MANAGEMENT PROCEDURES UPDATE AND CATCH ADVICE FOR 2023/24-2026/27 FISHING SEASONS FOR OUTSIDE YELLOWEYE ROCKFISH (*SEBASTES RUBERRIMUS*) IN THE PACIFIC REGION

Context

This Science Response (SR) evaluates the performance of new management procedures (MPs) for Outside Yelloweye Rockfish (OYE) fisheries against candidate management objectives that include alternative Target Reference Points (TRP). The scientific advice herein is intended to inform MP choices for 2023/24-2026/27 fishing years and support consultations with First Nations groups and stakeholders to determine reference points, management objectives, and rebuilding targets for OYE. The key tasks are as follows:

1. Proposing candidate management objectives for North and South OYE stocks to allow evaluation and ranking of management procedures (MPs), including i) risk tolerance for short-term (10 years) declines in biomass, ii) probability thresholds for maintaining biomass above the limit reference point (LRP) of $0.4B_{MSY}$ and target reference point (TRP) over the long-term (1.5 OYE generations), and iii) fishery objectives to maintain annual total allowable catch (TAC) above 200 t coastwide (125 t in North, 75 t in South) and limit annual change in TACs to less than 20% and less than 30 t for North and South stocks.

2. Visualizing the catch vs conservation trade-offs associated with alternative TRP choices for the weighted OYE operating model grid. Alternative TRP choices ($0.8B_{MSY}$, B_{MSY}, $1.2B_{MSY}$) indicate median annual coastwide TACs over the next 10-years would vary between 396 t (217 t in North, 179 t in South) for $0.8B_{MSY}$, 308 t (173 t in North, 135 t in South) for B_{MSY}, and 248 t (140 t in North, 108 t in South) for $1.2B_{MSY}$.

3. Defining empirical MPs to be evaluated using the closed-loop simulation framework developed for OYE during the 2019 rebuilding analyses. The MPs evaluated include i) the current index-based MP (idxSmuv) used to set TACs since 2020, and ii) new empirical MP options using the hard bottom longline (HBLL) stratified random survey index with different choices for moving averages (3 YR, 5 YR, 7 YR) and TRPs ($0.8B_{MSY}$, B_{MSY}, $1.2B_{MSY}$). The simulation results will be used to identify a candidate 2023 management strategy that will be used until the 2026/2027 fishing year.

4. Drafting a plan and timeline for updating operating models and re-evaluating MPs. The next operating model update and assessment of stock status will begin in 2024/25 with plans for completion in 2025/26, after which there will be a new evaluation of MPs to provide TAC advice for the 2027/28 fishing year.

5. Preparing a summary table clarifying OYE stock status and how the candidate 2023 management strategy complies with the Fish Stocks Provisions and the Sustainable Fisheries Framework (Table 1). Table 1 provides results from the HBLL 3 YR MP; however, a final decision for OYE MPs for 2023-2026 has not been made and additional MPs (HBLL 5YR and HBLL 7YR) with similar performance are presented in the report (Table 7). The current OYE stock status is above the LRP with 100% probability coastwide, 100% probability in the North, and 98% probability in the South, indicating a rebuilding plan is not required. The new harvest control

rule proposed uses the LRP ($0.4B_{MSY}$) as the lower control point, the upper stock reference ($0.8B_{MSY}$) as the upper control point and removal reference rates less than F_{MSY} ($0.95F_{MSY}$ in North, $0.99F_{MSY}$ in South).

Simulations that used HBLL MPs to set future OYE TACs indicate robust performance relative to the conservation, target, and fishery management objectives, with trade-offs in catch associated with different TRP choices. In the north, the current idxSmuv MP has similar conservation performance to the HBLL MPs using a B_{MSY} TRP, but provides 27-29 t less annual catch. In the south, the current idxSmuv MP has greater conservation performance than all HBLL MPs with a very high (95%) probability of biomass exceeding B_{MSY} after 1.5 generations (2081); however, it generates 41-46 t lower TACs than the HBLL MPs using a B_{MSY} TRP.

Fisheries and Oceans Canada (DFO) Fisheries Management has requested that Science Branch provide new management procedures that include analysis of trade-offs between catch and alternative Target Reference Points, recommend a candidate rebuilding target, and estimate the current stock status relative to the candidate rebuilding target. This Science Response results from the regional peer review of June 15, 2023 on the Management Procedures Update and Catch Advice for 2023/24-2026/27 Fishing Seasons for Outside Yelloweye Rockfish (*Sebastes ruberrimus*) in the Pacific Region.

Background and Summary of Policy Compliance

This project extends the rebuilding analyses of Cox et al. (2020) to update the Outside Yelloweye Rockfish (OYE) Management strategy, resolving issues that were not addressed in previous scientific reviews (Fig. 1). Specifically, the rebuilding analysis did not address the link between values in the fishery and risk tolerance in management via specification of a Target Reference Point (TRP) and fishery objectives.

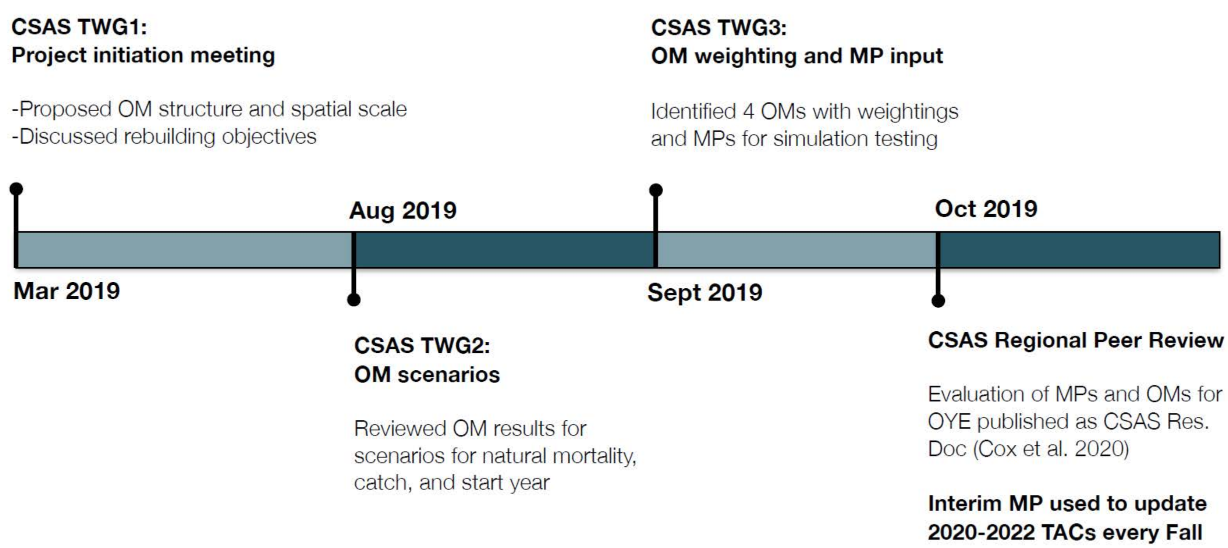

Figure 1. Timeline for the rebuilding evaluation for Outside Yelloweye Rockfish (OM=Operating Model, MP=Management Procedure).

Outside Yelloweye Science Response Technical Working Group

Fisheries and Oceans Canada hosted a series of virtual technical working group (TWG) meetings (Fig. 2) with representatives from DFO Science, DFO Management, Species At Risk (SARA)

Program, Committee on the Status of Endangered Wildlife in Canada (COSEWIC), Pacific Halibut Management Association, and Landmark Fisheries Research. In those meetings, participants reviewed the range of policies applying to OYE populations and fisheries and identified analyses for informing near-term decisions regarding their conservation and management.

The specific roles of the OYE Science Response Technical Working Group (SR TWG) were:

- Clarify policy (i.e., Fish Stock Provisions (FSP), Sustainable Fisheries Framework (SFF), COSEWIC, SARA) context and criteria used to derive stock status (e.g., Critical/Cautious/Healthy, Threatened/Endangered) and conservation/rebuilding objectives for OYE
- Propose candidate management objectives for North and South OYE stocks
- Provide input on management procedures to be evaluated in closed loop simulation framework
- Review results from initial and final phase of MP simulations and provide feedback for any changes needed for objectives or MPs
- Rank MP performance against conservation and fishery objectives to provide management advice for 2023-2026 TACs
- Define probability for the target rebuilt state needed for exiting rebuilding plans, should future estimates of OYE stock status trigger a rebuilding plan[1]

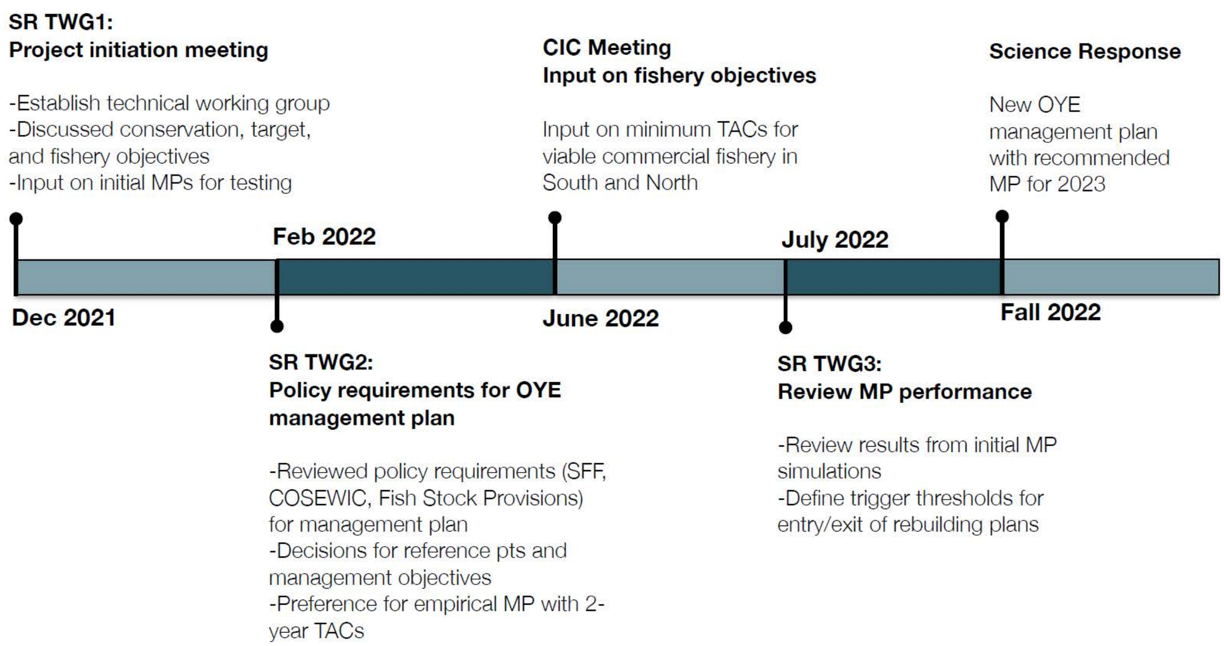

Figure 2. Timeline for development of new management plan for Outside Yelloweye (CIC=Commercial Industry Caucus).

