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Stock Status and Management Procedure Performance for the BC Sablefish (*Anoplopoma fimbria*) Fishery for 2022/23

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Foreword

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

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ABSTRACT

The British Columbia Sablefish fishery has been managed using a simulation tested harvest strategy since 2011. The operating model used to generate simulated stock and fishery data is revised at intervals to reflect new data and hypotheses about the management system. We use this paper to detail the migration of the Sablefish operating model (SAB-OM) from the unsupported AD model builder (ADMB) language to the leading-edge Template Model Builder (TMB) language. We detail a rigorous transition and bridging analysis between 2018 and 2021 data and hypotheses, as well as testing against several sensitivities, including at-sea release model assumptions, age composition likelihood weightings, and leading parameter prior distributions. At the same time, we also transition the Schaefer production model used to estimate biomass and operational control points within the Sablefish management procedure (MP) from ADMB to TMB, and re-evaluate performance of the updated MP against operational fishery objectives.

Sablefish biomass, productivity, and stock status for 2022, estimated over an ensemble of five SAB-OM ‘reference set’ hypotheses, indicate that the stock is currently not overfished and not experiencing overfishing. The spawning biomass at the start of 2022 is approximately 132% of optimal biomass B_{MSY}, and the 2021 harvest rate is about 71% of U_{MSY}, with recent dynamics driven by three large incoming year classes. Estimates of recruitment deviations from the base SAB-OM hypothesis are compared to environmental indices, but no significant relationships are evident, indicating that a more in-depth research project may be required to determine if a link exists that would have implications for operating model formulation or management procedure design. Finally, all tested Sablefish MPs, including the status-quo MP with a 5.5% harvest rate, meet the biomass conservation and target objectives across the reference set of operating models, satisfying Canada’s precautionary approach harvest policy requirements for management by reference points.

1. INTRODUCTION

1.1. OVERVIEW OF THE SABLEFISH MANAGEMENT SYSTEM

Fisheries and Oceans Canada (DFO) and the British Columbia (BC) Sablefish (*Anoplopoma fimbria*) fishing industry collaborate on a management strategy evaluation (MSE) process intended to develop and implement a transparent and sustainable harvest strategy. The Sablefish management system (SMS) is an adaptive approach in which three pillars of science – hypotheses, empirical data, and simulation – play a role in defining management objectives and in assessing management performance relative to those objectives. Harvest strategy sustainability is determined by evaluating alternative management procedures (MPs) against operational fishery objectives when applied to simulated fishery data. Those data are generated by operating models (OMs) that represent a range of hypotheses about uncertain Sablefish stock and fishery dynamics. The primary output control tactic for the Sablefish fishery is an annual total allowable catch (TAC) which has been guided by a simulation-tested MP since 2011 (Cox et al. 2011; DFO 2011).

The stakeholder driven MSE approach attempts to capture the entire process that gives rise to a recommended catch limit. The purpose of testing is to check that applying the MP will not lead to major problems, even if key assumptions about the resource (e.g., biomass, productivity) and fishery (e.g., selectivity, discard monitoring precision) are incorrect. Thus, each OM must first reconstruct a stock history consistent with observed data and current perceptions about stock abundance and dynamics. Second, each OM must also project simulated stock and fishery monitoring data into the future that plausibly reflect stock and monitoring system responses to exploitation. Simulated conservation and yield outcomes derived from the projections over the mid- to long-term provide a basis for choosing between different management options. Short-term outcomes provide an indication of the immediate consequences of MP application including expected yields. The existing SMS is defined by the following four components:

1. Operational fishery objectives used to assess the acceptability of alternative management procedures.
2. A management procedure that involves:
    a. Data – total landed catch and three abundance indices,
    b. An assessment method – a tuned Schaefer state-space production model, and
    c. A recti-linear harvest control rule defined using B_{MSY} values estimated annually from the production model along with the estimated legal biomass and target fishing mortality rate. The latter is derived via tuning the MP to meet defined objectives.
3. A simulation test of MP performance against fishery objectives over operating models representing select hypotheses about Sablefish stock dynamics, and
4. Application and monitoring of the MP in practice.

In this paper, we revise the operating model used in component (3). Sablefish operating models are updated on a 4-5 year cycle to incorporate new data and hypotheses about Sablefish stock and fishery dynamics. Updated operating models are then used for simulation testing and choosing an MP that will be used to recommend an annual catch limit for the remainder of the cycle. A history of operating model development for BC Sablefish is described in Appendix A.

1.2. PURPOSE OF THIS PAPER

The primary purpose of this paper is to revise the Sablefish OM (SAB-OM) and update it with new data to the end of 2021. The revised model structure is able to address larger suite of possible data (e.g., length composition) and uncertainties affecting the Sablefish stock and fishery than considered previously. In addition, the new OM is implemented in Template Model Builder (TMB) (Kristensen et al. 2015), which has more efficient methods for non-linear optimization and integration with Bayesian posterior samplers compared to the original implementation in AD Model Builder (ADMB) (Fournier et al. 2012). For example, TMB takes advantage of modern compilers and architectures, as well as dealing with sparse derivative matrices that occur in highly parameterized fisheries stock assessment models. Thus, non-linear model convergence is often noticeably faster and more stable when using TMB. Furthermore, Bayes posteriors may be sampled faster via the adaptive Hamiltonian Monte Carlo process in comparison to the Metropolis-Hastings algorithm used by ADMB.

Throughout this paper, we refer to the two alternative models as the TMB and ADMB implementations since the two implementations are almost identical in their mathematical specifications and differ mainly in software implementation. Transitioning the OM from ADMB to TMB requires verifying that the two implementations produce very similar outcomes, while also clarifying the roles of data and model software platform on interpretation of stock status and reference points.

The revised OM also updates estimated Sablefish stock status to 2022. Since 2011, assessment and management of Sablefish has been closely aligned with the requirements of Canada's Fishery Decision-Making Framework Incorporating the Precautionary Approach ('DFO PA Policy') (DFO 2009; Cox et al. 2011; DFO 2014; Cox et al. 2016; Cox et al. 2019). Fishery reference points, which are a core requirement of the DFO PA Policy, include: a limit reference point (LRP), an upper stock reference (USR) point, and a maximum fishing mortality rate ("removal reference", RR). The PA Policy also includes a target reference point (TRP) which may coincide with the USR. In this paper, stock status in 2022 is characterized relative to these reference points using estimates derived from an ensemble model approach.

Sablefish have recently been prescribed as a major fish stock in Regulations under Canada's revised *Fisheries Act* (2019), meaning that there is a legal requirement to maintain Sablefish at levels necessary to promote sustainability. When the stock cannot be maintained at levels necessary to promote sustainability then an LRP must be identified and the stock maintained above the LRP. If the stock falls below the LRP, then there is a legal obligation to implement a rebuilding plan within 2 years. The updated estimates of stock status will be used to inform this requirement.

The revised *Fisheries Act* also states that the Minister shall consider the biology of the fish and the environmental conditions affecting the stock when implementing management measures. Therefore, we summarize and explore links between environmental conditions and Sablefish stock dynamics for consideration in future OM development.

The specific outcomes we aim to accomplish are as follows:

1. Develop a new Sablefish operating model with similar underlying population dynamics and data likelihoods to that of Cox et al. (2023) and implement in TMB.
2. Compare estimated population dynamics, biological reference points, and statistical properties between the original operating model implementation using ADMB and the new implementation in TMB. Throughout the paper, we refer to these comparisons as the *transition analysis*.

Additionally, we assess how estimates under the TMB implementation change over time as new data are added, in what we refer to as the *bridging analysis*.

3. Review plausible OM scenarios for Sablefish population and fishery dynamics, considering the sensitivity of model estimates to major axes of uncertainty. This involves evaluating the performance of new OM features such as the trawl length composition data likelihood, which hopefully improves estimates of size-selectivity and sub-legal fishing mortality in trawl fisheries. These changes should also improve estimates of Sablefish production lost to sub-legal release mortality.
4. Compare the performance of the current Sablefish MP implemented in ADMB to an identical procedure implemented in TMB, and re-tune the target harvest rate for the TMB implementation in response to updated OM productivity estimates.
5. Characterize the stock status of BC Sablefish using MSY-based biomass and fishing mortality reference points.
6. Survey the existing literature linking environmental variables (EVs) to Sablefish population dynamics to identify EVs that may affect BC Sablefish population dynamics and present data-based explorations of links between EVs and the BC Sablefish population. In addition, make recommendations about future research directions and assess the utility of incorporating hypotheses that consider environmentally-driven change into the Sablefish MSE process.

2. METHODS

This section details the revised TMB operating model specifications and closed loop simulation approach used for evaluating the relative performance of management procedures.

Data used to fit operating models are documented in Appendices A and B, while additional methods for the transition and bridging analyses are provided in Appendix C. OM diagnostics, including sensitivity analyses, are presented in Appendix D.

2.1. TWO SEX STATISTICAL CATCH-AT-AGE/LENGTH OPERATING MODEL

The Sablefish operating model presented in this paper (SAB-OM) is sex-/age-structured and fit to:

1. fishery-specific landed catch from three gear types (trap, longline hook, and trawl; 1965-2021),
2. three indices of total abundance and age-composition for the trap fishery (1979-2009) standardised survey (Std; 1990-2009), and stratified random survey (StRS; 2003-2021),
3. length compositions from the trawl fishery (1970-2019), and
4. at-sea releases (2006-2021) in each of commercial trap, longline hook, and trawl fisheries (Figure 1).

Mathematical notation, process model equations, and statistical model equations for the revised version of SAB-OM are given in Tables 1, 2, and 3, respectively.

Summaries of catch data and abundance indices used to fit operating models are provided in Appendix A and Appendix B respectively, while age composition data are shown in Figures 2 and 3.

Assumed biological parameters for length-at-age, weight-at-age, and age-at-maturity relationships are estimated outside of the operating model. These parameters were kept at the same values used in 2016 and 2019 (DFO 2020; Cox et al. 2023). Analyses and supporting information used to develop these estimates are well documented in Cox et al. (2023). Similarly, length-based selectivity estimates from tagging data and their associated prior distributions were last updated in 2019 (DFO 2020). We chose not to update biological and selectivity parameters for this operating model update given the focus on transitioning to TMB software. We recommend that these analyses be updated for the next scheduled OM update to ensure that the values used are still supported by recent data.

SAB-OM partitions the model parameters into four subsets, consisting of leading parameters (θ^{lead}), nuisance catchability and variance parameters estimated conditionally on the leading parameters (θ^{cond}), fixed parameters for growth, maturity, discard mortality rates, and some fixed observation model variance parameters (θ^{fixed}), and parameters specifying the prior distributions (θ^{prior}) for other model parameters. Parameter membership in the fixed and estimated sets differs from the base model for some of the model variations considered in the sensitivity analysis (Appendix D).

The OM is driven by a Beverton-Holt stock-recruitment relationship (Table 1, and eq N.1 in Table 2) parameterized via stock-recruitment steepness (h), unfished female spawning biomass (B_0), and uncorrelated process deviations (ω_t) from the average stock-recruitment relationship. Fishing mortality rates by year and fishery ($F_{g,t}$) are estimated directly as a random walk (F.1, Table 1) assuming that catch is known with high precision in trap and longline fisheries, and moderate precision in the trawl fishery (CL.1, Table 3). Natural mortality rates for males (M_m) and females (M_f) are estimated independently (given identical prior distributions; Pr.2, Table 3).

2.1.1. Growth and Maturity

Sablefish mean length-at-age (cm) is modeled using a von Bertalanffy growth function (OM.1) fitted to length-at-age data collected on Sablefish surveys (Appendix D of Cox et al. (2023)). While the parameters for asymptotic length and length-at-age-1 are based on fitted growth functions, we use sex-specific growth rates, K_x, obtained from review of the literature as done in previous iterations of the Sablefish operating model (Cox et al. 2023). This is because available survey data lack observations of Sablefish at small body sizes, which results in unrealistically high estimates of K_x.

Length-at-age data collected between 1978 and 2020 from commercial fisheries and surveys were analysed to determine if there was any evidence of time-varying growth or body condition. While there was a slight decline in length-at-age over the data set (not shown), it was not considered significant enough to include for this update, but the data will continue to be monitored between MSE cycles.

Maturity-at-age of female Sablefish is estimated from biological samples obtained from fishery-independent trap surveys. It is likely that estimated age-at-50% and age-at-95% maturity are biased because we do not account for size-selectivity in the sampling the population (Cox et al. 2023).

2.1.2. Selectivity

Selectivity is assumed to depend on length, which enables a single selectivity-at-length function for both sexes. Sex-specific selectivity-at-age is derived by averaging each fleet's selectivity-at-length curve over length-at-age distributions for each sex (OM.7). A length-based process is assumed as priors on selectivity are taken from tagging estimates of fishery selectivity, which are only available based on length (Jones and Cox 2018; Cox et al. 2023). Length-based selectivity estimates from tagging and their associated prior distributions were last updated in 2018/19 (DFO 2020).

The tagging-based estimates are most important for longline hook and trawl fisheries because these fleets provide no age-composition data from which age-based selectivity can be estimated. The trawl fishery provides limited length composition data, which we fit directly (described below). Selectivity model parameters estimated from tagging are based on the dome-shaped models (Gaussian for trap and hook, and a Gamma for trawl), and are used to parameterise log-normal prior distributions on selectivity parameters for those fleets (Table 1).

2.1.3. State Dynamics

We assume that the numbers-at-age in 1965 (EQ.5) reflect an unfished equilibrium state because initial abundances-at-age are not estimable (confirmed in preliminary model testing) and there was little reported Sablefish fishing for several decades prior (Appendix A). The unfished spawning biomass-per-recruit (EQ.3) is computed based on natural mortality (EQ.2), weight-at-age (OM.5), and maturity-at-age (EQ.1) of female Sablefish. Equations N.1-N.3 give the stochastic Beverton-Holt recruitment and age-structured model dynamics.

Year-/gear-specific fishing mortality rates are estimated and parameterized based on (i) the initial fishing mortality rate $\log F_g' = \log F_{g,t_{0,g}}$ in the first year where catch is greater than zero and (ii) a simple random walk beginning at the initial $\log F_g'$ value then updated via annual deviations (F.1).

Equation F.3 gives the catch equation, which is adjusted for the proportion of fish retained as computed from OM.4. The expected biomass released at-sea is then given in F.6 (where the “D” stands for Discard). The effect of at-sea releases on total mortality depends on gear-specific post-release mortality rates (d_g) obtained from the literature (Cox et al. 2023).

2.1.3.1. At-sea Releases

At-sea release of sub-legal Sablefish (i.e., < 55 cm fork length) is a key process in the state dynamics of the BC Sablefish fishery (Cox et al. 2023). Therefore, we explicitly modeled the proportions of Sablefish retained-at-length (OM.4) as well as released at-sea (i.e., complement of OM.4) given a fixed distribution of length at age-a (OM.3). We obtained the proportion retained-at-length by numerically integrating the probability density function (OM.2) for the length-at-age distribution above the legal size limit at each age a (OM.4). The integration (OM.4) is approximated by deriving a probability mass for each modeled length-bin. This is achieved by normalising the probability density at the centre of each bin by the sum of the densities over all bin centres (OM.3).

With a few exceptions, model states (i.e., total, legal and biomass, numbers-at-age, etc.) are estimated at the beginning of the year. The only exceptions are vulnerable biomass estimates, which are derived at a given fractional time step (explained below). Therefore, even though data are only available until the end of 2021, spawning biomass and stock status relative to B_{MSY} are both estimated to the beginning of 2022.

2.1.4. Observation Models

Biomass index observations consist of catch per unit effort (CPUE) from the fishery (1979-2009), a standardised survey (1990-2010), and a stratified random survey (2003-2021). These three biomass indices are described in Appendix B. We use fishery CPUE (1979-2009) reluctantly, because it is the only time-series that extends into the 1980s when some of the largest and most influential cohorts entered the fishery and dominated the dynamics for many years. Trap CPUE during 1979-1987 are qualitatively different (and lower) than surrounding observations, so we use time-varying catchability to improve the fit to trap CPUE. This approach results in some down-weighting of this index and does not affect forward projections because the index is not used in management simulations. Both the fishery CPUE and standardised (Std) survey series were discontinued as of 2009 and 2010, respectively, based on simulation analyses suggesting that these indices did not improve future fishery performance, especially given the high cost of the Std survey (Cox et al. 2011). The stratified random survey (StRS), originating in 2003, has been the main source of fishery-independent abundance trend information for BC Sablefish since the 2011 assessment (Cox et al. 2023).

Both the trap CPUE and Std survey biomass indices are modeled using time-varying catchability (O.1, Table 3), constant selectivity, and assuming that the index is obtained after some fraction f_g of the year has expired (O.2, Table 2). Time-varying catchability for trap CPUE and Std survey indices was added in the previous OM updated when trap CPUE data points before 1987 were added to the index data set (DFO 2020). For the trap fishery, CPUE is assumed to be taken halfway through the year $f_g = 0.5$, while $f_g = 0.75$ for the surveys that occur in October and November.

Data for population age- and length-compositions include proportions-at-age in trap fishery biological samples (1982-2016 with several missing years), the standardised survey (1990-2009), and the stratified random survey (2003-2014), and proportions-at-length in the trawl fishery (1981, 1998-2000). Fishery age proportion samples are available back to 1979; however, we dropped 1979-1981 data because the samples appeared qualitatively different and would require year-effects parameters to obtain any reasonable models fits. With a few exceptions, the fishery age composition data show weak coherence in tracking Sablefish cohorts over time (Figure 2). The observation model and components for the expected proportions-at-age and -length are given in O.3 and O.5 (Table 3), while O.4 adjusts the true age proportions to account for ageing errors; that is, the ageing error matrix (see below) multiplied by the true proportions gives the expected proportions observed in the data that we use in the computing the likelihood function (AL.2). There are also additional years with length composition data, but the compositions for those years are very noisy and did not match the underlying population structure well with the current model selectivity structure. We recommend continuing to re-visit those data in the future to see if they can be informative to future iterations of the OM.

The survey age proportions (Figure 2, lower 2 rows), especially the stratified random survey (Figure 3), generally show better coherence in cohort tracking over time. Also, it appears that female age composition data show clearer cohort patterns with less noise compared to males (Figure 3), which could arise from differences in ageing errors (see below) and/or differences in movement and mixing with fish from outside Canadian waters.

2.1.4.1. Ageing Error Matrix

Sablefish are notoriously difficult to age because of their small and irregularly shaped otoliths, which can cause difficulties in locating the first annulus. The 2016 Sablefish operating model was the first to account for uncertainty in age determinations, and successive operating models have continued to revise that approach (Cox et al. 2019; DFO 2020; Cox et al. 2023).

An ageing error matrix corrects for how the true proportions-at-age (i.e., proportions-at-age in the operating model) get smeared among adjacent age classes resulting from random under-/over-estimation of fish ages, as well as systematic deviations due to bias over some age ranges. Thus, incorporating ageing error involves predicting what the observations will look like when the model age proportions get smeared to generate observed age proportions. This operation is given by equation O.4 in Table 3, where Q is the ageing error matrix.

The BC Sablefish ageing error matrix Q is developed using a method based on Hanselman et al. (2012), who used known-aged fish from tagging studies to develop an ageing error relationship for fish aged 3-18 years. Originally, a double-geometric formulation was used, which allowed for systematic bias in the assigned age (Hanselman et al. 2012; Cox et al. 2023). Since then, this matrix has been revised to a simpilfed formulation based on a discretized normal distribution (DFO 2020). The two major differences between these formulations are (i) that the error structure is constrained to be symmetric for the normal formulation, while the double geometric model allows for some skew in the error distribution, and (ii) the normal formulation assumes the assigned true age is the mode of the normal density, forcing an unbiased ageing error distribution. Figure 2 shows Sablefish age compositions from the trap fishery biological samples, Standardised survey, and Stratified random survey, while Figure 3 shows Stratified survey age composition data before and after error correction via the simplified Q matrix (DFO 2020).

Hanselman et al. (2012) did not mention how their ageing error could be applied to stock assessment models with a potentially large accumulator age class (i.e., the plus group). Therefore, we assumed that fish with a true age greater than 35 (i.e., the Sablefish plus-group age) were always correctly assigned to the accumulator age class.

2.1.5. Objective Function and Optimisation

The BC Sablefish operating model's statistical sub-model consists of likelihood functions for observations and prior distributions for selected leading model parameters and the annual deviations for time-varying parameters such as recruitment, fishing mortality, and catchability (Table 3).

2.1.5.1. Biomass Indices

Biomass index time series for Sablefish span varying time periods; we use the summations in NLL.1, AL.1, and LL.1 (Table 3) to add up the various observations by fishery and survey.

Biomass index observations are assumed to be log-normally distributed with expected values given by O.2, residual function NLL.2, and conditional variances NLL.4. The residual function is used to compute both the conditional maximum likelihood estimate (MLE) for StRS log-catchability, and the sum-of-squares in NLL.4. The concentrated negative log-likelihood, which is used when variances are unknown (Bard 1974), is given in NLL.5. Estimating conditional variances in this way leads to a so-called self-weighting overall likelihood where better fitting (i.e., lower residual variance) data sets naturally contribute more weight to the overall objective function. Unless otherwise stated, all results reported in this paper involve this self-weighted formulation. In the sensitivity analysis section, we use simple weight multipliers on some data likelihoods (not shown in Table 1) to assess the relative influence on the model estimates. Note that the concentrated likelihoods are multiplied by weight factors in the final objective function (OF.1, w_g^{idx}) to assess the implications of alternative data combinations and weighting schemes. Ultimately, the operating models within the final ensemble do not involve weighting multipliers.

2.1.5.2. Age and Length Composition Data

The age- and length-composition data are modelled using a multivariate-logistic (MVL) distribution on the proportions-at-age (AL.1-5) or -length (LL.1-5) (Schnute and Richards 1995; Schnute and Haigh 2007; Francis 2014), which step through the construction of the concentrated negative log-likelihood functions. Below, we discuss age-composition only for brevity, but the length composition likelihoods are similar.

We chose the MVL likelihood mainly because it has a self-weighting likelihood property in which variances are computed directly from the model fits rather than being implied by assumptions about effective sample sizes (e.g., as needed for multinomial likelihoods) or iterative re-tuning schemes. The biomass index and age composition variances are therefore comparable, which generally avoids composition likelihoods from totally dominating the objective function at the expense of critical biomass trend information. Each year of data is weighted identically in the likelihood.

In preliminary analyses, the model could not fit small age-proportions in some of the less populated age groups or those not strongly selected by the fishing gear. Here, we used 0.02 as a threshold such that any observed age proportion below this value was added to an accumulator bin, which functions similarly to plus group but is not confined by the age-structure (i.e., an accumulator bin can take observations from any age-class). We generate an expected value for this bin by summing over the age classes where observed proportions are less than the threshold of 0.02. The sample size for variance calculations is then reduced by $j - 1$, where j is the number of age classes contributing to the accumulator bin. This change improved model performance considerably, although we have not tested alternative values for the threshold. We do not include this accumulator bin calculation in Table 2 to avoid uneccessary clutter in the model notation because the above explanation is a straightforward implementation.

As noted above, we also apply weight factors to the age-composition likelihoods (w_g^{age}, w_g^{len}, OF.1) to determine their overall influence on model estimates in sensitivity analyses (Appendix D), but for the main analyses $w_g^{age} = w_g^{len} = 1$.

2.1.5.3. Landed Catch and At-sea Releases

We fit the model to landed catch using a fixed standard error $\tau_{C,g}$ (CL.1), corresponding to a 1% coefficient of variation for trap and longline hook landed catch data to ensure that the model catch closely matches the observed catch, and we allow a 10% coefficient of variation for trawl (Table 2). The small estimation error for trap and hook fisheries is reasonable given the long-standing 100% dockside monitoring coverage and more recent 100% electronic monitoring, and the 10% coefficient of variation (CV) was required for an acceptable fit to at-sea-releases in the trawl fishery while retaining more plausible model equilibria.

The at-sea monitoring program for the BC groundfish fishery is possibly unique in world fisheries for its intensity. For instance, all harvesters must maintain audited (via video verification or comparison to logbooks from at-sea observers) logbooks that include the number or weight of fish brought on board the vessel, as well as those discarded at-sea. This is especially important for Sablefish assessment because at-sea releases of fish under the 55 cm fork length minimum size limit sometimes represent a substantial component of annual production. Depending on post-release survival (which varies by capture method), this represents a potentially large loss of annual Sablefish production. The at-sea monitoring program thus provides the critical data needed to account for these losses in the assessment, as well as the potential to simulation test mitigating management measures (e.g., DFO 2020).

Sablefish at-sea releases are estimated from piece counts for trap and longline hook fisheries (2006–2021) and total weight reported by at-sea observers for trawl fisheries (1996–2020). In 2020, trawl at-sea observers were suspended due to the Covid-19 pandemic, and at-sea releases were estimated from at-sea logs until electronic monitoring was implemented in late 2020. Piece counts in trap and longline fisheries are converted to weight via assumed average individual whole sublegal fish weights of 1.5 kg for both trap and longline. At-sea releases are assumed to be log-normally distributed with expected values given by F.8 and a conditional maximum likelihood estimate of variance, similar to the biomass indices, for trap and longline, and a 10% coefficient of variation for the trawl releases. Like the landed catch monitoring, there is no reason to expect very high estimation variances for at-sea releases, especially since there is no penalty for releasing under-sized fish; however, there may be biases introduced via the estimation methods outlined above.

2.1.5.4. Prior Distributions

We use Beta and Normal prior distributions on stock-recruitment steepness and natural mortality (Pr.1, Pr.2), respectively, because these parameters are usually difficult to estimate (Figure 4). The baseline steepness prior parameters $(50, 25)$ imply a mean of $\bar{h} = 0.67$ and standard deviation of $s_h = 0.05$ (or around a 7% coefficient of variation). This is a tighter variance than in previous operating models, as we found a more informative prior was necessary for some scenarios (described below). For natural mortality, we used the same prior mean of $\mu_M = 0.1$ and standard deviation of $\sigma_M = 0.1$ for both males and females.

As noted above, noisy trap fishery age-composition along with missing longline hook and trawl fishery age compositions require prior information about selectivity (Pr.4). Baseline priors for the length-at-50% and length-at-95% selectivity are estimated from the long-term Sablefish tagging program conducted as part of routine annual surveys and at-sea biological sampling in longline trap, longline hook, and trawl fisheries (Table 1). Annual deviations in recruitment (Pr.4) and random walk deviations in fishing mortality (Pr.5) are constrained by Normal prior distributions. Finally, we defined an improper prior to penalise the magnitude of unfished biomass (Pr.6), which had a weighting scalar of $w_B = 100$ in the final objective function (OF.1). The weighting scalar was chosen based on the value used for the Sablefish operating model in previous years and is varied as part of the prior sensitivity analysis. The weighting scalar is required to keep unfished biomass at a level consistent with observed responses to exploitation levels, given that most of the model history is a 1-way trip (Hilborn and Walters 1992).

2.1.5.5. Optimisation

The negative log-posterior (OF.1, Table 3) is minimised via the nlminb() function in the R programming language (R Core Team 2015), which produces maximum posterior density estimates (MPDEs). Bayes posteriors are then obtained via numerical integration using Hamiltonian Monte Carlo (HMC) in the `{tmbstan}` R package (Monnahan and Kristensen 2018). Leading model parameters are sampled in 4 independent posterior chains, initialised at random starting values sampled from a multi-variate normal distribution centred at the MPDEs. These starting values are deliberately over-dispersed relative to the MPDEs by setting the standard deviation of the distribution to two times the standard errors of the MPDEs, to satisfy the assumptions of convergence metrics such as the scale reduction factor $\hat{R}$.

2.1.6. Transition and Bridging Analysis

Posterior distributions of operating model estimates are compared between TMB (2018 and 2021 datasets and hypotheses) and ADMB (2018 data set and hypothesis only) implementations in Appendix C. The *transition analysis* compares how estimated parameters and reference points change due to software implementation (ADMB vs. TMB) and model assumptions using the 2018 data. The *bridging analysis* compares the TMB estimates using 2018 and 2021 data to judge the impact of new data. Transition and bridging analyses are assessed via posterior distributions of leading biological parameters, fleet selectivity parameters, and key management quantities such as MSY-based reference points, current and historical spawning biomass, and fishing mortality.

2.1.7. Retrospective Analysis

A retrospective analysis of the ***baseOM*** hypothesis is performed by fitting SAB-OM to successive 'peels' of data, going from 2005 to 2021. Each peel is compared via posterior median estimates of spawning biomass time series, unfished biomass, unfished recruitment, natural mortality, and stock-recruit steepness. Finally, posterior median estimates of MSY-based reference points and posterior probabilities for stock status indicators are calculated for each data peel to understand the effect of new data on model equilibria and the associated management targets. For peels ending in years prior to 2018, the conditional maximum likelihood estimate of release observation standard errors are used instead of the fixed values in Table 1, as this was the practice in previous MSE cycles (Cox et al. 2019; Cox et al. 2023), and was required to improve convergence. Additionally, the lag for estimating the final recruitment deviation was changed from a 2-year lag to a 3-year lag in the 2020 peel (i.e., 2017 was the last estimated recruitment for both the 2019 and 2020 peels). The lag was changed as the model appeared sensitive to this choice and preliminary model fits showed that a using a 2-year lag after 2019 led to potential over-estimation of incoming year classes.

2.1.8. Operating Model Scenarios

We estimate BC Sablefish biomass, productivity, and stock status from SAB-OM over an ensemble of 5 operating model hypotheses. The ensemble is the union of two axes of uncertainty that intersect in a central "Base" operating model (***baseOM***), with one axis that varies the level of uncertainty in release observations, affecting terminal biomass, and a second axis that varies the prior mean value for stock-recruitment steepness, affecting productivity in the projections.

The first operating model grid axis varies the level of uncertainty in trawl release observations, which has the effect of increasing or reducing the size of recent year classes, thereby raising and lowering operating model estimates of terminal biomass. We refer to this axis as the 'CV (coefficient of variation) axis of uncertainty'. In the base OM, the residual standard error for trawl releases is $\tau_3^{rel} = 0.1$, and the additional levels are $\tau_3^{rel} = 0.05$ (***loRelCV***), which has the effect of increasing recent recruitments to match releases more closely, or estimating trawl release residual standard errors as a conditional maximum likelihood estimate (***hiRelCV***), which reduces the size of recent year classes.

The second axis of uncertainty adjusted the beta prior parameters for stock-recruitment steepness h. As in most stock assessment models, BC Sablefish steepness estimates are highly dependent on prior knowledge, and the posterior distributions of steepness have reflected this in prior MSE cycles. In the base OM, the beta prior distribution on steepness is $h \sim \beta(50, 25)$, indicating a prior mean of $m_h = 0.67$ and a prior standard deviation of $s_h = 0.05$. For the additional levels, the total sum of the beta prior shape parameters is held constant, but the allocation between the two parameters is shifted, effectively keeping the prior standard deviation constant while shifting the mean value left and right. The two additional levels tested a lower steepness scenario (***loProd***) with prior mean $m_h = 0.6$, and a higher steepness scenario (***hiProd***) with prior mean $m_h = 0.73$.

Composite estimates of Sablefish reference points and stock status are integrated over the operating model ensemble as a weighted average. Operating models are assigned weights based on expert judgement, with ***baseOM*** receiving a 50% weighting, and the other four operating models receiving 12.5% each.

2.1.9. Analysis of Lost Yield Due to Discard Mortality

We estimate lost legal yield due to discard mortality. To do so, an alternative model history is generated from ***baseOM*** MPDEs of all model biological, fishery, and process error parameters, assuming that there is no release-induced mortality in any fishery. The ***baseOM*** fishing mortality estimates are also used for the alternative history, so that as released fish return to the stock and grow, increasing underlying biomass, the catches increase as well.

The lost yield for each year t is then calculated as

$$L_t = \hat{C}_t^{dM=0} - \hat{C}_t^{dM>0} \tag{1}$$

where $\hat{C}_t^{dM=0}$ is the total landed catch in year t estimated by ***baseOM*** assuming that fish experience no release-induced mortality, and $\hat{C}_t^{dM=0}$ is the standard ***baseOM*** estimate of total catch in year t with release-induced mortality. The approach of using the same model but varying the post-release mortality is just one of several alternative approaches, but we considered it the simplest since all other model assumptions match ***baseOM***. The reasoning for keeping fishing mortality constant (rather than catch) across mortality scenarios is that, since 2011, the Sablefish stock has been managed under an MP with a target harvest rate, so higher TACs would often have been taken when higher biomass is detected.

2.2. CLOSED-LOOP SIMULATION FRAMEWORK

We develop a new closed-loop simulation framework (MS3-SAB) to update the framework used since Cox et al. (2011). As part of the update, we also developed a TMB implementation of the Sablefish state-space production model (SSPM) used to estimate annual biomass and control points for the current Sablefish MP. Internalizing all feedback computations in a TMB framework vastly reduces file management overhead relative to the former ADMB implementation, and therefore simulations are more efficient to run. Those efficiencies are multiplied when simulations are run on multi-core machines.

Simulations are used to test whether the current MP, which has been in place since 2016 (Cox et al. 2019), is still able to meet previously identified fishery objectives when using the revised operating model. In addition, modified versions of the current MP are considered that are tuned to updated estimates of productivity and other key management parameters from the revised operating model. Below, we provide an overview of the closed-loop simulation framework used to test MP performance.

2.2.1. Sablefish Objectives and Performance Measures

2.2.1.1. Fishery Management Objectives

Objectives for the BC Sablefish fishery have been iteratively developed via consultation with fishery managers, scientists, and industry stakeholders (Cox and Kronlund 2009; Cox et al. 2011; DFO 2014; Cox et al. 2019). The five primary objectives guiding BC Sablefish management decisions are:

1. $P(B > 0.4B_{MSY}) \geq 0.95$: Maintain female spawning stock biomass B above the limit reference point of $LRP = 0.4B_{MSY}$ in 95% of years measured over two Sablefish generations, where B_{MSY} is the female spawning biomass at maximum sustainable yield (MSY) for each operating model;
2. $P(decline)$: When female spawning stock biomass is between $0.4B_{MSY}$ and $0.8B_{MSY}$ at the beginning of the projection period (i.e., 2022), limit the probability of decline over the following 10 years (2022-2031) from very low (5%) at $0.4B_{MSY}$ to moderate (50%) at $0.8B_{MSY}$. At intermediate stock status levels, define the tolerance for decline by linearly interpolating between the extremes;
3. $P(B_{2052} > B_{targ}) = 0.5$: Maintain the 2052 female spawning stock biomass above the target reference point in at least 50% of simulation replicates, where the target reference point is (a) $B_{targ} = B_{MSY}$ when $B_{2022} \geq 0.8B_{MSY}$, or (b) $B_{targ} = 0.8B_{MSY}$ when $B_{2022} < 0.8B_{MSY}$;
4. $\max(P(C_t > 1.992))$: Maximize the probability that annual legal sized catch levels remain above 1,992 tonnes, measured over two Sablefish generations; and
5. MaxLegCatch: Maximize annual legal sized catch over 10 years, subject to Objectives 1-4.

Objective 2 is only considered when the operating model biomass is below $0.8B_{MSY}$ in the first year of the projection, and is automatically met (or not required) when the biomass is above that level. Given that stock status has a very high probability of being above $0.8B_{MSY}$ at present, this objective does not affect MP choice at present. Objective 4 was added in the 2017-18 MSE cycle (Cox et al. 2019) to acknowledge the minimum economically viable catch levels of 1,992 tonnes. Previously, the 1,992 tonne level was used as a hard lower limit on the TAC (DFO 2014), but was softened to the objective as stated when a hard limit was found to be infeasible (Cox et al. 2019).

2.2.1.2. Performance Measures

Evaluating management procedures by simulation requires a quantitative performance indicator for each fishery objective. Stock status indicators are all measured using the true operating model female spawning stock biomass. We use two Sablefish generations (36 years) as the ‘reasonable’ time frame required by the DFO Precautionary Approach Framework (DFO 2006), and 10 years as the short term to reflect industry economic interests.

Performance statistics corresponding to each of Objectives 1-5, as well as other quantities of interest, are listed in Table 4. Performance statistics are calculated for each simulation replicate ($n = 100$) for a given combination of OM scenario and MP. The expected performance of an MP given the data simulated by the OM is summarized by the mean (or median) over the replicates. Where an aggregate summary of performance over multiple scenarios is required, a weighted average of the performance metrics from each scenario is calculated.

2.2.2. Operating Model

The Sablefish MS3-SAB closed loop simulation framework is conditioned on the posterior distributions sampled from the 5 SAB-OM scenarios described under Scenario Analysis above, which defines the reference set of operating models. For all reference set OMs, the population dynamics and observation models within the MS3-SAB framework for generating simulated data largely match those defined for the estimation model implemented in TMB (Tables 2, 3), so we do not reproduce them in full. The only difference is in the method of simulating recruitments in the projections. Simulated recruitments have the following bias correction factor added:

$$R_t = \frac{4R_0 B_{t-1}}{B_0(1-h) + (5h-1)B_{t-1}} \cdot e^{\sigma_R \cdot \omega_t - 0.5\sigma_R^2}, \tag{2}$$

which is applied so that the median projected dynamics will match model equilibria (i.e., yield and biomass) when a constant fishing mortality is applied.

2.2.3. Sablefish Management Procedure

The Sablefish MP is made up of (i) Sablefish fishery monitoring data, (ii) a state-space production model (SSPM) for assessing legal-sized Sablefish biomass, and (iii) a harvest control rule for turning biomass and productivity estimates from the SSPM into a TAC recommendation.

The fishery monitoring data used for SSPM assessments is the same index and landings data used to fit the Sablefish operating model described earlier in this paper, so we do not describe it here. A description of the SSPM is provided in Appendix E.

2.2.3.1. Harvest Control Rule

The BC Sablefish Harvest Control Rule (HCR) determines a target harvest rate based on the SSPM estimates of Sablefish legal biomass (Figure 5). Specifically, within a closed loop simulation time step t, the SSPM generates a forecast of legal Sablefish biomass $\hat{B}_t$ and two operational control points $0.4\hat{B}_{MSY}$ and $0.6\hat{B}_{MSY}$, where $\hat{B}_{MSY}$ is the estimate of optimal biomass under the simplified production model structure (i.e., it is distinct from the fishery reference points derived from the age-structured operating model). SSPM estimates of biomass and control points are then used in a 2-stage HCR, where the first stage of the HCR sets the target harvest rate via the recti-linear function

$$U_t = \begin{cases} 0 & \hat{B}_t \leq 0.4B_{MSY} \\ U_{max} \cdot \frac{\hat{B}_t - 0.4\hat{B}_{MSY}}{0.6\hat{B}_{MSY} - 0.4\hat{B}_{MSY}} & 0.4\hat{B}_{MSY} < \hat{B}_t \leq 0.6\hat{B}_{MSY} \\ U_{max} & 0.6\hat{B}_{MSY} < \hat{B}_t \end{cases}. \tag{3}$$

The maximum target harvest of rate $U_{max} = 0.055$ has been in place since the 2022/23 fishing year, after a step-wise reduction from 0.095 in 2017/18 to 0.055 in 2022/23 (Cox et al. 2023). The resulting U_t is the harvest rate applied in the MP, which, when multiplied by the estimated legal biomass, produces a catch limit for year t, i.e., $Q'_t = U_t\hat{B}_t$. In the second stage, a minimum catch limit increase of 200 t is applied such that the catch limit only increases if the previous year's TAC exceeds 200 t, with no restriction on the catch limit decreases, i.e.,

$$Q_t = \begin{cases} Q'_t & Q'_t - Q_{t-1} \geq 200 \\ Q_{t-1} & 0 < Q'_t - Q_{t-1} < 200 \\ Q'_t & Q'_t - Q_{t-1} \leq 0 \end{cases} \tag{4}$$

The catch limit produced by the MP applied to the fishery has generally been adopted as the TAC by fishery managers (Table A.1).

2.2.4. Closed-loop Feedback Simulations

We use the following closed-loop algorithm to apply candidate MPs to simulated data generated by the OMs (Walters 1986; de la Mare 1998; Cooke 1999; Punt and Smith 1999; Sainsbury et al. 2000; Butterworth 2007):

1. For each operating model in the reference set, initialize a pre-conditioned simulation model for the period (1965 – 2021) based on a random draw from the operating model posterior distribution;
2. Project the operating model population and fishery into the future one time-step at a time. At each step, apply the following:
    i) Generate the catch and survey data available for stock assessment;
    ii) Apply the SSPM to estimate quantities required by the harvest control rule;
    iii) Apply the harvest control rule described above to generate a catch limit;
    iv) Update the operating model population given the fishing mortality rate generated by the MP catch limit and new recruitment;
    v) Repeat steps 2.i-2.iv until the projection period ends.
3. Repeat steps 1 and 2 for 100 random posterior draws; and
4. Calculate quantitative performance statistics across all 100 replicates.

For each simulation replicate, the same random seed is used across operating models so that process and observation errors are identical while the structural uncertainty varies. As such, the difference in performance metrics across operating model scenarios is primarily based on the structural differences, and the effect of randomness is minimized. Randomness cannot be completely removed, however, as the Hamiltonian Monte Carlo method for integrating model posteriors also includes an element of randomness that can not be removed via deliberate sampling.

The final performance of a management procedure is evaluated against all five operating models in the reference set. The final composite performance metrics for each objective are calculated as the weighted average over the models,

$$M = \sum_{m \in \mathcal{O}} \iota_m M_m, \tag{5}$$

where M is the composite metric, m is an index of each operating model in the reference set $\mathcal{O}$, ι_m is the weight of each model, and M_m is the model-specific performance metric defined in Table 4. The target harvest rate used to set BC Sablefish TACs has changed almost every year since 2011 (Appendix A). Future changes to the harvest rate are anticipated to only occur at OM updates (3-5 year intervals) going forward, so variation in harvest rates is not included in the closed loop simulations as it is hard to capture the tuning process in simulations, and re-tuned MPs will always be tested against updated OMs before adoption. We do note that all previous changes in maximum target harvest rate were simulation tested. First, in the early years (2011-2015), the historical variation was because the maximum target harvest rate was estimated from the SSPM, producing annual variation. After 2016, the maximum target harvest rate was fixed, but gradually reduced as explained above. In both cases, the methods of setting a harvest rate were simulation tested before the MPs were adopted.

2.2.5. Management Procedures

In total, 17 management procedures are simulation tested under the five reference set operating model scenarios. First, we tested the current management procedure (**currMP**), with its 5.5% target harvest rate and 200t minimum TAC increase. In addition to the current MP, a grid of alternative MPs is tested, which varies the target harvest rate U_{max} applied in the harvest control rule over a range of 6.0%-7.5% in 0.1% increments. These "grid" MPs are labelled **targHRX** where X is the target harvest rate.

2.3. CONSIDERATION OF ENVIRONMENTAL CONDITIONS

We consider the potential impact of environmental conditions on Sablefish population dynamics as detailed in Appendix F. We summarize previously published studies to identify known, or presumed, mechanistic linkages between Sablefish population processes (e.g., recruitment and growth dynamics) and environmental conditions. We then present data-based investigations of possible links between BC Sablefish population traits and a subset of the candidate environmental variables. Two different population traits are used to represent Sablefish dynamics: i. recruitment deviations from the underlying Beverton-Holt stock recruitment relationship from the base OM, and ii. a morphological index of annual Sablefish body condition based on fish weight relative to length.

3. RESULTS AND DISCUSSION

3.1. OPERATING MODEL FITS, STOCK STATUS, AND REFERENCE POINTS

Below we present results of the base operating model ***baseOM*** by first concentrating on fits to data, historical dynamics and reference point estimates. Then, the transition and bridging analyses (Appendix C) are summarised, as well as the retrospective analysis of ***baseOM*** fitting. Convergence metrics and sensitivity analyses for ***baseOM*** are detailed in Appendix D). Finally, the differences in estimates of biomass, productivity, and stock status among the five reference set operating models is presented.

3.1.1. Base Operating Model Fit to Data

Fits to trap fishery CPUE and the Std survey, both discontinued as of 2009, are comparable to those obtained using previous operating models (Figure 6). Although a run of positive residuals occurs for the recent StRS survey observations, the linear trend in residuals over the full time-series is not statistically significant ($p > 0.05$, Figure 6, bottom panel). This pattern of recent positive residuals could result from factors such as poor resolution of the timing and magnitude of recent recruitment events, migration to/from adjacent systems in the USA being aliased by the recruitment and natural mortality parameters, or possible mis-specification of selectivity (i.e., fish entering vulnerable sizes sooner than expected under the selectivity model).

Previous implementations of the Sablefish operating model have shown persistent lack-of-fit to the accumulator (plus-group) age class for trap fishery, Std survey, and StRS survey; these issues continue to varying degrees in SAB-OM (Figure 7). Issues with the trap age-compositions are not that surprising given that Sablefish size limits, age-composition, and sampling intensity have all changed over time, and the large plus-group residual appears to be primarily in samples taken during the 1980s; however, the plus group has also been over-estimated in more recent years (Appendix G). The Std survey shows a run of positive residual errors for the age 5-10 classes for both males and females (Figure 7), which is compensated by a run of negative residuals after age 15. The age 5-10 run of positive residuals in the time-averaged fit to Std age composition data is correlated with the 1992 data set (1064 samples), but is also influenced by 2002 data (Figure G.6), indicating it may be caused by ageing-error in observations of larger 1990 and 2000 year classes (not shown). The fit to the StRS age compositions is similar to the Std survey, although the residuals are smaller over the time series (Figure 7), which could represent the improved sampling design compared to the Std survey. A run of negative residuals for ages 12-19 is consistent between males and females for the StRS (Figures G.7, G.8), and is also consistent with fits from the ADMB model (DFO 2019; DFO 2020). Consistency with previous model implementations suggests that the residual pattern may arise from various combinations of ageing errors, sampling biases in the fishery and fixed location survey, as well as possible model mis-specification, e.g., assuming a closed offshore BC population.

Trawl length composition is the newest data addition for the Sablefish operating model (Figure 8). Although SAB-OM fits to these data are not exceptional, they do capture the ascending limb of the length distributions despite some low-quality fits in individual years (Appendix G). Further investigation into the origins of trawl length composition is probably warranted since most of the sample mass comes from sub-legal fish and there may be some challenges with on-deck measurements of fish prior to release. For example, length composition data fits are better for sex-specific data than the unsexed data, which might occur if there is difficulty sexing smaller fish, and, therefore, a higher proportion of unsexed observations in smaller length classes. Moreover, length classes in the lower tail of the length-at-age distributions are typically more difficult to fit, and may require changes to the length-at-age model, such as adjusting the coefficient of variation.

