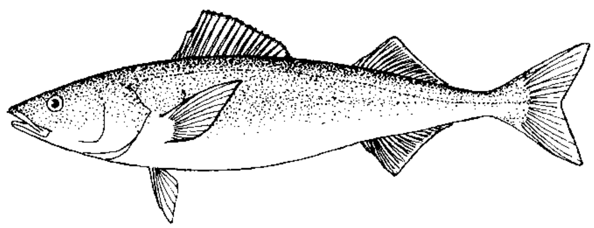
Fisheries and Oceans Canada / Pêches et Océans Canada

Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Pacific Region

Canadian Science Advisory Secretariat
Science Advisory Report 2023/010

A REVISED OPERATING MODEL FOR SABLEFISH IN BRITISH COLUMBIA IN 2022



*Sablefish (*Anoplopoma fimbria*), Courtesy DFO.*

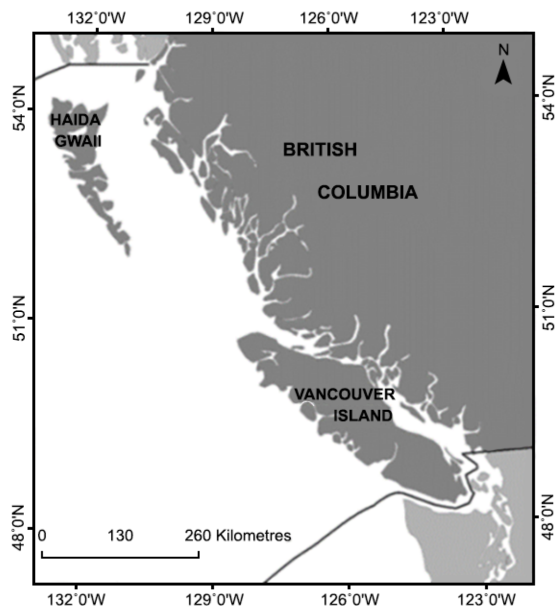


Figure 1. Assessment and management area for Sablefish in British Columbia, excluding seamounts.

Context:

*Management of Sablefish (*Anoplopoma fimbria*) in Pacific Region is guided by a Management Strategy Evaluation (MSE) process that uses an operating model (OM) to generate simulated management procedure (MP) performance across multiple scenarios about stock and fishery dynamics. Performance is evaluated against measurable objectives that represent conservation and socio-economic goals. Annual total allowable catches (TACs) for Sablefish have been informed by simulation-tested MPs since 2011.*

Fisheries and Oceans Canada (DFO) Fisheries Management has requested that Science Branch provide a revised Sablefish OM that uses updated stock and fishery monitoring data to estimate Sablefish stock status relative to reference points in 2022. Current and future demands for MSE simulations require migrating the Sablefish OM and MP to a new software framework for 2022. As a result, a comparison of updated OM and MP results to those obtained using the previous software is also needed. Adjustments to the target harvest rate specified in the existing Sablefish management procedure may be needed to reflect revised estimates of stock productivity.

This Science Advisory Report is from the November 15-16, 2022 regional peer review on a Revised Operating Model for Sablefish in British Columbia in 2022. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule] as they become available.

SUMMARY

- Management of Sablefish (*Anoplopoma fimbria*) in British Columbia (BC) is guided by a Management Strategy Evaluation (MSE) process that has been jointly developed by Fisheries and Oceans Canada (DFO) and the BC Sablefish fishing industry. The MSE process is aligned with the requirements of the Fish Stocks provisions and domestic harvest policy (DFO 2009). Annual total allowable catches (TACs) for BC Sablefish have been set in a transparent and sustainable manner using simulation-tested management procedures (MPs) since 2011.
- The Sablefish operating model (OM) is used to provide an updated assessment of stock status and to simulation-test MPs under alternative scenarios representing stock and fishery dynamics. A revised version of the OM has been developed for 2022 that incorporates updated data as well as new hypotheses about stock and fishery dynamics.
- The revised OM was transitioned to a new software platform that is better supported in the fisheries science community and has better estimation performance than the original platform. Transition analyses showed that both implementations produced similar results, while the new platform offered better model diagnostics and computational performance.
- Stock status in 2022 was assessed via a weighted-average of the five OM scenarios representing uncertainty about productivity and recent female spawning stock biomass (where, female spawning stock biomass is hereafter denoted as *B*). OM scenario weights were based on plausibility values assigned by analysts.
- BC Sablefish female spawning stock biomass for 2022 (B_{2022}) was estimated to be well above the level of female spawning stock biomass associated with maximum sustainable yield (B_{MSY}). The weighted average estimate of B_{2022} is above B_{MSY} with 92% probability (median value of 1.32 times B_{MSY}). The estimated harvest rate (U) of legal-sized Sablefish in 2021 is below the harvest rate at MSY (U_{MSY}) with 94% probability (median value of 0.72 times U_{MSY}).
- When viewed individually, each of the five OM scenarios indicated a 100% probability of B_{2022} being above the limit reference point (LRP) of $0.4B_{\mathrm{MSY}}$, and four of the five OMs estimated a 100% probability of B_{2022} being above the upper stock reference (USR) of $0.8B_{\mathrm{MSY}}$. The OM scenario representing the lowest recent female spawning stock biomass indicated a 92% probability of B_{2022} being above the USR.
- Closed-loop simulations were used to test whether the current MP, with a maximum target legal harvest rate of 5.5%, was able to meet operational fishery objectives under the revised OM scenarios. Alternative versions of the current MP with a range of target harvest rates were also tested. Simulation performance showed that an increase in the current maximum target legal harvest rate up to 7.5% could be considered while still meeting conservation objectives aimed at remaining above the LRP (objective 1) and achieving the target reference point (TRP; objective 3).
- Environmental variables (EVs) potentially affecting BC Sablefish population dynamics were examined via pairwise correlations between eight EVs, annual recruitment, and a body condition index. None of the EVs were strongly correlated to recruitment. While the impact of climate change on BC Sablefish is unknown, recent research indicates that increasing temperature may increase habitat suitability for Sablefish. The potential risk of not including EVs into the BC Sablefish operating model seems low at this time.

- Future operating models should further explore alternative approaches to modelling at-sea releases to better account for release mortality in operating model simulations.

INTRODUCTION

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 MSE approach attempts to capture the entire process that gives rise to a recommended catch limit within a simulated management system. An operating model (OM) with multiple scenarios representing uncertain stock and fishery dynamics is used to generate simulated data. The performance of candidate management procedures (MPs) for each alternative OM scenario is evaluated against measurable objectives that represent conservation and socio-economic goals. Annual total allowable catches (TACs) have been informed using these simulation-tested MPs since 2011.

