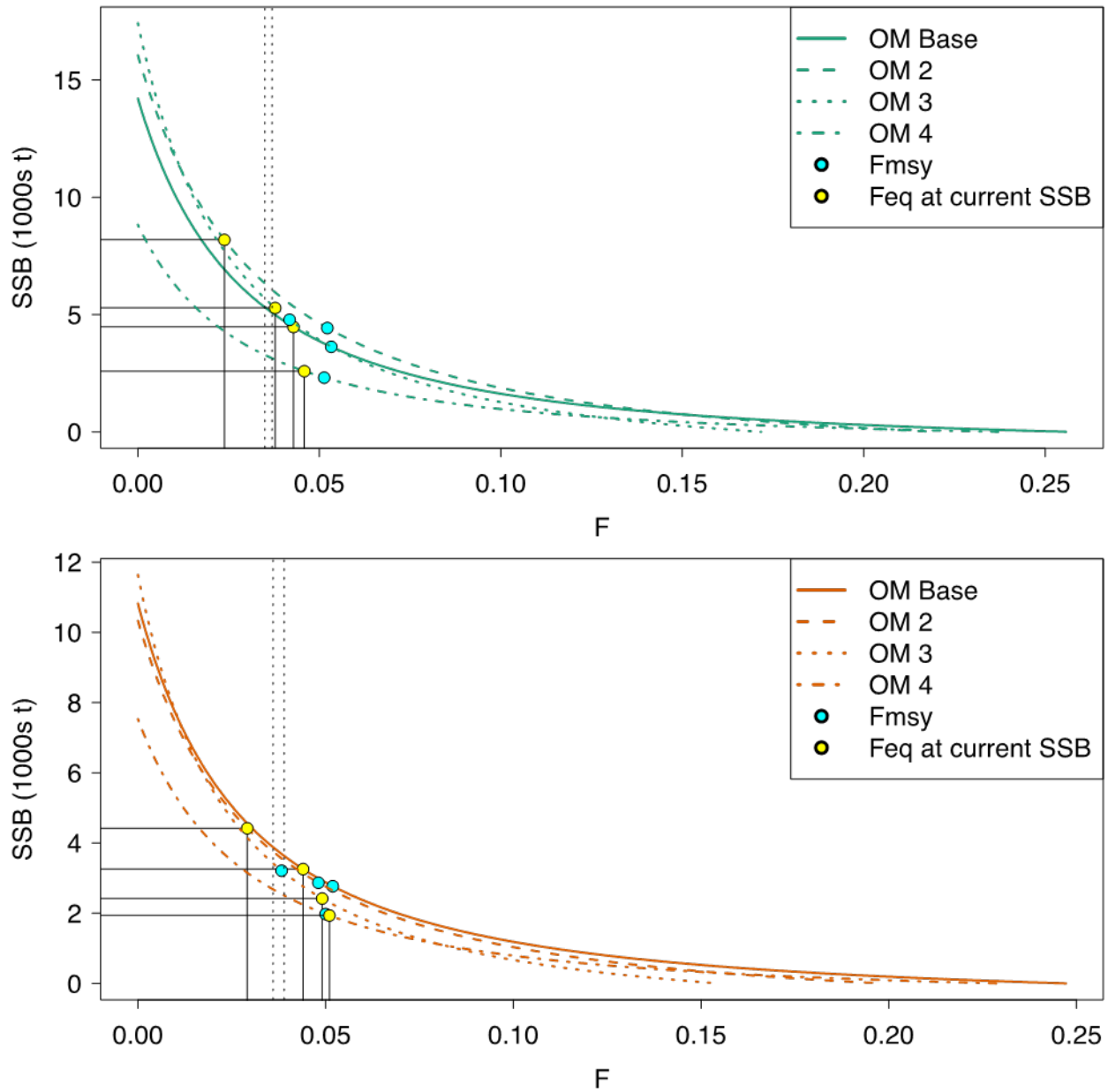
Figure 5. Equilibrium relationships between fishing mortality and OYE spawning stock biomass for each operating model in North (top) and South (bottom) stock areas. Yellow dots indicate the target fishing mortality for each operating model needed to maintain equilibrium spawning biomass near 2018 levels, while dashed vertical lines indicated tuned target Fs for CAA and CAA SMUV MPs.
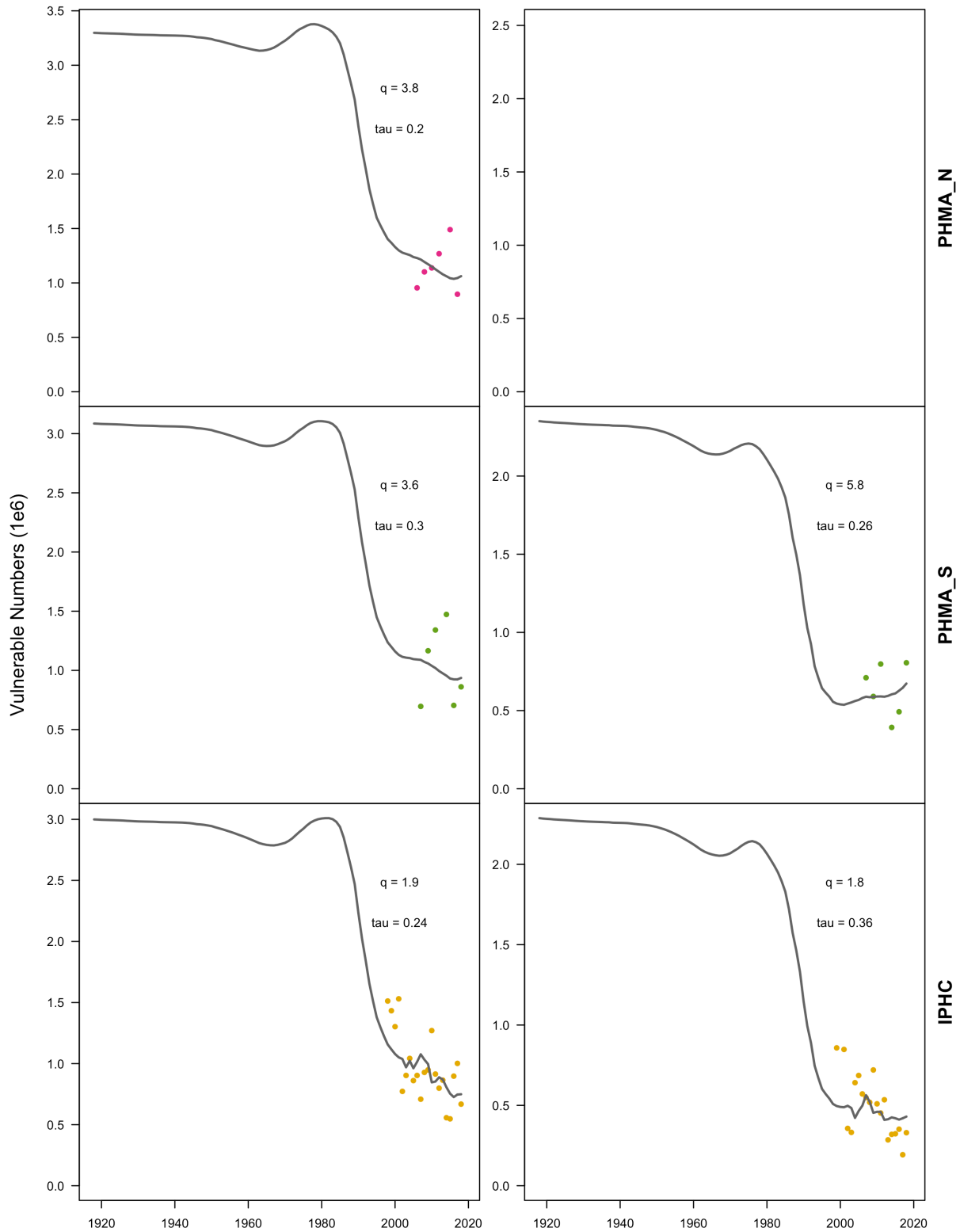
Figure 6. Operating model fits to survey abundance indices standardised to vulnerable numbers and the scaled standardised biomass indices for PHMA North survey (PHMA_N), PHMA South Survey (PHMA_S) and IPHC survey for (left) base_North and (right) base_South operating models.
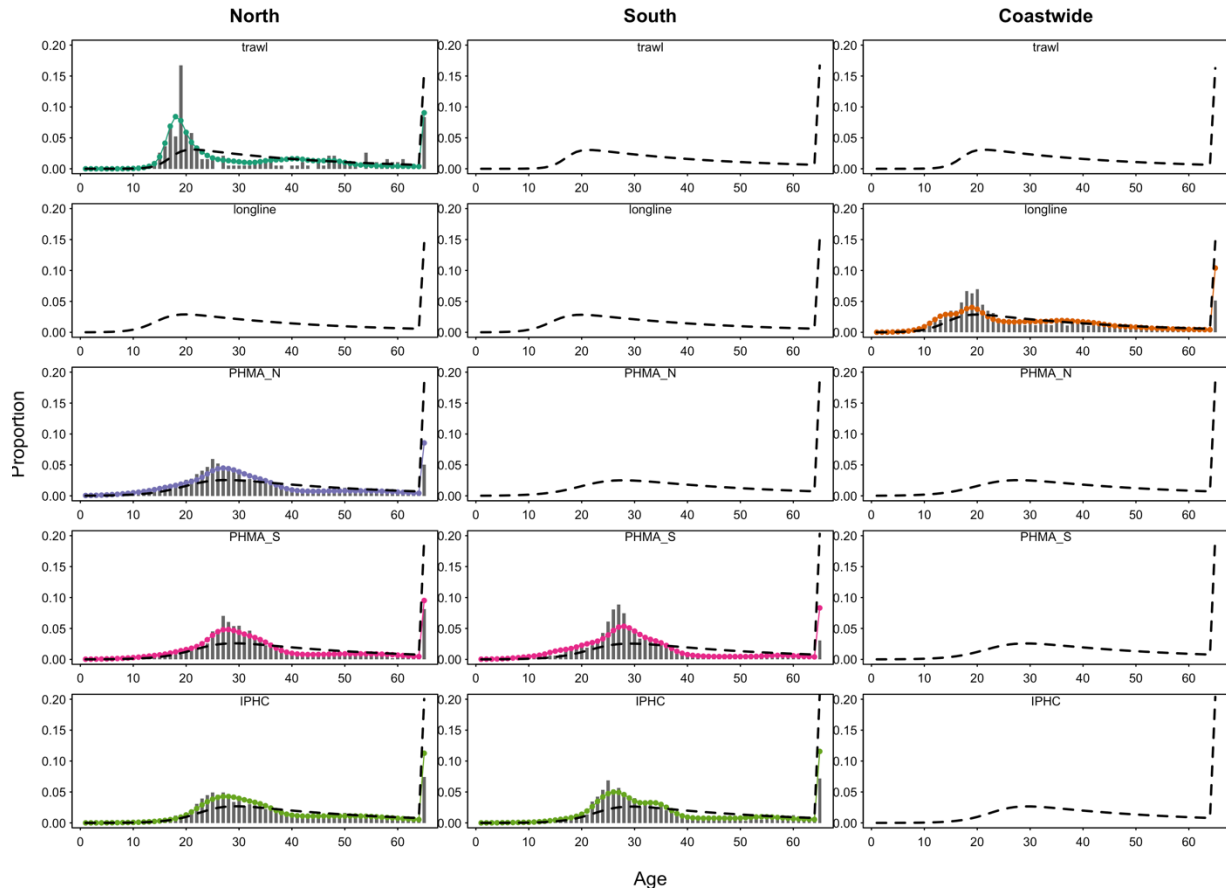
Figure 7. Average observed and fitted age-compositions under the base operating models for fleets contributing age-composition data. Black dashed lines indicate unfished equilibrium age composition adjusted by selectivity in each fleet.
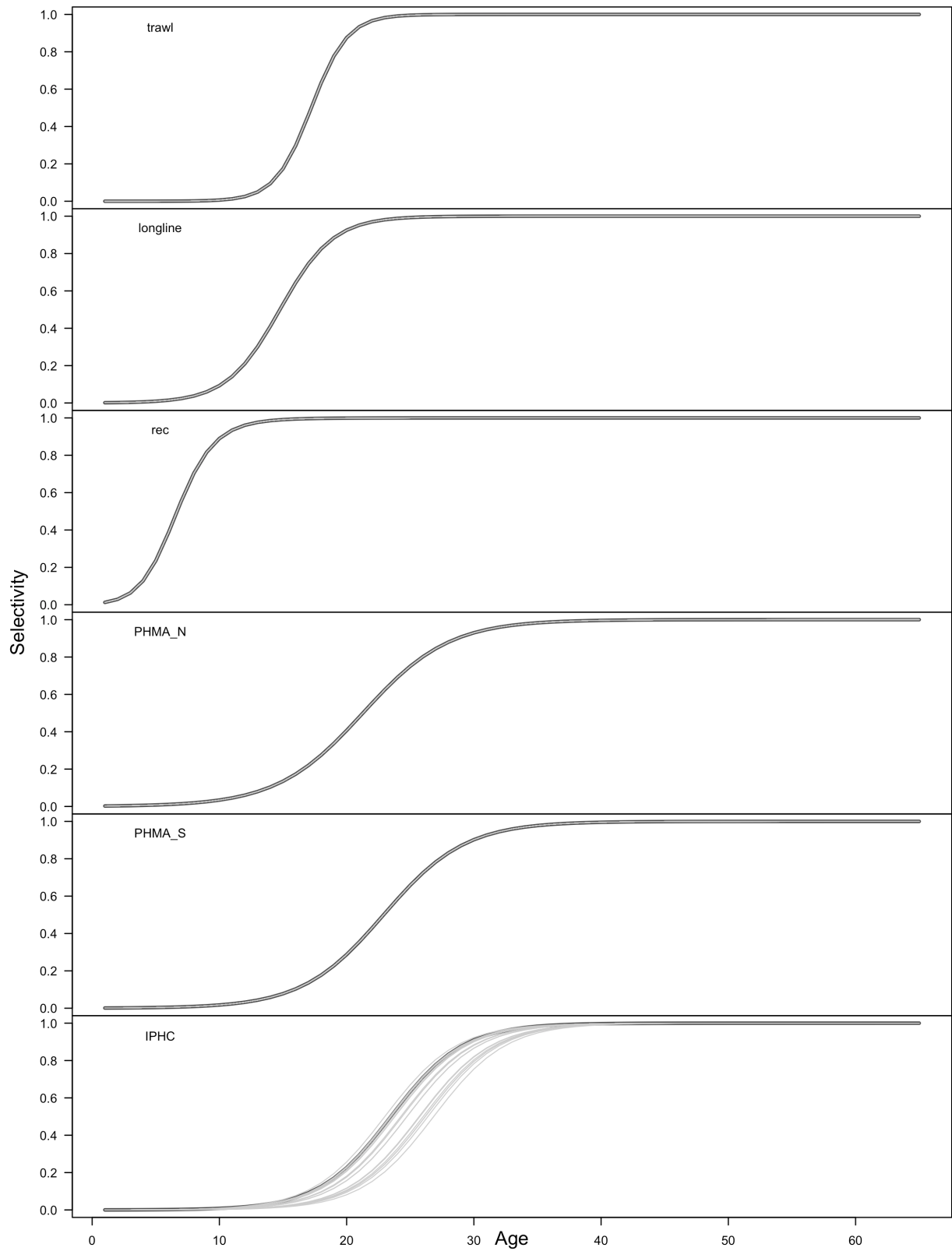
Figure 8. Estimated selectivity-at-age by fleet for the base operating model. These selectivity relationships are shared between North and South stocks except for PHMA surveys.
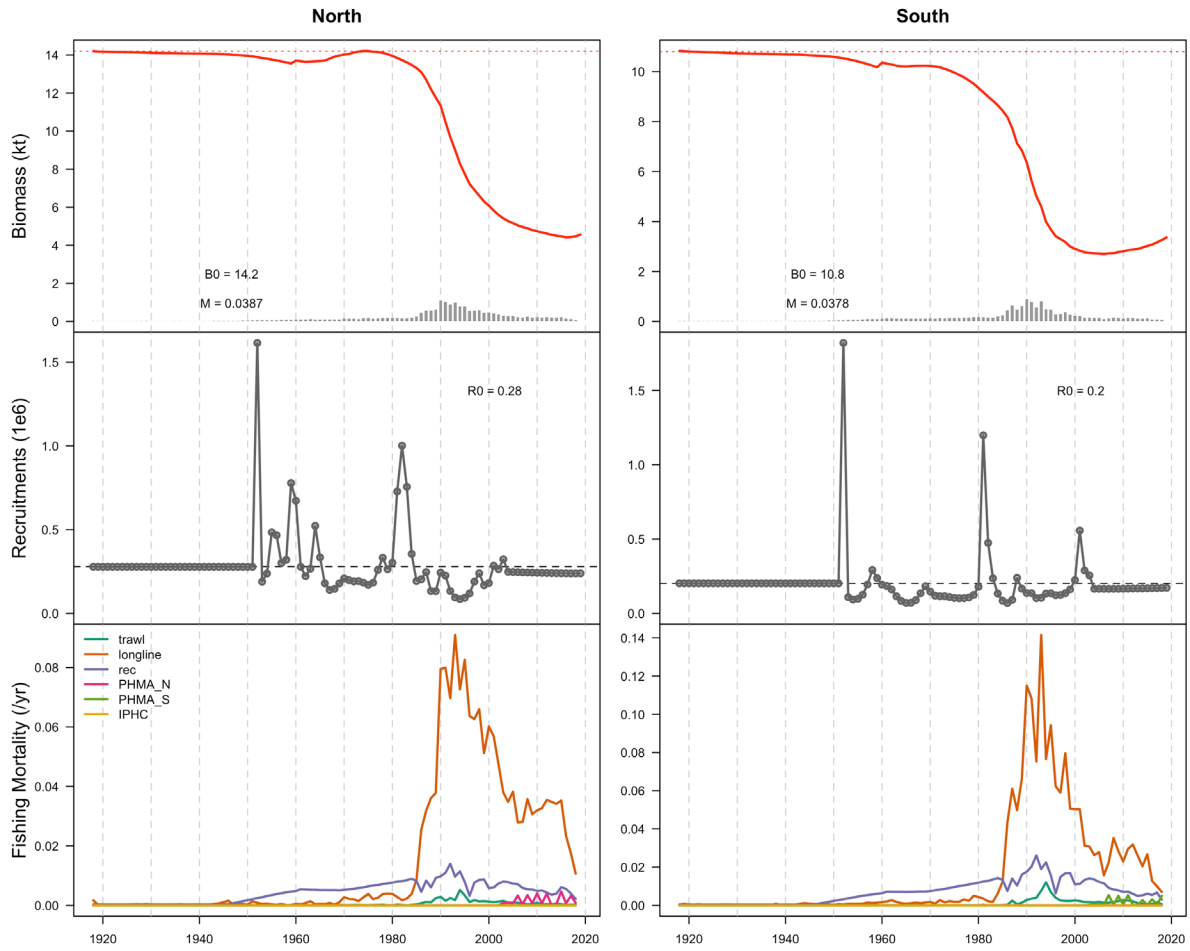
Figure 9. Base operating model estimates for North and South stock areas of spawning biomass (top, red line) and catch (grey bars); age-1 recruitment (middle); and fishing mortality by fleet (bottom).
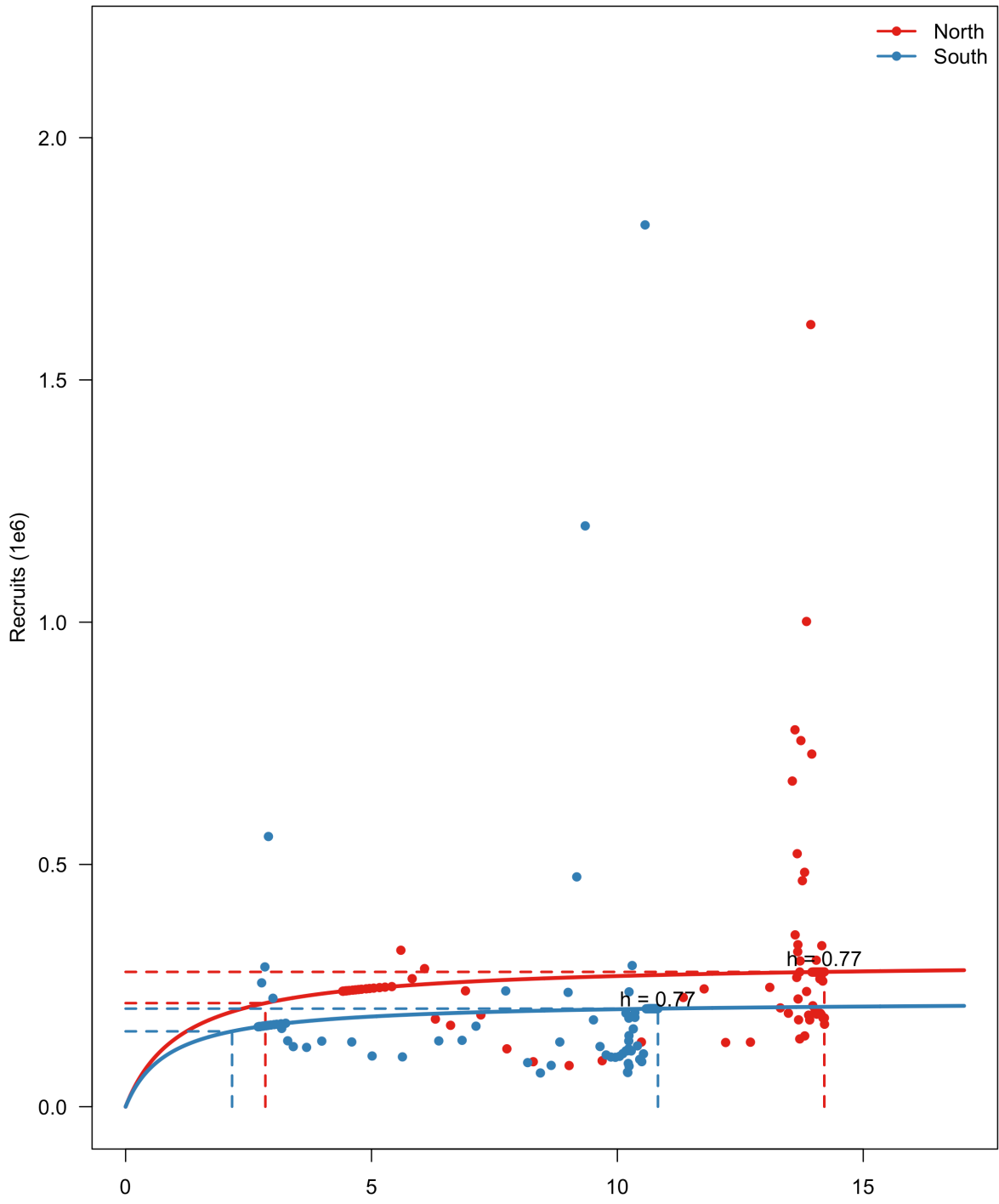
Figure 10. Estimated Beverton-Holt stock-recruitment relationships (solid lines) and recruitment estimates (points) for base_North (red) and base_South (blue) operating models.
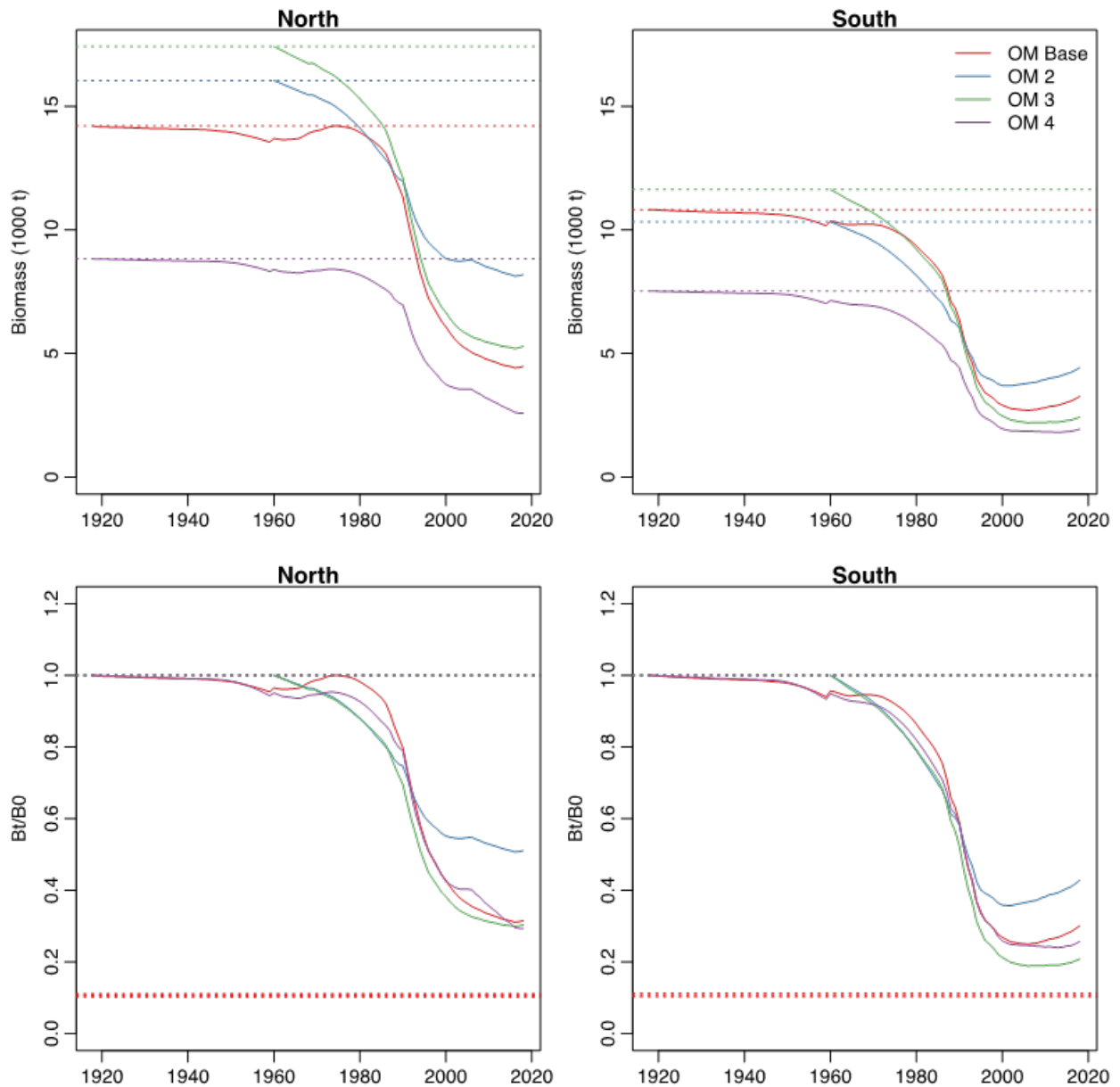
Figure 11. Absolute spawning biomass depletion (top) and relative depletion (bottom) for operating models using i) a 1918 start year and reconstructed commercial catch (OM Base), ii) a 1960 start date and lower bound on commercial catch (OM 2), iii) a 1960 start year and reconstructed commercial catch (OM3), and iv) a 1918 start year and lower bound on commercial catch (OM4). The red dotted lines in the bottom panel indicate the LRP for each OM, which range from 0.10B$_0$ to 0.11B$_0$.
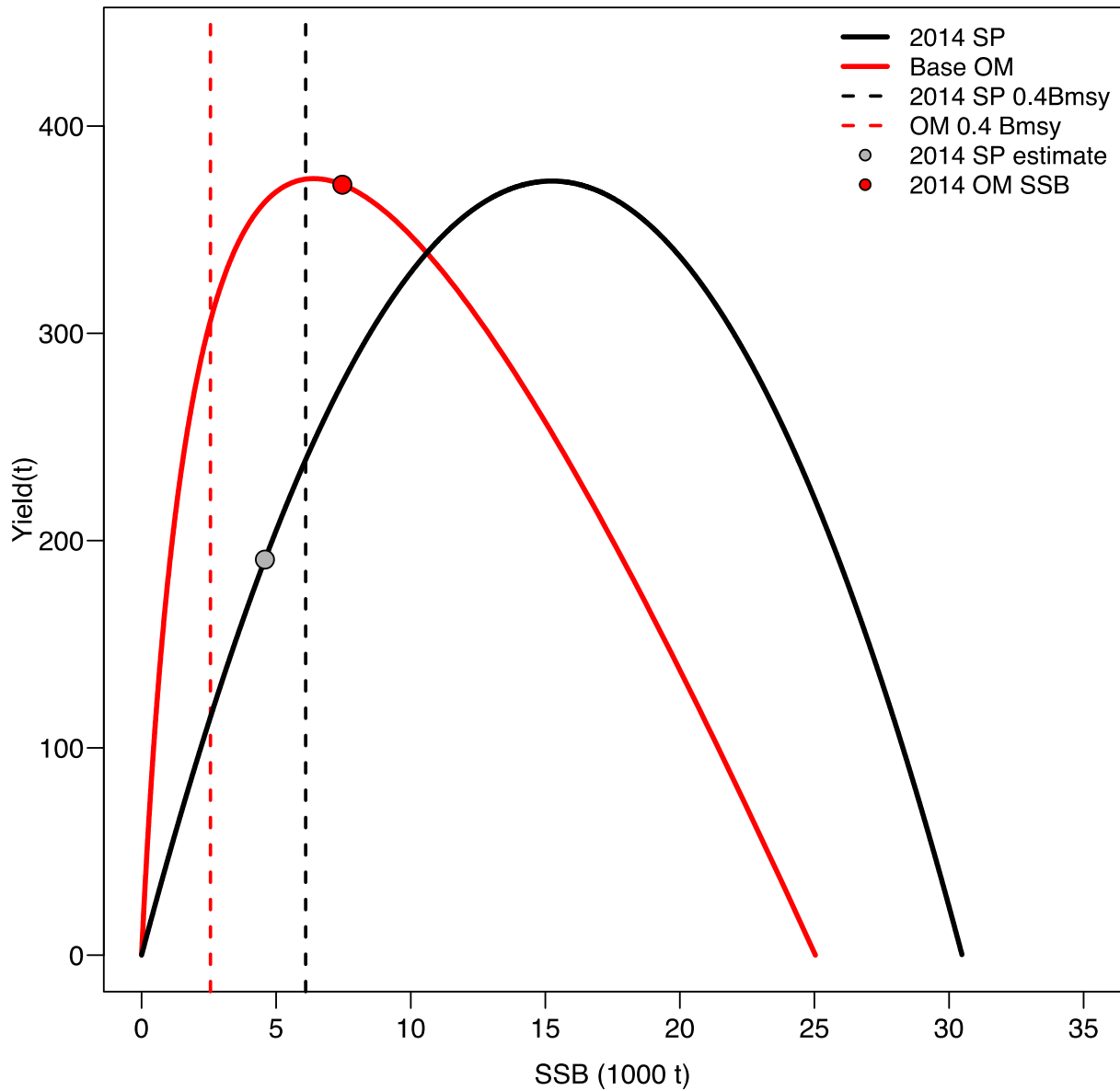
Figure 12. Equilibrium yield vs spawning stock biomass (SSB) curves for coastwide OYE for the base OM catch-age model and the surplus production model (2014 SP) from the 2014 assessment. Grey and red circles indicate 2014 biomass estimates from the 2014 assessment and the base OM, respectively.
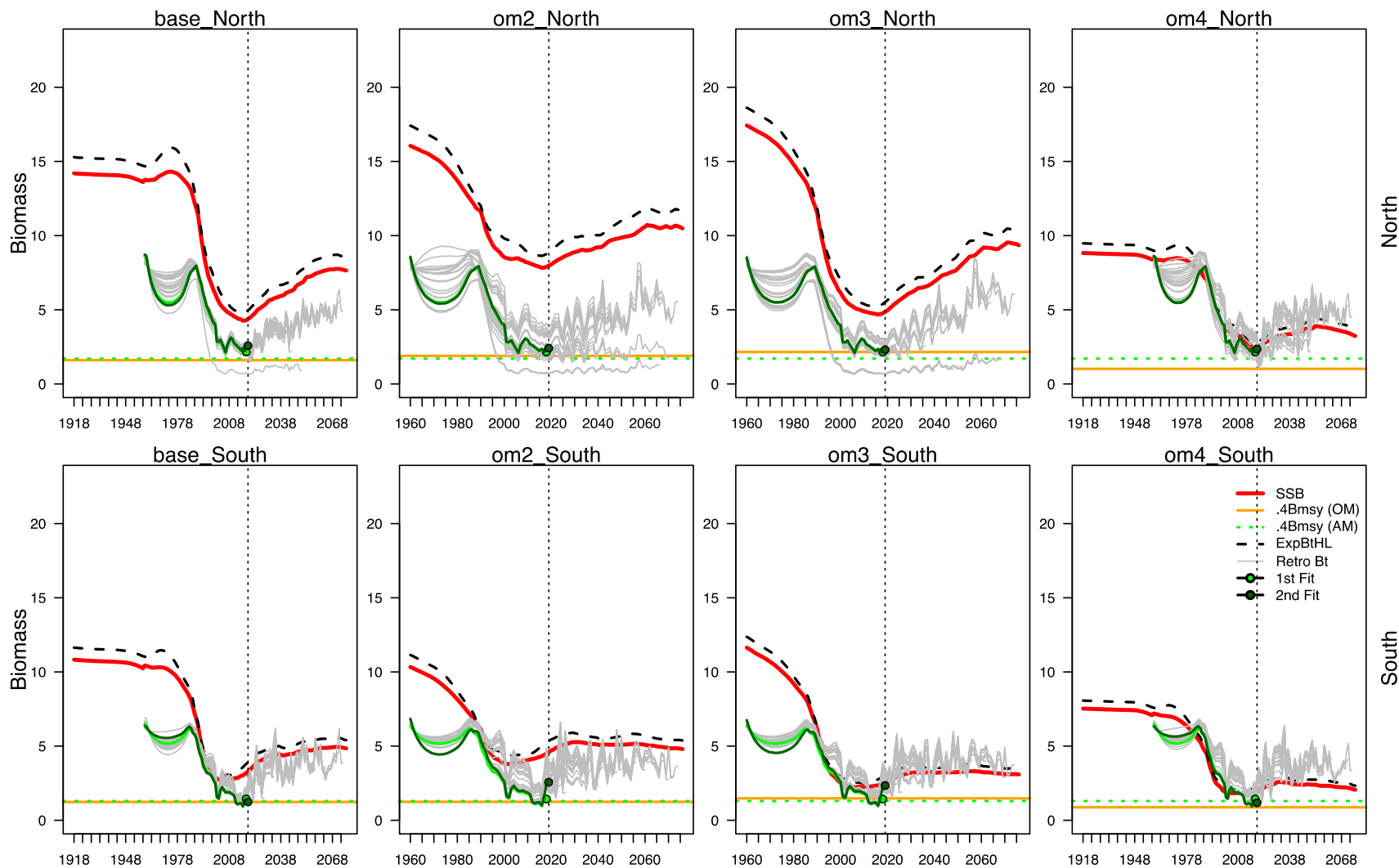
Figure 13. Single replicate example simulations from each operating model showing retrospective behaviour of the SP assessment model (AM) estimates of exploitable biomass (Retro Exp. Bt) given actual OM exploitable biomass for hook and line fleet (ExpBtHL). Other quantities include operating model spawning biomass (SSB), the operating model LRP (.4Bmsy (OM)), and the surplus production assessment estimate of the LRP (.4Bmsy (AM)) in the first assessment year.
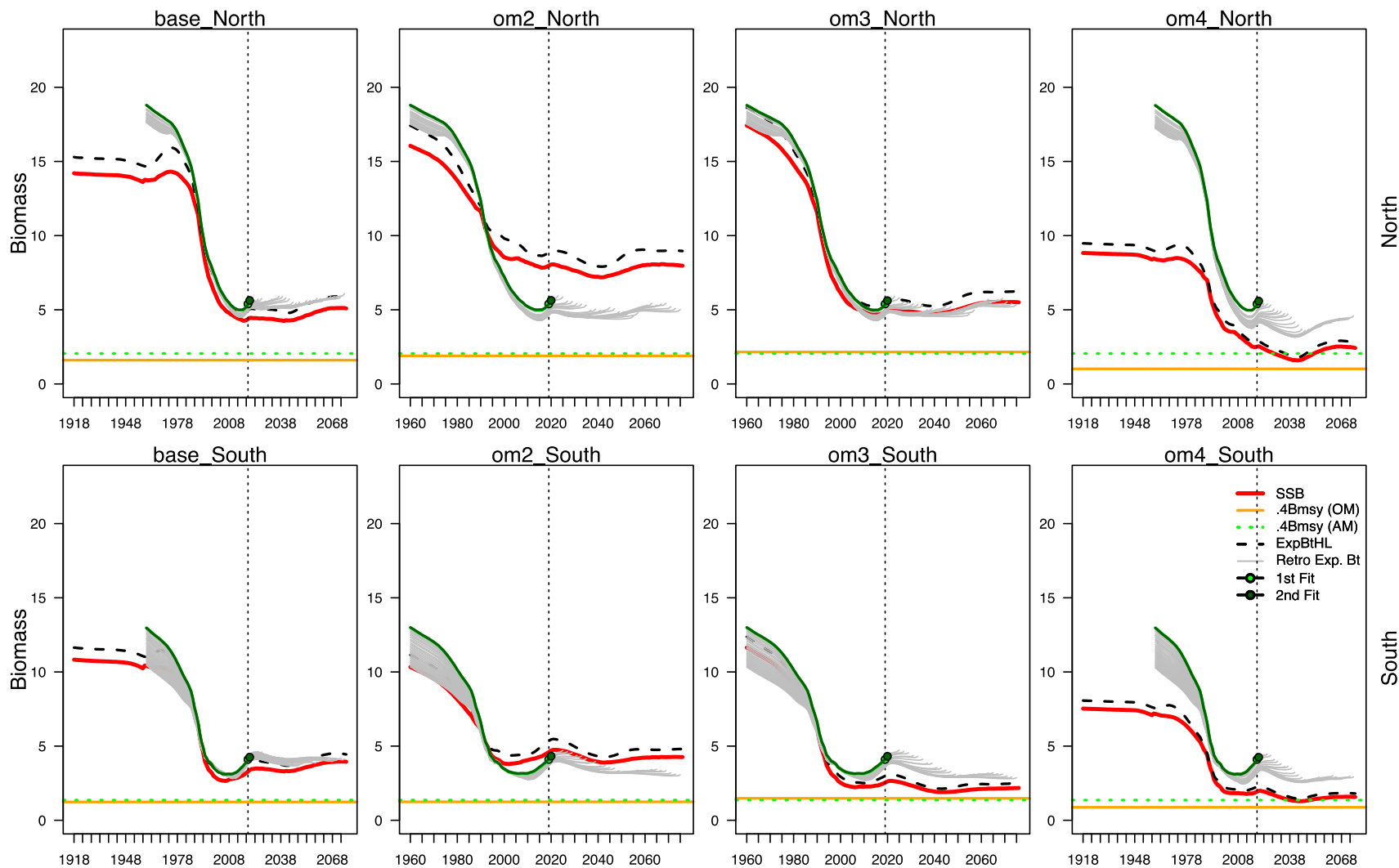
Figure 14. Single replicate example simulations from each operating model showing retrospective behaviour of the CAA assessment model (AM) estimates of exploitable biomass (Retro Exp. Bt for Hook and Line selectivity) given actual OM exploitable biomass for hook and line fleet (ExpBtHL). Other quantities include operating model spawning biomass (SSB), the operating model LRP (.4Bmsy (OM)), and the catch-at-age assessment estimate of the LRP (.4Bmsy (AM)) in the first assessment year
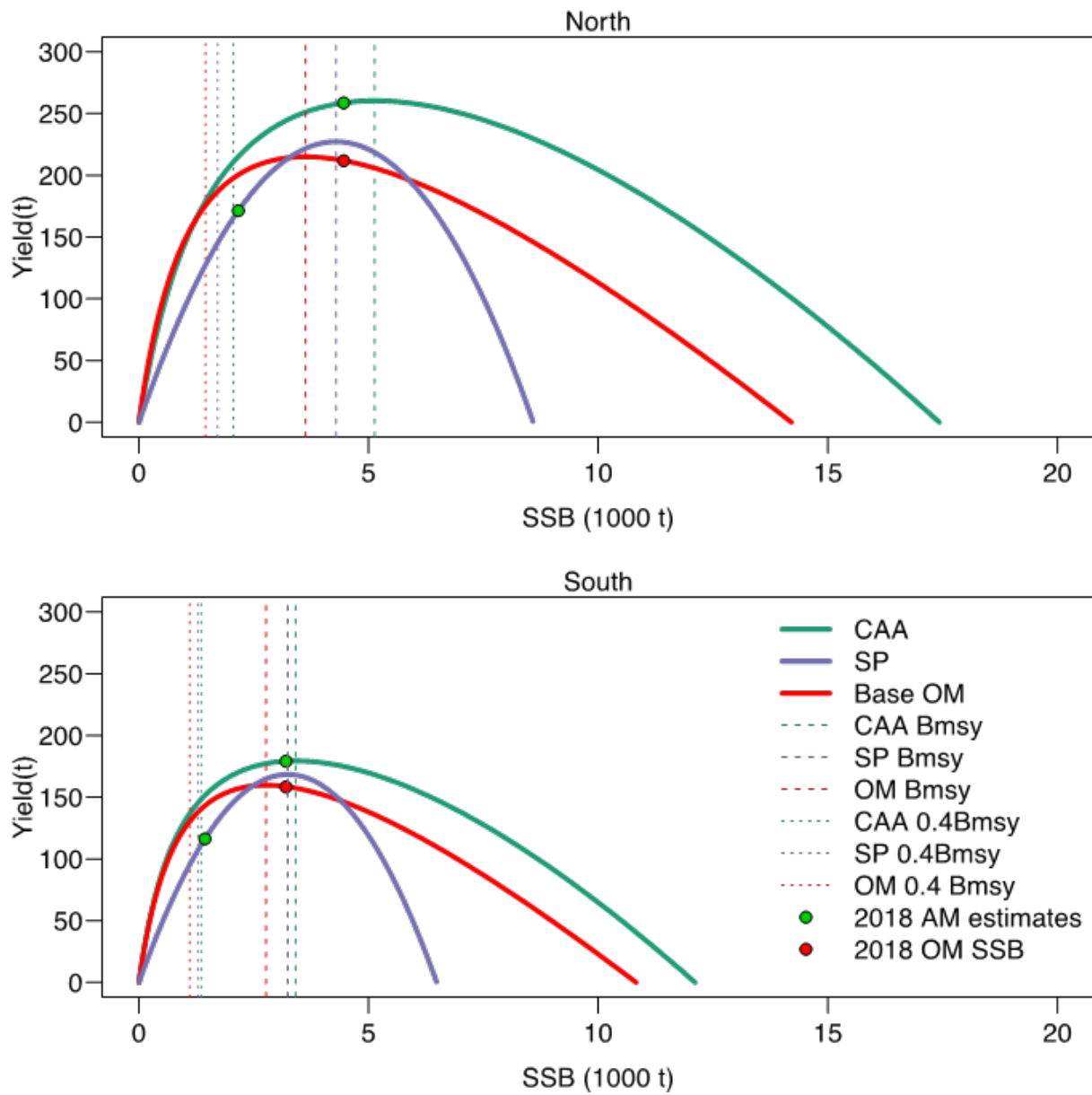
Figure 15. Equilibrium yield vs spawning stock biomass curves estimated from the catch-at-age (CAA) and surplus production (SP) assessments used in MPs for the first year fit (i.e., 2018)
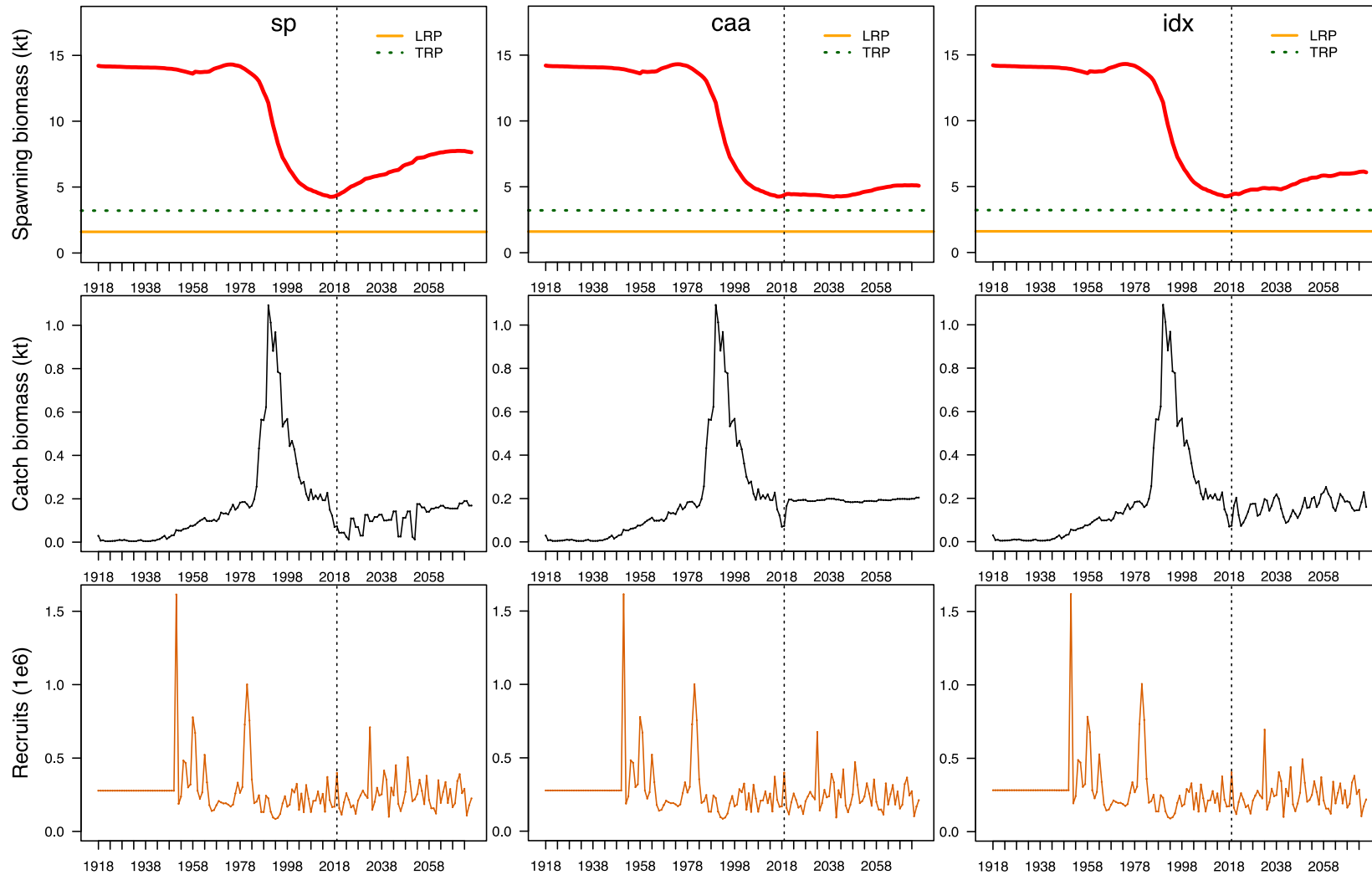
Figure 16. Single replicate example simulation of operating model (row1) spawning biomass, catch (row2), recruitment (row3), and fishing mortality (row4) under the base North operating model scenario. Columns show outcomes for management procedures: (left) surplus production (sp), (centre) catch-age model-based (caa), and (right) the empirical index (idx). The vertical dashed line separates the historical and projection periods and horizontal lines provide limit (LRP) and target (TRP, B_{MSY}) biomass reference points. Each MP is subject to the same random inputs for observation errors and recruitment process deviations.
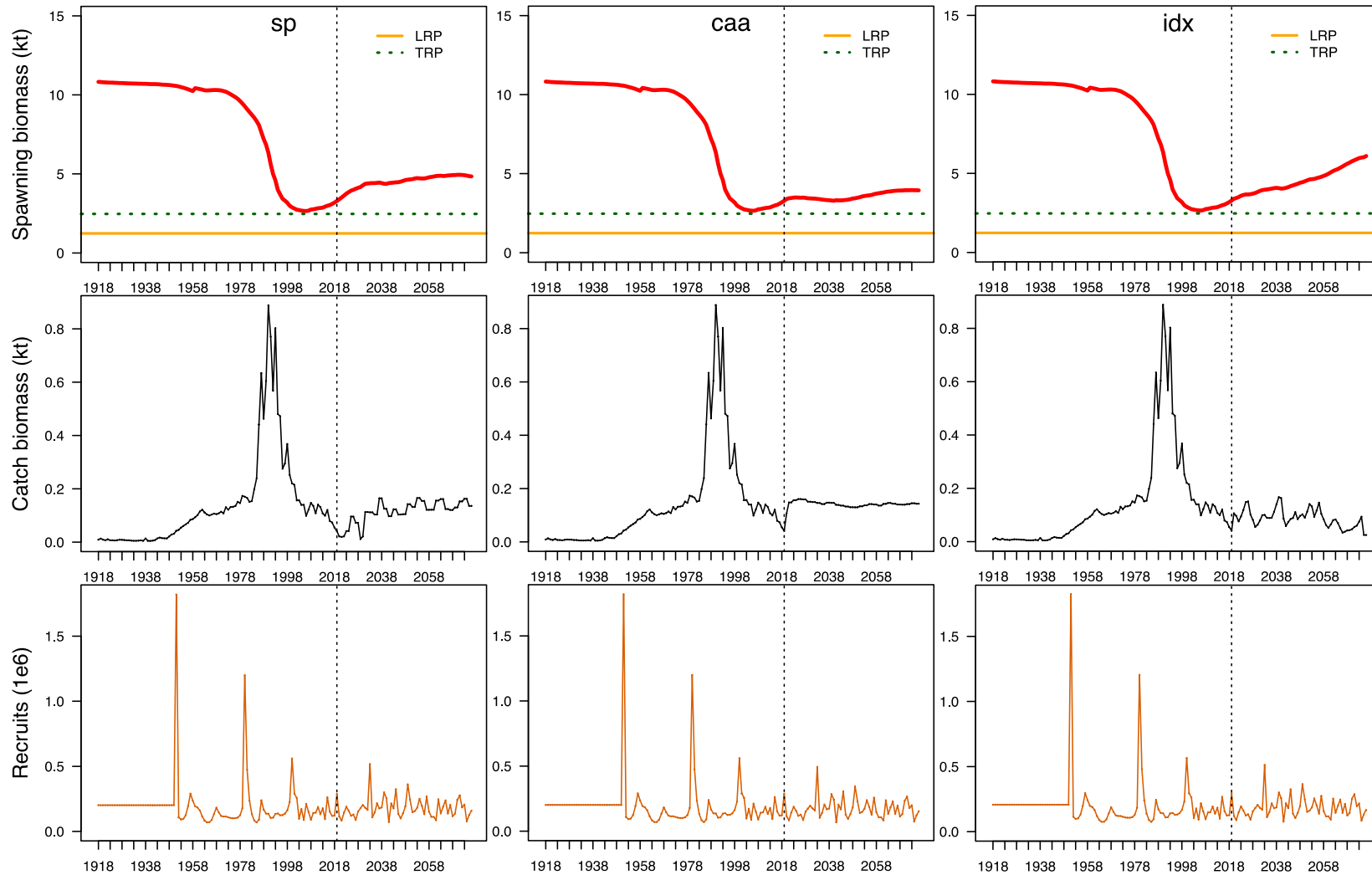
Figure 17. Single replicate example simulation of operating model (row1) spawning biomass, catch (row2), recruitment (row3), and fishing mortality (row4) under the base South operating model scenario. Columns show outcomes for management procedures: (left) surplus production (sp), (centre) catch-age model-based (caa), and (right) the empirical index (idx). The vertical dashed line separates the historical and projection periods and horizontal lines provide limit (LRP) and target (TRP, B_{MSY}) biomass reference points. Each MP is subject to the same random inputs for observation errors and recruitment process deviations.
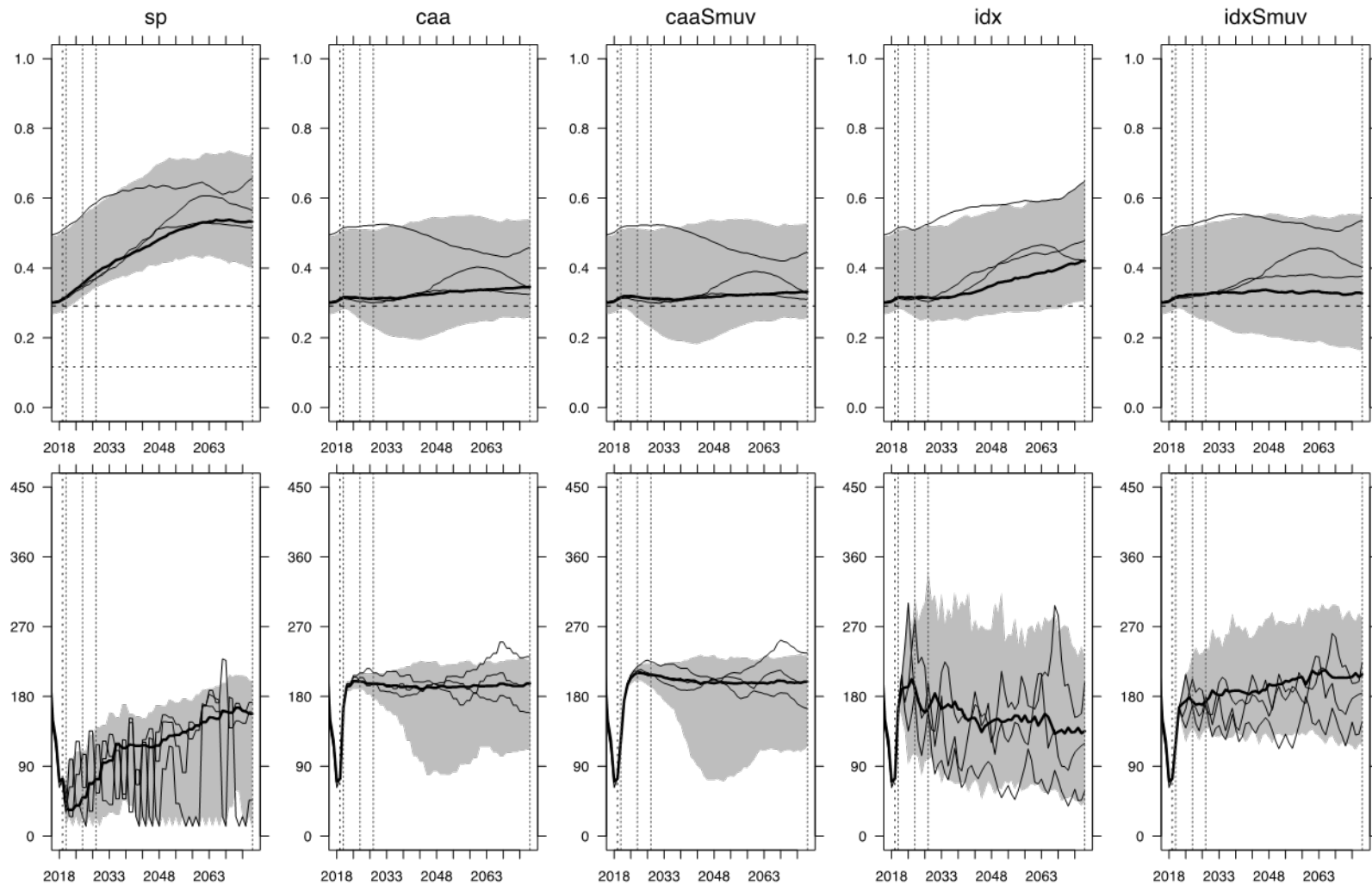
Figure 18. Weighted projection distributions for combined operating model North spawning biomass depletion (i.e., SB$_t$/SB$_0$) (top) over the 4 OMs and total catch (bottom) from the simulated management procedures (sp, caa, caa_Smuv, idx, idxSmuv). Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of 0.4B$_{MSY}$ (bottom, dotted line) and B$_{MSY}$ (top, dashed line). Vertical grey lines indicate short-term (5 years), medium-term(10 years), and long-term (57 years) projection periods used to generate MP performance metrics.
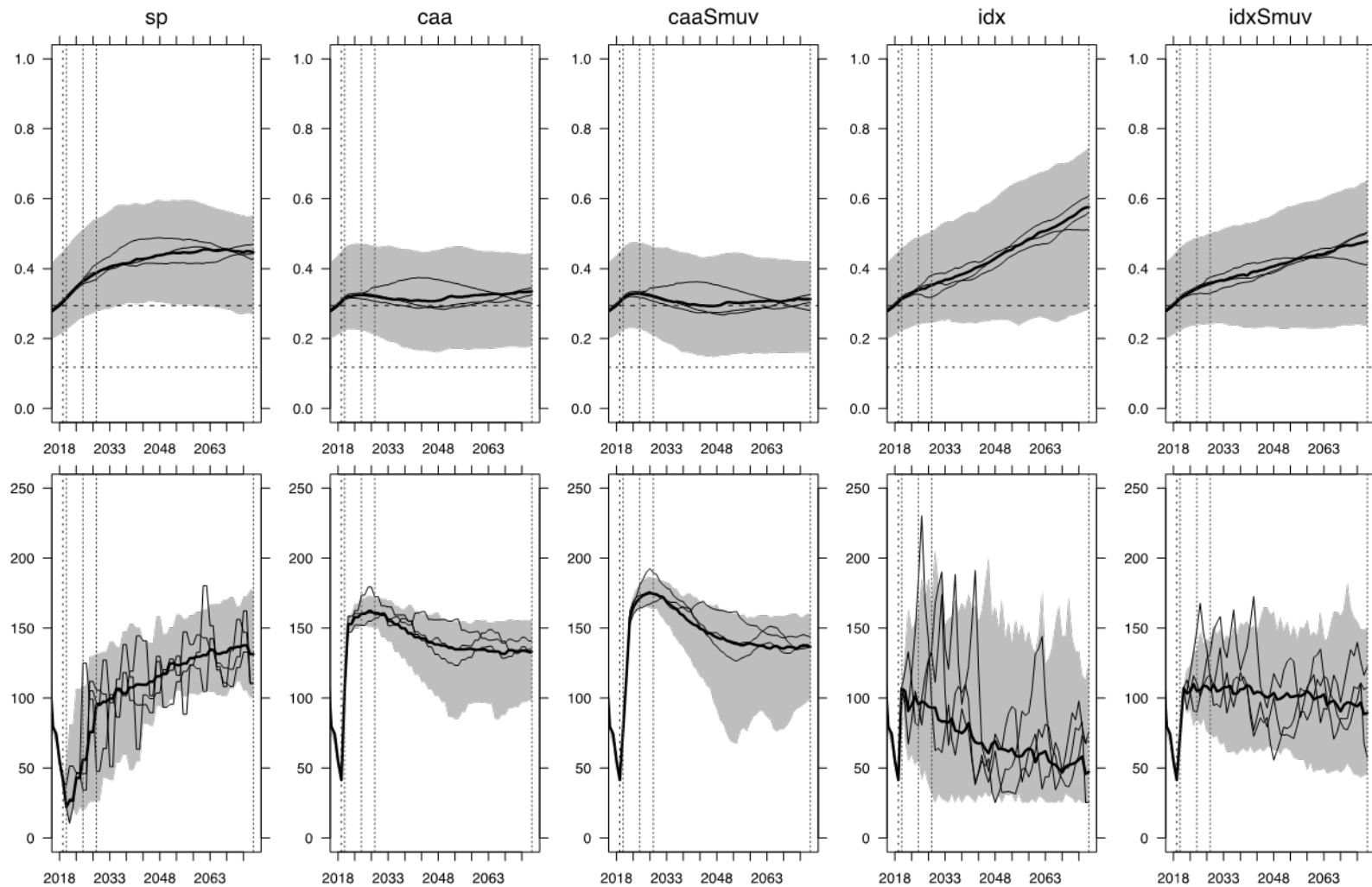
Figure 19. Weighted projection distributions for combined operating model South spawning biomass depletion (i.e., SB_t/SB_0) (top) over the 4 OMs and total catch (bottom) from the simulated management procedures (sp, caa, caa_Smuv, idx, idxSmuv). Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of 0.4B_{MSY} (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical grey lines indicate short-term (5 years), medium-term(10 years), and long-term (57 years) projection periods used to generate MP performance metrics.