Estimated recruitment deviations have a mean residual of around -0.23 standard deviations (Figure 9), indicating that recruitments are weaker than average for most years. The negative mean residual is consistent with the sporadic recruitment dynamics that characterise Sablefish stocks coastwide, with periods of low recruitment interspersed with strong year classes; however, negative mean residuals may also indicate that there are some removals that aren't being correctly accounted for. This situation could arise due to an underestimation of at-sea releases, or from reporting sub-legal landings as legal landings prior to 2017. The latter is believed to have occurred occasionally in trawl fisheries prior to 2017; especially in the mid-water hake trawl fishery (Appendix A). For years after 2017, in which estimates of sub-legal landings are available, these landings were accounted for as at-sea releases.

Landed catches from each of the commercial trap and longline fleets are fit with almost no residual error, as intended, and with some variation for the trawl fishery (Figure 10, left column). Although the at-sea releases fit reasonably well on average, the model has difficulty for recent years, despite forcing smaller residual standard errors in the trawl release likelihood (Figure 10, right hand column). The presence of large year classes may be exposing some weaknesses in our assumptions about how at-sea releases are generated. In particular, the current formulation assumes that sub-legal fish are caught in proportion to their abundance and the fleet-specific quotas. We know, for example, that this is not the case for trawl and to some extent non-directed longline hook sectors, which both intercept sub-legal Sablefish in fisheries targeting other species. Future operating models should consider ways of accounting for these at-sea releases in ways that are also amenable to forward projections. One option is to add non-directed fleets to the model, such as undirected trawl or longline fleets with the same selectivity as the directed portion but driven by fishing effort rather than fit to catch. For ***baseOM***, under-estimated releases lead to under-estimated fishing mortality, and to a lesser extent under-estimated recent recruitments.

3.1.2. Historical Dynamics and Reference Points

Updated SAB-OM estimates of BC Sablefish historical biomass, recruitment, and harvest rates are similar to previous model implementations. For the current implementation under the ***baseOM*** hypothesis, the biomass and recruitment estimates indicate that the historical decline of the stock has been reversed by the large incoming 2015-2017 year classes (Figure 11). Those year classes first recruited to the sub-legal biomass, which peaked around 2019/20, and then grew into the legal sized biomass, with females maturing to contribute to spawning biomass. As biomass is driven higher by large recruitments, and the MP implemented a step-wise reduction in maximum target harvest rates from 2017 to 2022, the effective legal and sub-legal harvest rates have continued to decline below U_{MSY}, reaching as low as 4.5% (legal) and 2.1% (sublegal) in recent years.

Estimates of age-1 recruitments over time show the same relative pattern as previous model implementations, but large year classes look more average compared to unfished recruitment (Figure 11, second row). Indeed, the previous large year classes with brood years in 2000, 2008, and 2013 are still larger than the rest of the time series, but the 2008 and 2013 year class have significant probability mass below the new higher estimate of R_0. The higher R_0 is influenced by the recent year classes being the highest recruitments estimated for this stock occurring at almost the lowest biomass (Figure 12).

SAB-OM estimates of biological reference points are also similar to previous implementations (Figure 13). The 2021 posterior median optimal legal harvest rate U_{MSY} is around 6.5% (***baseOM***), with 95% credibility interval (CI) ranging from 5.2% to 7.6%, with legal MSY at around 3,500 t, (2,980 t-4,100 t 95% CI), and optimal spawning biomass B_{MSY} around 22.8 kt (20.0 kt-26.1 kt 95% CI).

3.1.3. Transition and Bridging Analysis

The new implementation of the Sablefish OM in TMB presents no major problems based on results of the transition and bridging analyses (Appendix C). Although the two implementations differ in particular parameter estimates based on the 2018 data set and hypotheses considered, final estimates of biological reference points and stock status are mostly within the margins of estimation error. Moreover, some of the differences in parameter estimates between the two implementations fit to 2018 data are reversed when the TMB implementation is fit to 2018 and 2021 data under the current trawl catch and release CV assumptions.

3.1.4. Retrospective Analysis

Retrospective model fits for **baseOM** show a shift in unfished equilibria (B_0, R_0) and productivity (h, U_{MSY}) over time (Table 7). Since 2005, model estimates of unfished biomass, steepness, and female natural mortality have all varied, sometimes by around 10%. Estimated spawning biomass declined in both relative and absolute terms over the 2005-2019 period (Figure 14). Some years the estimated trend appears to reverse as survey index and age data indicated that the stock may have started recovering (e.g., the 2014 peel), but as new data were added the declining trend continued. The lag time between recruitment to surveys and recruitment to the spawning stock maintain the long-term decline even though survey data suggested the stock has been increasing since about 2017. Estimated spawning biomass and depletion reach their lowest values in 2018/19, with a slight increase to 2020 and then a very large jump after the addition of 2021 data (Figure 14, black heavy reference line).

MSY-based reference points have also changed over the 2005-2021 retrospective period (Table 7). Despite variations of up to 10% in biomass and 20% in productivity, B_{MSY} has remained relatively stable, ranging between approximately 20 kt to about 23 kt. The optimal legal harvest rate U_{MSY} is about as variable over the retrospective, period ranging from 0.054 in 2009 to 0.087 in 2021. Such variation is largely in response to year class strength and its influence on the stock-recruitment relationship.

Retrospective cohort strength shows that year class strength (i.e., standardised recruitment deviations) can stabilise after age 4 or 5 (Figure 15). This suggests that the 2015 and 2016 year classes may continue at their current estimated strength, although the negative correlation between the 2016 and 2017 retrospective cohort strength may indicate that there is age smearing occurring. Additionally, previous large year classes in 2008 and 2013 exhibit more variability after age 5 than the lower-than-average cases, as they migrate towards a zero deviation over time; however, that stability in lower-than-average year classes may be exaggerated by skew in the log-normal prior for recruitment process errors. What that means is that small changes in negative residuals have a bigger effect on absolute recruitment estimates than small changes in positive residuals. Furthermore, the movement towards zero in the 2008 and 2013 year classes is partially related to the increase in unfished recruitment R_0 over the same time period (Table 7), which may reverse as the current large recruitment event works its way through the fishery.

3.1.5. Comparison of Reference Set Operating Models

The main differences between the five reference set operating models in the period 1965-2021 are related to the release observation CV axis of uncertainty. As the release observation CV for trawl is decreased from the conditional maximum likelihood estimate of $\tau_{D,3} = 0.744$ to the fixed value of $\tau_{D,3} = 0.05$, the current posterior median spawning biomass increases from 21.65 kt under the ***hiRelCV*** OM to approximately 29 kt for ***baseOM*** and reaches a maximum of 35.93 kt for the ***loRelCV*** OM scenario (Table 5, Figure 16).

The increase in current spawning biomass across the release observation CV axis is largely driven by the size of the 2017 year class, which increases as the release observation CV is reduced in order to provide a sufficient number of small fish to explain trawl release observations (Figure 16). As described above, releases are proportional to abundance and fleet-specific landings; therefore, given the low absolute landings in the trawl fleet, abundance is the only remaining lever available for SAB-OM to reduce the trawl release observation residuals.

Relaxing release observation CVs reduces the negative log-likelihood function values for trawl release data, trawl catch data, and StRS age data (Table 6). Despite this, the ***hiRelCV*** OM is considered less plausible as the reduced likelihood function values for trawl releases are somewhat misleading. Likelihood function values are based on standardised residuals, and the conditional maximum likelihood estimate of the release standard error $\tau_{D,3} = 0.744$ under the ***hiRelCV*** OM is around 7.5 times the fixed value of $\tau_{D,3} = 0.1$ under the ***baseOM*** scenario. The higher release CV also allows SAB-OM to fit better to trawl landings, as there is far less tension between the catch and release likelihood components for the trawl fleet based on the assumption of proportionality between them. The resulting reduction in age-composition residual error is due to a smaller estimate of the 2017 year class (Figure 16), which in ***baseOM*** is based primarily on the release observations and not strongly supported by the offshore survey's age observation data. The lack of support in age observations could be the result of several interacting factors, such as ageing error, bias in the estimates of at-sea release observations from log-book data, or migration between the BC Sablefish population and populations in Southeast Alaska and the US West Coast affecting recruitment and mortality estimates.

The only significant differences between the two productivity axis scenarios ***hiProd*** and ***loProd*** and the ***baseOM*** is for estimates of MSY-based reference points (Table 5, 6). Indeed, small changes in stock-recruitment steepness often produce minor effects on the historical population dynamics of a stock, as the often high standard errors for recruitment process errors ω_t tend to compensate for small changes in the expected stock-recruit curves implied by different steepness parameter values. Changes in steepness tend to have larger effects on stock status estimates and the future performance of management procedures, both of which are discussed in more detail below.

3.1.6. Yield Lost Due to Discard Mortality

An estimated 12,000 t of cumulative legal yield has been lost due to discard mortality since the integration of the BC groundfish fishery in 2006 (Figure 17), or about 30% of the annual average yield. This is in comparison to the cumulative yield in the absence of discard mortality.

3.1.7. Stock Status

Inspection of SAB-OM results across the five reference set operating model scenarios suggests that the BC Sablefish female spawning biomass is currently above B_{MSY} and harvest rates are below U_{MSY} over a somewhat broad range of models. Composite stock status, when weighted over the ensemble of operating model scenarios, shows that start of year 2022 BC Sablefish female spawning biomass is above B_{MSY} with 92% probability, and 2021 harvest rates are below U_{MSY} with 94% probability (Table 5).

Composite 2022 stock status estimates are most heavily influenced by ***baseOM*** scenario estimates. The stock is estimated to be at 133% of B_{MSY} with 2022 spawning biomass above B_{MSY} with 97% probability. The 2021 legal sized harvest rate is below U_{MSY} with 97% probability, with a median estimate of 69% of U_{MSY} (Table 5). Current stock status in ***baseOM*** is largely driven by the high recruitment, and the resulting low legal harvest rates, for the incoming large year classes in 2015 (~7 million age-1 recruits), 2016 (~15 million), and 2017 (~16 million). Those three recruitment events have reversed the decades long decline of BC Sablefish female spawning biomass, which reached a low of about 15 kt (Figure 11), or 60% of B_{MSY}, in 2015 with harvest rates near U_{MSY} (Figure 18). Biomass and legal harvest rates appear to have been stable since around that time until the 2015-2017 year classes recruited to the spawning stock coincident with the planned reduction in harvest rates from 2017 (9.5%) to 2022 (5.5%), producing a rapid increase in spawning biomass.

Based on comparison with how historical recruitment estimates have played out in the Sablefish fishery (Figure 11), the estimates of large 2015- 2017 year classes could be a single large recruitment event smeared across the three years due to ageing error. In any case, large year classes may fail to materialise quite as impressively as the current estimates indicate, as with the 2000, 2008, and 2013 year classes. On the other hand, the 2015 year class was originally detected in the previous iteration of SAB-OM (DFO 2020), and while the current estimates of the 2015 year class are smaller now than previously estimated, it continues to show up as a larger than average recruitment in BC and both neighbouring populations in Alaska and the US West Coast (Figure 19), as does the 2016 year class (Goethel et al. 2021; Kapur et al. 2021). The 2017 year class is much less certain, as it is largely driven by the fit to at-sea releases, but it is corroborated by the 2021 Alaskan stock assessment, which also shows a large 2017 year class.

The uncertainty about the size of the large recent year classes, and the resulting differences in estimated stock status, are captured by the reference set of operating models (Figures 18, 20). The ***hiRelCV*** OM scenario is the most conservative in this regard, as it estimates that the 2017 year class is close to the stock-recruit curve, and that the 2016 year class is about 30% smaller than ***baseOM*** (Figure 16). As such, the ***hiRelCV*** OM produces the most conservative estimate of current stock status, with a 56% probability of 2022 female spawning biomass is above B_{MSY} and a 75% probability that 2021 legal harvest rates are lower than U_{MSY}. While stock status indicators under the ***hiRelCV*** OM are more conservative, there is still moderately high probability that BC Sablefish is not overfished (meaning U does not exceed U_{MSY}) as the median 2021 biomass is at around 1.02 B_{MSY}. The remaining operating models indicate larger biomass and lower harvest rates than ***hiRelCV***, with the largest difference occurring between ***baseOM*** and the ***loRelCV*** scenarios. For ***loRelCV***, posterior median 2022 spawning biomass is 161% of B_{MSY} and 2021 harvest rate is about 60% of U_{MSY} (Table 5). The productivity scenarios ***loProd*** and ***hiProd*** are more similar to ***baseOM*** in posterior medians (Table 5), but the distributions of stock status are narrower (Figure 20).

3.2. MANAGEMENT PROCEDURE PERFORMANCE

Given the general increase in estimates of stock productivity since the last OM update (DFO 2020), we present detailed plots of population dynamics, fishery catch limits, and legal harvest rates for the status-quo **currMP**, and two MPs with higher target harvest rates of 6.0% (**targHR6.0**) and 6.4% (**targHR6.4**) representing a moderate increase in target harvest rate and the optimal composite legal harvest rate across OMs, respectively. Harvest rates higher than 6.4% are tested to explore the relationship between maximum target harvest rate and the target reference point objective $P(B_{2052} > B_{MSY})$ (Objective 3).

All tested management procedures met the biomass conservation objectives (Objectives 1-3; Table 8). Given the size of the incoming year classes, BC Sablefish female spawning biomass is well above the LRP of $0.4B_{MSY}$ for greater than 95% of the time in any operating model, thereby meeting Objective 1 for individual OMs as well as the composite weighted metric. Similarly, given the influence of large year classes, the biomass is above B_{MSY} in most cases, so Objective 2 is achieved in most individual simulation replicates and therefore the composite weighted metric as well. Finally, despite median biomass peaking around 2027 and most simulation trajectories showing a plateau for 5-8 years followed by a decline until the end of the projection period, median female spawning biomass is above B_{MSY} in 2052 (Figure 21, vertical dashed line), meeting Objective 3's probability criterion of 50%.

The large estimates of incoming year classes dominate the BC Sablefish conservation performance for the next several years (i.e., Objectives 1-2 are satisfied). Therefore, alternative MPs are separated by their catch performance. There is a trade-off between the probability of keeping catches above the minimum level of 1,992 t required for a viable fishery (Obj. 4, Table 8) and median average catch over the next 10 years (Obj 5., Table 8). The former ranges from 98.5% for **currMP** to 95.5% for **targHR7.5**, while median average catch to 2031 ranges from 3,148 t (**currMP**) to 4,380 t (**targHR7.5**). At the same time, interannual variation in catch, or Average Annual Variation (AAV, Table 8), increases with the average catch, although its range of 3.95% - 5.86% is quite narrow and the variation is small.

The ability of the fishery to meet all three conservation objectives under any OM is a result of the large pulse of recently recruited fish working through the population, and realised legal harvest rates lower than U_{MSY} (i.e., underfishing). Those recently recruited fish are maturing and increasing in size, which has pushed the composite weighted female spawning biomass above B_{MSY} with very high probability, and that growth is expected to continue until 2027 (Figure 21). Median spawning biomass peaks around $1.75B_{MSY}$ in 2027 as the large 2015-2017 year classes reach their maximum size. At this time, their growth no longer dominates mortality in their contribution to the female spawning stock so they make up a smaller proportion of the spawning biomass each year as fish are removed by fishing and natural mortality. Beyond 2027, median female spawning biomass plateaus as growth balances removals, and begins to decline as the large recruitments age out after 2033/34 and are on average closer to the expected Beverton-Holt stock-recruitment curve. However, median spawning biomass never drops below B_{MSY} when applying the MP with a 7.5% maximum harvest rate (not shown).

The narrow range of probabilities for catch exceeding the lower limit of 1,992 tonnes (Objective 4, Table 8) is a function of the low realised harvest rate. The main reason is that the probability for Objective 4 is measured over 100 replicates and the entire 2-generation projection period for each operating model. Given the current state of the stock and low effective harvest rates there is very little chance of catches dropping below the minimum viable level before 2050 under composite OMs (Figure 21), and even for individual operating models with lower starting biomass (***hiRelCV***) or lower productivity (***loProd***). A better way to separate management procedures by catch performance under the current stock status, where the conservation objectives are met almost by default, is to consider a trade-off between short term average catch and the average catch when the catch limits are unviable over the long-term (i.e., metric $E(C_t|C_t < 1,992)$ in Table 8). This trade-off can be considered as harvest rates increase, and/or as the length of time that the fishery is economically unviable. For example, **currMP** has relatively minor variation around the median catches after 2050, with marginally unviable catch limits around 1,600-1,800 tonnes (Figure 21, left-hand column), while the small increases in harvest rate for **targHR6.0** and **targHR6.4** show much broader distributions of catch towards the end of the projection, and with a lower tail of TACs towards 1,000 tonnes (Figure 22, middle and right-hand columns).

A major reason for years with unviable catch limits even though the stock biomass is near target levels is that the SSPM in the MP tends to underestimate legal-sized biomass interpreted by SAB-OM. By design, the SSPM is a simple biomass dynamics model with a symmetric production relationship, while the operating model is fully age-structured with a more realistic production relationship that also accounts for discard induced mortality whereas the SSPM does not. There are also strict limits on the amount of process variation in the SSPM to avoid over-reacting to sudden large changes in stock indices which may be influenced by observation noise, which means that biomass estimated by the SSPM tends to lag the “true” SAB-OM biomass. As a result, the SSPM contributes precautionary behaviour to the management procedure. In most operating models and simulation replicates, especially in the earlier projection years for operating models with high biomass in 2022, the SSPM can under-estimate legal biomass by as much as 50% (Figure 22). Therefore, catch limits are lower, so realised harvest rates end up well below the target harvest rate in the harvest control rule (Figure 22, bottom row). For the replicate shown, the gap from under-estimation is widest during the first 10 years of the simulations, and narrows as the OM biomass is fished down and the weight of the data informs the SSPM; at the same time, effective harvest rates approach the target harvest rate within 1 percentage point by around 2045 (Figure 22, bottom row). In replicates where the spawning biomass declines below B_{MSY} before the end of the projection period (not shown), the SSPM estimates of biomass fall below the upper control point of the HCR, further reducing the harvest rate, sometimes producing unviable TACs. While unviable TACs are undesirable from an economic perspective for the directed fishery, the management procedure is functioning as required in the simulations to maintain spawning biomass above the limit reference point.

3.3. CONSIDERATION OF ENVIRONMENTAL CONDITIONS

None of the environmental variables considered in Appendix F) were singularly strong candidates for characterizing environmental conditions affecting Sablefish recruitment in BC. In contrast, our analysis of an annual length-weight body condition index showed moderate correlations with a wide range of environmental variables. Our simple correlation analyses are only meant to serve as an initial exploration of potential links. We make recommendations for future research directions aimed at characterizing links between environmental conditions and Sablefish population dynamics in Appendix F.

4. CONCLUSIONS

4.1. TRANSITION TO A REVISED SABLEFISH OPERATING MODEL

The transition and bridging analyses imply no issues in the migration of the SAB-OM to TMB. Although estimates of specific parameters differ between the ADMB and TMB implementations based on the 2018 data set, their final estimates of biological reference points and stock status are mostly within the margins of estimation error. Moreover, some of the differences in parameter estimates between the two implementations when fit to 2018 data are reversed when data are updated to 2021 for the TMB implementation.

4.2. SABLEFISH STOCK STATUS IN 2022

Stock status for BC Sablefish relative to reference points is estimated using an ensemble model approach that covers two axes of uncertainty. The first axis is stock-recruitment steepness (productivity), while the second axis is terminal biomass in the last year of the assessment. The latter axis is controlled by varying the level of uncertainty in release observations. Five operating models were developed along these axes, and each operating model was assigned a plausibility weight. A weight of 50% was assigned to the base operating model based on our belief that it was the best representation of the Sablefish Management System, while the remaining four cases were each weighted equally (12.5%). The composite measure of stock status was then computed as a weighted average of OM outputs. The ensemble model approach allows key structural uncertainties in the specification of SAB-OM to be integrated into estimated stock status.

Results suggest the Sablefish stock in BC is not overfished nor experiencing overfishing. The weighted average spawning stock across the OMs at the beginning of 2022 is estimated at 29.9 kt, or around 1.32 times B_{MSY} ($P(B_{2022} > B_{MSY}) = 92\%$), while the 2021 harvest rate of legal Sablefish is estimated to be 71% of U_{MSY} ($P(U_{2021} < U_{MSY}) = 94\%$).

4.3. MANAGEMENT PROCEDURE PERFORMANCE

All management procedure options considered (i.e., the MP currently applied in the 2022/23 fishing year, and alternative MPs with higher target harvest rates from 6.5% to 7.0%) met biomass conservation metrics and have satisfactory performance on catch objectives. Given that MP performance relative to conservation objectives (1-2) and target biomass objective 3 are satisfied, MP choice is largely a trade-off decision between yield and the probability of an economically viable fishery. An increase in the target harvest rate from the current value of 5.5% could be considered based on simulation outcomes from the suite of MPs tested.

4.4. ENVIRONMENTAL CONSIDERATIONS

None of the environmental variables considered in Appendix F were strong candidates for characterizing environmental conditions linked to BC Sablefish recruitment. In contrast, our analysis of a body condition index for adult Sablefish showed correlation with a wide range of environmental variables; however, the extent to which the observed variation in body condition would affect Sablefish population dynamics (e.g., natural mortality, reproductive potential) is unknown. Our simple correlation analyses represent an exploration of potential links. Future research into environmental drivers of Sablefish population dynamics could consider using generalized linear models (GLMs) to explain variability in BC Sablefish recruitment as a function of multiple environmental variables operating at various spatio-temporal scales and life history stages (Tolimieri et al. 2018; Haltuch et al. 2020). Alternatively, dynamic factor analysis [DFA; Zuur et al. (2003)] could be used to find a common trend in multiple environmental variables that could then be used to predict variation in recruitment (Haltuch et al. 2019).

While GLM or DFA approaches could improve understanding of how environmental conditions relate to BC Sablefish, it is unknown whether incorporating these approaches into operating model development for BC Sablefish would improve management performance. Efforts to incorporate environmental variability into stock assessment model predictions most often involve structural changes to the stock-recruitment function, with the expected number of recruits in a given year adjusted by that year's anomaly in an environmental variable (Schirripa et al. 2009). Previous work has shown little difference in Sablefish stock assessment model predictions when comparing models that include environmental variables to those without when sufficient survey and age composition data are available to provide recruitment signals (Shotwell et al. 2014; Johnson et al. 2016). This condition is currently the case for Sablefish in BC.

In terms of the effects of long-term environmental change on Sablefish, two recent studies have focused on examining how environmental change in the last 1-2 decades has influenced the distribution, biodiversity, and density of groundfish species and communities (English et al. 2022; Thompson et al. 2022). These studies have included Sablefish, specifically on Sablefish old enough to be recruited to trawl gear. Environmental changes during this period were associated with temporal fluctuations in the biomass of individual species and the community as a whole; however, the amount of variability explained by changing environmental conditions was generally small compared to the ongoing recovery of the demersal fish community from recent reductions in commercial fishing intensity (Thompson et al. 2022). English et al. (2022) found that Sablefish had among the highest increases in habitat suitability among groundfish species in response to temperature increases, thereby making them one of the species most unlikely to experience population declines with increasing temperatures.

Currently the potential risk of not including EVs into the BC Sablefish operating model (or management procedure) seems low. Risk mitigation is also applied by the iterative MSE process used to guide harvest advice. Specifically, the SMS responds to new data and hypotheses about stock dynamics by virtue of periodic (3-5 year) updates of the operating model and simulation-test of candidate MPs. Annual application of the Sablefish MP provides a strong feedback link between current management action and future stock response, such that fishing pressure is reduced when the stock is perceived to decline, regardless of the mechanism. Annual evaluation of abundance trends means that departures from projected management performance are likely to be detected quickly, allowing the opportunity for invention when required.

4.5. PRECAUTION IN THE SABLEFISH MANAGEMENT SYSTEM

Sablefish have recently been prescribed as a major fish stock in Regulations under Canada's revised Fisheries Act, making them subject to the Fish Stock provisions. Under these provisions, there is a legal requirement to maintain major fish stocks at levels necessary to promote sustainability, and to develop and implement rebuilding plans for stocks that have declined below their LRPs. Estimates of stock status relative to reference points are expected to be one type of information used by DFO to evaluate fisheries sustainability under the Fisheries Act (Marentette et al. 2021). Table 9 presents a summary of Sablefish harvest strategy components that demonstrate compliance with these regulations.

Precautionary fisheries management involves systems that measure catches and abundance, rules that determine how catches should be adjusted in relation to stock and fishery monitoring data, and enforcement of management actions (Hilborn 2002). In particular, the SMS includes the core requirements for fisheries sustainability (Hilborn et al. 2015):

1. Specific objectives for abundance and fishing pressure;
2. Monitoring of (a) fishing pressure via 100% at-sea electronic monitoring of retained and released catch coupled with dockside validation of landings, and (b) abundance via an annual directed fishery-independent abundance survey and tag release-recovery program;
3. Assessments to determine if targets are being met according to pre-determined performance metrics via regular updates of the Sablefish OM;
4. Application of a simulation-tested MP that incorporates feedback effects to adjust fishing pressure in response to the assessments of stock trajectory and restrict fishing pressure when it is too high; and
5. Enforcement systems to assure compliance with regulations via catch monitoring and DFO's Conservation and Protection Branch.

The SMS follows a structured decision-making approach (Gregory et al. 2012), where performance measures are linked to specific objectives and the relative performance of management options codified by MPs is compared. As per the PA Policy requirement to consider uncertainty, uncertain stock and fishery dynamics are represented by operating models that generate simulated data with which to test candidate MPs. Collated performance measures are used to filter out those MPs that do not meet imperative or "satisficing" objectives and to quantify trade-offs between management outcomes for other objectives. This allows a strategic choice of MP, as opposed to simple replacement of an existing management option with no evidence that management performance will improve.

Objectives defined for the SMS meet legislative requirements under the Fish Stocks provisions and are aligned with the PA Policy (DFO 2006) intent to:

1. apply reduced tolerance for stock decline as stock status approaches a limit, and
2. specify measures that promote stock growth to a desired level.

Conservation objectives 1-2 of the SMS reflect the policy goal to avoid poor biological outcomes by constraining management choice of an MP to those that avoid the LRP of $0.4B_{MSY}$ with high probability (Objective 1). Objective 2 is a literal interpretation of Table 1 of the DFO PA Policy[^1], specifying a linear reduction in tolerance for further stock decline from moderate probability

(50%) at $0.8B_{MSY}$ to very low (5%) at $0.4B_{MSY}$. Those MPs that do not show simulation performance consistent with that constraint are rejected from consideration. Objective 2 also addresses the PA Policy intent to introduce corrective management action well in advance of reaching an LRP and provides a pre-specified foundation for a rebuilding plan should the stock decline to an undesirable level. Objective 1 may at first appear redundant to Objective 2, as the same tolerance for further stock decline is specified at the LRP (5%); however, the longer 36-year time frame for evaluation for Objective 1 compared with the 10-year time horizon for Objective 2 emphasizes long-term conservation performance by creating a constraint that is harder to meet when stock biomass is near the LRP. Objective 3 serves to constrain MP choice to those that can achieve a target stock level of B_{MSY} in 2052, by definition at least 50% of the time.

Sablefish stock management receives annual attention. The coastwide stock is indexed annually by the dedicated area- and depth-stratified random trap gear survey which is very selective for Sablefish and achieves relatively high precision. Application of the MP means that the survey data are analyzed each year and compared to the range of outcomes determined by the simulation for discrepancies. Undesirable departures of realised performance from that projected in simulation is unlikely to go unnoticed, allowing for corrective interventions when required. Finally, annual adjustments to the harvest rate in response to SSPM estimates of stock trajectory means stabilizing negative feedback control is exerted to establish a link between current management action and future stock response.

The SMS operates under the assumption that unpredictable changes in stock and fishery dynamics will happen and applies a consistent process for evaluating the consequences of uncertainty on decision-making. Regular (3-5 year) updating of the Sablefish operating model allows for incorporation of new data and hypotheses, or elimination of those hypotheses for which there is low support.

4.6. CURRENT LIMITATIONS

Like all assessments, the current Sablefish operating model has several uncertainties arising from data limitations and assumptions about population and fishery dynamics. Abundance index and age composition data are lacking for any gear type during the early part of the fishery (i.e., in the 1960s-1970s). In addition, age and size composition data are lacking for the longline hook fishery, which means that we continue to rely heavily on tag release-recovery data for estimating the size-selectivity of this fleet. Biological sampling in trap and longline fisheries is voluntary, so while recent data collection from these fisheries has improved relative to the 1980s-1990s, sample sizes for the most recent 4 years are still insufficient. Furthermore, the cessation of the at-sea observer program for trawl fisheries at the start of the COVID-19 pandemic in 2020 has resulted in a loss of age- and length-composition data from this fishery. Work is in progress to resume a trawl biological sampling program; however, it is not clear when the program will be re-stated, creating at least a 3-4 year gap in the time series.

Fitting to trap fishery age compositions is an ongoing source of uncertainty for population parameter inferences and MP performance. Specifically, the trap fishery overestimates the accumulator class of age-35+ male fish, and this overestimate is induced by the fits to high frequency observations of the same aged male fish in the survey data. SAB-OM overestimates catch-at-age-35+ in the trap fishery because a large group of age-35+ male fish is required to fit to the survey data and trap fishery selectivity-at-age has only a slight dome due to the lower asymptotic length for male Sablefish. Such over-estimates may point to a mis-specified selectivity curve for males, which would create positive bias in fishing mortality-at-age during the projections; on the other hand, SAB-OM fits much better to female age compositions, so the underlying selectivity-at-length model is likely well formulated. Another source of bias could be the conversion to selectivity-at-age via the growth model, the revision of which is a priority for future work. Finally, there may be bias in the sampling of biological data, which may be able to be addressed with some standardisation method (Thorson 2019).

The assumption of a closed population remains a key uncertainty in our analysis. Decades of tag release-recovery data in both the USA and Canada indicate that Sablefish in BC is not a closed population. Although the majority of Sablefish tagged in BC are recaptured within BC, we have yet to examine the relative role of local production via spawning versus net movement of Sablefish into BC from the Gulf of Alaska (GOA) in the north and the US west coast to the south. Research could be directed towards the exploration of options for taking a more coastwide view of the stock. We note, however, that the risk to the stock of incorrect assumptions about stock structure is mitigated by the inclusion of annual feedback into the BC Sablefish management system via the MP, as well as tightly regulated management and regular assessment in the three jurisdictions concerned (Alaska, BC, and the US west coast).

We continue to assume that the BC Sablefish population is at unfished equilibrium biomass in 1965. Although reported catch is low during the 1960s, thus supporting the unfished assumption, the fishing industry feels that considerable catch went unreported prior to the 1970s. The assumption of an equilibrium state in 1965 is considered necessary however given the lack of age composition and abundance index data prior to the mid-1960s, which would make the estimation of a non-equilibrium starting condition for SAB-OM difficult.

Poor fits to at-sea release data in recent years indicate that SAB-OM has difficulty representing release dynamics, especially for trawl and longline fleets. We believe that the presence of large year classes in recent years may be exposing some weaknesses in assumptions about how at-sea releases are generated. The current formulation assumes that sub-legal fish are caught in proportion to their abundance and the fleet-specific quotas; however, this is not expected to be the case for trawl and to some extent non-directed longline hook sectors, which intercept sub-legal Sablefish in fisheries targeting other species. Future operating model updates should consider alternative ways of accounting for at-sea releases.

4.7. FUTURE REASEARCH RECOMMENDATIONS

Our ongoing iterative improvement of the Sablefish OM has resolved some challenges but those related to modelling at-sea releases need further work. In addition, the Sablefish OM is highly dependent on age composition data which is not well represented in two of the commercial gear types and fish ageing capacity shortfalls may affect future availability of age composition data. The following recommendations are intended to address these considerations over future MSE cycles.

1. A revised approach to modelling at-sea releases that captures the appropriate generating mechanisms with less impact on parameter sensitivity. There should be an experimental approach, testing various options such as modifying likelihood weights (i.e., as suggest above), implicitly modeling fleet structure changes via a time-varying selectivity component, or more explicitly splitting the trawl fleet into multiple components like bottom/mid-water and/or directed/undirected components, with effort data included to drive bycatch of Sablefish during undirected fishing.
2. Prioritise the collection of additional compositional data for legal and sub-legal sized fish from the longline and trawl fleets, with a standardised sampling protocol.

3. Consider new approaches to using index and compositional data from the trap fishery. First, trap fishery CPUE may benefit from a new standardisation method, as it currently uses nominal CPUE. On the other hand, the trap CPUE is not used as an index after 2009, so the method used for developing that index may have limited effects on the assessment outcomes. Second, there may be ways to address the fit to trap fishery age composition data (described above in limitations). Possible options include some kind of standardisation method, or an alternative growth or selectivity model to account for differences in fish availability between the surveys and the trap fishery.
4. Consider increasing the accumulator age-class above age 35. Current survey catch-at-age data observations have the highest frequency in the accumulator age-class for males, which is often interpreted as an indication that the accumulator age class is set too low.
5. Investigate the sensitivity of the operating model to the level of age composition data available, as well as the sensitivity to different allocations of ageing effort among the research survey and the three different commercial fishery gears. Given the high data requirements of SAB-OM and limited capacity for groundfish ageing in the Pacific Region, this type of analysis will help make the best use of available resources for the next OM update.
6. Consider a fished initialisation of the model rather than assuming the stock is at unfished equilibrium in 1965. While catch records immediately prior to 1965 are low, catches are known to have occurred in the early 1900s. These pre-1965 catches, combined with batch spawning behaviour, could mean that Sablefish were not at equilibrium biomass in 1965. Potential impacts of a mis-specified starting equilibrium year could be tested using simulation.
7. Consider a new prior for natural mortality rates M. The current M prior is very diffuse and does not consider Sablefish life history, while a more informative prior based on life-history characteristics may improve estimates of productivity (Burch et al. 2023).
8. Revise the treatment of length-composition data in the trawl fleet. Adding a random-at-length likelihood (Piner et al. 2018) component within SAB-OM could reduce sensitivity to growth parameter assumptions (which are currently fixed), as well as accounting for within-year growth of fish for the biomass index observations.
9. Tuning of the SSPM model to decrease bias in the legal biomass estimates, either by introducing a random-walk in SSPM process errors (a.k.a., red noise) to allow for higher variability, and/or by adjusting the skew in the SSPM production relationship.
10. Consider ways to detect effects of trans-boundary migration from the Sablefish assessment results, and include them in some way. A simple way to detect the effects would be via comparison of model estimates to those from stock assessments in neighbouring regions, where negative correlation in compositional data residuals could indicate trans-boundary movement. An incremental step to including those effects in SAB-OM would be to apply some age-specific process errors to mortality, which could mimic the effects of emigration and immigration by raising and lowering age class abundance independent of mortality and fishing (Nielsen and Berg 2014). While the risk of not accounting for Sablefish migration is low compared to risks of at-sea release related mortality, there may be some value in quantifying these effects.
11. Incorporate up-to-date tagging data. At the least, the tag-based selectivity priors could be updated to use data collected since 2018, which would also cover the time period of the recent large recruitments. Alternatively, the tagging data could be directly integrated into SAB-OM for better estimates of selectivity and mortality.

12. Update all biological model assumptions. There are several fundamental assumptions regarding the biology of BC Sablefish (i.e., growth, maturity, etc.) that match assumptions from previous models or are based fits to data from 2018 (or earlier). We recommend that these assumptions be updated before the next scheduled OM revision to ensure that biological parameters are still supported by recent data and literature. In addition, we recommend ongoing monitoring of the biological data for temporal and spatial changes in length-at-age and body condition (Kapur et al. 2021).
13. Identify a rebuilt condition for BC Sablefish. Although the stock is not in need of rebuilding at present or even in the short term, Canada's revised *Fisheries Act* requires that rebuilding plans be put in place for prescribed stocks that are at or below their LRPs. While the entry condition into a rebuilding plan has been established, a criterion for exiting the plan is also needed to transition to management under an IFMP. A point of the MSE process is to pre-plan actions in response to new data and information, so integration of a rebuilt condition into future MP evaluations will help to establish evidence that MPs are able to apply corrective feedback leading to desired management outcomes when required.
14. Continue work on the effects of environmental factors on Sablefish productivity. For example, a 'regime' approach could be taken to estimating potential environmental effects on stock recruitment dynamics (Punt et al. 2014; Perälä et al. 2016; Maunder and Thorson 2018).

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7. TABLES

Table 1. Notation used in the Sablefish Operating Model.

Symbol	Value	Description
T	57	Total number of time steps 1965 - 2021
A	35	Plus group age-class
t	$1, 2, \ldots, T$	Time step
a	$1, 2, \ldots, A$	Age-class index
λ	$17.5, 22.5, ..., 112.5$	Set of length-bin midpoints for length-at-age calculations
g	$1, 2, 3, 4, 5$	Gear index for (1) commercial trap, (2) longline hook, and (3) trawl fisheries, as well as (4) Standardised (Std) and (5) Stratified Random (StRS) trap surveys.
$t_{0,g}$	$9, 1, 1$	Initial time step with positive catch in trap (1973, g = 1) longline (1965, g = 2), and trawl (1965, g=3) fisheries
$i_{0,g}$	$15, 26$	Initial time step with biomass index for the trap fishery (1979, g = 1) and Standardised survey (1990, g = 4)
$\mathcal{I}_g$		Set of time steps with CPUE indices for gear $g \in \{1, 4, 5\}$
x	$1, 2$	Sex index for males ($x = 1$) and females ($x = 2$)
B_0		Unfished female spawning stock biomass
h		Beverton-Holt stock-recruitment steepness
R_0		Unfished equilibrium age-1 recruitment
$S_{a,x}$		Unfished equilibrium survivorship-at-age and sex
ϕ		Unfished equilibrium spawning biomass per recruit
a_h, b_h	$50, 25$	Beta prior parameters for steepness
ω_t		Annual recruitment processs error log-deviations
σ_R	1	Standard error of ω_t recruitment deviations
q_g		Catchability coefficient for StRS ($g = 5$)
$q_{g,t}$		Time-varying catchability coefficient Trap ($g = 1$) and Std ($g = 4$)
$\iota_{g,t}$		Annual jumps in $\log q_{g,t}$ for Trap ($g = 1$) and Std ($g = 4$)
τ_g^q	0.1	Standard deviation in jumps $\iota_{g,t}$ for Trap ($g = 1$) and Std ($g = 4$)
M_x		Natural mortality rate for males ($x = 1$) and females ($x = 2$)
μ_M	0.1	Natural mortality prior mean for males and females
σ_M	0.1	Natural mortality prior standard deviation for males and females
$L_{\infty,x}$	$68, 72$	Asymptotic length (cm) for males ($x = 1$) and females ($x = 2$)
$\sigma_{L,x}$	$0.12, 0.12$	CV in length-at-age distribution
K_x	$0.29, 0.25$	von Bertalanffy growth constant for males and females
L_1	32.5	Length-at-age 1 (same for males and females)
c_1, c_2	$1.04e - 5, 3.08$	Allometric length-weight transformation coefficients

Symbol	Value	Description
a_{50}, a_{95}	$5, 12$	Age-at-50% and -95% maturity
L_{lim}	55	Minimum size limit (cm) for commercial fisheries
$L_{a,x}$		Mean length-at-age (cm) for males and females
$w_{a,x}$		Mean weight-at-age (cm) for males and females
m_a		Proportion females mature-at-age
$p^R_{a,x,g,t}$		Proportion of age class a fish retained by gear type g in year t
$s_{l,g}$		Selectivity-at-length for gear g
$s_{a,x,g}$		Mean selectivity-at-age for gear g and sex x
α_g		Selectivity α parameter for gear g, either length-at-50%, length-at-max, or shape parameter depending on functional form (asymptotic, normal, or gamma, resp.)
β_g		Selectivity β parameter for gear g, either length-at-95%, variation, or scale parameter depending on functional form (asymptotic, normal, or gamma, resp.)
μ_{α_g}	$62.83, 63.73, 32.5, 52, 52$	Selectivity α parameter prior mean for gear g
σ_{α_g}	$0.186, 0.1, 3.25, 100, 100$	Selectivity α parameter prior mean for gear g
μ_{β_g}	$4, 4, 1, 9.97, 9.97$	Selectivity β parameter prior standard deviation for gear g
σ_{β_g}	$0.649, 0.1, 0.1, 100, 100$	Selectivity β parameter prior standard deviation for gear g
d_g	$0.16, 0.35, 1.6$	Instantaneous discard mortality rate (yr^{-1}) for Trap, Hook, and Trawl ($g \in \{1, 2, 3\}$)
$N_{a,x,t}$		Numbers-at-age a for sex x in year t
B_t		Female spawning biomass in year t
$C_{g,t}$		Observed total catch (biomass units) for gear g in year t
$F_{g,t}$		Fully selected instantaneous fishing mortality rate (yr^{-1}) for gear g in year t
$\delta_{g,t}$		Annual jumps in $\log F_{g,t}$ for gear g from year $t-1$ to t
σ_F	0.3	Standard deviation of jumps in $\log F_{g,t}$ random walk
$Z_{a,x,t}$		Total instantaneous mortality rate (yr^{-1}) for age a and sex x in year t
$C_{a,x,g,t}$		Expected catch-at-age (numbers) a and sex x by gear g in year t
$C'_{a,x,g,t}$		Expected catch-at-age (biomass units) a and sex x by gear g in year t
$C_{g,t}$		Observed total legal sized landings (biomass units) for gear g in year t
$\hat{C}_{g,t}$		Expected total legal sized landings (biomass units) for gear g in year t
τ^{cat}_g	$0.01, 0.01, 0.1$	Assumed standard error in landing observation residuals for $g = 1, 2, 3$
$D_{a,x,g,t}$		Expected discards-at-age (numbers) a and sex x by gear g in year t
$D'_{a,x,g,t}$		Expected discards-at-age (biomass units) a and sex x by gear g in year t
$D_{g,t}$		Observed total sub-legal at-sea releases (biomass units) for gear g in year t
$\hat{D}_{g,t}$		Expected total sub-legal at-sea releases (biomass units) for gear g in year t
τ^{rel}_g	0.1	Assumed standard error in at-sea release observation residuals for trawl $g = 3$

Symbol	Value	Description
B_t^{leg}		Legal sized biomass in year t
$U_{g,t}$		Legal harvest rate by gear g in year t
U_t		Total legal harvest rate in year t
$I_{g,t}$		Observed biomass index for gear $g \in \{1,4,5\}$ in year t
$\hat{I}_{g,t}$		Expected biomass index for gear $g \in \{1,4,5\}$ in year t
$\hat{\tau}_g^{idx}$		Conditional MLE of biomass index observation log-residual standard error
$u_{a,g,t}$		Observed composition data for age a by gear g at time t
$\hat{u}_{a,g,t}$		Expected composition data for age a by gear g at time t
$\hat{\tau}_{g,x}^{age}$		Conditional MLE of age composition sampling error
$u_{\lambda,g,t}$		Observed composition data for age a by gear g at time t
$\hat{u}_{\lambda,g,t}$		Expected composition data for age a by gear g at time t
$\hat{\tau}_{g,x}^{len}$		Conditional MLE of length composition sampling error
Q		Ageing error distribution matrix

Table 2. Process and observation model equations for the Sablefish Operating Model.