Objectives for the BC Sablefish fishery have been iteratively developed via consultation with fishery managers, scientists, and industry stakeholders. The five objectives used to evaluate MP performance are:

1. **Avoid LRP:** Maintain female spawning stock biomass 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. **Avoid stock decline when below USR:** 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 (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. **Achieve target biomass:** Maintain the 2052 female spawning stock biomass above the target reference point in 50% of simulation replicates, where the target reference point is (a) $B_{Targ} = B_{MSY}$ when $B \geq 0.8B_{MSY}$, or (b) $B_{Targ} = 0.8B_{MSY}$ when $B < 0.8B_{MSY}$;
4. **Avoid economically unviable catch:** Maximize the probability that annual legal-sized catch levels remain above 1,992 tonnes, measured over two Sablefish generations; and
5. **Maximize legal-size catch:** Maximize annual legal-sized catch over 10 years, subject to Objectives 1-4 being met.

The Sablefish MSE process has been peer reviewed via several Canadian Science Advisory Secretariat (CSAS) processes (DFO 2014, 2017, 2020), and via peer review in scientific literature (Cox and Kronlund 2008; Cox et al. 2013).

Sablefish OMs are updated on a 3-5 year cycle to incorporate new data and hypotheses about Sablefish stock and fishery dynamics and to provide periodic assessments of stock status relative to reference points. The last regional peer review of the Sablefish operating model was in 2016 (DFO 2017), followed by an update in 2019 that was done via a Science Response (DFO 2020). Assessment and management of Sablefish is closely aligned with the requirements of Canada's Fishery Decision-Making Framework Incorporating the Precautionary Approach ('DFO PA Policy', DFO 2009), and the more recent revisions to the *Fisheries Act* (i.e., Fish Stocks Provisions; see Appendix). Fisheries and Oceans Canada (DFO) Fisheries Management has requested that Science Branch provide a revised Sablefish OM that updates stock status estimates for 2022 relative to key reference points identified by the DFO PA Policy, which include a limit reference point (LRP), an upper stock reference (USR) point, a target reference point, and a maximum fishing mortality rate.

Current and future demands for simulation-evaluation of MP performance require migrating the Sablefish OM and MP to a new, more efficient software platform. For 2022, a revised OM is implemented using 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). In addition, the revised model structure addresses a larger suite of possible data (e.g., length composition) and uncertainties affecting the Sablefish stock and fishery than considered previously. The paper provides a direct comparison of OM characteristics between the two software implementations. Simulations using the TMB version are then used to evaluate the current MP and alternatives that reflect revised OM productivity estimates.

ANALYSIS

Revised Operating Model

The revised Sablefish operating model is a two-sex statistical catch-at-age model fit to (i) fishery-specific landed catch from three gear types (trap, longline hook, and trawl; 1965-2021), (ii) at-sea releases from each of the three fishery gear types (2006-2021), (iii) three indices of total abundance including the trap fishery (1979-2009), a standardized survey (Std; 1990-2009), and a stratified random survey (StRS; 2003-2021), (iv) age composition data from the trap fishery and the Std. and StRS research surveys, and (v) length compositions from the trawl fishery (1970-2019).

The revised OM now also fits to length-frequency data, in addition to age-frequency data, in an attempt to improve estimates of size-selectivity and sub-legal fishing mortality by trawl fisheries. Selectivity is assumed to depend on length, which enables a single selectivity-at-length function for both sexes. A length-based process is assumed because priors on selectivity are taken from tagging estimates of fishery selectivity, which are only available based on length. 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 are fit directly.

Transition and Bridging Analyses

A transition analysis compared how estimated parameters changed between ADMB and TMB software implementations as well as the effect of model assumptions. This comparison used data to 2018 when the ADMB-based OMs were last updated. A bridging analysis compared TMB-based estimates using data to 2018 vs. data to 2021 to judge the impacts of new data on model estimates. Transition and bridging analyses were 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.

Overall, temporal patterns of female spawning biomass and fishing mortality were very similar among all models considered in the bridging and transition analyses (Figure 2). The most substantial differences occurred for length-based selectivity in all fisheries and surveys.

Estimated steepness and female natural mortality differed by 3.4% and 10% between the ADMB and TMB versions, respectively, given the same data and assumptions, while the derived optimal harvest rate U_{MSY} was only 5% higher for TMB. Differences in absolute spawning biomass were more substantial with estimated B_{2018} 30% higher for the TMB implementation; however, the TMB estimate was still within the margin of error of ADMB model estimates. Some differences between TMB and ADMB can be attributed to ADMB under-representing uncertainty due to autocorrelation in samples from the Bayesian posterior distribution of model parameters. Such undesirable autocorrelation was negligible in the TMB implementation.

Several differences observed between ADMB and TMB were reversed when the statistical error (CV) assumed for trawl catch and at-sea release data was increased from 1% to 10%, which was the value assumed for the 2021 TMB implementation. A larger CV was required in 2021 to improve fits to the recent peak values in at-sea releases from the trawl fishery without pushing recent recruitment estimates to highly improbable values.

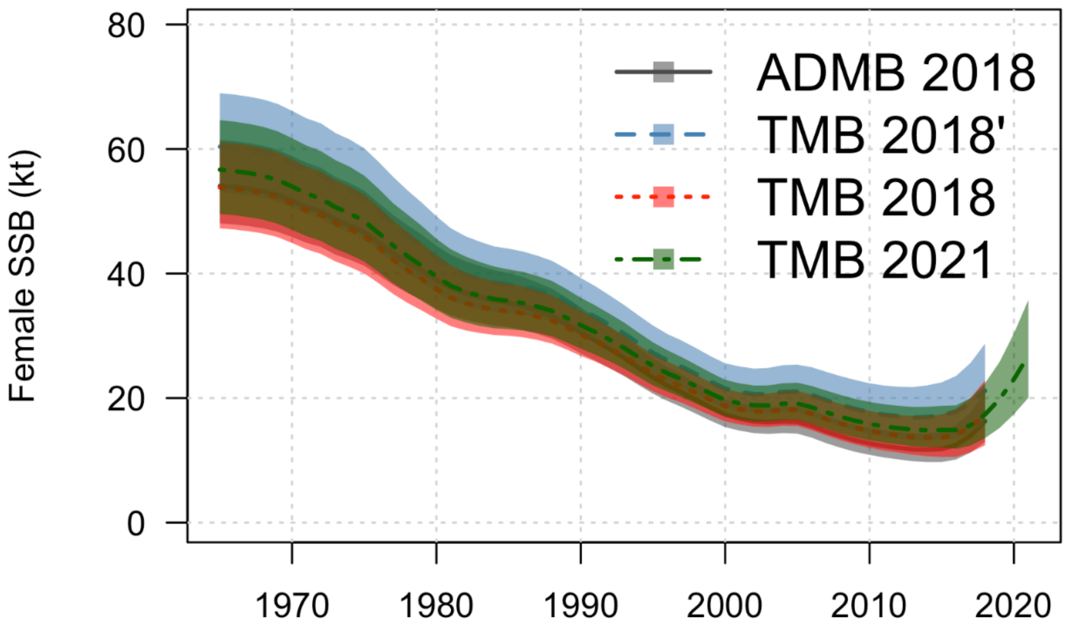


Figure 2. Overlaid posterior distributions of female spawning biomass from each of the four models compared in the transition and bridging analyses.