APPENDIX A. OPERATING MODEL SELECTION

This appendix describes the suite of 24 operating model scenarios that were evaluated and the selection of the 4 representative OMs to use in simulation testing. Operating models (OMs) tested included upper and lower bound catch scenarios for recreational and commercial fisheries, a 1960 or 1918 start date, and 5 different priors on natural mortality with $\bar{M}$ ranging from 0.03 - 0.06 yr^{-1}. OMs using the same commercial catch series and start years were assigned to 4 groups, reflecting the major sources of uncertainty for model data inputs (Table A.1).

The different data inputs produced a wide range of estimates of key biological and management parameters (i.e., *B0, M, B$_{MSY}$, MSY, F$_{MSY}$, B$_{2018}$, B$_{2018}$/B$_0$, B$_{2018}$/B$_{MSY}$*), some of which did not appear to be consistent with the history of the fishery and biology of the species (Table A.2). The main effect of the different catch inputs and M scenarios were to scale biomass up or down. The lower bound catch series and lower values of $\bar{M}$ used in natural mortality priors produced smaller estimates of stock size that scaled down *B$_0$, B$_{MSY}$, MSY*, as well as lower B$_{2018}$/B$_0$ (i.e., more depletion). Depletion estimates were particularly sensitive to the choice of the natural mortality prior.

We excluded OM scenarios that generated MSY > 500t, as these were not considered realistic given the history of BC fisheries. This removed all the natural mortality scenarios with M>0.04/yr, and left 14 OMs for further consideration (Table A.1). For groups 1, 2, and 4 we selected a representative OM that used the less informative baseM prior for natural mortality ($\bar{M} = 0.0345, \sigma_M = 0.01$) and the upper bound (i.e. reconstructed) recreational catch series, which was considered a more realistic catch scenario (Table B.9). For group 3, we used the OM with M.03 prior ($\bar{M} = 0.03, \sigma_M = 0.0001$), since the baseM scenario had coastwide MSY > 500 t.

Table A.1. OM inputs for start year, commercial catch, recreational catch and hierarchical priors on natural mortality rate (M). Catch scenarios include upper bounds using reconstructed catches and lower bound catch based on reported datasets. Natural mortality prior scenarios use log-normal distribution $log\,M \sim N(log\bar{M}, \sigma_M)$ using values of $\bar{M} = 0.0345, \sigma_M = 0.01$ (baseM) and $\bar{M} = 0.03, 0.04, 0.05, 0.06, \sigma_M = 0.0001$ (M.03, M.04, M.05, M.06). Bold scenario names indicate OMs with coastwide MSY < 500 t.

Group	Start Year	Commercial Catch Bound	Recreational Catch Bound	Natural Mortality Prior	OM Scenario Name
				baseM	**baseM_1918_str2018**
				M.03	**M.03_1918_str2018**
1	1918	upper	upper	M.04	**M.04_1918_str2018**
				M.05	M.05_1918_str2018
				M.06	M.06_1918_str2018
			lower	baseM	**baseM_1918_str2018_lbRec**
				baseM	**baseM_1960_lbComm**
				M.03	**M.03_1960_lbComm**
2	1960	lower	upper	M.04	**M.04_1960_lbComm**
				M.05	M.05_1960_lbComm
				M.06	M.06_1960_lbComm
			lower	baseM	**baseM_1960_lbComm_lbRec**
				baseM	baseM_1960_str2018
				M.03	**M.03_1960_str2018**
3	1960	upper	upper	M.04	M.04_1960_str2018
				M.05	M.05_1960_str2018
				M.06	M.06_1960_str2018
			lower	baseM	**baseM_1960_str2018_lbRec**
				baseM	**baseM_1918_lbCom**
				M.03	**M.03_1918_lbComm**
4	1918	lower	upper	M.04	**M.04_1918_lbComm**
				M.05	M.05_1918_lbComm
				M.06	M.06_1918_lbComm
			lower	baseM	**baseM_1918_lbComm_lbRec**

Table A.2. Biological parameter and management reference point estimates for full suite of 24 operating models evaluated. Groupings are based on model data inputs, which use 1918 start year and reconstructed catch (Group 1), 1918 start year and reported catch (Group 2), 1960 start year and reported catch (Group 3), or 1960 start year and reconstructed catch (Group 4). Biomass and MSY units in kt.

Group	Scenario	Stock	Unfished Biomass (kt) B_0	Mortality (yr^{-1}) M	Recruitment Steepness h	Reference Points B_{MSY}	F_{MSY}	MSY	Current Status B_{2018}	B_{2018}/B_0	B_{2018}/B_{MSY}
1	baseM_1918_str2018	North	14.3	0.039	0.77	3.6	0.054	0.22	4.6	0.32	1.27
		South	10.9	0.038	0.77	2.8	0.052	0.16	3.3	0.31	1.20
	baseM_1918_str2018_lbRec	North	10.3	0.039	0.80	2.5	0.057	0.16	3.4	0.33	1.35
		South	6.9	0.038	0.80	1.7	0.056	0.11	2.0	0.29	1.20
	M.03_1918_str2018	North	12.2	0.032	0.80	3.0	0.047	0.16	2.7	0.22	0.89
		South	9.6	0.031	0.80	2.4	0.046	0.12	1.8	0.18	0.73
	M.04_1918_str2018	North	16.1	0.042	0.76	4.1	0.057	0.26	6.4	0.40	1.56
		South	12	0.041	0.76	3.1	0.056	0.19	4.7	0.39	1.53
	M.05_1918_str2018	North	36.4	0.051	0.74	9.4	0.069	0.72	26.0	0.71	2.76
		South	21.2	0.051	0.74	5.5	0.068	0.41	15.0	0.71	2.74
	M.06_1918_str2018	North	211.5	0.061	0.72	55.6	0.080	4.85	167.2	0.79	3.00
		South	73.3	0.061	0.72	19.3	0.080	1.68	66.4	0.91	3.44
2	baseM_1960_lbComm	North	16.5	0.044	0.71	4.5	0.052	0.26	8.6	0.52	1.90
		South	10.5	0.041	0.71	2.9	0.048	0.16	4.6	0.44	1.58
	baseM_1960_lbComm_lbRec	North	7.4	0.043	0.82	1.7	0.082	0.14	2.6	0.35	1.50
		South	2.7	0.039	0.82	0.6	0.072	0.04	0.5	0.19	0.82
	M.03_1960_lbComm	North	10.6	0.034	0.71	3.0	0.040	0.13	2.9	0.27	0.97
		South	8	0.031	0.71	2.3	0.037	0.09	1.3	0.17	0.59
	M.04_1960_lbComm	North	16.9	0.045	0.71	4.6	0.053	0.27	9.0	0.53	1.93
		South	10.6	0.041	0.71	2.9	0.049	0.16	4.8	0.45	1.62
	M.05_1960_lbComm	North	66.6	0.054	0.71	17.9	0.067	1.32	51.9	0.78	2.89
		South	22.2	0.051	0.71	6.0	0.062	0.41	17.7	0.80	2.94

Group	Scenario	Stock	Unfished Biomass (kt) B_0	Mortality (yr^{-1}) M	Recruitment Steepness h	Reference Points			Current Status		
						B_{MSY}	F_{MSY}	MSY	B_{2018}	B_{2018}/B_0	B_{2018}/B_{MSY}
	M.06_1960_lbComm	North	207.6	0.062	0.68	57.4	0.074	4.61	151.1	0.73	2.63
		South	80.3	0.060	0.68	22.3	0.071	1.73	76.6	0.95	3.44
	baseM_1960_str2018	North	31.1	0.044	0.73	8.3	0.055	0.51	18.9	0.61	2.27
		South	16.2	0.041	0.73	4.4	0.051	0.25	8.5	0.52	1.93
	baseM_1960_str2018_lbRec	North	14	0.043	0.79	3.4	0.070	0.24	4.3	0.31	1.24
		South	4.9	0.039	0.79	1.2	0.062	0.08	0.7	0.15	0.59
	M.03_1960_str2018	North	17.7	0.034	0.73	4.8	0.043	0.23	5.6	0.32	1.17
		South	11.8	0.031	0.73	3.2	0.039	0.14	2.6	0.22	0.80
3	M.04_1960_str2018	North	31.8	0.045	0.73	8.5	0.056	0.53	19.6	0.61	2.30
		South	16.4	0.041	0.73	4.4	0.051	0.25	8.7	0.53	1.96
	M.05_1960_str2018	North	132.3	0.054	0.71	35.5	0.067	2.63	106.0	0.80	2.99
		South	34.9	0.051	0.71	9.4	0.063	0.65	29.1	0.83	3.09
	M.06_1960_str2018	North	387.5	0.062	0.68	106.8	0.074	8.62	283.7	0.73	2.66
		South	131.2	0.060	0.68	36.3	0.071	2.83	126.6	0.96	3.49
	baseM_1918_lbComm	North	8.9	0.039	0.76	2.3	0.052	0.13	2.7	0.30	1.16
		South	7.6	0.038	0.76	2.0	0.051	0.11	2.0	0.27	1.03
	baseM_1918_lbComm_lbRec	North	5.2	0.039	0.79	1.3	0.057	0.08	1.8	0.34	1.38
		South	3.9	0.038	0.79	1.0	0.056	0.06	1.1	0.29	1.17
	M.03_1918_lbComm	North	7.8	0.032	0.80	1.9	0.048	0.10	1.7	0.22	0.91
		South	6.9	0.031	0.80	1.7	0.047	0.09	1.3	0.19	0.78
4	M.04_1918_lbComm	North	9.8	0.042	0.74	2.6	0.054	0.16	3.5	0.36	1.36
		South	8.2	0.041	0.74	2.2	0.053	0.13	2.8	0.34	1.28
	M.05_1918_lbComm	North	19.4	0.051	0.73	5.1	0.067	0.38	12.5	0.64	2.45
		South	13.8	0.051	0.73	3.6	0.066	0.26	9.1	0.66	2.50
	M.06_1918_lbComm	North	107	0.061	0.71	28.3	0.079	2.44	83.2	0.78	2.94
		South	47.2	0.061	0.71	12.5	0.079	1.08	42.1	0.89	3.37

APPENDIX B. DATA INPUTS

B.1 ABUNDANCE INDICES

B.1.1 PHMA Survey indices

The Pacific Halibut Management Association of BC (PHMA) hard bottom longline survey is a stratified random design that divides the sampling frame into 2 km x 2 km grid cells with 3 depth strata (20-70 m, 71-150 m, 151-260 m) in Yelloweye hard-bottom habitats for the BC Outside Yelloweye population (Figures B.1-B.2). The survey was initiated in 2006 to provide abundance indices for Yelloweye and Quillback rockfishes, and alternates between North and South sampling frames every year (Doherty et al. 2019).