No.	Equation
Model Parameters	
(P.1)	$\Theta^{lead} = \big(B_0, \{\omega_t\}_{t\in 1:T}, M_x, \{\log F_{g,t_{0,g}}\}_{g\in 1:3}, \{\delta_{g,t}\}_{g\in 1:3,t\in 1:T}, \{\alpha_g\}_{g\in 1:3}, \{\beta_g\}_{g\in 1:3}, \{\log q_{g,i_{0,g}}\}_{g\in\{1,4\}}, \{\iota_{g,t}\}_{g\in\{1,4\},t\in\mathcal{I}_g}\big)$
(P.2)	$\Theta^{cond} = \left(\{\log q_5\}, \{\tau_g^{age}\}_{g\in\{1,4,5\}}, \tau_3^{len}\right)$
(P.3)	$\Theta^{fixed} = \left(\{m_a\}_{a\in 1:35}, \sigma_R, \sigma_F, \{\tau_g^{q}\}_{g\in\{1,4\}}\right)$
(P.4)	$\Theta^{priors} = (\mu_M, \sigma_M, a_h, b_h, \{m_{\alpha,g}, s_{\alpha,g}, m_{\beta,g}, s_{\beta,g}\}_{g\in 1:5})$
Growth and selectivity	
(OM.1)	$L_{a,x} = L_1 + (L_1 - L_{\infty,x}) \cdot e^{-K_x(a-1)}$
(OM.2)	$D(\lambda \mid a,x) = e^{-\left(\frac{(\lambda - L_{a,x})}{2\cdot\sigma_L \cdot L_{a,x}}\right)^2}$
(OM.3)	$P(\lambda \mid a,x) = \dfrac{D(\lambda \mid a,x)}{\sum_{\lambda'} D(\lambda' \mid a,x)}$
(OM.4)	$p^R_{a,x,g} = \dfrac{\sum_{\lambda > 55} D(\lambda \mid a,x)}{\sum_{\lambda'} D(\lambda \mid a,x)}$
(OM.5)	$w_{a,x} = c_1 L_{a,x}^{c_2}$
(OM.6)	$s_{\lambda,g} = \begin{cases} \left(1 + e^{-\log 19 \frac{\lambda - \alpha_g}{beta_g}}\right)^{-1} & g = 4,5 \\ e^{-\left(\frac{\lambda - \alpha_g}{\beta_g}\right)^2} & g = 1,2 \\ \lambda^{\alpha_g - 1} e^{-\lambda/\beta_g} & g = 3 \end{cases}$
(OM.7)	$s_{a,x,g} = \sum_{\lambda} s_{\lambda,g} P(\lambda \mid a,x)$
Unfished equilibrium states	
(EQ.1)	$m_a = \left(1 + e^{-\log 19 \frac{a - a_{50}^{mat}}{a_{95}^{mat} - a_{50}^{mat}}}\right)^{-1}$
(EQ.2)	$S_{a,x} = \begin{cases} 0.5 & a = 1, \\ S_{a-1,x} e^{-M_x} & 1 < a < A \\ S'_{a-1,x} e^{-M_x}/(1 - e^{-M_x}) & a = A. \end{cases}$
(EQ.3)	$\phi = e^{-M_f} \cdot \sum_a S_{a,f} \cdot w_{a,f} \cdot m_a$
(EQ.4)	$R_0 = B_0/\phi$
(EQ.5)	$N_{a,x,1} = R_0 \cdot S_{a,x}$
Recruitment, numbers-at-age, and spawning biomass	
(N.1)	$R_t = \dfrac{4R_0 B_{t-1}}{B_0(1-h) + (5h-1)B_{t-1}} \cdot e^{\sigma_R \cdot \omega_t}$

(N.2) $$N_{a,x,t} = \begin{cases} 0.5 \cdot R_t & a = 1, \\ N_{a-1,x,t-1} \cdot e^{-Z_{a-1,x,t-1}} & 1 < a < A \\ N_{A-1,x,t-1} \cdot e^{-Z_{A-1,x,t-1}} + N_{A,x,t-1} \cdot e^{-Z_{A,x,t-1}} & a = A. \end{cases}$$

(N.3) $$B_t = \sum_{a=1}^{A} (m_a w_{a,2} N_{a,2,t})$$

Fishing mortality

(F.1) $$\log F_{g,t} = \begin{cases} \log F'_g & t = t_{0,g} \\ \log F_{g,t-1} + \sigma_F \cdot \delta_{g,t} & t > t_{0,g} \end{cases}$$

(F.2) $$Z_{a,x,t} = M_x + \sum_g s_{a,x,g} \cdot F_{g,t} \left(p^R_{a,x,g} + (1 - p^R_{a,x,g}) d_g \right)$$

(F.3) $$C_{a,x,g,t} = N_{a,x,t} \frac{s_{a,x,g} F_{g,t} p^R_{a,x,g}}{Z_{a,x,t}} \left(1 - e^{-Z_{a,x,t}} \right)$$

(F.4) $$C'_{a,x,g,t} = C_{a,x,g,t} \cdot w_{a,x}$$

(F.5) $$\hat{C}_{g,t} = \sum_a \sum_x C'_{a,x,g,t}$$

(F.6) $$D_{a,x,g,t} = N_{a,x,t} \frac{s_{a,x,g} F_{g,t} (1 - p^R_{a,x,g})}{Z_{a,x,t}} \left(1 - e^{-Z_{a,x,t}} \right)$$

(F.7) $$D'_{a,x,g,t} = D_{a,x,g,t} \cdot w_{a,x}$$

(F.8) $$\hat{D}_{g,t} = \sum_a \sum_x D'_{a,x,g,t}$$

(F.9) $$B_{g,t} = \sum_a \sum_x \left(s_{a,x,g} w_{a,x} N_{a,x,g} e^{-f_g Z_{a,x,t}} \right)$$

Table 3. Statistical model prior and likelihood functions for the Sablefish Operating Model. The function $\mathbf{1}(X)$ *is the indicator function, taking value 1 when* X *is true, and 0 when* X *is false.*

No.	Equation
Observation models for biomass index and composition data	
(O.1)	$q_{g,t} = \begin{cases} q_g & t = t_{g,1} \\ q_{g,t-1} e^{\tau_g^q \iota_{g,t}} & t_{g,1} < t < t_{g,n_g} \end{cases}$
(O.2)	$\hat{I}_{g,t} = q_{g,t} B_{g,t}$
(O.3)	$u'_{a,x,g,t} = \dfrac{p^{rep}_{a,x,g} s_{a,x,g} N_{a,x,g} e^{-f_g Z_{a,x,t}}}{\sum_{a'} s_{a',x,g} N_{a',x,g} e^{-f_g Z_{a',x,t}}}$
(O.4)	$\hat{u}_{a,xg,t} = Q \cdot u'_{x,g,t}$
(O.5)	$\hat{u}_{l,x,g,t} = \dfrac{\sum_a P(l \mid a,x) s_{a,x,g} N_{a,x,g} e^{-f_g Z_{a,x,t}}}{\sum_{l'} \sum_{a'} P(l \mid a',x) s_{a',x,g} N_{a',x,g} e^{-f_g Z_{a',x,t}}}$
Biomass index likelihood	
(NLL.1)	$n_g = \sum_{t=1}^{T} \mathbf{1}(I_{g,t} > 0)$
(NLL.2)	$z_{g,t} = \begin{cases} \log \frac{I_{g,t}}{B_{g,t}} & g = 5 \\ \log \frac{I_{g,t}}{q_{g,t} B_{g,t}} & g = 1,4 \end{cases}$
(NLL.3)	$\hat{q}_g = \dfrac{1}{n_g} z_{g,t}, \quad g = 4$
(NLL.4)	$(\hat{\tau}_g^{idx})^2 = \begin{cases} \frac{1}{n_g} \sum_t \mathbf{1}(I_{g,t} > 0) \cdot (z_{g,t} - \hat{q}_g)^2 & g = 5 \\ \frac{1}{n_g} \sum_t \mathbf{1}(I_{g,t} > 0) \cdot (z_{g,t})^2 & g = 1,4 \end{cases}$
(NLL.5)	$l_{g,1} = \dfrac{1}{2} \left(n_g \log \hat{\tau}^2 + n_g \right)$
Catch and Release Likelihoods	
(CL.1)	$l_{g,2} = \dfrac{1}{2(\tau_g^{cat})^2} \sum_{t,g} \left(\log C_{g,t} - \log \hat{C}_{g,t} \right)^2$
(CL.2)	$(\hat{\tau}_g^{rel})^2 = \dfrac{1}{\sum_{t'} \mathbf{1}(D_{g,t'} > 0)} \cdot \sum_t \mathbf{1}(D_{g,t} > 0) \cdot (\log D_{g,t} - \log \hat{D}_{g,t})^2$
(CL.3)	$l_{g,3} = \sum_{t,g} \dfrac{\left(\log D_{g,t} - \log \hat{D}_{g,t} \right)^2}{2(\hat{\tau}_g^{rel})^2}$
Age composition likelihood	
(AL.1)	$n^{age}_{x,g,t} = \sum_a \mathbf{1}(u_{a,x,g,t} > 0)$
(AL.2)	$\eta_{a,x,g,t} = \log u_{a,x,g,t} - \log \hat{u}_{a,x,g,t}$
(AL.3)	$Z_{x,g} = \sum_t \sum_a \left(\eta_{a,x,g,t} - \dfrac{1}{n^{age}_{x,g,t}} \sum_{a'} \eta_{a',x,g,t} \right)$

(AL.4) $$(\hat{\tau}^{age}_{g,x})^2 = \frac{1}{\sum_t n^{age}_{x,g,t}} Z_{x,g}$$

(AL.5) $$l_{g,4} = \sum_x \left(\frac{1}{2} \sum_t n^{age}_{x,g,t} \cdot \log(\hat{\tau}^{age}_{g,x})^2 \right)$$

Length composition likelihood

(LL.1) $$n^{len}_{x,g,t} = \sum_a \mathbf{1}(u_{l,x,g,t} > 0)$$

(LL.2) $$\eta_{l,x,g,t} = \log u_{l,x,g,t} - \log \hat{u}_{l,x,g,t}$$

(LL.3) $$Z_{x,g} = \sum_t \sum_a \left(\eta_{l,x,g,t} - \frac{1}{n^{len}_{x,g,t}} \sum_{l'} \eta_{l',x,g,t} \right)$$

(LL.4) $$(\hat{\tau}^{len}_{g,x})^2 = \frac{1}{\sum_t n^{len}_{x,g,t}} Z_{x,g}$$

(LL.5) $$l_{g,5} = \sum_x \left(\frac{1}{2} \sum_t n^{len}_{x,g,t} \cdot \log(\hat{\tau}^{len}_{g,x})^2 \right)$$

Model priors

(Pr.1) $$p_h = -\left[(a_h - 1) \log h + (b_h - 1) \log(1 - h) \right]$$

(Pr.2) $$p_M = \frac{M_m - \mu_m}{2\sigma^2_M} + \frac{M_f - \mu_f}{2\sigma^2_M}$$

(Pr.3) $$p_s = \sum_g \left(\frac{\alpha_g - \mu_{\alpha_g}}{2\sigma^2_{\alpha_g}} + \frac{\beta_g - \mu_{\beta_g}}{2\sigma^2_{\beta_g}} \right)$$

(Pr.4) $$p_R = \sum_{t=2}^{T} \omega_t^2$$

(Pr.5) $$p_F = \sum_g \sum_{t=2}^{T} \delta^2_{t,g}$$

(Pr.6) $$p_{B_0} = -\log B_0$$

(Pr.7) $$p_q = \sum_{g \in \{1,4\}} \sum_{t \in \mathcal{I}_g} \iota^2_{g,t}$$

Objective Function

(OF.1) $$f = \sum_g \left(w^{idx}_g l_{g,1} + l_{g,2} + l_{g,3} + w^{age}_g l_{g,4} + w^{len}_g l_{g,5} \right) + p_h + p_M + p_s + p_R + p_F + w_B p_{B_0}$$

Table 4. Performance statistics calculated for BC Sablefish closed loop simulations for each reference set operating model. Biomass $B_{t,i}$ represents spawning stock biomass in year t and simulation replicate i, and reference points with a subscript i (e.g., $B_{MSY,i}$) represent the particular reference point value for the OM posterior draw that replicate is conditioned upon. The indicator function $\mathbf{1}(X\ is\ TRUE) = 1$ *or* $\mathbf{1}(X\ is\ FALSE) = 0$.

Performance Measure	Description	Definition
Objective 1 $P(B > 0.4B_{MSY})$	Proportion of simulation trials and years where spawning biomass exceeds the limit reference point of $0.4B_{MSY}$ over a 2 generation time period.	$P(B > .4B_{MSY}) = \frac{\sum_{i=1}^{100}\sum_{t=2022}^{2057}\mathbf{1}(B_{t,i}>0.4B_{MSY,i})}{36\cdot100}$
Objective 2 $P(Decline)$	Proportion of simulation trials where spawning biomass in 2031 is lower than spawning biomass in 2022.	$P(B_{2031} < B_{2022}) = \frac{1}{100}\sum_{i=1}^{100}\mathbf{1}\left(B_{2031,i} < B_{2022,i}\right)$
Objective 3 $P(B_{2052} > B_{targ})$	Proportion of simulation trials where spawning biomass in 2052 is above B_{targ}	$P(B_{2052} \geq B_{targ}) = \frac{1}{100}\sum_{i=1}^{100}\mathbf{1}\left(B_{2052,i} \geq B_{targ,i}\right)$
Objective 4 $P(C_t > 1,992)$	Proportion of simulation trials and years where catch is above the minimum viable level of 1,992 tonnes, over 2 Sablefish generations	$P(C_t \geq 1.992) = \frac{1}{36\cdot100}\sum_{i=1}^{100}\sum_{t=2022}^{2057}\mathbf{1}\left(C_{t,i} > 1.992\right)$
Objective 5 $\bar{C}$	Median across replicates of average annual landed catch from 2022 - 2031	$\bar{C}_t = \text{median}_i\left(\frac{1}{10}\sum_{t=2022}^{2031}C_{t,i}\right)$
Catch Variability AAV	Median across replicates of average absolute annual change in landed catch	$AAV = \text{median}_i\sum_{t=2022}^{2057}\left(\frac{\lvert C_{t,i}-C_{t-1,i}\rvert}{\sum_{t=2022}^{2057}C_{t,i}}\right)$
Average unviable catch $E(C_t \mid C_t < 1,992)$	Median across replicates of average catch in years where TACs are below the minimum viable level of 1,992 tonnes, over 2 Sablefish generations	$E(C_t\ \lvert C_t < 1992) = \text{median}_i\left(\frac{C_{t,i}\mathbf{1}(C_{t,i}<1.992)}{\mathbf{1}(C_{t,i}>1.992)}\right)$

Table 5. Sablefish operating model reference set Bayesian posterior estimates of life history parameters, MSY based reference points, and 2021 stock status relative to those reference points. The table header shows the reference set operating model label, while the row labels describe the estimated quantity. Biomass quantities (B_0, B_{2021}, B_{MSY}, and MSY) are in kilotonnes, recruitment is in millions of fish, stock-recruit steepness h, harvest rates U_{2021}, U_{MSY} are unitless, and natural mortality M_m, M_f have units yr^{-1}. Relative biomass and harvest rates are also unitless, and posterior probabilities are used to describe the stock status relative to $0.4B_{MSY}$, $0.8B_{MSY}$, B_{MSY}, and U_{MSY}.

	baseOM	hiProd	loProd	hiRelCV	loRelCV	Composite
B_0	56.56 (3.83)	56.15 (3.78)	56.38 (3.67)	55.42 (3.69)	55.65 (3.7)	-
R_0	3.81 (0.35)	3.78 (0.35)	3.8 (0.34)	3.66 (0.34)	3.76 (0.35)	-
h	0.67 (0.05)	0.74 (0.05)	0.61 (0.06)	0.65 (0.06)	0.67 (0.05)	-
M_m	0.052 (0.003)	0.051 (0.003)	0.052 (0.003)	0.05 (0.003)	0.051 (0.003)	-
M_f	0.094 (0.003)	0.094 (0.003)	0.094 (0.003)	0.093 (0.003)	0.094 (0.003)	-
B_{2022}	30.29 (4.71)	29.86 (4.61)	29.38 (4.82)	22.93 (3.83)	36.17 (5.89)	29.94
U_{2021}	0.045 (0.007)	0.045 (0.007)	0.046 (0.007)	0.055 (0.009)	0.039 (0.006)	0.046
B_{MSY}	22.82 (1.55)	21.93 (1.44)	23.49 (1.59)	22.58 (1.58)	22.49 (1.49)	22.72
U_{MSY}	0.065 (0.006)	0.072 (0.006)	0.058 (0.006)	0.063 (0.007)	0.065 (0.006)	0.064
MSY	3.5 (0.29)	3.71 (0.29)	3.28 (0.28)	3.37 (0.28)	3.47 (0.29)	3.47
B_{2022}/B_{MSY}	1.33 (0.19)	1.38 (0.19)	1.25 (0.19)	1.02 (0.16)	1.61 (0.24)	1.32
$p(B_{2022} > 0.4B_{MSY})$	1	1	1	1	1	1
$p(B_{2022} > 0.8B_{MSY})$	1.00	1.00	1.00	0.92	1.00	0.99
$p(B_{2022} > B_{MSY})$	0.970	0.990	0.930	0.560	1.000	0.918
U_{2021}/U_{MSY}	0.69 (0.13)	0.63 (0.11)	0.8 (0.16)	0.87 (0.19)	0.6 (0.11)	0.72
$p(U_{2021} < U_{MSY})$	0.97	1.00	0.88	0.75	1.00	0.94

Table 6. Sablefish operating model reference set likelihood function values, broken into fleet and data components.

	baseOM	hiProd	loProd	hiRelCV	loRelCV
All data					
Total NLL	-1153.85	-1153.68	-1153.99	-1391.61	-1055.06
Biomass index data					
Total Index NLL	-66.19	-66.27	-66.10	-66.09	-65.52
Comm. Trap	-41.73	-41.73	-41.72	-41.80	-41.65
Std. Survey	-7.03	-7.03	-7.04	-7.02	-7.04
StRS Survey	-17.43	-17.51	-17.34	-17.27	-16.84
Catch data					
Total Catch NLL	146.52	146.41	146.63	14.53	258.03
Comm. Trap	0.08	0.08	0.08	0.08	0.08
Longline Hook	0.11	0.11	0.11	0.11	0.11
Trawl	146.34	146.23	146.44	14.34	257.84
Release data					
Total Release NLL	99.21	99.12	99.31	40.61	19.27
Comm. Trap	6.43	6.42	6.45	5.52	7.68
Longline Hook	6.21	6.22	6.21	5.78	6.51
Trawl	86.57	86.48	86.65	29.31	5.07
Age composition data					
Total Age NLL	-1341.21	-1340.75	-1341.63	-1389.92	-1274.65
Comm. Trap	-356.08	-355.66	-356.52	-351.62	-355.54
Std. Survey	-431.96	-431.65	-432.27	-434.60	-426.49
StRS Survey	-553.17	-553.44	-552.84	-603.70	-492.62
Length composition data					
Total Length NLL	7.81	7.81	7.82	9.26	7.81
Trawl	7.81	7.81	7.82	9.26	7.81

Table 7. SAB-OM posterior estimates of leading model parameters and MSY based reference points under a retrospective analysis, varying the last model year from $T = 2005, ..., 2021$. Biomass quantities (B_0, B_T, B_{MSY} and MSY) are in kilotonnes, and stock-recruit steepness h and harvest rates U_T, U_{MSY} are unitless.

T	B_0	R_0	h	B_T	U_T	B_{MSY}	U_{MSY}	MSY	B_T/B_{MSY}	$P(B_T > LRP)$	$P(B_T > B_{MSY})$	$P(U_T < U_{MSY})$	U_T/U_{MSY}
2005	51.39	3.85	0.63	15.44	0.111	21.32	0.058	3.20	0.73	1.00	0.00	0.00	1.89
2006	49.21	3.47	0.59	18.70	0.087	20.63	0.056	3.01	0.91	1.00	0.26	0.02	1.53
2007	50.30	3.53	0.58	16.64	0.076	21.32	0.055	3.00	0.79	1.00	0.07	0.09	1.38
2008	48.70	3.23	0.57	19.81	0.056	20.89	0.054	2.87	0.96	1.00	0.41	0.43	1.05
2009	48.89	3.37	0.57	15.91	0.060	20.74	0.057	3.00	0.77	1.00	0.07	0.44	1.04
2010	50.43	3.66	0.62	12.86	0.070	20.68	0.065	3.37	0.62	1.00	0.00	0.34	1.08
2011	52.37	3.69	0.61	13.58	0.062	21.34	0.065	3.43	0.64	1.00	0.00	0.61	0.95
2012	50.82	3.60	0.60	12.15	0.074	21.01	0.064	3.34	0.58	1.00	0.00	0.24	1.16
2013	51.14	3.60	0.60	12.18	0.063	21.14	0.064	3.35	0.57	1.00	0.00	0.51	0.99
2014	51.18	3.64	0.70	11.40	0.061	19.91	0.079	3.78	0.57	1.00	0.00	0.97	0.78
2015	52.72	3.82	0.65	11.66	0.093	21.07	0.074	3.74	0.55	1.00	0.00	0.08	1.27
2016	52.90	3.76	0.61	14.24	0.057	21.65	0.068	3.56	0.66	1.00	0.00	0.81	0.84
2017	52.21	3.67	0.69	10.59	0.077	20.84	0.073	3.63	0.51	0.93	0.00	0.39	1.05
2018	53.71	3.57	0.65	17.23	0.061	21.85	0.066	3.41	0.79	1.00	0.04	0.66	0.93
2019	54.26	3.59	0.65	23.65	0.052	22.12	0.065	3.38	1.07	1.00	0.68	0.87	0.80
2020	56.26	3.94	0.68	21.87	0.046	22.26	0.071	3.70	0.99	1.00	0.46	0.99	0.66
2021	56.56	3.81	0.67	26.62	0.045	22.82	0.065	3.50	1.16	1.00	0.87	0.97	0.69

Table 8. BC Sablefish management performance metrics under current management procedure, and 16 alternative procedures that differ by the maximum target harvest rate. Conservation objectives have all been met by the tested MPs, which is indicated by a bullet. Catch objectives 4 and 5 have no threshold and are shown as numerical values, which have units of probability (Obj. 4) and catch in tonnes (Obj 5). Additional performance statistics shown include catch in 2022 (C_{2022}), average catch when the catch limits are unviable over the long-term ($E(C_t \mid C_t < 1.992)$), average annual variation in catch (AAV; units = percentage), and spawning biomass in 2022 (B_{2056}; units = thousands of tonnes).

	Obj. 1	Obj. 2	Obj. 3	Obj. 4	Obj. 5				
MP	$P(B_t > 0.4B_{MSY})$	$P(B_{2031} < B_{2022})$	$P(B_{2052} > B_{MSY})$	$P(C_t > 1992)$	$\bar{C}_t$	AAV	C_{2022}	$E(C_t \mid C_t < 1992)$	B_{2057}
currMP	●	●	●	0.98	3,148	3.95	2494	1,683	33.067
targHR6	●	●	●	0.97	3,629	4.45	2970	1,516	30.193
targHR6.1	●	●	●	0.97	3,680	4.55	3019	1,476	29.898
targHR6.2	●	●	●	0.97	3,732	4.62	3069	1,450	29.605
targHR6.3	●	●	●	0.97	3,783	4.68	3119	1,403	29.315
targHR6.4	●	●	●	0.97	3,834	4.78	3169	1,356	29.027
targHR6.5	●	●	●	0.97	3,885	4.85	3219	1,344	28.743
targHR6.6	●	●	●	0.97	3,936	4.95	3269	1,292	28.458
targHR6.7	●	●	●	0.97	3,987	5.05	3318	1,251	28.182
targHR6.8	●	●	●	0.97	4,036	5.14	3368	1,234	27.907
targHR6.9	●	●	●	0.96	4,087	5.19	3418	1,208	27.636
targHR7	●	●	●	0.96	4,136	5.29	3468	1,210	27.367
targHR7.1	●	●	●	0.96	4,185	5.39	3518	1,184	27.103
targHR7.2	●	●	●	0.96	4,234	5.50	3568	1,219	26.842
targHR7.3	●	●	●	0.95	4,283	5.64	3618	1,237	26.580
targHR7.4	●	●	●	0.95	4,332	5.75	3668	1,222	26.328
targHR7.5	●	●	●	0.94	4,380	5.86	3718	1,266	26.077

Table 9. Policy compliance of the Sablefish Management System with the Fish Stocks provisions and PA Policy (DFO 2009).

Component	Description
Stock	Sablefish (Pacific, Coastwide)
Management Paradigm	Management Strategy Evaluation (MSE) Simulation-tested Management Procedure (MP, defined below) for annual TACs consistent with objectives (defined below) Operating models (OMs) updated on a 3-5 year cycle for stock assessment and MP simulation testing
Reference Points	MSY-based reference points estimated by OMs on a 3-5 year MSE / stock assessment cycle * Limit Reference Point: LRP = 0.4B_{MSY} * Upper Stock Reference: USR = 0.8B_{MSY} * Target Reference Point: TRP = B_{MSY}
Assessment / Operating Model	Weighted ensemble of 5 age-/sex-structured operating models with uncertainty characterized via Bayes posteriors. Assessment/operating models fitted to biomass indices (fishery and 2 survey), age composition (fishery and 2 surveys) and at-sea releases of sub-legal Sablefish, along with auxiliary data from > 30 years of tag release/recovery programs.
Management Procedure:	
a. Data	Trap fishery CPUE (1979-2009) Standardized trap survey (1990-2009) Stratified random trawl survey (2003-2021) Landings (1965 - 2021)
b. Assessment method	Schaefer state-space production model (SSPM) fitted to data described in (a) above
c. HCR	Recti-linear shape with two SSPM-estimated control points: * Lower control point: LCP = 0.4B_{MSY} * Upper control point: UCP = 0.6B_{MSY} Removal reference: * Maximum target harvest rate in 2023 = 6.4%. Control points estimated annually by the SSPM. Maximum target harvest rate selected via tuning simulated MP performance against objectives (defined below)

Component	Description
Stock Status (2022):	
a. Female spawning biomass	Stock is above B_{MSY}
	B_{2022} = 29.9 kt (95% CI: 19.6 kt - 42.9 kt)
	B_{2022}/B_{MSY} = 1.32
	Stock is above LRP with high probability:
	$P(B_{2022} > LRP)$ = 100%
	Stock is above USR with high probability:
	$P(B_{2022} > USR)$ = 99%
	Stock is above TRP with moderate probability:
	$P(B_{2022} > TRP)$ = 92%
b. Harvest rate	Harvest rate is less than U_{MSY} with high probability:
	$P(U_{2021} < U_{MSY})$ = 94%
Rebuilding Plan	Not required
	Sablefish are not overfished ($B > B_{MSY}$) and not subject to overfishing ($U < U_{MSY}$)
Rebuilding Criteria	Entry:
	Terminal year stock status estimated at or below LRP with greater than 50% probability
	Exit (Rebuilt state):
	Not required at present
Objectives:	1) $P(B > B_{LRP}) \geq 0.95$: Maintain female spawning biomass above the limit reference point of $LRP = 0.4B_{MSY}$ in 95% of years measured over 2 Sablefish generations
	2) $P(decline)$: When female spawning stock biomass is between 0.4B_{MSY} and 0.8B_{MSY}, limit the probability of decline over the next 10 years from very low at 0.4B_{MSY} to moderate (50%) at 0.8B_{MSY}. At intermediate stock status levels, define tolerance for decline by linearly interpolating between the extremes.
	3) $P(B_{2052} > B_{Targ})$ = 0.50: Maintain a 50% probability of female spawning biomass above the target reference point in 2052, where the target reference point is (a) B_{MSY} when $B \geq 0.8B_{MSY}$ and (b) $0.8B_{MSY}$ when $B < 0.8B_{MSY}$.

Component	Description
	4) max(P(C_t > 1,992 tonnes)): Maximize the probability that annual catch levels remain above 1,992 tonnes, measured over two Sablefish generations 5) MaxCatch: Maximize the annual catch over 10 years

8. FIGURES

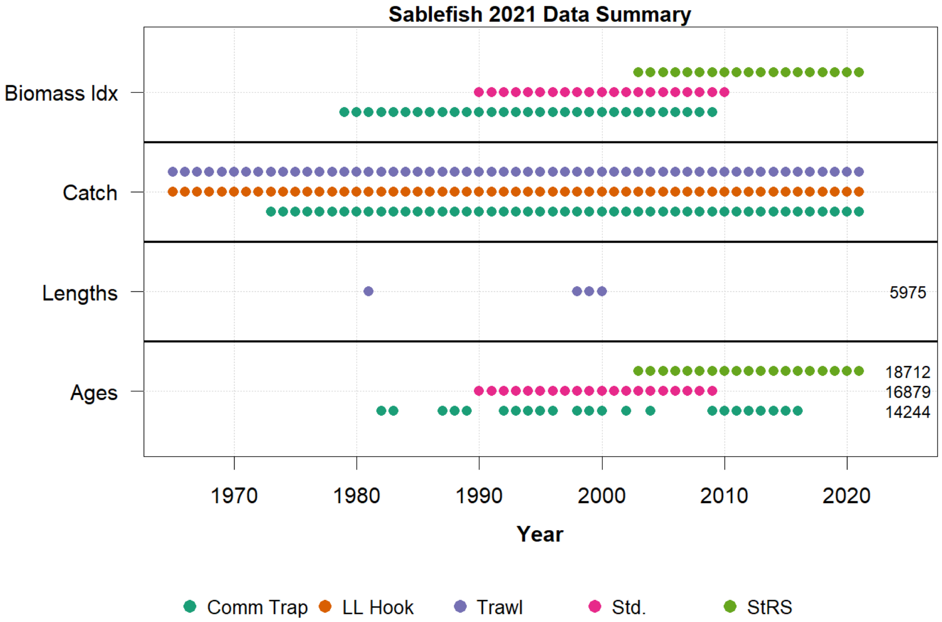

Figure 1. Summary of available index, catch, age-, and length-composition data for the Sablefish operating model as of 2021. Points indicate the presence of data in each year (x-axis) and fleet (colours explained in figure legend). For age and length composition data, the total sample size over all years is shown at the right-hand end of the panel.

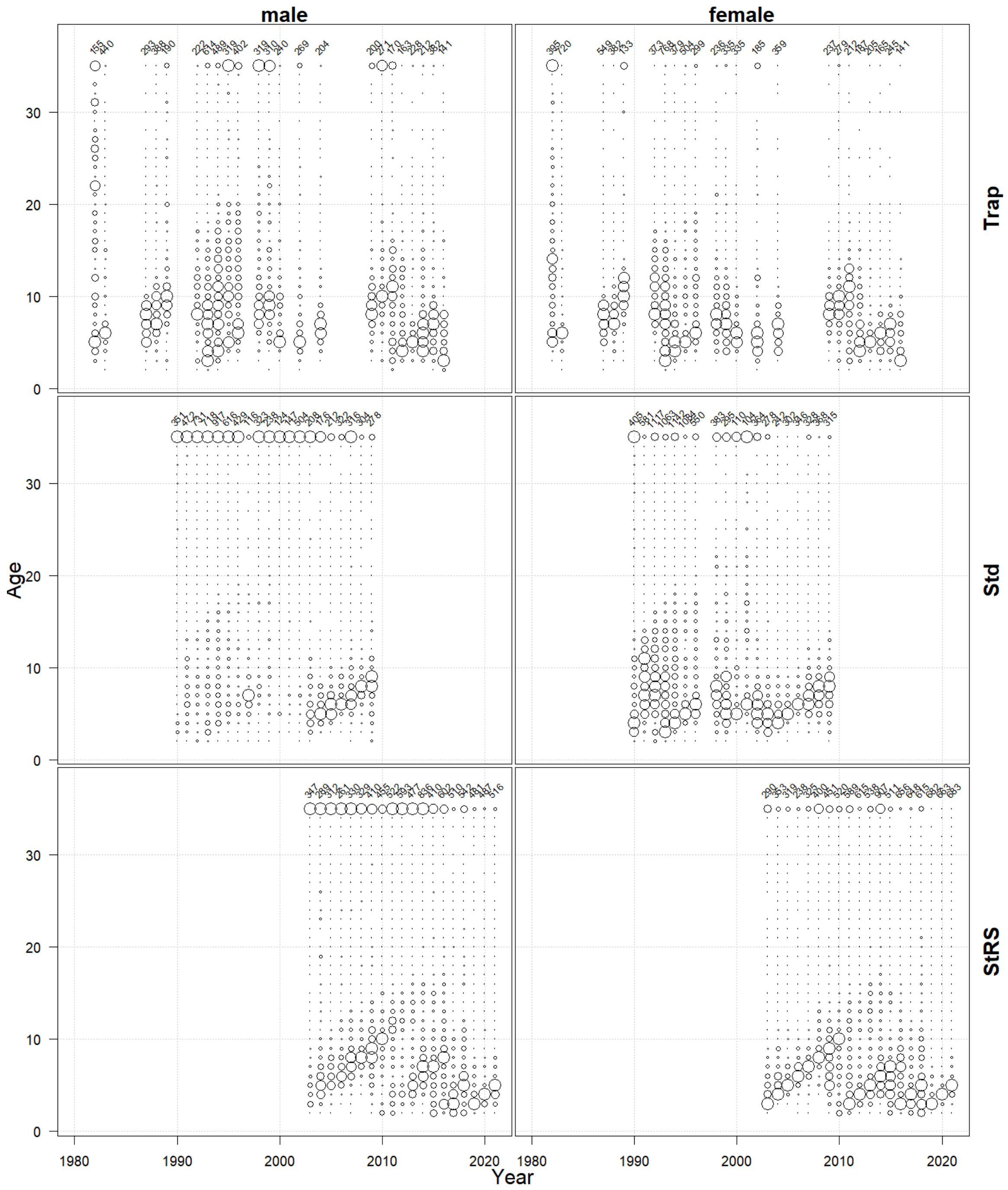

Figure 2. Age composition data for male (left) and female (right) Sablefish captured by the commercial trap fishery (top row), Standardised trap survey (middle row), and Stratified Random Survey (bottom row).

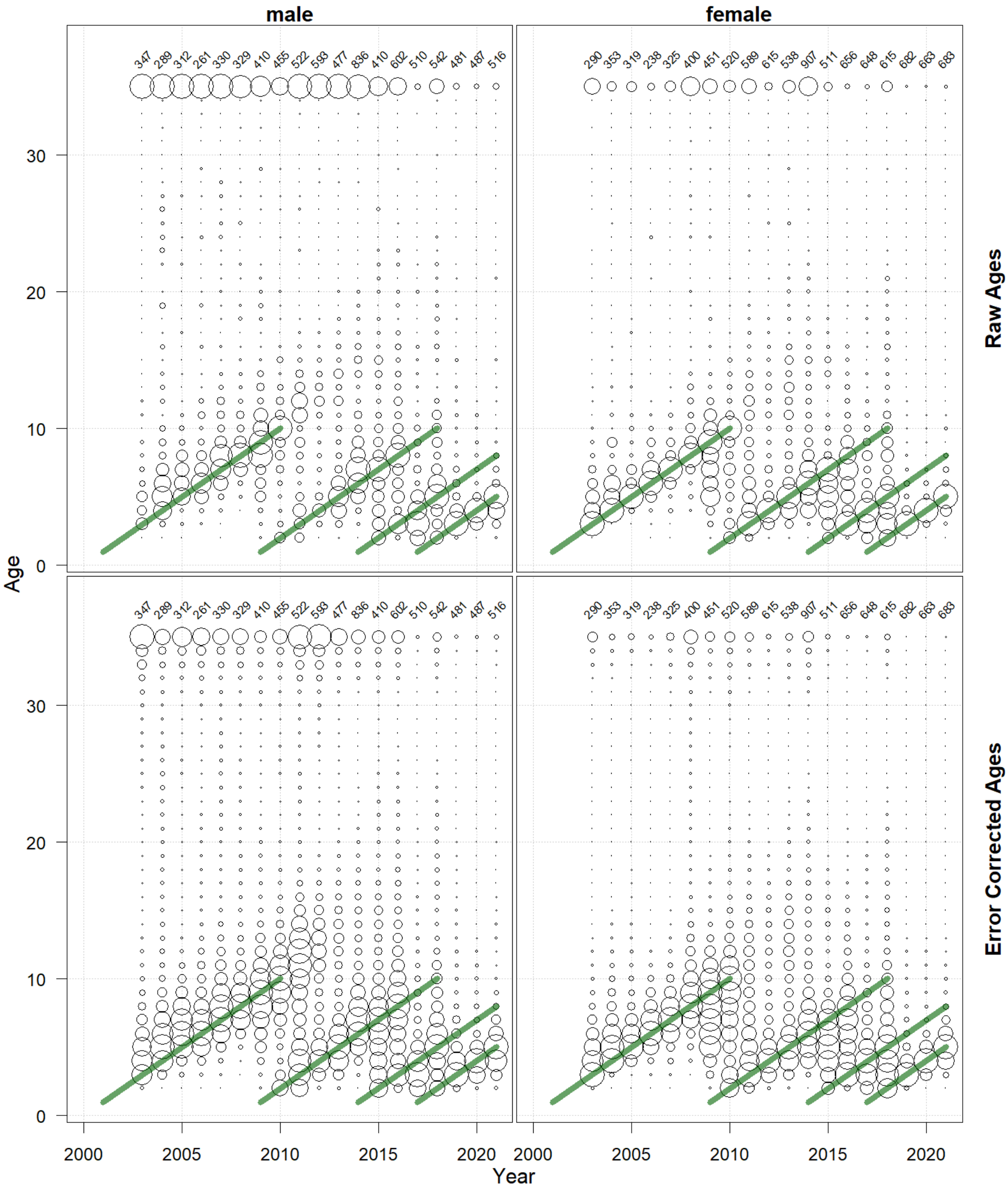

Figure 3. Age composition data in raw form (top row) and ageing-error-corrected (bottom row) for male (left) and female (right) Sablefish captured by the Stratified Random Survey. Large year classes are indicated by green lines for age-0 Sablefish in 2000, 2007, 2013, and 2016.

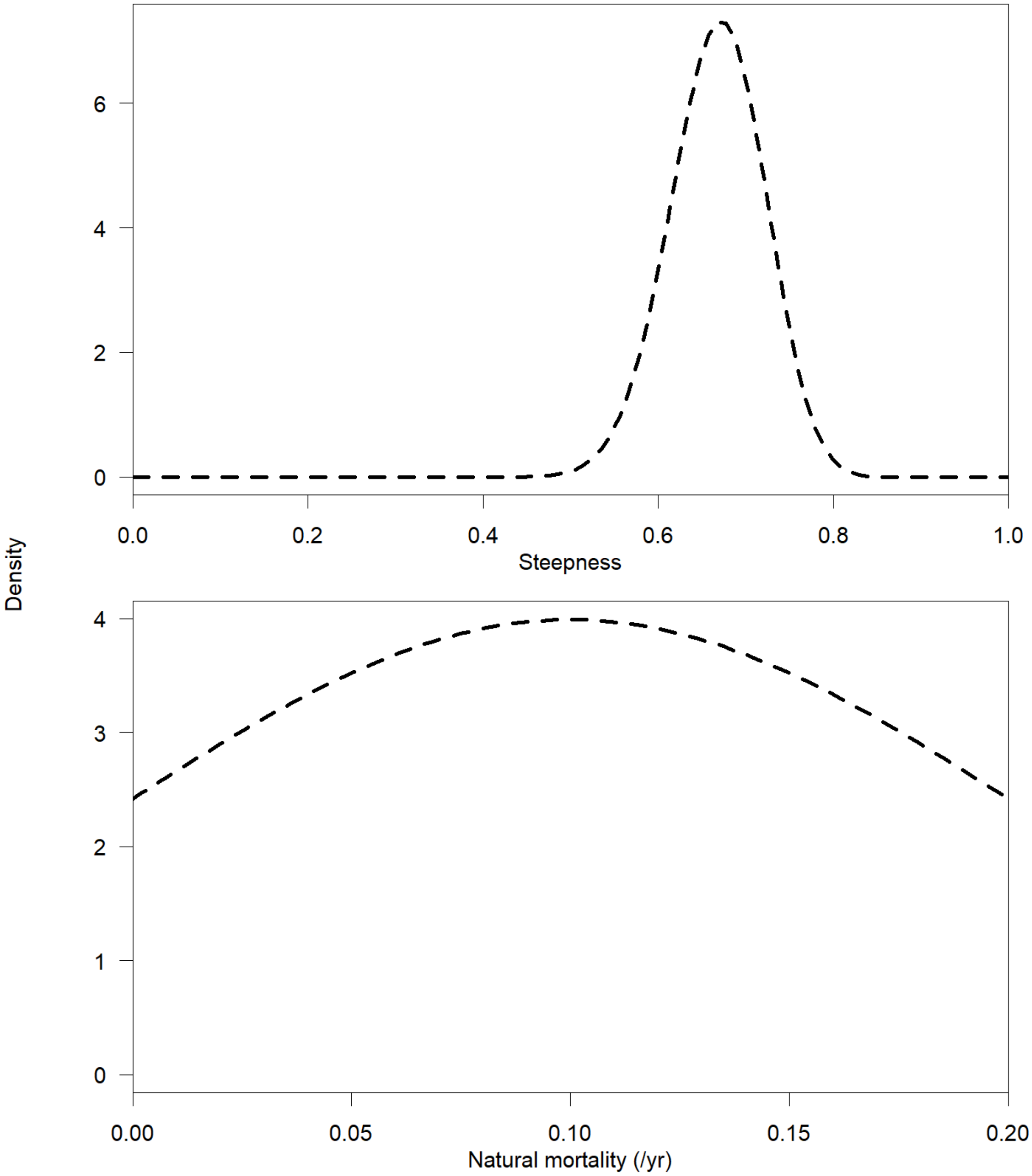

Figure 4. Prior density functions for steepness (top) and natural mortality (bottom).

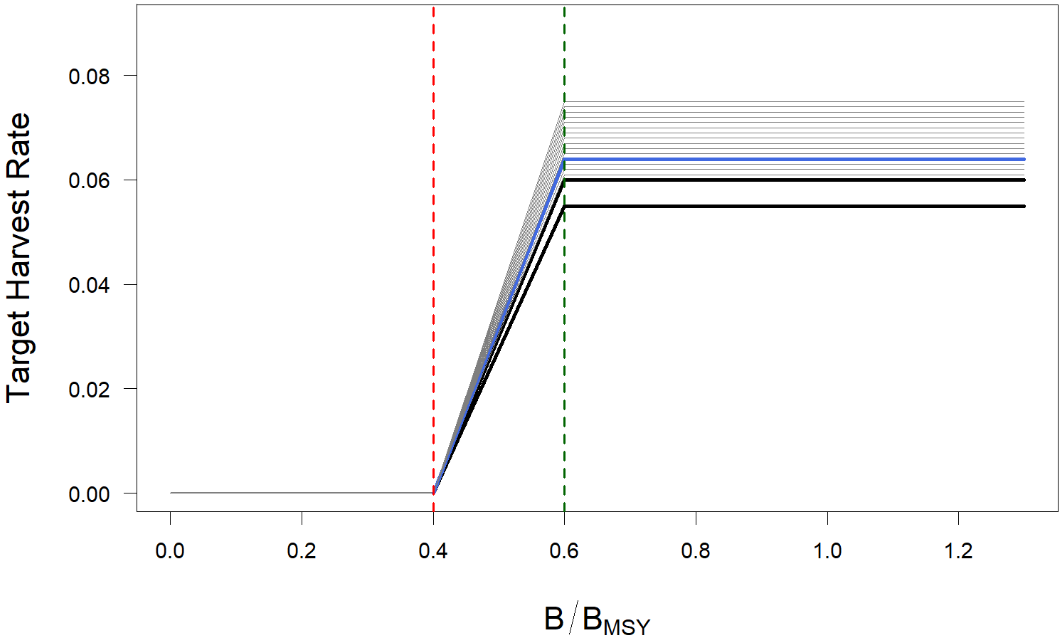

Figure 5. Harvest control rules with a range of different maximum target harvest rates (U_{max}). The x-axis is the SSPM estimate of B/B_{MSY}, from which the target harvest rate (y-axis) is determined. Each line shows an HCR that was tested in closed loop simulation, with bold black lines showing the HCR in the current MP with a maximum target harvest rate of 5.5% ($U_{max} = 0.055$) and an HCR with a 6% maximum target harvest rate ($U_{max} = 0.06$). An HCR with the weighted average optimal harvest rate of 6.4% ($U_{max} = 0.064$) is shown as a blue line.

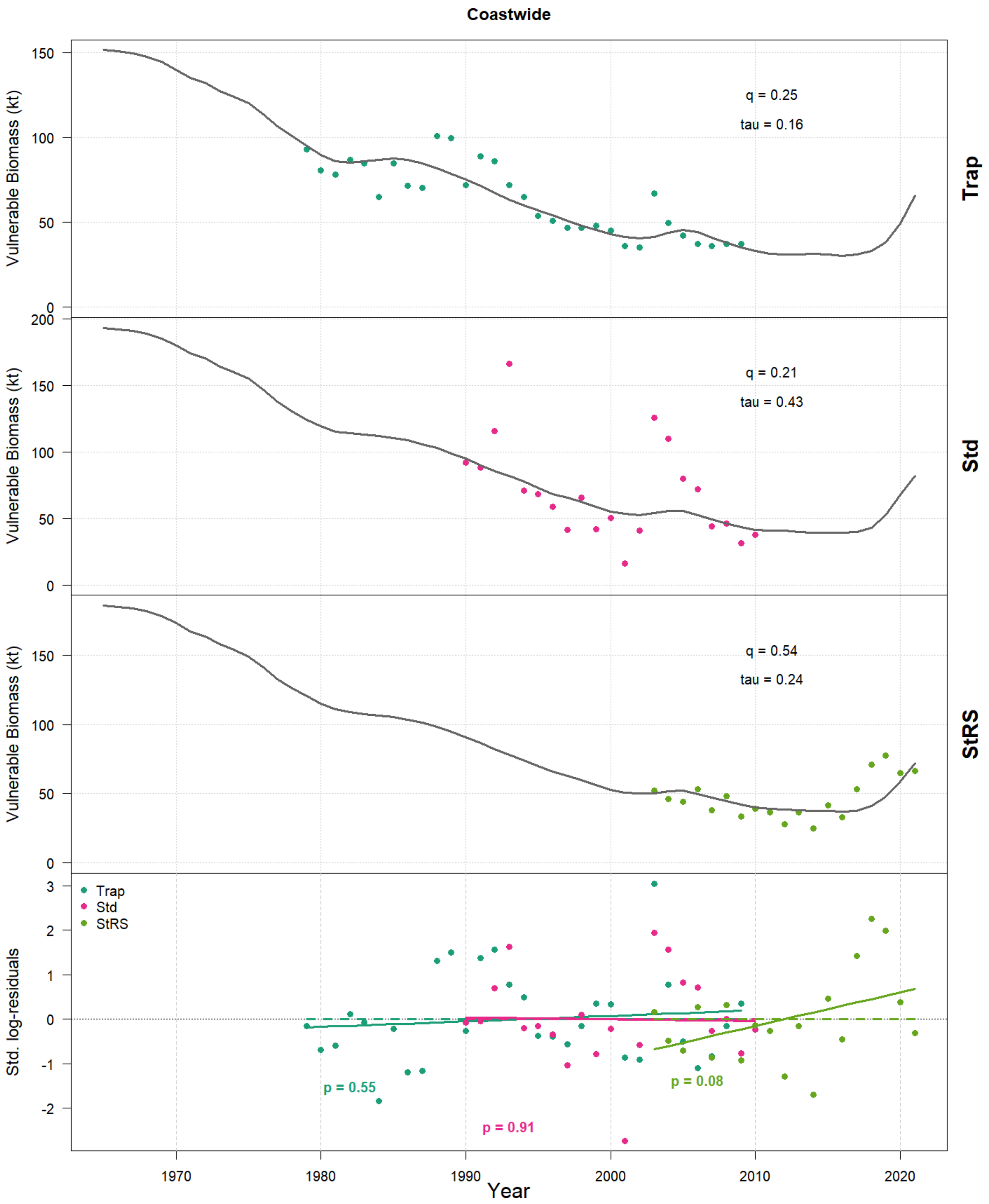

Figure 6. SAB-OM fits to abundance and biomass indices, with standardised log-residuals for each index (bottom panel).

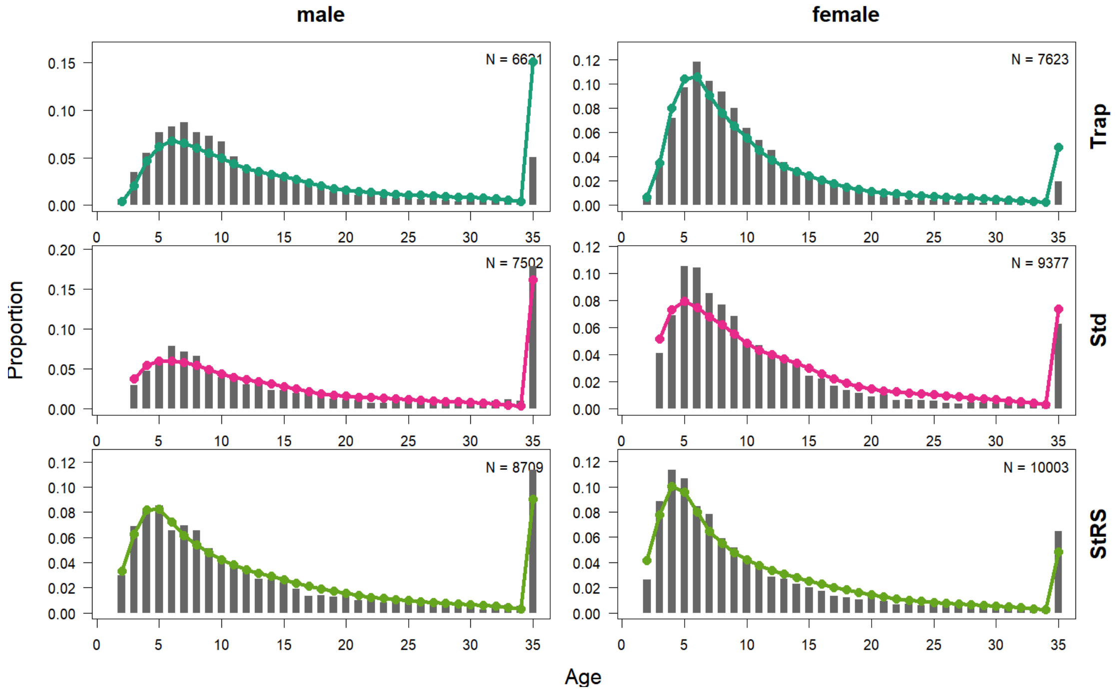

Figure 7. Time-averaged SAB-OM fits to age composition data for males (left) and females (right), sampled by, from top to bottom, Trap fishery, Standardized survey (Std), and Stratified random survey (StRS) fleets.