Model Diagnostics

Retrospective operating model fits between 2005 and 2021 were produced by successively removing one year of data from 2021 to 2005. The results show variation in estimated unfished equilibria (B_0, R_0) and productivity (h, U_{MSY}) over time as new data were added to the model; however, annual deviations were generally less than 10%. Variability was highest for U_{MSY}, for which estimated values varied between 0.054 and 0.079 from 2005-2021 using the revised OM. The 2021 estimate of U_{MSY}=0.065 is in the mid-point of this range. In contrast, estimated unfished spawning biomass, B_0, showed a consistently increasing trend over time. These variations are believed to be largely in response to updated information on year class strength each year, and its influence on the stock-recruitment relationship. Retrospective examination of cohort strength shows that estimated year class strength (i.e., standardised recruitment deviation) typically stablilises after age 4 or 5, suggesting that the above-average values currently estimated for the 2015 and 2016 year classes may continue to be large. This result provides further evidence that one or more large year-classes has recruited to the BC Sablefish fishery.

The revised OM was assessed for sensitivity of estimated parameters to several key assumptions including likelihood weights for selected data, parameter prior distributions, model precision for at-sea releases as well as release mortality values, and the last year of modeled recruitments. Over the range of sensitivity scenarios examined, estimates for unfished female spawning biomass were mostly within the 50-60 kt range, while the stock-recruitment steepness parameters fell within the 0.65-0.69 range. Negative correlations between biomass and productivity meant that biological reference points were even more narrowly constrained with optimal harvest rates ranging from approximately 0.06 to 0.08 and MSY between approximately 3,500 to 4,500 t.

Exceptions to these results occurred for sensitivity analyses that (i) adjusted the last year of estimated recruitment deviations, (ii) changed the likelihood weight on age composition data from the trap fishery, and (iii) shifted prior distributions for unfished biomass and stock recruitment steepness. First, changing the last year in which recruitment deviations were estimated shifted how the model attempted to explain recent increases in at-sea releases by increasing estimates of the overall size of the stock (via unfished biomass) and/or increasing the size of recent year classes. Second, reducing the likelihood weight for trap fishery age composition data reduced B_0 (and R_0) by almost 50% and MSY by over 30%. This high sensitivity is a result of age composition data providing the main source information on recruitment timing and magnitude, which drives recent trends in the StRS index, catch, and at-sea releases. Finally, stock-recruit steepness changed from 0.827 when 2015 was the last year of estimated recruitment deviations, to 0.63 when 2019 was the last year; this change also resulted in lower estimates of U_{MSY} (from 0.089 to 0.063) and MSY (from 4807 to 3425 tonnes).

Operating Model Scenarios

Stock status relative to reference points for BC Sablefish is characterized using an ensemble model approach that covers uncertainty about stock-recruitment steepness (productivity) and biomass in the terminal year of the assessment. Five operating model scenarios are defined that vary these quantities with each scenario assigned a plausibility weight. The five OM scenarios are labelled as ***baseOM*** (i.e., the base model that is used as a mid-point among OM scenarios), ***hiProd*** and ***loProd***, (representing high and low productivity assumptions, respectively), and ***hiRelCV*** and ***loRelCV*** (representing low and high terminal year biomass, respectively). The ***hiProd*** and ***loProd*** scenarios are parameterized by adjusting the prior distribution on the stock-recruitment steepness parameter, while the ***hiRelCV*** and ***loRelCV*** scenarios varied the level of uncertainty in trawl release observations. Varying uncertainty in trawl release observations has the effect of increasing or reducing the size of recent year classes, thereby raising or lowering operating model estimates of terminal biomass (Figure 3).

A composite measure of stock status relative to reference points is computed as a weighted average of scenario outputs, with a weight of 50% assigned to ***baseOM*** and each of the remaining four scenarios weighted equally at 12.5% each.