Accounting for uncertainty in operating models and management performance

The OYE management system uses age-structured operating models (OMs) developed in (Cox et al. 2020) to assess OYE stock status and evaluate management strategies. The approach for

[1]Because current stock status is above the LRP, OYE does not currently require a rebuilding plan.

evaluating OYE MPs uses a weighted average of performance metrics under four OM scenarios for the North and the South (Refer to Sections 2.2.1 and 2.3 in Cox et al. (2020) for rationales on splitting OYE into two areas and OM weightings). Independent closed-loop simulations are used for testing MPs in the North and the South, while coastwide performance metrics are also reported for compliance with DFO policies (Table 1).

The four OM scenarios account for three major sources of structural uncertainty:

1. model start date (1918 or 1960);
2. alternative historical catch series; and
3. assumed natural mortality.

In addition to the structural uncertainties, the four scenarios also cover a broad range of parameter uncertainty that propagates into derived biological reference points and stock status (e.g., B_0, M, B_{MSY} , F_{MSY} , B_{2018}, B_{2018}/B_{MSY} ,). Maximum likelihood estimates for 2018 biomass are within 3,000-5,400 t in the North, and 2,400-4,300 t in the South, with a combined range of 5,500-9,900 t coastwide (Table 3). For the weighted average OM, 2018 biomass is estimated as 4,600 t (95% CI: 2,900-7,600 t) in the North, 3,500 t (95% CI: 1,800-7,000 t) in South, and 8,300 t (95%CI: 4,900-13,500) coastwide (Table 3). No single factor clearly explains the range of biomasses because natural mortality, absolute catch levels, and historical recruitments have both indirect and direct effects on biomass and recruitment estimates. The 1960 start year generally has the higher unfished and current biomass, while the lower commercial catch series produces lower unfished and current biomass estimates.

Additional uncertainty is included in the closed-loop simulations via simulated i) survey indices with log-residuals $\epsilon_{t,g} \propto N(\tau_g^2/2, \tau_g^2)$ generated according to survey-specific coefficient of variations (CVs), and ii) age-1 recruitment from a Beverton-Holt recruitment model with log-deviations that are normally distributed $N(0, 1)$.

Table 1. Summary table for 2020 interim (Cox et al. 2020) and 2023 candidate management strategies for OYE with stock status and policy requirements under the Fish Stocks Provisions (FSP) and the Sustainable Fisheries Framework (SFF). The right side of the table summarizes advice for future OYE management decisions, where yellow shading highlights new candidate USR, TRP, rebuilding plan, management objectives, and MPs proposed by the OYE Science Response Technical Working Group (TWG). Note that a final decision for OYE MPs for 2023-2026 has not been made and this table provides results from the HBLL 3 YR MP, while additional MPs (HBLL 5YR and HBLL 7YR) with similar performance are presented in the report. The stock status and spawning biomass are based on the 2018 operating models described in Cox et al. 2020. Acronyms/symbols in order of appearance are: P()=probability, B=spawning biomass, MSY= maximum sustainable yield, LRP=Limit Reference Point, USR=Upper Stock Reference, TRP=Target Reference Point, Removal Reference=F_{REF}, Harvest Control Rule=HCR, Lower Control Point=LCP, Upper Control Point=UCP, TAC=Total allowable catch, Management Procedure=MP, Operating Model=OM.

Policy Requirement	2020 interim management strategy			2023 candidate management strategy		
	North	South	Coastwide	North	South	Coastwide
2018 Spawning Biomass	4,600 t (95% CI: 2,900-7,600)	3,500 t (95% CI: 1,800-7,000)	8,300 t (95% CI: 4,900-13,500)	4,600 t (95% CI: 2,900-7,600)	3,500 t (95% CI: 1,800-7,000)	8,300 t (95% CI: 4,900-13,500)
2018 Stock Status	Healthy Zone B_{2018}/B_{MSY}: 1.15 (95% CI: 0.66-2.06) P(B_{2018} >LRP) = 100% P(B_{2018} >USR) = 89%	Healthy Zone B_{2018}/B_{MSY}: 1.16 (95% CI: 0.55-2.40) P(B_{2018} >LRP) = 98% P(B_{2018} >USR) = 80%	Healthy Zone B_{2018}/B_{MSY}: 1.17 (95% CI: 0.67-2.08) P(B_{2018} >LRP) = 100% P(B_{2018} >USR) = 87%	Healthy Zone B_{2018}/B_{MSY}: 1.15 (95% CI: 0.66-2.06) P(B_{2018} >LRP) = 100% P(B_{2018} >USR) = 89%	Healthy Zone B_{2018}/B_{MSY}: 1.16 (95% CI: 0.55-2.40) P(B_{2018} >LRP) = 98% P(B_{2018} >USR) = 80%	Healthy Zone B_{2018}/B_{MSY}: 1.17 (95% CI: 0.67-2.08) P(B_{2018} >LRP) = 100% P(B_{2018} >USR) = 87%
Rebuilding plan currently required	Unclear, exit criteria undefined	Unclear, exit criteria undefined	Unclear, exit criteria undefined	No	No	No
Reference points and stock status zones	Incomplete LRP: $0.4B_{MSY}$ USR: ? TRP: ?	Incomplete LRP: $0.4B_{MSY}$ USR: ? TRP: ?	Incomplete LRP: $0.4B_{MSY}$ USR: ? TRP: ?	Yes LRP: $0.4B_{MSY}$ USR: $0.8B_{MSY}$ TRP: B_{MSY}	Yes LRP: $0.4B_{MSY}$ USR: $0.8B_{MSY}$ TRP: B_{MSY}	Yes LRP: $0.4B_{MSY}$ USR: $0.8B_{MSY}$ TRP: B_{MSY}
Harvest Control Rule	Yes TAC adjustment HCR with 50% smoother LCP: -50% Biomass UCP: +25% Biomass F_{REF}: NA	Yes TAC adjustment HCR with 50% smoother LCP: -50% Biomass UCP: +25% Biomass F_{REF}: NA	Yes Coastwide harvest determined by HCRs for North and South	Yes Hockey Stick HCR LCP: $0.4B_{MSY}$ UCP: $0.8B_{MSY}$ F_{REF}: $0.95F_{MSY}$	Yes Hockey Stick HCR LCP: $0.4B_{MSY}$ UCP: $0.8B_{MSY}$ F_{REF}: $0.99F_{MSY}$	Yes Coastwide harvest determined by HCRs for North and South
Conservation Objectives	Short-term (10 years) *When the spawning stock biomass is between $0.4B_{MSY}$ and 0.8 B_{MSY}, limit the probability of decline over the next 10 years from very low (5%) at the LRP to moderate (50%) at B_{MSY}. At intermediate stock status levels, define the tolerance for decline by linearly interpolating between these probabilities.*			Short-term (10 years) *When the spawning stock biomass is between the LRP ($0.4B_{MSY}$) and USR ($0.8B_{MSY}$), limit the probability of decline over the next 10 years from very low (5%) at the LRP to moderate (50%) at the USR. At intermediate stock status levels, define the tolerance for decline by linearly interpolating between these probabilities.*		

Policy Requirement	2020 interim management strategy			2023 candidate management strategy		
	North	South	Coastwide	North	South	Coastwide
	Long-term (59 years) *Grow the spawning stock biomass out of the critical zone (i.e., above the LRP of $0.4B_{MSY}$), where B_{MSY} is the operating model biomass at MSY), with a very low (5%) probability of further decline, measured over 1.5 to 2.0 generations.*			Long-term (59 years) *Maintain spawning stock biomass out of the critical zone (i.e., above the LRP of $0.4B_{MSY}$), where B_{MSY} is the operating model biomass at MSY, with a very high (95%) probability, measured at the end of 1.5 generations.*		
Target Objectives	None			Long-term (59 years) *Maintain spawning stock biomass above the TRP (B_{MSY}), where B_{MSY} is the operating model biomass at MSY, with a neutral (50%) probability of decline, measured at the end of 1.5 generations.*		
Rebuilding Plans	Entry point for rebuilding plan A rebuilding plan was triggered based on the 2014 stock status (Yamanaka et al. 2018) estimate that biomass was below the LRP with 63% probability. End point for rebuilding plan Not Defined Rebuilding Target Not Defined			Entry point for rebuilding plan *Final year stock status estimated from the operating model is at or below the LRP with a greater than 50% probability: $P(B \leq LRP) > 50\%$* End point for rebuilding plan *Final year stock status estimated from the operating model is above the LRP, with less than a 25% probability that stock is below its LRP: $P(B < LRP) < 25\%$* Rebuilding Target Median stock status[1] when $P(B < LRP) = 25\%$.		
Management procedure performance (2023-2081)	MP: idxSmuv B_{2081}/B_{MSY}: 0.98 $P(B_{2081} > LRP) = 99\%$ $P(B_{2081} > B_{MSY})$[2] = 49% $P(F < F_{MSY})$[3] = 81%	MP: idxSmuv B_{2081}/B_{MSY}: 1.65 $P(B_{2081} > LRP) = 100\%$ $P(B_{2081} > B_{MSY})$[2] = 95% $P(F < F_{MSY})$[3] = 100%	MP: idxSmuv B_{2081}/B_{MSY}: 1.27 $P(B_{2081} > LRP) = 100\%$ $P(B_{2081} > B_{MSY})$[2] = 77% $P(F < F_{MSY})$[3] =98%	MP: HBLL 3YR B_{2081}/B_{MSY}: 0.99 $P(B_{2081} > LRP) = 100\%$ $P(B_{2081} > TRP) = 50\%$ $P(F < F_{REF}) = 83\%$	MP: HBLL 3YR B_{2081}/B_{MSY}: 1.0 $P(B_{2081} > LRP) = 100\%$ $P(B_{2081} > TRP) = 50\%$ $P(F < F_{REF}) = 90\%$	MP: HBLL 3YR B_{2081}/B_{MSY}: 1.0 $P(B_{2081} > LRP) = 100\%$ $P(B_{2081} > TRP) = 50\%$ $P(F < F_{REF})$[4] = 83%
Recommended harvest for 2023/24 using survey indices up to 2021	158 t	71 t	229 t	190 t	134 t	324 t
Timeline for future Outside Yelloweye management research	To be determined			2024/25: Begin next OM update 2025/26: Complete OM update and CSAS review October 2026: Complete next management strategy evaluation to inform MP choices for 2027/28 fishing year		

[1] For the probability distribution of the current weighted operating model, the median stock status when $P(B_{2081} < LRP) = 25\%$ is $0.48B_{MSY}$ in the North and $0.53B_{MSY}$ in the South. This calculated via simulations that use $F_{REF} > F_{MSY}$ to drive stocks into the cautious zone below B_{MSY} over a 59-year projection. See Appendix B for more details on calculating rebuilding targets.