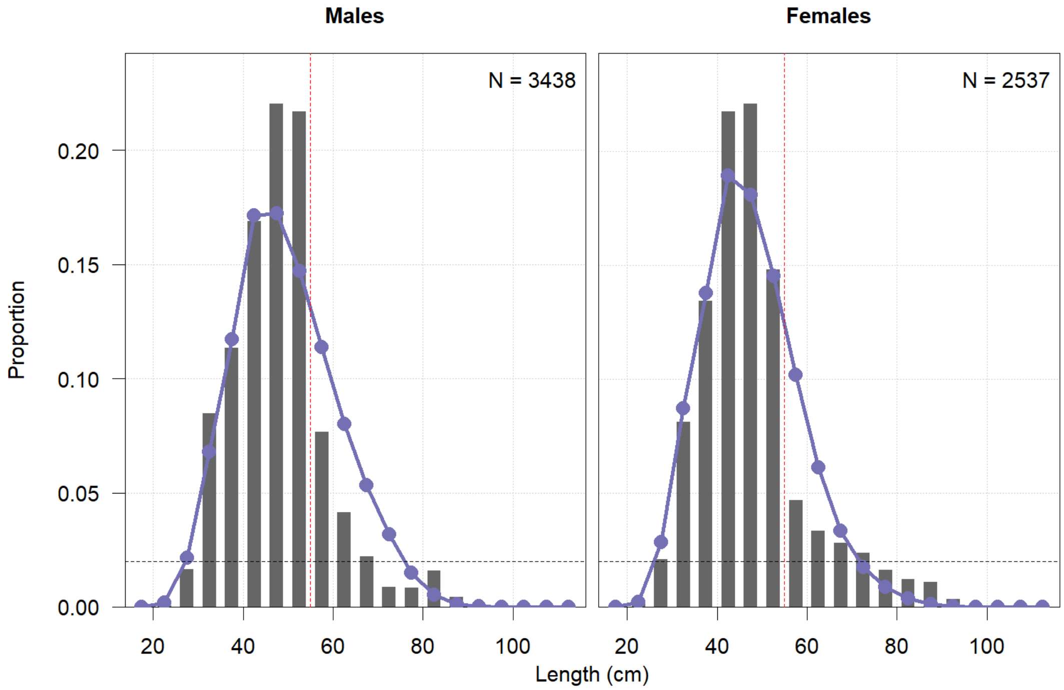

Figure 8. Time-averaged SAB-OM fits to trawl fishery length composition data for males (left) and females (right). The red dashed line shows the 55cm (fork length) minimum size limit for Sablefish retention.

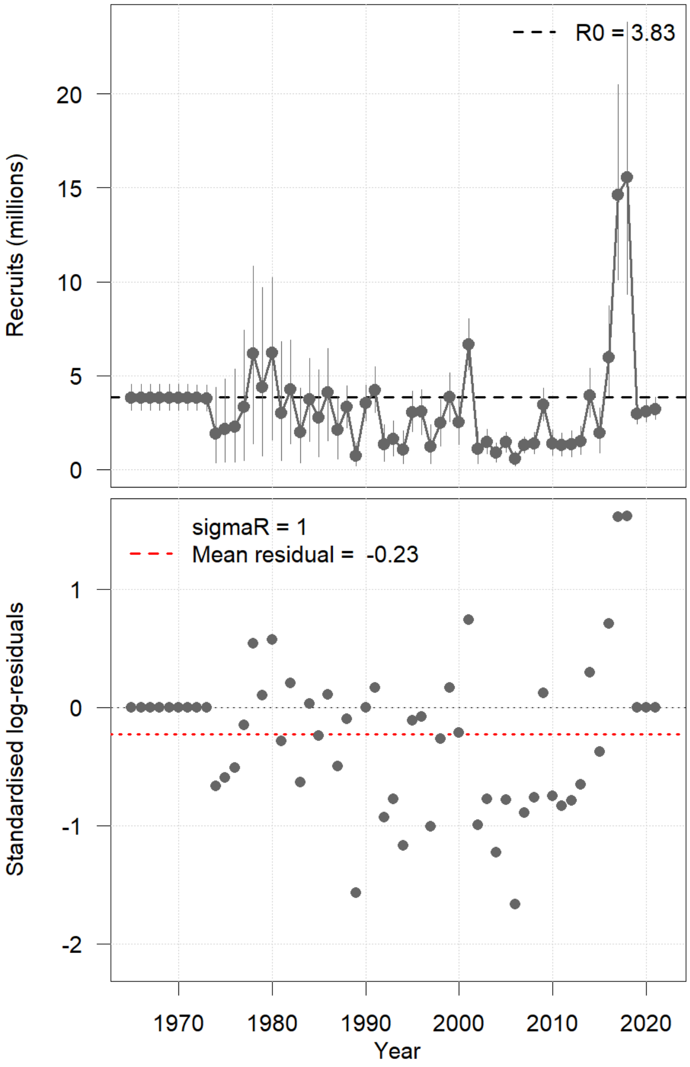

Figure 9. Time series of age-1 Sablefish recruitments (top) and standardised recruitment log-residuals (bottom). Absolute recruitments show equilibrium unfished recruitment R_0 (horizontal dashed line), and 95% credibility intervals (vertical line segments), and residuals are plotted with the average estimated residual (horizontal red dashed line).

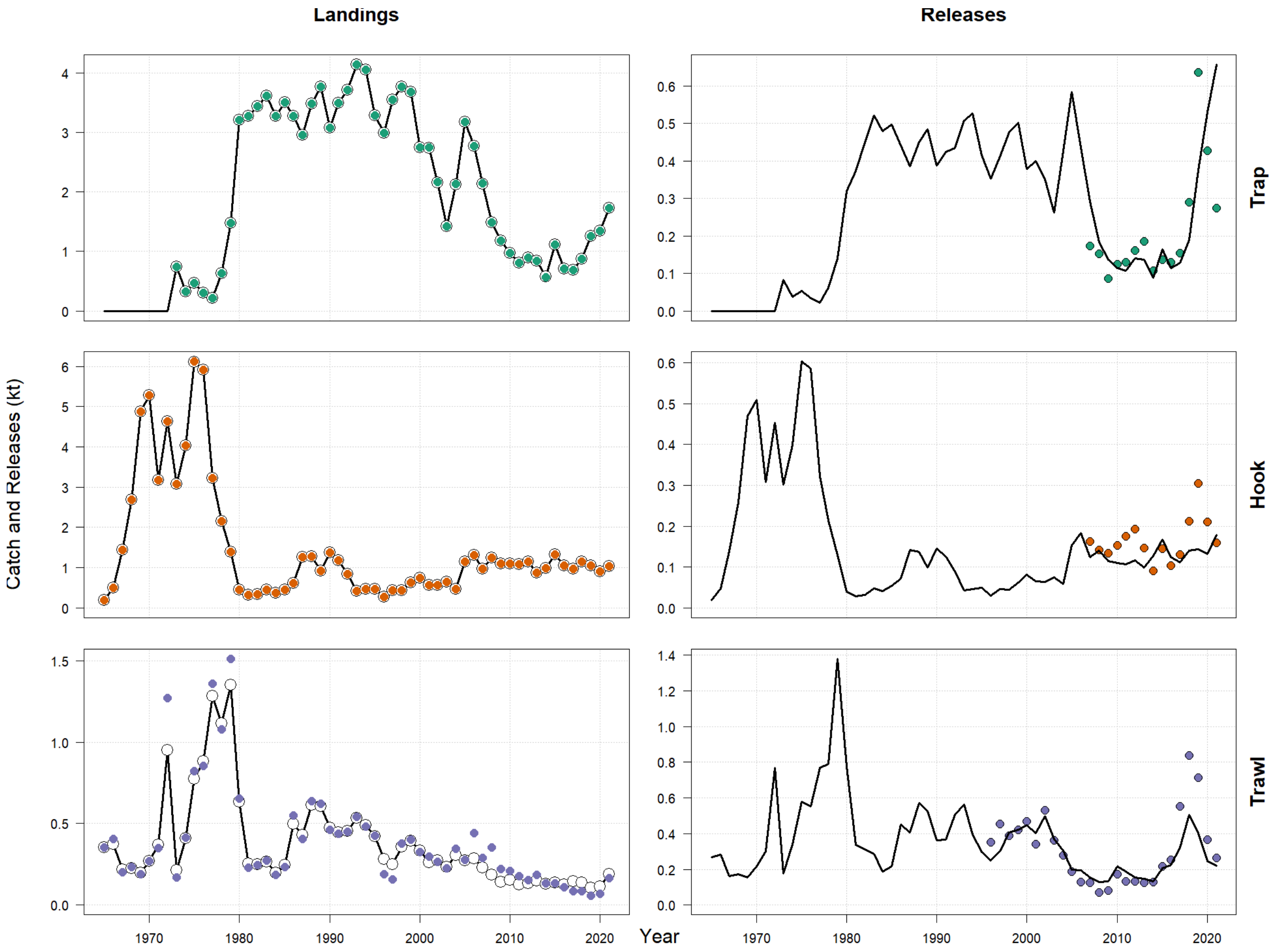

Figure 10. SAB-OM fits to landings (left) and releases (right). Observations are shown as coloured points, with model estimates shown as lines. Release observations are fit with a fixed standard deviation of 0.05 for trap and longline, and 0.1 for trawl. Discarded fish are modeled as a proportion of landed legal sized fish (i.e., loosely a relative proportion of TACs).

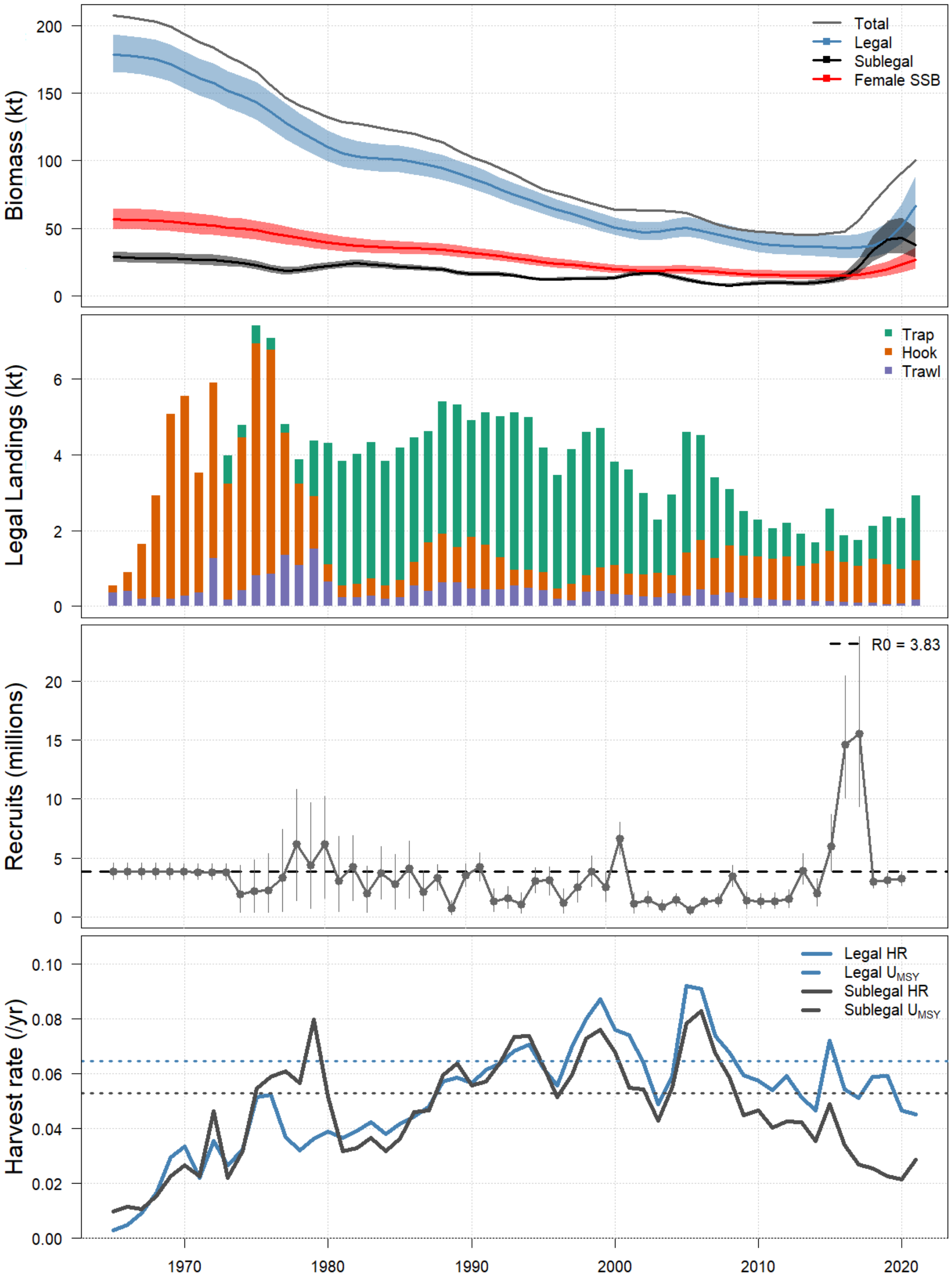

Figure 11. Time series of posterior median total (black line), and posterior 95% credibility intervals of legal (blue), spawning (red), and sub-legal (grey) biomass (top panel), total legal landings by commercial gear type (coloured bars; middle panel), recruitments (third panel), and harvest rates (bottom panel) for the SAB-OM model.

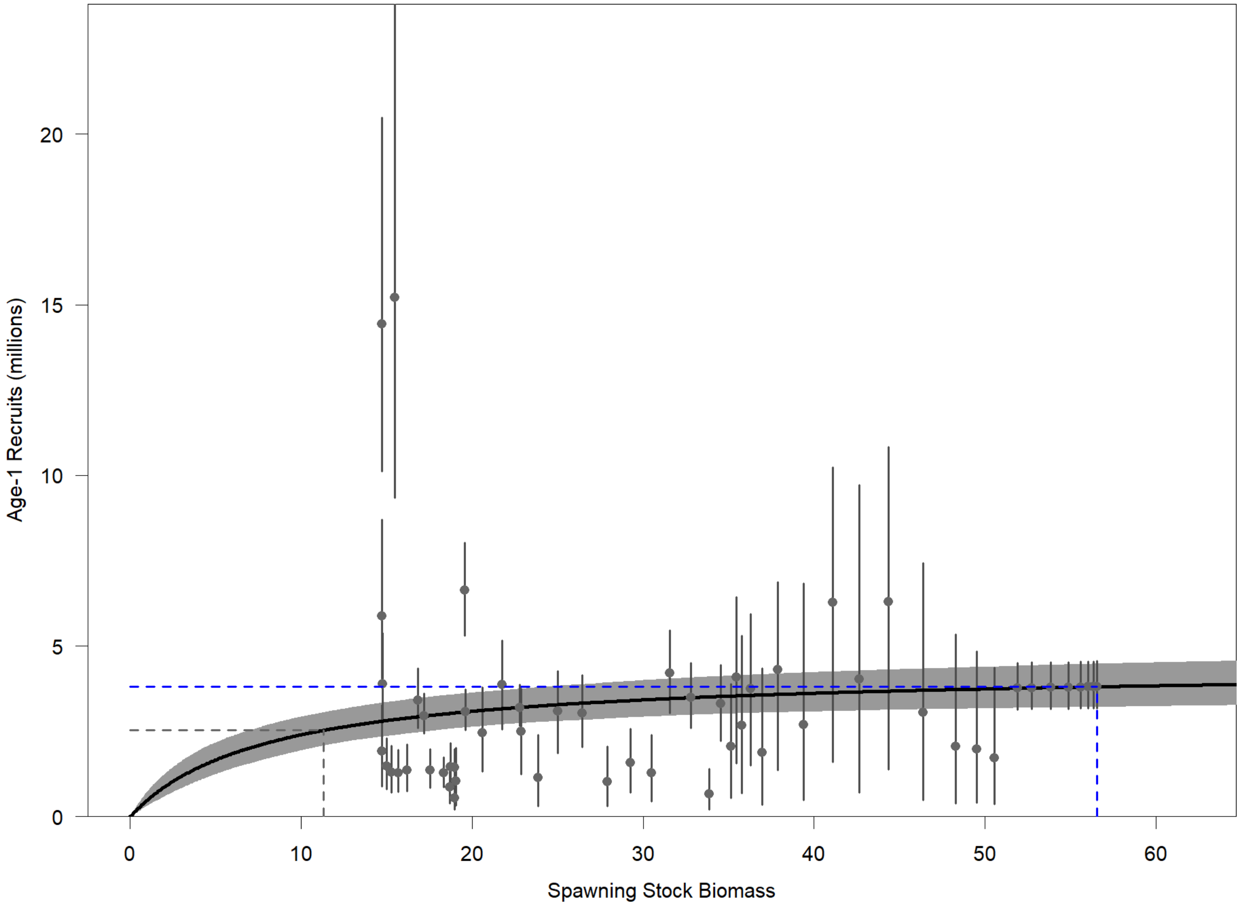

Figure 12. Stock-recruit curve (solid line) and absolute recruitments (points with 95% credibility intervals) for BC Sablefish under the SAB-OM model. Dashed lines show unfished biomass and recruitment (blue dashed line), and biomass and recruitment at 20% of unfished (grey dashed lines).

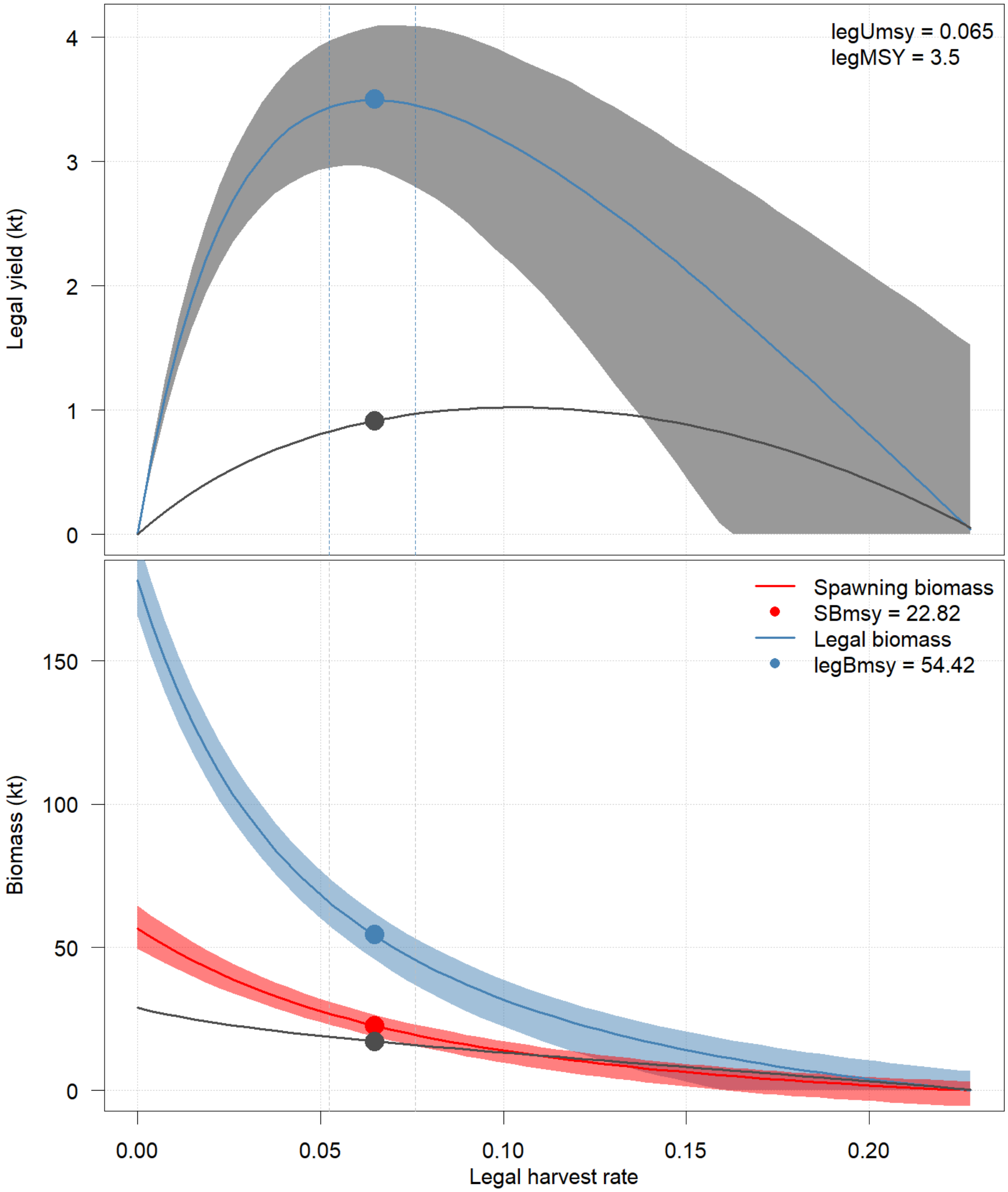

Figure 13. Equilibrium legal and sublegal yield (top) and biomass (bottom) as a function of total legal harvest rates. Reference points associated with the legal U_{MSY} *harvest rate are shown as closed circles on each line. Posterior 95% credibility intervals in yield and biomass are shown as envelopes, and posterior median sublegal yield is shown by a black line, while the 95% credibility interval for legal* U_{MSY} *is shown by the vertical dashed lines.*

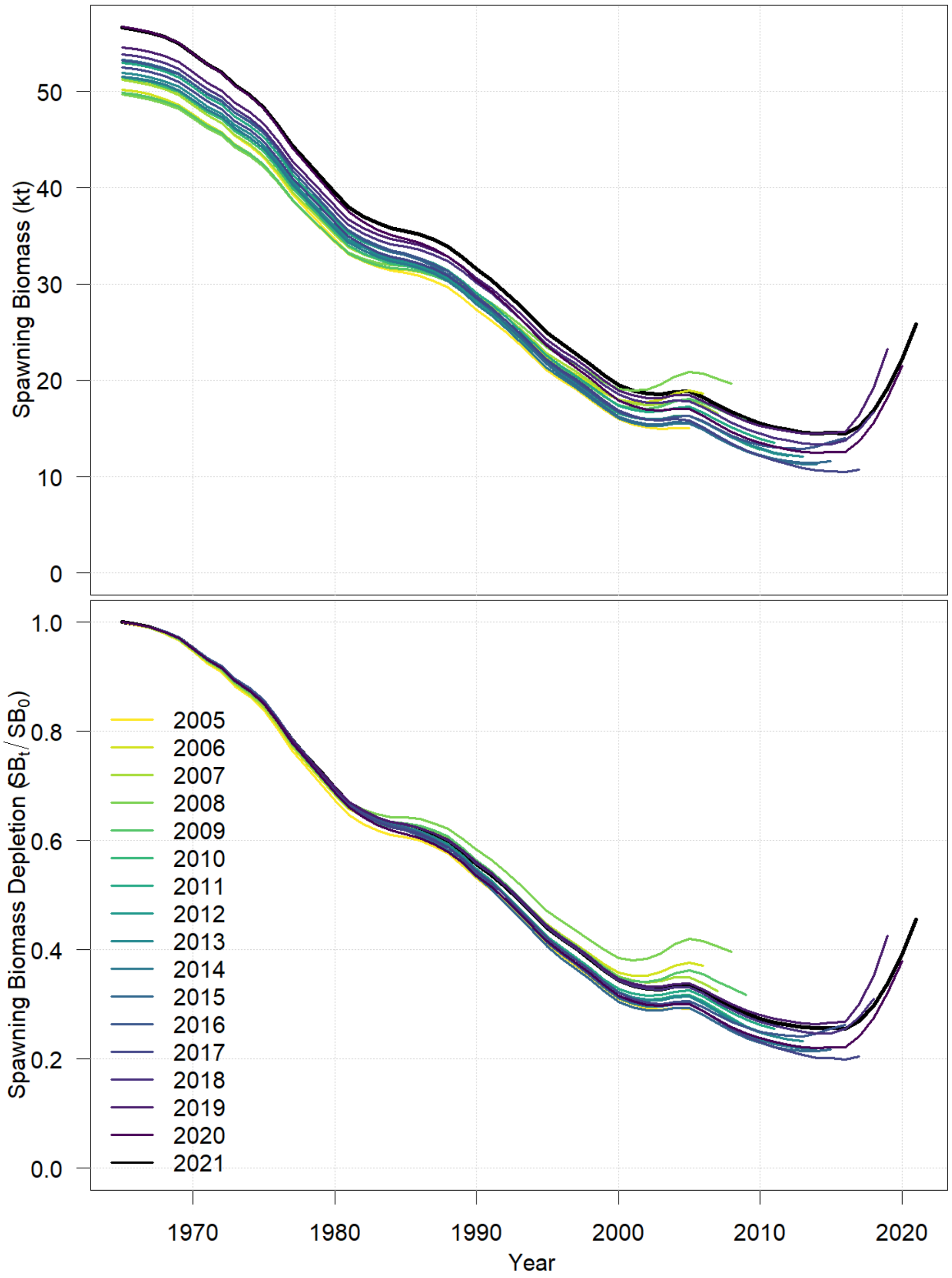

Figure 14. Maximum likelihood estimates of spawning biomass for the Sablefish operating model fit to data from 2005 to 2021 in a retrospective analysis.

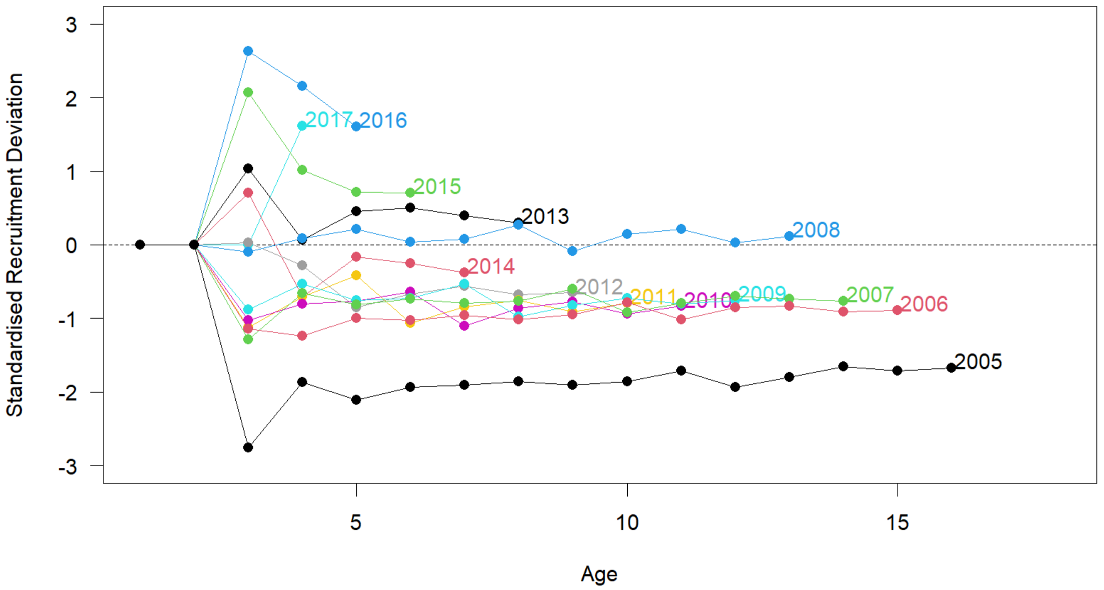

Figure 15. Retrospective cohort strength (log-normal recruitment deviations). Labels indicate the cohort, and points/lines show how the estimates of recruitment process error deviations (y-axis) changed as each cohort increased in age (x-axis). The labeled point for each cohort shows the recruitment deviation estimated in the final peel.

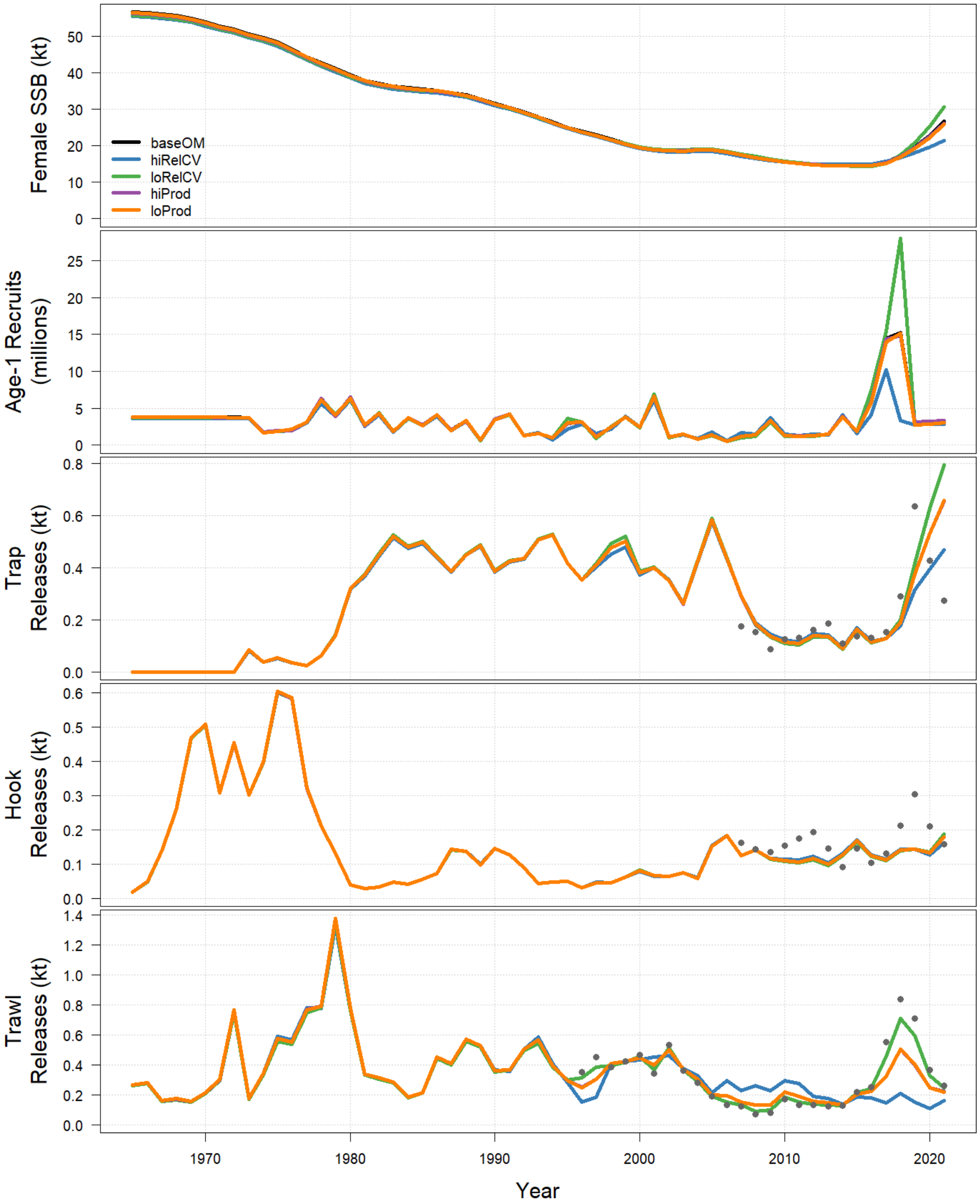

Figure 16. A comparison of estimates (lines) of female spawning biomass, age-1 recruitment, and at-sea release observations (points) for each commercial fleet across the reference set of operating models (coloured lines explained in caption).

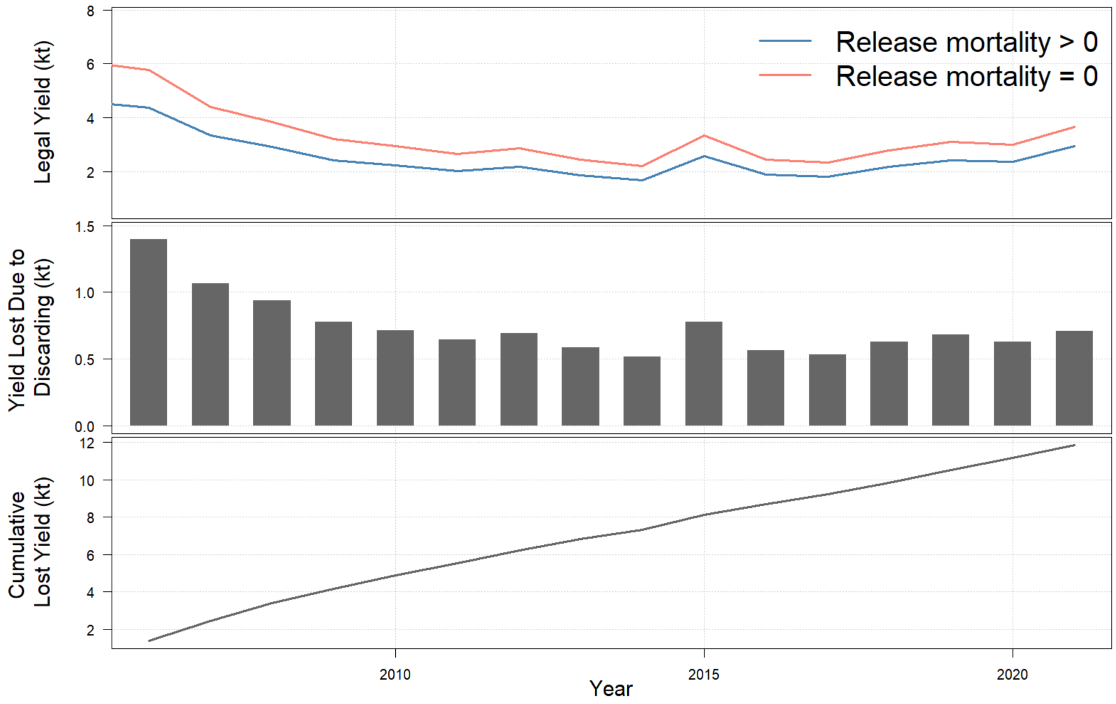

Figure 17. Estimates of legal Sablefish yield lost due to discarding since 2006, showing yield with and without release-induced mortality over model histories assuming the same life-history parameters and annual fishing mortality rates (top row). Lower rows show the difference in yield between model histories (middle), and the cumulative lost yield since 2006 (bottom row).

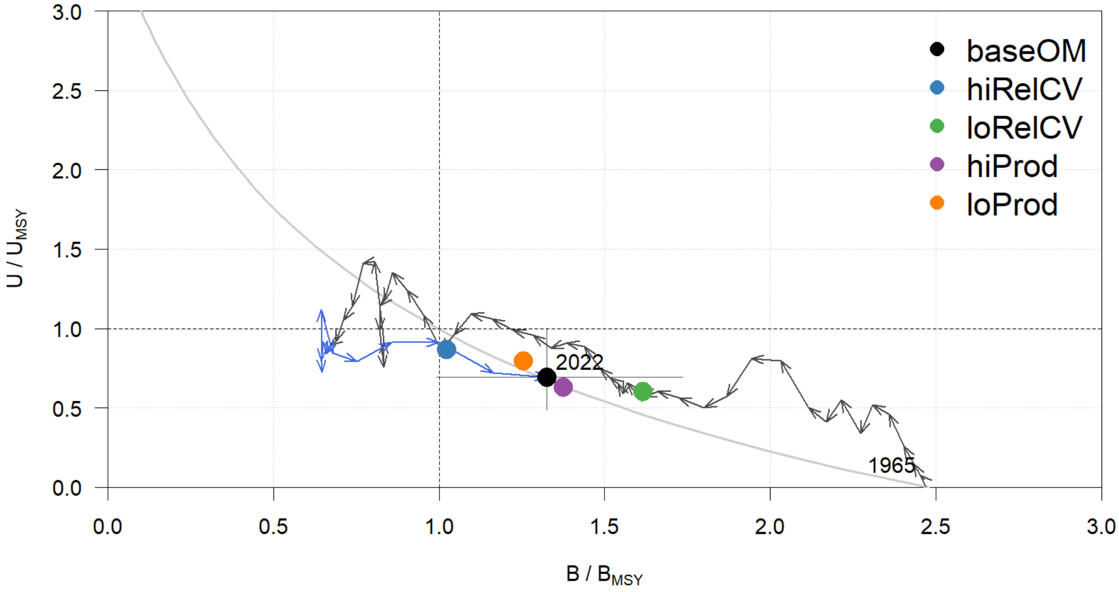

Figure 18. Phase plot of posterior median spawning biomass (horizontal axis) and total legal harvest rate (vertical axis) relative to U_{MSY} reference points. Arrows show the direction of time, beginning in 1965 and ending in 2022, with the years since the inception of the BC Sablefish MSE in 2011 coloured blue. At the end of the time series is a crosshair showing the 95% credibility intervals in the current stock status under the base OM, while median stock status for the 4 lower weighted OMs are shown as coloured filled circles. The equilibrium relationship between spawning biomass and legal harvest rate is shown as a faint grey curve in the background of the plot.

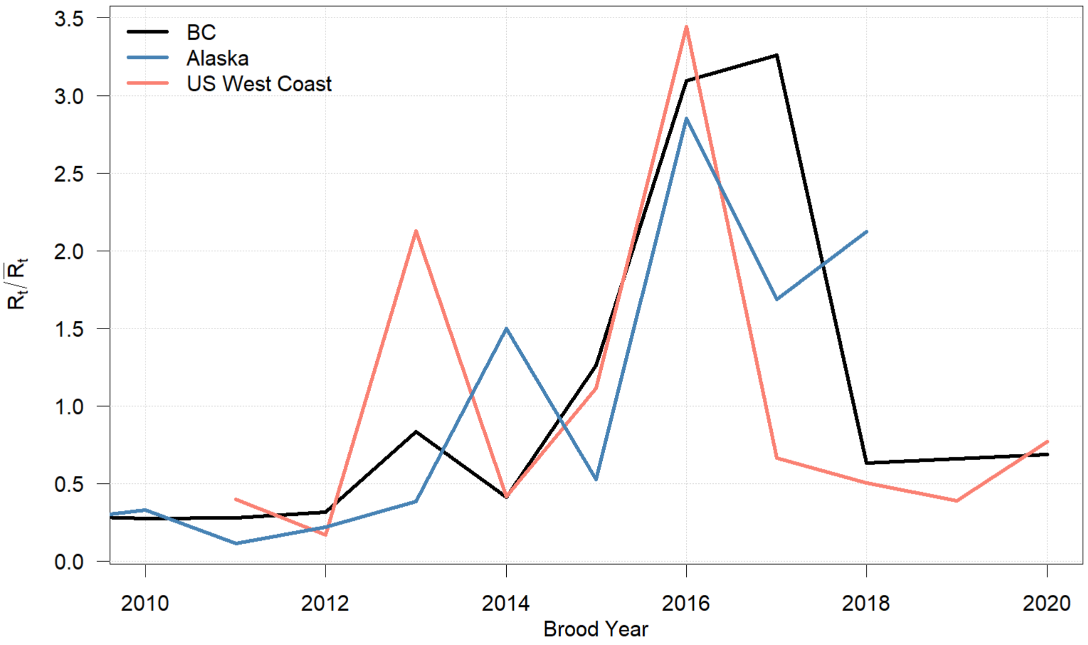

Figure 19. Recruitment estimates from Sablefish stock assessments in BC, US West Coast, and Alaska. The x-axis shows the brood year, and the y-axis shows recruitment estimates relative to the mean over the shown time period.

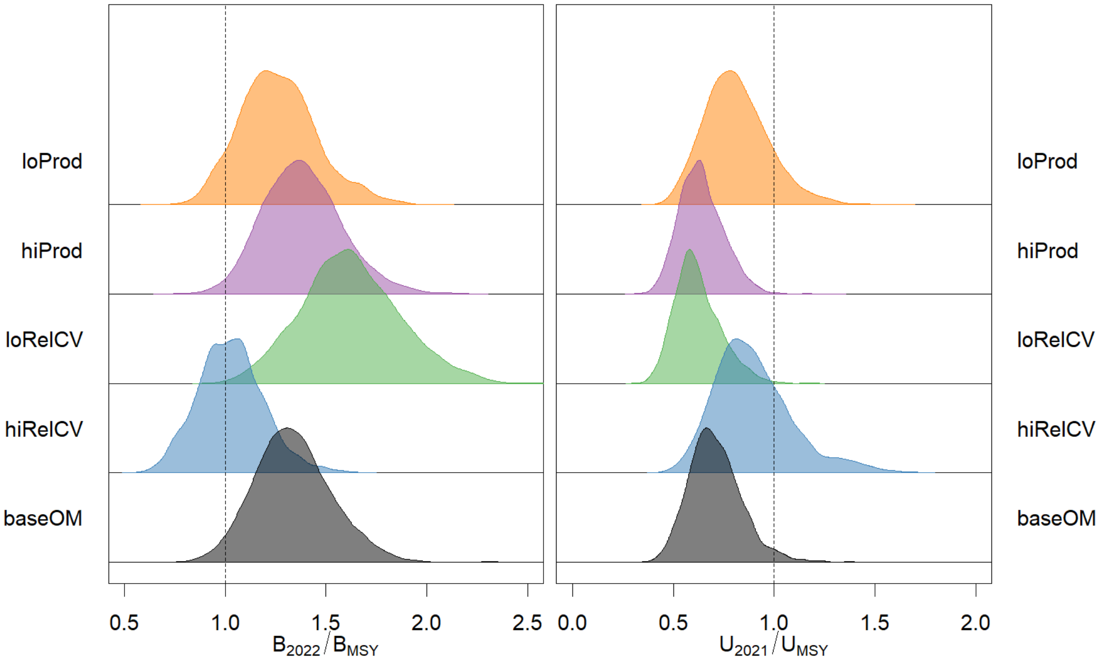

Figure 20. Stacked posterior densities of stock status relative to MSY-based reference points for the five operating models in the reference set. The left column shows 2022 start of year spawning biomass relative to operating model B_{MSY}, and the right-hand column shows 2021 legal harvest rate relative to operating model legal U_{MSY}.

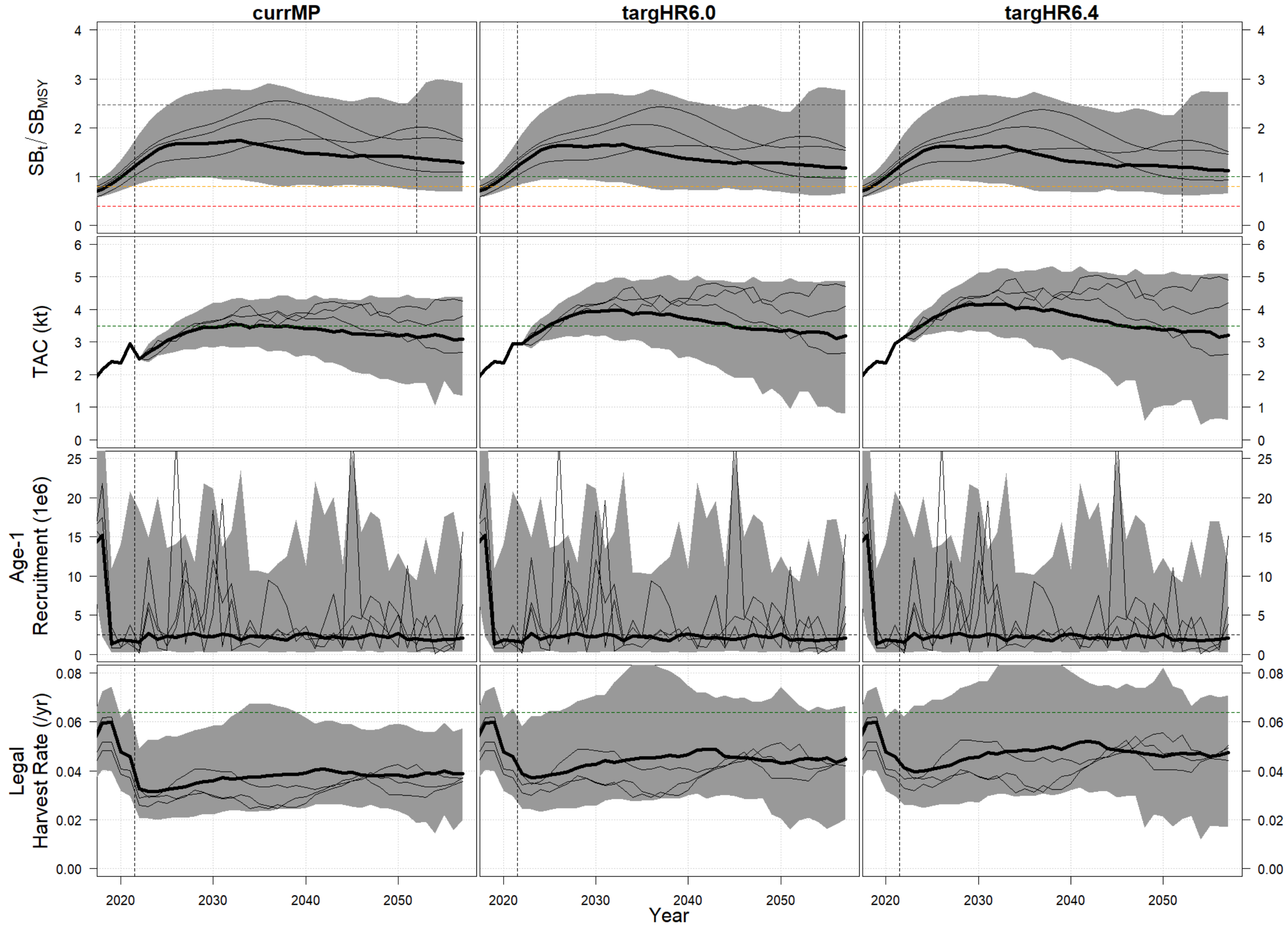

Figure 21. Weighted composite simulation envelopes of stock status (top), MP recommended TACs (second row), age-1 recruitment (third row), and effective legal harvest rates (bottom), under the current MP with a 5.5% harvest rate (left), and two alternative MPs with a 6.0% harvest rate (middle) and 6.4% harvest rate (right). Grey regions show the central 95% of outcomes, thick black lines show the median, and thin black lines show three random simulation replicates. Composite OMs are built by sampling over the reference set OMs in proportion to their weighting. Posterior median reference points from composite weighted OMs are shown as horizontal dashed lines. In the top row, B_0 (grey), B_{MSY} (green), $0.8B_{MSY}$ (orange) and $0.4B_{MSY}$ (red) are shown, with 2022 and 2052 shown by vertical dashed lines. The next three rows show MSY (green, second row), R_0 (black, third row), and U_{MSY} (green, fourth row).