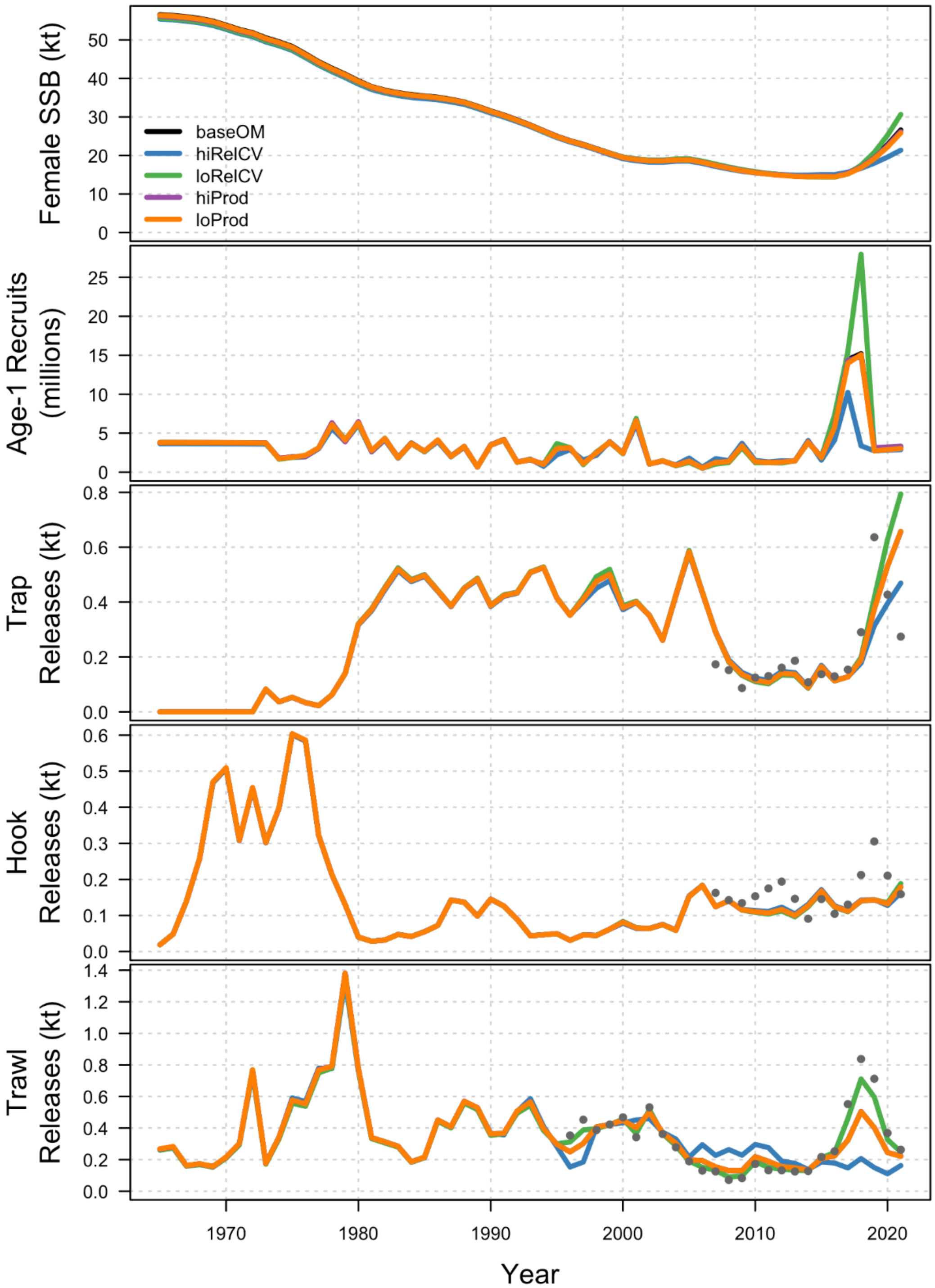


Figure 3. A comparison of estimates (lines) of female spawning biomass, age-1 recruitment, and at-sea release observations (points) for each commercial fleet across the five operating model scenarios (coloured lines explained in legend).

Stock Status Relative to Biological Reference Points

Estimated spawning stock biomass in BC showed consistent declines between 1965 and 2010 (Figures 4, 5). During this period, occasional years of relatively strong recruitment in the late-

1970s to early-1980s and in 2000 led to brief periods of increasing or stabilized biomass. However, harvest rates that were frequently above U_{MSY} contributed to reductions in biomass as these waves of recruitment were fished. Biomass levels stabilized around 2008-2011 when estimated harvest rates were reduced to levels below U_{MSY}. Recent large recruitment events in 2015 and 2016, by far the largest estimated in the reconstructed time series, have resulted in a substantial increase in biomass through to 2022.

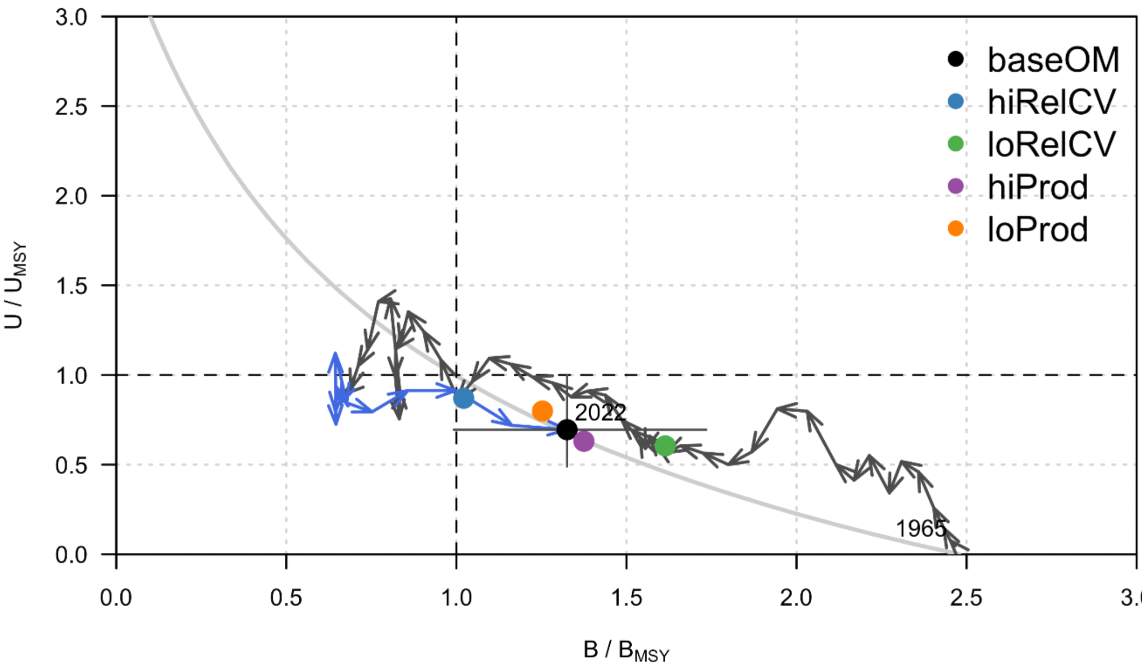


Figure 4. Historical relationship between posterior median spawning biomass (horizontal axis) and total legal harvest rate (vertical axis) relative to their corresponding MSY-based reference points. Arrows show the direction of time, beginning in 1965 and ending in 2022, with the years since the introduction of a simulation-tested MP in 2011 coloured blue. The crosshair indicates the median and 95% credibility intervals for the current stock status under baseOM, and the median values for all other OM updates are shown as coloured circles. The theoretical path at equilibrium based on the model is shown as a faint grey curve.

Results suggest a high probability that BC Sablefish is above the target biomass of B_{MSY} in 2022, and that the harvest rate in 2021 was below U_{MSY} (Table 1, Figure 6). The weighted average spawning biomass across the five OMs is estimated at 30 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 72% of U_{MSY} ($P(U_{2021} < U_{MSY}) = 94\%$). All five OM scenarios estimated a very high (100%) probability of B_{2022} being above the LRP of $0.4B_{MSY}$. Four of the five OMs estimated a 100% probability of B_{2022} being above the USR of $0.8B_{MSY}$ while the estimate for the ***hiRelCV*** scenario was 92%, or a high probability, of B_{2022} being above the USR.