[2] We use $P(B_{2081} > B_{MSY})$ for summarizing performance for interim index MP idxSmuv since TRP was not specified for the interim management strategy.

[3] We use $P(F < F_{REF})$ for summarizing performance for interim index MP idxSmuv since Harvest Control Rules do not specify F_{REF}.

[4] We use an unfished biomass weighted $F_{REF}=0.97F_{MSY}$ for summarizing coastwide performance since Harvest Control Rules only specify F_{REF} for North and South Stocks.

Rebuilding plan status

The current OYE weighted operating model estimates that the 2018 stock status is above the LRP with 100% probability coastwide, 100% probability in the North and 98% probability in the South (Table 3) and therefore **a rebuilding plan is not currently required for OYE**. Outside Yelloweye Rockfish were included in the first batch of major stocks subject to the *Fisheries Act's* Fish Stock Provisions where it was determined that a rebuilding plan is not needed (Government of Canada 2022).

Analysis

In the sections below, we describe OYE management objectives, closed loop simulation, OYE operating models, management procedures, catch vs conservation trade-offs for alternative TRPs, and the approach for evaluating management procedures against conservation and other candidate management objectives.

Conservation objectives

The current OYE conservation objectives were established by the steering committee for the 2019 rebuilding evaluation (Section 2.1 in Cox et al. 2020) and have had some minor revisions by the technical working group for this project to clarify compliance with DFO's Sustainable Fisheries Framework (SFF), including the Precautionary Approach (PA) and Fish Stock Provisions (FSP) policies (Table 1-2):

Long-term conservation objective (C.1):

Maintain spawning stock biomass (B) out of the critical zone (i.e., above the LRP of 0.4BMSY), where BMSY is the operating model biomass at MSY, with a very high (95%) probability, measured at the end of 1.5 generations.

Short-term conservation objective (C.2):

When the spawning stock biomass (B) is between the LRP (0.4BMSY) and the USR (0.8BMSY), limit the probability of decline over the next 10 years from very low (5%) at the LRP to moderate (50%) at the USR. At intermediate stock status levels, define the tolerance for decline by linearly interpolating between these probabilities.

The short-term conservation objective was revised from Cox et al. (2020) to include 'LRP' and 'USR' when referring to $0.4B_{MSY}$ and $0.8B_{MSY}$, respectively. Although the objective in Cox et al. (2020) included $0.8B_{MSY}$, it did not specify that this was the USR. The revised objective specifies that $USR = 0.8B_{MSY}$ based on the default PA policy choice (DFO 2009; Kronlund et al. 2021) and recommendations by the TWG.

Rebuilding objectives

Although a rebuilding plan is not currently required for OYE, it is possible that future assessments may estimate stock status below the LRP and trigger a rebuilding plan. For completeness of the OYE management strategy, the OYE TWG specified rebuilding objectives, rebuilt targets, and clear criteria for entering and exiting rebuilding plans in compliance with the FSP (DFO 2022c).

According to section 2.1 of (DFO 2022c), a rebuilding plan will be triggered for OYE if the stock status estimated from the weighted operating model in the final year is at or below the LRP with a greater than 50% probability (i.e., P(B $\leq$ LRP) > 50%). To exit a rebuilding plan, the policy guidelines are: *"once the stock reaches its rebuilding target, the rebuilding plan will come to an end and the fisheries on the stock will be subject to an IFMP or other management plan. The* *rebuilding target must be set at a level above the LRP so that there is a very low to low likelihood of the stock being below its LRP (<5-25% probability)*" section 2.3 (DFO 2022c).

The TWG proposed that the end point for any future OYE rebuilding plans is when the stock status estimated from the weighted operating model in the final year is above the LRP with at least 75% probability (i.e., P(B < LRP) < 25%). When the stock is below the LRP, a rebuilding target expressed as B_{MSY} can be determined by using a simulation approach to identify the median stock status (i.e., B/B_{MSY}) for the minimum rebuilding plan exit criteria P(B <LRP) = 25%. Refer to Appendix B for clarification on policy guidance for selecting rebuilding targets under the FSP.

The OYE rebuilding objectives for OYE have been updated by the SR TWG to reflect recent guidance from the FSP. Note that the rebuilding objectives would only apply in the event that future estimates of stock status trigger a rebuilding plan.

Long-term rebuilding objective (R.1):

When spawning stock biomass (B) is below the rebuilding target, grow B above the rebuilt target with a high (at least 75%) probability measured after T_{MIN} to $3T_{MIN}$, where T_{MIN} is the time to grow the stock to the rebuilt target in the absence of fishing.

There are 2 specific choices required for the long-term rebuilding objective R.1: i) the time period (1-3T_{MIN}) and ii) the probability for achieving the rebuilding target (at least 75%). These choices will consider trade-offs for conservation, socio-economic, and cultural impacts (DFO 2022c) when specifying rebuilding objectives for OYE, should a rebuilding plan be necessary in the future.

Short-term rebuilding objective (R.2):

When the spawning stock biomass is below the rebuilding target, limit the probability of decline over the next 10 years to very low (5%).

Target and fishery objectives

A lack of a long-term target biomass objective (i.e., TRP) for OYE was identified as a limitation for OYE management during the 2019 rebuilding evaluation (Cox et al. 2020), since a TRP is needed for evaluating and differentiating between candidate MP choices. Furthermore, the guidelines section 4.1.1 for implementing the FSP (DFO 2022b) requires specifying a TRP along with management measures that aim to maintain long-term stock biomass at the TRP. Following an evaluation of catch-conservation trade-offs associated with alternative TRP choices (described in subsequent sections of this report), an interim Target Reference Point of B_{MSY} was recommended by the SR TWG to develop a target objective for OYE (Table 1-2).

Long-term target objective (T.1):

Maintain spawning stock biomass (B) above the TRP (BMSY), where BMSY is the operating model biomass at MSY, with a neutral (50%) probability of decline, measured at the end of 1.5 generations.

Fishery objectives (F.1-F.2, Table 2) were developed in consultation with the Commercial Industry Caucus and the TWG with an aim to ensure viable commercial fisheries by maintaining stable interannual TACs and quota access for other species.

Further collaborative work with First Nations and fishery stakeholders is planned to refine and fully specify conservation, target, and additional fishery objectives for OYE.

Updates to Operating Models to correct for errors in age-composition likelihood

The 4 operating models from the 2019 rebuilding evaluation (Cox et al. 2020) were updated to correct for an error in the age-composition likelihood (Tables 3-4). Although the model notation was correctly described in Cox et al. (2020), it was incorrectly implemented in Template Model Builder (TMB, Kristensen et al. 2016) code used for model fitting. After correction of the age-composition likelihood, the main effect was a slight reduction in estimates for natural mortality, F_{MSY} and MSY across all 4 operating model scenarios (Fig. 3). New data was not added as part of the operating model update in the current SR, and therefore stock status estimates for OYE still reflect spawning biomass at the end of 2018 as in Cox et al. (2020). New data (e.g., age compositions, survey indices, catch) for 2019-2023 will be incorporated into the next operating model update planned for completion in 2025/26.