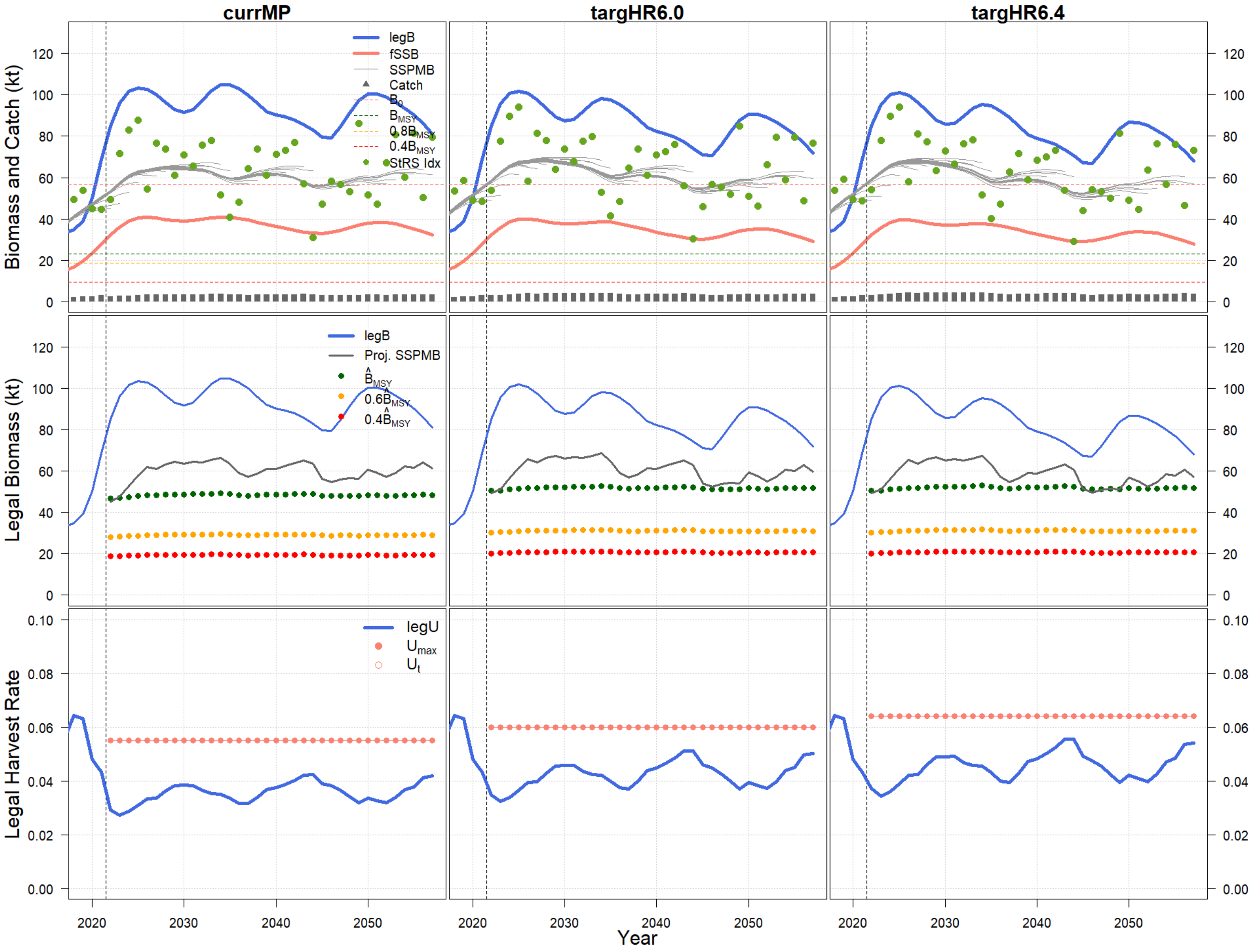

Figure 22. Illustration of the relative performance of three MPs (left to right) on the same simulation replicate from the baseOM. Top row: OM legal biomass (legB) and female spawning biomass (fSSB), and retrospective traces of the MP biomass estimates (SSPMB), which were fit to catch (bars) and StRS indices (green points, scaled by SSPM catchability in 2057). Second row: inputs to the MP HCR, including projected estimates of biomass (SSPMB), estimated B_{MSY} from the SSPM, and associated control points (0.4B_{MSY}, 0.6B_{MSY}), along with true OM legal biomass (legB) for reference. Bottom row: maximum reference removal rate U_{max} versus final target harvest rate U_t set by the HCR, which coincide when biomass estimates are above the upper control point. The effective legal harvest rate (legU) shows the rate actually applied to the simulated stock.

APPENDIX A. MANAGEMENT AND CATCH HISTORY

A.1. MANAGEMENT HISTORY

A detailed history of Sablefish fishery management from 1981 to 2015 is provided in Cox et al. (2023). In this appendix, we provide a brief overview of substantive management changes (Table A.1), and refer readers to Cox et al. (2023) for more detail.

Table A.1. Overview of substantive changes in Sablefish management through time.

Year	Action
1945	- Application of a weight-based size limit that when converted to fork length, effectively created a 63 cm fork length limit.
1965	- A length-based minimum size of a 54 cm fork length was adopted.
1977	- A length-based minimum size of a 55 cm fork length was adopted. - By regulation, sub-legal Sablefish must be released at-sea by all commercial licence categories. - Establishment of the Canadian 200-mile Economic Exclusion Zone in 1977 resulted in departure of foreign fleets fishing Sablefish in Canadian waters by 1981.
1981	- Introduction of licence limitation which created 49 licence holders under the “K” designation, fishing either longline trap or longline hook gear. (Note that there are currently 48 licences available).
1990	- Individual Transferable Quota (ITQs) introduced to Sablefish licence sector.
1994	- Voluntary cessation of directed fishing for Sablefish by K licensed vessels in mainland inlets; inlets thought to be important rearing areas for juveniles. - A ’carry-over’ provision is introduced for the first time. This provision allows ITQ holders the opportunity to delay catching current fishing year ITQ until the following year (an underage), and to accommodate over-runs of ITQ in the current fishing year (an overage). Various changes have been made to Sablefish carry-over rules since 1994 (Cox et al. 2022).
2006	- Introduction of at-sea electronic monitoring (EM) to the non-trawl groundfish fleets, including the Sablefish licensed fleet. Changes in quota transferability beginning in 2006 with the introduction of the Integrated Groundfish Pilot Project that allowed non-K licence holders to access a portion of Sablefish K quota on a temporary basis; the 2010/2011 fishing year was the first year of permanency for the Commercial Groundfish Integration Program (DFO 2010).
2011	- The Sablefish MSE process first implemented; it has been applied annually since 2011.

A.1.1. HISTORY OF THE SABLEFISH MSE PROCESS

Since 2011, the BC Sablefish fishery has been managed using an MSE process. The Sablefish MSE operates on a cycle, with operating models (OMs) updated every 3-5 years to incorporate new data and hypotheses about Sablefish stock and fishery dynamics. Once a set of OMs have been updated, simulation testing of the current management procedure (MP), as well as a suite of alternative MPs, is undertaken to identify a single MP that will be applied to develop harvest advice for the remainder of the MSE cycle. MP selection is based on simulated management performance relative to established management objectives. In Table A.2 below, we summarize the Sablefish MSE process from 2011 to present, including management outcomes.

A.1.2. SABLEFISH OPERATING MODEL DEVELOPMENT

Each time the OM is revised, data are updated including a stock index derived from a fishery-independent stratified random trap survey (StRS) and catch-at-age data for the StRS and commercial longline trap fishery. Retained catch and total at-sea releases (in biomass units) are updated for the commercial longline trap, longline hook, and trawl fisheries. Estimates of fishery selectivity derived from tag release-recovery data may also be updated. The first Sablefish OM was a combined sex, age-structured model that included a growth group formulation (Cox and Kronlund 2009; Cox et al. 2011). However, a sex-/age-structured approach has been the core OM used for periodic formal assessments of stock status as well as for simulation testing of MP performance since 2017 (Cox et al. 2016). The last full peer review of the Sablefish operating model was in 2016 (DFO 2016; Cox et al. 2023). A smaller update was undertaken in 2019 as part of an evaluation of MPs, reviewed through a CSAS Science Response process (DFO 2020). Updates to the MP applied to the fishery typically occur following revisions to the OM, but have been implemented without alterations to the OM when fishery objectives change (DFO 2014).

The 2016 version of the OM replaced the combined-sex model used for the 2011 and 2014 Sablefish MSE analyses (Cox et al. 2011; DFO 2014). Stock and fishery monitoring data were also updated at this time. Key revisions to the OM made in 2016 (Cox et al. 2023) included:

1. Developing a two-sex statistical catch-age model. Although the model structure changed compared to the 2010 model, likelihood formulations were largely the same except for a minor change in the age-composition likelihood that accumulates all age proportions less than 0.005 into a single accumulator bin. This change reduced model sensitivity to small proportions that inevitably arise for long-lived species. The additional complexity of splitting male and female Sablefish in the data and operating model improved model fits to the age-35+ class in the data, but provided similar results to the previous sexes-aggregated model. Preliminary estimates of male (~ 0.06) and female (~ 0.09) natural mortality rates were also obtained from the two-sex model.
2. Implementing an ageing error matrix applied to the model age proportions, which improved model fit to observed age-composition data, improved overall stability, and reduced auto-correlation in estimated recruitment. Including ageing error in the Sablefish OM produced recruitment estimates that were clearly more realistic than those estimated by Cox and Kronlund (2009). Even though an ageing error function parameterized from a US ageing lab was used, results were remarkably consistent with reasonably well-known recruitment events that occurred in BC in the 1970s, 2000, and 2008. The improved recruitment estimates had only marginal effects on key population dynamics parameters; however, the most beneficial effect is better representation of recruitment in harvest strategy simulations.

3. Evaluating whether time-invariant and time-varying fishery selectivity estimated from the Sablefish tagging program improved model fit to age composition data and trawl fishery at-sea releases. Tagging-based estimates of selectivity parameters were used as priors for fisheries, especially longline hook and trawl fisheries that lack age-composition data. Constant selectivity models, constrained by priors developed from tagging estimates, were shown to produce reasonably good results, especially for fitting at-sea releases.

A number of small changes were made to the OM in 2019 (DFO 2020) to improve the fit to various data sources, including new catch-at-age and catch-at-length data sets for the trawl fishery. These were needed to help estimate trawl selectivity, which is the key determinant of sub-legal Sablefish catch in trawl. Revisions in 2019 included:

4. Changing the functional form of trawl selectivity to a gamma distribution probability density function.
5. Reducing the youngest observed age class from age-3 to age-2 for all age composition series to better reflect the range of age-composition observations.
6. Adding new commercial trawl age-composition data, derived from trawl length-composition data via an age-length key.
7. Adding an estimated recruitment deviation in 2015, rather than using the expected recruitment off the stock-recruit curve, to improve fits to recent and very high trawl at-sea release observations. Otherwise, the OM would be simulating effects of at-sea releases based on a model that could not adequately fit historical at-sea releases.
8. Updating the ageing-error matrix to use a simpler normal approximation recommended in the previous CSAS review (Cox et al. 2019).
9. Imposing a standard deviation of $\tau = 0.15$ (on the log-scale) on trawl at-sea release observation errors to force a better fit to those data.
10. Adding trap CPUE data points from 1979-1987, and time-varying catchability for the trap CPUE and Std Survey data to account for variation apparent in those series.

There were also some incremental changes made to the revised OM for this update:

11. Switching from fitting the OM to trawl age compositions derived from an age-length key to directly fitting to trawl length compositions, reducing selection biases from the conversion from age to length.
12. Reducing to a standard deviation of $\tau_{rel} = 0.1$ (on the log-scale) on trawl at-sea release observation errors to force a better fit to those data (with alternatives tested across the reference set of operating models).
13. Relaxing the standard deviation on trawl landings observation errors to $\tau_{cat} = 0.1$ (on the log-scale) to enable a better fit to releases without creating large increases in equilibrium biomass and optimal harvest rates.

Table A.2. Summary of Sablefish management targets and resulting TACs from application of Sablefish Management Procedures (MPs) since 2011. Quantities shown include the maximum harvest rate permitted by that year's MP (maxHR), the calculated target harvest rate for a year based on the 'MP estimate' of stock status (mpHR), the TAC prescribed the MP (mpTAC), and the final adopted TAC used for management (finalTAC). Note that harvest rate is a function of biomass estimated by the surplus production model in the MP, not the OM estimated biomass. Catch limit increases are only recommended by the MP if the limit exceeds the previous year's TAC by at least 200 t; catch limit decreases are always recommended. The Sablefish Advisory Committee (SAC) is an advisory body to DFO.

Fishing Year	maxHR	mpHR	mpTAC	finalTAC	Notes
2011-12	10.5	10.5	2254	2300	OM and MP revised (Cox et al. 2011).
2012-13	10.3	10.3	2293	2293	
2013-14	9.5	9.1	1992	1992	MP revised (DFO 2014)
2014-15	9.5	9.5	2192	2192	
2015-16	8.2	6.1	1992	1992	
2016-17	8.6	7.5	1992	1992	OM revised (DFO 2016, Cox et al. 2023)
2017-18	9.5	8.6	2276	2276	MP revised (DFO 2017, Cox et al. 2019). Maximum target harvest rate based on tuning in simulation beginning in 2017-18.
2018-19	8.7	8.7	2720	2526	SAC recommended a TAC set below the MP catch limit (mpTAC) to enhance rebuilding efforts and allow time for recent recruitment to grow biomass.
2019-20	7.9	7.9	2955	2526	SAC recommended a target harvest rate of 7.1% instead of the mpHR of 7.9% to reduce fishing pressure on juvenile Sablefish and promote continued biomass growth. Operating model underwent minor updates (DFO 2020).
2020-21	7.1	7.1	3057	3057	
2021-22	6.3	6.3	2887	2887	
2022-23	5.5	5.5	2623	2623	OM revised (this paper)

A.2. CATCH DATA

Catches by calendar year are taken from several different DFO Groundfish databases. These databases, as well as the years they apply to, are described here:

1. **GFCatch** Legacy database that includes commercial daily fisher logbooks, landing records derived from sales slips or validation records, interviews with vessel skippers and waterfront observations for all gears from 1965 to 1995 (Rutherford 1999). GFCatch includes trawl logbooks from 1954 to 1995, trap logbooks from 1979 to 1995, and longline hook logbooks from 1979 to 1986.
2. **PacHarv3** Legacy database containing landings records derived from commercial sales slips from 1987-1994 for longline hook and 1982-2002 for “other” gears.
3. **PacHarvSable** Legacy Sablefish catch database that includes fishery logbooks for longline trap and hook gears from 1990 to March 2006 and dockside validated landings records from 1995 to 2002. PacHarvSable also includes fishing by foreign countries for all gear types from 1965 to 1980, synthesized in part from previous databases and historical data files.
4. **PacHarvHL** Legacy hook and line catch database that contains:
    a. fisher logbooks for commercial ZN and Schedule II licence categories for 1996 to March 2006, and
    b. some at-sea observer logs and dockside validated landings for Pacific Halibut from 1991 to 2002.
5. **PacHarvest** Legacy Regional database that contains commercial trawl observer logs, some fisher logs, and dockside validated landings records from 1996-Mar 31, 2007.
6. **GFFOS** Groundfish stand-alone database derived from Pacific Region Fisheries Operation Systems (FOS) database that includes:
    a. commercial groundfish trawl observer logs and fisher logs from April 1, 2007 to the present,
    b. commercial fisher logs from April 1, 2006 to present for Pacific Halibut, Sablefish, combination Pacific Halibut and Sablefish, North Pacific Spiny Dogfish, Lingcod, rockfish outside and inside,
    c. dockside validated landings records from 2003 to present for the Sablefish licence category and combined Sablefish and Pacific Halibut fishing,
    d. dockside validated landings from 2006 to present for Pacific Halibut, and
    e. dockside validated landings from April 1, 2006 to present for North Pacific Spiny Dogfish, Lingcod, rockfish outside and inside.

A.2.1. RETAINED CATCH

Records of retained catch for Sablefish in BC start in 1913; however, catch data between 1913 and 1964 were not used to fit operating models since catches prior to the mid-1960s were relatively modest (with some exceptions in the early years; Figure A.1) and the Sablefish trap fishery had not yet developed. Furthermore, there are no abundance indexing or age composition data to support the catch series in these early years. There were some relatively high catch years between 1913 and 1920, with catches peaking at 5,956 t in 1917 before declining to lower levels for the remainder of the pre-1965 time series . Between 1920 and 1964, catches were smaller, ranging between 209 t (1956) and 1,895 t (1949).

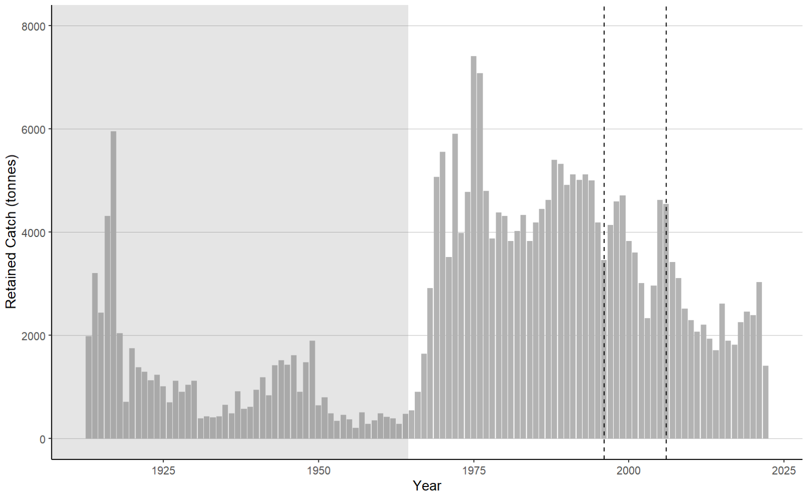

Figure A.1. Annual Sablefish retained catch (t) from 1913 to 2021 from commercial sources (gray bars). Grey shading prior to 1965 indicates that catch values were not used to fit operating models while vertical dashed lines demarcate changes in data reporting, including the start of trawl at-sea observer period in 1996 and the start of catch monitoring for all groundfish sectors in 2006.

Retained catch data by fishing gear used to fit operating models start in 1965 and are provided in Table A.3, while time series of catch by gear and fishing fleet are shown in Figure A.2 (top panel). Catches increased significantly in the late 1960s with the arrival of foreign longline hook fleets from Japan, the US, the USSR and the Republic of Korea (McFarlane and Beamish 1983; Table A.3, Figure A.2). The largest annual landings of Sablefish occurred during this period with a peak 7,408 t reported landed in 1975. Canada established its Economic Exclusion Zone in 1977, at which time foreign fishing was reduced. Some foreign fishing was allowed between 1977 and 1980; however, by 1981 only Canadian vessels were operating. Since 1981, retained catch has ranged from 5,399 t (1988) to 1,711 t (2014), with an average retained catch of 3,601 t over this period. Landings declined from 4,620 t in 2005 to 1,711 t in 2014 in response to TAC reductions and declining estimates of stock biomass. Catches have increased again in recent years, with catch reaching 3,224 t in 2021.

Table A.3. Sablefish retained catch (t) by calendar year and gear type. Note that when fitting operating models to catch data for the current update, retained trawl fishery catches in 2017-2021 were reduced to 85.2t, 84.6t, 58.2t, 68 t, and 170.7 t, respectively, to remove known sub-legal sized landings from the retained catch series. Sub-legal landings from these years were counted as 'released fish' when fitting operating models.

Year	Step	Trap	Longline	Trawl	Std.Survey	StRS.Survey
1965	1	0	193	354	0	0
1966	2	0	500	407	0	0
1967	3	0	1,442	204	0	0
1968	4	0	2,682	232	0	0
1969	5	0	4,882	191	0	0
1970	6	0	5,284	270	0	0
1971	7	0	3,173	350	0	0
1972	8	0	4,636	1,270	0	0
1973	9	746	3,070	171	0	0
1974	10	327	4,036	414	0	0
1975	11	469	6,117	821	0	0
1976	12	303	5,918	855	0	0
1977	13	215	3,224	1,358	0	0
1978	14	635	2,160	1,078	0	0
1979	15	1,480	1,389	1,512	0	0
1980	16	3,211	448	652	0	0
1981	17	3,275	326	229	0	0
1982	18	3,438	344	246	0	0
1983	19	3,610	451	274	0	0
1984	20	3,275	365	187	0	0
1985	21	3,501	458	233	0	0
1986	22	3,277	619	552	0	0
1987	23	2,954	1,269	407	0	0
1988	24	3,488	1,274	637	0	0
1989	25	3,772	929	623	0	0
1990	26	3,072	1,372	461	10	0
1991	27	3,494	1,179	439	6	0
1992	28	3,710	849	449	10	0
1993	29	4,142	424	543	8	0
1994	30	4,051	468	483	7	0
1995	31	3,282	474	427	5	0
1996	32	2,984	278	191	5	0
1997	33	3,554	430	156	4	0
1998	34	3,772	444	376	6	0
1999	35	3,677	628	403	5	0
2000	36	2,745	752	326	7	0
2001	37	2,743	564	300	3	0
2002	38	2,162	564	267	16	0
2003	39	1,419	640	228	20	22
2004	40	2,128	467	345	16	9
2005	41	3,175	1,146	277	14	8

Year	Step	Trap	Longline	Trawl	Std.Survey	StRS.Survey
2006	42	2,774	1,307	442	12	11
2007	43	2,140	972	289	9	10
2008	44	1,487	1,246	353	10	12
2009	45	1,174	1,107	223	6	12
2010	46	976	1,096	209	7	11
2011	47	804	1,082	176	0	11
2012	48	892	1,150	155	0	11
2013	49	841	877	184	0	32
2014	50	571	985	132	0	23
2015	51	1,111	1,329	133	0	41
2016	52	711	1,054	109	0	29
2017	53	690	973	105	0	51
2018	54	877	1,156	170	0	51
2019	55	1,260	1,046	112	0	44
2020	56	1,339	912	103	0	33
2021	57	1,773	1,038	192	0	29

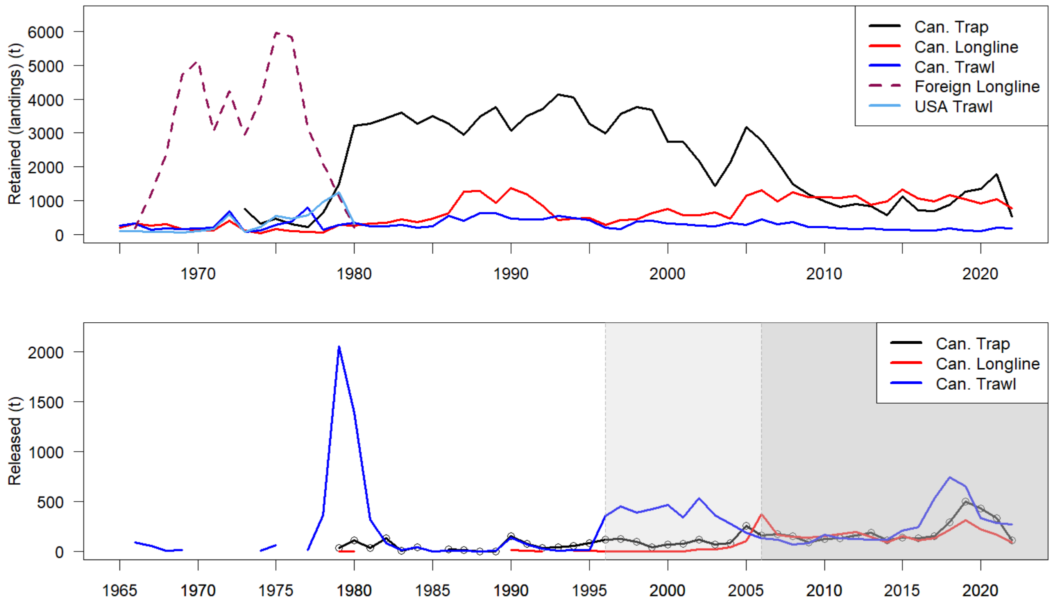

Figure A.2. Upper panel: Annual commercial retained catches (t) of Sablefish from domestic Canadian (Can.) and foreign fisheries from 1965 to 2021. Lower panel: Released catch for Canadian trap, longline hook and trawl fisheries. Vertical dotted lines indicate the start of full at-sea observer coverage in 1996 for the trawl sector and start of full at-sea monitoring for all sectors in 2006.

A.2.1.1. Presence of Sub-Legal Sablefish in Trawl Catch

While retained catch from the trawl fishery shown in Table A.3 is composed of predominately legal-sized fish, sub-legal fish are also known to occur within these totals. Estimates of the magnitude of sub-legal retained catch is only available starting in 2017. Prior to this time, sub-legal and legal landings are grouped together. Dockside monitoring staff working for Archipelago Marine Research began recording sub-legal Sablefish as 'sub-legal' instead of 'Quota' in February 2017. In the FOS database, landed sub-legal Sablefish are now recorded under the Buyer category: 'Offal' and Catch Category: 'Other'. This shift in reporting was driven by increased observations of sub-legal Sablefish in landed catch in 2017 as a result of recent high recruitment. High recruitment during this period lead to increased encounters of sub-legal fish in all fisheries. Since 2017, the retention of sub-legal Sablefish has been highest in the Hake trawl fishery, for which sorting at sea is challenging due to small Sablefish being hard to detect in large tows of Hake. While sub-legal Sablefish are also retained on occasion from bottom trawl fisheries, between 68% and 92% of retained sub-legal Sablefish have been from mid-water trawl between 2017 and 2021. The division of retained trawl catch between legal and sub-legal-sized fish for 2017 to 2021 is shown in Table A.4. When fitting operating models to data in this assessment, the sub-legal landings shown in Table A.4 were treated as sub-legal releases, as described in the captions for Table A.4 and Table A.5.

Table A.4. Breakdown of trawl fishery catch (in tonnes) between legal and sub-legal size categories.

Year	Legal Trawl	Sub-legal Trawl	Total Trawl
2017	85	20	105
2018	85	85	170
2019	58	54	112
2020	69	35	103
2021	171	21	192

A.2.2. RELEASED CATCH

A.2.2.1. Trawl Releases

Estimates of released catch weight from the trawl sector between 1996 and 2019 were taken directly from at-sea observer logbooks. The cessation of the at-sea observer program in March 2020 due to the start of the COVID-19 pandemic resulted in released weights being reported by skippers for the remainder of 2020 and 2021. Between March and November 2020, release data are only available from fisher logbooks. The logbook data entry system did not allow fishers to separate out sub-legal and legal releases, so release data cannot be distinguished between the two sub-categories for this time period. Starting in November 2020, fishers were required to fill-out the "Observer Logbook" form, in which sub-legal and legal releases are separated out. As a result, sub-legal and legal releases can be distinguished again starting in November 2020.

Estimates of Sablefish releases from trawl gear over the 1996 to 2021 period ranged from ~70 t (2008) to ~745 t (2018; Table A.5). Most releases are categorized as sub-legal Sablefish, and no liced Sablefish are reported from trawl gear. Sablefish trawl releases frequently exceed retained trawl catch, including from 1996 to 2003 and more recently from 2015 to 2021. Since the trawl licence category is allocated 8.75% of the Sablefish TAC, the general decline in retained catch and releases between 2006 and 2014 can be attributed in part to reductions in TAC. In addition, trawl industry sources cite gear modifications and improved communication between fishing masters as a possible contributing factor to reduced interception and subsequent release of sub-legal Sablefish over the past several years (i.e., avoidance behaviour). High reported releases since 2015 have been associated with recent strong recruitment of incoming Sablefish year classes to the fishery. Releases were at a time series high of 754 t in 2018, and since have declined to 94 t in 2021.

A.2.2.2. Trap and Longline Releases

Estimates of released catch from trap and longline fisheries were obtained from fishery logbook data archived in the FOS database maintained by Fisheries and Oceans Canada, Pacific Region and the GFFOS system maintained by the Groundfish Section, Pacific Biological Station. Non-trawl releases are generally reported in logbooks by count rather than by estimated weight. For this analysis, release counts were converted to weights using an average round weight of 1.5 kg for sub-legal Sablefish and 3.0 kg for legal Sablefish. These values were calculated from individual round fish weights obtained during Sablefish trap surveys from 1990 to 2009.

Fishery-independent release data are not available for non-trawl commercial groundfish licence categories until 2006 (Table A.5). Although the non-trawl licence categories joined the at-sea electronic monitoring program at different dates between March 2, 2006 and March 31, 2007, reported release data are taken as reliable estimates starting from the 2006 calendar year . The Pacific Halibut and Sablefish licence categories, which account for most of the longline Sablefish catch, joined March 2, 2006 and August 1, 2006, respectively.

Table A.5. Sablefish released catch (t) by calendar year aggregated by gear type. Note that when fitting operating models to catch data for the current update, released trawl fishery catches in 2017-2021 were increased to 544.6t, 830.6t, 708.4t, 365.4t, and 307.3t, respectively, so that they included known sub-legal sized landings. Sub-legal landings from these years were removed from the retained catch series (see Table B.2 above).

Year	Step	Trap	Longline	Trawl
1996	32	-	-	353.4
1997	33	-	-	452.9
1998	34	-	-	387.5
1999	35	-	-	422.7
2000	36	-	-	468.1
2001	37	-	-	341.8
2002	38	-	-	531.5
2003	39	-	-	362.2
2004	40	-	-	278.2
2005	41	-	-	189.2
2006	42	-	-	131.8
2007	43	173.8	164.3	121.1
2008	44	152.7	144.1	69.9
2009	45	87	135.7	81.6
2010	46	125.4	154.5	168.2
2011	47	130.7	176.3	132.3
2012	48	161.3	195	126.7
2013	49	186.4	147.3	119.2
2014	50	108	91.8	119.6
2015	51	137.5	146.9	205.7
2016	52	129.7	105.7	245
2017	53	154.2	131.8	524.9
2018	54	290.7	213.9	745.3
2019	55	497	306.1	654.4
2020	56	427.7	211.7	330.8
2021	57	329.5	167.3	286.1

A.3. CATCH DISTRIBUTION

A.3.1. SPATIAL DISTRIBUTION

The distributions of Sablefish catch from longline hook, trap, and trawl fisheries are shown in Figure A.3 using five-year increments. Sablefish are caught along the entire coast of British Columbia, with the highest proportion of catch typically taken from the northwest coast of Haida Gwaii and from deep canyons and troughs along Queen Charlotte Sound and the west coast of Vancouver Island. The commercial trap fishery typically avoids fishing in Hecate Strait and voluntarily ceased fishing in mainland inlets in 1994 to protect areas inhabited by juvenile Sablefish. As a result, catches for this fishery more constrained than those of longline and trawl gears that fish in Hecate Strait and Queen Charlotte Sound. The longline hook fleet also catches Sablefish in some mainland inlets. The longline hook fleet is largely dominated by directed fishing for Pacific Halibut, combination fishing for Pacific Halibut and Sablefish, and to a lesser degree fishing for rockfish (*Sebastes sp.*) (under a Rockfish Outside licence) as well as Lingcod and North Pacific Spiny Dogfish (fished under a Schedule II licence).

A.3.2. DEPTH DISTRIBUTION

Commercial fishing effort for the three gear types that catch Sablefish differ markedly in their depth distribution (Figure A.4). Longline hook and trawl gears tend to catch most Sablefish at shallower depths than trap gear. While Sablefish are encountered at very shallow depths for longline hook and trawl fisheries (<100 m), they are more commonly encountered during deeper sets by these gears. In contrast, Sablefish are caught on almost all trap gear sets.

The weekly depth distributions of sets that caught Sablefish are shown for longline hook, longline trap and bottom trawl gear in Figure A.5. For longline hook gear, the distributions of depths of fishing become shallower in the mid-March through mid-November, in coincident with the opening of the Pacific Halibut fishery. The lowest mean depths are found in July and August, which further coincides with the movement of Pacific Halibut to shallower waters in the summer months Loher (2011). Deeper fishing using longline hook gear during the period from December through February is likely directed at Sablefish and Pacific Halibut moving to the deeper waters. Longline trap fishing changes depth distribution as Sablefish become available at shallower depths on the continental shelf in summer and into the fall, but fishing remains distributed within about 400 to 700 m depth throughout the year. Fishing by bottom trawl gear is shallowest in June through October and is distributed at deeper depths from December through April.

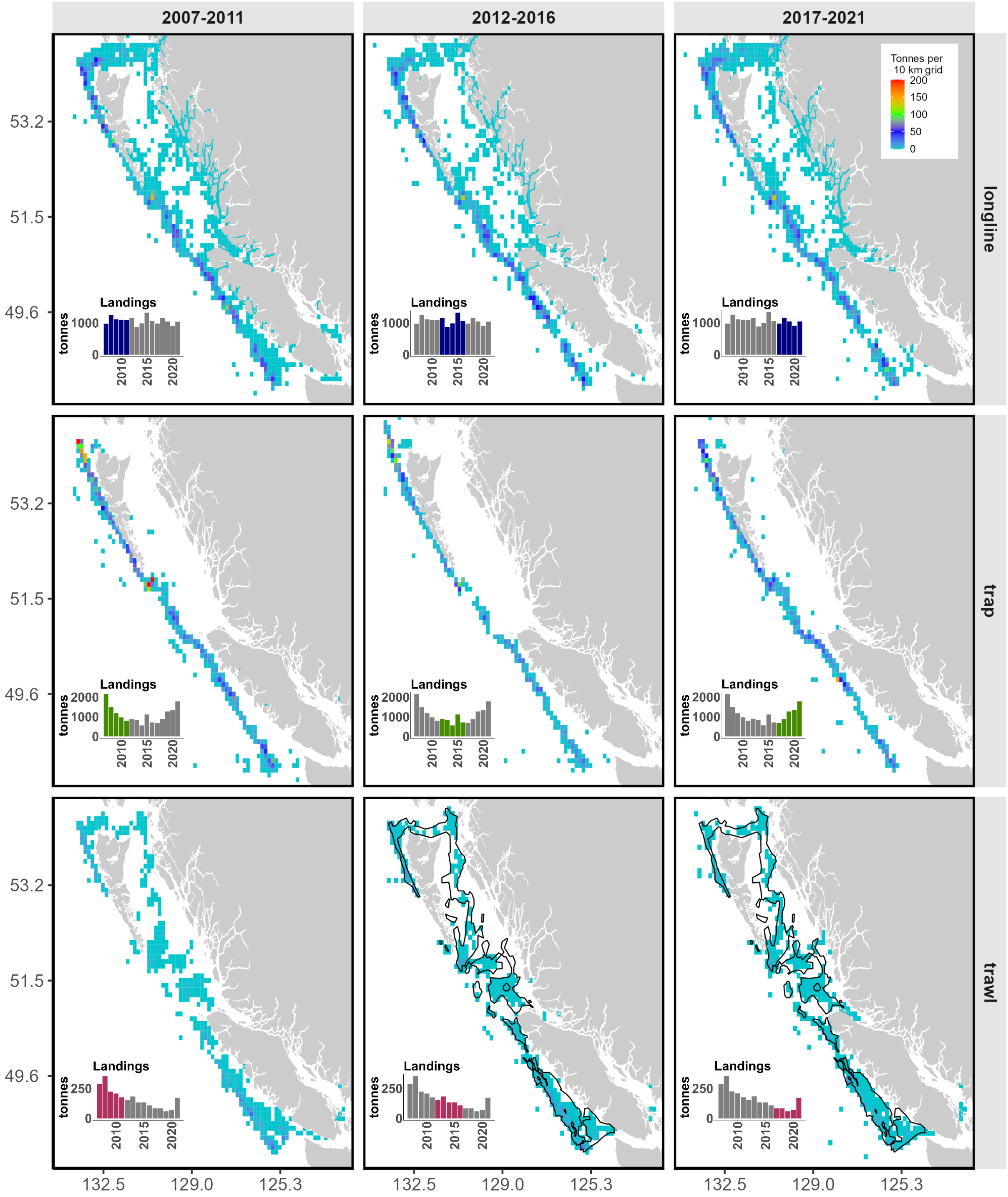

Figure A.3. Landed catch (t) of Sablefish summarized on a 10 x 10 km-squared grid three recent time periods (2007-2011, 2012-2016, 2017-2021) and three gear types: longline hook ('longline'; upper panels), longline trap ('trap'; centre panels), and trawl ('trawl'; bottom panels). Histograms show the total landings by year. The black outline on trawl maps shows the fishery footprint, within which the bottom trawl industry voluntarily agreed to restrict their fishing to, starting in 2012.

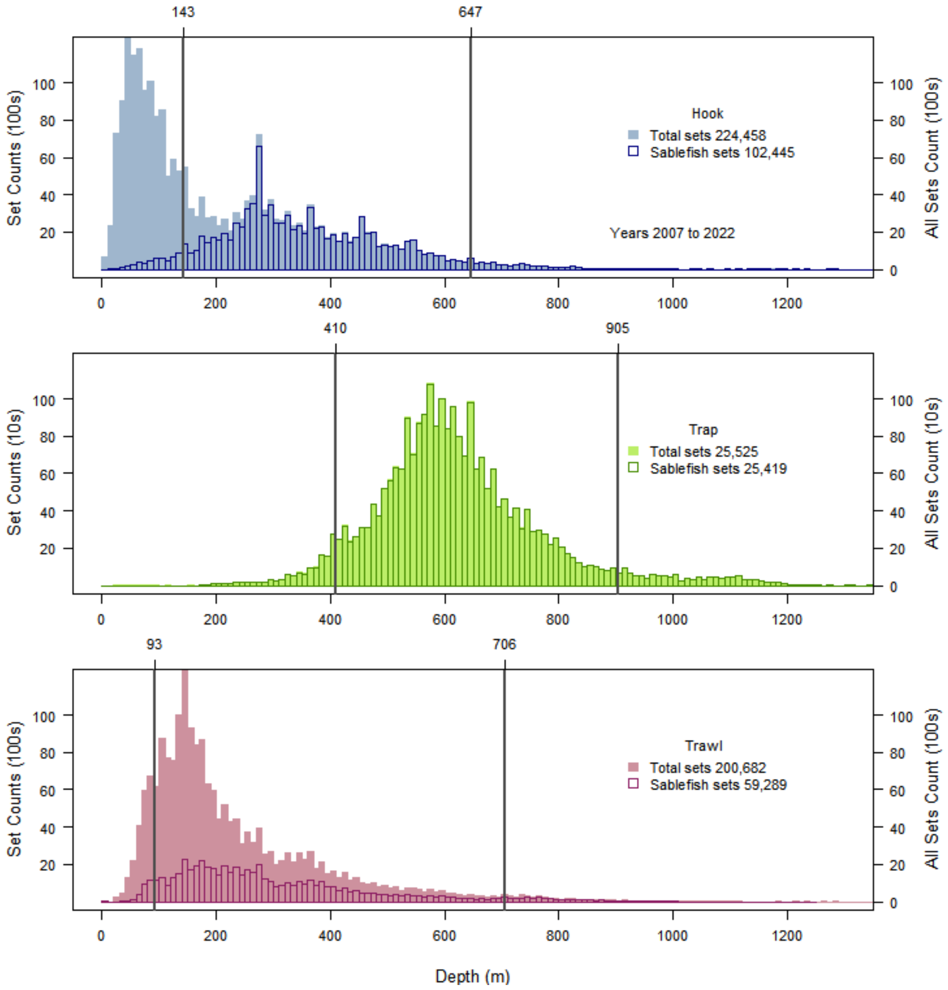

Figure A.4. Depth distribution of all sets (solid bars) and sets that captured Sablefish (outlined bars) for commercial longline hook (top panel), trap (center panel) and trawl (bottom panel) gear types. Data are summarized for commercial fisheries in British Columbia between 2006 and October 2021. Vertical lines denote the 5th and 95th percentiles of the depth distribution for Sablefish catch. The total number of sets and total number of sets that captured Sablefish are listed in each panel.

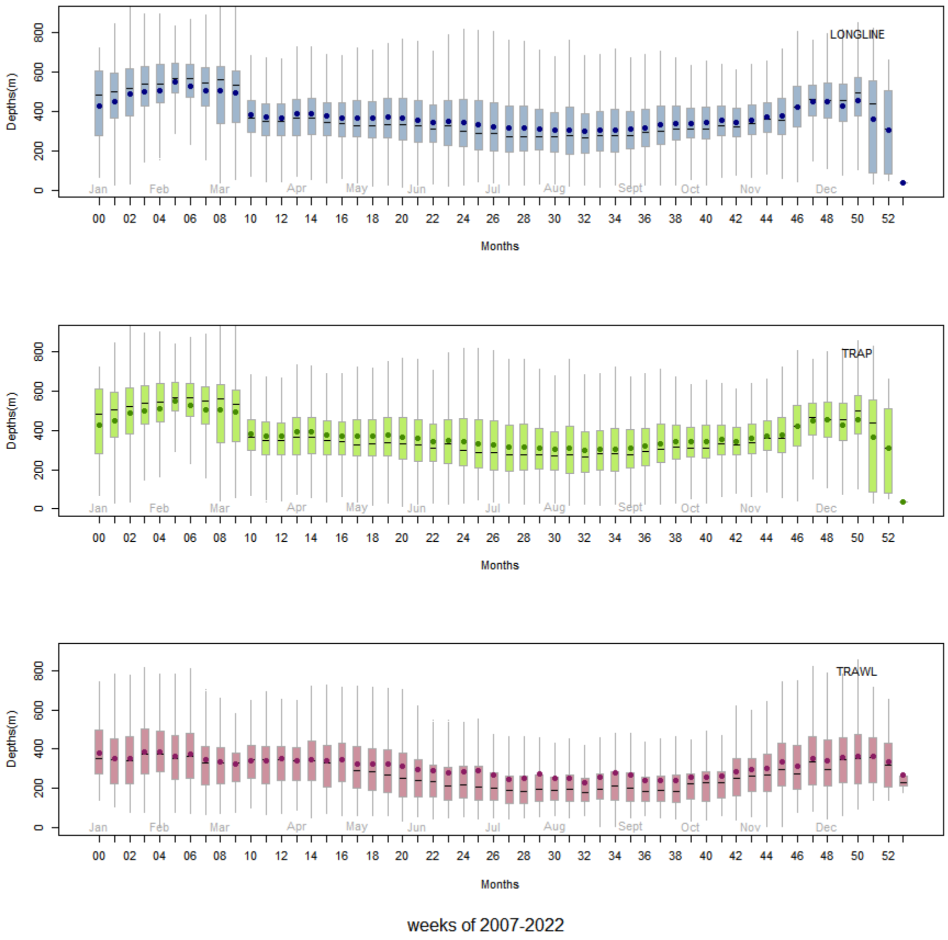

Figure A.5. Distribution of Sablefish depth-of-capture by week of the calendar year for 2006 to 2021 coastwide for longline hook (upper panel), longline trap (centre panel), and bottom trawl gears (lower panel). Boxplots show the 10%, 25%, 50%, 75%, and 90% quantiles of depth distribution using the lower whisker, lower hinge, median, upper hinge, and upper whisker, respectively.

APPENDIX B. STOCK INDICES

Fishery-dependent catch and effort data, and data from two fishery-independent surveys, were used to derive three relative abundance indexing series for Sablefish in BC waters.

Annual catch per unit effort indices were derived from:

1. Commercial Sablefish trap fishery catch and effort (1979-2009),
2. Standardised (Std.) trap survey (1990-2009), and
3. Stratified random sampling (StRS) survey (2003-2021).

All three indexing series use longline trap gear (hereafter “trap” gear). Catch per unit effort (CPUE) is calculated in units of kg/trap for each set. All three indices were used to fit operating model (OM) scenarios for the current update. Cox et al. (2023) considered a range of OM scenarios in 2016 that differed in the data sets used to fit the model. These scenarios sequentially removed or down-weighted data until only the StRS survey remained. For example, one scenario examines the implications of using fishery CPUE as a biomass index by excluding only it (i.e., the Std. and StRS survey indices were retained), while another scenario removed both fishery CPUE and the Std. survey index. They found that all data scenarios produced qualitatively similar patterns in spawning biomass and depletion over time, with relatively small changes in estimated spawning biomass and exploitation rates in 2016. As a result, they chose to retain all three indices in OM scenarios used to test management procedures (Cox et al. 2016; DFO 2020). We retain this approach for the current OM update and use all three indices that have been used previously.

In this appendix, we provide an overview of methods and resulting time series for each abundance index. Note however that only the StRS survey has been updated since the last OM update (DFO 2020). We also include a brief overview of additional data sources that have been previously evaluated for their suitability to index Sablefish abundance and deemed unsuitable.

B.1. COMMERCIAL SABLEFISH TRAP FISHERY INDEX

Set by set trap fishery logbook data are not available until 1990. Prior to 1990, one fishing record can represent multiple sets. As with the previous OM, Sablefish trap fishery CPUE from 1979 to 2009 was calculated as the sum of annual trap retained catches divided by the sum of trap effort subject to the following filtering:

1. Gear is restricted to longline trap,
2. Records with missing or out of range dates were excluded,
3. Sets reported to be at seamounts or in inlets are excluded, i.e., “offshore” records only were included,
4. Research or experimental sets are excluded,
5. Records with null catch values in the logbook data were excluded from the calculations rather than assigning zeros to those records, however there is little difference in the annual CPUE estimates if nulls are treated as zeros,
6. Only records with valid reported effort are included as null entries cannot be distinguished from zeros, and,
7. Beginning in 2006, retained weights per set recorded in logbooks were adjusted to correct for skippers entering product weight rather than round weight as required by the logbook program, which occurred frequently after the change in logbooks in 2006 under the Commercial

Groundfish Integration Program. The adjustment was calculated as the ratio of the dockside monitoring program landed weight (converted to round weight) to the total logbook weight for each trip.