PHMA survey CPUE were stratified by management areas (3C, 3D, 5A4B, 5B, 5C, 5D, 5E) and depth stratum (20-70 m, 71-150 m, 151-260 m) to generate annual mean catch rates $\bar{y}_{h,y}$ and sampling variances $s_{h,y}^2$ for each stratum and year that were used to calculate stratified means $\bar{y}_{str,y}$ and variance $V(\bar{y}_{str,y})$ for North and South Outside Yelloweye Stocks, using standard Cochran (1977) estimators:

$$\bar{y}_{str,y} = \sum_{h=1}^{L} W_h \bar{y}_{h,y}$$

$$V(\bar{y}_{str,y}) = \sum_{h=1}^{L} W_h^2 \frac{s_{h,y}^2}{n_{h,y}} \left(1 - \frac{n_{h,y}}{N_h}\right)$$

$$s_{h,y}^2 = \sum_{i=1}^{n_{h,y}} \frac{\left(y_{h,y,i} - \bar{y}_{h,y}\right)^2}{\left(n_{h,y} - 1\right)}$$

where $h = \left\{1,2,...,L\right\}$ are the number of strata and $i = \left\{1,2,...,n_{h,y}\right\}$ are the individual sets in each strata and year. Stratified means and variances are weighted in proportion to the total N_h number of 2 km x 2 km blocks in each h stratum relative to the number of 2 km x 2 km blocks in the entire sampling space N, giving stratum weight $W_h = \frac{N_h}{N}$.

The southern PHMA survey area includes grid cells within the North Outside Yelloweye Stock (5B) and the South Outside Yelloweye stock (3CD5A) areas. Sets from southern survey years (2007, 2009, 2011, 2014, 2016) were used to generate a 5B Queen Charlotte Sound index (PHMA_QCS) using only sets within area 5B and a southern PHMA index (PHMA_S) for the remaining survey area that is stratified by management area 5A4B, 3C, and 3D. The northern PHMA sampling grid is entirely within the Northern Outside Yelloweye Stock are and was used to generate a northern PHMA index (PHMA_N) that is stratified by management areas 5B, 5C, 5D, and 5E (Table B.1, Figure B.3).

B.1.2 IPHC Survey Indices

The International Pacific Halibut Commission (IPHC) conducts an annual fishery-independent setline survey (FISS) with a fixed station design in BC. In 1998, the survey began using fixed stations spaced equally apart in northern BC (Groundfish management areas 5ABCDE) and in 1999 the survey grid was expanded to include the west coast Vancouver (Groundfish management areas 3CD). The north coast IPHC stations were surveyed every year from 1998-2018, while the WCVI stations were surveyed in 1999 and from 2001-2018 (Table B.2, Figure B.4). We excluded the IPHC survey data from 1995-1997 that used different station configurations (Gertseva and Cope 2017, Yamanaka et al. 2018,).

Annual indices for northern (I_{North}^{IPHC}) and southern (I_{South}^{IPHC}) Outside Yelloweye stocks were calculated as the average number of Yelloweye pieces (C_{it}) caught per effective skate (E_{it}) using only chum-baited skates (as described in Yamanaka et al. 2018 and Anderson et al. 2019), where an effective skate is equivalent to approximately 100 observed hooks:

$$I_t^{IPHC} = \frac{1}{n_t} \sum_{i=1}^{n_t} \frac{C_{it}}{E_{it}}$$

The IPHC survey stations in BC are designed to provide an index of abundance for Pacific Halibut and many stations occur in areas outside of Yelloweye Rockfish Habitat (Doherty et al. 2019). IPHC stations that were outside of Yelloweye Habitat were excluded from index calculations to reduce the proportion of zeros in CPUE index calculations and increase precision. The number of years that each station captured at least one Yelloweye was used as an indicator of the quality of Yelloweye habitat being surveyed (Table B.2). We calculated the average coefficient of variation (standard error/mean CPUE) using different thresholds for excluding stations based on the number of years with Yelloweye presence. We found a reduction in CVs up to a cut-off threshold of 11 years (i.e., Yelloweye catch in at least 11 years), and thus stations with Yelloweye catch in less than 11 years were excluded from index calculations (Table B.3, Figures B.2-B.3).

The majority of stations in the southern area were only surveyed from 1999 and 2001-2017; however, there were 4 stations in the original IPHC sampling frame in northern 5A (I_{n5A}^{IPHC}) that caught Yelloweye in at least 11 years, which have been surveyed from 1998-2018 (Figure B.4). We fit a linear regression with log transformed indices to predict I_{South}^{IPHC} in 1998 and 2000 (Figures B.7-B.8):

$$I_{South}^{IPHC} = \beta_0 (I_{n5A}^{IPHC})^{\beta_1} e^v$$

$$\log(I_{South}^{IPHC}) = \log \beta_0 + \beta_1 \log(I_{n5A}^{IPHC}) + v$$

$$v \sim N(0, \sigma^2)$$

In some years (1998-2002, 2013), Yelloweye catch was only recorded for 20-24% of hooks (approximately 100-160 hooks per set, Table B.2) with a sub-sampling strategy targeting the first 20 hooks from each skate. In some cases, sub-sampling occurred from 20 consecutive hooks from other sections of the skate (Dykstra et al. 2002, 2003). Analysis from the previous Yelloweye assessment (Yamanaka et al. 2018) suggested CPUE estimates from sub-sampling

years were positively biased and applied an adjustment to standardize across indices with 20% (CPUE20) and 100% (CPUE100) hook observations (Data provided by A. Edwards, DFO Pacific Biological Station). One possible mechanism for a positive bias in CPUE20 is a greater proportion of hooks fished from the skate ends (i.e., an end effect), as end hooks can have less fishable area overlap compared to other hooks on the skate (Eggers et al. 1980, Monnahan and Stewart 2018). We compared CPUE20 and CPUE100, generated using all sets and non-zero sets from IPHC stations with a minimum of 1 and 11 years of Yelloweye catch (Figures B.9-B.10). When accounting for year and area (North/South) effects, we found that indices that excluded zero sets had some evidence of a positive bias in CPUE20 (p=0.04, ANOVA), whereas CPUE20 indices that included zero stations had no evidence of bias (p=0.6, ANOVA) and a greater proportion of zeros. We determined there are two potential sources of bias from the CPUE20 IPHC indices: 1) a positive bias from an end effect, and 2) a negative bias due to a greater proportion of stations with zero Yelloweye catch. It appears as though these two sources of bias may cancel each other out leading to little bias in CPUE20 when zero sets are included. The proportion of stations with zero YE catch is increasing over time for both the North and South, which could be indicative of local Yelloweye depletion at some stations. Further investigation of spatial CPUE trends across stations and the benefits of using a model (e.g. delta approach) to generate IPHC indices would be informative for future rockfish assessment research.

We evaluated different fits (Appendix C) for operating models using the following adjustments to IPHC indices:

1. adjusted years with only 20-24% hook coverage to account for mean CPUE20 bias

2. included predicted indices for 1998 and 2000 in the South

3. used different cut-off thresholds (i.e. minimum years with Yelloweye catch) for including stations in indices

The base OM was not sensitive to any of the above modifications to IPHC indices and the final OMs used the IPHC survey index i) without any adjustment for CPUE20 years, ii) without 1998 and 2000 predicted indices for the South, and iii) that used all stations with at least 1 year of Yelloweye catch.

B.2 BIOLOGICAL DATA

All available biological data (age, length, sex, and maturity) from commercial fisheries and research surveys (synoptic trawl, IPHC, PHMA) were used to estimate growth curves, length-weight relationships and maturity-at-age curves for north and south Outside Yelloweye stocks (Figures B.11-B.13).

B.2.1 Standardizing Commercial Age Compositions

Age composition data from the commercial hook and line fleet were standardized by area and year to attempt to account for biased sampling in different management areas from 1986-2010 (Fig B.15). We used the design-based approach described in Thorson et al. (2014) to standardize annual age-composition data as:

$$\bar{D}_a = \sum_{i=1}^{n_t} \left(\sum_{s=1}^{n_s} I(S_i = s) \frac{L_s}{l_s} \right) \left(\frac{C_i}{c_i} \right) D_{a,i}$$

where c_i is the amount of Yelloweye catch sampled from fishing trip i, C_i is the total Yelloweye catch from trip i, l_s is the total amount of Yelloweye catch sampled in each management area

stratum, L_s is the total Yelloweye catch in each management area, $D_{a,i}$ is the age count data for trip i. The $I()$ is an indicator function that equals 1 when *Si=s* and 0 otherwise, which is used to match the $\frac{L_s}{l_s}$ term with the appropriate management area stratum for weighting.

For trips where the total Yelloweye catch (C_i) was not recorded, we used the average $\frac{C_i}{c_i}$ from trips in that year. If C_i was not recorded for any trips in a given year, then we used the average $\frac{C_i}{c_i}$ from all trips. The standardized commercial age-comps are provided in Figure B.15.

B.2.2 Ageing Error Matrix

The Yelloweye age-structured assessment model relies on catch-at-age data to estimate the true age-composition of the population; however, observed catch-at-age data are based on otolith readings that are imperfectly known. Failure to account for errors in otolith readings may lead to smoothing estimates of age-classes; making it more difficult to detect strong recruitment years or stock-recruit relationships (Hanselman et al. 2012) or providing bias estimates of growth parameters, maturity schedules, and natural mortality (Lai and Gunderson 1987; Tyler et al. 1989).

We developed ageing-error matrices using otoliths that had been read by two different readers at the DFO Pacific Biological Station ageing lab. These data account for approximately 6% of the total otolith readings for BC Yelloweye, which are read by a primary reader and then by a secondary reader as a quality control. In only 22% of cases did both readers agree and in the 78% of cases where readings differed, both readers conferred to resolve the discrepancy and agree on the final age assigned. In most cases the final age reading was that assigned by the secondary or primary reader, but in 10% of otoliths a new age was assigned.

We applied statistical models for estimating the probability of observing an age class (a) given the true age (*b*) based on methods described in Richards et al. 1992 and Heifetz et al. 1999. The model assumes a normal ageing-error distribution where the estimated standard deviation of the observed age $\sigma(b)$ for a true age *b* is based on three parameters $\Phi = \left\{ \sigma_1, \sigma_A, \alpha \right\}$ in the form:

$$\sigma(b) = \begin{cases} \sigma_1 + (\sigma_A - \sigma_1)\dfrac{1 - e^{-\alpha(b-1)}}{1 - e^{-\alpha(A-1)}}; & \alpha \neq 0 \\[4mm] \sigma_1 + (\sigma_A - \sigma_1)\dfrac{b-1}{A-1}; & \alpha = 0 \end{cases}$$

Parameters σ_1 and σ_A are the standard deviations for b=1 and b=A, representing the minimum and maximum ages, respectively. The α parameter determines the non-linearity of the function, such that $\sigma(b)$ becomes linear as α approaches 0. The age-error matrix $q(a \mid b, \Phi)$ is defined as:

$$q(a \mid b, \Phi) = \frac{x_{ab}(\Phi)}{\displaystyle\sum_{a=1}^{A} x_{ab}(\Phi)}$$

$$x_{ab} = \frac{1}{\sqrt{2\pi\sigma(b)^2}} e^{-\frac{1}{2}\left[\frac{a-b}{\sigma(b)}\right]^2}$$

Given that the true age of the fish is unknown, it is not possible to accurately determine bias in the age readings and whether certain age classes are more likely to be under or over-estimated. We test 2 different approaches for the assumed "true age", using 1) the mean of the two reader ages (Heifetz et al. 1999) rounded to the nearest even integer, and 2) the final age assigned. For both approaches we set A=119, based on the maximum assigned age by the readers.

The likelihood (*L*) of observed ages A and true ages B is then defined as:

$$L(A\,|\,B) = \prod_{i=1}^{I} \prod_{j=1}^{J} q(a_{ij}\,|\,b_i, \Phi)$$

where b_i is the assumed 'true age' of fish i, and a_{ij} is the age assigned by reader j to the individual fish i. Maximum likelihood parameter estimates, predicted standard deviation at age, and age-error matrices are provided in Table B.4 and Figure B.15-B.17.

The probability of observed ages for the 65+ group was estimated using a weighted average of the probability of observed age distributions for true ages 65-119, based on an expected age composition at B_0 with M=0.0345. The ageing-error matrix that assumed 'true age' was the mean of the reader ages (Case 1) was used in the catch-at-age assessment and operating model parameterization.

B.3 CATCH

B.3.1 Commercial Catch

A reconstructed time series of commercial catch was developed for the previous stock assessment in 2014 and updated to 2018 for this analysis (Figure B.18). Reported commercial catch data were extracted from various groundfish databases, which are described in Table B.5. Catch from both the reconstructed and reported time series were partitioned into northern (5BCDE) and southern (5A3CD) populations according to PMFC management areas. Data extractions were provided by Maria Surry, of the groundfish data unit, and the information provided is licensed under the Open Government License, Canada.

Reported Commercial Data

British Columbia catches (landings and discards) of Outside Yelloweye Rockfish from groundfish commercial fisheries by year and major area are provided from 1969 (the earliest available date) to present (Table B.6) from data sets verified by the groundfish data unit. The spatial distribution of commercial fisheries since 2008 is shown in Figure B.19.

Commercial Catch Reconstruction

The reported historical commercial data is considered to be incomplete data for Yelloweye Rockfish. A method to reconstruct commercial catch for rockfish species was developed by Rowan Haigh and Lynn Yamanaka of DFO, and is explained in Haigh and Yamanaka (2011). The outside Yelloweye catch reconstruction was used in the last stock assessment and was updated by Rowan Haigh for the current analysis. Data used in the reconstruction were extracted from the merged GFCatch and PacHarv3 databases, for hook and line fisheries, described in Table B.5.

The catch was reconstructed for five fishing fleets: Trawl (bottom + midwater), Halibut, Sablefish, Dogfish/Lingcod, and H&L Rockfish (ZN). The reconstruction provides annual catch (by calendar year) and by major PMFC area code (4B, 3C, 3D, 5A, 5B, 5C, 5D, 5E), which we aggregated by region (North: 5BCDE and South: 5A3CD). As in the 2014 stock assessment for outside Yelloweye, foreign catches (1865-1976) recorded as "other rockfish" (ORF) were not used (i.e., no catch from offshore foreign fleets was included). Records of catch from seamounts were also excluded, as were Langara Spit experiment catches of ORF. Halibut and Sablefish combined trips were assigned to the Halibut Fishery and were not double-counted in the Sablefish fishery.

The Outside Yelloweye catch data can be grouped into 3 major eras: i) historic 1918 – 1950, ii) early electronic (compiled from various sources) 1951 – 2005, and iii) modern - from 2006 onwards. The historic and early electronic data periods suffer from two forms of uncertainty with respect to outside Yelloweye catches. The first uncertainty is that commercial landings of rockfish other than Pacific Ocean Perch (other rockfish, ORF) were reported in an aggregate group. Conversion of ORF landings to Outside Yelloweye Rockfish (OYE) landings, by fishery sector and PMFC major area, was calculated using the ratio of OYE catch to ORF, in a period with credible landings data (1997-2005) from the hook and line dockside monitoring program. The OYE:ORF ratio (γ) was then applied to the period of questionable Yelloweye catch (Table B.7) in the catch reconstruction algorithm (Haigh and Yamanaka 2011).

The second uncertainty concerns unreported fish that were discarded at sea. Non-retained Yelloweye Rockfish catch (releases or discards) was estimated for all fleets, excluding trawl, using the ratio of Yelloweye discarded by a fishery to fishery-specific landed targets (δ). Following advice from industry during the 2015 stock assessment process and catch history review, no discarding was calculated for the trawl fishery (i.e., δ=0, Yamanaka et al. 2018). The δ for hook and line and trap fisheries was calculated using discard and landings data from a credible period of 2000-2004 observer logs (Table B.6). The catch reconstruction assumes no discarding prior to 1986 and that discards are fully reported in DFO databases since 2006.

A stratified method was used for calculating γ and δ ratios (Yamanaka et al. 2018) whereby fisheries landings were stratified by year (1997-2005), management area, and 100-m depth intervals. Within any given year, area, and fishery, at least 10% of the records had to contain a non-zero depth value to be stratified by depth. Otherwise, the year-area-fishery stratum was assumed to contain one depth zone. This was the case for all of the Halibut data because we have no depth information for this fleet. These reconstructions use all records that contain a non-zero ORF landing. Recent catch reconstructions for Redstripe Rockfish and Bocaccio have used a geometric mean, rather than the stratified method used here (R. Haigh, pers. com.); however, the stratified method (Table B.8) was used in this analysis to maintain a similar catch series to what was used in previous assessment (Yamanaka et al. 2018). Sensitivity analyses (not shown) indicated that operating models were not sensitive to the use of stratified or geometric methods for catch reconstructions.

Commercial Salmon Troll Catch

Some outside Yelloweye Rockfish are caught in the commercial salmon troll fishery. There is no recorded historical catch, and the years for which estimates are available (2001-2014) have small catches (0.3-0.8 tonnes). Catches of this size have little effect on the operating model parameterizations and salmon troll catch was not included in the historical period. For the projections, we included 0.5 t of salmon troll catch based on the 2019 IFMP TAC allocation.

B.3.2 Recreational Catch

Historical recreational catch data for outside Yelloweye Rockfish do not exist prior to 2000. Yamanaka et al. (2018) identified recreational data as a major source of uncertainty and this remains true. In addition to an absence of historical data, species identification in landings data are also uncertain, and there are inconsistent regional catch monitoring and catch data reporting. Historical recreational fishing data for different time periods are available from surveys and lodge logbook data for the West Coast of Vancouver Island (WCVI), Central Coast (CC), North Coast (NC), and Haida Gwaii (HG), however; there is no comprehensive source of recreational data for the whole outside coast. A coast-wide, internet-based survey of tidal water licence holders (iRec) has collected Yelloweye data since 2012, but the results of the survey have not been calibrated to account for biases and uncertainties such as non-response bias, and were not considered in this analysis (DFO 2015). Two time series of recreational catch, representing the upper and lower bounds for recreational catch scenarios are described in this section and shown in Table B.9.

Reported Recreational Catch

Recreational creel survey and lodge logbook data from WCVI, CC, NC, and HG were compiled and used as a lower bound (i.e., minimum estimate) scenario for recreational catch without any expansion to account for years and areas with unreported catch (Figure B.18). The earliest and most comprehensive creel survey data for Yelloweye are from the WCVI creel survey in PFMA areas 20-27 between 2000 and 2018, which include data on retained and released fish (Lewis 2004). Yelloweye data from the CC lodge and guide logbook program in PFMA areas 7, 8 and 9 are available from 2002-2017, however; they are limited to retained fish and don't account for released fish (K. Wong, Pers. Com). The North Coast (NC) creel survey in PFMA areas 3 and 4 provide retained Yelloweye data in 2011 and 2013-2017 (Van Tongeren and Winther 2010), while the HG creel survey in Areas 1 and 2 estimated retained and released Yelloweye for 2016-2018 (Peter Katinic, Pers. Com). In 2018, non-retention of recreational Outside Yelloweye was instated, but North Coast Creel and Central Coast lodge log book surveys were not modified to collect data on Yelloweye releases. Therefore, the total outside Yelloweye recreational mortality for 2018 was estimated using the 2017 ratios for NC/WCVI and CC/WCVI Yelloweye pieces (Shane Petersen and Adam Keizer, DFO, Pers. Com.). All recreational data are recorded in pieces of fish and converted to weights using an assumed average Yelloweye weight (Yamanaka et al. 2018).

Reconstructed Recreational Catch

Historical recreational catch (1918-2011) have been imputed from estimates of fishing effort derived for the WCVI in previous stock assessments to extend the index of recreational fishing effort (Stanley et al. 2012; Yamanaka et al. 2018). To impute historical catches, they used the WCVI and CC surveys from 2007-2014 to estimate a catchability coefficient. We used the recreational catch reconstruction from Yamanaka et al. (2018) updated with data to 2018 in this analysis as the upper bounds of the recreational catch (Table B.9). The updated data for 2015-2018 were provided by the Groundfish Management Unit that were presented to the Sport Fish Advisory Board (SFAB) Groundfish Shellfish Working Group on February 7, 2019 (Shane Petersen, Pers. Com).

The previous reconstructions were for the whole outer BC coast and needed to be allocated to the North (5BCDE) and South (5A3CD) areas for this project. There is limited information for determining the proportion of coastwide catch from the north and south prior to 2016, as recreational data are incomplete prior to 2016 when the HG estimates of Yelloweye catch are first available. Between 2016-2017 there was roughly a 50:50 split in catch between north and

south areas, which was used as the rationale to split reconstructed catch equally between the north and south areas for 1918-2014 (Table B.9).

B.3.3 Aboriginal Food, Social, and Ceremonial (FSC) Fishery Catch

FSC fisheries catch associated with a commercial fishing event (i.e., dual fishing trips) are recorded in DFO's FOS database from 2007-2018. The annual catches range from 5-24 t and are included in both the reconstructed and reported commercial catch time series used for OM data scenarios. For the projections, we included 18.9 t of FSC catch allocated equally to the North and South based on the 2019 IFMP TAC allocation.

B.4 APPENDIX B TABLES

Table B.1. IPHC and PHMA survey indices (pieces/100 hooks) for north and south Outside Yelloweye stocks. The PHMA QCS index is developed from 5B sets in Queen Charlotte Sound that occur in northern stock area during southern PHMA survey years and IPHC indices exclude stations that have never encountered Yelloweye.

| Year | North | | | South | |
	IPHC	PHMA North	PHMA QCS	IPHC	PHMA South
1998	2.80	-	-	-	-
1999	2.66	-	-	1.56	-
2000	2.41	-	-	-	-
2001	2.84	-	-	1.55	-
2002	1.43	-	-	0.65	-
2003	1.67	-	-	0.61	-
2004	1.93	-	-	1.17	-
2005	1.60	-	-	1.25	-
2006	1.67	3.59	-	1.04	-
2007	1.31	-	2.50	1.00	4.14
2008	1.72	4.15	-	0.95	-
2009	1.76	-	4.18	1.31	3.44
2010	2.35	4.28	-	0.93	-
2011	1.69	-	4.81	0.82	4.65
2012	1.48	4.77	-	0.98	-
2013	1.60	-	-	0.52	-
2014	1.03	-	5.28	0.58	2.28
2015	1.01	5.61	-	0.59	-
2016	1.66	-	2.53	0.64	2.87
2017	1.86	3.37	-	0.35	-
2018	1.24	-	3.09	0.60	4.69

Table B.2. Summary of IPHC survey sets encountering Yelloweye Rockfish in British Columbia from 1998-2018. Note this table excludes the 131 new IPHC station locations surveyed in 2018.

Year	Number of stations	Mean number of hooks observed	Mean % of hooks observed	Number of stations with Yelloweye
1998	128	159	24%	44
1999	168	160	24%	61
2000	128	140	20%	46
2001	170	100	20%	50
2002	170	100	20%	40
2003	169	794	100%	71
2004	169	791	100%	69
2005	167	697	100%	69
2006	169	569	100%	64
2007	170	495	100%	56
2008	169	494	100%	65
2009	170	695	100%	74
2010	170	796	100%	67
2011	170	589	100%	65
2012	170	399	100%	50
2013	170	120	20%	36
2014	170	700	100%	62
2015	170	698	100%	55
2016	161	598	100%	56
2017	165	497	100%	51
2018	166	697	100%	53

Table B.3. Summary of encounter rates for IPHC stations used to generate indices, excluding stations without at least 1 year of Yelloweye catch, for a) North and b) South Outside Yelloweye stocks.

a) North

Management Area	Number of Stations	Proportion of years with at least 1 Yelloweye caught (%)		Number of years with at least 1 Yelloweye caught	
		Minimum	Mean	Minimum	Mean
5B	35	4.8%	56%	1	10.5
5C	39	4.8%	69%	1	8.7
5D	13	4.8%	50%	1	4.4
5E	13	4.8%	77%	1	8.4

b) South

Management Area	Number of Stations	Proportion of years with at least 1 Yelloweye caught (%)		Number of years with at least 1 Yelloweye caught	
		Minimum	Mean	Minimum	Mean
5A	14	5.3%	44%	1	7.1
3C	12	16%	63%	1	7.4
3D	15	4.8%	56%	1	11.1

Table B.4. Maximum likelihood parameter estimates for ageing-error matrix model for the two different cases considered for "true age"

Case	True Age	σ_1	σ_A	α
1	Mean Reader Age	0.32	2.95	0.024
2	Final Age Assigned	1.71	19.67	-0.038

Table B.5 Details for the databases used to store commercial groundfish data. Except where noted, data are stored at the level of individual fishing events (sets) and include location details and catch weights. In general, landed weights are prorated to individual fishing events or locations based on proportions recorded at sea.

Database	Sector	Years	Source	Details
GFCatch	Groundfish Trawl	1969-1995	Fisher logbooks, sales slip data, port observations	Discard information is thought to be incomplete
PacHarvTrawl	Groundfish Trawl-excludes foreign and Joint-Venture Hake fisheries	1996- March 31, 2007	At-sea observer logbooks, fisher logbooks, dockside monitoring	-
GFBio	Foreign and Hake Joint-Venture Fisheries	1982-2004	At-sea observer logbooks	"Sets" are usually trawl codends offloaded at sea to a factory vessel
GFFOS	Groundfish Trawl - Including Hake Joint-Venture Fisheries	April 1st, 2007-2018	At-sea observer logbooks, dockside monitoring	Part of the FOS database, formatted for groundfish. Data are managed by the Groundfish Management Unit
GFCatch	Line - Sablefish	1979-1994	Fisher logbooks, sales slip data, port observer information, may include dockside monitoring	Discard information is thought to be incomplete
PacHarvSable	Line - Sablefish	1995-Feb 2006	Fisher logbooks, Dockside Monitoring	Discard information is thought to be incomplete
PacHarvHL	Line-Excluding Sablefish	1985-2006	Fisher logbooks, Dockside Monitoring	Discard information is thought to be incomplete

Table B.6. Time series of reported commercial catch (t).

Year	North			South		
	trawl	longline	Total	trawl	longline	Total
1960	0	0	0	0	0	0
1961	0	0	0	0	0	0
1962	0	0	0	0	0	0
1963	0	0	0	0	0	0
1964	0	0	0	0	0	0
1965	0	0	0	0	0	0
1966	0	0	0	0	0	0
1967	0	0	0	0	0	0
1968	0	0	0	0	0	0
1969	0	0	0	0.24	0	0.24
1970	0	0	0	0	0	0
1971	0	0	0	0	0	0
1972	0.1	0	0	0	0	0
1973	0	0	0	0	0	0
1974	0	0	0	0	0	0
1975	0	0	0	0	0	0
1976	0	0	0	0	0	0
1977	0.2	0	0	0.3	0	0.3
1978	1.6	0	1.6	2.8	0	2.8
1979	0.7	0	0.7	0.1	0	0.1
1980	0.5	0	0.5	0.3	0	0.3
1981	3.4	0	3.4	2.5	0	2.5
1982	2.0	0	2.0	0.0	0	0.0
1983	0	0	0.0	0.8	0	0.8
1984	1.8	0	1.8	0.6	0	0.6
1985	4.1	0	4.1	1.0	0	1.0
1986	9.4	67.7	77.1	1.6	168.3	169.9
1987	13.9	152.8	166.7	21.7	252.5	274.2
1988	12.0	130.6	142.7	5.6	151.8	157.4
1989	27.7	49.6	77.3	10.0	153.2	163.2

	North			South		
Year	trawl	longline	Total	trawl	longline	Total
1990	31.6	518.6	550.3	16.8	474.0	490.7
1991	14.5	583.1	597.6	17.7	360.3	378.0
1992	21.1	405.1	426.2	17.4	208.0	225.3
1993	14.3	360.7	375.0	31.0	464.1	495.1
1994	39.3	331.4	370.7	42.4	213.0	255.4
1995	23.4	284.9	308.3	22.5	159.6	182.1
1996	6.2	299.7	305.9	10.9	168.7	179.6
1997	6.5	279.4	285.9	5.0	163.3	168.4
1998	2.0	319.7	321.6	1.8	228.6	230.4
1999	2.1	244.3	246.4	3.1	132.2	135.3
2000	1.8	151.2	153.0	4.8	92.1	96.9
2001	3.6	122.9	126.5	2.5	93.8	96.3
2002	2.6	97.1	99.8	1.8	42.8	44.7
2003	3.9	42.3	46.2	1.6	41.2	42.7
2004	2.8	31.6	34.4	1.3	36.6	37.9
2005	2.1	49.7	51.8	2.2	39.2	41.4
2006	3.1	150.6	153.7	1.5	45.3	46.7
2007	1.5	138.0	139.5	1.4	61.1	62.5
2008	1.0	175.3	176.2	1.0	101.1	102.1
2009	0.4	145.5	145.9	2.3	79.4	81.7
2010	1.7	146.2	147.9	3.2	63.2	66.4
2011	0.5	150.3	150.8	3.0	86.0	89.0
2012	0.9	161.1	162.0	2.6	92.0	94.6
2013	0.8	164.9	165.7	0.8	80.5	81.3
2014	1.6	155.9	157.5	0.9	62.6	63.5
2015	0.7	163.3	164.0	0.6	87.0	87.6
2016	0.2	102.6	102.9	0.7	40.1	40.8
2017	0.2	75.4	75.6	2.6	30.9	33.5
2018	0.2	45.1	45.3	0.3	21.9	22.1

Table B.7. Values used to calculate the proportion of Yelloweye Rockfish from unassigned rockfish landings (i.e., catch assigned as 'Other Rockfish' ORF in database) and discard rates (δ) for each fishery by area for reconstructed catch. The data used to calculate δ are from observer logs from 2000-2005. Note that ratios shown are percentages.

a) Assumed proportion of Yelloweye Rockfish in ORF (γ) for reconstructed catch

Fishery Period Applied	Trawl 1918-1978	Halibut 1918-1981	Sablefish 1918-1995	Dogfish/lingcod 1918-1981	H&L Rockfish 1918-1981
4B	0.0	87.8	0.0	87.4	12.0
3C	0.0	40.4	0.0	23.9	18.4
3D	0.0	44.0	0.0	45.1	33.4
5A	0.0	57.1	0.0	72.5	22.8
5B	0.1	47.6	0.0	61.1	31.1
5C	0.1	64.6	0.0	61.8	49.0
5D	0.0	50.5	0.0	49.4	24.1
5E	0.0	35.9	0.0	45.9	18.5

b) Discard rates (δ) for reconstructed catch

Fishery Period Applied	Trawl 1954-1995	Halibut 1986-2005	Sablefish 1986-2005	Dogfish/lingcod 1986-2005	H&L Rockfish 1986-2005
4B	0.0	0.3	0.0	0.1	0.0
3C	0.0	0.0	0.1	0.3	1.0
3D	0.0	0.7	0.1	0.2	1.5
5A	0.0	1.1	0.1	0.8	0.1
5B	0.0	0.7	0.0	2.0	0.4
5C	0.0	0.8	0.0	0.9	0.6
5D	0.0	0.3	0.0	1.1	7.5
5E	0.0	1.9	0.0	3.2	0.0

Table B.8. Reconstructed commercial catch (t) by area.