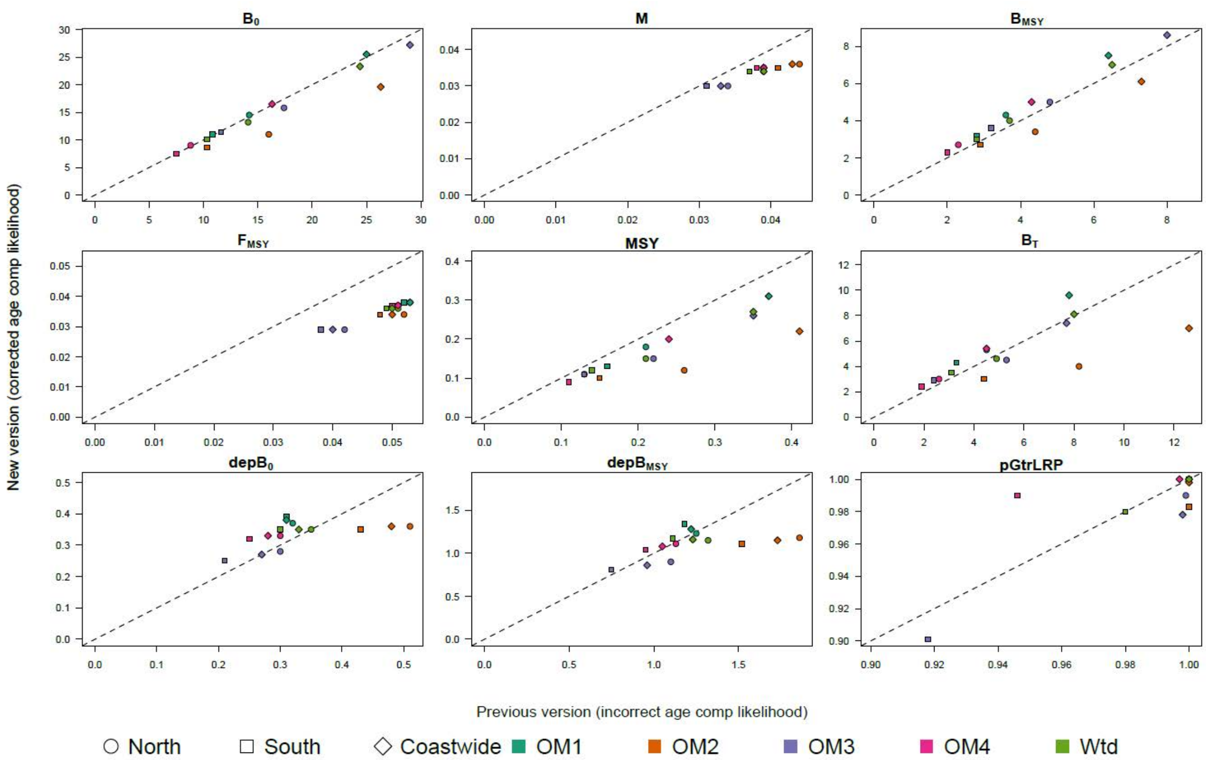

Figure 3. Comparison of biological parameter and management reference point Maximum Likelihood Estimates (MLEs) for revised operating models with corrected age composition likelihood (y-axis) and original operating models shown in Cox et al. (2020). The main change in the revised OMs was a slight reduction in estimates for natural mortality, F_{MSY} and MSY across all 4 operating model scenarios.

Closed-loop simulations

We use a closed-loop simulation approach for testing harvest management procedures, which is well documented in the literature (e.g., see references in Cox and Kronlund (2008)). The approach proceeds as follows (adapted from Cox et al. (2010)):

1. Define a range of alternative management procedures (MPs) defined by (i) data types and precision, (ii) assessment methods for establishing stock status, (iii) harvest control rules for setting base catch limits.

2. Specify operating models (OMs) to enable simulation of alternative plausible scenarios for data generation mechanisms and OYE population responses to fishing. This step involves fitting operating models to available data to estimate model parameters consistent with the stock history and structural assumptions of OM scenarios. Such a process is termed conditioning. For the current OYE management strategy, we use the 4 operating model scenarios developed in Cox et al. (2020) that were fit with data up to 2018 (Table 3) and project these forward to 2022 using the catch data from 2019-2021 and 2022 TAC.

3. Project OYE stock dynamics and fishery harvesting forward from 2022 state to 2081 for each management procedure under each alternative OM scenario. Each year of the projection involves the following steps:

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

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

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

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

   e. Return to Step 3a until final projection year; and

   f. Repeat Steps 3a–f for 100 independent replicate simulations.

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

Steps 3a-e use the operating models that were identified in Step 2 to simulate the state of the population over time and generate data that will be collected in the future. Data simulated by the operating models in projections are generally the fishery and survey data that are currently being accumulated by sampling programs. Note that we also simulate HBLL index data for 2022 as these data were not available, while observed survey indices are used prior to 2022. Here, we only consider empirical MPs that use simple running averages of survey indices of abundance for the harvest control rule (i.e., there is no stock assessment model fitting each year).

Each management procedure component in steps 3a-d requires a particular set of choices. For a given MP, choices include: i. the assessment data (e.g., what survey indices are used); ii. the assessment method (e.g., the number of years used in the running average of indices); and iii. the form of the harvest control rule (e.g. Cox et al. 2010).

Each choice affects fishery performance and are therefore the main focus of management strategy evaluation (rather than focusing exclusively on fitting a single ‘best’ model to the data). Details are given in the sections below on the alternative OYE management procedures considered and the performance measures used to compare them.

Management procedures

The TWG requested that new MPs developed for OYE would establish 2-year TACs using an empirical index-based management procedure. The rationale for a 2-year TAC is that the hard bottom longline (HBLL) stratified random survey index for Outside Yelloweye abundance (Cox et al. 2020) occurs every other year (i.e., biennially) in northern and southern survey areas (Fig. 4). Furthermore, the use of 2-yr TACs provides greater certainty for short-term planning and reduces costs associated with meetings and reporting compared to updating TACs every year. We refer to the new empirical MPs as HBLL MPs hereafter.

We also run the interim index MP (idxSmuv) from Cox et al. (2020) that has been used to set TACs from 2020-2022. This uses an empirical assessment of trends in the HBLL and International Pacific Halibut Commission (IPHC) Fishery Independent Setline Survey (FISS) indices to adjust TACs up or down relative to previous year's TAC with a 2-year moving average to limit interannual variation in TACs (Refer to Cox et al. 2020 for details on idxSmuv).

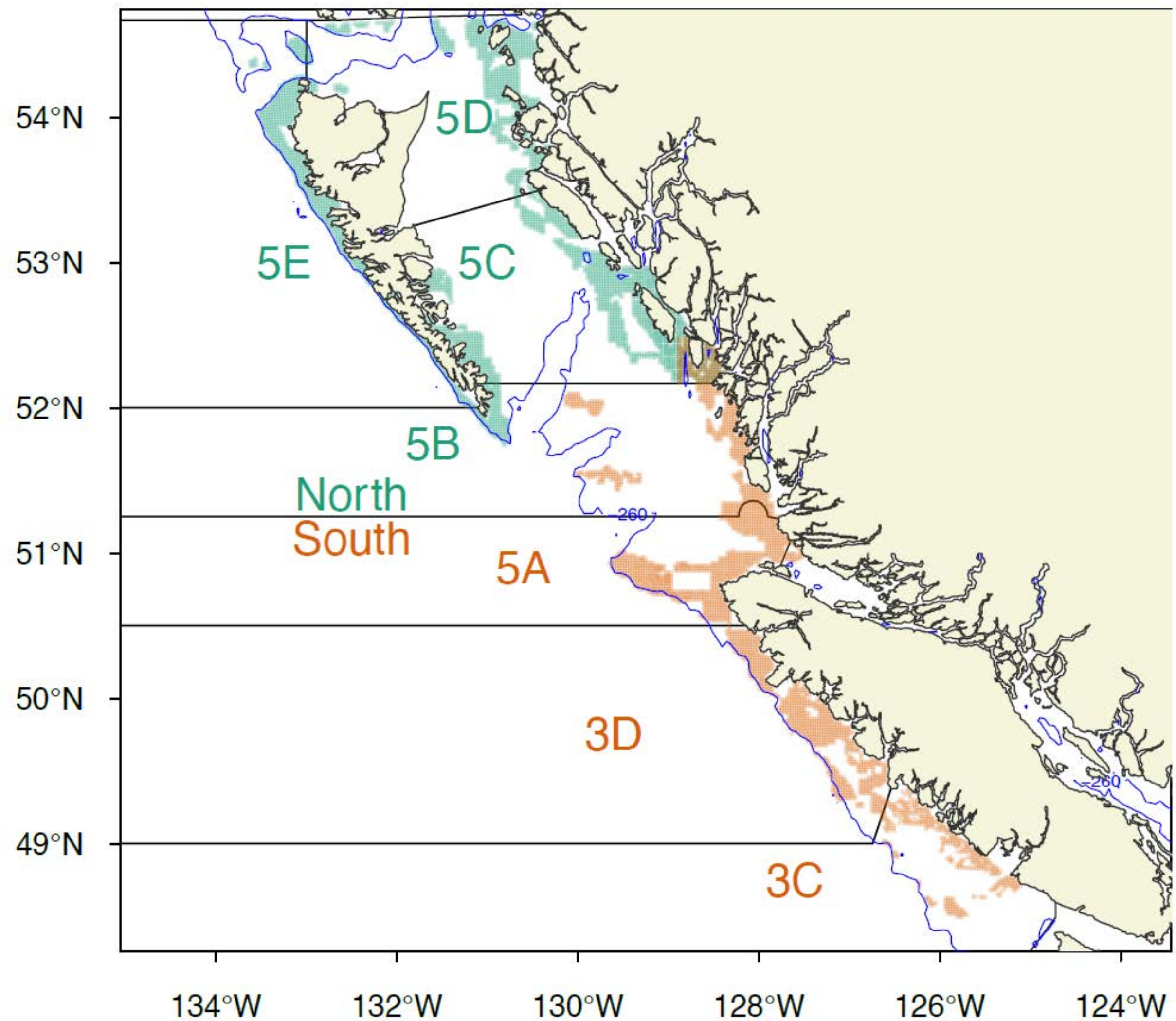

Figure 4. Map of BC groundfish major management areas used to bound the North Outside Yelloweye Stock in areas 5BCDE (green) and the South Outside Yelloweye Stock in areas 3CD5A (orange). The HBLL northern survey grid (yellow) and southern survey grid (pink) are shown along with 260 m contour lines at the deep end of the depth range for Yelloweye habitats.

Assessment data

The idxSmuv MP uses survey trends (Cox et al. 2020) from both the Outside HBLL stratified survey and IPHC FISS, whereas the HBLL MPs use only on data from the Outside HBLL survey. We did not evaluate new MPs using the IPHC FISS indices of abundance for OYE as assessment data because i) the IPHC FISS is a fixed station survey that is designed for indexing Pacific Halibut and there is some uncertainty about how well this index captures OYE trends in abundance (Cox et al. 2020), and ii) recent changes to IPHC FISS sampling design are expected to increase variability and bias in OYE abundance indices for the South (Doherty and Haggarty 2022).

For the projection period, we assume that annual catches are equal to the annual TACs and that catch is known exactly in the assessments regardless of the method (i.e., there is no under-utilization, unreported catch, or unreported discarding). There is a 1-year lag in the availability of HBLL survey data for use in MPs, since HBLL surveys take place in the summer and the data is not available by fall when TAC updates are completed. For example, the MP used to set 2023 TACs is run in the fall of 2022 using HBLL index data up to 2021.