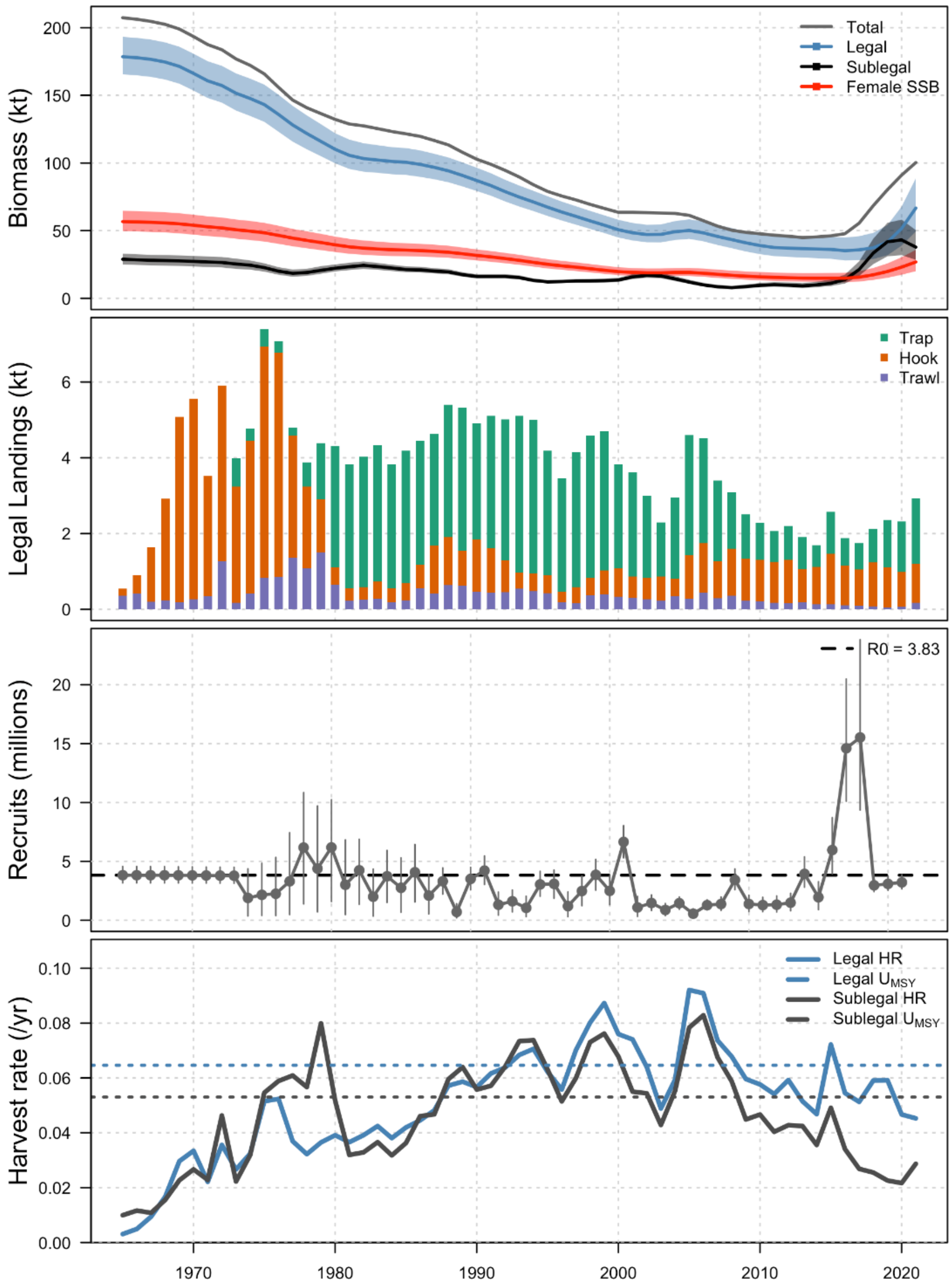


*Figure 5. Time series of Sablefish total, legal, female spawning, and sub-legal biomass estimates (top), total legal sized landings (bars; second row), recruitments (third row), and harvest rates (bottom row) for the **baseOM** scenario.*

Table 1. Bayesian posterior estimates of model parameters, MSY-based reference points, and 2021 stock status relative to those reference points for the five operating model scenarios as well as a weighted-average composite estimate. The table header shows the operating model label, while the row labels describe the estimated quantity. Parameter definitions and units are as follows: B_0 = unfished equilibrium female spawning biomass (kilotonnes; kt), B_{2022} = female spawning biomass at the start of 2022 (kt), MSY = maximum sustainable yield (kt), B_{MSY} = female spawning biomass at MSY (kt), R_0 = unfished equilibrium age-1 recruitment (millions of fish), h = stock-recruit steepness, M_m and M_f = natural mortality for males and females, respectively (yr^{-1}), U_{2021} = harvest rate in 2021, and U_{MSY} = harvest rate associated with MSY. Posterior probabilities, denoted 'Pr(outcome)', are used to describe the probability of stock status relative to reference points.

	Operating Model Scenario					
	baseOM	*hiProd*	*loProd*	*hiRelCV*	*loRelCV*	*Composite*
Parameter						
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_{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
Status						
B_{2022}	30.29 (4.71)	29.86 (4.61)	29.38 (4.82)	22.93 (3.83)	36.17 (5.89)	29.94
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
U_{2021}	0.045 (0.007)	0.045 (0.007)	0.046 (0.007)	0.055 (0.009)	0.039 (0.006)	0.046
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
$Pr (B_{2022} > 0.4B_{MSY})$	1	1	1	1	1	1
$Pr (B_{2022} > 0.8B_{MSY})$	1.00	1.00	1.00	0.92	1.00	0.99
$Pr (B_{2022} > B_{MSY})$	0.970	0.990	0.930	0.560	1.000	0.918
$Pr (U_{2021} < U_{MSY})$	0.97	1.00	0.88	0.75	1.00	0.94