Year	North			South		
	trawl	longline	Total	trawl	longline	Total
1918	<0.1	25.2	25.2	<0.1	4.6	4.6
1919	<0.1	3.0	3.0	<0.1	8.9	8.9
1920	<0.1	4.3	4.3	<0.1	5.0	5.0
1921	<0.1	0.2	0.2	<0.1	2.9	2.9
1922	<0.1	0.1	0.1	<0.1	6.5	6.5
1923	<0.1	0.4	0.4	<0.1	2.9	2.9
1924	<0.1	1.1	1.1	<0.1	2.8	2.8
1925	<0.1	1.6	1.6	<0.1	1.8	1.8
1926	<0.1	3.7	3.7	<0.1	3.4	3.4
1927	<0.1	5.8	5.8	<0.1	4.8	4.8
1928	<0.1	4.2	4.2	<0.1	4.4	4.4
1929	<0.1	6.3	6.3	<0.1	3.7	3.7
1930	<0.1	3.3	3.3	<0.1	2.7	2.7
1931	<0.1	0.5	0.5	<0.1	2.7	2.7
1932	<0.1	0.3	0.3	<0.1	1.4	1.4
1933	<0.1	0.1	0.1	<0.1	0.9	0.9
1934	<0.1	0.3	0.3	<0.1	0.9	0.9
1935	<0.1	3.7	3.7	<0.1	1.1	1.1
1936	<0.1	5.7	5.7	<0.1	2.4	2.4
1937	<0.1	1.0	1.0	<0.1	0.6	0.6
1938	<0.1	0.4	0.4	<0.1	9.4	9.4
1939	<0.1	0.3	0.3	<0.1	0.5	0.5
1940	<0.1	0.4	0.4	<0.1	0.3	0.3
1941	<0.1	2.9	2.9	<0.1	1.3	1.3
1942	0.1	2.5	2.6	0.05	3.4	3.4
1943	0.3	7.0	7.3	0.17	9.4	9.6
1944	0.1	9.6	9.8	0.08	12.7	12.7
1945	1.4	15.8	17.2	0.81	9.8	10.6
1946	0.7	23.3	24.0	0.39	8.6	8.9
1947	0.3	3.4	3.8	0.19	2.5	2.7
1948	0.6	5.4	5.9	0.31	4.0	4.3
1949	0.7	7.3	8.0	0.38	5.4	5.8
1950	1.2	2.9	4.1	0.71	2.2	2.9
1951	1.3	20.1	21.4	0.58	7.4	7.9
1952	1.0	12.3	13.4	0.53	5.5	6.0
1953	0.4	7.4	7.8	0.25	8.9	9.1
1954	0.6	8.2	8.8	0.35	9.0	9.3
1955	0.6	4.6	5.2	0.39	9.1	9.5
1956	0.3	2.6	2.8	0.36	9.6	9.9
1957	0.5	6.6	7.1	0.32	15.4	15.7
1958	0.6	1.3	1.9	0.33	13.0	13.3
1959	0.8	1.4	2.2	0.60	14.8	15.4
1960	0.6	7.2	7.8	0.57	18.1	18.7
1961	0.7	5.2	5.9	0.69	21.8	22.5
1962	1.1	11.1	12.2	0.89	28.4	29.3
1963	0.8	20.0	20.8	0.54	19.5	20.0
1964	0.7	5.5	6.2	0.44	11.9	12.3

Year	North			South		
	trawl	longline	Total	trawl	longline	Total
1965	0.6	7.3	7.9	0.51	9.7	10.2
1966	0.7	6.3	7.0	0.75	11.9	12.7
1967	0.8	11.9	12.7	0.47	15.9	16.4
1968	0.9	4.1	5.0	0.70	12.5	13.2
1969	1.6	15.6	17.2	1.1	16.6	17.7
1970	1.3	42.0	43.3	0.94	19.8	20.8
1971	1.3	33.1	34.3	0.79	9.8	10.6
1972	1.8	31.4	33.2	0.74	30.2	31.0
1973	1.8	22.2	23.9	0.89	17.1	18.0
1974	1.2	42.2	43.4	0.56	24.1	24.6
1975	1.1	59.6	60.6	0.40	19.8	20.2
1976	1.8	32.2	34.0	0.20	19.7	19.9
1977	1.9	40.0	41.9	0.40	32.9	33.3
1978	2.8	58.2	61.0	0.39	24.5	24.9
1979	0.7	60.3	61.1	0.09	49.9	50.0
1980	0.5	58.4	58.8	0.30	43.5	43.8
1981	3.4	42.2	45.6	2.5	34.0	36.4
1982	2.0	26.1	28.1	0.00	19.9	19.9
1983	0.1	33.2	33.3	0.85	17.2	18.1
1984	2.1	55.2	57.3	0.65	56.5	57.1
1985	4.4	122.7	127.1	1.2	109.2	110.4
1986	9.8	353.2	363.0	2.3	369.9	372.2
1987	14.5	426.0	440.5	19.0	491.3	510.3
1988	12.5	462.1	474.6	4.3	370.7	375.0
1989	28.4	463.2	491.5	9.3	463.7	473.0
1990	32.3	929.5	961.8	17.3	740.2	757.5
1991	15.5	859.0	874.5	18.4	613.6	632.0
1992	22.5	691.2	713.7	18.4	380.7	399.2
1993	15.2	845.4	860.7	31.8	663.2	695.0
1994	39.9	625.6	665.5	43.1	317.1	360.2
1995	24.2	676.6	700.7	22.9	372.0	394.9
1996	7.6	496.7	504.3	12.3	233.7	246.0
1997	11.5	476.4	487.9	7.9	218.4	226.3
1998	8.6	486.7	495.3	7.2	288.0	295.2
1999	9.1	363.4	372.5	7.0	174.1	181.1
2000	7.9	414.5	422.4	7.7	168.3	176.1
2001	6.6	377.0	383.7	6.7	164.1	170.8
2002	7.5	302.1	309.6	5.0	99.3	104.3
2003	8.5	233.0	241.5	4.9	96.6	101.5
2004	5.3	208.0	213.3	4.3	81.7	85.9
2005	5.2	222.3	227.5	5.2	85.9	91.2
2006	4.4	157.2	161.6	3.6	48.0	51.6
2007	2.9	154.2	157.0	3.8	69.3	73.1
2008	1.9	192.7	194.6	4.8	108.1	112.8
2009	2.0	160.5	162.5	6.1	86.4	92.5
2010	4.2	164.1	168.3	7.3	69.9	77.2
2011	1.6	164.4	166.0	6.7	91.1	97.9
2012	1.8	175.8	177.5	5.8	99.0	104.9
2013	1.5	170.1	171.5	3.1	82.6	85.6

Year	North			South		
	trawl	longline	Total	trawl	longline	Total
2014	2.6	165.5	168.0	2.4	66.9	69.3
2015	1.7	170.5	172.2	2.1	90.7	92.8
2016	0.6	111.9	112.4	2.0	44.6	46.6
2017	0.8	85.2	85.9	5.1	36.4	41.5
2018	1.0	52.3	53.2	1.9	26.6	28.5

Table B.9. Reconstructed and reported recreational catch time series for north and south outside Yelloweye Rockfish populations, from 1918 to 2018.

Year	Reconstructed Catch			Reported catch	
	Total	North	South	North	South
1918	10	5	5	-	-
1919	10	5	5	-	-
1920	10	5	5	-	-
1921	10	5	5	-	-
1922	10	5	5	-	-
1923	10	5	5	-	-
1924	10	5	5	-	-
1925	10	5	5	-	-
1926	10	5	5	-	-
1927	10	5	5	-	-
1928	10	5	5	-	-
1929	10	5	5	-	-
1930	10	5	5	-	-
1931	10	5	5	-	-
1932	10	5	5	-	-
1933	10	5	5	-	-
1934	10	5	5	-	-
1935	10	5	5	-	-
1936	10	5	5	-	-
1937	10	5	5	-	-
1938	10	5	5	-	-
1939	10	5	5	-	-
1940	10	5	5	-	-
1941	10	5	5	-	-
1942	10	5	5	-	-
1943	10	5	5	-	-
1944	10	5	5	-	-
1945	10	5	5	-	-
1946	11.9	6.0	6.0	-	-
1947	23.9	12.0	12.0	-	-
1948	35.1	17.6	17.6	-	-
1949	46.8	23.4	23.4	-	-
1950	58.0	29.0	29.0	-	-
1951	70.1	35.1	35.1	-	-
1952	80.6	40.3	40.3	-	-
1953	91.3	45.7	45.7	-	-
1954	103.6	51.8	51.8	-	-
1955	115.2	57.6	57.6	-	-
1956	126.2	63.1	63.1	-	-
1957	137.3	68.7	68.7	-	-

	Reconstructed Catch			Reported catch	
Year	Total	North	South	North	South
1958	147.1	73.6	73.6	-	-
1959	157.0	78.5	78.5	-	-
1960	166.0	83.0	83.0	-	-
1961	186.1	93.1	93.1	-	-
1962	185.5	92.8	92.8	-	-
1963	183.0	91.5	91.5	-	-
1964	184.1	92.1	92.1	-	-
1965	180.7	90.4	90.4	-	-
1966	182.8	91.4	91.4	-	-
1967	182.5	91.3	91.3	-	-
1968	184.4	92.2	92.2	-	-
1969	181.7	90.9	90.9	-	-
1970	187.6	93.8	93.8	-	-
1971	195.4	97.7	97.7	-	-
1972	201.1	100.6	100.6	-	-
1973	208.7	104.4	104.4	-	-
1974	215.5	107.8	107.8	-	-
1975	225.6	112.8	112.8	-	-
1976	232.5	116.3	116.3	-	-
1977	237.0	118.5	118.5	-	-
1978	243.8	121.9	121.9	-	-
1979	248.4	124.2	124.2	-	-
1980	254.2	127.1	127.1	-	-
1981	260.2	130.1	130.1	-	-
1982	263.5	131.8	131.8	-	-
1983	272.3	136.2	136.2	-	-
1984	282.0	141.0	141.0	-	-
1985	258.5	129.3	129.3	-	-
1986	139.5	69.8	69.8	-	-
1987	249.7	124.9	124.9	-	-
1988	177.8	88.9	88.9	-	-
1989	264.4	132.2	132.2	-	-
1990	264.0	132.0	132.0	-	-
1991	278.4	139.2	139.2	-	-
1992	338.1	169.1	169.1	-	-
1993	217.4	108.7	108.7	-	-
1994	242.2	121.1	121.1	-	-
1995	156.3	78.2	78.2	-	-
1996	60.0	30.0	30.0	-	-
1997	138.4	69.2	69.2	-	-
1998	146.9	73.5	73.5	-	-
1999	143.1	71.6	71.6	-	-

Year	Reconstructed Catch			Reported catch	
	Total	North	South	North	South
2000	90.3	45.2	45.2	-	5.6
2001	89.7	44.9	44.9	-	14.3
2002	105.5	52.8	52.8	3.4	5.2
2003	111.5	55.8	55.8	3.4	5.7
2004	106.3	53.2	53.2	4.3	4.3
2005	97.1	48.6	48.6	4.4	8.6
2006	93.4	46.7	46.7	5.5	11.2
2007	76.2	38.1	38.1	8.1	23.0
2008	70.0	35.0	35.0	6.2	32.7
2009	67.9	34.0	34.0	3.6	24.5
2010	61.9	31.0	31.0	2.8	25.8
2011	64.1	32.1	32.1	5.3	41.8
2012	54.6	27.3	27.3	4.1	36.7
2013	45.0	22.5	22.5	6.8	22.9
2014	49.6	24.8	24.8	9.3	20.6
2015	67.5	38.8	28.8	7.9	28.8
2016	61.5	35.2	26.3	27.9	26.3
2017	58.5	25.7	32.8	27.9	32.8
2018	29.5	14.2	15.3	14.0	15.3
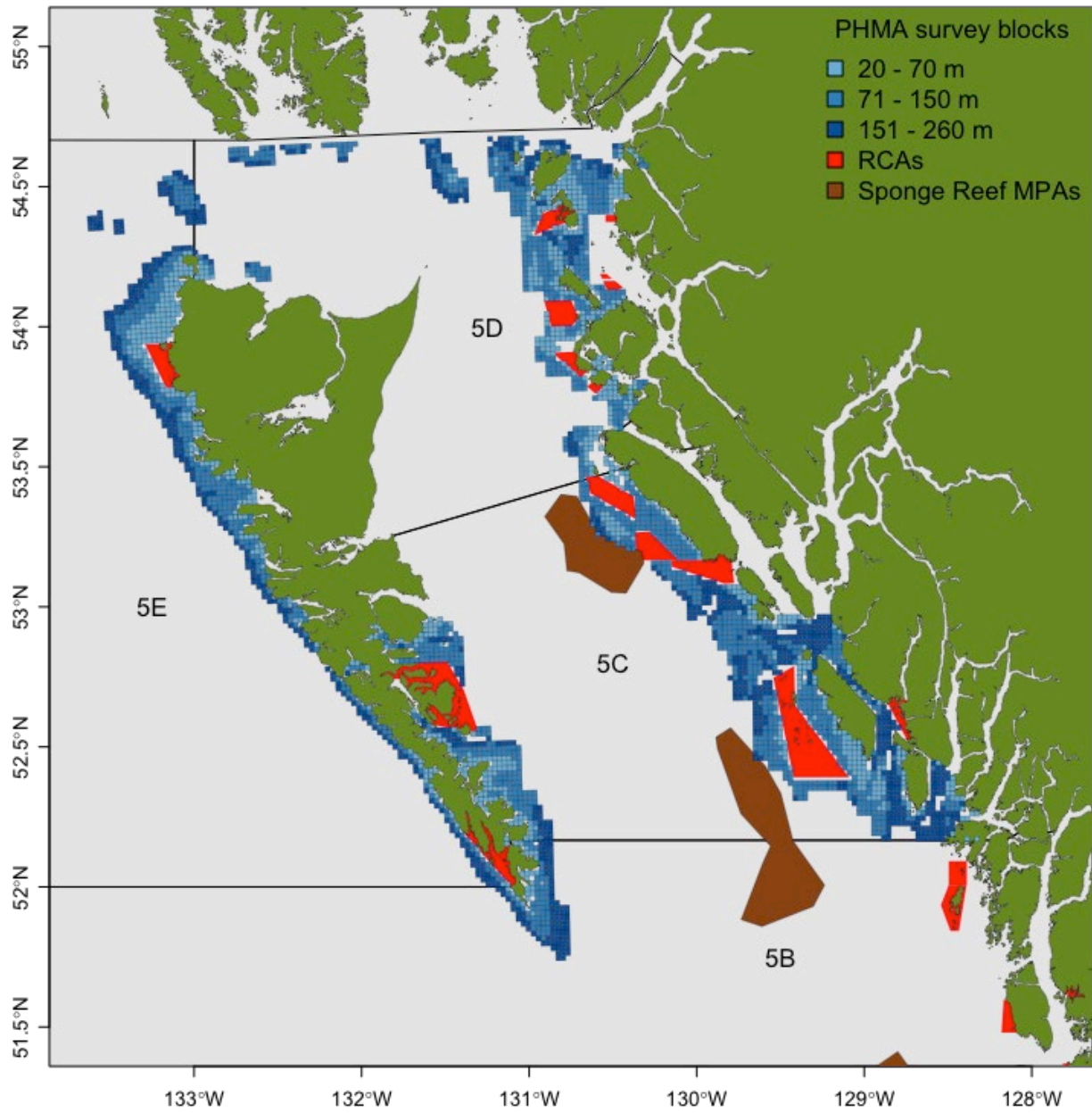
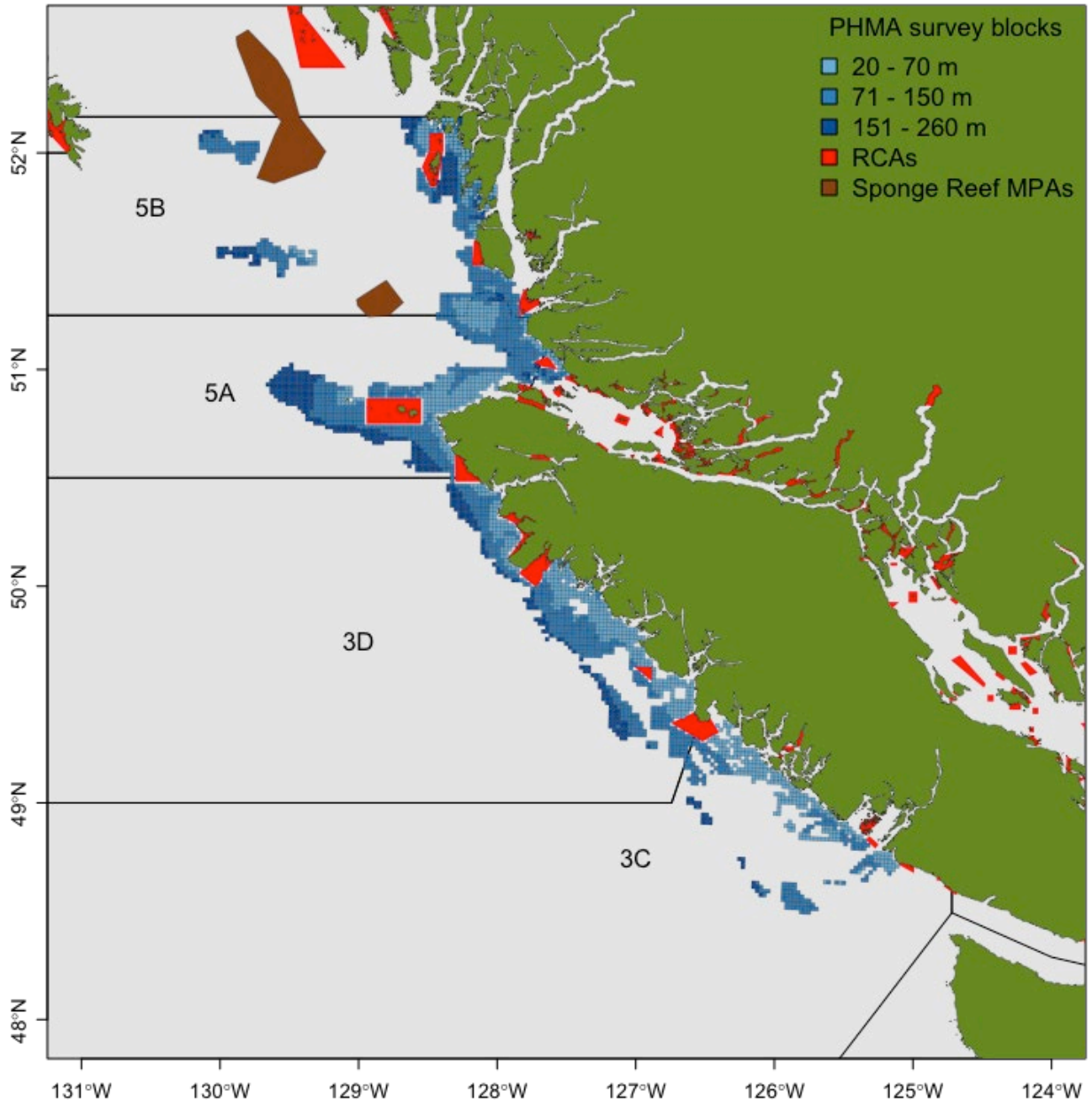*Figure B.1. PHMA survey 2x2 km grid cells by depth strata for northern survey area.*

Figure B.2. PHMA survey 2x2 km grid cells by depth strata for southern survey area.
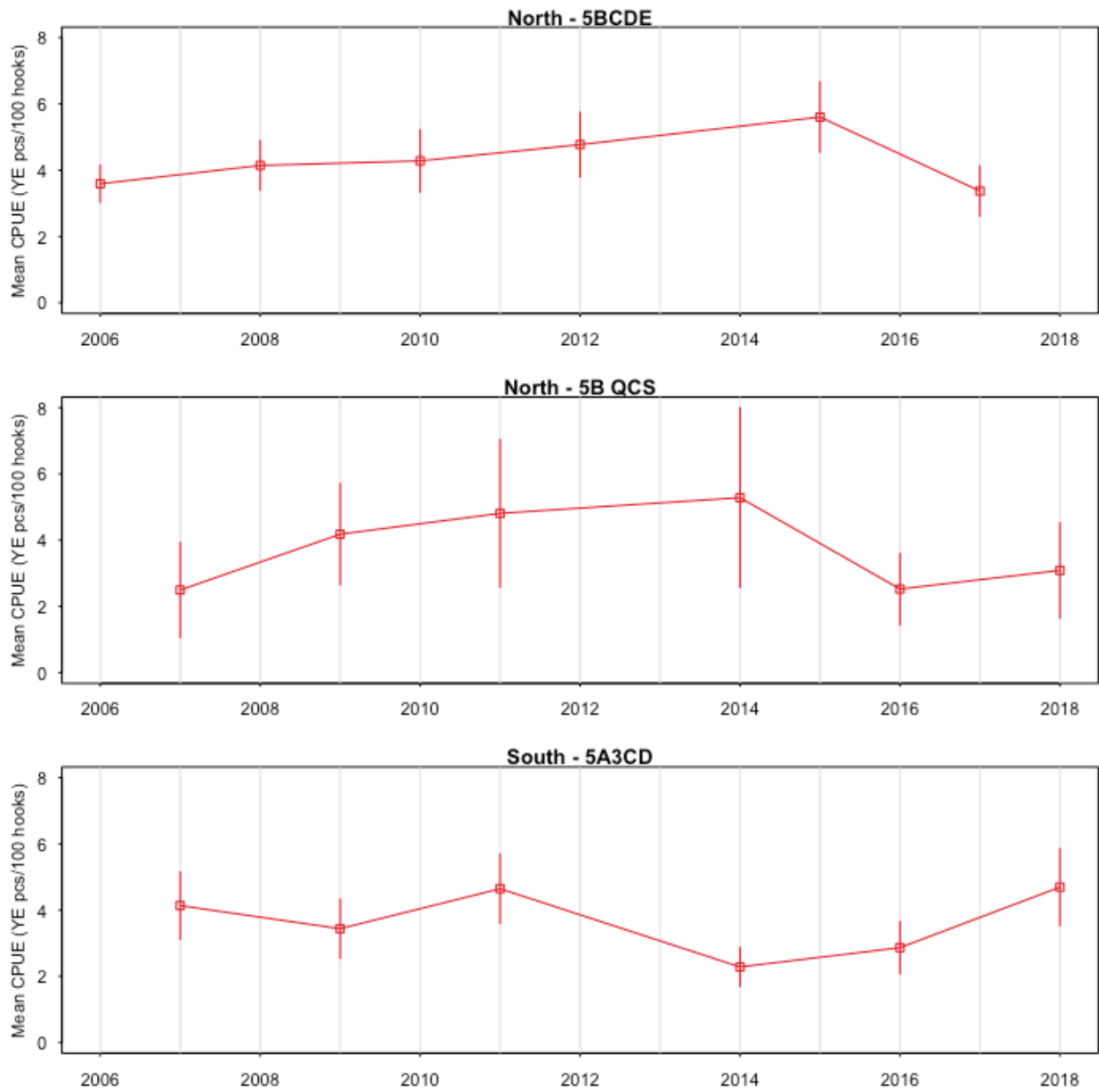
Figure B.3. Stratified means +/- 1.96SE from PHMA survey for the Northern PHMA index in 5BCDE (top), the Queen Charlotte Sound index in 5B (middle), and the southern PHMA survey index in 5A3CD (bottom)
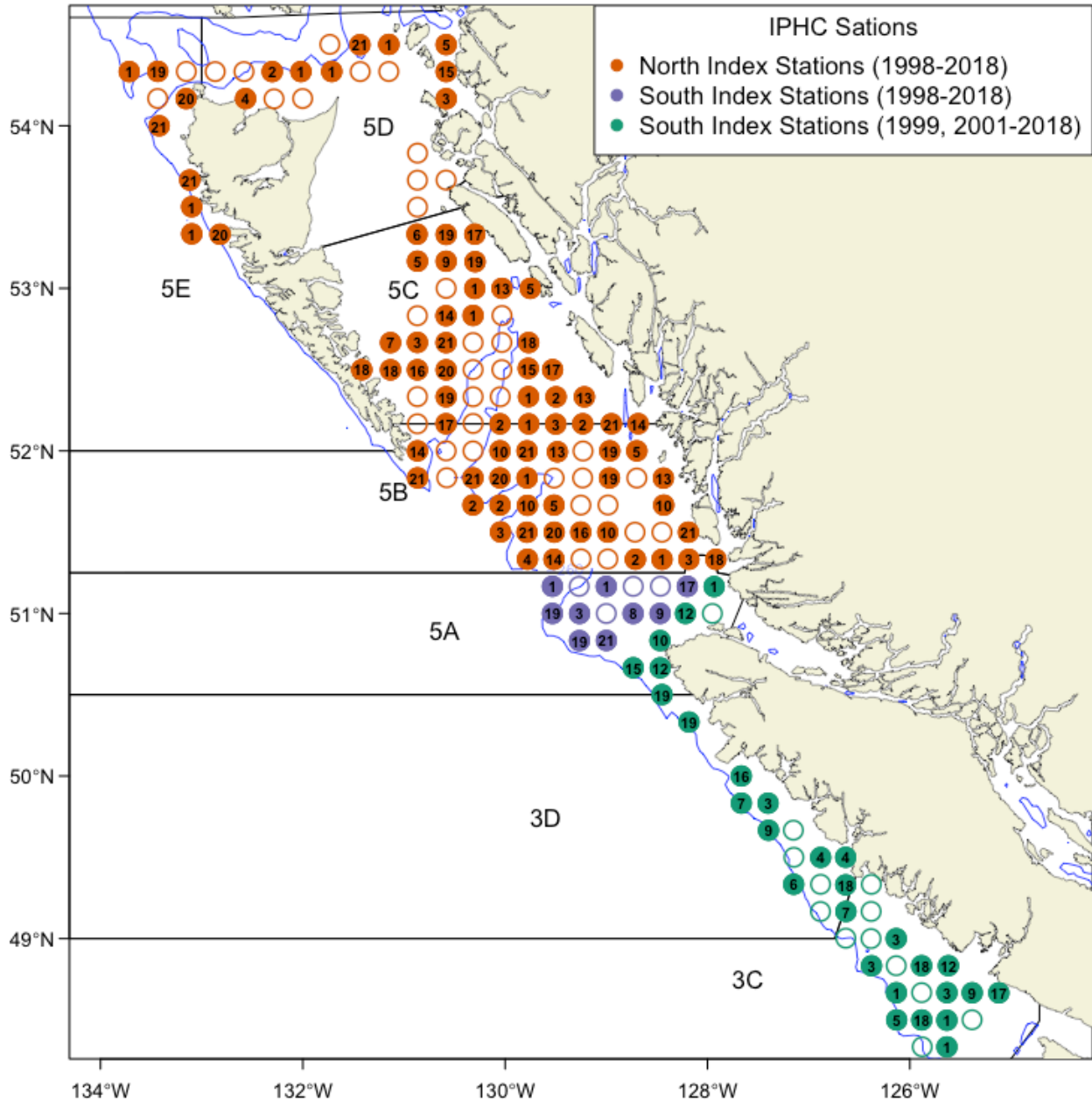
Figure B.4. IPHC stations used to generate survey indices for northern and southern Yelloweye Stocks, with numbers indicating the number of years that stations caught at least 1 Yelloweye Rockfish. Circles without a number indicate IPHC stations that have never caught Yelloweye Rockfish.
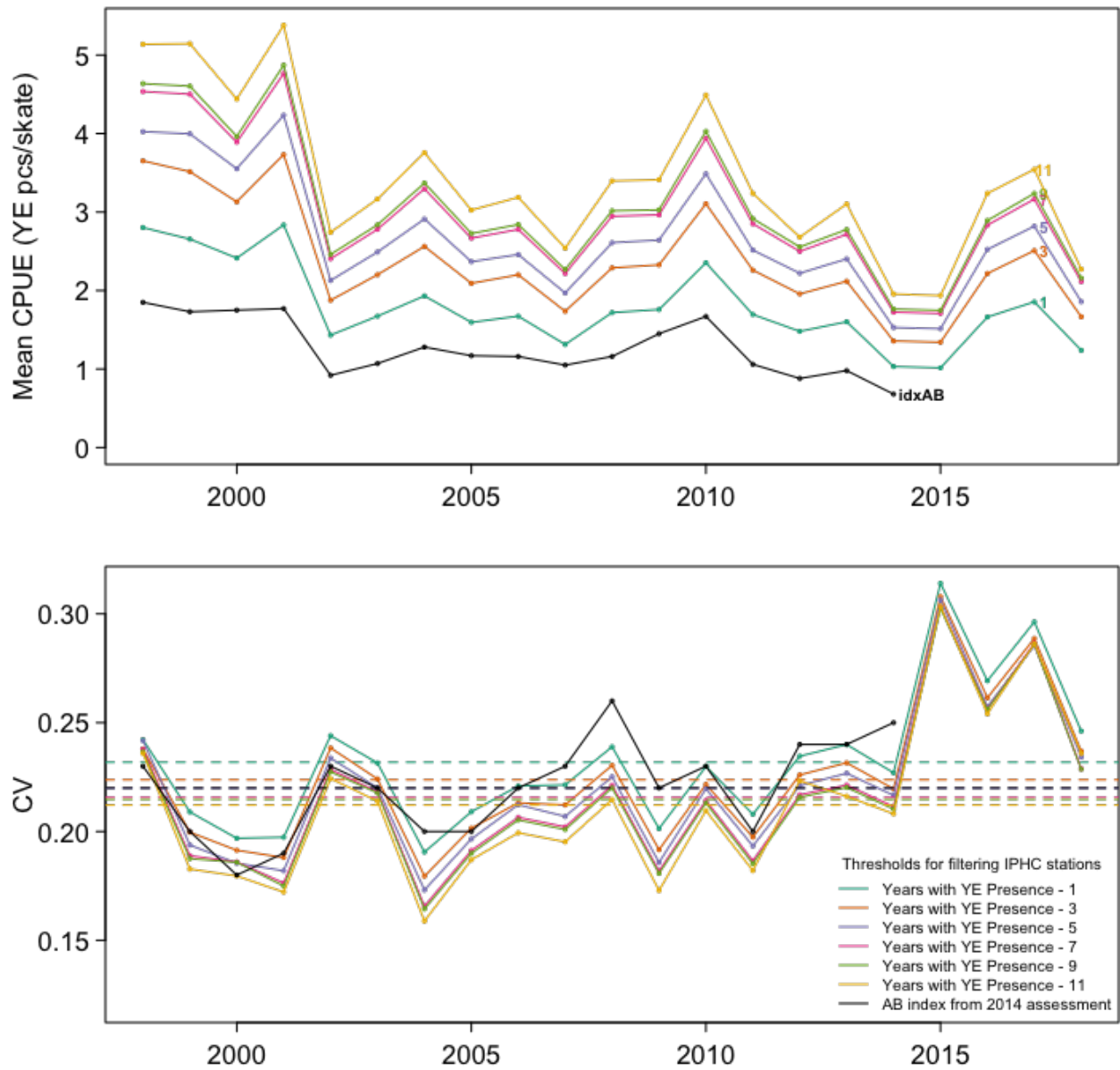
Figure B.5. Annual IPHC indices (top) and CVs (bottom) for the northern Yelloweye Stock in 5BCDE calculated using different thresholds for filtering IPHC stations. The AB series used in the 2014 assessment (Yamanaka et al. 2018) is shown for comparison purposes. Dotted lines in bottom panel indicate mean CV.
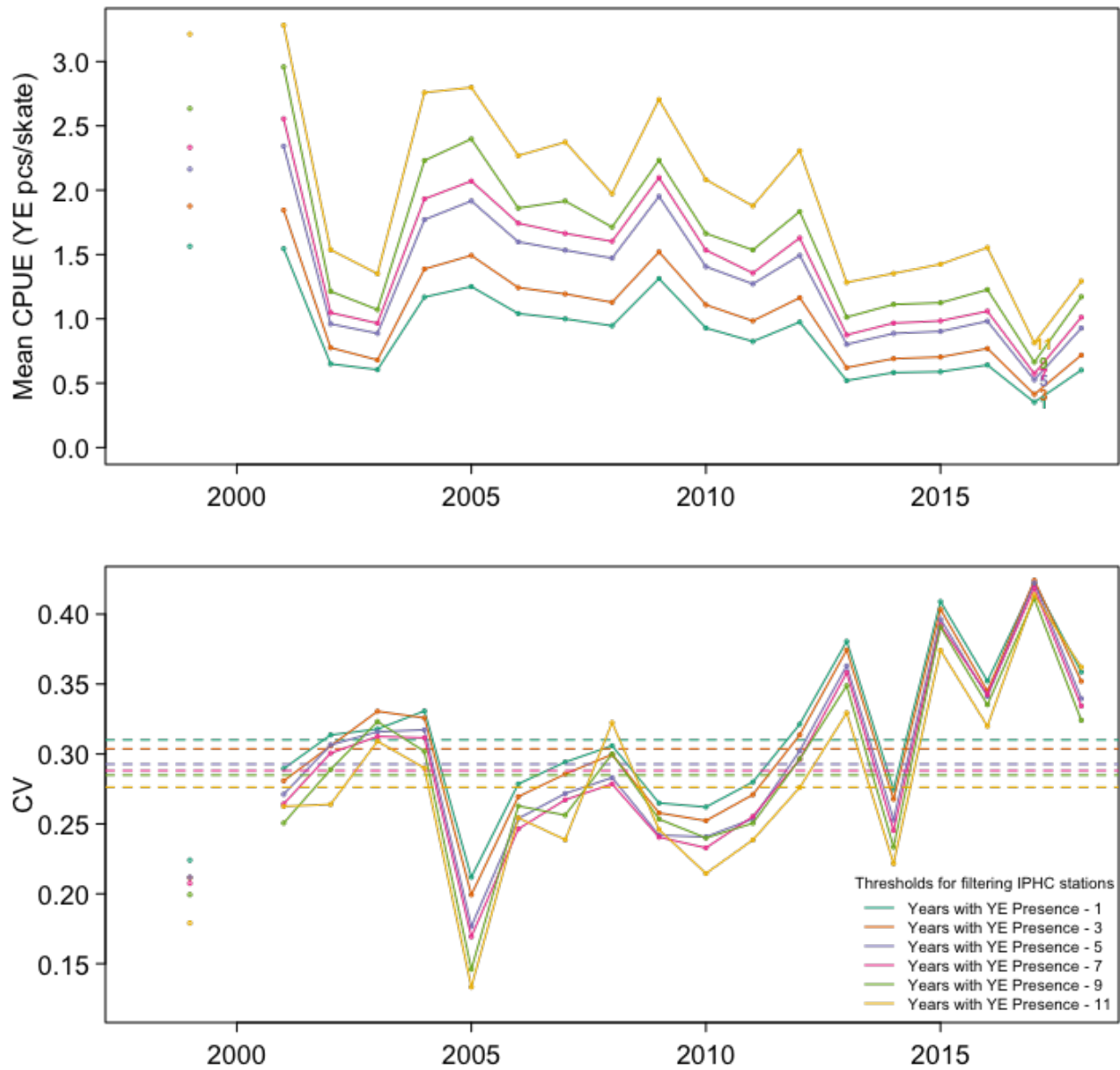
Figure B.6. Annual IPHC indices (top) and CVs (bottom) for the southern Yelloweye Stock in 5BCDE calculated using different thresholds for filtering IPHC stations. Dotted lines in bottom panel indicate mean CV.
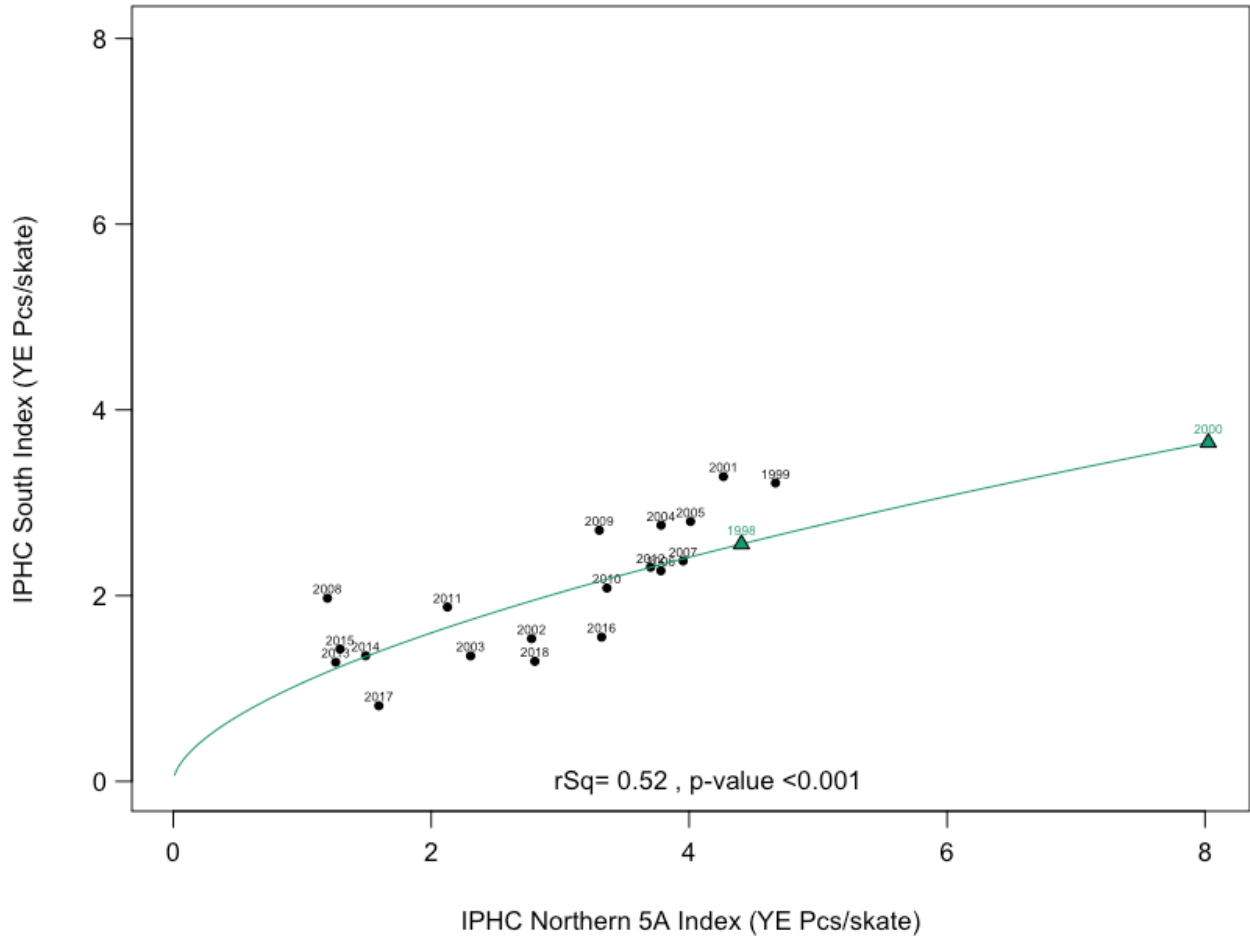
Figure B.7. Estimated relationship from linear regression fits of log-transformed indices for I_{n5A}^{IPHC} and I_{South}^{IPHC}, where $I_{South}^{IPHC} = \beta_0 (I_{n5A}^{IPHC})^{\beta_1} e^\nu$. The green triangles are predicted values for I_{South}^{IPHC} in 1998 and 2000 based on observed CPUE for I_{n5A}^{IPHC} in those years.
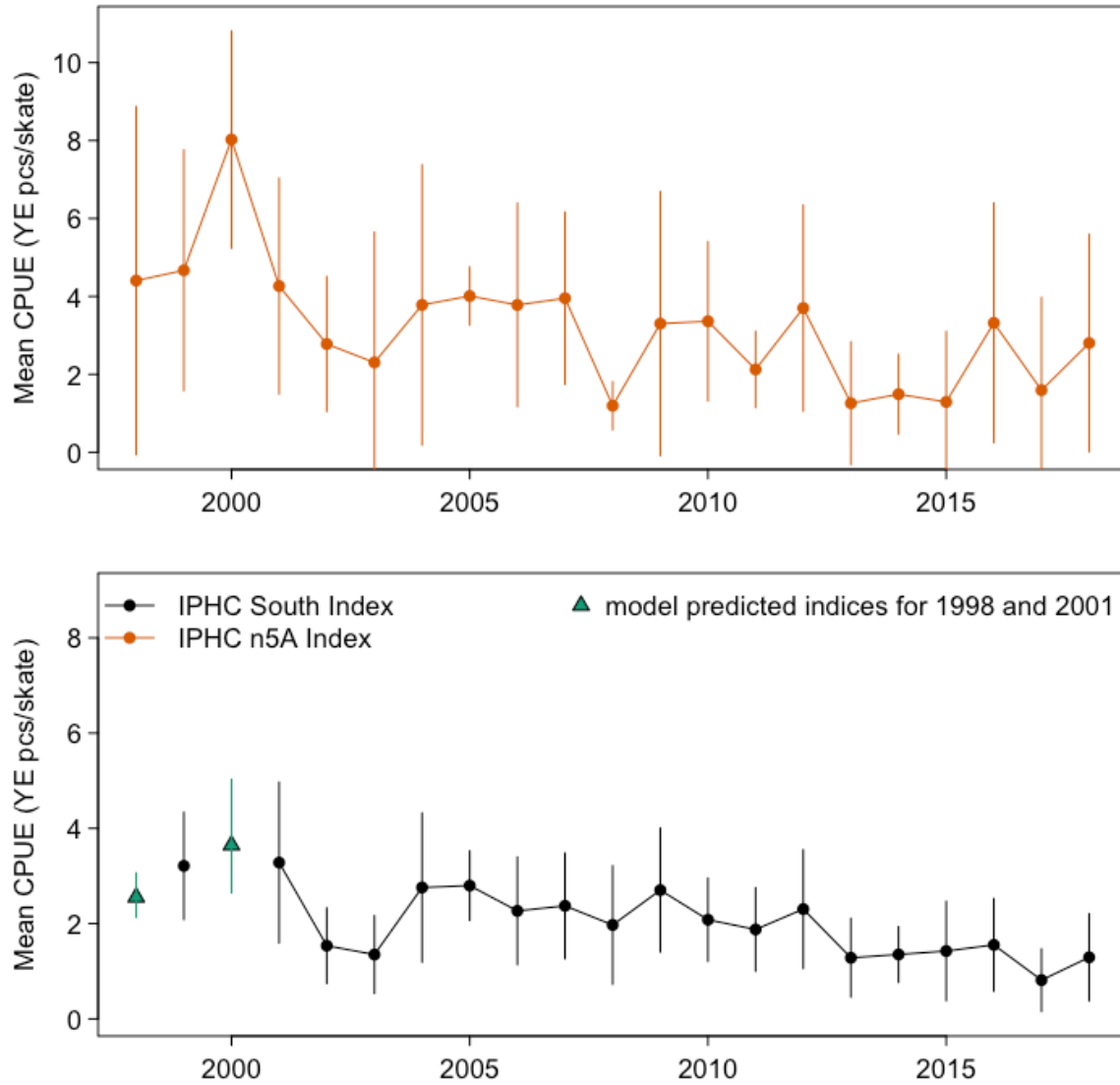
Figure B.8. Annual indices +/- 1.96SE for I_{n5A}^{IPHC} (top) and I_{South}^{IPHC} (bottom) from 1998-2018 using stations with at least 11 years of Yelloweye catch.
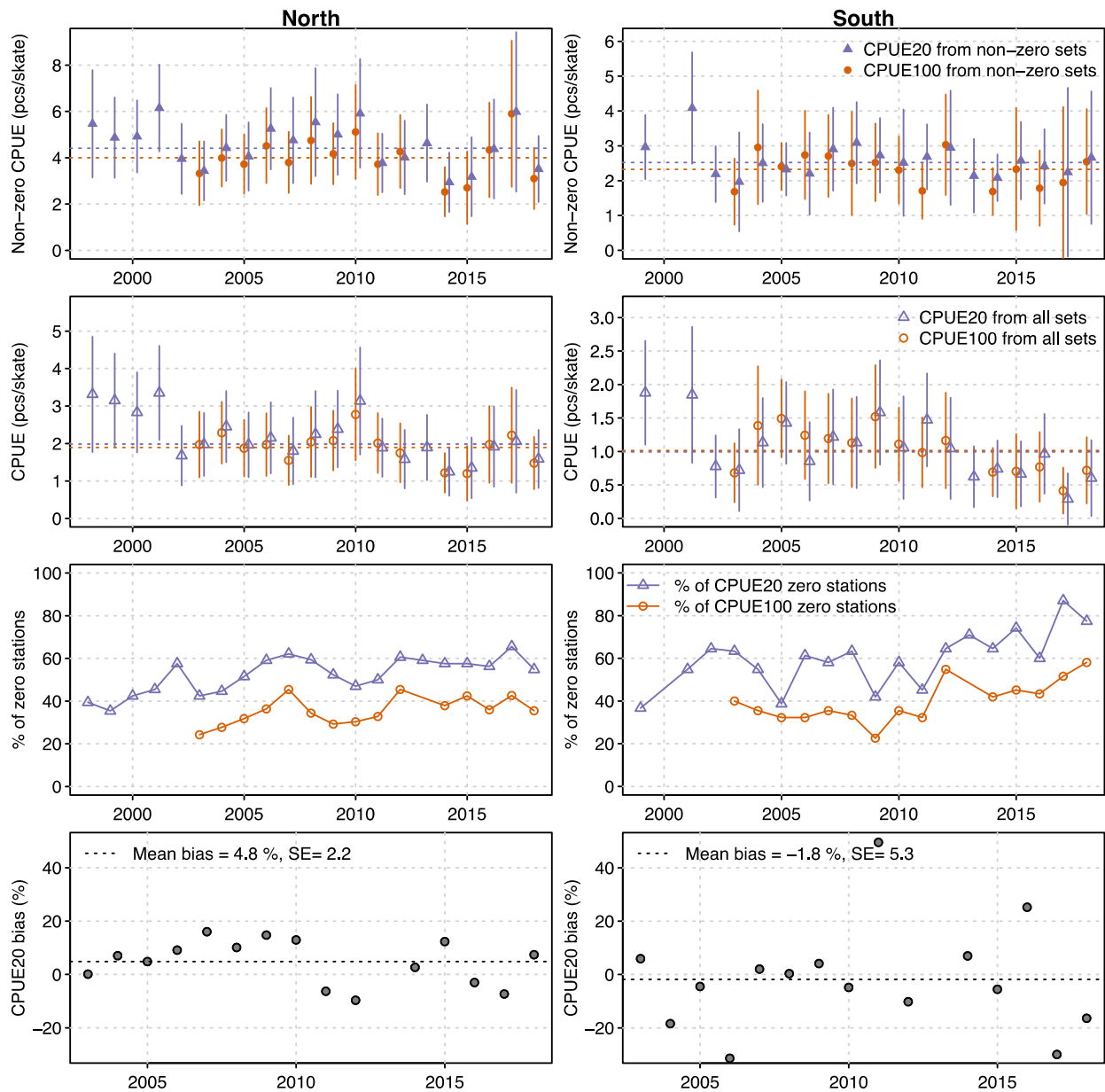
Figure B.9. Comparison of Yelloweye CPUE +/- 1.96SE using the first 20 hooks (CPUE20) of each skate and all hooks (CPUE100) for stations with at least 1 year of Yelloweye catch.
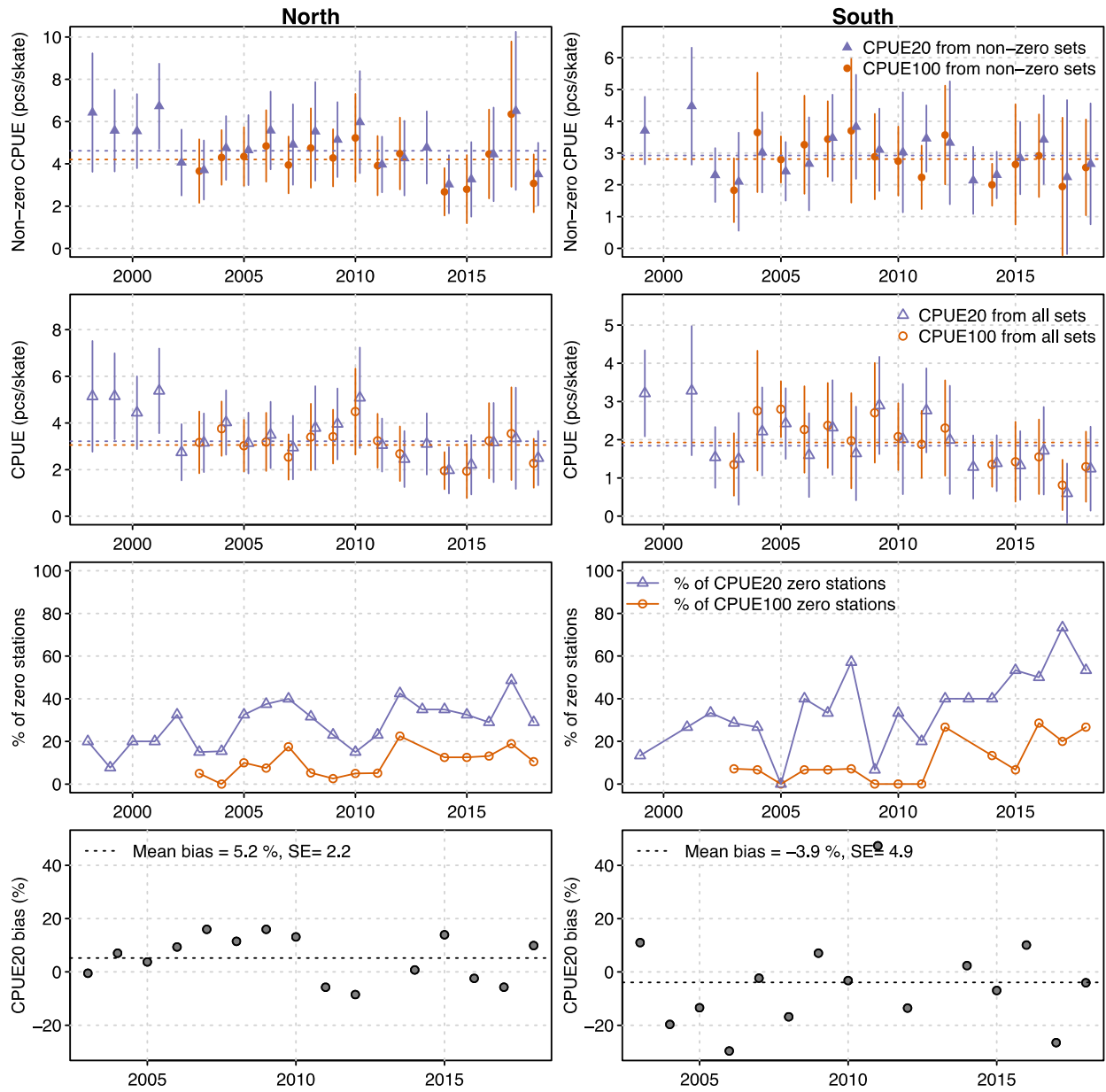
Figure B.10. Comparison of Yelloweye CPUE +/- 1.96SE using the first 20 hooks (CPUE20) of each skate and all hooks (CPUE100) for stations with at least 11 years of Yelloweye catch.