The southern HBLL survey area includes the South OYE stock area (Groundfish management areas 3CD5A) and a portion of the North OYE stock area in Queen Charlotte Sound (Groundfish management area 5B), while the northern HBLL survey area overlaps with the rest of the OYE North stock area (Groundfish management areas 5BCDE, (Fig. 4). Therefore, there is one biennial HBLL index for the south OYE stock area in 3CD5A, while the north stock area has 2 indices in alternating years: i) an area 5BCDE index, and ii) a Queen Charlotte Sound (5B-QCS) index. Refer to Appendix B in Cox et al. (2020) for more details on generating stratified indices for OYE.

Assessment method: HBLL

The HBLL MPs use an empirical estimate of the hook and line fleet exploitable biomass ($\hat{B}_{HL}$) using a K-year average of survey indices, where K = 3 (n=2 data points for South, n=K data points for North), K = 5 (n=3 data points for South, n=K data points for North), or K = 7 (n=4 data points for South, n=K data points for North). The biomass estimate is derived from survey indices g and a model-averaged catchability as:

$$N_{g,t} = I_{g,t}/\bar{q}_g \tag{1}$$

$$W_{g,m} = \frac{1}{20}\sum_{t=1999}^{2018}\frac{B_{HL,t,m}}{N_{g,t,m}} \tag{2}$$

$$\bar{W}_g = \sum_{m\in\mathbb{O}}\omega_m W_{g,m} \tag{3}$$

$$\hat{B}_{HL,g,t} = \frac{1}{K}\sum_{t'=t\quad 1}^{t\quad K} N_{t',g}\bar{W}_g \tag{4}$$

where $I_{t,g}$ is the survey index of abundance in number of fish per 100 hooks for HBLL survey index g and year t, $N_{t,g}$ are vulnerable numbers of fish for the HBLL survey, and $\bar{q}_g$ is the HBLL catchability coefficient averaged over operating models. The average weight of fish $W_{g,m}$ vulnerable to the HBLL survey is estimated by averaging the ratio of vulnerable biomass to numbers estimated within an operating model m over the last 20 years (1999-2018), while $\bar{W}_g$ is the weighted average of $W_{g,m}$ over the set of operating models $\mathbb{O}$, with weights ω_m of 50% (Base OM), 16.7% (OM 2), 16.7% (OM 3), 16.7% (OM 4). Similarly, the catchability $\bar{q}_g$ uses the same weightings to generate a weighted mean from catchabilities $q_{g,m}$ from the 4 operating models in the north and south.

For example, when setting 2023 TACs in the North using an HBLL MP with a 3-year moving average (K=3) applied in year $t = 2022$, there are observations from odd years from the 5BCDE index and even years from the 5B QCS index. In this case $t^{'} = 2021$ and $t - K = 2019$, in which case exploitable biomass ($\hat{B}_{HL}$) estimates for 2019 and 2021 in 5BCDE and 2020 in 5B QCS are used for the assessment.

In the south there is only 1 HBLL survey index (i.e., g=1) used by the empirical assessment with indices only available in even years and biomass estimates are:

$$\hat{B}_{HL,t} = \frac{1}{n} \sum_{i=0}^{n\quad 1} N_{t^* \quad 2i} \bar{W} \tag{5}$$

where t^* = $t - 2$ when t is an even year and t^* = $t - 1$ when t is an odd year.

For example, when setting 2023 TACs in the South using an HBLL MP with a 3-year moving average (K=3, n=2) applied in year $t = 2022$, there are only observations for even years from the 5A3CD index. In this case $t^* = 2020$ and exploitable biomass ($\hat{B}_{HL}$) estimates for 2018 and 2020 from 5A3CD are used for the assessment.

Since there are two HBLL survey indices in the North (i.e., g=1,2) used by the empirical assessment, biomass estimates are a weighted mean according to the inverse survey variances:

$$\rho_g = \frac{1}{\log(\tau_g^2 + 1)} / \sum_{j=1}^{2} \frac{1}{\log(\tau_j^2 + 1)} \tag{6}$$

where the ρ_g survey weighting is calculated using standard Cochran (1977) estimators of survey CVs τ_g of 0.10, 0.23, and 0.13 for indices in 5BCDE, 5B QCS, and 5A3CD, respectively.

Assessment method: idxSmuv

The idxSmuv assessment estimates the proportional change in biomass via a simple biomass trend estimator derived from a weighted combination of HBLL and IPHC survey indices. The trend-based approach assumes that survey catchabilities remain constant over time, but otherwise are unknown.

An OYE weighted biomass trend index ($\Delta\hat{B}_t$) is estimated as the weighted proportional change in stock biomass from the most recent survey indices ($I_{g,t_{2,g}}$, $I_{g,t_{1,g}}$), weighted by the inverse-variances (ρ_g, as in eqn. 6)

$$\hat{B}_t = \sum_{g=1}^{n} \rho_g \frac{I_{g,t_{2,g}} \quad I_{g,t_{1,g}}}{I_{g,t_{1,g}}} / \sum_{j=1}^{n} w_j \tag{7}$$

Time subscripts $t_{2,g}$ and $t_{1,g}$ give the most recent (subscript “2”) and second most recent (subscript “1”) index values for survey g with n=3 survey indices in the North (HBLL 5BCDE, HBLL 5B QCS, IPHC North) and n=2 indices in the South (HBLL 5A3CD, IPHC South). The CVs used for weighting IPHC indices are 0.23 for IPHC North and 0.38 for IPHC South indices. The times for estimated trends depend on the survey because Outside HBLL surveys occur every other year, while the IPHC FISS occur every year. Therefore, the HBLL indices are re-used in off years, while a new IPHC FISS index is used every year.

Harvest Control Rules

All HBLL MPs use a typical ‘Hockey Stick’ harvest control rule (HCR) described in the Sustainable Fisheries Framework (DFO 2009). The empirical assessment of stock status ($\hat{B}_{HL}/B_{MSY}$), using

using the weighted operating model B_{MSY} (Table 3), relative to lower ($0.4B_{MSY}$) and upper control points ($0.8B_{MSY}$) is used to determine the target fishing mortality (HCR, Fig. 6) for setting TACs. Target fishing mortality is zero when stock status is estimated below the lower control point, and when stock status is above the upper control point the target fishing mortality is equal to a reference removal rate (e.g., maximum fishing mortality or exploitation rate). The reference removal rates for MPs are tuned to achieve the target objective, such that P(B2081 > TRP) = 50% for weighted performance across OMs. We present MPs using TRPs of $0.8B_{MSY}$, $1.0B_{MSY}$, and $1.2B_{MSY}$ to allow comparison of catch-conservation trade-offs related to the TRP choice. The HCR is run every 2 years to match the frequency of the HBLL surveys to provide 2-year constant TACs.

The idxSmuv MPs (Cox et al. 2020) set TACs by adjusting the previous year's TAC according to the estimated proportional change in stock biomass $\Delta\hat{B}_t$ (Fig. 6), when -50% $\geq$ $\Delta\hat{B}_t leq$ 25%. The maximum TAC increase is capped at 25% and a minimum TAC ($TAC^f loor$) is imposed for $\Delta\hat{B}_t \leq$ -50%. The $TAC^f loor$ is set according to the coastwide catch allocated for FSC fisheries and ceremonial (FSC) fisheries (18.9 t) and research surveys (15.8 t) in the 2019 Integrated Fishery Management Plan (IFMP).

Annual TACs are allocated among fisheries (FSC, commercial, recreational) and research surveys by the DFO groundfish management unit. The commercial sector has clear criteria for allocating annual OYE TAC among the different groundfish sectors for North and South stock areas, while the other fisheries and surveys are allocated coastwide TACs based on forecasted catch (DFO 2022a). For closed-loop simulations, FSC fisheries and research surveys use the same allocations as the 2019 rebuilding evaluation (Cox et al. 2020), while the remainder is distributed among commercial and recreational fisheries according to the mean proportions allocated in the 2021/22 and 2022/23 fishing seasons (Table 5). The FSC allocation is split evenly between the North and South areas in each year, whereas survey catches are allocated to the North or South in proportion to HBLL survey blocks fished in each area.

Catch vs conservation trade-offs for Candidate Target Reference Points

The removal reference rates for HBLL MPs (Fig. 6) using a 3-year average of survey indices were adjusted to achieve long-term biomass targets for alternative TRP choices ($0.8B_{MSY}$, B_{MSY}, $1.2B_{MSY}$) and evaluate the effects on catch. Median annual coastwide TACs over the next 10-years varied between 396 t (217 t in North, 179 t in South) for $0.8B_{MSY}$, 308 t (173 t in North, 135 t in South) for B_{MSY}, and 248 t (140 t in North, 108 t in South) for 1.2_{BMSY} (Fig. 7-8).