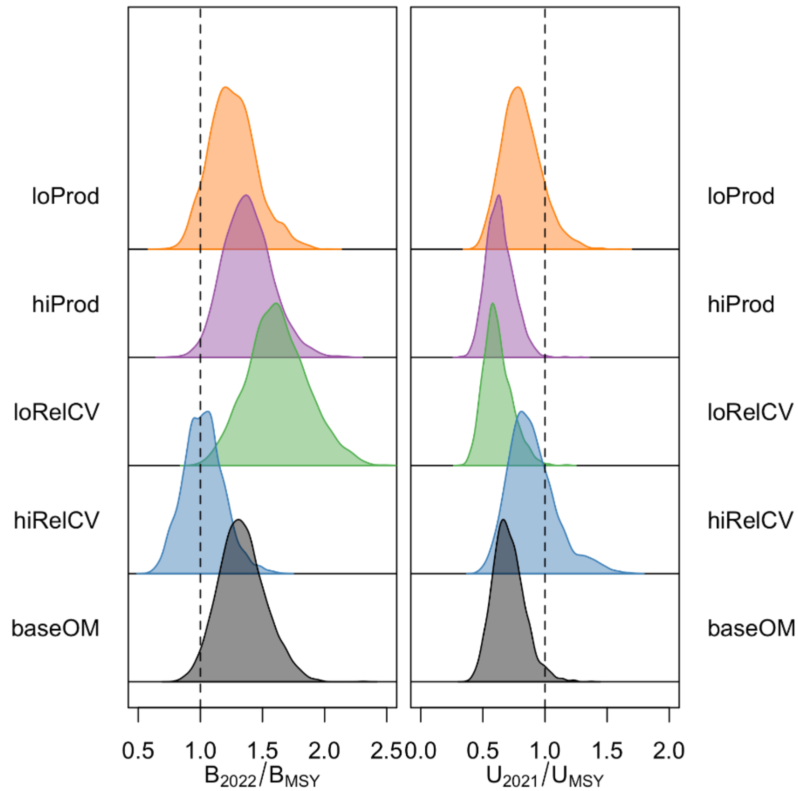


Figure 6. Stacked posterior densities of stock status relative to MSY-based reference points for the five reference set operating models. The left column shows 2022 start of year spawning biomass relative to operating model B_{MSY}, and the right-hand column shows 2021 legal harvest rate relative to operating model legal U_{MSY}.

Closed-Loop Simulation Framework

Simulations were used to test whether the current MP, which has been applied since 2016 (Cox et al. 2019), is able to meet objectives 1-3 under the five OM scenarios, and to show the nature of trade-offs for objectives 4-5. In addition, modified versions of the current MP were considered that varied the maximum target harvest rate of the harvest control rule (HCR) in light of updated estimates of productivity and other key management parameters from the revised OM. Performance statistics corresponding to each of objectives 1-5 provided in the 'Introduction' section above were used to quantify MP performance. Performance statistics were measured using the operating model estimates of female spawning stock biomass and legal-sized catch.

Management Procedure

The Sablefish MP is a specific, repeatable algorithm for computing a catch limit. The MP is made up of (i) Sablefish fishery monitoring data, (ii) a state-space surplus production model (SSPM) for estimating vulnerable Sablefish biomass, (iii) a harvest control rule (HCR), (iv) a post-rule constraint on catch limit increases. Data used to fit the SSPM model include total fishery landings for all gears combined (1965-2021) and the three abundance indices used to fit the operating model: trap fishery catch per unit effort (CPUE, 1979-2009), Std. research survey (1990-2010), and StRS research survey (2003-2021). The SSPM is a simple model used to estimate vulnerable biomass and the operational control points used to determine the target harvest rate from the HCR as explained below.

For a given year t, the SSPM estimates legal sized biomass at the start of the following year, Bt+1, and optimal legal sized biomass, BMSY. The BMSY estimate is then used to define operational control points (OCPs) used within the HCR. The SSPM biomass estimates, as well as the estimated OCPs, are inputs to the annual management procedure and are not used to characterize stock status; stock status is strictly derived from the OM. Lower and upper control points are set at LCP=0.4BMSY and UCP=0.6BMSY, respectively. These values are used to determine the harvest rate via a recti-linear harvest control rule which linearly reduces from a maximum target harvest rate, Umax, at the UCP to zero at the LCP (Figure 7). The legal sized biomass estimated by the SSPM is an input to the HCR used to assign a harvest rate and generate a catch limit based on that harvest rate. A post-HCR constraint is applied that imposes a minimum catch limit increase of 200 t. If the recommended catch limit from the HCR is less than 200 t higher than the previous year's TAC, no increase is applied; there is no restriction on downward adjustments of the catch limit. The MP-derived catch limit informs the choice of total allowable catch (TAC) and has generally been adopted as the TAC since 2011 with few deviations.

In addition to the MP currently applied to the fishery for the 2022/23 fishing year (U_{max}=5.5%), alternative MPs were tested that increased U_{max} from 6% to 7.5% in 0.1% increments (Figure 6). These alternatives reflected the increase in productivity estimated by the revised OM compared to the previous OM updated in 2016 and 2019 (DFO 2016, DFO 2020).

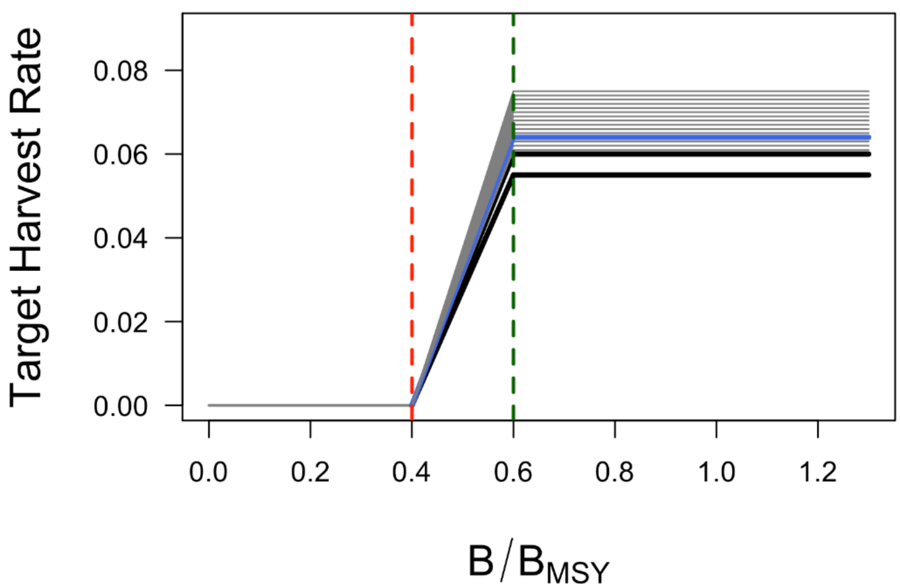


Figure 7. Harvest control rules with a maximum target harvest rate of 5.5% (current MP) and a range of maximum target harvest rates from 6% to 7.5% in 0.1% increments. The x-axis is the SSPM estimate of B/B_{MSY}, from which the target harvest rate (y-axis) is determined. Each line shows an HCR that was tested in closed loop simulation, with bold lines showing the HCR in the current MP and a HCR with a 6% target harvest rate. A HCR with the weighted average optimal harvest rate of 6.4% is shown as a blue line.