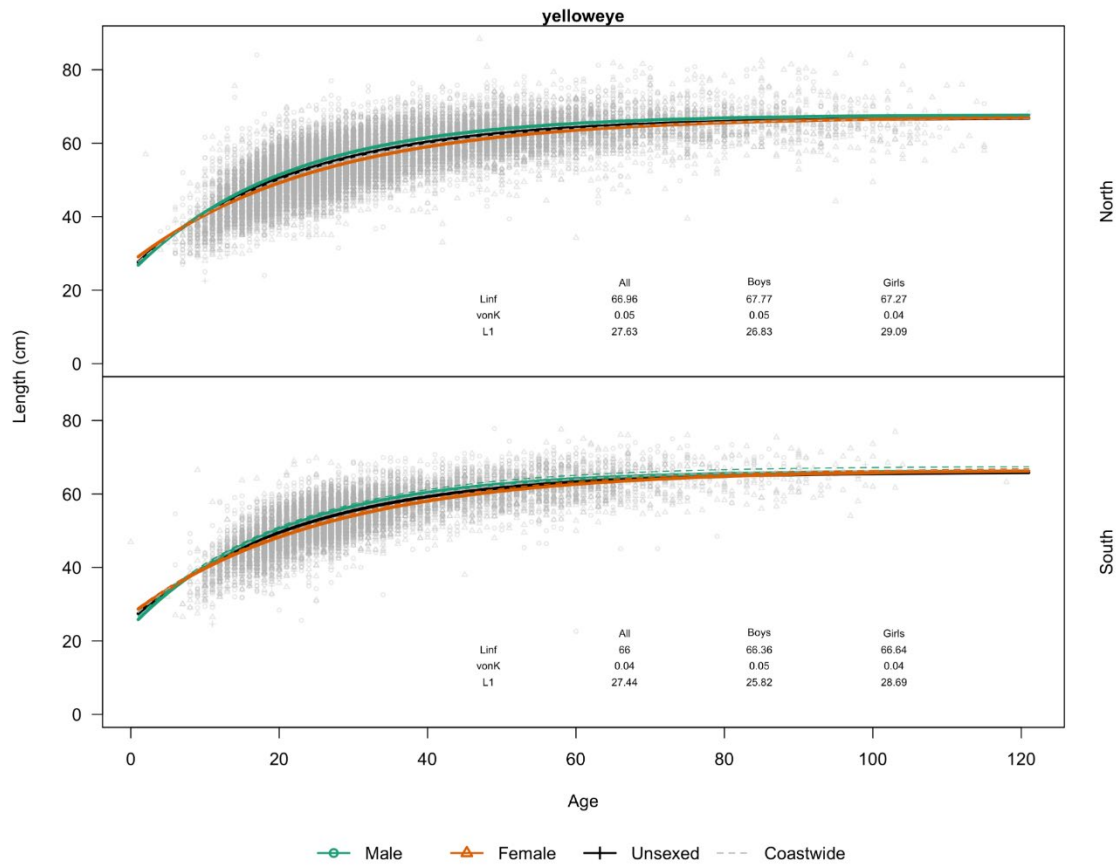*Figure B.11. Von Bertalanffy growth curve fits for north and south Yelloweye stocks.*
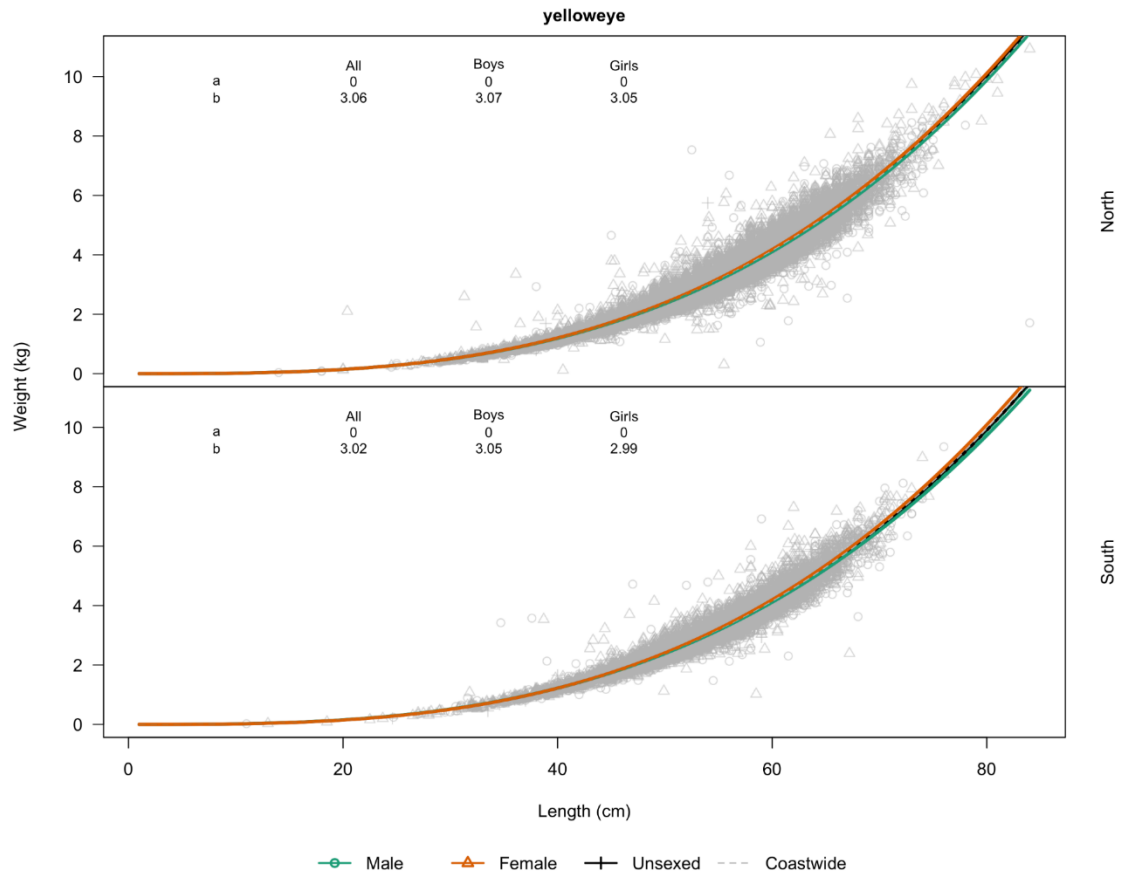
Figure B.12. Length-weight relationships for north and south Yelloweye stocks.
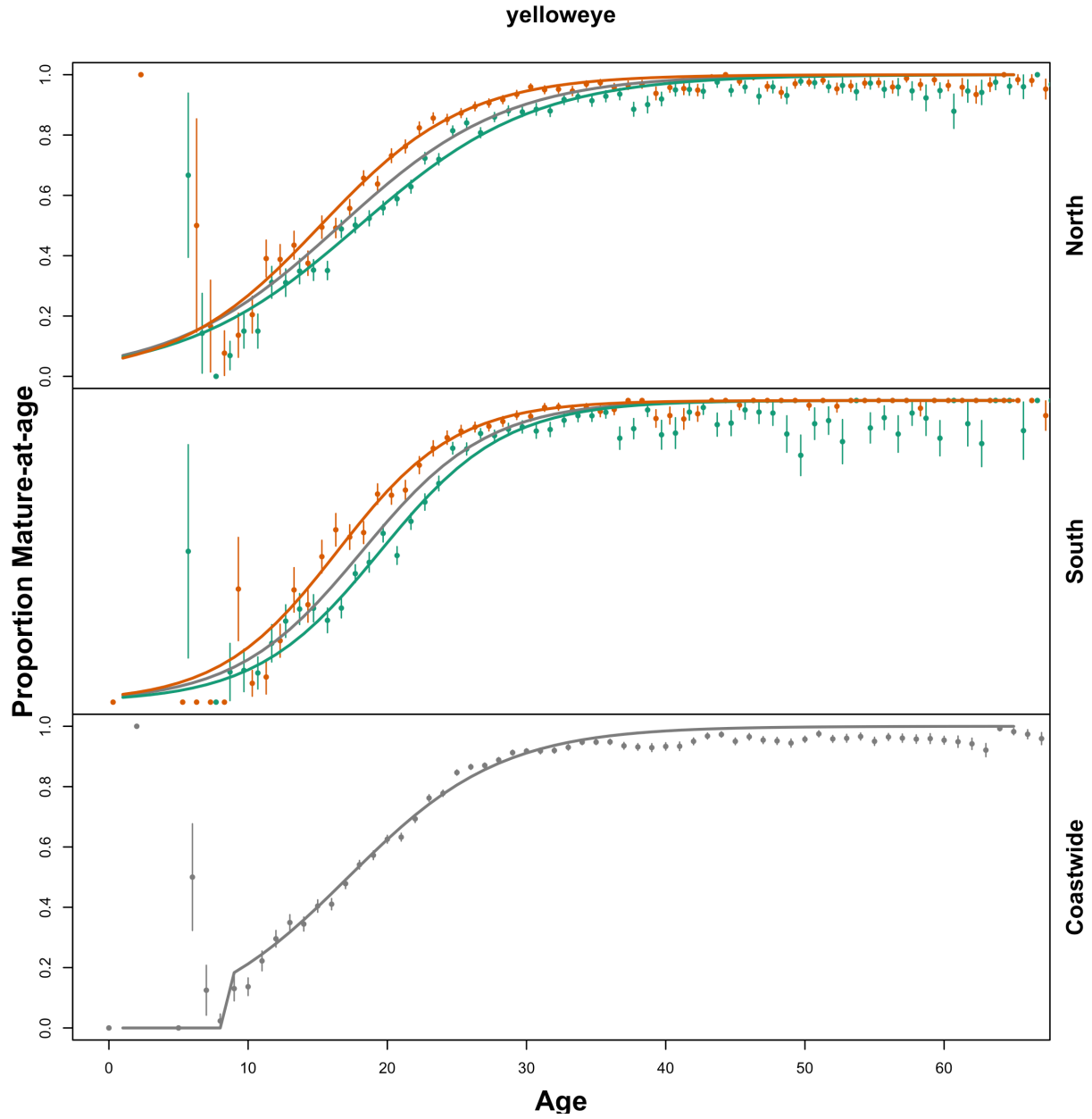
Figure B.13. Maturity at age curves for north, south, and coastwide Yelloweye stock areas for males (green), females (orange) and both sexes combined (grey). The coastwide maturity-at-age curve (bottom plot) was used in all operating models.
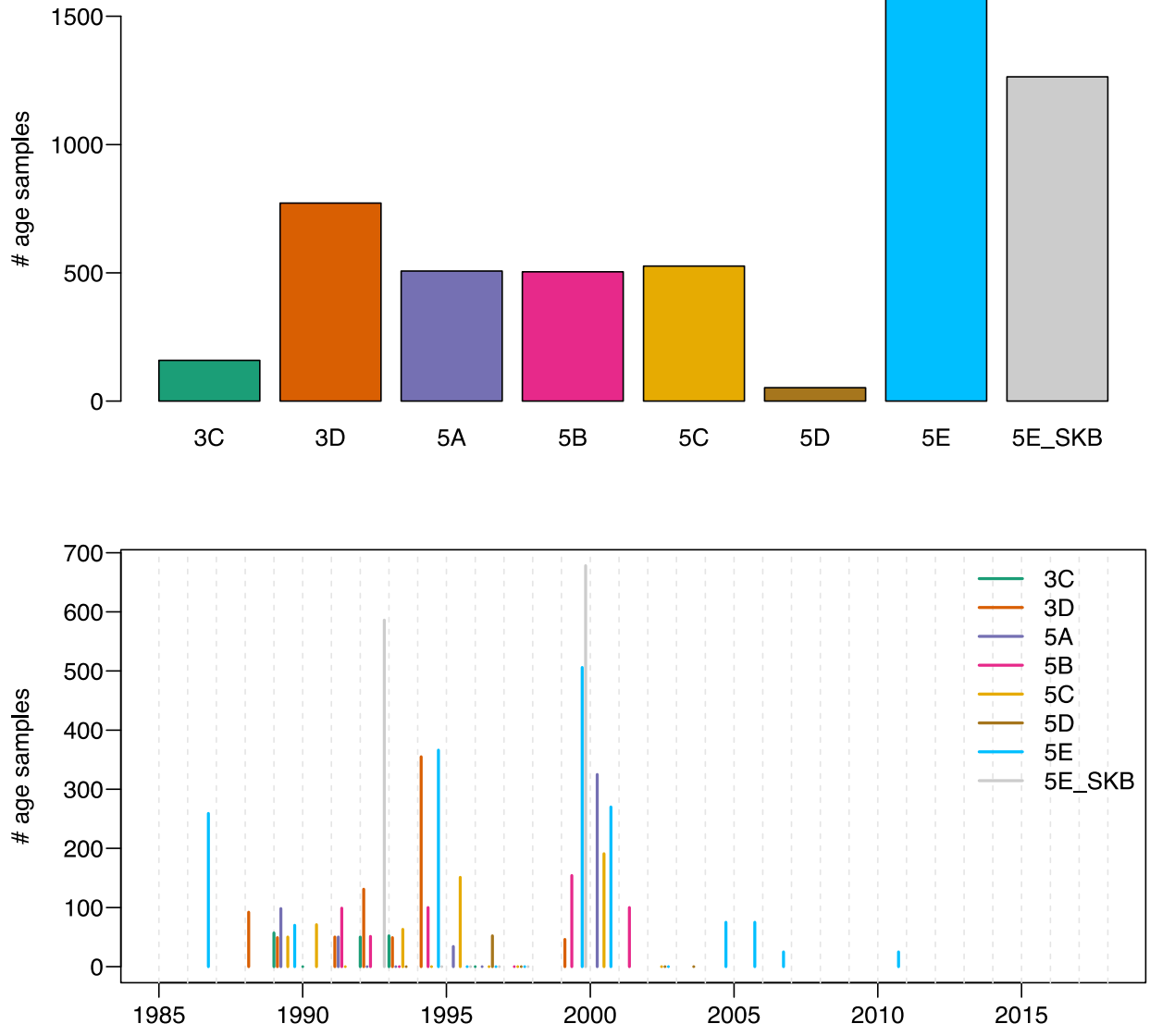
Figure B.14. Total samples sizes for Outside Yelloweye ages from commercial hook and line fleets by area (top) and year (bottom). Samples from SGaan Kinghlas – Bowie Seamount (SK-B) were not included in the age composition data used for OYE age-structure models.
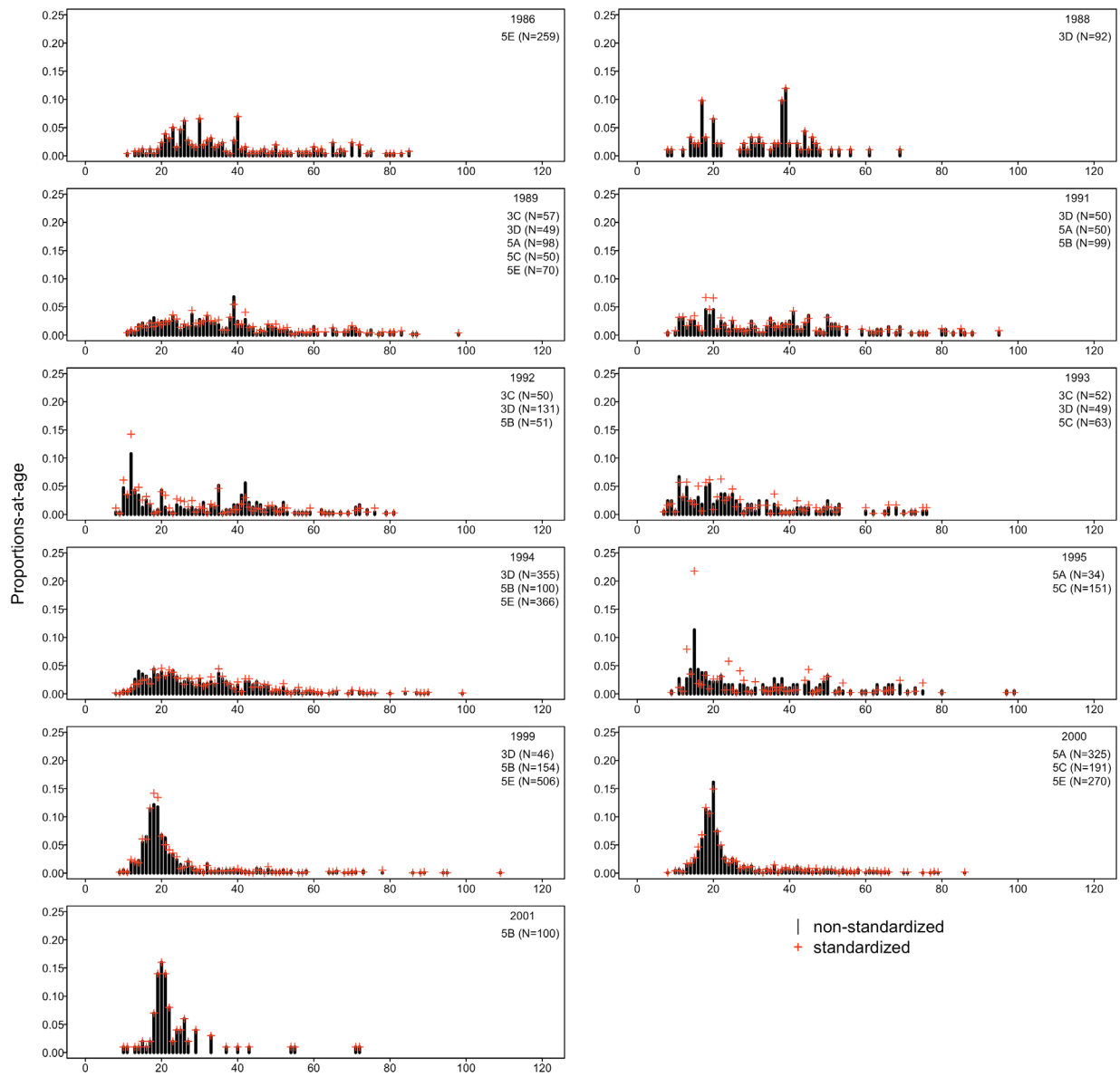
Figure B.15. Standardized age compositions for Outside Yelloweye from commercial hook and line fleets used as data inputs for age-structured models.
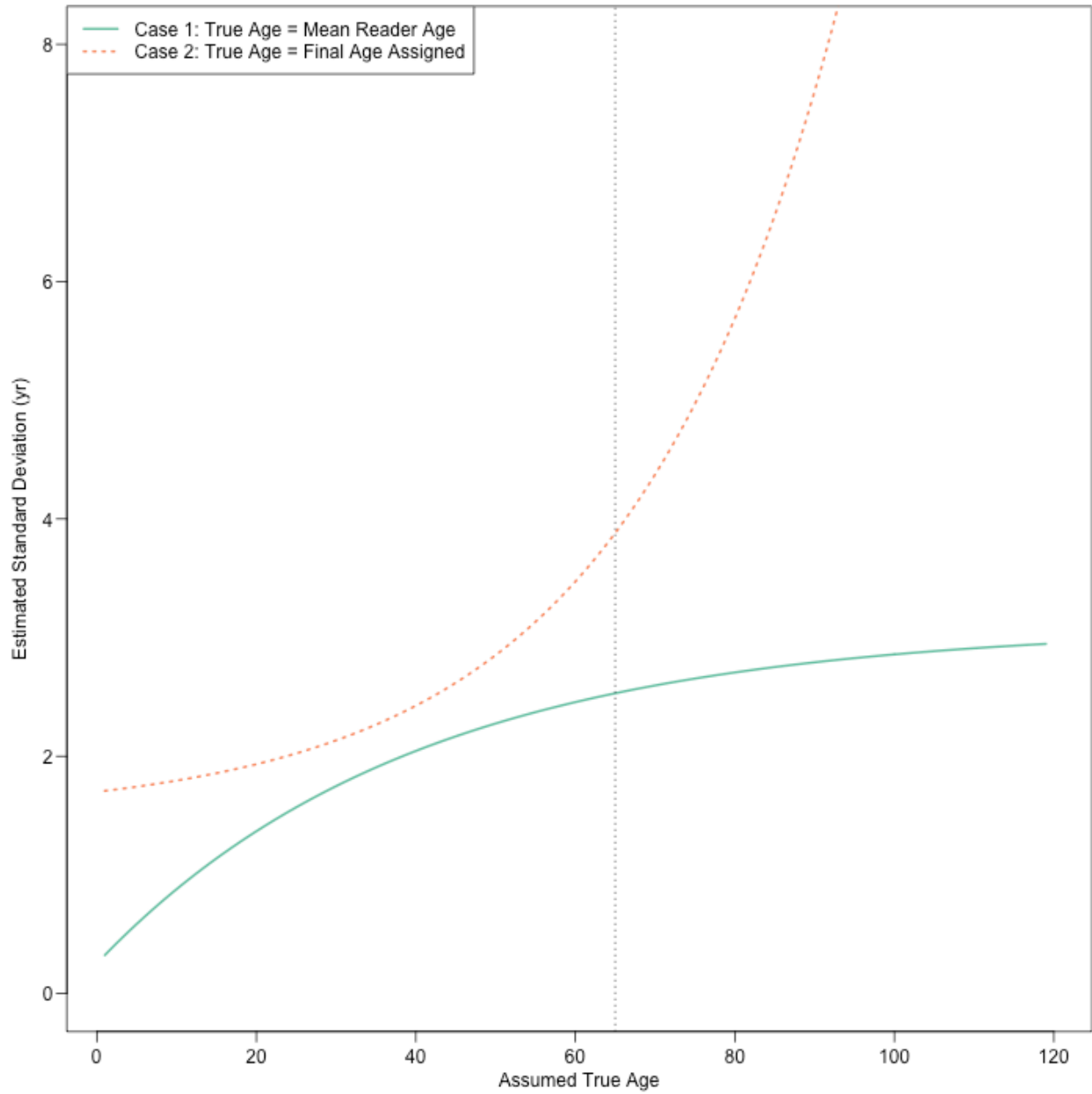
Figure B.16. Estimated standard deviation of observed ages for the two cases considered.
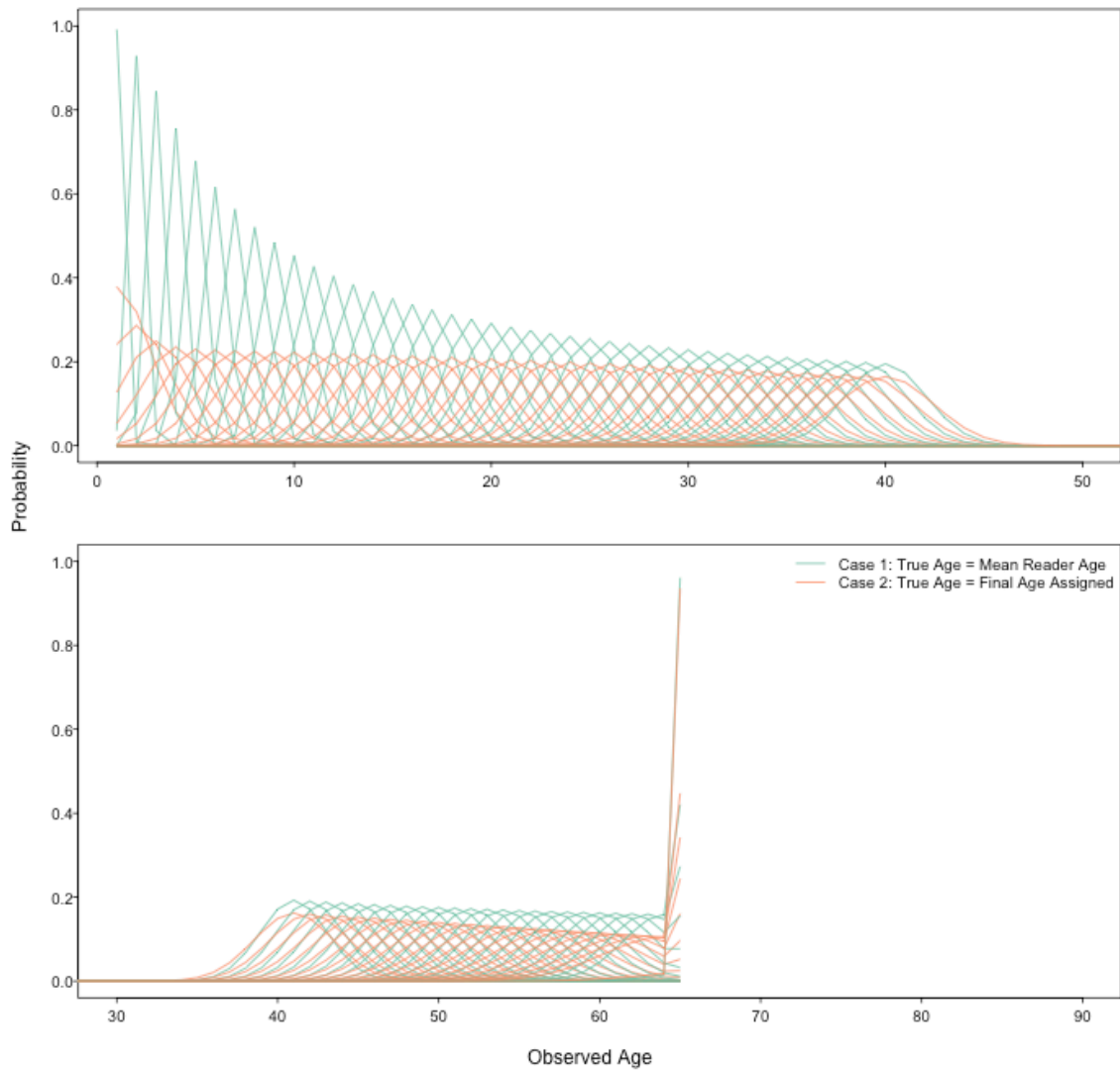
Figure B.17. Probability of observed ages given the true ages 1-40 (top) and 41-65+ (bottom) for both cases considered. Each curve represents probability distribution for one true age.
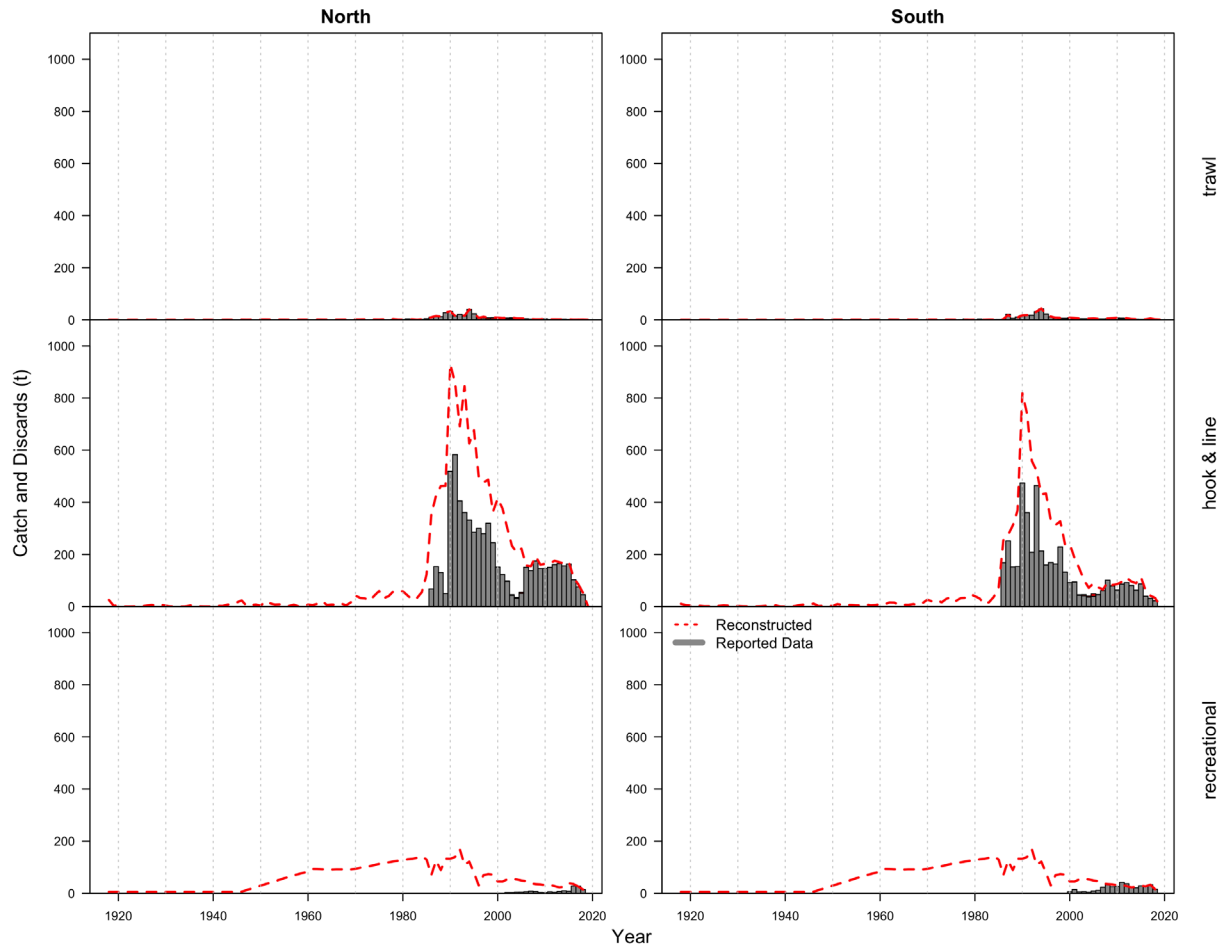
Figure B.18. Time series of reconstructed and reported catch data from 1918-2018 for trawl, hook and line, and recreational fleets.
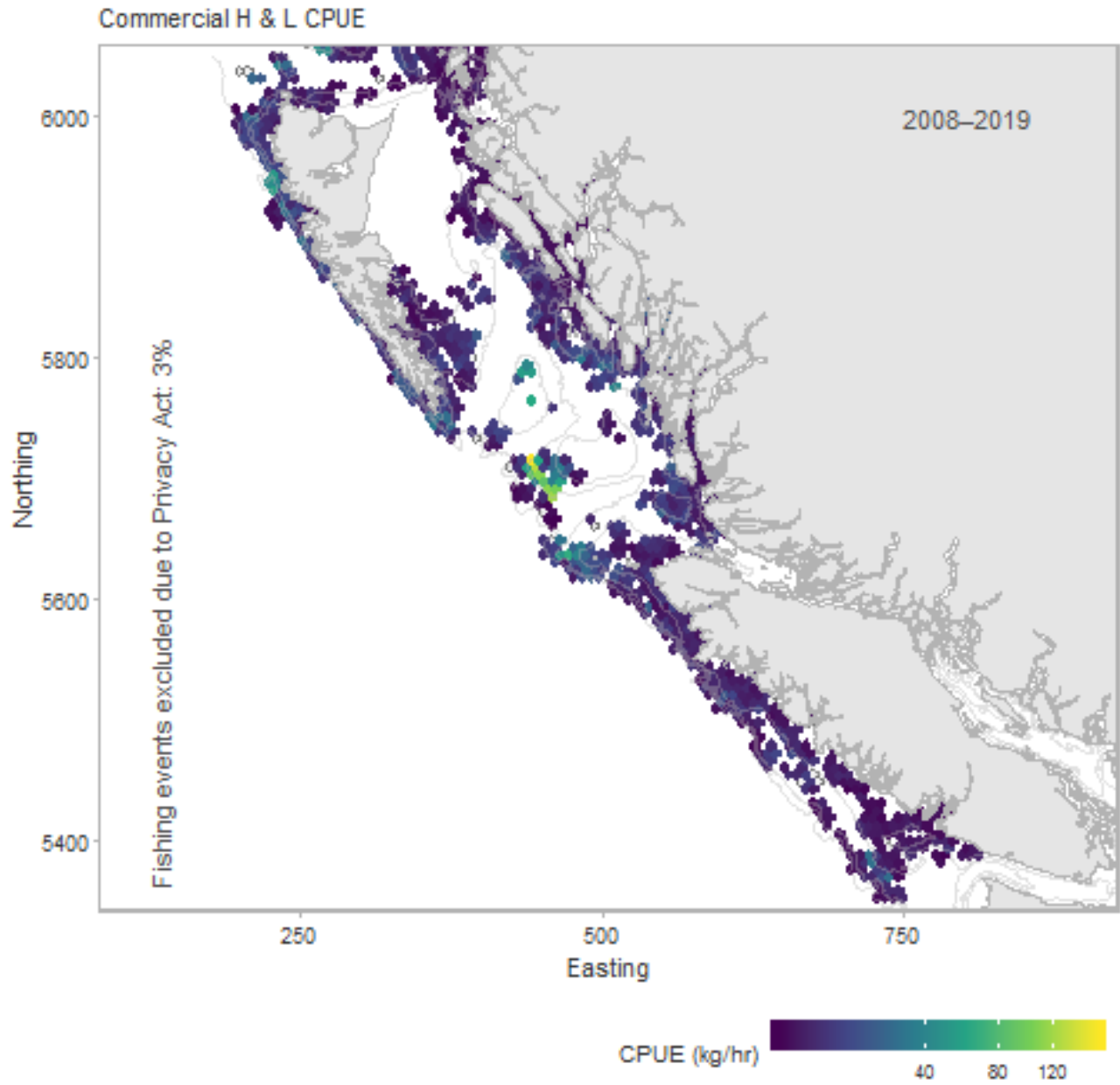
Figure B.19. Spatial distribution of Yelloweye Rockfish CPUE (kg/hr) in BC from commercial hook and line fisheries from 2008-2019. Note that these maps are restricted to hexagons in which 3+ vessels were fishing in a given year in compliance with the Privacy Act. The empty hexagons represent areas fished with 3+ vessels prior to 2008 (hl).
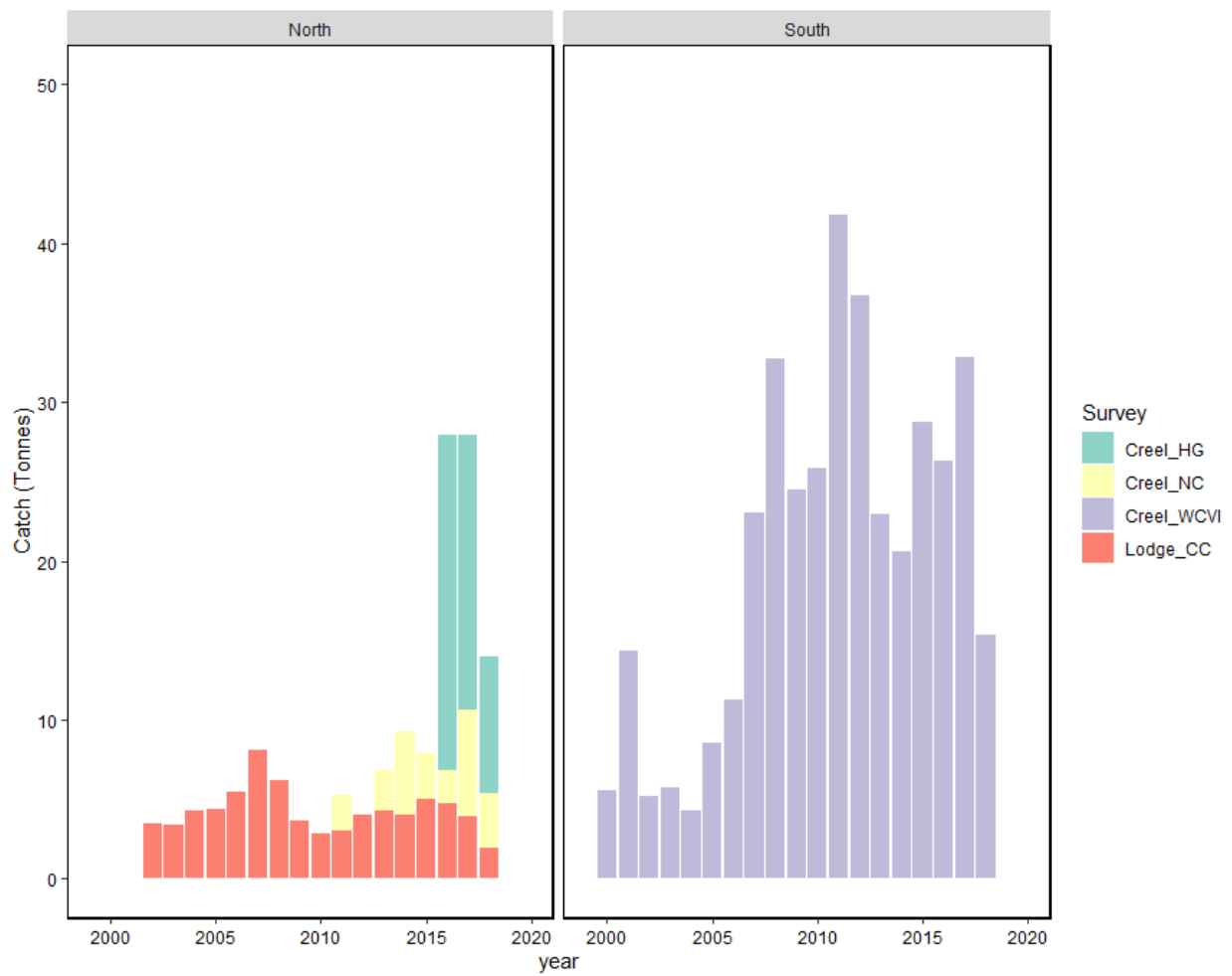
Figure B.20. Reported recreational data for creel surveys and lodge data for Haida Gwaii (HG), North Coast (NC), West Coast of Vancouver Island (WCVI), and Central Coast (CC).