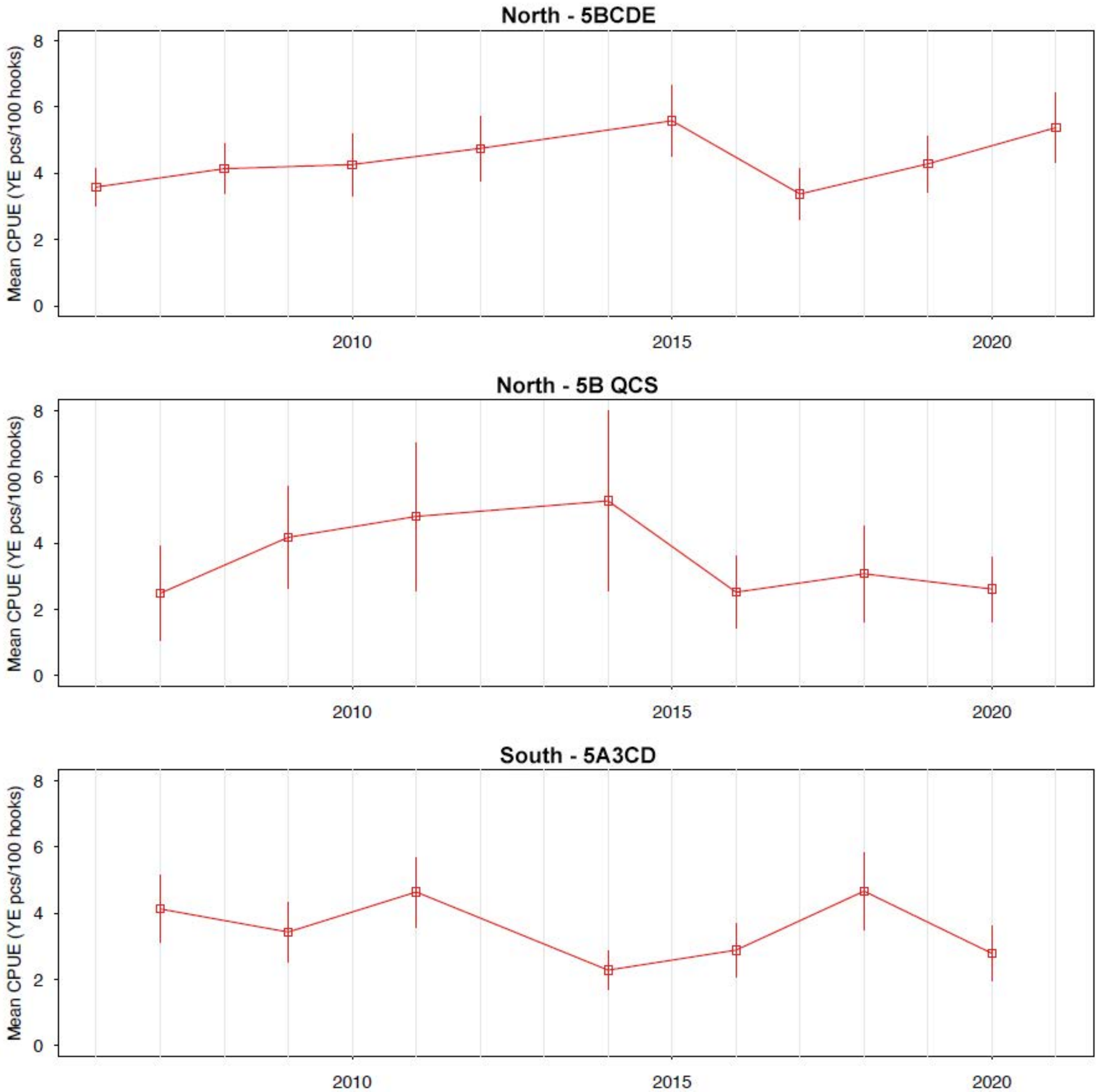

Figure 5. Outside hard-bottom longline (HBLL) survey stratified mean CPUE for North and South Outside Yelloweye stocks from 2006-2021. The top panel shows indices for the North stock for areas 5BCDE from Outside North HBLL survey years (2006-2021), the middle panel shows indices for the North stock for Queen Charlotte Sound (QCS) from the Outside South HBLL survey years (2007-2020), and the bottom panel shows indices for the South stock for areas 5A3CD from Outside South HBLL survey years (2007-2020).

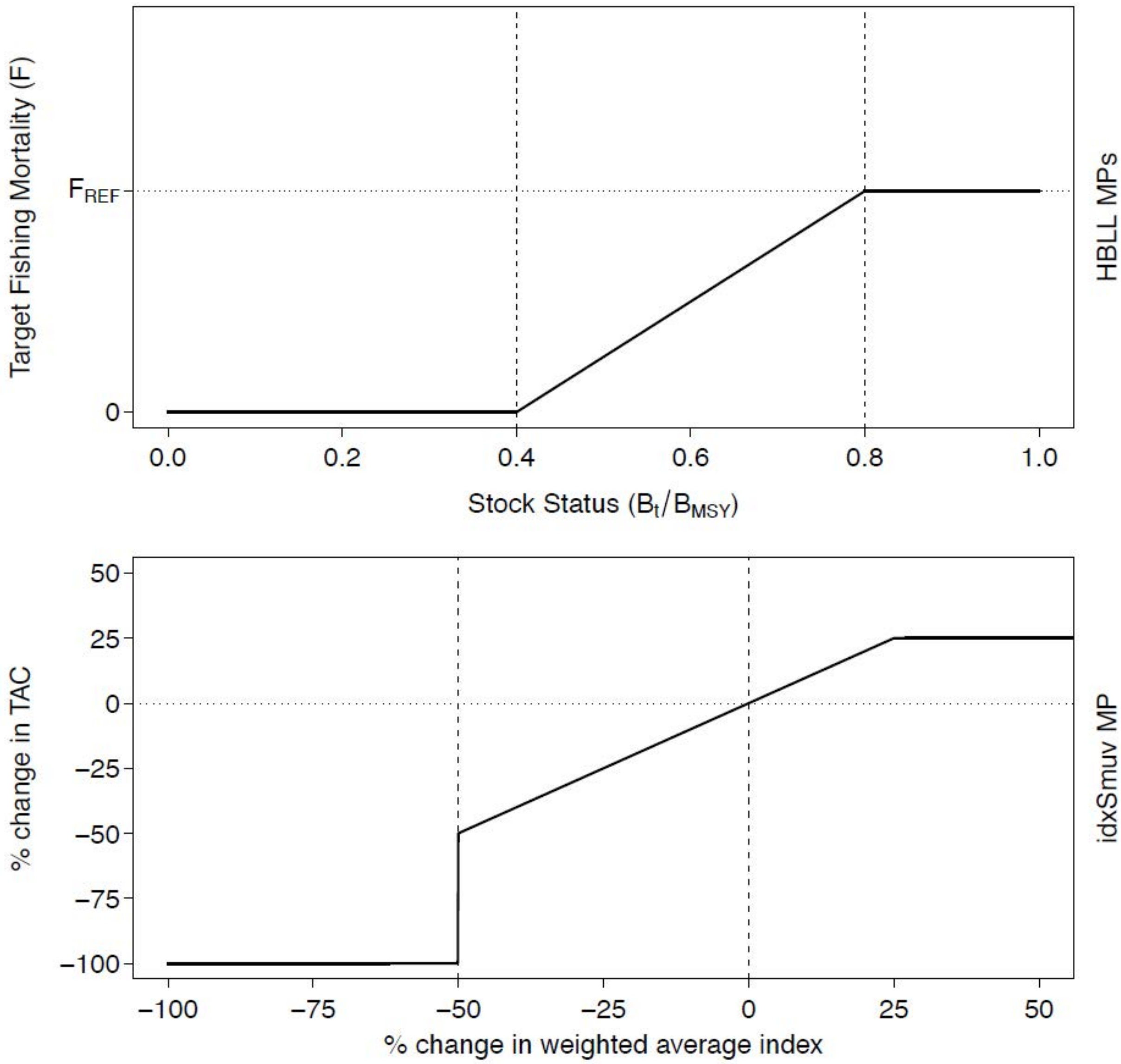

Figure 6. Outside Yelloweye Rockfish harvest control rules for new HBLL MPs (top) and current idxSmuv MP (bottom). The removal rates (F_{REF}) for HBLL MPs are set to achieve either a B_{MSY} TRP (F_{REF}=0.34 in North, F_{REF}=0.36 in South) or a $1.2B_{MSY}$ TRP (F_{REF}=0.27 in North, F_{REF}=0.28 in South). The idxSmuv MP use a 1:1 slope to determine the TAC change in proportion to changes in the survey index with a maximum TAC increase of 25% and fishery closures for a decline in the index greater than 50%.

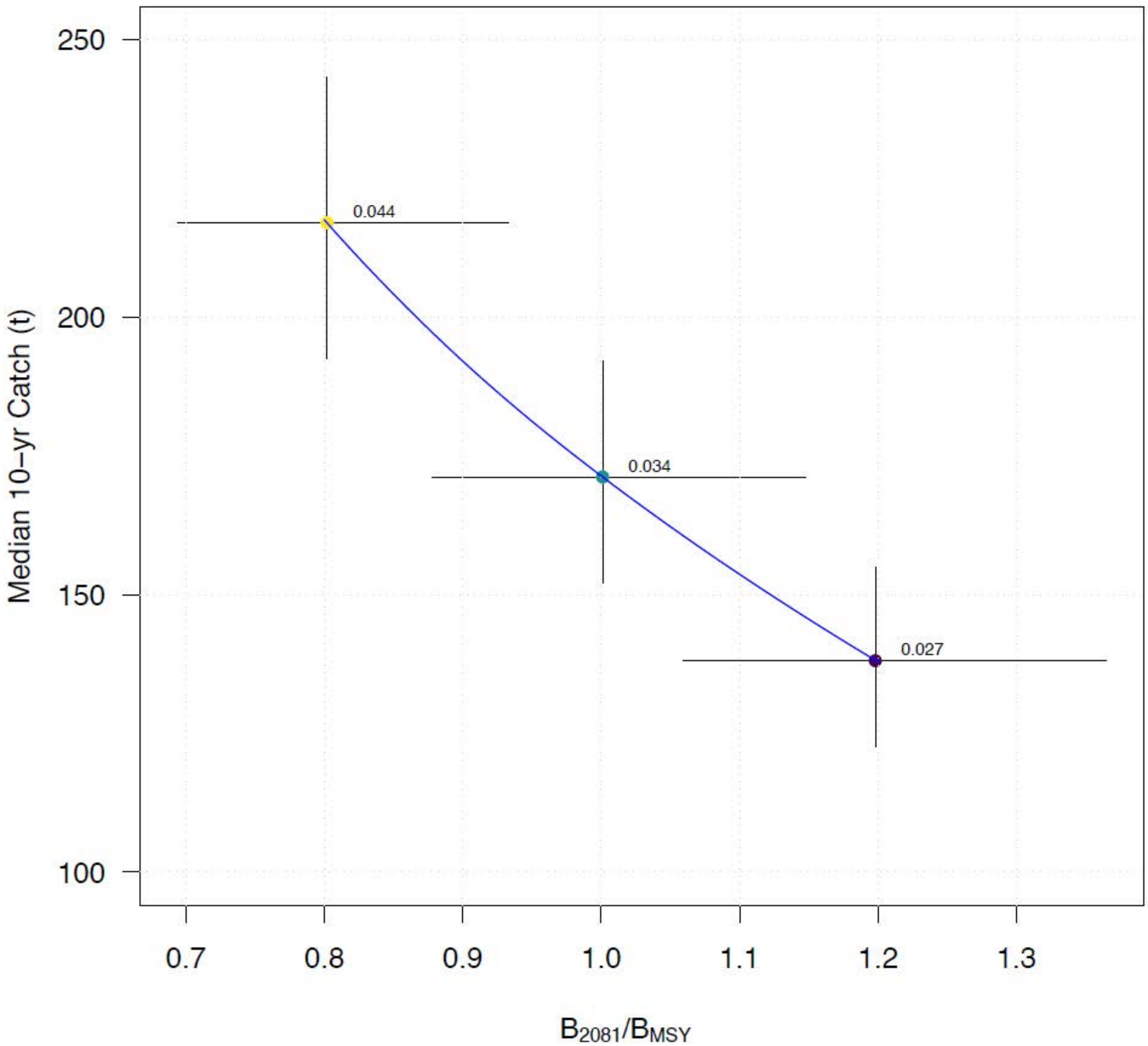

*Figure 7. Median 10-year annual catch and final biomass depletion relative to B_{MSY} at the end of the 59-year projection period (2081) for the **North** from the **HBLL 3YR** simulated management procedures with changing removal reference rates. Dots represents the simulation results for different choices of Target Reference Points ($0.8B_{MSY}$, B_{MSY}, $1.2B_{MSY}$) along with implied catch and removal reference rates (F=0.027, 0.034, 0.044). A spline (blue line) is used to interpolate between simulation results to indicate the catch for different TRP choices between $0.8B_{MSY}$ and $1.2B_{MSY}$. Points indicate medians and error bars represent the central 90% of 100 simulation replicate outcomes.*