Closed-loop Feedback Simulations

A new closed-loop simulation framework for testing MP performance was developed, which required the development of a TMB implementation of the SSPM component of the MP.

Internalizing all computations required for the feedback MP in a TMB framework vastly reduced file management overhead relative to the former ADMB implementation, making simulations more efficient to run.

Closed-loop feedback simulations were conducted using the five operating model scenarios used to estimate stock status. For each OM scenario, simulations were conditioned using 100 random draws from posterior distributions. Population dynamics and fishery impacts were then projected forward one year at a time. For each year, (i) simulated catch and survey data were generated, (ii) the SSPM was fit to the simulated data, (iii) the HCR and post-HCR constraint were used to calculate a catch limit, and (iv) the operating model was updated for the next year given the fishing mortality from the catch-limit and new recruitment. Composite performance metrics relating to each of the five Sablefish fishery objectives were averaged over results from the five scenarios using the plausibility weights described above.

Results from feedback simulations showed that all candidate MPs met biomass conservation objectives (objectives 1-2) and the target biomass objective (objective 3) (Table 2). Given that MP performance relative to conservation and target biomass objectives are satisfied, MP choice is largely related to a trade-off decision between yield and the probability of economically unviable catches (objectives 4-5).

Consideration of Environmental Conditions

An investigation of environmental variables (EVs) potentially affecting BC Sablefish population dynamics was undertaken as part of this work. Eight EVs were selected for investigation based on previously published relationships with Sablefish population dynamics in Alaska, BC, and the United States (US) West Coast. Pairwise correlation analyses were then used to identify variables that were relevant for BC Sablefish in 2022 using two different population traits: (i) recruitment deviations from the underlying stock recruitment relationship and (ii) a morphological index of Sablefish body condition based on fish weight relative to length.

None of the EVs considered were singularly strong candidates for characterizing environmental conditions linked to BC Sablefish recruitment. Only two EVs, spring sea surface temperature (SST) off the west coast of Vancouver Island and offshore primary productivity during spring, showed weak correlation with recruitment variability. The simple correlation analyses conducted as part of this work represent an initial exploration of potential links. Future research into environmental drivers of Sablefish recruitment strength could consider using more complex models to explain variability as a function of multiple environmental variables operating at various spatio-temporal scales and life history stages.

The potential impacts of long-term environmental change on BC Sablefish are unknown; however, some recent research in Alaska and BC have examined this question. In the Bering Sea, a recent assessment of climate variability scored Sablefish as being moderately vulnerable to future climate change (National Oceanic and Atmospheric Association [NOAA] 2019). Sablefish were assessed as being most sensitive to future predictions of ocean acidification, followed by changes to bottom temperature and sea surface temperature. Within BC specifically, a recent study of groundfish populations vulnerable to trawl gear 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 (English et al. 2022).

Table 2. BC Sablefish management performance metrics, weighted over all five operating model scenarios, under the current management procedure (currMP), and 16 alternative procedures. The alternative MPs differ by the maximum target harvest rate, and are labeled as 'targHRx', where x indicates the maximum target harvest rate. A black dot (●) is used to show than a management procedure meets an objective when tested in all five operating model scenarios. Catch objectives 4 and 5 have no threshold and are shown as numerical values, which have units of probability units (Obj. 4), and tonnes (Obj 5). Also shown are performance metrics for average annual catch variability (AAV; units = percentage points), the 2022 catch limit (C_{2022}; units = tonnes), the average unviable catch ($E(C_t \mid C_t < 1.992)$; units = tonnes), and average female spawning biomass in 2057 (B_{2057}; units = tonnes).

MP	Obj. 1	Obj. 2	Obj. 3	Obj. 4	Obj. 5	AAV	C_{2022}	$E(C_t \mid C < 1992)$	B_{2057}
	Avoid LRP	*Avoid Decline When Below USR*	*Achieve Target*	*Avoid Unviable Catch*	*Maximize Catch*				
currMP	●	●	●	0.98	3,148	3.95	2,494	1,683	33,067
targHR6	●	●	●	0.97	3,629	4.45	2,970	1,516	30,193
targHR6.1	●	●	●	0.97	3,680	4.55	3,019	1,476	29,898
targHR6.2	●	●	●	0.97	3,732	4.62	3,069	1,450	29.605
targHR6.3	●	●	●	0.97	3,783	4.68	3,119	1,403	29.315
targHR6.4	●	●	●	0.97	3,834	4.78	3,169	1,356	29.027
targHR6.5	●	●	●	0.97	3,885	4.85	3,219	1,344	28.743
targHR6.6	●	●	●	0.97	3,936	4.95	3,269	1,292	28.458
targHR6.7	●	●	●	0.97	3,987	5.05	3,318	1,251	28.182
targHR6.8	●	●	●	0.97	4,036	5.14	3,368	1,234	27.907
targHR6.9	●	●	●	0.96	4,087	5.19	3,418	1,208	27.636
targHR7	●	●	●	0.96	4,136	5.29	3,468	1,210	27.367
targHR7.1	●	●	●	0.96	4,185	5.39	3,518	1,184	27.103
targHR7.2	●	●	●	0.96	4,234	5.50	3,568	1,219	26.842
targHR7.3	●	●	●	0.95	4,283	5.64	3,618	1,237	26.580
targHR7.4	●	●	●	0.95	4,332	5.75	3,668	1,222	26.328
targHR7.5	●	●	●	0.94	4,380	5.86	3,718	1,266	26.077

The potential risk of not including EVs into the BC Sablefish operating model (or management procedure) seems low at this time. Previous research in the US has shown little difference in Sablefish stock assessment model predictions when comparing models that include EVs to those without, when sufficient survey and age composition data are available to provide recruitment signals (Shotwell et al. 2014; Johnson et al. 2016), which is the case for BC Sablefish. Furthermore, annual application of the Sablefish MP provides a strong feedback link between current management action and the stock response, such that fishing pressure is reduced when the stock is perceived to decline, regardless of the underlying mechanism. Annual evaluation of abundance trends also means that departures from projected management performance are likely to be detected quickly, allowing the opportunity for intervention when required.

Sources of Uncertainty

The ensemble model approach allows for a sub-set of key structural uncertainties in the five specifications of the Sablefish OM to be integrated into estimated stock status. However, several additional uncertainties exist that are not captured in operating model results.