B.6 APPENDIX B REFERENCES

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APPENDIX C. BASE OM SENSITIVITY ANALYSES AND AGE COMPOSITION FITS

This appendix describes base OM sensitivity analyses for data inputs in Table C.1 and sensitivity of key biological and management parameters (Table C.2). Age composition fits for the base OM for each year and fleet are provided in Figures C.1-C.7.

Table C.1. Data scenarios for sensitivity analyses on base OM

Data Inputs	Base OM data input	Sensitivity Analyses	
		Data input change	Sensitivity Scenario Name
IPHC Survey			
age-at-50% selectivity	time-varying	constant over time	noTvSel
Predicted South index years	none	1998, 2000	predSouthIdx
Minimum number of years with YE catch at a station for inclusion in index	1 year	11 years	stnThresh11
Correction factor for years (1998-2002, 2013) with 20-24% hook observations	none	North = 1.05 South = 0.98	hook20Correction
Maturity			
Proportion mature-at-age for $a=1,…,8$	$m_a = 0$	$m_a = \left(1 + e^{-log19\frac{a-a_{50}^{mat}}{a_{95}^{mat}}}\right)^{-1}$	noMinMatAge
Selectivity			
Priors on age-at-95% selectivity (a_{95}^{sel}) selectivity	no prior	$a_{95}^{sel} = N(\bar{a}_{95}^{sel}, 0.25\bar{a}_{95}^{sel})$, where $\bar{a}_{95}^{sel} = (19,19,25,26,24)$ for trawl, hook and line, PHMA_N, PHMA_S, and IPHC	selPriorCV25
Age Compositions			
Standardized commercial longline age composition	non-standardized	standardized by area	stdAgeComps
Weighting for age-composition likelihoods	100%	25%	ageLikWt25
Senescence			
natural mortality (M_{sen}) for plus group (A=65+)	No M_{sen}	$M_{sen} = 0.08$ yr^{-1}	Msen08

Table C.2. Biological parameter and management reference point estimates for base OM sensitivity analyses. Biomass and MSY are in in kt.

OM scenario	Stock	Unfished Biomass (kt)	Natural Mortality (yr^{-1})	Recruitment Steepness (h)	Current Status				
					B_{MSY}	F_{MSY}	B_{2018}	B_{2018}/B_0	B_{2018}/B_{MSY}
baseOM	North	14.2	0.039	0.77	0.053	0.21	4.5	0.31	1.23
	South	10.8	0.038	0.77	0.052	0.16	3.3	0.30	1.18
noTvSel	North	14.8	0.039	0.73	0.048	0.21	5.3	0.36	1.32
	South	11.7	0.038	0.73	0.047	0.16	4.5	0.39	1.42
predSouthIdx	North	14.2	0.039	0.77	0.053	0.21	4.4	0.31	1.21
	South	10.7	0.038	0.77	0.051	0.16	3.1	0.29	1.11
stnThresh11	North	14.2	0.039	0.77	0.053	0.21	4.5	0.32	1.24
	South	10.8	0.038	0.77	0.052	0.16	3.2	0.30	1.17
hook20Correction	North	14.3	0.039	0.77	0.053	0.22	4.6	0.32	1.26
	South	10.8	0.038	0.77	0.052	0.16	3.3	0.30	1.18
noMinMatAge	North	14.3	0.039	0.77	0.054	0.22	4.6	0.32	1.24
	South	10.9	0.038	0.77	0.053	0.16	3.3	0.31	1.18
selPriorCV25	North	14.3	0.039	0.77	0.054	0.22	4.6	0.32	1.27
	South	10.9	0.038	0.77	0.052	0.16	3.3	0.31	1.20
stdAgeComps	North	14.1	0.039	0.77	0.053	0.21	4.4	0.31	1.22
	South	10.7	0.038	0.77	0.051	0.16	3.1	0.29	1.14
ageLikWt25	North	13.6	0.036	0.73	0.044	0.18	3.8	0.28	1.04
	South	9.8	0.035	0.73	0.043	0.13	1.8	0.19	0.69
Msen08	North	14.3	0.035	0.73	0.049	0.23	4.9	0.34	1.17
	South	11.0	0.035	0.73	0.048	0.17	3.9	0.35	1.20

PHMA_N
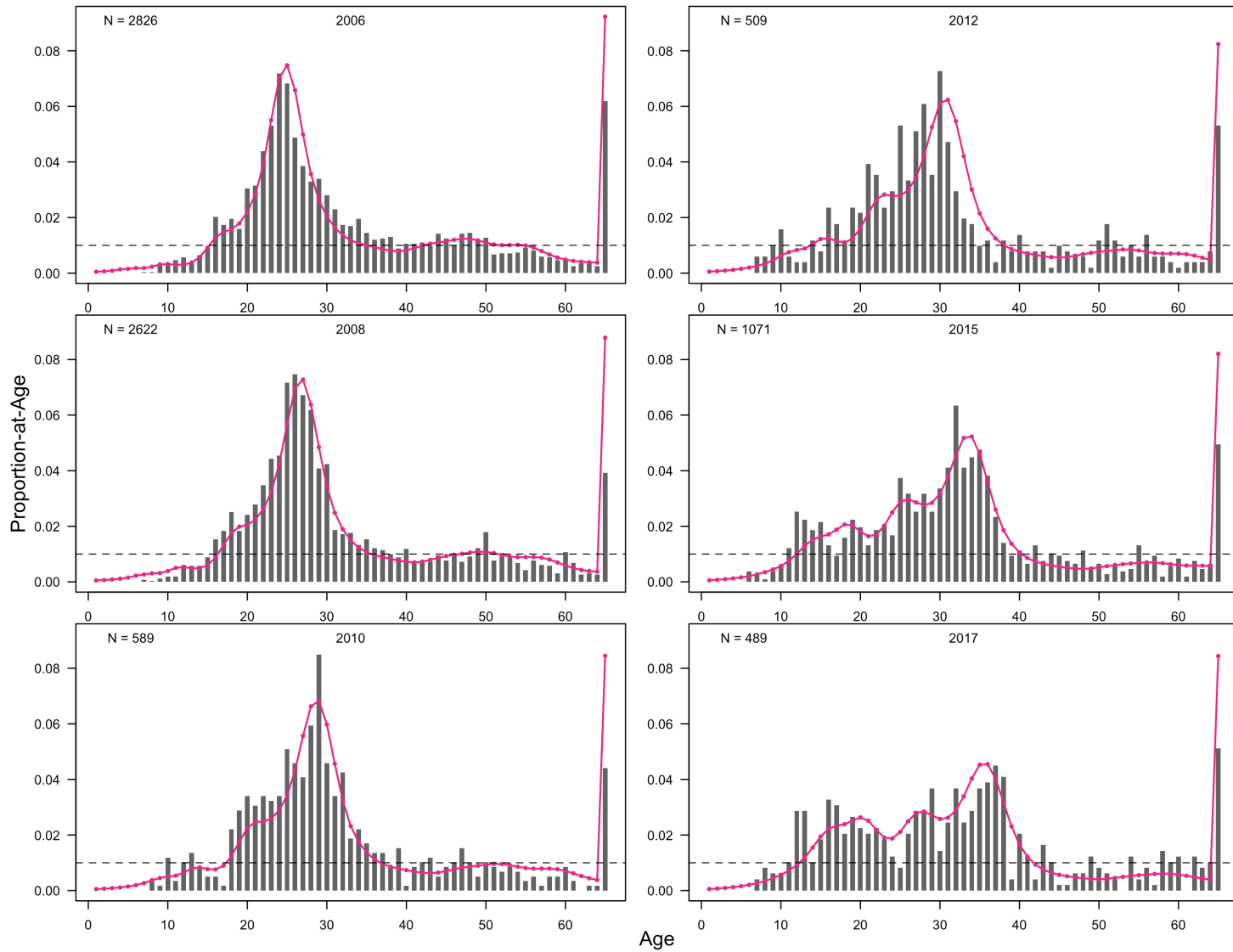
Figure C.1. Predicted (solid line) and observed (grey bars) age compositions for PHMA_N survey by year for North stock area

PHMA_S
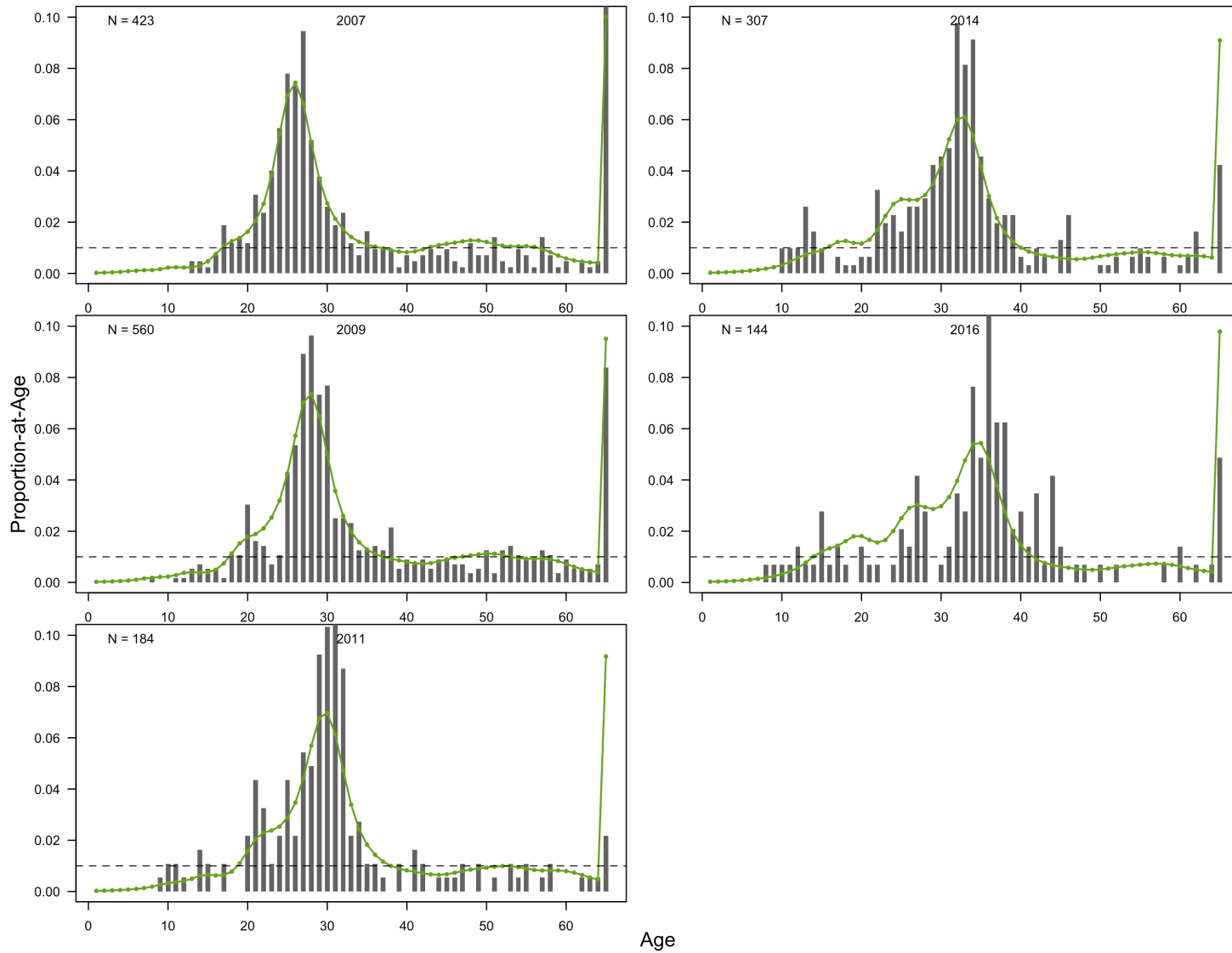
Figure C.2. Predicted (solid line) and observed (grey bars) age compositions for PHMA_QCS survey by year for North stock area
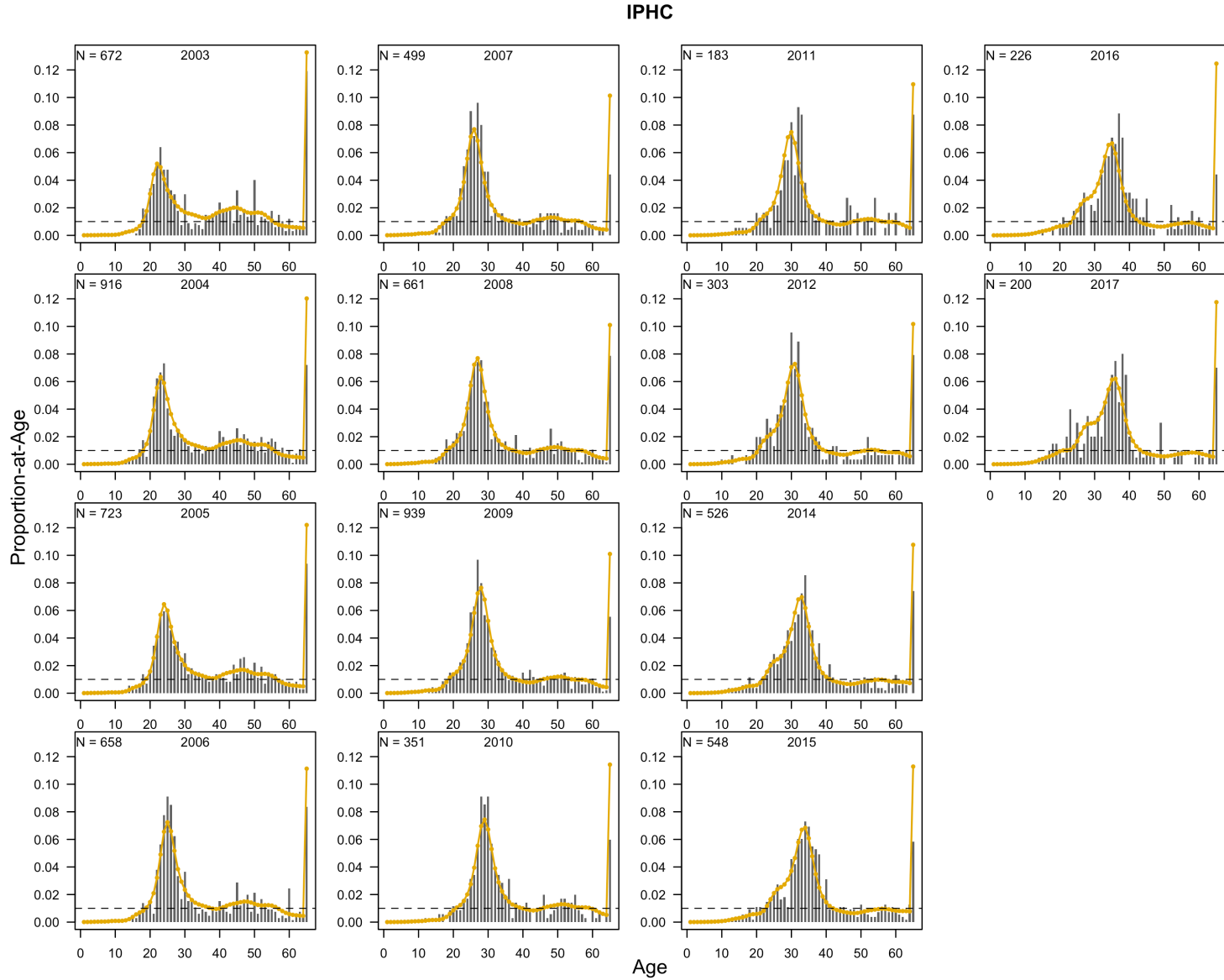
IPHC