The CPUE series was ended in 2009 as the number of trips by vessels fishing trap gear declined and to reduce reliance on fishery-dependent data for abundance indexing. Nominal trap CPUE fluctuated around ~15 kg/trap until the late 1980s when historic highs from ~20 to ~25 kg/trap were recorded (Figure B.1). Catch rates subsequently declined until 2001 but increased significantly in 2003. The 2003 observation can be attributed to the effects of (i) recruitment of the 2000 year class to the trap fishery, and (ii) the lack of trap activity from March to September of 2003 which meant that catch was taken during winter months when trap fishery CPUE is generally higher than average. The restricted trap activity in 2003 was due to low quota availability following an in-season TAC reduction in the 2001/2002 fishing year. This reduction was in response to the historically low standardised survey index value observed in 2001. Nominal catch rates declined from near 20 kg per trap in 2003 to ~10 kg/trap by 2009.

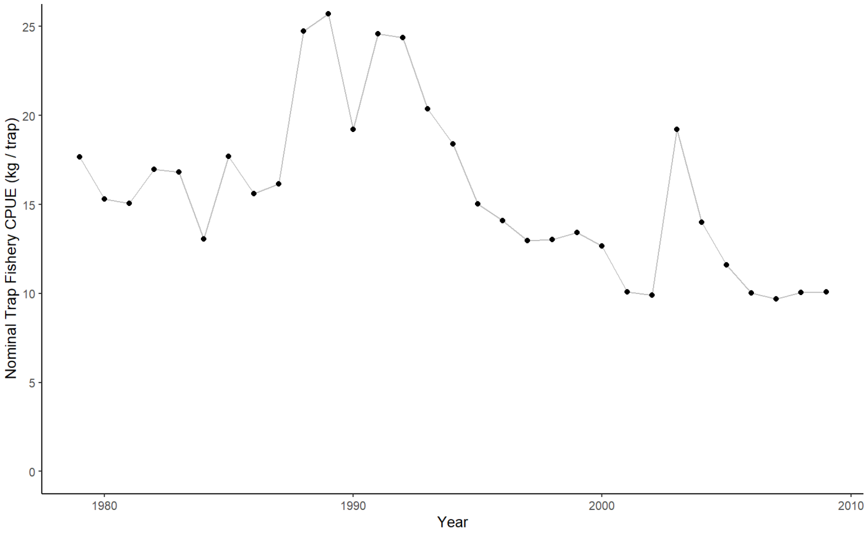

Figure B.1. Annual nominal commercial trap fishery catch-per-unit-effort (kg/trap), 1979-2009.

B.2. STANDARDISED TRAP SURVEY

A standardiSed trap survey (Smith et al. 1996; Downes et al. 1997; Wyeth and Kronlund 2003; Wyeth et al. 2004a) was conducted annually between 1990 and 2010 using the same bait in all years (approximately 1 kg of frozen squid in a bait bag). The standardised survey was a fixed locality survey, usually conducted by a chartered commercial Sablefish trap fishing vessel. Nine offshore survey localities were consistently surveyed in each year of the survey except in 1990 when only southern localities were surveyed (Figure B.2). The localities selected were commercial fishing grounds and were spatially dispersed about 60 nm apart such that the coast-wide survey could be conducted in about 30 days given favourable weather. Thus, the survey design was not randomized. Survey localities typically included high-relief bathymetric features such as gullies or canyons, which reflects the original intention to index Sablefish abundance in “core” fishing areas that represented what was believed to be prime habitat. Trap escape rings were sewn closed during survey fishing.

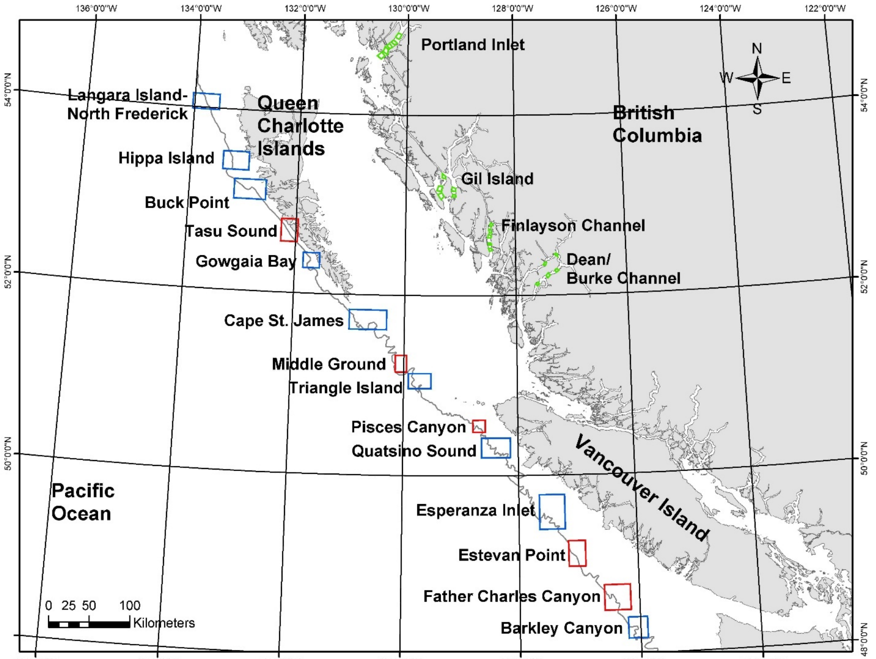

Figure B.2. Geographic boundaries of the standardised survey localities. Blue boxes indicate a Sablefish Standardised Survey locality. Tagging localities are indicated by red boxes, and green boxes indicate the locations within the mainland inlet localities. The 1000 m depth contour is shown.

Over the course of the survey between 5 and 7 different depth intervals were fished within each locality, although only the five core depth intervals identified as D1-D5 were fished consistently over the history of the survey. These core depth intervals lie between 274 and 1,189 m (or 150 to 650 fm). The depth intervals are designated D1 (274-457 m), D2 (457-641 m), D3 (641-824 m), D4 (824-1,006 m), and D5 (1,006-1,189 m). Usually only one set was conducted within each depth interval at each survey locality. Thus, there is no replication of sets within each combination of depth and locality except for selected localities in 1990-91 and 1993, and three selected localities in 2002. Also, the spatial position of each set was at the discretion of the fishing master rather than being selected at random.

The offshore standardised mean CPUE (weight/number of traps) used for the current OM update (2022) was calculated using the five core depth stratum D1 to D5 and all available localities in the database (up to 14 localities, although 5 of these were only sampled in 1-2 years). For each depth stratum, an annual mean CPUE was calculated for that stratum. A single annual CPUE was then calculated by assigning a weight equal to the number of sets fished at various localities within each depth stratum relative to the total number of sets fished that year. Sets used to calculate CPUE included those recorded as ‘fully usable traps’ (Code 1) and ‘not all traps fishing correctly’ (Code 12). This approach differs from the method used for previous OM updates (Cox et al. 2023), in which the index was calculated based on the mean of the catch per trap (kg/trap) observations for depth intervals D1-D5 and only nine core offshore standardised sites (Langara Island-North Frederick, Hippa Island, Buck Point, Gowgaia Bay, Cape St. James,Triangle Island, Quatsino Sound, Esperanza Inlet, Barkley Canyon). In addition, the 2016 analysis used an empirical likelihood method to calculate mean CPUE and associated confidence intervals (Owen 2001; Cox et al. 2023).

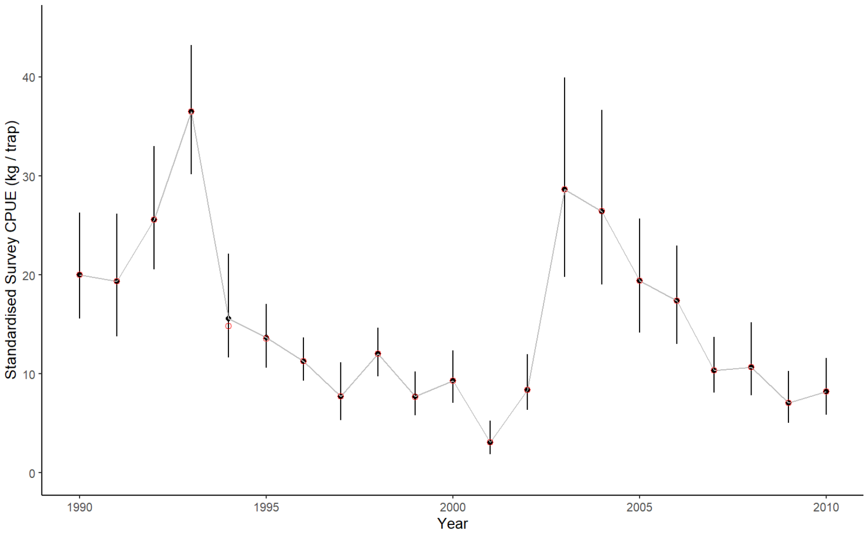

Figure B.3. Annual standardised survey catch rates (kg/trap) from 1990 to 2010. Annual mean catch rates based on the empirical likelihood method used in 2016 are shown in black (black circles, with error bars showing the 95% confidence intervals), while the simple mean catch rates used in the current 2022 update are shown as open red circles.

The switch to a new method in 2022 was unintentional, and was not recognized until late in the report writing stage. Differences in annual index values among the two approaches are almost negligible in most years, with the exception of 1994, so we do not expect that this change will meaningfully impact OM results (Figure B.3, Table B.1). However, future OM updates should use the empirical likelihood approach constricted to the nine core sites. An advantage of the empirical likelihood approach is that it allows confidence intervals to be calculated without requiring assumptions of a particular distribution (Owen 2001).

The coast-wide trends of survey catch rates show a decline over time from relatively high mean values in the early 1990s, fluctuating around 10 kg/trap beginning by the mid to late-1990s (Figure B.3). The 2001 survey produced the lowest mean and median catch rates observed in the time series, with marked reduction of the variance. Catch rates improved from 2001 to 2002 to a level like those observed in the mid-1990s. The catch rates in 2003 and 2004 were substantially higher than those observed during the previous nine years and comparable to those observed in 1992 and 1993. Catch rates consistently declined from 2003 to 2009. Ageing data by sex is available from 1990 to 2009; no ageing data is available for 2010 because of the decision to discontinue the survey after 2010 and the priority to age commercial and StRS survey samples.

A comparison by Cox et al. (2023) found that commercial trap fishery nominal CPUE and the standardised survey showed similar patterns and variability, which is consistent with the placement of standardised survey sets in core fishing areas.

Table B.1. Annual standardised mean catch per unit effort (kg/trap) used for 2022 vs the 2016 empirical likelihood estimates of the annual mean catch per unit effort (kg/trap), 95% confidence intervals (CI), and coefficient of variation (CV) for the Sablefish standardised trap survey.

Year	**2022 Version**	**2016 Version**			
	Mean CPUE	**Mean CPUE**	**Lower CI**	**Upper CI**	**CV**
1990	20.018	20.017	15.576	26.268	0.156
1991	19.336	19.336	13.802	26.2	0.177
1992	25.574	25.569	20.557	33.024	0.146
1993	36.508	36.509	30.175	43.207	0.092
1994	14.834	15.571	11.63	22.113	0.21
1995	13.563	13.665	10.64	17.037	0.123
1996	11.257	11.258	9.32	13.678	0.108
1997	7.722	7.721	5.343	11.185	0.224
1998	12.039	12.037	9.73	14.654	0.109
1999	7.652	7.72	5.801	10.223	0.162
2000	9.295	9.296	7.058	12.366	0.165
2001	3.082	3.092	1.88	5.248	0.349
2002	8.393	8.401	6.343	11.996	0.214
2003	28.652	28.656	19.768	39.925	0.197
2004	26.444	26.415	19.005	36.65	0.194
2005	19.43	19.432	14.169	25.708	0.161
2006	17.385	17.382	13.034	22.966	0.161
2007	10.347	10.348	8.111	13.735	0.164
2008	10.682	10.662	7.821	15.229	0.214
2009	7.085	7.087	5.033	10.274	0.225
2010	8.193	8.198	5.86	11.609	0.208

B.3. STRATIFIED RANDOM TRAP SURVEY

The Sablefish stratified random trap survey (StRS) was initiated in 2003 and follows a depth and area stratified random sampling design. The offshore survey area is partitioned into five spatial strata (S1 to S5) and three depth strata (RD1 to RD3) for a total of 15 strata (Figure B.4). The five spatial strata are S1 (South West Coast Vancouver Island, SWCVI), S2 (North West Coast Vancouver Island, NWCVI), S3 (Queen Charlotte Sound, QCS), S4 (South West Coast of Haida Gwaii, SWCHG), and S5 (North West Coast of Haida Gwaii, NWCHG). The three targeted depth ranges are 100-250 fathoms (RD1), 250-450 fathoms (RD2), and 450-750 fathoms (RD3). The area within each of the 15 strata are sectioned into 2 km x 2 km grid cells or ‘fishing blocks’ from which set locations are randomly chosen. From 2003 through 2005, five grid cells were randomly selected in each stratum for a total of 75 blocks. From 2006-2010, the number was increased to six grid cells within each block, for a total of 90 offshore blocks coastwide. Another temporary increase occurred in 2011 and 2012, when the total number of coastwide blocks jumped to 110. In 2013, the total number of blocks selected was decreased to 91 coastwide to reduce survey costs. Since this time, the annual target number of blocks has been 91 (~ 5-6 blocks per stratum); however, the number of blocks successfully fished has varied from 72-91 due to weather. Annual survey reports have been published for most years documenting survey methods and outcomes (Wyeth et al. 2004b, 2006; Lacko et al. 2020, 2021, 2022). Survey

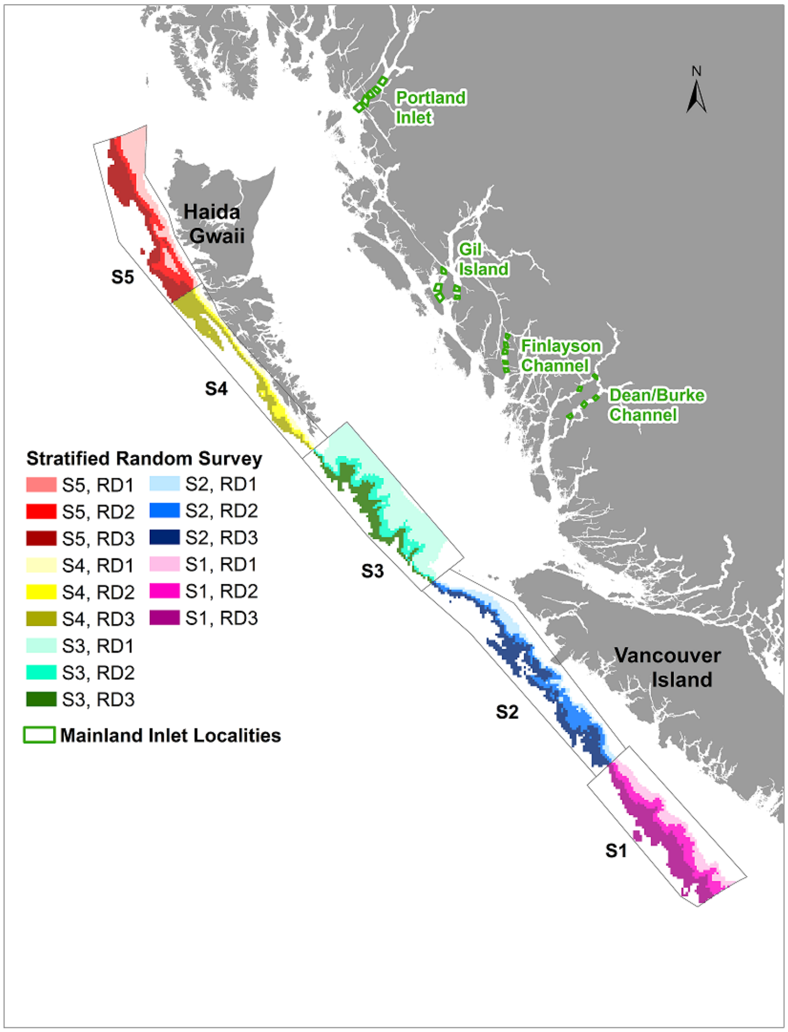

Figure B.4. Location of the survey design boundaries of the mainland inlet localities, and the five spatial areas (S1-S5) of the stratified random survey design. The three depths strata (RD1-RD3) are colour-coded and nested within each of the five spatial strata.

catch is completely enumerated and weighed by species and by trap for each set. A sample of Sablefish is retained from each set for (i) measurements of length, weight, sex and maturity, and (ii) extraction of otoliths for ageing. Finally, Sablefish are tagged and released on each set. Like the standardised survey gear, trap escape rings are sewn shut however the StRS survey traps are baited with a combination of Pacific Hake (*Merluccius productus*) and squid to follow the practice used by the commercial trap fishery.

Stratified random sampling mean index values and 95% confidence intervals were calculated by year using the classical survey stratified random sampling estimator (Cochran 1977) and the number of possible sampling units per stratum provided by Wyeth et al. (2007). The StRS survey means and 95% confidence intervals are shown in Figure B.5. An initial declining trend in survey catch rates occurred over 2003-2014 punctuated by high observations in 2006, 2008, and 2015. Between 2017 and 2019, survey catch rates increased steeply with 2019 having the highest CPUE value observed since the beginning of the time series in 2003. Catch rates have decreased somewhat in the last two years since 2019; however, the CPUE index in 2021 was still the third highest value observed since 2003.

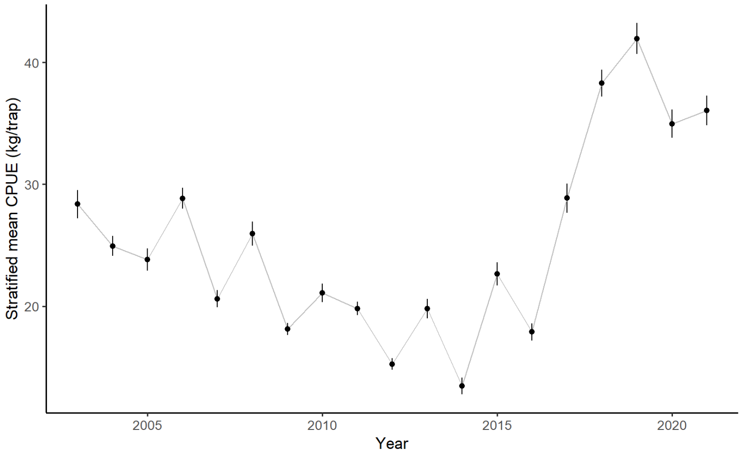

Figure B.5. Annual stratified random survey mean catch-per-unit-effort (kg/trap) from 2003 to 2021. Solid circles indicate the stratified mean. Vertical lines show the upper and lower 95% confidence limits.

B.4. SURVEY SOURCES NOT USED

Cox et al. (2023) summarized attributes of additional surveys conducted in BC that captured Sablefish to identify any further data sources that could be used to index Sablefish abundance. A subset of the surveys considered included the BC groundfish synoptic bottom trawl surveys (West Coast Vancouver Island, Queen Charlotte Sound, Hecate Strait, and West Coast Haida Gwaii; ~2003-present), the Hecate Strait multispecies assemblage bottom trawl survey (1984-2003), the International Pacific Halibut Commission (IPHC) fishery-independent setline survey (2003-present), the Pacific Halibut Management Association (PHMA) hard bottom longline hook survey (~2006-present), and the Queen Charlotte Sound and west coast Vancouver Island shrimp surveys (1974-present).

None of the additional survey series considered were deemed appropriate for OM fits (Cox et al. 2023). First, the spatial and depth coverage of most surveys did not encompass the offshore coastal biomass of adult Sablefish because they mostly occurred at depths shallower than typically occupied by adult Sablefish (e.g., shrimp trawl surveys, IPHC survey) or they only occurred in only a portion of the coast (e.g., Hecate Strait multispecies assemblage study). Second, each indexing series added to the model requires selectivity to be estimated and, for most series, a time-series of age data are not available. An exception to this is the recent synoptic bottom trawl surveys from which Sablefish ageing structures are collected. However, these division of these surveys into four different spatially segregated surveys that operate every second year means that their temporal and spatial coverage are still limited for Sablefish. Furthermore, while ageing structures are collected, the requirement to estimate four different sets of selectivity parameters for each of these surveys would require limited ageing resources to be diverted from ageing StRS trap survey and commercial fishery ages. As a result, the inclusion of the groundfish synoptic bottom trawl surveys into the Sablefish OM is not considered a high priority at this time.

APPENDIX C. OPERATING MODEL TRANSITION AND BRIDGING ANALYSIS

C.1. METHODS

Posterior distributions of operating model estimates are compared between TMB (2018 and 2021 data sets) and ADMB (2018 data set only) implementations, with two versions of the TMB operating model. The two TMB versions differ in whether they use hypotheses for the 2018 operating model update (DFO 2020), or the hypotheses for the base operating model in this paper. For the remainder of this appendix, we refer to these implementations as ADMB 2018, TMB 2018’ (TMB implementation with ADMB model data and hypotheses), TMB 2018 (updated hypotheses for TMB 2021, but with 2018 ADMB data), and TMB 2021 (updated data and hypotheses described in this paper). The cross-implementation comparison on 2018 data represents the transition analysis, comparing estimated parameters and reference points between the two alternate software implementations (ADMB 2018 and TMB 2018’) and hypotheses (TMB 2018’ and TMB 2018) to evaluate their component effects, while TMB 2018 vs. TMB 2021 represents the bridging analysis to judge the effect of additional data. Transition and bridging analyses are assessed via posterior distributions of leading biological parameters, fleet selectivity parameters, and key management quantities such as MSY-based reference points, current and historical spawning biomass, and fishing mortality.

Our bridging analysis tested the sensitivity of the TMB model to updated data by sequentially fitting TMB 2021 to one updated data set at a time. For example, first the catch data set is extended from 2018 to 2021, with no other data updated. Then, we sequentially update each remaining data set to 2021, starting with biomass index series, age- and length-compositions (individually and together), and finally fit to the full 2021 data set. For the Catch only, Catch and StRS, and Catch and Lengths scenarios, steepness was fixed to $h = 0.7$ and the conditional estimates of release observation standard errors were used to promote convergence.

Finally, we tested the new TMB implementation of the SSPM model on closed loop simulations conditioned by the TMB 2021 operating model (see the main body for the management procedure definition). The ADMB and TMB SSPM implementations were compared via fishery objective performance metrics.

C.2. RESULTS

C.2.1. COMPARISON OF OPERATING MODELS

Relative differences in leading parameter values (i.e., those driving the population dynamics and reference points) between ADMB 2018 and TMB 2018’ ranged from 3.4% for Beverton-Holt steepness to 31% for male natural mortality rate M_m (Table C.1). The TMB 2018’ female natural mortality M_f, which is more strongly integrated into the population dynamics than male M_m via links to spawning biomass and recruitment, was only 10% higher than ADMB 2018. At an unfished recruitment of 3.577 million age-1 fish, this difference in M_f equates to approximately 126,000 fewer females surviving to age-8, where they begin contributing to the spawning biomass. The 30% increase in absolute spawning biomass for TMB 2018’ is a bit more concerning, but is still within +/- 2 estimation standard errors of the ADMB 2018 estimates.

The range of differences between TMB 2018’ and ADMB 2018 reference points derived from the leading parameters was smaller than the range of leading parameter estimates themselves because parameter correlations lead to offsetting impacts on calculations involving products. For example, the product $x \cdot y = z$ will yield lower variation for z if x and y are inversely correlated since large x times small y is the similar to small x times large y. Therefore, estimates of MSY and spawning biomass depletion are very similar (Table C.1). The derived optimal harvest rate U_{MSY} for TMB 2018' was only 5% higher than ADMB 2018, mainly because this reference point is highly dependent on stock-recruitment steepness, which itself is fairly tightly constrained by the same prior distribution for both implementations. Note also that the ADMB 2018 estimated optimal harvest rate of approximately 7% is considerably higher than the previous operating model estimate from 2016 (Cox et al. 2019), which was about 4%. This higher average productivity arises from data updated to 2018 that include large year-classes from 2014-2016.

Several changes observed for TMB 2018' reversed when the hypotheses were changed for TMB 2018, which matches the hypotheses of the TMB 2021 model. Changes between TMB 2018' and TMB 2018 were driven by the CV assumed for trawl release and catch data, as the remaining changes were fairly minor. For example, there is a more informative prior on steepness h, but that tends to have only minor effects on population dynamics in the history, as noted in the main body results section. With the updated hypotheses, most estimates were revised down (Table C.1), with the exception of steepness and biomass depletion. Despite a higher steepness value, optimal harvest rate U_{MSY} decreased by around 21%, and MSY by around 23%, given the reduction in natural mortality and the resulting change in stock productivity via unfished recruitment (not shown). Interestingly, the changes in absolute biomass estimates B_{2018}, B_0, and B_{MSY} were compounded so that resulting 2018 depletion and stock status estimates were fairly stable, given each was revised down by a similar amount.

Finally, updating the data from TMB 2018 to TMB 2021 in the bridging analysis shows that the new TMB implementation and hypothesis are not strongly sensitive to the data update. Unlike the ADMB-TMB transition, updating the data led to fairly stable estimates of life history parameters B_0, h, M_m, M_f, biological reference points MSY, B_{MSY}, and U_{MSY}, which all increased by less than 5% (Table C.1), well within a posterior standard error. There are larger changes in 2018 spawning biomass and stock status, as a result of a second revision downwards of B_{2018} by -11.7%, bringing it more inline with the ADMB 2018 estimate. As a result, stock status and depletion in 2018 are also reduced because the of the increase in equilibria.

Temporal patterns of spawning biomass and fishing mortality were very similar between the four models (Figure C.1), differing largely in absolute biomass scale as described above. TMB 2021 estimates similar size biomass to ADMB 2018 in the early model history, but a larger biomass recently, leading to lower recent fishing mortality rates, especially for the trawl fishery where the trawl catch CV is higher under TMB 2018 and TMB 2021.

Some differences between TMB 2018' and ADMB 2018 can be attributed, in part, to higher parameter auto-correlation from the Bayesian posteriors sampled by ADMB 2018 (Figures C.2 - C.4; e.g., M_m, as well as selectivity parameters for the trawl fishery, the longline hook fishery, and the two fishery-independent surveys). In some cases, auto-correlation can make parameter estimates over-precise (e.g., trawl selectivity) when chains get 'stuck' in a high density area, or under-precise when chains spend longer than necessary sampling low posterior density areas before eventually moving on. While auto-correlation is not completely absent from TMB model posterior chains, there is much less, leading to higher quality estimates of uncertainty.

The most substantial differences among all four OMs occurred for length-based selectivity in all fisheries and surveys (Figure C.3). Length-at-50%-selectivity for the trap fishery was least impacted by the switch to TMB and hypothesis updates, probably because there is a long time-series of age-composition data. In fact, the trap fishery length-at-50% selectivity looks somewhat over-precise. The longline hook and trawl fisheries, on the other hand, have no age-composition and, therefore, rely on tagging only (longline hook) or tagging combined with length-frequency data (trawl). Length-at-50% selectivity for trawl and longline hook fisheries varies quite a bit between the four OMs. The prior for trawl selectivity parameters was highly informative for ADMB 2018, which appears to have tightly controlled the posterior samples (Figures C.3 and C.4, Trawl), which was not evident for the three TMB models.

The large differences in length-at-50% selectivity between ADMB 2018 and the TMB models for the two fishery-independent surveys is the most surprising, particularly for the stratified random survey, which has a relatively large and somewhat precise age-composition data set. There may be some effect of the large incoming year classes that is influencing these parameters. On the other hand, length-selectivity curves derived from the above parameters were qualitatively very similar, despite somewhat large differences in their posterior distributions as described above (Figure C.5).

Biological MSY-based reference point posteriors (Figure C.6) paint a similar picture to the comparison of posterior means (Table C.1). The largest shift was in the step from TMB 2018' to TMB 2018, where the relaxing of the CV on trawl landings allowed optimal harvest rates U_{MSY} and optimal biomass B_{MSY} to reduce closer to the ADMB 2018 values.

C.2.2. DATA UPDATES FROM 2028 TO 2018

Updating just the catch data from TMB 2018 to TMB 2021 reduces the average biomass and increases the productivity (Table C.2). Surprisingly, subsequently adding the StRS index to the catch update has hardly any effect on estimated leading parameters and reference points. As noted above, there is a recent pattern of somewhat large residuals for the StRS survey, so the lack of influence may be the result of a pattern of biomass increase that is driven by data sources other than that survey. In particular, including the age composition data has a relatively large influence on parameters and reference points, increasing MSY by 8% over the ‘Catch’ only and ‘Catch & StRS’ versions. As expected, ‘Catch & Lengths’ had little impact over that of ‘Catch’ alone since we have limited quantities and length data are generally weakly informative anyway. Including all the new data up to 2021 returned the same MSY as the ‘Catch & Ages’ scenario.

C.2.3. MP PERFORMANCE COMPARISON

The two MPs performed almost identically under the TMB 2021 operating model. Performance metrics for Objectives 1-3 were identical, and the only differences were observed catch metrics. These differences were minor (1%-2%), and could be tuned to match with no loss of conservation performance.

Table C.1. Key parameter posterior mean values (and standard deviations) for four versions of the Sablefish operating model (i) ADMB model fit to 2018 data (ADMB 2018), (ii) TMB model fit to 2018 data with 2018 hypotheses (TMB 2018'), (iii) TMB model fit to 2018 data with 2021 hypotheses (TMB 2018), and (iv) TMB model fit to 2021 data and hypotheses (TMB 2021). Stock status is shown relative to unfished biomass (B_t/B_0), theoretical most productive spawning biomass (B_t/B_{MSY}), and the limit reference point ($B_t/(0.4B_{MSY})$) for 2018. The bottom row shows the posterior probability of spawning biomass being above the limit reference point in 2018. Biomass quantities are in kilotonnes, mortality and harvest rates in yr^{-1}, and stock status indicators are unitless.

	ADMB 2018	TMB 2018'	% Diff	TMB 2018	% Diff	TMB 2021	% Diff
B_0	54.086 (3.318)	60.367 (3.945)	11.6	53.83 (3.485)	-10.8	56.679 (3.826)	5.3
M_m	0.042 (0.003)	0.055 (0.003)	31	0.05 (0.003)	-9.1	0.052 (0.003)	4
M_f	0.088 (0.002)	0.097 (0.003)	10.2	0.094 (0.003)	-3.1	0.094 (0.003)	0
h	0.617 (0.062)	0.638 (0.064)	3.4	0.648 (0.056)	1.6	0.667 (0.055)	2.9
B_{2018}	16.292 (2.005)	21.186 (3.25)	30	17.314 (2.707)	-18.3	17.364 (2.251)	0.3
B_{2021}	-	-	-	-	-	26.846 (3.985)	-
B_{MSY}	20.432 (1.67)	23.698 (1.75)	16	21.921 (1.459)	-7.5	22.896 (1.555)	4.4
Legal U_{MSY}	0.077 (0.011)	0.081 (0.01)	5.2	0.066 (0.007)	-18.5	0.065 (0.006)	-1.5
MSY	4.37 (0.445)	4.418 (0.424)	1.1	3.419 (0.289)	-22.6	3.516 (0.288)	2.8
B_{2018}/B_0	0.301 (0.032)	0.351 (0.046)	16.6	0.322 (0.046)	-8.3	0.306 (0.033)	-5
B_{2018}/B_{MSY}	0.8 (0.096)	0.895 (0.128)	11.9	0.791 (0.117)	-11.6	0.759 (0.086)	-4
$B_{2018}/(0.4B_{MSY})$	1.999 (0.239)	2.238 (0.319)	12	1.976 (0.293)	-11.7	1.897 (0.215)	-4
B_{2021}/B_0	-	-	-	-	-	0.474 (0.061)	-
B_{2021}/B_{MSY}	-	-	-	-	-	1.173 (0.159)	-
$B_{2021}/(0.4B_{MSY})$	-	-	-	-	-	2.933 (0.397)	-
$P(B_{2018} \geq 0.4B_{MSY})$	1	1	0	1	0	1	0
$P(B_{2021} \geq 0.4B_{MSY})$	-	-	-	-	-	1	-

Table C.2. Sablefish TMB operating model maximum likelihood estimates of life history parameters and MSY based reference points under the data series update sensitivity analysis. The Data column shows the sets of data that are extended to 2021 for the TMB 2021 model. Biomass quantities (B_0, B_{MSY} and MSY) are in kilotonnes, stock-recruit steepness h is unitless, and natural mortality and harvest rates have units yr^{-1}.

Data	B_0	R_0	h	M_m	M_f	B_{MSY}	U_{MSY}	MSY
All data up to 2018	53.80	3.896	0.639	0.054	0.099	22.11	0.061	3.268
Catch	53.80	3.896	0.639	0.054	0.099	22.11	0.061	3.268
Catch & StRS Index	54.11	3.909	0.651	0.054	0.099	22.10	0.062	3.317
Catch & Ages	56.39	3.834	0.670	0.052	0.095	22.75	0.065	3.539
Catch & Lengths	52.82	3.573	0.653	0.050	0.095	21.48	0.067	3.440
Catch & Age/Lengths	56.39	3.834	0.670	0.052	0.095	22.75	0.065	3.539
All data up to 2021	56.64	3.825	0.672	0.052	0.094	22.82	0.065	3.542

Table C.3. Sablefish management performance metrics under the ADMB and TMB surplus production stock assessment models.

	Obj. 1	Obj. 2	Obj. 3	Obj. 4	Obj. 5		
Assessment Model	$P(B_t > 0.4B_{MSY})$	$P(B_{2031} < B_{2021})$	$P(B_{2052} > 0.8B_{MSY})$	$P(C_t > 1992)$	$\bar{C}_t$	AAV	B_{2056}
ADMB SP	1	0	0.98	0.99	3,826	3.9	35.56
TMB SP	1	0	0.98	1.00	3,721	3.7	34.95

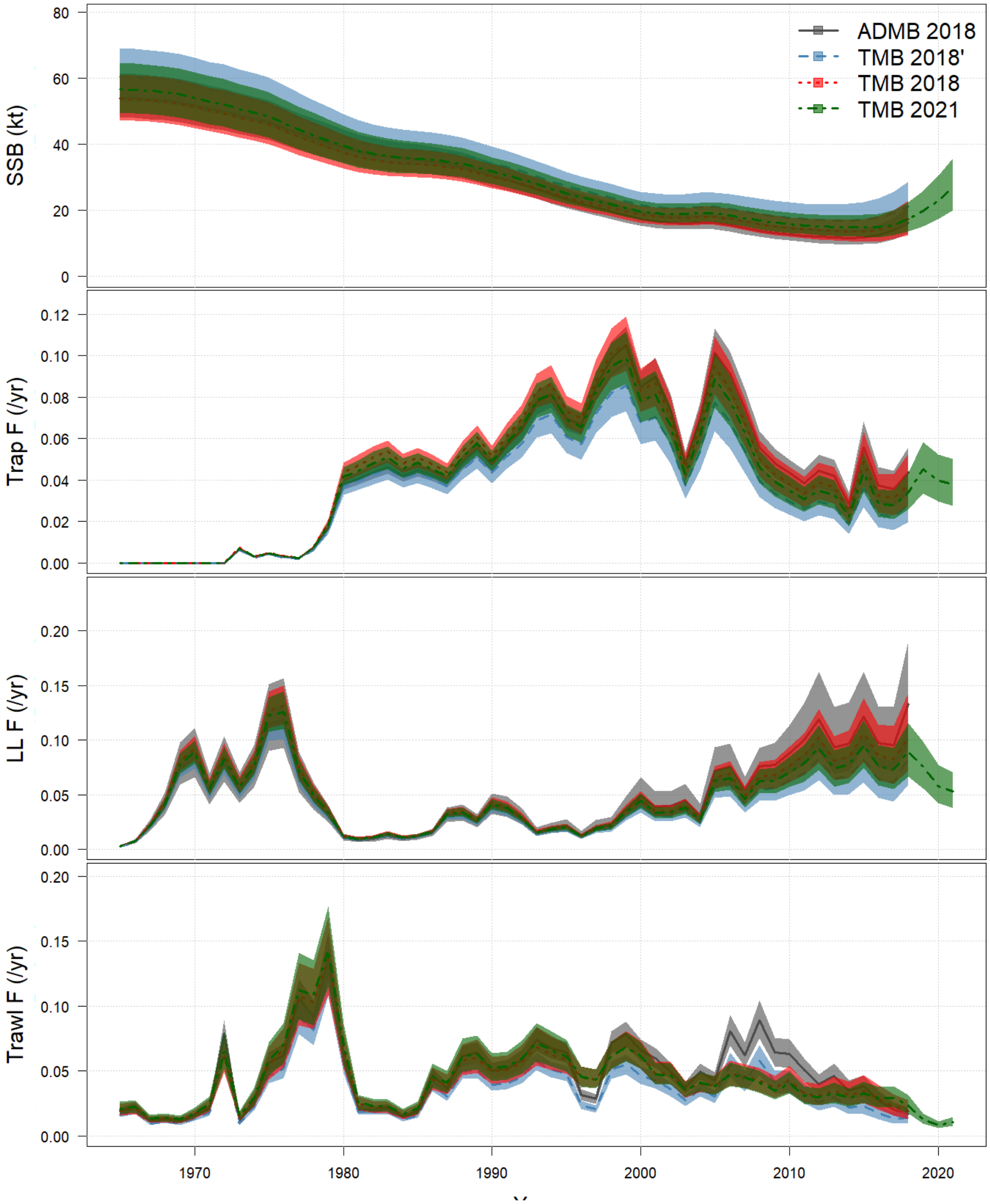

Figure C.1. Posterior distributions of spawning biomass (top) and fishing mortality (rows 2-4) time series from the four operating models for the transition and bridging analysis.

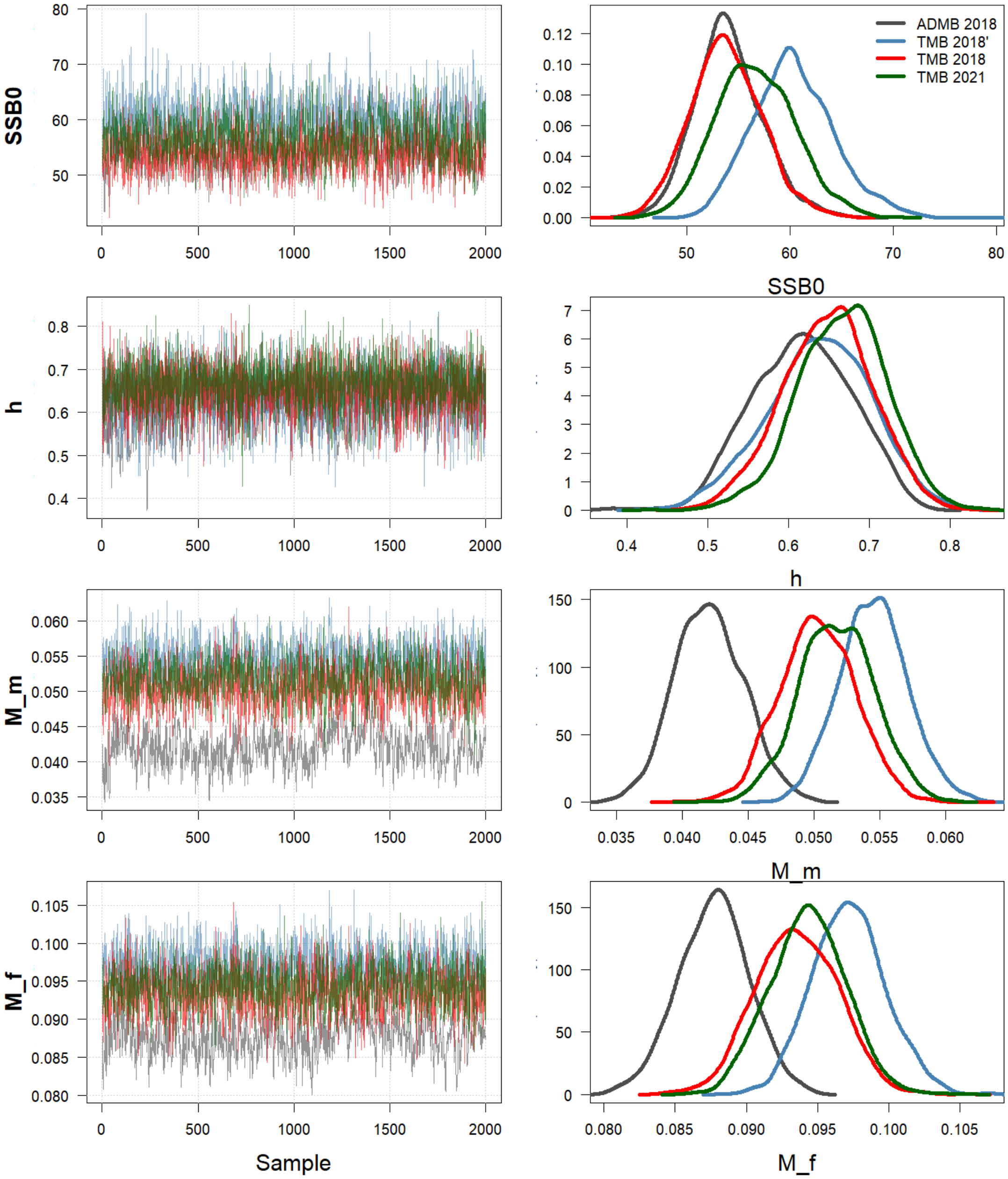

Figure C.2. Leading parameter posterior distributions showing posterior chains (left) and densities (right) unfished female spawning biomass (SSB0), stock-recruit steepness (h), and natural mortality for males (M_m) *and females* (M_f) *under the four operating models in the transition and bridging analysis.*

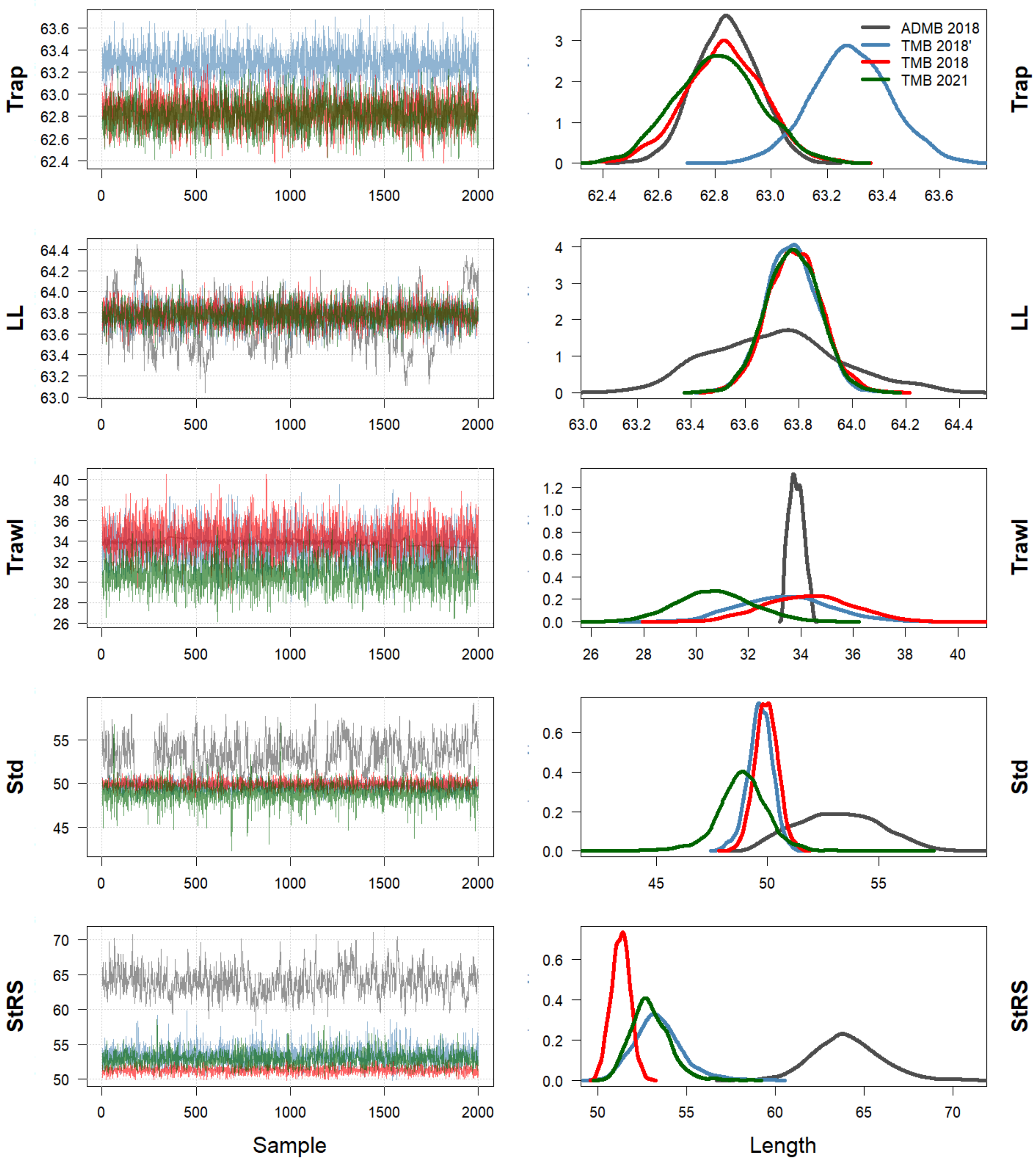

Figure C.3. Selectivity alpha parameter posterior distributions (i.e., length-at-50% selectivity for all fleets except for trawl, which is the shape parameter for a gamma probability density function) showing posterior chains (left) and densities (right) for, top to bottom, Trap, LL, Trawl, Std, and StRS fleets under the four operating models for the transition and bridging analysis.