The revised OM assumes that the BC Sablefish stock is a closed population, and as such, does not account for movement of Sablefish into US waters in Alaska and the lower west coast of the US. Such movement of Sablefish between BC and the US is well-documented from tag release-recovery data. Transboundary movements may affect Sablefish stock dynamics in BC that are not currently captured by the revised operating model. However, active assessment and management programs in all three jurisdictions provide frequent status updates and corrective actions to reduce or increase catches as required.

Future operating models should further explore alternative approaches to modelling at-sea releases to better account for release mortality in operating model simulations. The current formulation of the Sablefish OM assumes that sub-legal fish are caught in proportion to their abundance and 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. Mis-specification of these release dynamics may account for observed poor fits to at-sea release data in recent years. Future operating models should consider alternative ways of accounting for at-sea releases, such as time-varying selectivity or additional fleet structure that captures the true process more accurately.

CONCLUSIONS AND ADVICE

The revised operating model for 2022 is suitable for characterizing stock and fishery dynamics for BC Sablefish and should be used within the MSE process to estimate stock status and simulation test management procedures going forward. The switch to implementing the OM in TMB software presented no major problems and offered several advantages over the former software framework that include improved convergence of posterior chains for estimating uncertainty and faster execution of feedback simulations.

Sablefish have recently been prescribed as a major fish stock in regulations under Canada's revised *Fisheries Act*, making them subject to the Fish Stocks provisions. 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). The Appendix presents a summary of Sablefish harvest strategy components that demonstrate compliance with these regulations and alignment with all the requirements of Canada's Precautionary Approach policy (DFO 2009).

Based on an ensemble model approach that incorporated key uncertainties from five operating model scenarios, the Sablefish stock in BC is estimated to be well above the target biomass of B_{MSY} in 2022. The stock has a very high probability of being above both the LRP (100%) and USR (99%) in 2022, and very high probability that the legal harvest rate in 2021 was below U_{MSY}.

All MPs that were evaluated met the biomass conservation and target objectives, and the choice of future management procedure can be made based on the catch performance metrics. Varying the target harvest rate produced trade-offs between the probability of avoiding an economically unviable catch (objective 4) and the average maximum catch (objective 5). However, most of the contrast is in average catch performance as all MPs showed a 94% to 98% probability of avoiding an unviable catch.

Environmental variables potentially affecting BC Sablefish population dynamics were examined via pairwise correlations between eight EVs, annual recruitment, and a body condition index. None of the EVs were strongly correlated to recruitment. While the impact of climate change on BC Sablefish is unknown, recent research indicates that increasing temperature may increase habitat suitability for Sablefish. The potential risk of not including environmental variables into the BC Sablefish operating model (or management procedure) seems low at this time.

Management Strategy Evaluation is an iterative process aimed at improving management outcomes over time. It is recommended that BC Sablefish operating models be reevaluated for suitability at intervals of 3-5 years, at which time estimates of BC Sablefish stock status will also be updated and management procedures revised to maintain the desired performance against conservation and yield objectives.

OTHER CONSIDERATIONS

Increased frequency of biological catch sampling from longline hook and trawl fleets was highlighted as a key research recommendation; these data are needed to support estimation of fishery selectivity for longline hook and trawl gears. In the case of longline hook fisheries, this will require working with commercial fishers to increase sampling rates. In the case of the trawl fishery, this will require the development of a new catch sampling program to replace the at-sea-observer program that was discontinued with the switch to electronic monitoring in 2020. The efficacy of both efforts also requires adequate capacity to age the collected samples.

Additional high priorities for future OM development include a revised approach to modelling at-sea releases that better captures release dynamics. A longer-term research priority is the development of OM scenarios that account for transboundary movements of Sablefish between Canada and the US. Ongoing support for the BC Sablefish tagging program is recommended to ensure high-quality data are available to support the development of movement scenarios.

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SOURCES OF INFORMATION

This Science Advisory Report is from the November 15-16, 2022 regional peer review on a Revised Operating Model for Sablefish in British Columbia in 2022. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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APPENDIX

Table A-1. Compliance of the Sablefish Management System with the Fish Stocks provisions and PA Policy (DFO 2009). Stock status estimates are based on a weighted composite of the five 2022 operating model scenarios described in this paper. Note that the probability of an outcome is indicated by P(outcome), e.g., the probability that female spawning biomass is above B_{MSY} is denoted $P(B > B_{MSY})$. Classification of probability levels is based on DFO (2009), with 'Very high' indicating a greater than 95% probability of a given outcome and 'high' indicating a 75 – 95% probability.

Harvest strategy 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 updated on 3-5 year cycle for stock assessment and MP testing
Reference Points	MSY-based reference points in terms of female spawning biomass and estimated on 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 five age-/sex-structured statistical catch-at-age models with uncertainty characterized via Bayes posteriors Assessment/Operating models fitted to biomass indices (fishery and 2 surveys), 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 trap survey (2003-2021) Landings (1965-2021)
b. Assessment method	Schaefer state-space production model (SSPM) fitted to data described in (a)
c. Harvest control rule	Recti-linear ("hockey stick") rule with lower and upper operational control points: LCP = 40% of the SSPM B_{MSY} UCP = 60% of the SSPM B_{MSY} Maximum Target Harvest Rate in 2022 = 5.5%

Harvest strategy component	Description
	Operational control points are estimated annually by the SSPM (note that control points are not used to characterize stock status). Maximum Target Harvest Rate selected via tuning simulated MP performance against objectives.
Stock status (2022): Female Spawning Biomass Harvest Rate	 Stock is above B_{MSY} B_{2022} = 29.9 kt (95% CI: 19.6-42.9 kt) B_{2022}/B_{MSY} = 1.32 Stock is above Limit Reference Point with very high probability: P(B_{2022} > LRP) = 100% Stock is above Upper Stock Reference with very high probability: P(B_{2022} > USR) =99% Stock is above Target Reference Point with high probability: P(B2022 > B_{MSY}) = 92% Harvest rate of legal-size fish is less than U_{MSY} with high probability: P(U < U_{MSY}) = 94%
Rebuilding Plan	Not required, 100% probability that stock is above its LRP.
Rebuilding Criteria	*Entry*: Terminal year stock status estimated at or below LRP with greater than 50% probability *Exit (Rebuilt state)*: To be developed.
Consideration of Environmental Conditions	Mechanisms by which environmental conditions affect BC Sablefish are not understood at this time. An initial investigation of seven environmental variables (EVs) showed that none of them were strongly correlated to recruitment. While the impact of climate change on BC Sablefish is also unknown, recent research indicates that increasing temperature may increase habitat suitability for BC Sablefish.

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