Figure C.3. Predicted (solid line) and observed (grey bars) age compositions for IPHC survey by year for North stock area
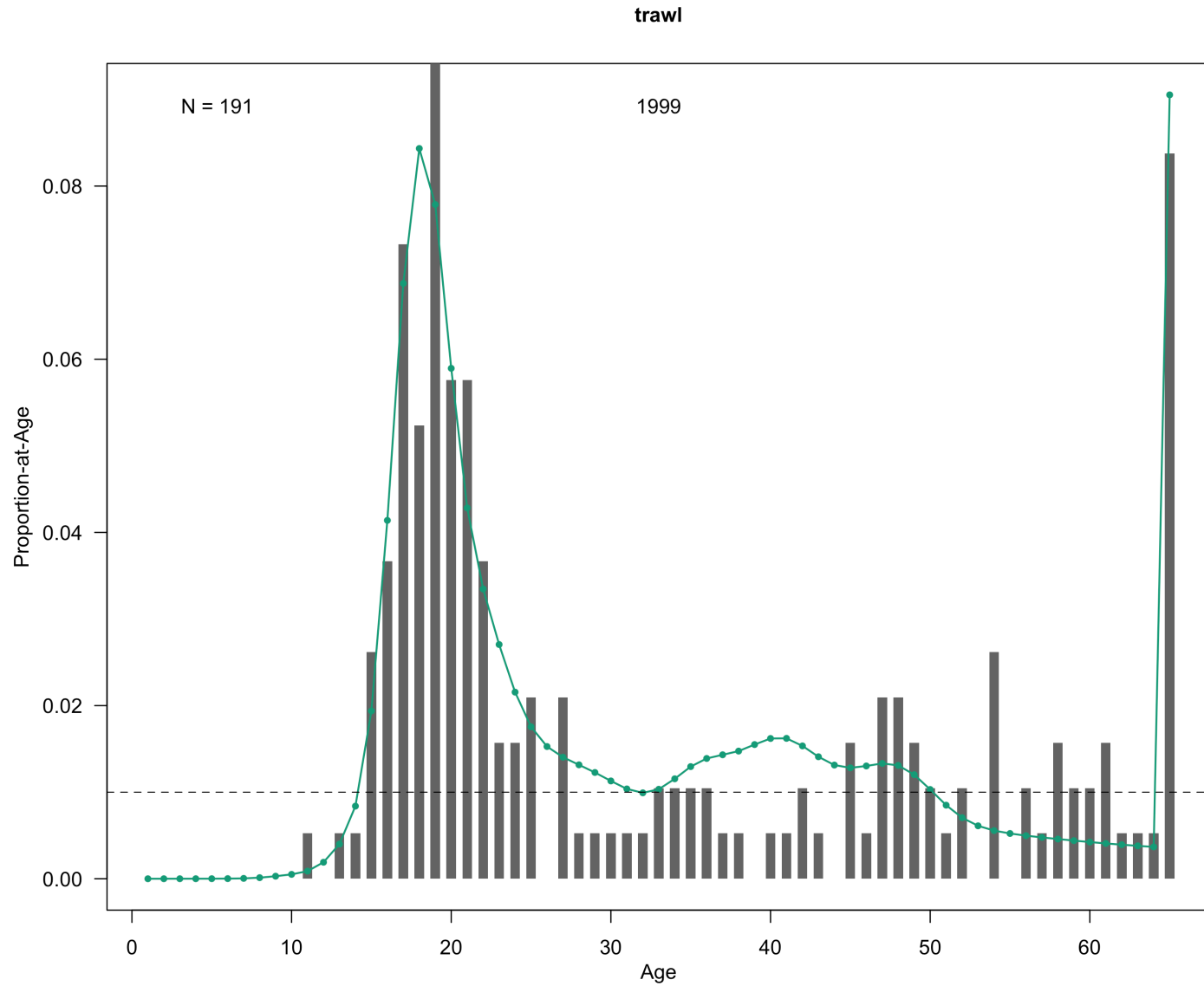
Figure C.4. Predicted (solid line) and observed (grey bars) age compositions by year for trawl fleet for North stock area
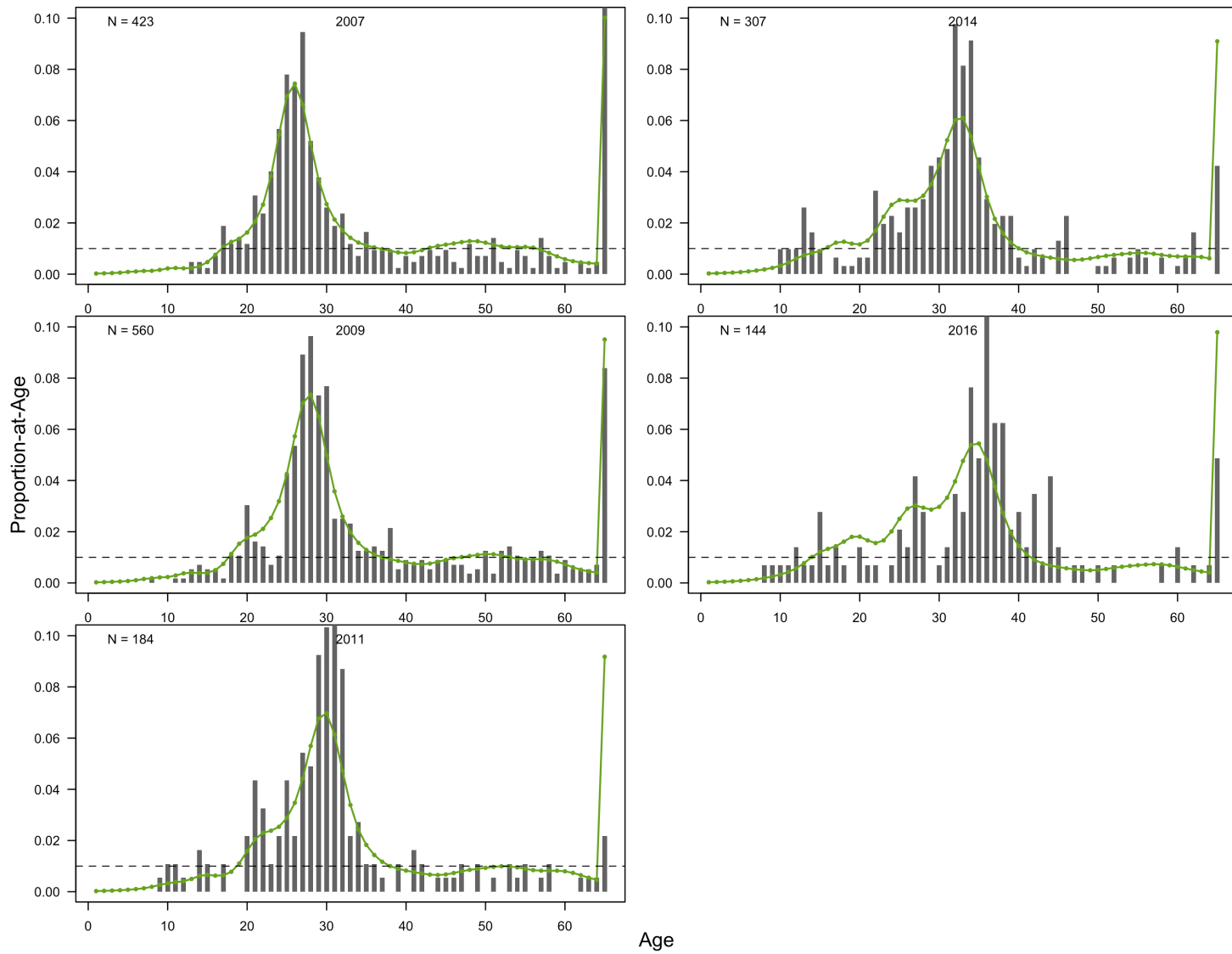
Figure C.5. Predicted (solid line) and observed (grey bars) age compositions by year for PHMA_S survey for South stock area
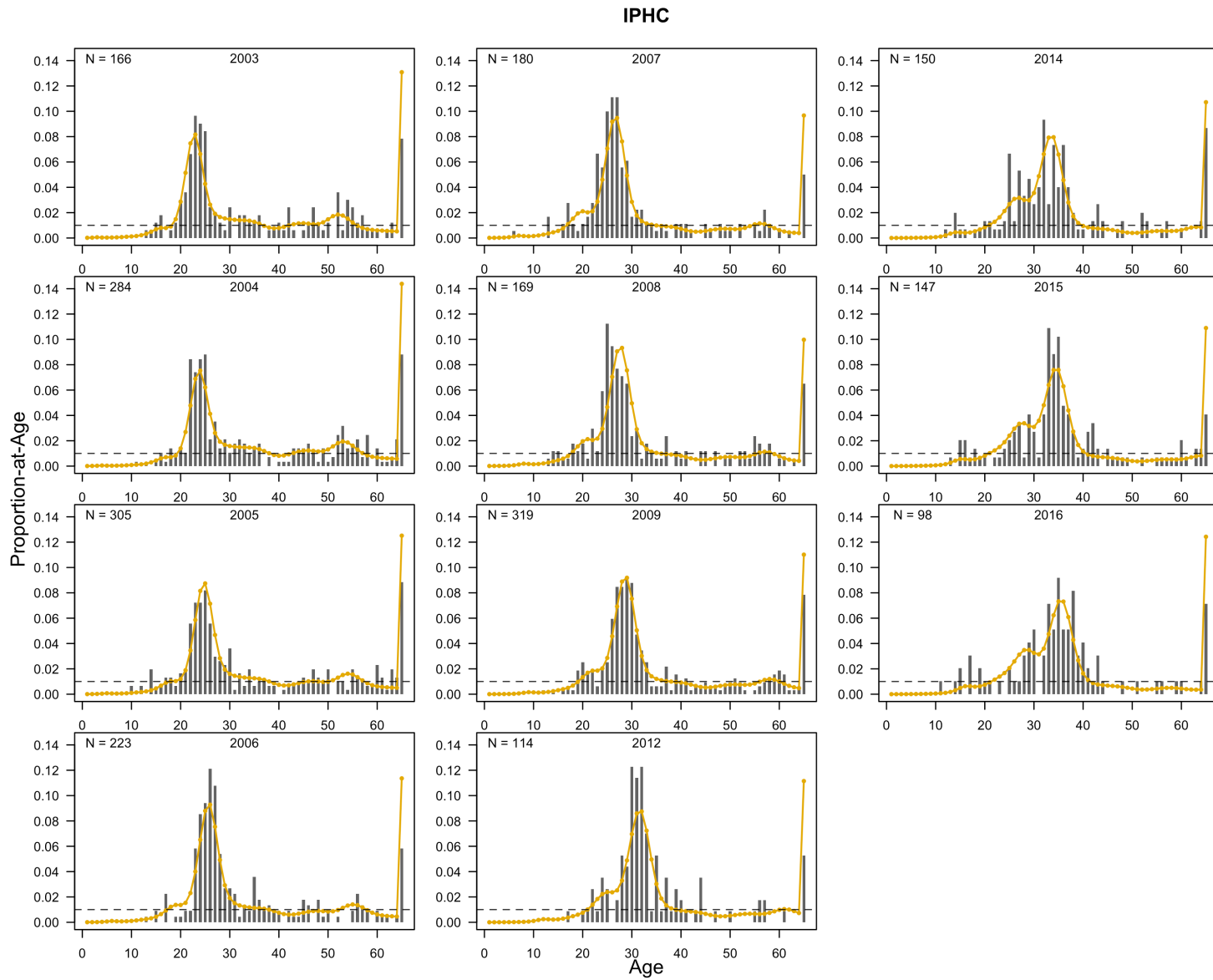
Figure C.6. Predicted (solid line) and observed (grey bars) age compositions by year for IPHC survey for South stock area

longline
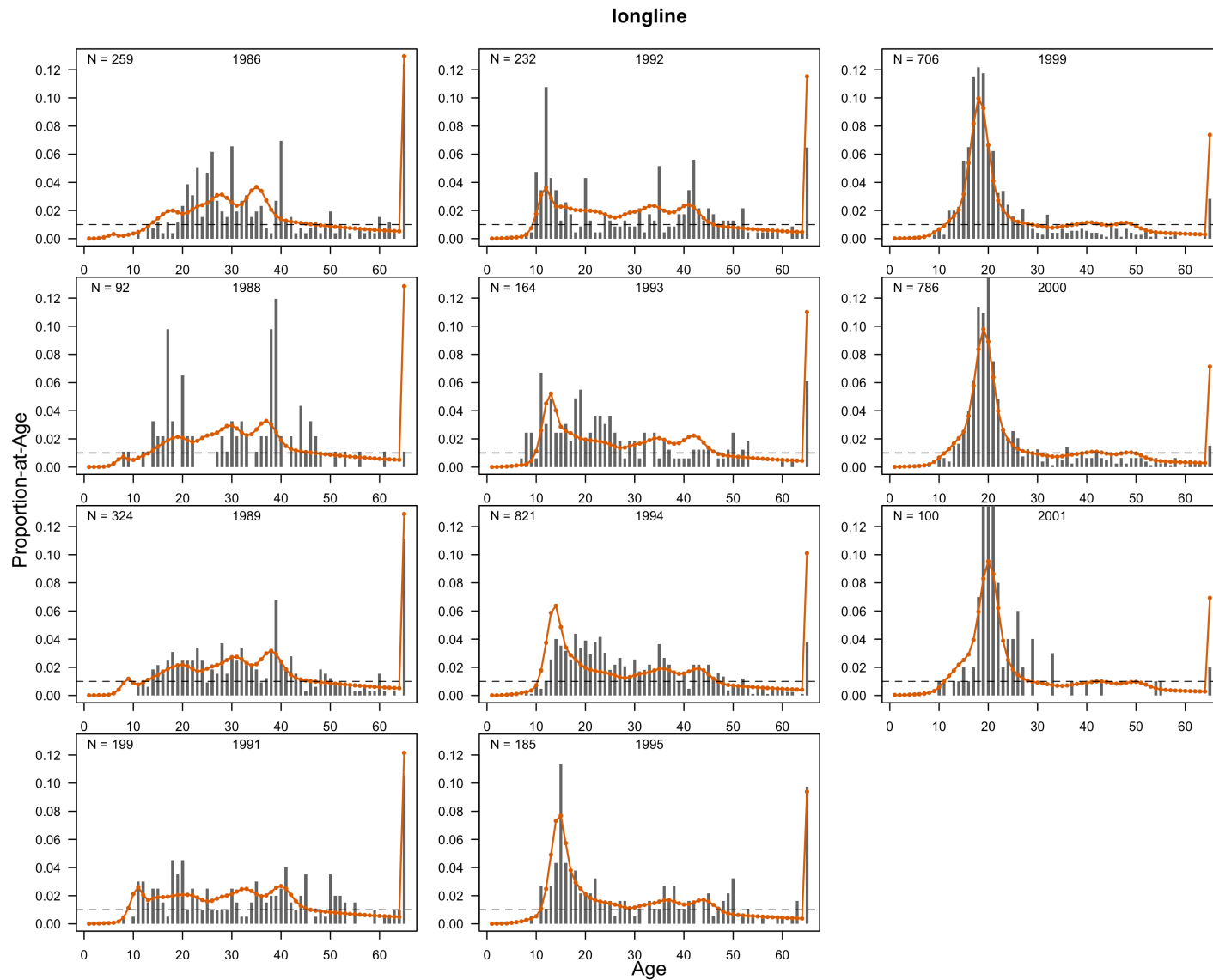
Figure C.7. Predicted (solid line) and observed (grey bars) age compositions by year for hook and line fleet for coastwide stock area

APPENDIX D. MP PERFORMANCE FOR INDIVIDUAL OPERATING MODELS

In this section, we present the performance metrics tables (Tables D.1-D.8) for all MPs tested for each of the 4 operating models in the north (base_North, om2_North, om3_North, om4_North) and south (base_South, om2_South, om3_South, om4_South). The projected distributions of SSB depletion and catch are shown for 5 of the selected MPs (sp, caa, caaSmuv, idx, idxSmuv) in Figures D.1-D.8.

*Table D.1. Management procedure performance for **base North** operating model.*

| MP | Conservation Objectives | | Other Performance Measures | | | | | | | |
| | 1 | 2 | Long-term depletion | | Short-term Catch (5 years) | | | Medium-term Catch (10 years) | | |
	$P(B_{2076}>LRP)$	$P(B_{2029}<B_{2020})$	B_{2076}/B_0	B_{2076}/B_{MSY}	P(>62t)	Median (t)	AAV	P(>62)	Median (t)	AAV
sp	1	0	0.54	1.93	0.23	47	40	0.38	58	36
sp_2xRec	1	0	0.51	1.79	0.28	51	42	0.42	64	39
caa	1	0.43	0.35	1.24	1	191	13	1	195	7
caa_Smuv	1	0.43	0.34	1.19	1	182	15	1	197	7
caa_2xFSC	1	0.54	0.34	1.20	1	200	13	1	203	7
caa_2xRec	1	0.69	0.31	1.11	1	217	14	1	220	8
idx	1	0.39	0.41	1.46	1	188	22	0.99	187	19
idxSmuv	1	0.14	0.33	1.16	1	162	16	1	167	12
idx_2xFSC	1	0.60	0.39	1.36	1	213	22	1	209	18
idx_2xRec	1	0.83	0.34	1.21	1	261	24	1	254	20
idx_2020	1	0	0.44	1.56	0.96	99	15	0.96	109	15
idx_dec100	1	0.39	0.41	1.46	1	188	22	0.99	187	19
idxFlr	1	0.39	0.41	1.46	1	188	22	1	187	19

*Table D.2. Management procedure performance for **om2 North** operating model.*

| MP | Conservation Objectives | | Other Performance Measures | | | | | | | |
| | 1 | 2 | Long-term depletion | | Short-term Catch (5 years) | | | Medium-term Catch (10 years) | | |
	$P(B_{2076}>LRP)$	$P(B_{2029}<B_{2020})$	B_{2076}/B_0	B_{2076}/B_{MSY}	$P(>62t)$	Median (t)	AAV	$P(>62t)$	Median (t)	AAV
sp	1	0	0.71	2.42	0.24	45	42	0.34	57	39
sp_2xRec	1	0	0.69	2.33	0.28	49	46	0.4	62	43
caa	1	0.46	0.53	1.81	1	191	13	1	195	7
caa_Smuv	1	0.46	0.52	1.76	1	181	15	1	196	7
caa_2xFSC	1	0.55	0.52	1.77	1	200	13	1	203	7
caa_2xRec	1	0.71	0.50	1.69	1	217	14	1	219	8
idx	1	0.40	0.58	1.97	1	192	20	1	196	18
idxSmuv	1	0.21	0.50	1.70	1	162	15	1	174	11
idx_2xFSC	1	0.67	0.55	1.87	1	216	19	1	222	18
idx_2xRec	1	0.92	0.50	1.70	1	266	22	1	274	20
idx_2020	1	0	0.62	2.11	0.97	99	13	0.96	108	15
idx_dec100	1	0.40	0.58	1.97	1	192	20	1	196	18
idxFlr	1	0.40	0.58	1.97	1	192	20	1	196	18

*Table D.3. Management procedure performance for **om3 North** operating model.*

MP	Conservation Objectives		Other Performance Measures							
	1	2	Long-term depletion		Short-term Catch (5 years)			Medium-term Catch (10 years)		
	$P(B_{2076}>LRP)$	$P(B_{2029}<B_{2020})$	B_{2076}/B_0	B_{2076}/B_{MSY}	$P(>62t)$	Median (t)	AAV	$P(>62t)$	Median (t)	AAV
sp	1	0	0.51	1.64	0.18	37	50	0.34	54	40
sp_2xRec	1	0	0.48	1.56	0.21	40	53	0.37	59	44
caa	1	0.15	0.33	1.08	1	189	13	1	193	7
caa_Smuv	1	0.14	0.32	1.04	1	181	15	1	194	7
caa_2xFSC	1	0.27	0.32	1.04	1	198	12	1	201	7
caa_2xRec	1	0.51	0.30	0.97	1	215	13	1	217	8
idx	1	0.23	0.37	1.20	1	190	20	1	194	18
idxSmuv	1	0.05	0.30	0.96	1	163	15	1	177	11
idx_2xFSC	1	0.52	0.35	1.11	1	214	19	1	219	18
idx_2xRec	1	0.90	0.31	0.99	1	263	21	1	265	20
idx_2020	1	0	0.41	1.33	0.96	96	13	0.97	107	14
idx_dec100	1	0.23	0.37	1.20	1	190	20	1	194	18
idxFlr	1	0.23	0.37	1.20	1	190	20	1	194	18

*Table D.4. Management procedure performance for **om4 North** operating model.*

| MP | Conservation Objectives | | Other Performance Measures | | | | | | | |
| | 1 | 2 | Long-term depletion | | Short-term Catch (5 years) | | | Medium-term Catch (10 years) | | |
	$P(B_{2076}>LRP)$	$P(B_{2029}<B_{2020})$	B_{2076}/B_0	B_{2076}/B_{MSY}	$P(>62t)$	Median (t)	AAV	$P(>62t)$	Median (t)	AAV
sp	1	0	0.44	1.51	0.11	33	57	0.19	42	47
sp_2xRec	1	0	0.42	1.46	0.14	35	62	0.24	45	50
caa	1	1	0.26	0.90	1	187	13	1	187	7
caa_Smuv	1	1	0.26	0.89	1	179	14	1	189	7
caa_2xFSC	1	1	0.25	0.88	1	196	12	1	194	7
caa_2xRec	1	1	0.25	0.86	1	212	13	1	209	8
idx	1	0.80	0.38	1.33	0.98	166	25	0.98	154	23
idxSmuv	1	0.88	0.19	0.66	1	159	17	1	157	13
idx_2xFSC	1	0.90	0.35	1.21	0.99	188	24	0.98	172	22
idx_2xRec	1	0.98	0.32	1.12	0.99	227	26	0.98	201	24
idx_2020	1	0.03	0.42	1.44	0.82	83	15	0.82	89	17
idx_dec100	1	0.80	0.38	1.33	0.98	166	25	0.98	154	23
idxFlr	1	0.81	0.35	1.21	0.99	166	25	0.98	154	23

*Table D.5. Management procedure performance for **base South** operating model.*

MP	Conservation Objectives		Other Performance Measures							
	1	2	Long-term depletion		Short-term Catch (5 years)			Medium-term Catch (10 years)		
	$P(B_{2076}>LRP)$	$P(B_{2029}<B_{2020})$	B_{2076}/B_0	B_{2076}/B_{MSY}	$P(>38t)$	Median (t)	AAV	$P(>38t)$	Median (t)	AAV
sp	1	0	0.46	1.63	0.47	40	32	0.69	60	29
sp_2xRec	1	0	0.39	1.36	0.53	47	42	0.73	73	36
caa	1	0.17	0.34	1.21	1	147	16	1	155	8
caa_Smuv	1	0.18	0.32	1.14	1	138	19	1	157	9
caa_2xFSC	1	0.31	0.33	1.15	1	155	15	1	163	8
caa_2xRec	1	0.76	0.27	0.96	1	188	18	1	195	10
idx	1	0.01	0.6	2.09	1	107	26	0.98	108	23
idxSmuv	1	0	0.5	1.76	1	100	19	1	106	14
idx_2xFSC	1	0.08	0.55	1.94	1	130	23	0.99	131	21
idx_2xRec	1	0.76	0.46	1.62	1	200	26	0.98	204	24
idx_2020	1	0	0.67	2.34	0.9	53	17	0.89	55	18
idx_dec100	1	0.01	0.6	2.09	1	107	26	0.98	108	23
idxFlr	1	0.01	0.57	1.99	1	107	26	1	108	23

*Table D.6. Management procedure performance for **om2 South** operating model.*

MP	Conservation Objectives		Other Performance Measures							
	1	2	Long-term depletion		Short-term Catch (5 years)			Medium-term Catch (10 years)		
	$P(B_{2076}>LRP)$	$P(B_{2029}<B_{2020})$	B_{2076}/B_0	B_{2076}/B_{MSY}	$P(>38t)$	Median (t)	AAV	$P(>38t)$	Median (t)	AAV
sp	1	0	0.53	1.77	0.46	39	34	0.61	53	32
sp_2xRec	1	0	0.47	1.56	0.53	47	43	0.67	64	39
caa	1	0.42	0.44	1.47	1	145	16	1	153	8
caa_Smuv	1	0.45	0.42	1.40	1	137	19	1	155	9
caa_2xFSC	1	0.57	0.42	1.41	1	154	15	1	161	8
caa_2xRec	1	0.97	0.37	1.24	1	186	18	1	193	10
idx	1	0.03	0.67	2.23	0.98	99	28	0.96	99	24
idxSmuv	1	0	0.57	1.90	1	99	19	1	104	14
idx_2xFSC	1	0.11	0.62	2.07	0.98	120	23	0.98	122	21
idx_2xRec	1	0.75	0.56	1.85	0.98	183	25	0.97	189	24
idx_2020	1	0	0.72	2.40	0.84	49	18	0.82	50	20
idx_dec100	1	0.03	0.67	2.23	0.98	99	28	0.96	99	24
idxFlr	1	0.03	0.64	2.11	1	99	28	1	99	24

*Table D.7. Management procedure performance for **om3 South** operating model.*

| MP | Conservation Objectives | | Other Performance Measures | | | | | | | |
| | 1 | 2 | Long-term depletion | | Short-term Catch (5 years) | | | Medium-term Catch (10 years) | | |
	$P(B_{2076}>LRP)$	$P(B_{2029}<B_{2020})$	B_{2076}/B_0	B_{2076}/B_{MSY}	$P(>38t)$	Median (t)	AAV	$P(>38t)$	Median (t)	AAV
sp	1	0	0.32	1.01	0.45	38	32	0.66	56	30
sp_2xRec	1	0	0.25	0.78	0.5	44	42	0.69	68	36
caa	1	0.77	0.2	0.62	1	145	16	1	153	8
caa_Smuv	1	0.81	0.18	0.56	1	137	19	1	156	9
caa_2xFSC	1	0.96	0.18	0.56	1	154	15	1	161	8
caa_2xRec	1	1	0.14	0.45	1	186	18	1	192	10
idx	1	0.06	0.42	1.33	0.99	101	26	0.98	103	24
idxSmuv	1	0	0.33	1.05	1	100	18	1	106	14
idx_2xFSC	1	0.26	0.37	1.16	0.99	122	22	0.99	126	21
idx_2xRec	1	0.88	0.29	0.92	0.99	185	24	0.98	187	25
idx_2020	1	0	0.51	1.62	0.88	50	18	0.87	53	19
idx_dec100	1	0.06	0.42	1.33	0.99	101	26	0.98	103	24
idxFlr	1	0.06	0.4	1.26	1	101	26	1	103	24