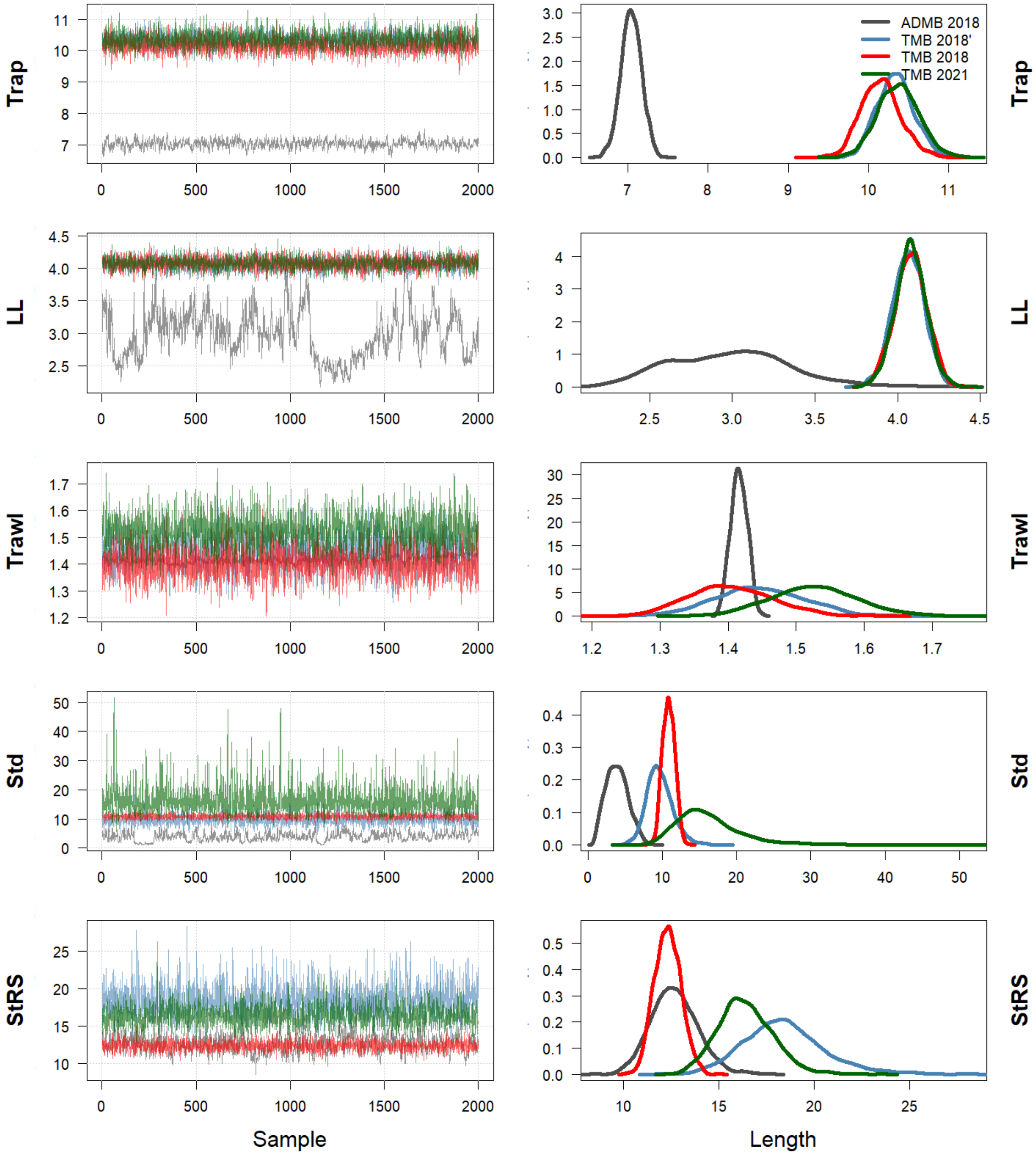

Figure C.4. Selectivity beta parameter posterior distributions (i.e., difference between length-at-50% and length-at-95% selectivity for all fleets but trawl, which is the scale parameter for the gamma probability density function) showing posterior chains (left) and densities (right) for, top to bottom, Trap, LL, Trawl, Std, and StRS fleets under the four operating models for the transition and bridging analysis.

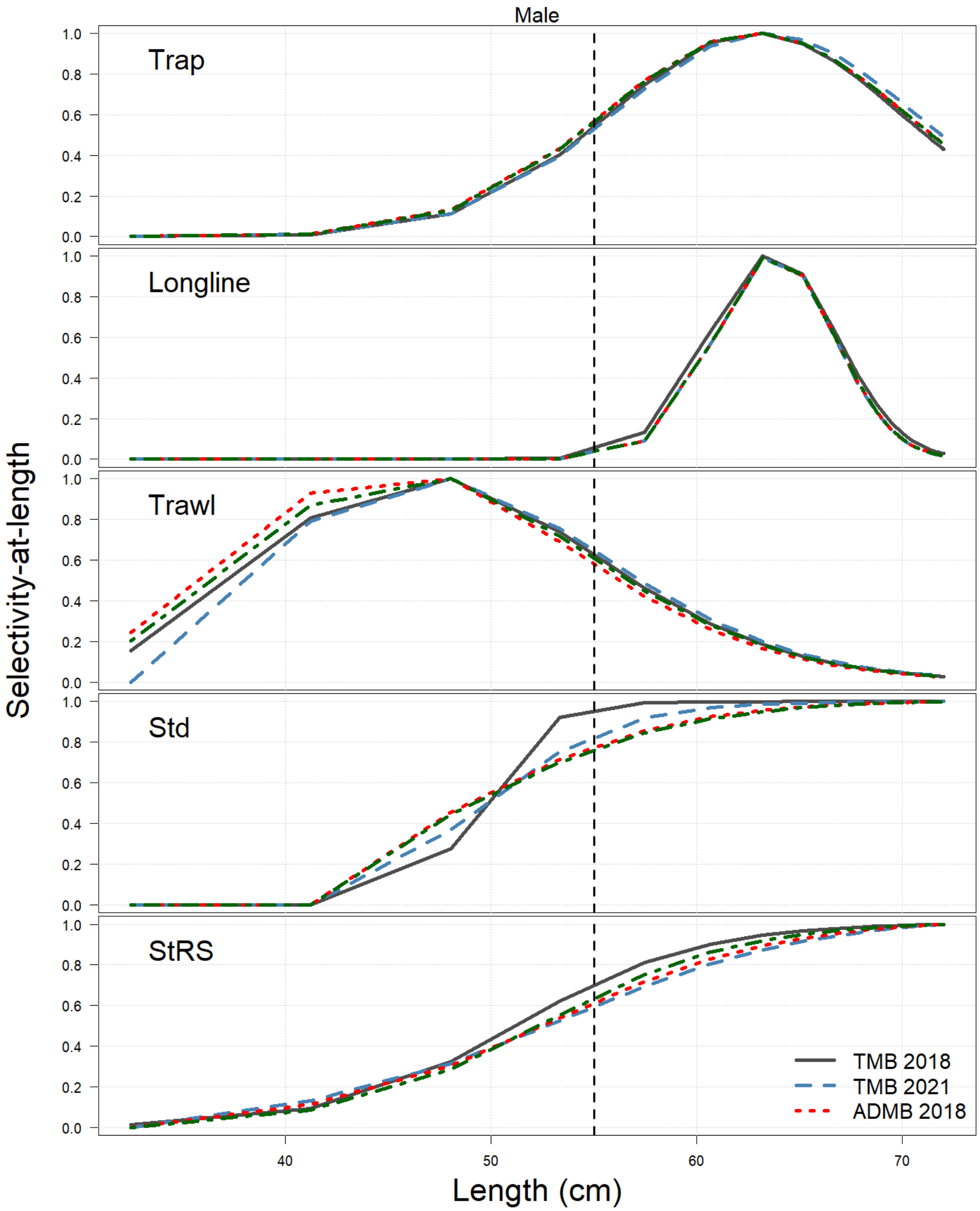

Figure C.5. Estimated selectivity functions for fishing fleets and surveys under the four operating models for the transition and bridging analysis.

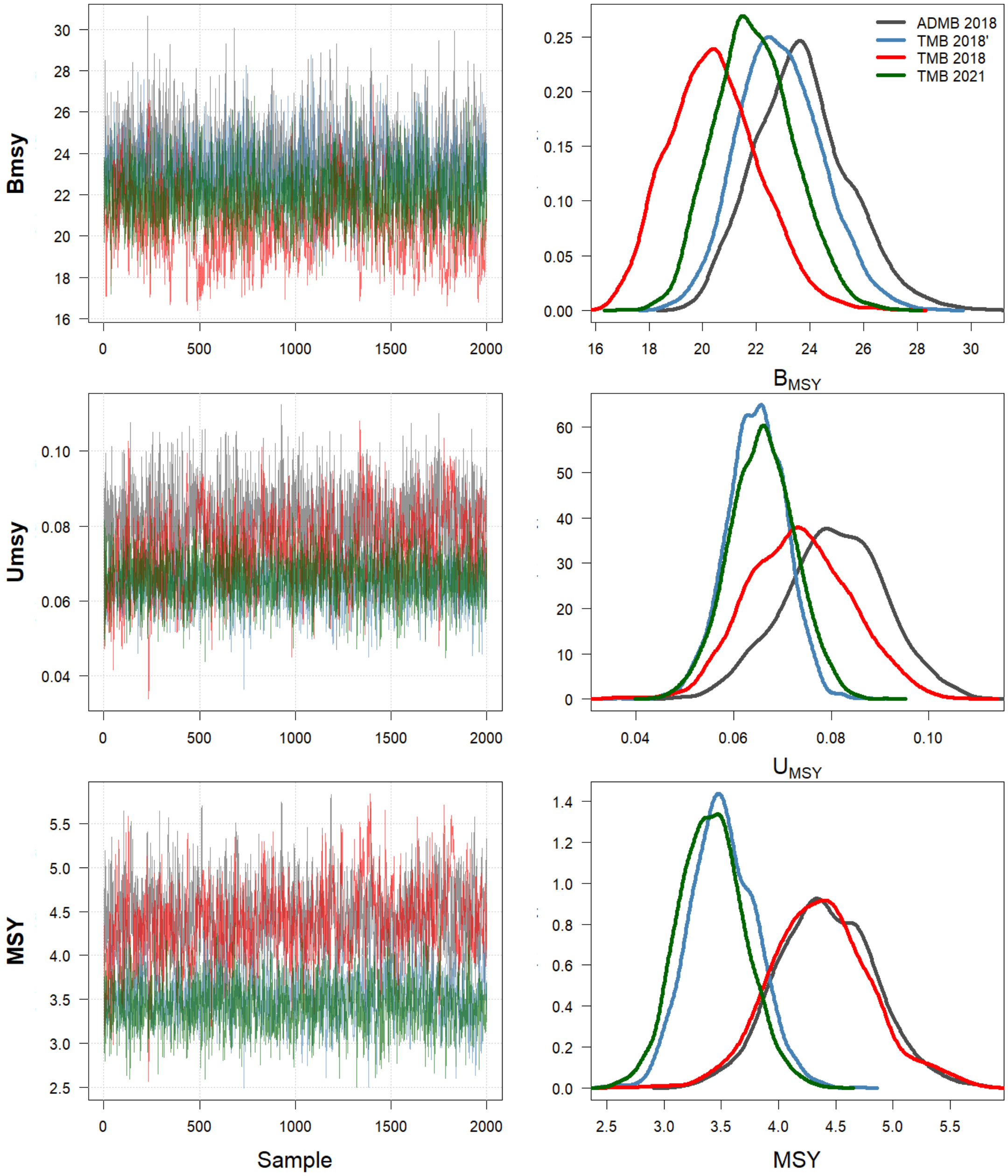

Figure C.6. MSY-based reference point posterior distributions showing chains (left) and densities (right) of maximum sustainable yield (MSY, top), optimal legal harvest rate (U_{MSY}, middle), and optimal biomass producing maximum sustainable yield (B_{MSY}, bottom) under the four operating models for the transition and bridging analysis.

APPENDIX D. OPERATING MODEL DIAGNOSTICS

The Sablefish operating model is assessed for goodness of fit, sensitivities to assumptions, and stability as data are removed in a retrospective analysis.

D.1. METHODS

D.1.1. GOODNESS OF FIT

We assess SAB-OM for its goodness of fit to the latest data. Goodness of fit is mainly reflected in posterior chain characteristics, including within-chain autocorrelation, correlation among leading parameters, potential scale-reduction factors (i.e., $\hat{R}$ values less than 1.01), and effective sample size (at least 100 per chain).

D.1.2. SENSITIVITY ANALYSES

We assessed TMB 2021 for sensitivity to likelihood weights for selected data, parameter prior distributions, at-sea release model precision and mortality assumptions, and the last year of modeled recruitments. For each set of sensitivity tests, we produced a table of maximum probability density estimates (MPDEs) for leading parameters and derived variables, as well as plots of model fits for selected cases.

We varied the last year for estimated recruitment deviations from 2015 up to 2019 to test how that choice affected leading parameters and reference points. For these sensitivity analyses, the release observation standard deviation was estimated conditional on the residuals, rather than fixed as in Table 1, to improve model convergence.

Model sensitivities to at-sea release model assumptions were tested in two ways. First, the assumed discard mortality rate was adjusted by scalar multiples of 0.25, 0.5, and 1.5 times the baseline values in Table 1. Second, the at-sea release observation model standard errors for all fleets were set to 0.05, 0.1, 0.15 and their fleet-specific conditional maximum likelihood estimates.

Age composition weights for the Trap fishery (0.1, 0.25, 0.5, and 1.0) were also tested to determine their relative influence on model estimates since this series is the longest one available.

Information content of prior distributions for natural mortality rates, stock-recruit steepness prior variance, and fleet selectivity were all modified via their corresponding prior standard deviations, making them more or less informative. The improper prior on unfished biomass magnitude was adjusted to test less restrictive values, and finally the prior mean for natural mortality was varied to test for differences in magnitude.

D.2. RESULTS

D.2.1. CONVERGENCE AND GOODNESS OF FIT

Standard Bayesian posterior chain diagnostics suggest that chains have converged (Figure E.1) with scale reduction factors for all parameters $\hat{R}$ less than 1.01 (i.e., posterior standard deviations within each chain are within 1% of each other across chains) except for a time-varying q parameter, which had $\hat{R} = 1.05$, but these are expected to be quite uncertain parameters in any case. Further, the effective sample size of all parameters is well above 400 (i.e., 100 effective samples per individual chain) (Betancourt and Girolami 2015). While some parameters have quite high coefficients of variation (Figure E.1, $CV(\theta)$, measured as posterior standard deviation relative to the posterior mean), indicating higher uncertainty, CVs are high for time-varying catchability parameters, which are expected to be quite uncertain even at convergence. Parameter lag-1 autocorrelation within the chains ranged between -0.5 and 0.5, but most of the density was between -0.3 and the mean value of -0.1, which is expected for Hamiltonian Monte Carlo (Monnahan and Kristensen 2018).

D.2.2. SENSITIVITY ANALYSES

D.2.2.1. Last Recruitment Deviation

Adjusting the last year of recruitment deviations shifted how the model attempted to explain at-sea releases, either by increasing the overall size of the stock (via unfished biomass) or increasing the size of recent year classes (Table D.1). Stock-recruit steepness went from 0.827 when 2015 was the last recruitment deviation, to 0.63 when 2019 was the last year. Similarly, R_0 and U_{MSY} dropped with steepness, bringing MSY down as well. Such effects are based on the current upward stock trajectory, which would require higher unfished recruitment (productivity) to match in the absence of recruitment process errors. On the other hand, there was little effect of recruitment deviations on optimal biomass levels, with B_{MSY} under all tests within 300 t.

Table D.1. TMB 2021 estimates of life history parameters and MSY based reference points under the last estimated recruitment deviation sensitivity analysis. The Year column shows the year of the last estimated recruitment deviation, after which the expected recruitment off the stock-recruit curve is used. Biomass quantities (B_0, B_{MSY} and MSY) are in kilotonnes, stock-recruit steepness h is unitless, and natural mortality and harvest rates have units yr^{-1}.

Year	B_0	R_0	h	M_m	M_f	B_{MSY}	U_{MSY}	MSY
lastRdev2015	62.55	4.999	0.827	0.061	0.105	23.11	0.089	4.807
lastRdev2016	61.31	4.822	0.815	0.060	0.104	22.84	0.087	4.642
lastRdev2017	58.07	4.131	0.720	0.054	0.098	22.78	0.072	3.893
lastRdev2018	56.64	3.825	0.672	0.052	0.094	22.82	0.065	3.542
lastRdev2019	56.16	3.707	0.657	0.051	0.093	22.82	0.063	3.425

D.2.2.2. Discard Mortality Rate and At-sea Release Precision

Higher at-sea release mortality rates generally lead to higher unfished biomass and recruitment estimates, and lower legal-sized MSY (Table D.2, top 4 rows). The higher biomass arises because there would need to be more fish to support the catches and increasing biomass trend, while the lower legal MSY is simply that fewer sub-legal fish survive to legal size to contribute to the equilibrium yield.

Trawl at-sea release data CVs had little impact on most parameters, given the higher trawl catch CVs in the base OM used for the sensitivity analyses. Greater precision of at-sea release estimates forces a closer fit to those data, but primarily acts via increased year class strength for the incoming year classes (not shown) and not via increased biomass and productivity estimates (Table D.2, bottom four rows).

Table D.2. TMB 2021 model estimates of life history parameters and MSY based reference points under the at-sea release sensitivity analysis, varying discard mortality rates (dM) and precision of at-sea release observations (tauRel). Biomass quantities (B_0, B_{MSY} and MSY) are in kilotonnes, stock-recruit steepness h is unitless, and natural mortality and harvest rates have units yr^{-1}.

modelHyp	B_0	R_0	h	M_m	M_f	B_{MSY}	U_{MSY}	MSY
dM0	48.13	3.068	0.668	0.048	0.091	16.75	0.113	4.344
dM.25	50.35	3.260	0.669	0.049	0.092	18.72	0.092	4.023
dM.5	52.50	3.451	0.670	0.050	0.093	20.29	0.080	3.810
dM1.5	60.58	4.191	0.674	0.054	0.096	24.94	0.056	3.382
tauRel.05	55.95	3.783	0.674	0.052	0.094	22.56	0.065	3.514
tauRel.1	56.64	3.825	0.672	0.052	0.094	22.82	0.065	3.542
tauRel.15	56.85	3.823	0.667	0.052	0.094	22.94	0.065	3.531
condMLErelObs	55.88	3.690	0.647	0.051	0.093	22.75	0.063	3.418

D.2.2.3. Age Composition Weightings

Reducing the likelihood weight from 1.0 to 0.1 for trap fishery age composition data reduced unfished equilibrium values (i.e., B_0 and R_0) by almost 50% and MSY by over 30% (Table D.3). This is comparable to the data bridging analysis (Appendix C) where including 2019-2021 age composition data increased the average biomass and production estimates over catch data alone. Age composition is the main source of recruitment timing and magnitude, which drives recent trends in the StRS index, catch, and at-sea releases. As noted above, the lack of catchability as a fudge factor on releases may increase sensitivity of SAB-OM to recruitment timing and magnitude indicators.

Table D.3. TMB 2021 model estimates of life history parameters and MSY based reference points under the trap age composition likelihood weight sensitivity analysis. Biomass quantities (B_0, B_{MSY} and MSY) are in kilotonnes, stock-recruit steepness h is unitless, and natural mortality and harvest rates have units yr^{-1}.

Likelihood Weight	B_0	R_0	h	M_m	M_f	B_{MSY}	U_{MSY}	MSY
0.10	32.69	2.334	0.690	0.036	0.098	14.46	0.064	2.516
0.25	39.33	2.630	0.688	0.039	0.094	16.82	0.063	2.753
0.50	46.77	3.088	0.682	0.044	0.093	19.41	0.064	3.078
1.00	56.64	3.825	0.672	0.052	0.094	22.82	0.065	3.542

D.2.2.4. Selected Prior Distributions

Reducing the weighting scalar on the improper (i.e., not finitely integrable) Jeffereys prior for unfished biomass increased the value of unfished biomass, going from around 56 kt for SAB-OM (not shown) to around 110 kt (Table D.4, jeffWtB0). The biomass increase was accompanied by a modest increase in natural mortality and decrease in steepness, leading to a slightly higher legal U_{MSY}. This behaviour is consistent with how models react to less informative 1-way trip fishing data (i.e., biomass only declines over the model history), which has been true of Sablefish until only recently. When data show a 1-way trip, models have trouble estimating the size of the stock, and prefer to set the biomass so high that fishing mortality is negligible, and sometimes making the compositional data easier to fit by varying selectivity in unrealistic ways.

The stock-recruit steepness prior (Table D.4, priorh) has minor effects on unfished biomass, recruitment, and natural mortality, but, of course, affects the optimal harvest rate more. Less informative priors (i.e., lower β_1, β_2 values) produce lower stock-recruit steepness estimates and lower optimal harvest rates, although none were outside the range of either pre-existing estimates or values from other jurisdictions.

Increasing the prior mean on natural mortality from 0.08 to 0.1 increases unfished biomass and leads to a small decrease in steepness. As a result, B_{MSY} and MSY increase by a small amount. (Table D.4, priorM(.1,.01)). At the same time, the effect of relaxing the prior standard deviations to 0.1 from 0.01 was minor.

Finally, more informative selectivity priors had a dome shaped relationship with biomass, and negative relationship with productivity estimates (Table D.4, selPriorSD). When selectivity prior standard deviations were halved, unfished biomass decreased to about 53 kt and optimal harvest rates U_{MSY} increased to 0.67. Doubling prior SDs (i.e., decreasing how informative the prior is) increased unfished biomass to 56 kt but decreased U_{MSY} to 0.63, and quadrupling the standard deviation dropped unfished biomass again to around 55 kt, and U_{MSY} to about 0.061. Most other life history parameters were fairly stable, while h behaved like U_{MSY}. The observed relationship may be related to the difficulty fitting to release observations given the low selectivity of sub-legal fish in the trap and longline hook fleets.

Table D.4. TMB 2021 model estimates of life history parameters and MSY based reference points under the selected priors sensitivity analysis. Biomass quantities (B_0, B_{MSY} and MSY) are in kilotonnes, stock-recruit steepness h is unitless, and natural mortality and harvest rates have units yr^{-1}.

Sensitivity	B_0	R_0	h	M_m	M_f	B_{MSY}	U_{MSY}	MSY
jeffWtB0 1	105.78	7.991	0.651	0.072	0.102	40.90	0.070	6.216
jeffWtB0 10	94.69	7.050	0.652	0.069	0.101	36.81	0.069	5.604
jeffWtB0 50	71.45	5.061	0.660	0.060	0.097	28.24	0.067	4.336
priorM (.08,.1)	56.62	3.822	0.672	0.052	0.094	22.82	0.065	3.540
priorM (.1,.01)	60.87	4.275	0.665	0.055	0.097	24.37	0.067	3.822
priorh (20,10)	56.61	3.821	0.679	0.052	0.094	22.73	0.066	3.562
priorh (30,30)	57.45	3.922	0.525	0.053	0.095	24.89	0.049	3.032
priorh (80,40)	56.65	3.826	0.670	0.052	0.094	22.85	0.065	3.537
selPriorSD x.5	53.76	3.765	0.672	0.051	0.097	21.93	0.067	3.522
selPriorSD x2	56.67	3.706	0.675	0.051	0.092	22.82	0.063	3.431
selPriorSD x4	55.77	3.540	0.680	0.050	0.091	22.50	0.061	3.282

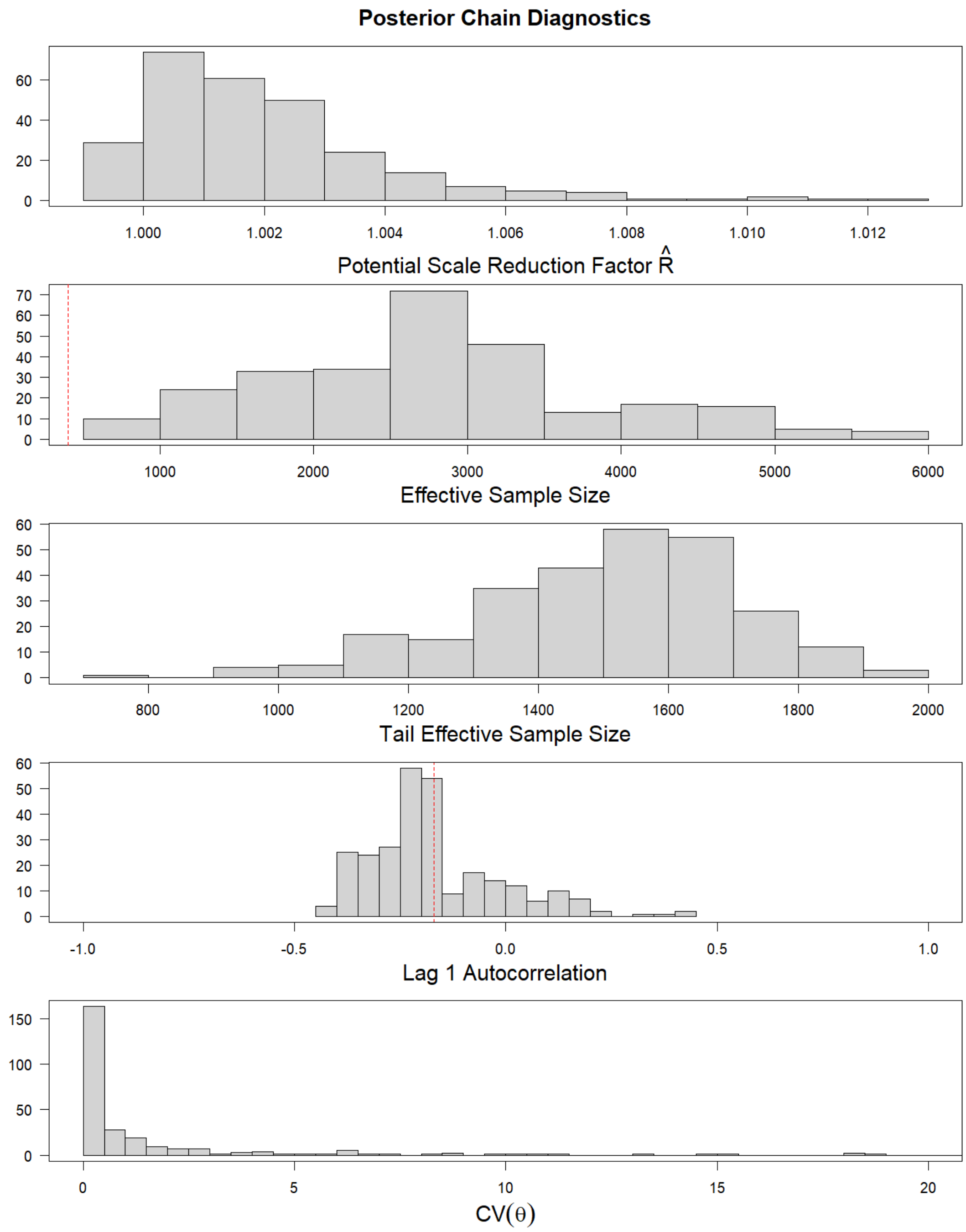

Figure D.1. Distributions of Hamiltonian Monte Carlo convergence diagnostics over all estimated parameters in the SAB-OM model. Diagnostics shown are (clockwise from top left): between chain relative standard error ($\hat{R}$), effective sample size, within chain lag-1 autocorrelation, and coefficient of variation for posterior distributions ($CV(\theta)$). Red vertical lines show minimum threshold for effective sample size, and the mean lag-1 autocorrelation over all parameters.

APPENDIX E. SABLEFISH STATE-SPACE PRODUCTION MODEL

The SSPM used for the annual stock assessment component of the BC Sablefish management procedure is a Schaefer surplus production model. Notation and equations are listed in Tables E.1 and E.2, respectively. The production model derives inferences about management parameters from time-series observations of total landed catch, and any combination of Trap fishery CPUE, Standardised survey CPUE, and Stratified Random survey CPUE. The assessment takes no account of legal and sub-legal discarding, even though both processes occur within the operating model.

Production models pool the effects of recruitment, growth, and natural mortality into a single production function to predict 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 landed 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

$$B_{t+1} = \left(B_t + rB_t\left(1 - B_t/B_0\right) - C_t\right)e^{\omega_t}, \tag{E.1}$$

where B_t and C_t (both in kilotonnes) are the stock biomass at the start of year t and catch in biomass units during year t, respectively, and r and B_0 are the usual logistic growth rate and carrying capacity (unfished biomass) parameters, respectively. 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, for example, the net result of (i) Sablefish immigration into BC from Alaska or the lower west coast US, (ii) emigration out of the stock that is present in BC at any moment, and/or (iii) random deviations from the average production relationship within BC. We assumed that production deviations, however they arise, are independent and identically distributed (Table E.2). The Schaefer form assumes that fish production is a symmetric, dome-shaped function of existing stock biomass so that $U_{MSY} = r/2$ and $MSY = rB_0/4$ define the optimum exploitation rate and maximum sustainable yield, respectively. The maximum sustained yield biomass level is $B_{MSY} = B_0/2$. These quantities can be used by "passive adaptive" management strategies that attempt to steer fisheries exploitation toward theoretically optimal levels (see Walters (1986) for full description of adaptive harvest policies). We re-parameterized Equation (E.1) so that two management parameters U_{MSY} and MSY are estimated directly. The resulting production model is given by equation (SP.4) in Table E.2.

The same three indices of relative abundance for the operating model (Trap CPUE, Std, and StRS) are used in estimating production model parameters via a log-normal observation model of the form

$$I_{g,t} = q_g B_t e^{\zeta_{g,t}}, \tag{E.2}$$

where q_g is as constant catchability coefficient and $\zeta_{g,t}$ is a normally distributed random observation error in year t for index $g = 1, 4, 5$.

E.1. LIKELIHOOD FUNCTION

Different assumptions about how to allocate random deviations in the data to the stock dynamics (ω_t) or index observations ($\zeta_{g,t}$) 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 (E.1) with $\omega_t = 0$ for all time-steps t. Thus, observation error models ignore inter-annual changes in stock biomass that may occur via unmodelled 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 $\zeta_{g,t} = 0$ in the observation model (Equation SP.5) for all values of t and g leads to a "process error" estimator in which the observations are assumed to be exact, i.e., $I_{g,t} = q_g B_t$, implying that inter-annual fluctuations in the data indicate changes in true stock biomass. For the process error estimator, the variance σ^2 and individual terms ω_t must be estimated as free parameters in the stock assessment model.

It is important to incorporate uncertainty in both the observations and the underlying population dynamics. Therefore, we use an errors-in-variables estimator to define the total error variance

$$\kappa^2 = \tau^2 + \sigma^2. \tag{E.3}$$

If the observation error proportion $\rho = \tau^2/(\tau^2 + \sigma^2)$ is assumed to be known, the individual variance components can then be expressed as $\tau^2 = \rho\kappa^2$ and $\sigma^2 = (1 - \rho)\kappa^2$ for observation and process errors, respectively. For designing a Sablefish management procedure based on the SSPM, the variable ρ is considered to act 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. Experience gained through simulation of production model assessments suggests that high values of ρ performed adequately for longer-lived species such as sablefish, so we set $\rho = 0.95$ (Cox and Kronlund 2009). The resulting negative log-likelihood function is given by (SP.9).

E.2. PRIOR DISTRIBUTIONS

We used informative prior distributions on U_{MSY} and MSY to control the behaviour of the production model in closed loop simulations. Priors were both based on the normal distribution with means μ_U and μ_{MSY}, and standard deviations σ_U and σ_{MSY}, respectively (SP.10), with prior mean and standard deviation values found via tuning in previous MSE cycles. 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).

Table E.1. Notation for the state-space surplus production model used for annual Sablefish stock assessments.

Symbol	Value	Description
Model indices and ranges		
T		Year in which stock assessment is performed
t	$1, 2, \ldots, T$	Time step in SP model
g	$1, 2, 3$	Survey index for (1) Comm. Trap, (2) Std Survey, and (3) StRS survey
Data		
C_t		Total landings for year t (biomass units)
$I_{g,t}$		Biomass index observation for gear g in year t
Leading parameters		
MSY		Maximum Sustainable Yield
U_{MSY}		Optimal exploitation rate
Nuisance parameters		
q_g		Catchability coefficient for biomass index g
κ^2		Total error variance
ρ		Observation error proportion of total variance (assumed at 0.95)
Model states		
B_t		Model biomass at the beginning of year t
Derived Reference Points		
B_{MSY}		Biomass that produces MSY
Model prior distributions		
$N(\mu_{MSY}, \sigma_{MSY})$		Normal prior on MSY
$N(\mu_{U_{MSY}}, \sigma_{U_{MSY}})$		Normal prior on U_{MSY}
Statistical error distributions		
$\zeta_{g,t} \sim N(0, \rho\kappa^2)$		Observation error in year t for index g
$\omega_t \sim N(0, (1-\rho)\kappa^2)$		Process error in year t

Table E.2. Errors-in-variables state-space surplus production model used for annual stock assessments in Sablefish management procedure simulations. The function **1**(X) *is the indicator function, taking value 1 when* X *is true, and 0 when* X *is false.*

No.	Equation
Model Parameters	
(SP.1)	$\Theta = \left(\log U_{MSY}, \log MSY \{\omega_t\}_{t=1}^{T-1}\right)$
Biomass dynamics model	
(SP.2)	$B_{MSY} = MSY/U_{MSY}$
(SP.3)	$B_1 = 2B_{MSY}$
(SP.4)	$B_{t+1} = \begin{cases} \left(B_t + 2U_{MSY}B_t\left(1 - \frac{B_t}{2B_{MSY}}\right) - C_t\right)e^{\omega_t} & 1 \leq t \leq T-1, \\ B_t + 2U_{MSY}B_t\left(1 - \frac{B_t}{2B_{MSY}}\right) - C_t & t = T \end{cases}$
Residuals	
(SP.5)	$\zeta_{g,t} = \log \dfrac{I_{g,t}}{B_t}$
Conditional Maximum Likelihood estimates	
(SP.6)	$n_g = \sum_t \mathbf{1}(I_{g,t} > 0)$
(SP.7)	$\widehat{\log q}_g = \dfrac{1}{n_g} \sum_t \mathbf{1}(I_{g,t} > 0)\zeta_{g,t}$
(SP.8)	$\hat{\kappa}^2 = \dfrac{1}{\sum_g n_g + T - 1}\left(\dfrac{1}{\rho}\sum_g\sum_t \mathbf{1}(I_{g,t} > 0)\left(\zeta_{g,t} - \widehat{\log q}_g\right)^2 + \dfrac{1}{1-\rho}\sum_{t=1}^{T-1}\omega_t^2\right)$
Negative log-likelihood and objective functions	
(SP.9)	$l(\vec{I}_{g,t} \mid \Theta) = \dfrac{\sum_g n_g + T - 1}{2}\left(\log \hat{\kappa}^2\right)$
(SP.10)	$G(\Theta \mid \vec{I}_{g,t}) \propto l(\vec{I}_{g,t} \mid \Theta) + \dfrac{\left(MSY - \mu_{MSY}\right)^2}{2\sigma_{MSY}^2} + \dfrac{\left(U_{MSY} - \mu_{U_{MSY}}\right)^2}{2\sigma_{U_{MSY}}^2}$

APPENDIX F. CONSIDERATION OF ENVIRONMENTAL CONDITIONS

Under the Fish Stock provisions of Canada's revised *Fisheries Act*, management measures for all prescribed stocks must take into account both the stock's biology and environmental conditions affecting the stock. In this appendix, we review previously published studies to identify known, or presumed, mechanistic linkages between Sablefish population processes (e.g., recruitment and growth dynamics) and environmental conditions. We then present data-based investigations of possible links between BC Sablefish population traits and a subset of candidate environmental variables identified through this literature review. These analyses are a first step in identifying ecosystem conditions affecting the BC Sablefish stock and can be used to make recommendations about future research directions as well as to assess the utility of incorporating hypotheses that consider environmentally-driven change into the Sablefish MSE process. Relationships between Sablefish recruitment strength and environmental variables were previously considered in 2000 (King et al. 2000), so the exploratory analyses presented here update this past work with an additional 21 years of data.

F.1. SUMMARY OF PREVIOUS RESEARCH

F.1.1. ENVIRONMENTAL DRIVERS OF SABLEFISH RECRUITMENT

In BC and Alaska, Sablefish recruitment has been positively linked with the intensity of the Aleutian Low pressure system (McFarlane and Beamish 1992; King et al. 2000; Shotwell et al. 2014). The Aleutian Low is a dominant climate feature in the North Pacific that enhances onshore advection of surface waters. Colder than average water in the offshore Northeast Pacific and increased storm activity during years with intense Aleutian Low conditions lead to strong southerly winds that bring warm, moist air along the coasts of British Columbia and Alaska. As a result, coastal regions in BC and Alaska experience higher sea surface temperatures (SST), higher precipitation, increased downwelling, increased freshwater discharge, and earlier and more intense spring blooms (Francis et al. 1998). The most commonly hypothesized mechanism for this relationship between Sablefish recruitment and the Aleutian Low pressure system has been increased primary productivity during the Sablefish larval stage, and subsequent increases in copepod abundance. Copepod nauplii are a key food source for larval Sablefish, and increased abundance may be expected to increase rates of growth and survival at this key life stage (McFarlane and Beamish 1992; Sigler et al. 2001).

Research in the California Current system also supports the general pattern of large-scale climate forcing leading to regional changes in alongshore and cross-shelf ocean transport that affect Sablefish recruitment through increased food availability and quality (Schirripa and Colbert 2006). However, regional scale factors driving Sablefish recruitment, as well as the direction of impact, are not necessarily the same as seen in Alaska and BC. For example, within the California Current, colder sea surface temperatures and high upwelling during larval stages were advantageous for Sablefish recruitment (Schirripa and Colbert 2006; Tolimieri et al. 2018), while in Alaska and BC, warmer coastal SSTs and downwelling were advantageous (King et al. 2000; Shotwell et al. 2014). These differences are not surprising given the different current systems dominating regional environments.

In the following sub-sections, we provide more detailed descriptions of previous research by region along the Pacific Coast.

British Columbia

Early research into climatic influences on Sablefish recruitment in BC focused on the importance of copepod production and ocean conditions related to the Aleutian Low pressure system (McFarlane and Beamish 1992; King et al. 2000). These studies used indices of relative year class abundance to represent recruitment strength. McFarlane and Beamish (1992) used standardised age composition data from commercial catch in 1980-1989 to reconstruct a year class index from 1960- 1982, while King et al. (2000) combined several data sources using a weighted average approach, including the same commercial age composition data as McFarlane and Beamish (1992), age composition data from a coastwide research survey (1977-1995), and length composition data from the Hecate Strait Trawl survey (8 years between 1984 and 1997). For some years, adjustments to the annual weighting factor were made using additional information from larval surveys and Sablefish discard rates.

McFarlane and Beamish (1992) showed that stomach contents from larval Sablefish were comprised primarily of copepod nauplii. Positive correlations between time series of copepod abundance and an index of the strength of the Aleutian Low meant that both variables were related to Sablefish year class abundance, with stronger year-classes occurring during years of more intensive Aleutian Lows and higher copepod abundance. Subsequent work by King et al. (2000) found that periods of strong year class abundance were associated with increased south-westerly winds and warm sea surface temperatures off the west coast of Vancouver Island, in addition to intensifying Aleutian Lows.

Alaska

Sablefish recruitment in the Gulf of Alaska has also been strongly linked to the intensity of the Aleutian Low, with higher recruitment occurring in years with strong Aleutian Lows (Shotwell et al. 2014). Recent research in Alaska has focused on identifying the mechanisms driving this relationship.

Shotwell et al. (2014) hypothesized that in years with strong Aleutian Lows, Sablefish distribution during shoreward migration overlapped with the transport of high productivity waters and high zooplankton abundance, which in turn increased juvenile Sablefish growth and survival. Increased eddy activity and circulation during Aleutian Lows was also hypothesized to facilitate the transport of larvae from peripheral spawning locations, thereby increasing total recruitment to the Gulf population in those years. Further empirical support for the importance of food supply for larval Sablefish was provided by (Yasumiishi et al. 2015). They found that indices of August primary production (chlorophyll-a concentration) and juvenile Pink Salmon abundance (*Oncorhynchus gorbuscha*; used as an index of nearshore rearing habitat) during the age-0 stage positively influenced age-2 Sablefish recruitment.

Coffin and Mueter (2016) examined relationships between recruitment, basin-scale indices linked to ocean conditions (e.g., the Pacific Decadal Oscillation), and finer-scale regional indices that were thought to affect inshore advection of age-0 Sablefish (e.g., down-welling favourable winds and freshwater discharge). While they were unable to find significant relationships between their regional indices based on age-0 distribution and Sablefish recruitment, subsequent exploratory analyses did show significant relationships between recruitment and regional environmental indices encountered in the eastern Gulf of Alaska when Sablefish were age-1 (July upwelling favourable winds and freshwater discharge).

Gibson et al. (2019) further explored the hypothesis that recruitment variability in the Gulf of Alaska was influenced primarily by advective transport of juvenile larvae from offshore spawning grounds to inshore nursery areas through the development of a biophysical, individual-based model of the early life stages of Sablefish. No single environmental variable had a strong correlation with recruitment. Instead, Sablefish recruitment was best explained by a combination of indices including annual connectivity between adult spawning and juvenile nursery areas, spring offshore primary production, summer onshore primary production, and cross-shelf flow over the west-central Gulf. The authors concluded that Sablefish recruitment relies on a variety of factors, including successful transport between spawning and nursery areas and an adequate food supply.

Taken together, results from these studies highlight that mechanisms linking large-scale ocean oceanic patterns to Sablefish recruitment are complex and likely operate at multiple life stages. While there is evidence that it may be a combination of both food availability and favourable larval advection Gibson et al. (2019), hypotheses of increased food availability have been most commonly supported Yasumiishi et al. (2015).

US West Coast

Sablefish recruitment along the US West Coast (Washington, Oregon, and California) has been linked to oceanographic conditions within the California Current System (Schirripa and Colbert 2006; Tolimieri et al. 2018). The California Current System originates around southern Vancouver Island, where the eastward North Pacific Current diverges to the north (towards Alaska) and south (towards Washington). From here, the California Current flows southward along the coast bringing cold water from the edge of British Columbia to California. As with Alaska and BC, large-scale oceanographic forcing is thought to drive regional-scale changes in environmental variables that affect Sablefish recruitment primarily through changes in food supply for Sablefish larvae.

Significant relationships have been found between Sablefish recruitment, sea level (an indicator of depth independent horizontal transport), and Ekman transport at various times and directions within a year (Schirripa and Colbert 2006). Schirripa and Colbert (2006) found that two indices of Ekman transport and sea level were able to explain up to 70% of the variation in modelled recruitment deviations. They hypothesized that these variables affected zooplankton community structure for feeding larvae, with recruitment being higher in years with higher abundance of northern copepod species. These conditions are believed to occur in years with colder than average temperature, high upwelling, and stronger southward currents.

In another study, (Tolimieri et al. 2018) developed a seven-stage life history model for Sablefish in the northern portion of the California Current to explore the influence of stage-specific oceanographic and biological variables on sablefish recruitment. They found that five variables from different life history stages explained 57% of variation in recruitment deviations. Positive recruitment deviations arose from: colder temperatures pre-spawning, warmer water temperatures during the egg stage, stronger cross-shelf transport to near-shore nursery habitats during the egg stage, stronger long-shore transport to the north during the yolk-sac stage, and cold surface water temperatures during the larval stage. Their results emphasize that Sablefish recruitment is likely affected by multiple mechanisms acting at different stages of egg and larval development.

F.1.2. EFFECT OF ENVIRONMENTAL CHANGE ON ABUNDANCE & DISTRIBUTION

Recent research in BC has focused on examining how environmental change in the last 1-2 decades has influenced the distribution, biodiversity, and density of groundfish species and communities Thompson et al. (2022). These studies have included Sablefish, specifically on Sablefish old enough to be recruited to trawl gear. Environmental changes during this period were associated with temporal fluctuations in the biomass of individual species and the community as a whole; however, the amount of variability explained by changing environmental conditions was generally small compared to the ongoing recovery of the demersal fish community from recent reductions in commercial fishing intensity (Thompson et al. 2022). For Sablefish specifically, both mean summer primary production and mean summer cross-shore and along-shore current velocities near the seafloor had positive effects on biomass levels, while near-bottom mean summer temperature, near-bottom mean summer dissolved oxygen, and fishing intensity did not have significant effects (Thompson et al. 2022). None of these factors had a significant impact on Sablefish presence-absence. English et al. (2022) found that Sablefish had among the highest increases in habitat suitability among groundfish species in response to temperature increases, thereby making them one of the species most unlikely to experience population declines with increasing temperatures.

In the Bering Sea, a recent assessment of climate variability scored Sablefish as being moderately vulnerable to future climate change [Spencer et al. (2019); NOAA 2019]. Sablefish in the Bering Sea were assessed as being most sensitive to future predictions of ocean acidification, followed by changes to bottom temperature and sea surface temperature (NOAA 2019). Pelagic larval and nearshore settlement stages were thought to be the most vulnerable life history stages for Sablefish due to the high energetic costs of rapid body growth. By the time Sablefish reached later juvenile and adult life stages, prey availability was not thought to have a large impact on sablefish dynamics due to them being generalist feeders that can easily switch prey species.

F.2. PRELIMINARY INVESTIGATIONS FOR BC SABLEFISH IN 2022

F.2.1. CHARACTERIZING SABLEFISH POPULATION DYNAMICS

We characterize Sablefish populations in two ways. First, Sablefish recruitment was quantified as recruitment deviations from an underlying assumed Beverton-Holt stock recruitment relationship.

- **RecDevs**: Annual recruitment deviations were taken from the base operating model fit. These deviations represent the entire coastwide BC Sablefish population.

Second, we used a morphological index of annual fish body condition based on fish weight relative to fork length (i.e., residuals from an allometric length-weight relationship; $W = aL^b$). Morphological indices of fish body condition are often used to characterize fish health and energetic status, with several studies linking indices of body condition to environmental conditions and species interactions (Boldt and Rooper 2009; Boldt et al. 2019; Rodgveller 2019).

- **LWDevs**: Sablefish body condition characterized as the residuals of a sex-specific allometric length weight relationship. Length weight relationships were calculated using data from the Sablefish standardised random trap survey (StRS) collected between 2003 and 2021.

F.2.2. CHARACTERIZING SABLEFISH ECOSYSTEMS

We selected 8 environmental variables for our analysis based on the outcomes of the literature review summarized above. These variables include:

- **ALPI: Aleutian Low Pressure Index**: a relative measure of the intensity of the Aleutian Low pressure system calculated based on anomalies of the winter (December to March) mean area (km^2) in the north-east Pacific which has a sea level pressure of 1,000.5 mb or less.