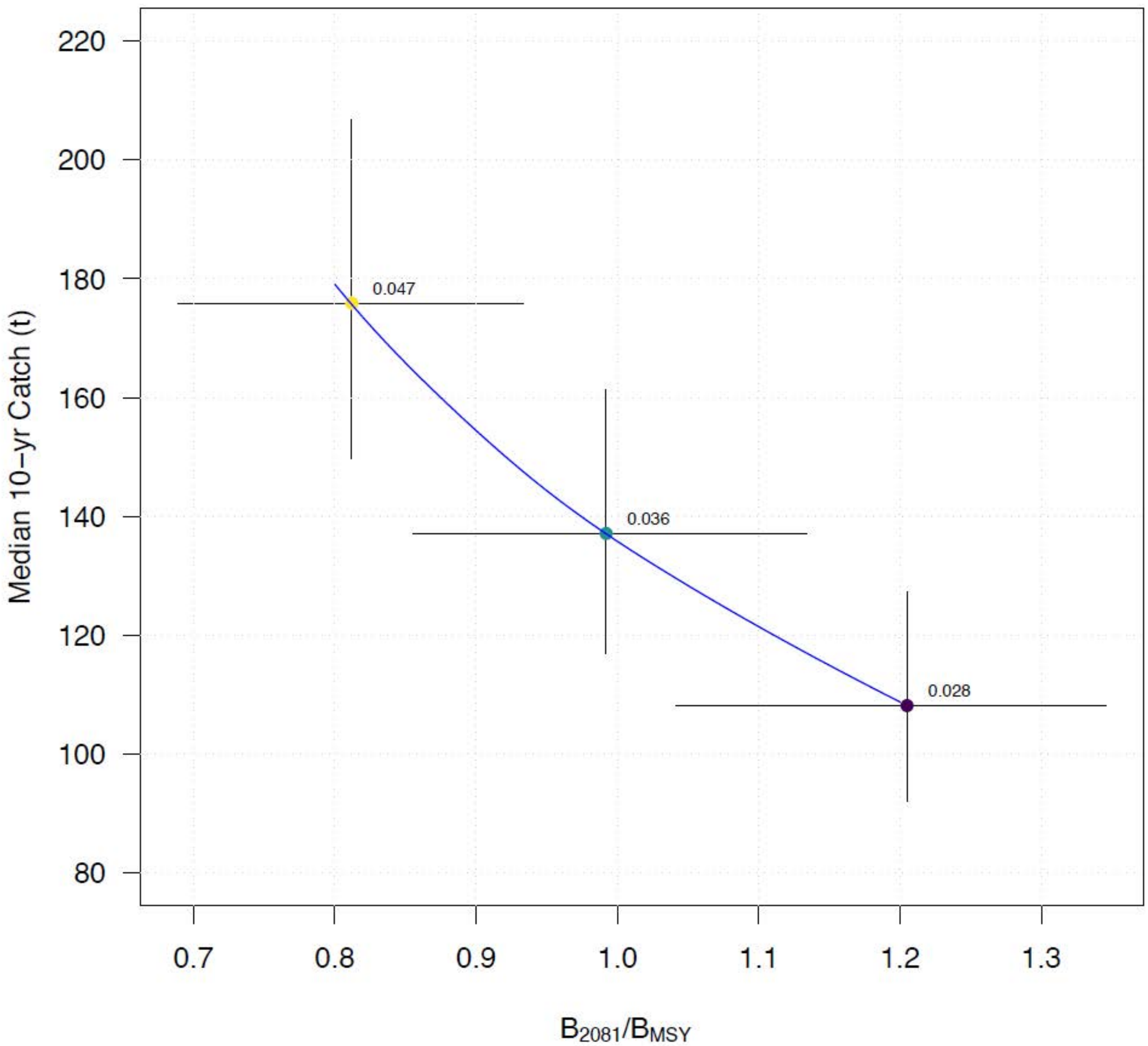

*Figure 8. Median 10-year annual catch and final biomass depletion relative to B_{MSY} at the end of the 59-year projection period (2081) for the **South** from the **HBLL 3YR** simulated management procedures with changing removal reference rates. Dots represents the simulation results for different choices of Target Reference Points ($0.8B_{MSY}$, B_{MSY}, $1.2B_{MSY}$) along with implied catch and removal reference rates (F=0.028, 0.036, 0.047). A spline (blue line) is used to interpolate between simulation results to indicate the catch for different TRP choices between 0.8B_{MSY} and 1.2B_{MSY}. Points indicate medians and error bars represent the central 90% of 100 simulation replicate outcomes.*

Management procedure performance

Evaluating management procedures by simulation requires quantitative performance indicators for each fishery objective. Stock status indicators are all measured using the true operating model spawning stock biomass and, where necessary 1.5 OYE generations (59 years) calculated using the base OM natural mortality estimates of M = 0.035/yr (Table 3). We use the average age of the unfished spawning stock to calculate a generation time (G) of 39 years for OYE (Seber 1997; Cox et al. 2011), i.e.:

$$G = \frac{\sum_{a=1}^{A} a S_a m_a}{\sum_{a=1}^{A} S_a m_a} \tag{8}$$

where maturity at age m_a and survivorship at-age S_a are defined as:

$$m_a = \begin{cases} (1 + e^{-\log 19 \frac{a - a_{50}^{mat}}{a_{50}^{mat} - a_{95}^{mat}}})^{-1} & a > 8 \\ 0 & a \leq 8 \end{cases} \tag{9}$$

$$S_a = e^{-(a-1)M} \tag{10}$$

for an age at 50% maturity $a_{50}^{mat} = 17$ and an an age at 95% maturity $a_{95}^{mat} = 33$

The long-term conservation objective (Table 1) can be stated probabilistically as $P(B_{2081} > LRP) \geq 0.95$ and the target objective can be stated probabilistically as $P(B_{2081} > TRP) \geq 0.50$; to estimate both we simply compare to the proportion of 100 simulation replicates for which these conditions are true (Table 6); that is, operating model spawning biomass in 2081 is greater than the LRP of $0.4B_{MSY}$ and candidate TRPs ($0.8B_{MSY}$, B_{MSY}, $1.2B_{MSY}$), respectively (Fig. 9-11).

Performance statistics calculations for the biomass-based and fishery objectives, as well as other quantities that may be of interest are shown in Table 7. Each statistic is calculated for a simulation replicate and then expected MP performance is summarized as the median or proportion of the 100 simulation replicates (See Table 6 for performance statistic calculations). Performance measures are calculated separately for the 4 OMs for each stock and then weighted to generate one weighted-performance table for North and South stock areas, using the OM weighting schemes established in Cox et al. (2020). The 4 OMs are classified into a “most plausible” base model and three alternatives that are weighted accordingly. The base models are weighted 50% and the alternatives 16.67% for the purpose of evaluating rebuilding procedures and providing a single concise summary of MP performance (as requested by Groundfish Management Unit). These weightings were used in the absence of a preferred weighting scheme in 2020 (Cox et al. 2020). Weightings could be adjusted during future OM development or alternative weighting schemes could be tested in future sensitivity analyses.

All HBLL MPs (HBLL 3 YR, HBLL 5 YR, HBLL 7 YR) achieve conservation and target objectives (Table 7, Fig. 12-13) with similar catch for MPs using the same TRPs (B_{MSY} or $1.2B_{MSY}$). The catch trade-off associated with using a $1.2B_{MSY}$ TRP compared to a B_{MSY} TRP is 59-60 t per year in the first 10 years (32-33 t in North and 27 t in the South), while a $0.8B_{MSY}$ TRP leads to 85-93 t more catch annually than the B_{MSY} TRP (44-47 t in North and 41-46 t in the South). For the north stock, the 3 YR HBLL MP produces a median 10-year TAC of 140 t for a $1.2B_{MSY}$ TRP, 173 t for a B_{MSY} TRP, and 217 t for a $0.8B_{MSY}$ TRP. In the south, the 3 YR HBLL MP produces a median 10-year TAC of 108 t for a $1.2B_{MSY}$ TRP, 135 t for a B_{MSY} TRP, and 176 t for a $0.8B_{MSY}$ TRP.