*Table D.8. Management procedure performance for **om4 South** operating model.*

| MP	Conservation Objectives		Other Performance Measures							
	1	2	Long-term depletion		Short-term Catch (5 years)			Medium-term Catch (10 years)		
	$P(B_{2076}>LRP)$	$P(B_{2029}<B_{2020})$	B_{2076}/B_0	B_{2076}/B_{MSY}	$P(>38t)$	Median (t)	AAV	$P(>38t)$	Median (t)	AAV
sp	1	0	0.30	1.02	0.32	31	38	0.56	49	32
sp_2xRec	1	0	0.24	0.82	0.39	35	46	0.62	58	39
caa	1	1	0.20	0.68	1	145	16	1	150	8
caa_Smuv	1	1	0.19	0.66	1	137	18	1	152	9
caa_2xFSC	1	1	0.19	0.64	1	153	15	1	158	8
caa_2xRec	1	1	0.18	0.60	1	185	17	1	188	10
idx	1	0.17	0.45	1.54	1	98	27	0.99	96	22
idxSmuv	1	0.17	0.32	1.11	1	98	19	1	102	14
idx_2xFSC	1	0.54	0.39	1.33	1	119	24	0.99	116	21
idx_2xRec	1	0.96	0.31	1.06	1	177	25	0.98	172	25
idx_2020	1	0	0.54	1.86	0.85	48	18	0.85	50	17
idx_dec100	1	0.17	0.45	1.54	1	98	27	0.99	96	22
idxFlr	1	0.17	0.41	1.41	1	98	27	1	96	22
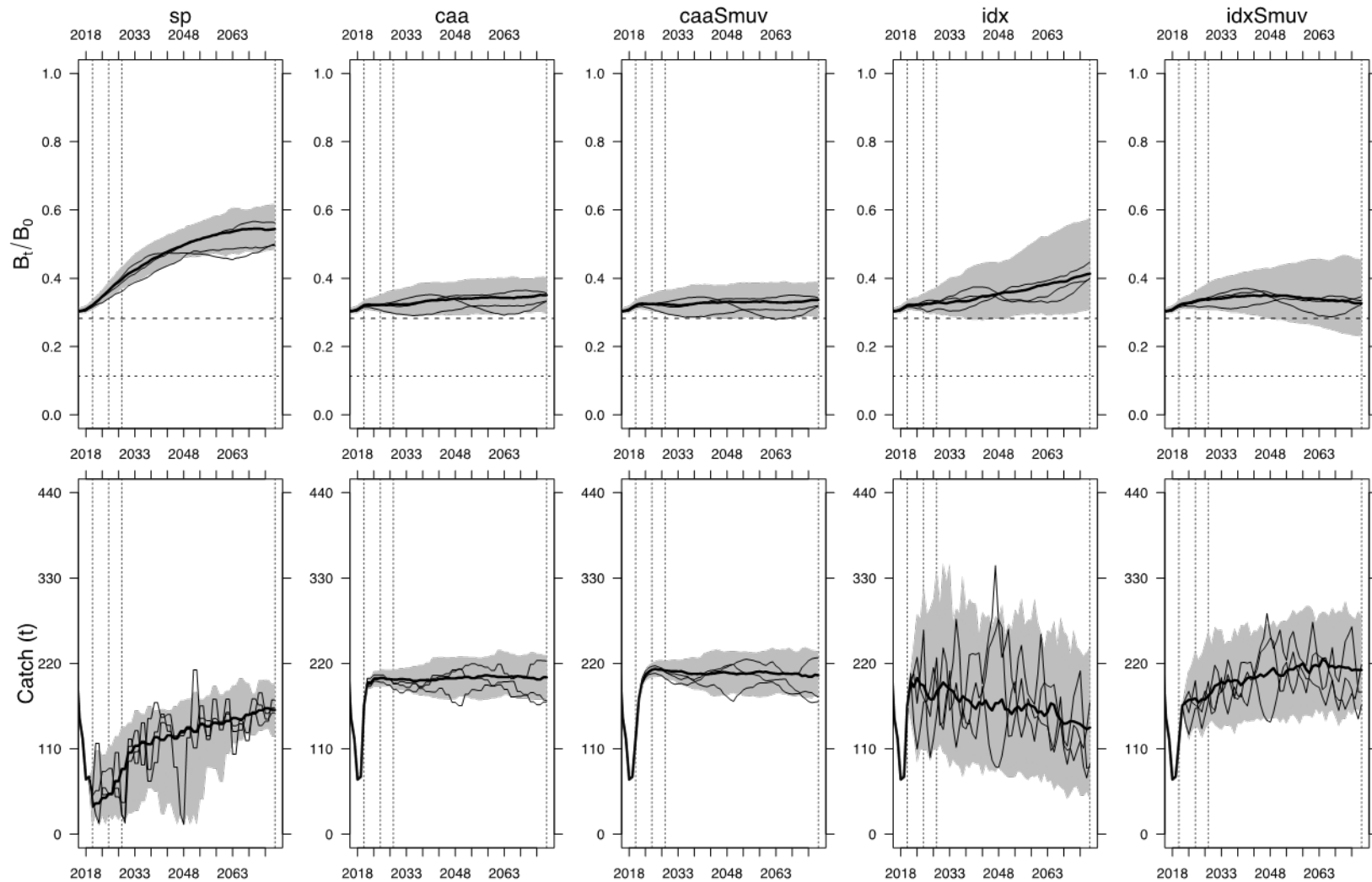
*Figure D.1. Projection distributions for operating model spawning biomass depletion (i.e., SB_t/SB_0) (top) and total Yelloweye mortality (bottom) from the simulated management procedures (sp, caa, caa_Smuv, idx, idxSmuv) for the **base North** operating model. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical grey lines indicate short-term (5 years), medium-term(10 years), and long-term (57 years) projection periods used to generate MP performance metrics.*
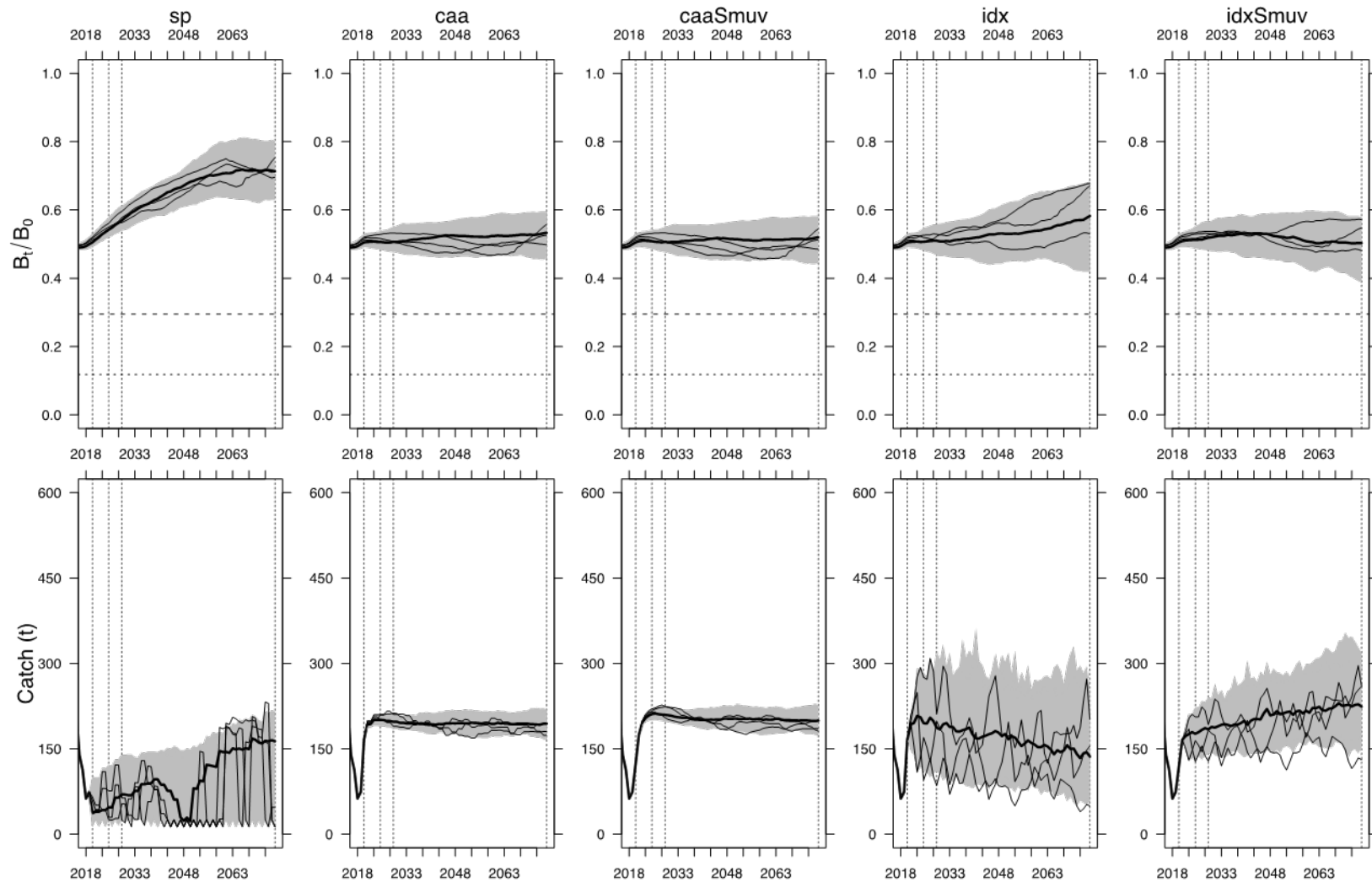
*Figure D.2. Projection distributions for operating model spawning biomass depletion (i.e., SB$_t$/SB$_0$) (top) and total Yelloweye mortality (bottom) from the simulated management procedures (sp, caa, caa_Smuv, idx, idxSmuv) for the **om2 North** operating model. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point of 0.4B$_{MSY}$ (bottom, dotted line) and B$_{MSY}$ (top, dashed line). Vertical grey lines indicate short-term (5 years), medium-term(10 years), and long-term (57 years) projection periods used to generate MP performance metrics.*
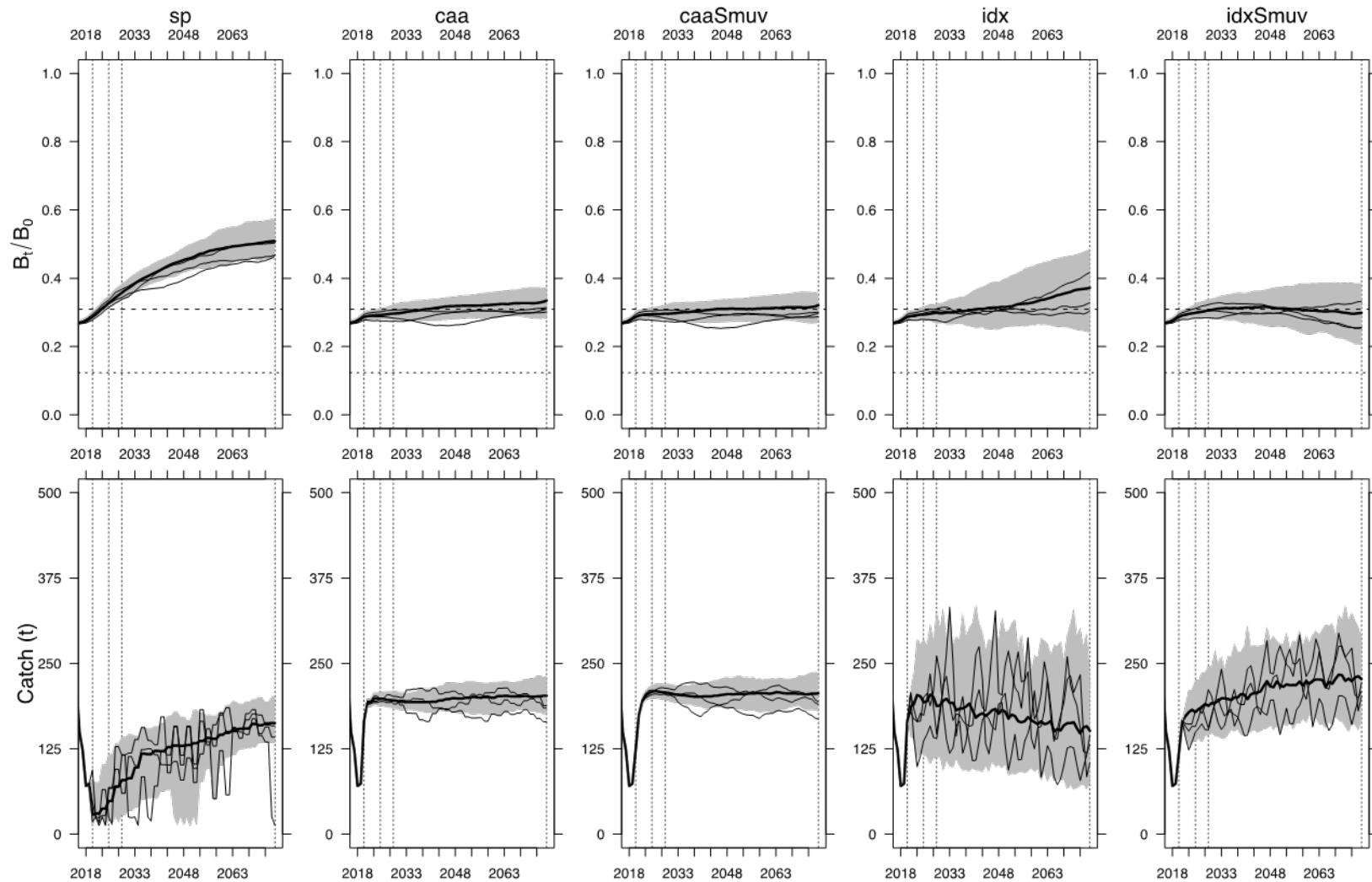
*Figure D.3. Projection distributions for operating model spawning biomass depletion (i.e., SB$_t$/SB$_0$) (top) and total Yelloweye mortality (bottom) from the simulated management procedures (sp, caa, caa_Smuv, idx, idxSmuv) for the **om3 North** operating model. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point of 0.4B$_{MSY}$ (bottom, dotted line) and B$_{MSY}$ (top, dashed line). Vertical grey lines indicate short-term (5 years), medium-term (10 years), and long-term (57 years) projection periods used to generate MP performance metrics.*
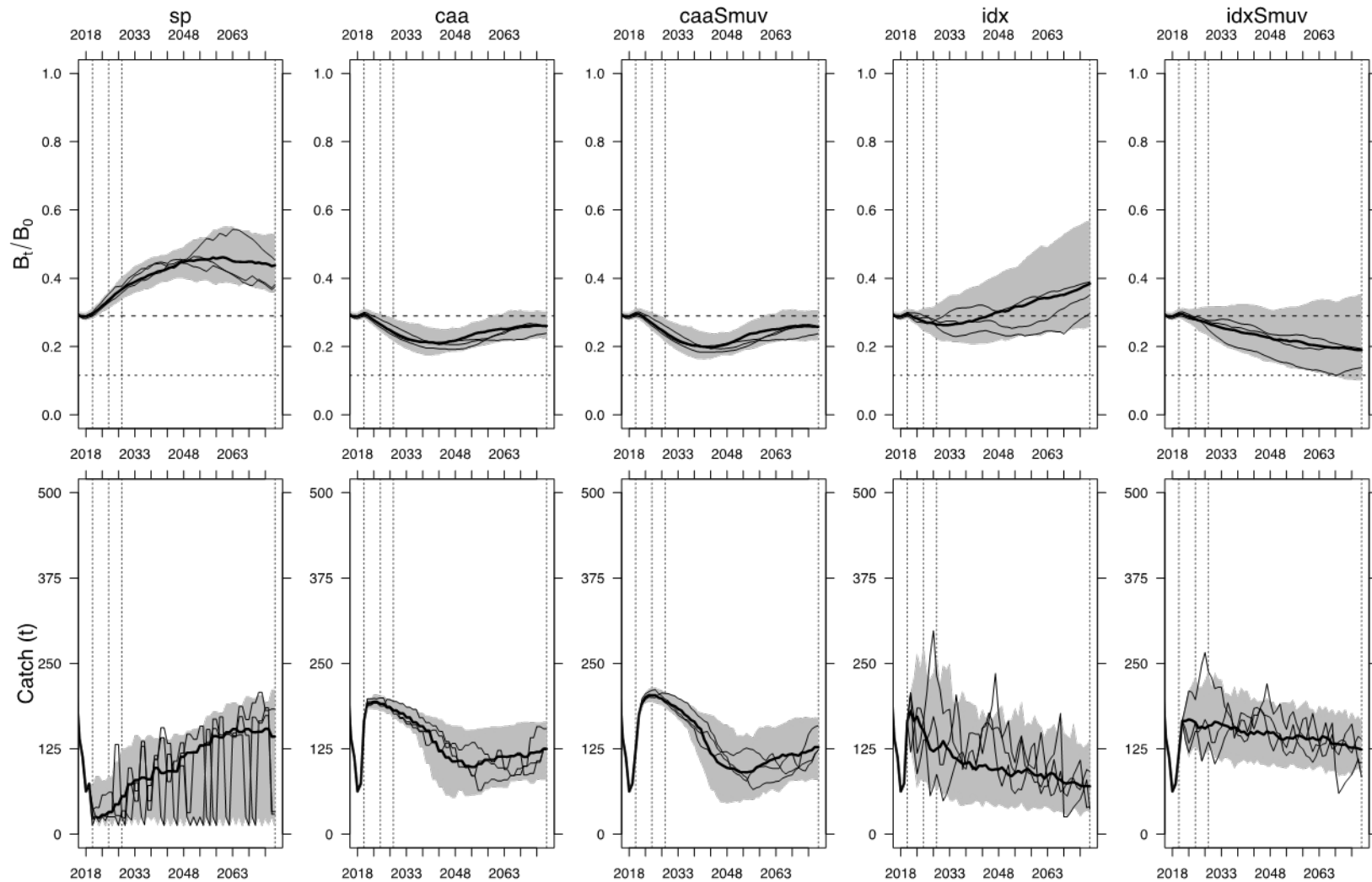
*Figure D.4. Projection distributions for operating model spawning biomass depletion (i.e., SB_t/SB_0) (top) and total Yelloweye mortality (bottom) from the simulated management procedures (sp, caa, caa_Smuv, idx, idxSmuv) for the **om4 North** operating model. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point of 0.4B_MSY (bottom, dotted line) and B_MSY (top, dashed line). Vertical grey lines indicate short-term (5 years), medium-term (10 years), and long-term (57 years) projection periods used to generate MP performance metrics.*
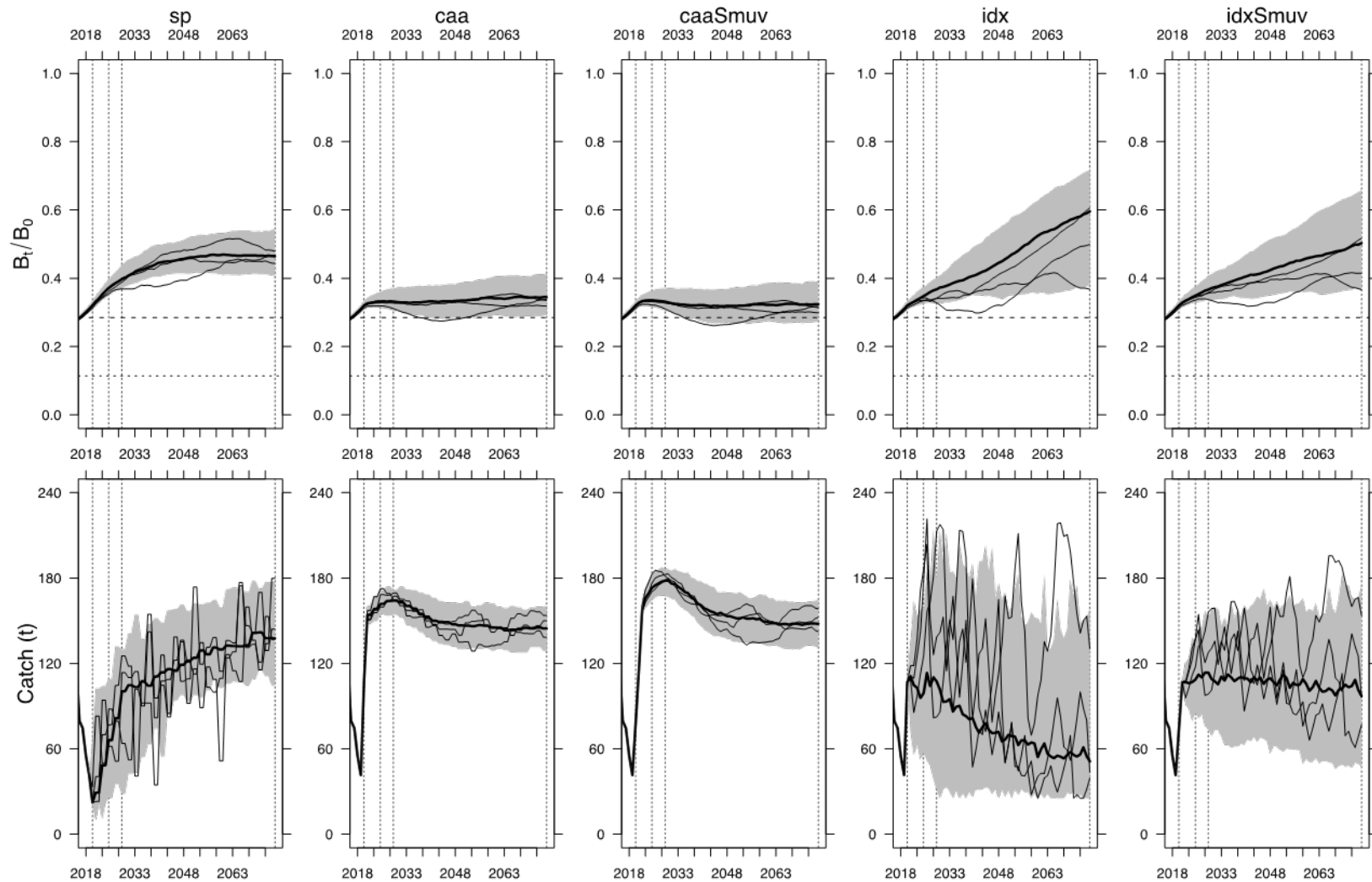
*Figure D.5. Projection distributions for operating model spawning biomass depletion (i.e., SB_t/SB_0) (top) and total Yelloweye mortality (bottom) from the simulated management procedures (sp, caa, caa_Smuv, idx, idxSmuv) for the **base South** operating model. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical grey lines indicate short-term (5 years), medium-term (10 years), and long-term (57 years) projection periods used to generate MP performance metrics.*
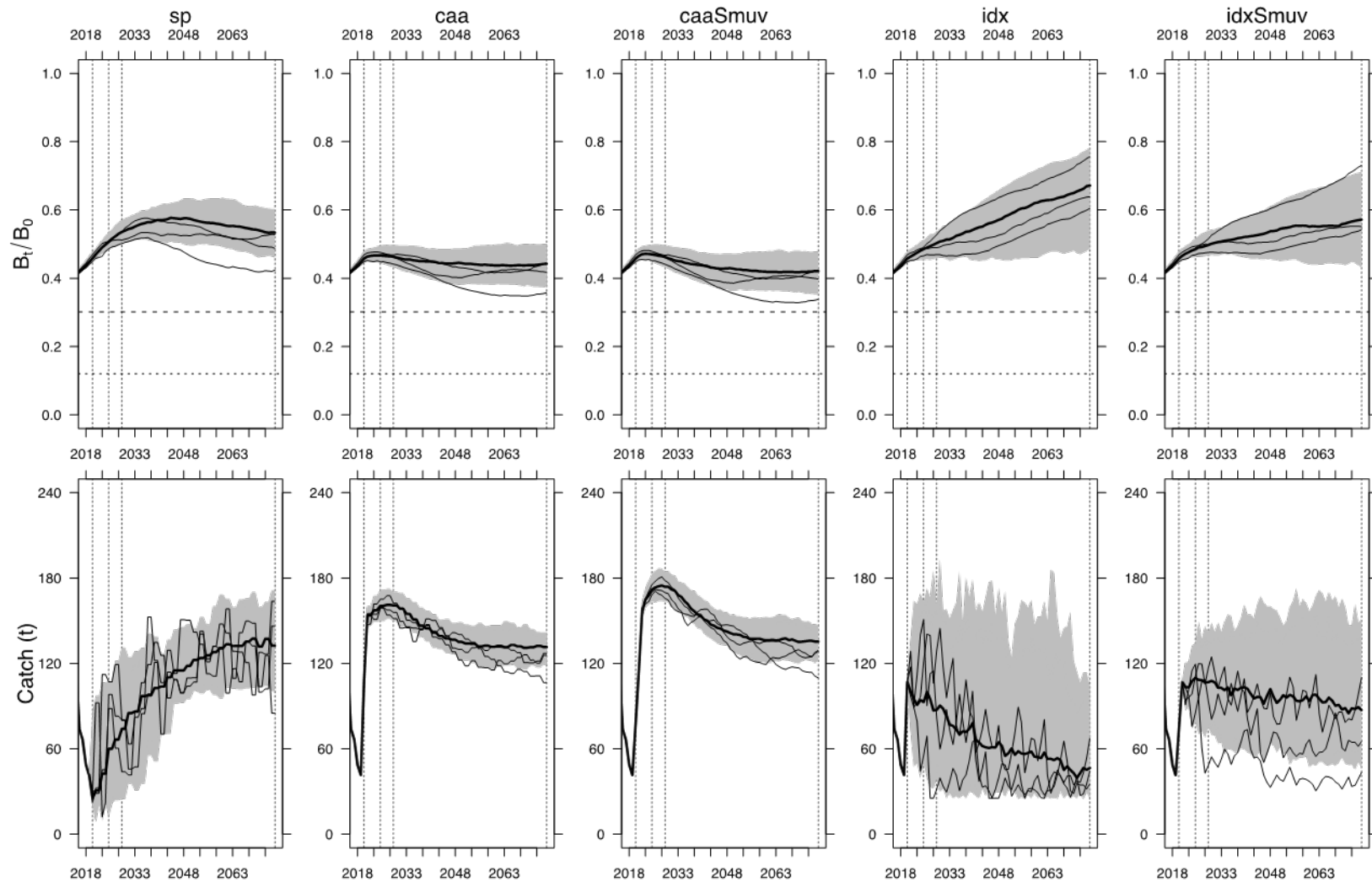
*Figure D.6. Projection distributions for operating model spawning biomass depletion (i.e., SB_t/SB_0) (top) and total Yelloweye mortality (bottom) from the simulated management procedures (sp, caa, caa_Smuv, idx, idxSmuv) for the **om2 South** operating model. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical grey lines indicate short-term (5 years), medium-term (10 years), and long-term (57 years) projection periods used to generate MP performance metrics.*

*Figure D.7. Projection distributions for operating model spawning biomass depletion (i.e., SB_t/SB_0) (top) and total Yelloweye mortality (bottom) from the simulated management procedures (sp, caa, caa_Smuv, idx, idxSmuv) for the **om3 South** operating model. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point of 0.4B_{MSY} (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical grey lines indicate short-term (5 years), medium-term (10 years), and long-term (57 years) projection periods used to generate MP performance metrics.*
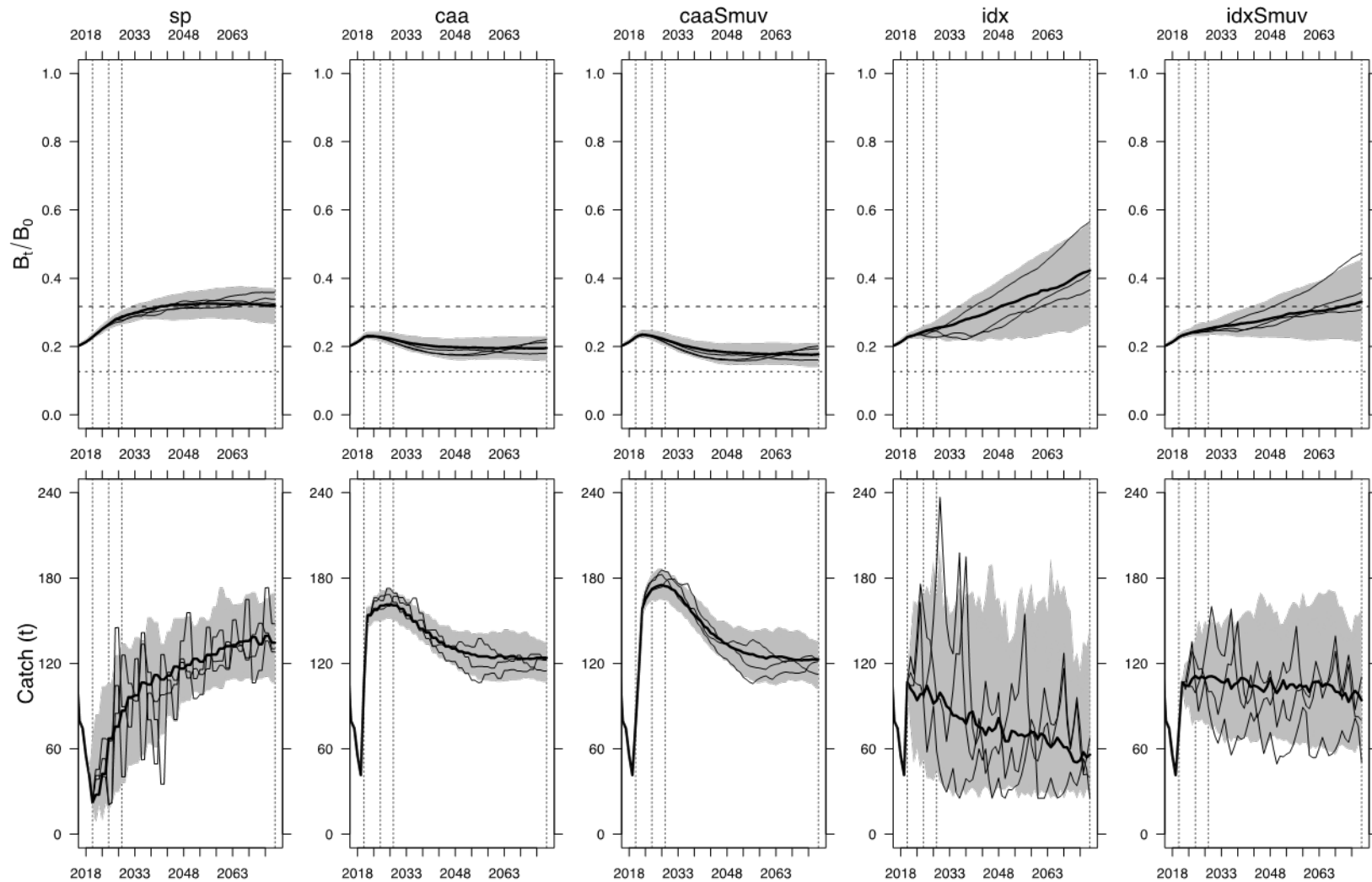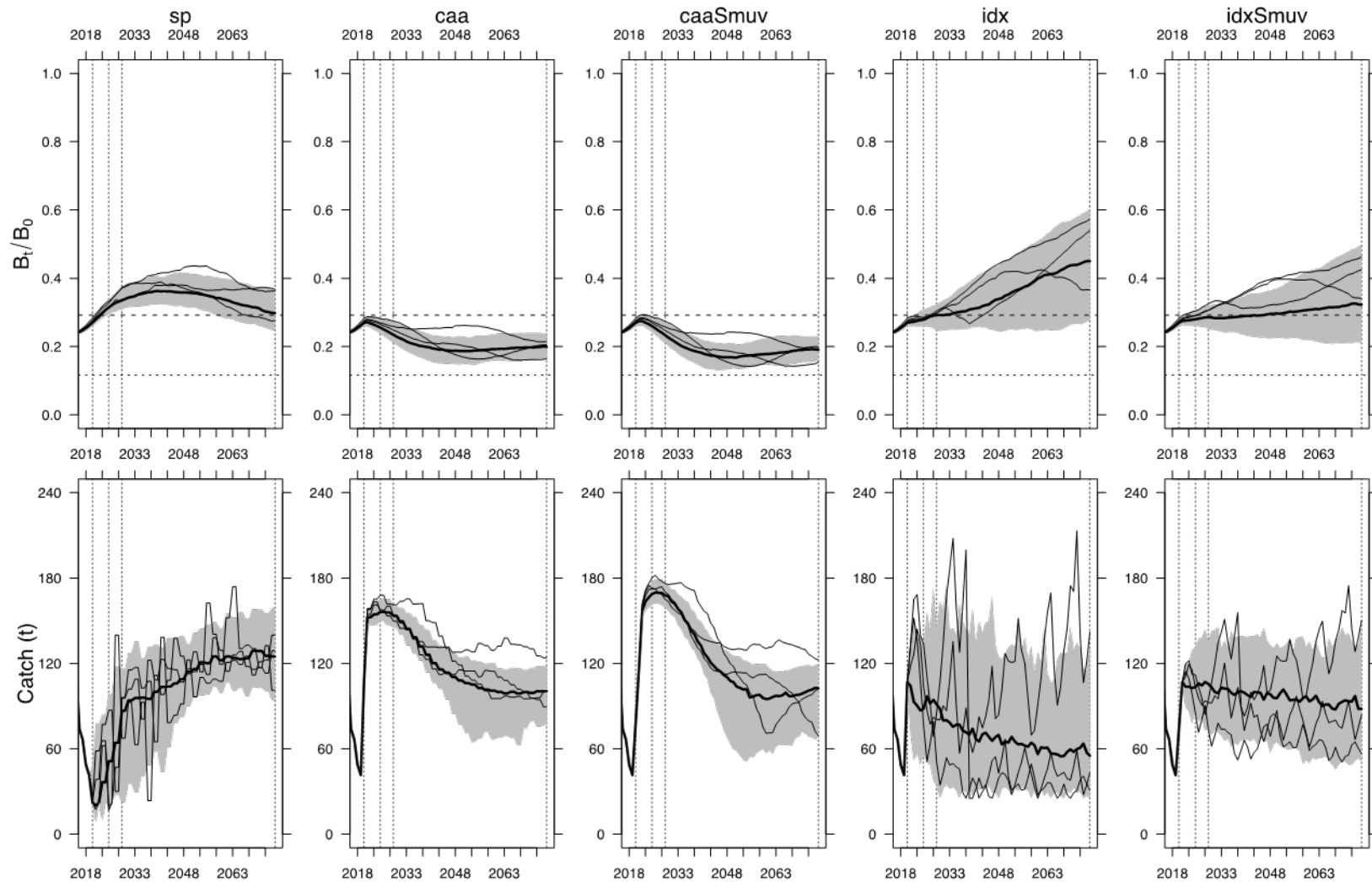
*Figure D.8. Projection distributions for operating model spawning biomass depletion (i.e., SB_t/SB_0) (top) and total Yelloweye mortality (bottom) from the simulated management procedures (sp, caa, caa_Smuv, idx, idxSmuv) for the **om4 South** operating model. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point of 0.4B_{MSY} (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical grey lines indicate short-term (5 years), medium-term (10 years), and long-term (57 years) projection periods used to generate MP performance metrics.*

APPENDIX E. MAJOR MANAGEMENT CHANGES AND QUOTA FOR BC GROUNDFISH FISHERIES (COASTWIDE AND OUTSIDE)

Table E.1. Chronology of British Columbia inshore rockfish outside and coastwide fishery management actions– updated from Yamanaka and Logan (2010). **Asterisks denote management milestones.** *(TAC = total allowable catch; RCA = rockfish conservation area)*

Year	Area	Management action
<1986	Coastwide	Unrestricted fishery
1986	Coastwide	Introduced a category ''ZN'' license* for the directed hook-and-line rockfish fishery with a voluntary logbook program
1990	Outside	Provisional 650-metric-ton quota
	Outside	Portions closed, area 7
	Outside	Jan 1 to Apr 30 closed west coast of Vancouver Island
1991	Coastwide	Area licensing, * 592 inside and 1,591 outside
	Outside	Rotational closure was initiated in area 7
	Coastwide	Limited-entry licensing program was announced
1993	Outside	Limited-entry licensing with 183 eligible outside licenses
	Coastwide	TAC quota management* for ''red snapper'' and ''other rockfish'' by five management regions
	Coastwide	Region/time closures
1994	Coastwide	User-pay logbook program
	Coastwide	Trip limits for trawl species
	Coastwide	Incidental catch allowances
1995	Coastwide	User-pay dockside monitoring program*
	Coastwide	Aggregate species quota management for yelloweye rockfish, quillback rockfish, copper rockfish, china rockfish, and tiger rockfish
	Coastwide	Monthly fishing periods, monthly fishing period limits, annual landing options, and annual trip limits
	Coastwide	Relinquishment of period limit overages
1996	Coastwide	Change to species quotas, * yelloweye rockfish TAC, aggregate 1&2 TAC (quillback rockfish, copper rockfish, china rockfish, and tiger rockfish)
1997	Coastwide	Initiate 5% quota allocation for research purposes
1998–1999	Outside	92% of commercial rockfish TAC allocated to the trawl sector, 8% to hook-and-line sector

Year	Area	Management action
1999–2000	Coastwide	10% at-sea observer coverage
1999–2000	Coastwide	Quillback rockfish, copper rockfish, china rockfish, tiger rockfish TAC reduced by 25%
	Coastwide	Selected area closures: rockfish protection areas, closed fishing areas to commercial groundfish hook-and-line gear types*
2000–2001	Coastwide	Allocation of rockfish species between the Pacific Halibut and hook-and-line sectors
2001–2002	Outside	License option elections before fishing season, monthly fishing period limits
2002–2003	Outside	50% reduction of inshore rockfish TAC from 1997–1998*
	Coastwide	Expansion of catch monitoring programs
	Coastwide	Introduced 1% interim areas of restricted fishing, closed to all commercial groundfish fisheries (both hook-and-line and trawl gear types)
2004–2005	Coastwide	RCAs expanded to 8% of rockfish habitats
2005–2006	Coastwide	Introduce groundfish license integration pilot program: 100% catch monitoring*
2006–2007	Outside	RCAs expanded to 15% of rockfish habitats
	Coastwide	Introduce groundfish integrated fishery management program*
	Outside	Yelloweye Rockfish TAC set at 284 tonnes for all commercial fisheries
2010	Outside	Implemented Gwaii Haanas National Marine Conservation Area (GHNMCA) interim management plan and zoning plan
2012	Coastwide	Introduce trawl fishery boundaries in consultation with industry*
2015-2016	Outside	Introduced Yelloweye Rockfish rebuilding plan: Yelloweye Rockfish TAC reduced by 39 %
2016-2017	Outside	Yelloweye Rockfish commercial TAC reduced to 173 tonnes*
2017	Outside	Implemented Hecate Strait/Queen Charlotte Strait Glass Sponge Reef Marine Protected Area which includes commercial closures
2017-2018	Outside	Yelloweye Rockfish commercial TAC reduced by 41%*
2018-19	Outside	Parks Canada implemented a management plan which includes strict protection zones closed to commercial fishing in GHNMAC. Two RCAs in GHNMCA rescinded.

Table E.2. Chronology of British Columbia inshore rockfish recreational fishery management and Yelloweye Rockfish-specific management actions for the Outside or Coastwide Areas.

Year	Area	Management action
1986	Coastwide	8 rockfish daily bag limit per person implemented.
	North (Haida Gwaii, North and Central Coast)	Inshore Rockfish Conservation Strategy - Daily limit reduced to 5 rockfish in Areas 1 to 10, 101 to 111 and 130 to 142. Yelloweye daily limit of 3.
	South Coast (WCVI)	Inshore Rockfish Conservation Strategy - Daily limit reduced to 3 rockfish in Areas 11, 21 to 27 and 121 to 127 and Subareas 20-1 to 20-4. Yelloweye daily limit of 2.
2002-2007	Coastwide	Rockfish Conservation Areas (RCAs) established - RCAs closed to fin fish harvest in recreational fishery.
2016	North (Haida Gwaii, North and Central Coast)	Outside Yelloweye Rebuilding Plan - Daily Yelloweye limit reduced to 2, all rockfish limit remains at 5 in Areas 1 to 10, 101 to 110 and 130 to 142.
	South Coast (WCVI)	Outside Yelloweye Rebuilding Plan - Daily Yelloweye limit reduced to 1, all rockfish limit remains at 3 in Areas 11, 21 to 27, 111, 121 to 127 and Subareas 20-1 to 20-4.
2017	North (Haida Gwaii, North and Central Coast)	Daily rockfish limit reduced to 3, Yelloweye limit remains at 2. Clearly defined closed times (November 16 to March 31).
	South Coast (WCVI)	Daily rockfish limit reduced to 2, Yelloweye limit remains at 1 in Areas 11, 21 to 27, 111, 121 to 127 and Subareas 20-1 to 20-4. Clearly defined closed times (November 16 to March 31).
2018	Outside	3 Rockfish daily, only 1 of which may be a China, Tiger or Quillback Rockfish; possession limits are twice the daily limit. 0 daily + possession limit for Yelloweye Rockfish and Bocaccio. Season length April 1 – November 15
2019	Coastwide	Condition of License: "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 F. MEMBERS OF THE STEERING COMMITTEE AND TECHNICAL TEAMS FOR THIS PROJECT

Name	Affiliation	Steering Committee	Technical Team
Dana Haggarty	Groundfish Section, Science Branch, DFO	X	X
Ashleen Benson	Landmark Fisheries	X	X
Sean Cox	Landmark Fisheries and Simon Fraser University		X
Beau Doherty	Landmark Fisheries		X
Rob Kronlund	Ecosystems Science Directorate, Fish Population Science, National Capital Region, DFO	X	X
Greg Workman	Groundfish Section, Science Branch, DFO	X	X
Adam Keizer	Groundfish Management Unit, Fisheries Management Branch, DFO	X	X
Shane Petersen	Groundfish Management Unit, Fisheries Management Branch, DFO		X
Chris Sporer	Pacific Halibut Management Association	X	X
Brian Mose	Deep Sea Trawlers Association		X
David Boyes	Pacific Halibut Management Association		X
Paul Grant	SARA Science Coordinator, Ecosystem Sciences Division, DFO	X	
Andy Edwards	Quantitative Assessment Methods, Science, DFO		X
John Holmes	Stock Assessment and Research Division (StAR), Science Branch, DFO	X	
John Candy	Center for Science Advice Pacific, DFO	X	
Lisa Christensen	Center for Science Advice Pacific, DFO	X	
Roger Kanno	Sustainable Fisheries Framework, Fisheries and Aquaculture Management, DFO	X	
Rhona Govender	SARA, Fisheries Resource Management, DFO	X	