- **offshoreProd**: an index of primary productivity in the offshore (areas with bottom depths from 300-2000 m along the BC coast) in spring. This index is the sum of the standard 8 day interval MODIS estimates (Behrenfeld and Falkowski 1997) of net primary productivity (mg Carbon/m^2/day*10^{-6}) each year during the spring (March – May). The data are based on chlorophyll measurements from SeaWiFS, MODIS and VIIRS satellites. Data were downloaded from the Oregon State University's Ocean Productivity website.
- **inshoreProd**: an index of primary productivity in the inshore (areas with bottom depths from 100-300 m along the BC coastline) in summer. This index is the sum of the standard 8 day interval estimates (Behrenfeld and Falkowski 1997) of net primary productivity (mg Carbon/m^2/day*10^{-6}) each year during the summer (June – August). The data are based on chlorophyll measurements from SeaWiFS, MODIS and VIIRS satellites. Data were downloaded from the Oregon State University's Ocean Productivity website.
- **Copepod**: an index of copepod abundance off the west coast of Vancouver Island (see red outline in Figure F.1). The index calculation is constrained to summer months (May-September). It is standardised by the volume filtered and then aggregated by year. This index is based on historical zooplankton sampling during DFO cruises off the WCVI and can be downloaded from the Government of Canada's Open Government website.
- **SST: Sea Surface Temperature**: an index of spring sea surface temperature off west coast of Vancouver Island (Figure F.1). This index is the mean springtime (March-May) sea surface temperature measured by Advanced Very High Resolution Radiometer (AVHRR) satellite data integrating in situ observations to generate an optimally interpolated SST coverage. Daily data were downloaded from NOAA's National Centre for Environmental Information.
- **EkmanSpring**: Ekman onshore transport in spring (March-May). Onshore transport was derived from the prevailing angle of the coastline and northward and eastward Ekman transports ($m^3/s/km$). The index was downloaded from NOAA's Environmental Research Division's Upwelling Indices as 6 hour interval data at 48 N, 125 W and averaged across months, days and hours to create an annual index.
- **EkmanSummer**: Ekman onshore transport in summer (June-August) Onshore transport was derived from the prevailing angle of the coastline and northward and eastward Ekman transports (m3/s/km). The index was downloaded from NOAA's Environmental Research Division's Upwelling Indices as 6 hour interval data at 48 N, 125 W and averaged across months, days and hours to create an annual index.

We also included an annual index of abundance based on the annual StRS trap survey CPUE to look for evidence of density-dependent relationships between body condition and annual Sablefish abundance.

- **CPUE**: An index of annual sablefish biomass from the Sablefish stratified random trap survey (2003-2021) in units of mean kg / trap. This is the same index used to fit operating models (Appendix B).

Annual time series for each of these variables are shown in Figure F.2.

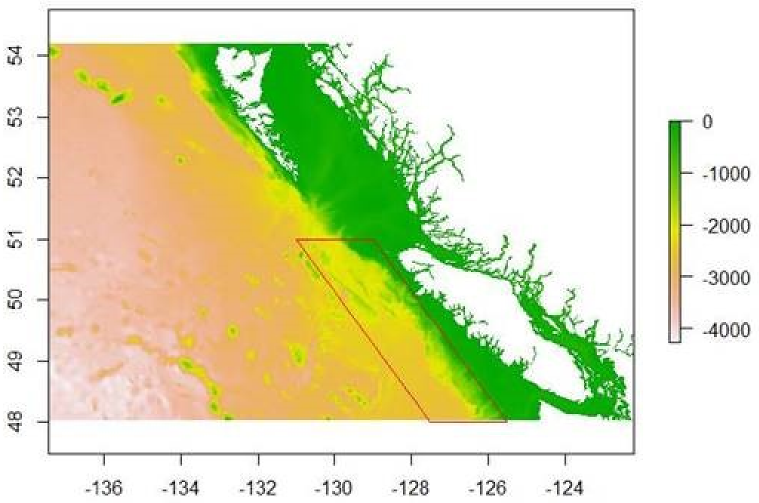

Figure F.1. BC coast with the spatial distribution used to calculate indices for copepod abundance and Sea Surface Temperature off west coast Vancouver Island shown in red outline.

F.2.3. EXPLORATORY GRAPHICAL ANALYSES

F.2.3.1. Recruitment Strength

We calculated correlation matrices among recruitment deviations and environmental variables (Figure F.3). The highest correlation was between ALPI and spring SST off Vancouver Island, which show a positive relationship (correlation coefficient = 0.51). This supports the hypotheses that years with strong Aleutian lows bring warm air along the southern BC coast. While SST showed a weak positive correlation with Sablefish recruitment deviations (correlation coefficient = 0.28), there were no positive links between SST and inshore primary productivity in the summer or copepod abundance. This pattern does not support the hypothesis of McFarlane and Beamish (1992) that intense Aleutian lows and high SST is related to inshore primary and secondary productivity along the west coast of Vancouver Island. McFarlane and Beamish (1992) found stronger year-classes occurred during years of more intensive Aleutian Lows and higher copepod abundance. The difference in results may be due to different approaches used to quantify annual recruitment strength. McFarlane and Beamish (1992) and King et al. (2000) used an index of total year class abundance based primarily on age and/or length composition data. A limitation of this approach is that it relies on the assumption that total mortality has been relatively constant since the inception of the fishery, which is not supported by our current operating model reconstructions of historic harvest rates. In contrast, we used annual modelled deviations from a spawner recruit curve, which removes the influence of spawning stock size on recruitment and accounted for variable harvest rates through time. Our approach matches that taken in recent studies in Alaska and the California current systems. For the 24 years in which the recruitment series we used and that of King et al. (2000) can be compared (1974-1997), there are some periods of agreement, but also several deviations. For example, King et al. (2000) estimate a very large year class in 1977, while our recruitment series has an average recruitment residual in 1977 followed by

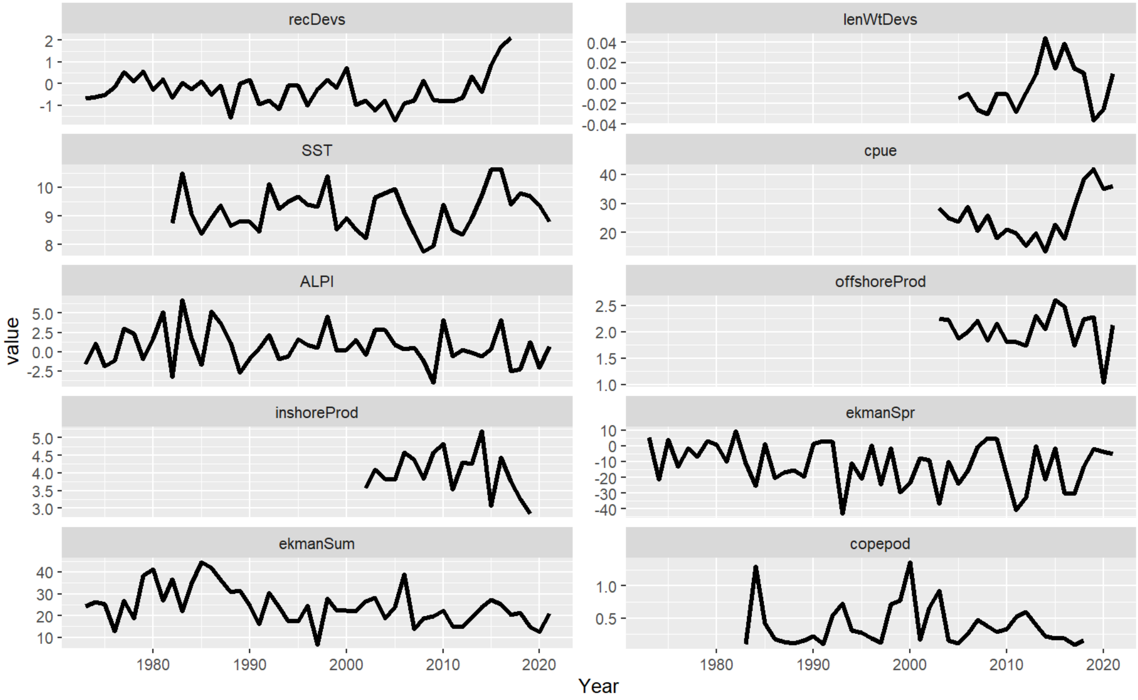

Figure F.2. Time series of available indices used for correlation analyses, including recruitment residuals and the body condition index.

higher-than average residuals in 1978-1980. King et al. (2000) also estimate high recruitment indices in 1989-1990, while our recruitment residuals are below average in 1989 and average in 1990.

Our correlation analysis did show a weak positive relationship between recruitment strength and offshore primary productivity in the spring. Overall, recruitment deviations tended to be higher in years with high offshore primary productivity and warm SST in the spring, which corresponds with the timing of early larval stages. Indices of onshore Ekman transport during spring and summer were shown to have no relationship to recruitment deviations.

F.2.3.2. Body Condition

We also calculated correlation matrices among the length-weight based index of body condition, environmental variables, and an index of total population biomass (Figure F.4). Body condition showed moderate correlations with all environmental variables considered. The strongest correlation was between spring SST and body condition, which were positively related (correlation coefficient = 0.54). Indices of the strength of Ekman onshore transport in the summer months, offshore primary production in the spring, and inshore primary production in the summer were also positively related to body condition. In contrast, indices of Ekman onshore transport in the spring, copepod abundance, and the survey CPUE index were negatively related to body condition.

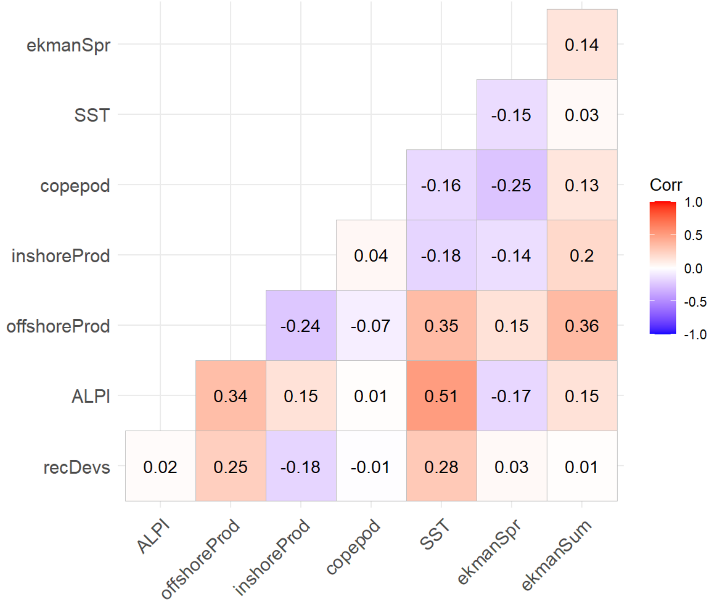

Figure F.3. Pairwise correlation coefficients among recruitment deviations and selected environmental indices.

Moderately strong positive relationships between body condition and spring SST, and between body condition and the indices of primary productivity, mean that Sablefish tend to have larger body weight at length in years with warm coastal waters and high primary productivity; however, the specific mechanisms through which these correlations arise are not known given that adult Sablefish primarily feed offshore and at depth. Furthermore, bottom temperature was not considered in our analyses, which has been identified as an important predictor for body condition for some Alaskan groundfish stocks (Grüss et al. 2020).

The negative relationship between body condition and total biomass on its own could be taken as evidence of decreased condition due to increased competition for food; however, a mix of positive and negative correlations with multiple environmental variables suggests that several factors are likely influencing Sablefish simultaneously. Furthermore, key determinants of body condition are likely to change over time and space. For example, between 2003 and 2013 body condition had little to no correlation with survey CPUE (correlation coefficient = 0.11), while for the 8 years between 2014 and 2021 there was a strong negative correlation (correlation coefficient = -0.84). The latter time period included a steep decline in body condition with rapidly increasing Sablefish biomass between 2015 and 2020 (Figure F.2).

Sablefish body condition in 2019 was at the lowest level observed since the start of the estimated time series in 2003. At this time, fish in the 2016 birth cohort would have been three years old and included in the survey data set used to calculate the body index. In the most recent two years since 2019, the body condition index has increased, and was above average in 2021.

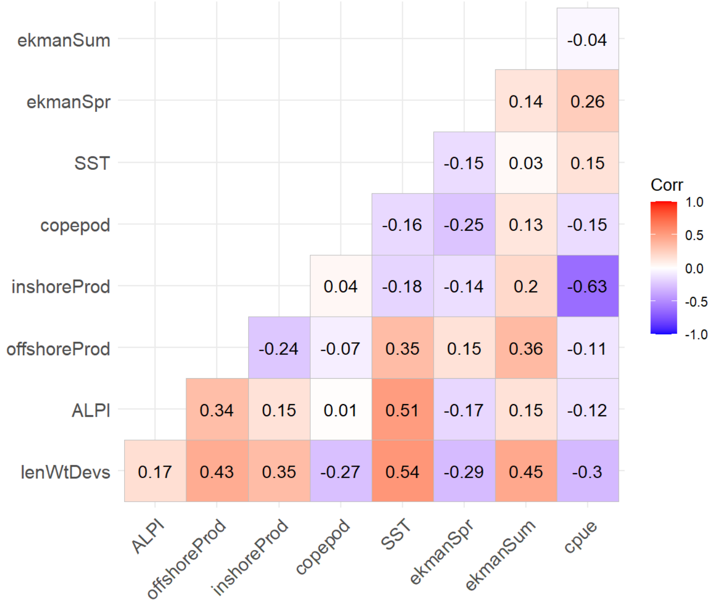

Figure F.4. Pairwise correlation coefficients among length-weight body condition index (lenWtDevs), selected environmental indices, and annual catch-per-unit-effort (CPUE) from the stratified random Sablefish trap survey.

F.3. CONCLUSIONS & RECOMMENDATIONS FOR FUTURE RESEARCH

None of the environmental variables considered in Appendix F were singularly strong candidates for characterizing environmental conditions linked to BC Sablefish recruitment. However, our simple correlation analyses are only meant to serve as an initial exploration of potential links. Future research into environmental drivers of Sablefish recruitment strength could consider using generalized linear models (GLMs) to explain variability in BC Sablefish recruitment as a function of multiple environmental variables operating at various spatio-temporal scales and life history stages Haltuch et al. (2020). Alternatively, dynamic factor analysis (Zuur et al. 2003, DFA) could be used to find a common trend in multiple environmental variables that could then be used to predict variation in recruitment (e.g., Haltuch et al. 2019).

The only environmental variable to show a weak correlation with recruitment variability was spring SST off WCVI. Recruitment deviations were higher in years with higher SST. SST was at a time series high in 2015-2016, which coincided with the large Sablefish recruitment event in 2016. Since that time, SST has declined towards more average levels, with SST in 2020 and 2021 slightly above and slightly below the 1982-2021 average, respectively. We constrained our SST index to the west coast of Vancouver Island to match work previously done for BC Sablefish (King et al. 2000). Future research into links between SST and Sablefish recruitment in BC should consider expanding the spatial extent of the SST index to match the distribution of the coastwide Sablefish stock.

In contrast, our analysis of a body condition index for adult Sablefish showed correlation with a wide range of environmental variables; however, the extent to which the observed variation in body condition would affect Sablefish population dynamics (e.g., natural mortality, reproductive potential) is unknown. Rodgveller (2019) showed that Sablefish fecundity could be sensitive to changes in body condition, suggesting that fluctuations in body condition may affect productivity by affecting both total egg production and maturation. In contrast, a risk assessment for Bering Sea Sablefish identified adult life history stages as having relatively low vulnerability to climate change [Spencer et al. (2019); NOAA 2019]. In this assessment, prey availability was not thought to have a large impact on Sablefish dynamics due to them being generalist feeders that can easily switch prey species. Body condition has been shown to vary considerably over space and time for groundfish species (Thorson 2015), so further research looking for links between Sablefish body condition, environmental variables, and density-dependent responses to Sablefish abundance would benefit from a more detailed spatio-temporal approach. For example, spatio-temporal generalized linear mixed model GLMMs have been used to predict fish condition for several groundfish stocks in the US (Thorson 2015; Grüss et al. 2020). Recent DFA work off the west coast of Vancouver Island indicates that there may be two primary time trends in pressures by humans and the environment that have led to a single nonlinear trend explaining ecosystem changes since 1985 (Boldt et al. 2021). Future research could focus on incorporating patterns in Sablefish recruitment and population dynamics into this type of framework.

APPENDIX G. ANNUAL FITS TO COMPOSITION DATA

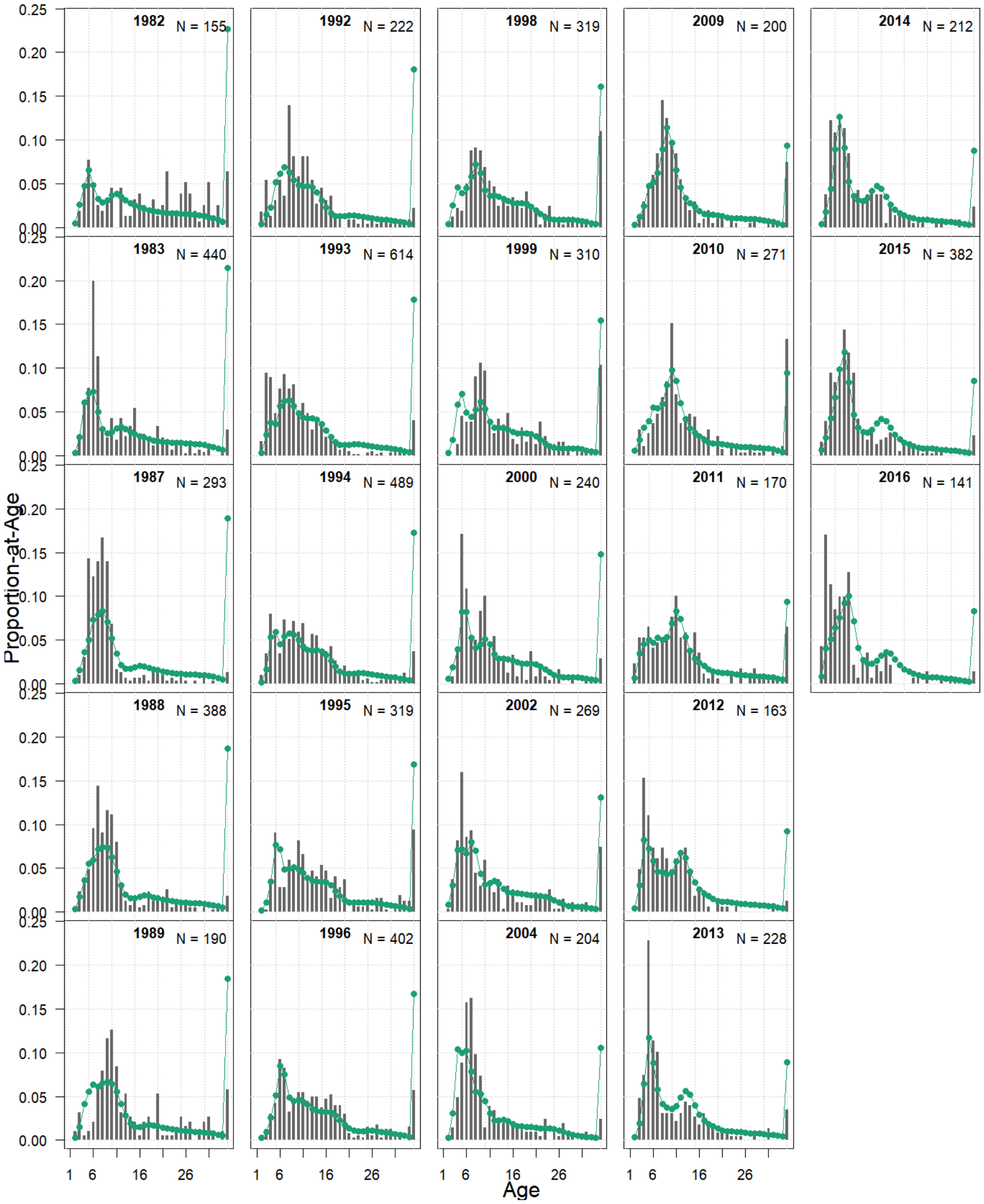

Figure G.1. TMB 2021 fits to male age composition data from the commercial trap fishery.

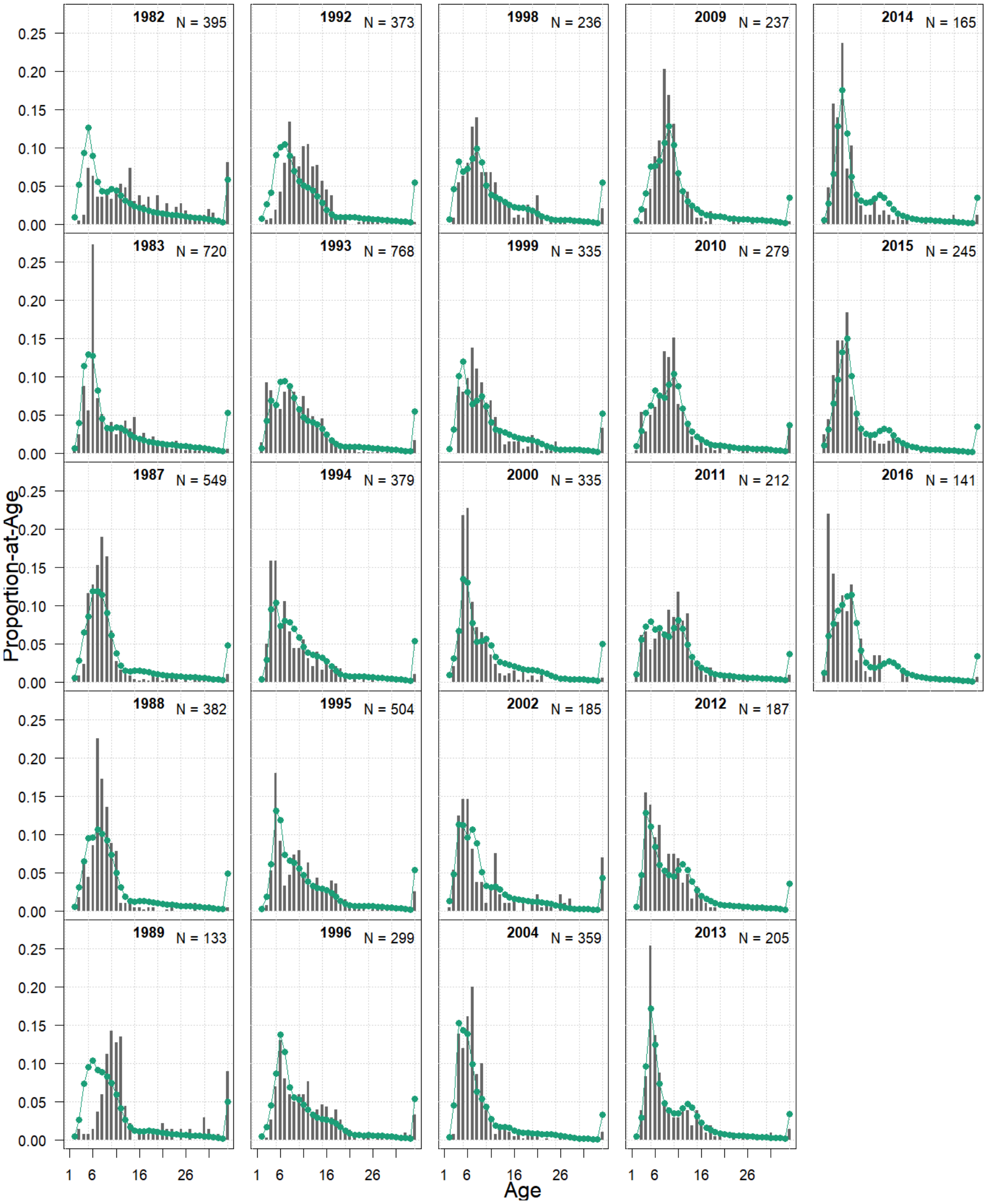

Figure G.2. TMB 2021 fits to female age composition data from the commercial trap fishery.

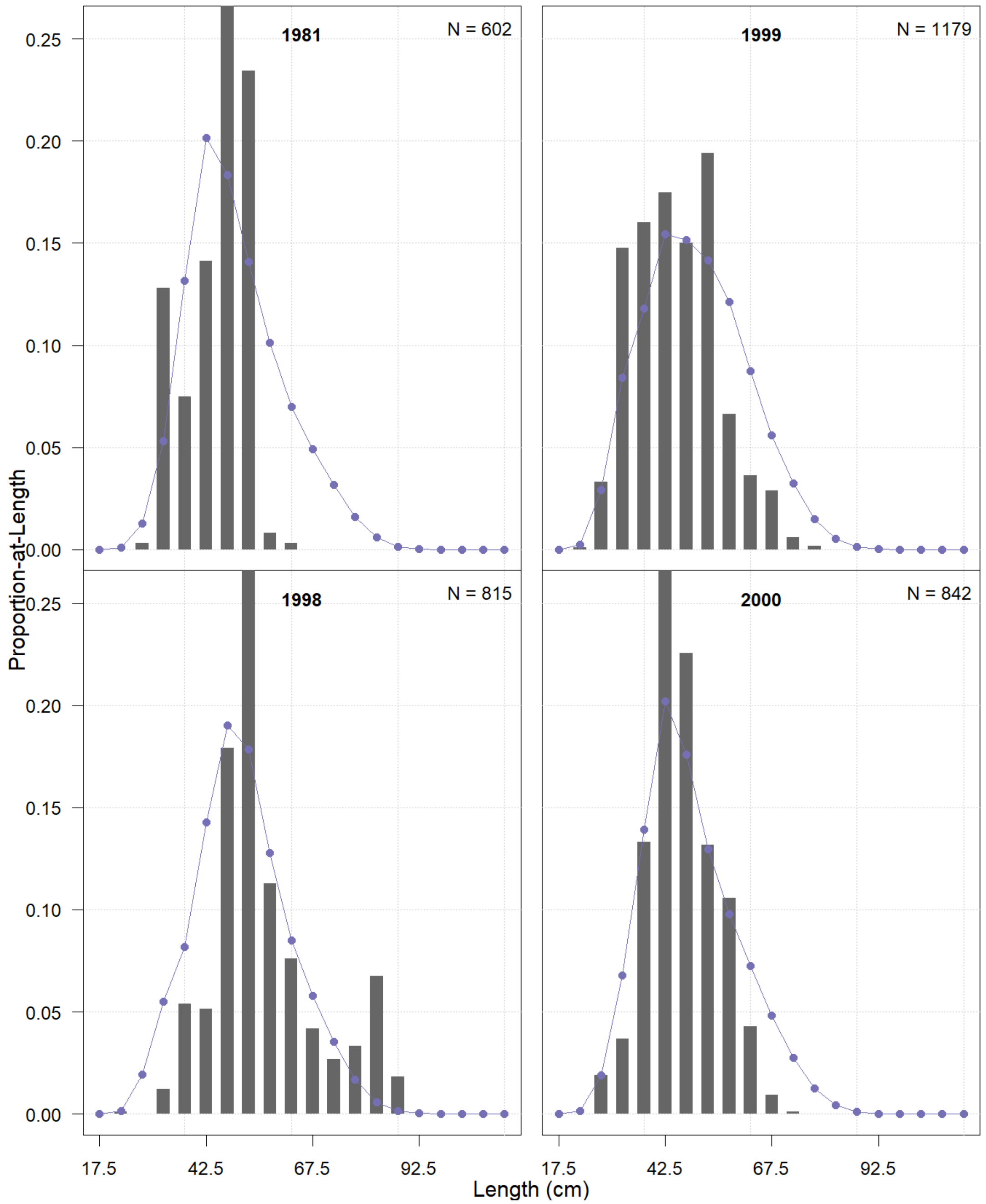

Figure G.3. TMB 2021 fits to male length composition data from the trawl fishery.

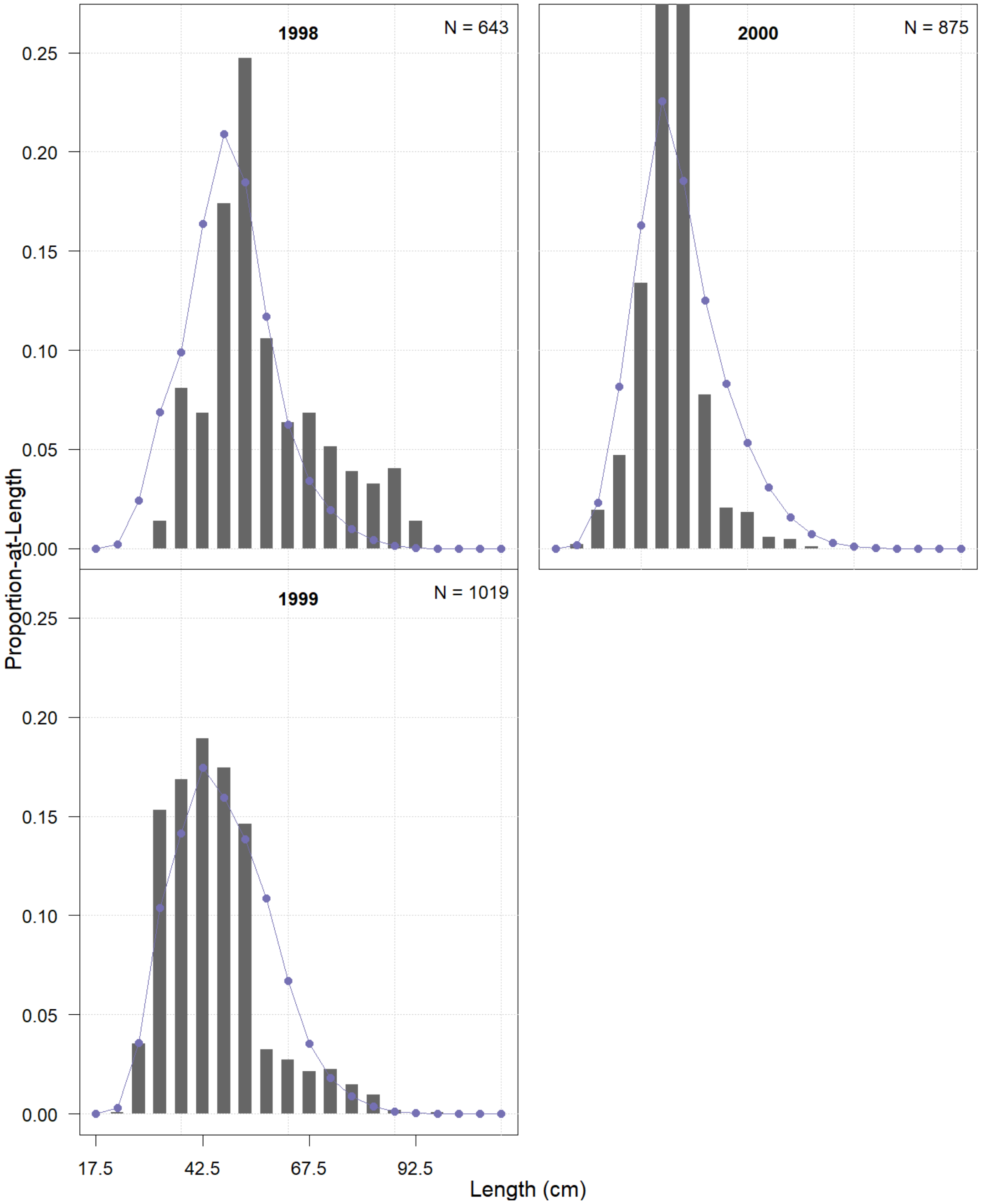

Figure G.4. TMB 2021 fits to female length composition data from the trawl fishery.

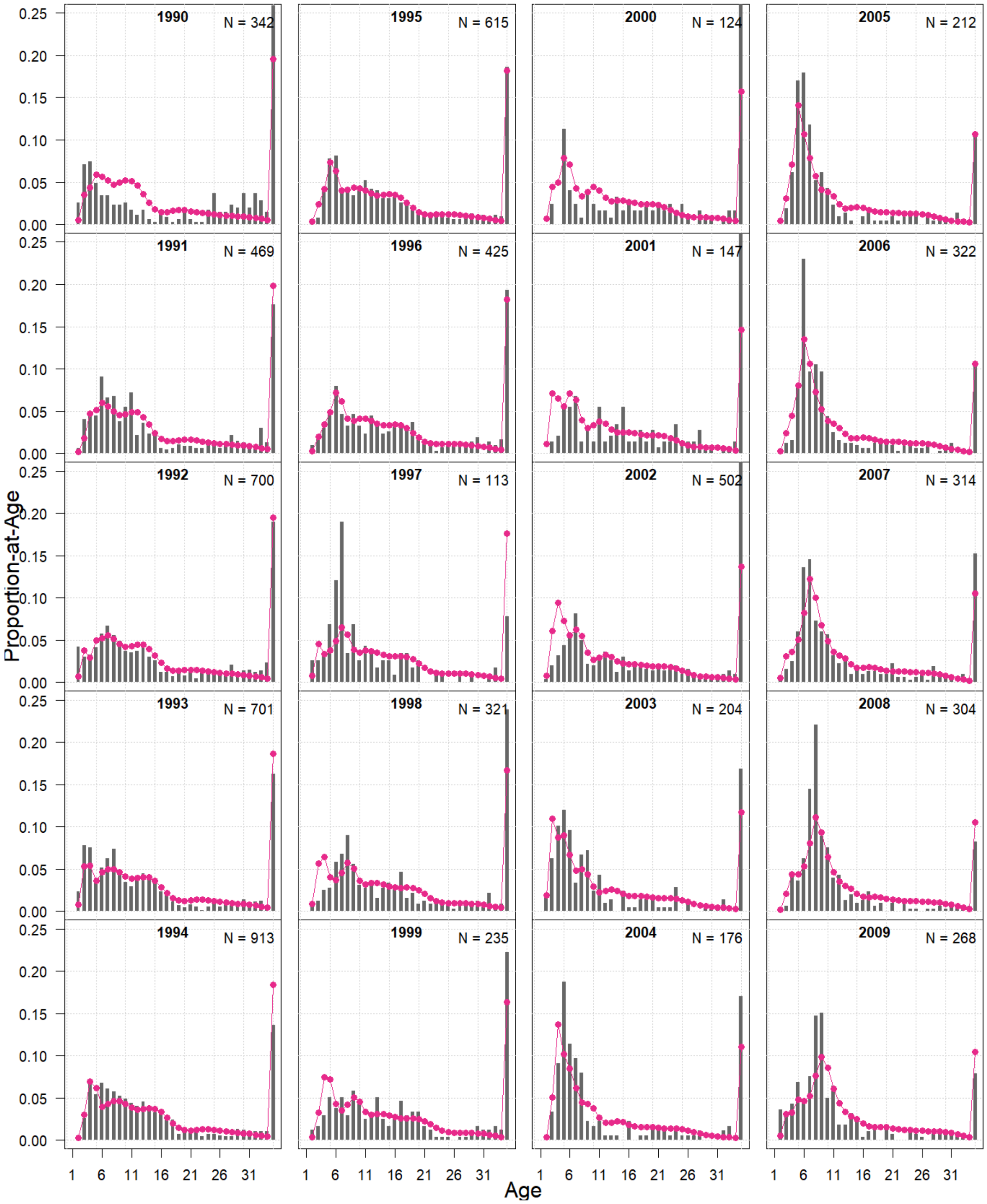

Figure G.5. TMB 2021 fits to male age composition data from the Standardised trap survey.

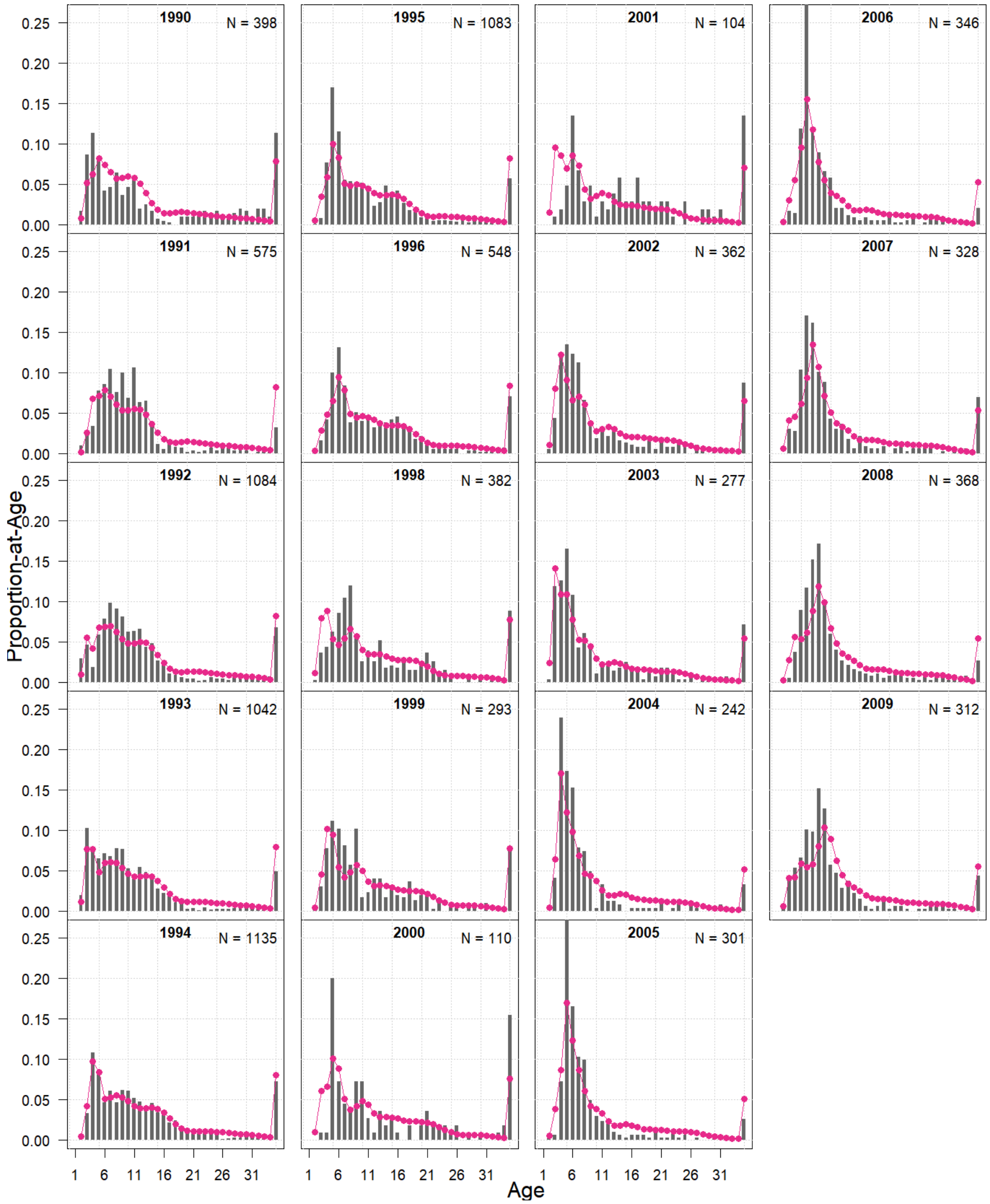

Figure G.6. TMB 2021 fits to female age composition data from the Standardised trap survey.

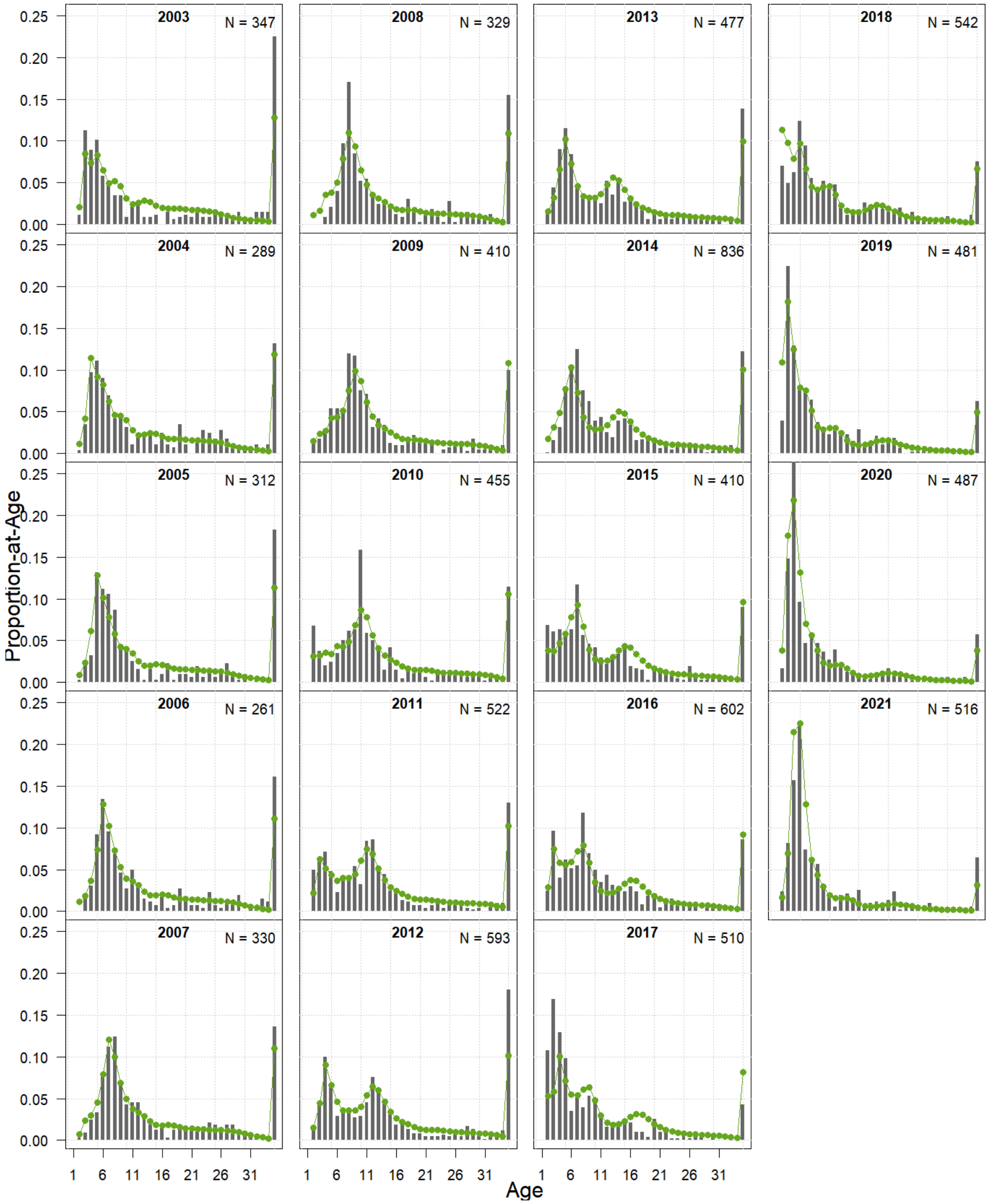

Figure G.7. TMB 2021 fits to male age composition data from the Stratified Random trap survey.

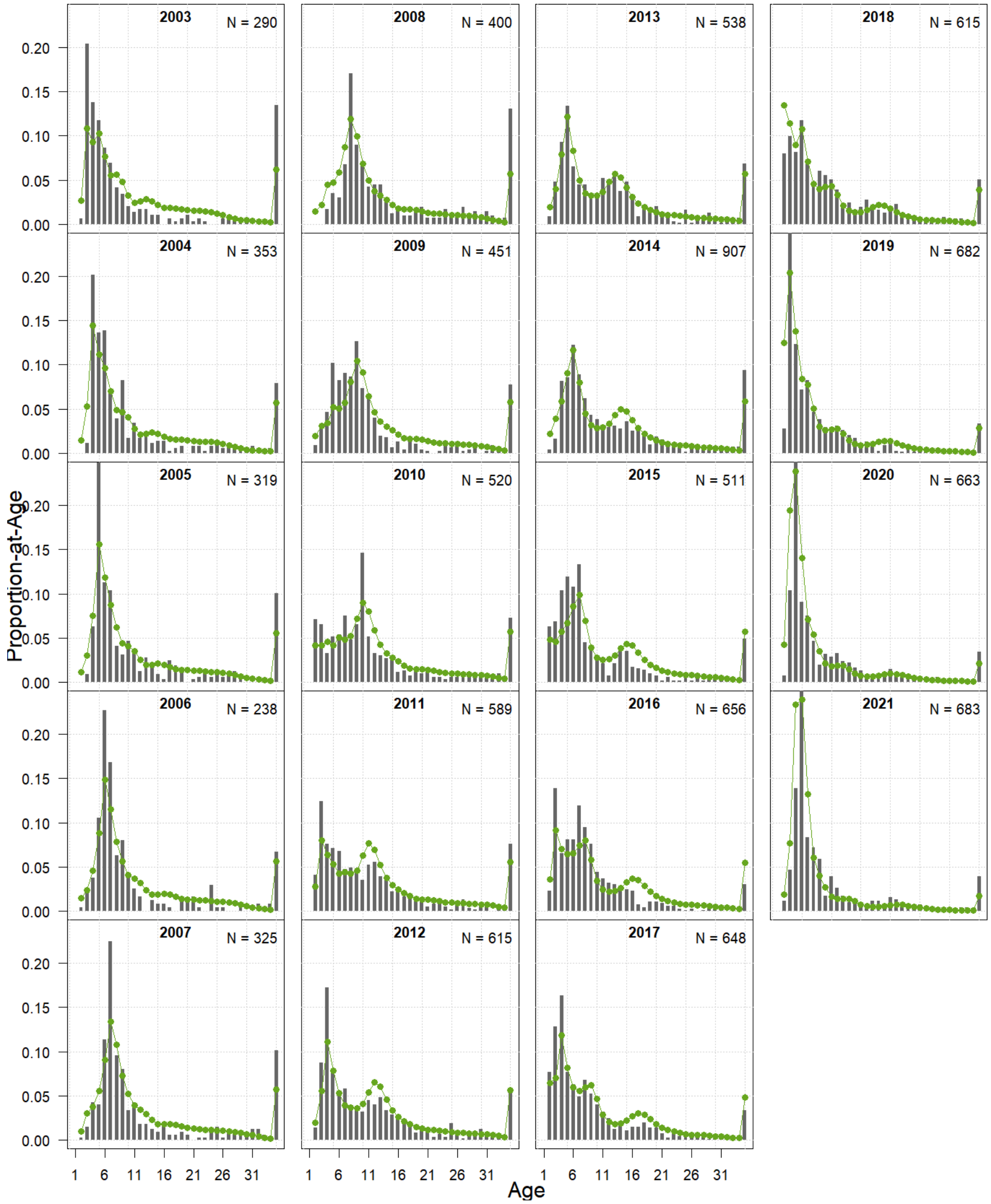

Figure G.8. TMB 2021 fits to female age composition data from the Stratified Random trap survey.