The different moving averages for the HBLL MPs (3 YR, 5 YR, 7 YR) had little effect on catch. HBLL MPs with a B_{MSY} TRP have median 10-year TACs of 171-173 t in the North and 130-135 t in the South, while those using a $1.2B_{MSY}$ have median 10-year TACs of 139-140 t in the North and 103-108 t in the South. Differences in annual catch variability are driven by the number of survey indices used by empirical biomass estimator ($\bar{B}_{HL}$) in each MP. MPs using 3-year averages of survey indices (HBLL 3YR) are more responsive to variation in survey index data, producing the highest annual average annual catch variability (5-7% in North for different TRPs, 9-10% in South). In contrast the MPs that use 5-year (HBLL 5 YR) or 7-year (HBLL 7YR) average survey indices are less responsive to the newest survey index, resulting in lower long-term catch variability and lower probabilities of exceeding annual TAC changes of 30 t or 20%. The trade-off for the lower catch-variability is that the longer moving averages will be slower to respond to changes in the survey indices and possibly lead to slightly longer recoveries should the stock fall below B_{MSY}, although this was barely noticeable in biomass trajectories for HBLL 3 YR, 5 YR, and 7 YR MPs (Fig. 12-13). The number of years used to average survey indices (3 YR, 5 YR, 7 YR) has no effect on the long-term median catch over the 59-year projection period and therefore small differences in the 10-year catch shown in Table 7 are driven by historical HBLL indices from 2014-2021. For example, the HBLL 7 YR MP produces lower catch in the South since it includes the 2014 HBLL index observation, which is the lowest data point in the time series (Fig. 5).

The idxSmuv MP for the North has similar conservation performance to the HBLL MPs using a B_{MSY} with lower catch (144 t). It narrowly fails to meet the long-term conservation objective as it only achieves a 49% probability of biomass exceeding B_{MSY} in 2081 (Table 7, Fig. 9, 10, 14). The idxSmuv MP for the North has greater conservation performance than all HBLL MPs with a 95% probability of biomass exceeding B_{MSY} in 2081 and median depletion of $1.65B_{MSY}$ in 2081; however, it generates much lower catch with a median 10-year TAC of 89 t. The current idxSmuv MP and all the new HBLL MPs result in catch distributions in projections that are much lower than the high historical catch period from 1986-2005 (See Appendix A Figures A.1-A.5 for historical and projected biomass depletion and catch).

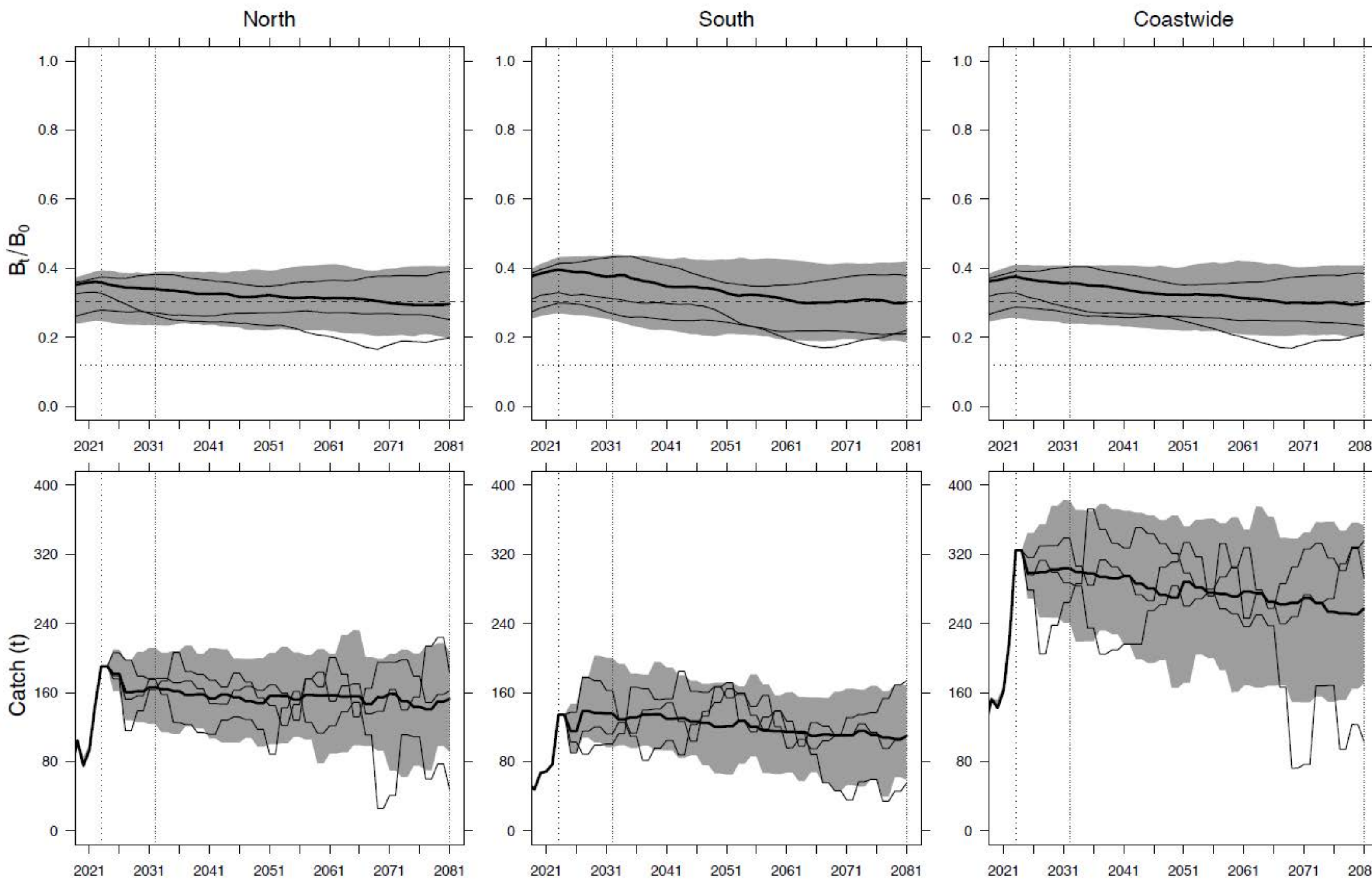

*Figure 9. Weighted projection distributions for spawning biomass depletion (i.e., B_t/B_0) (top) and total catch (bottom) for 4 operating models from **2021-2081** in the **North, South, and Coastwide** from the **HBLL 3YR** simulated MP tuned to a $\mathbf{B_{MSY}}$ **TRP**. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical dashed line indicates start of projection period (2023), while vertical dotted lines indicate short-term (10 years) and long-term (59 years) projection periods used to generate MP performance metrics.*

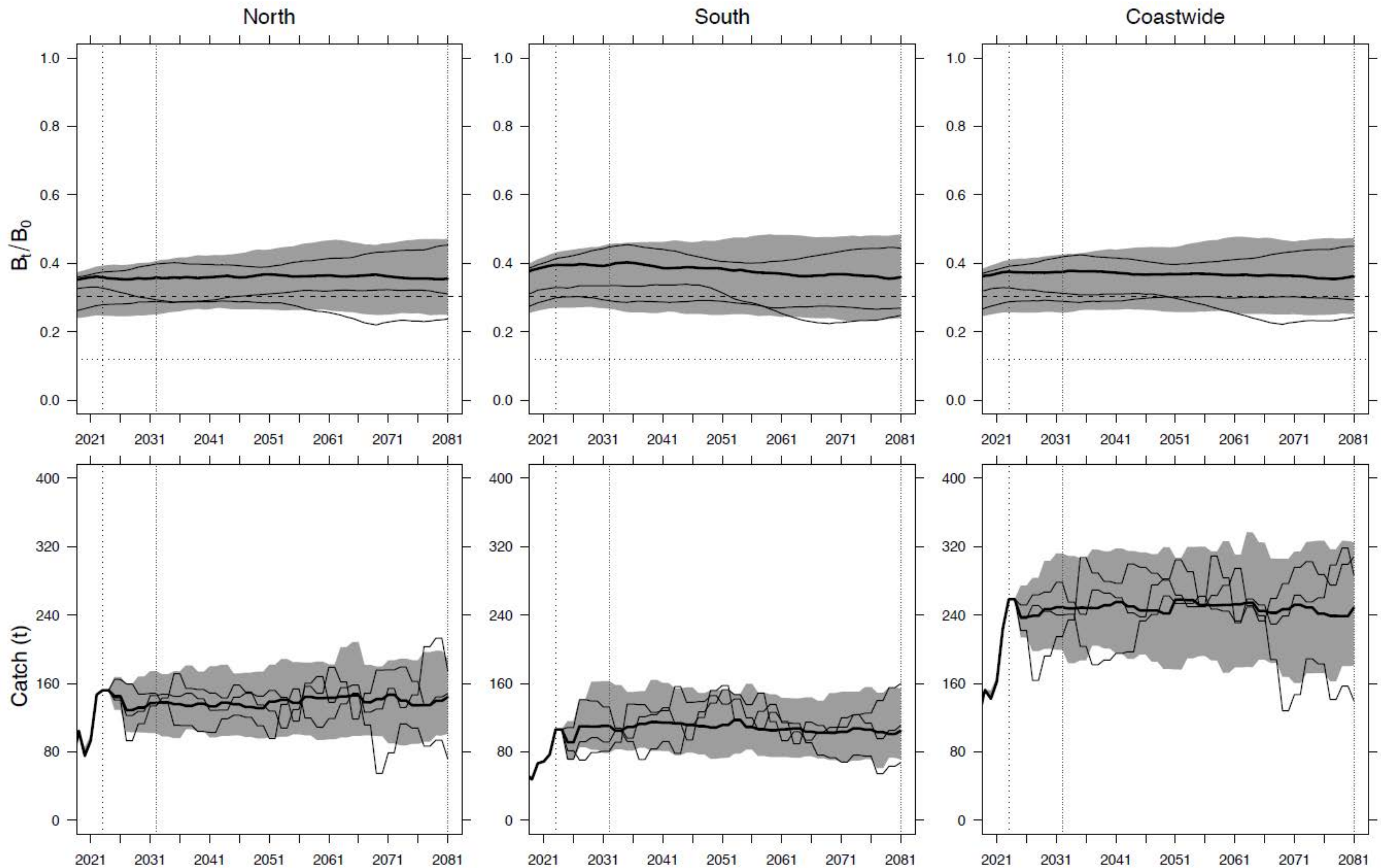

Figure 10. Weighted projection distributions for spawning biomass depletion (i.e., B_t/B_0) (top) and total catch (bottom) for 4 operating models from ***2021-2081*** *in the* ***North, South, and Coastwide*** *from the* ***HBLL 3YR*** *simulated MP tuned to a* ***1.2B_{MSY} TRP****. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical dashed line indicates start of projection period (2023), while vertical dotted lines indicate short-term (10 years) and long-term (59 years) projection periods used to generate MP performance metrics.*

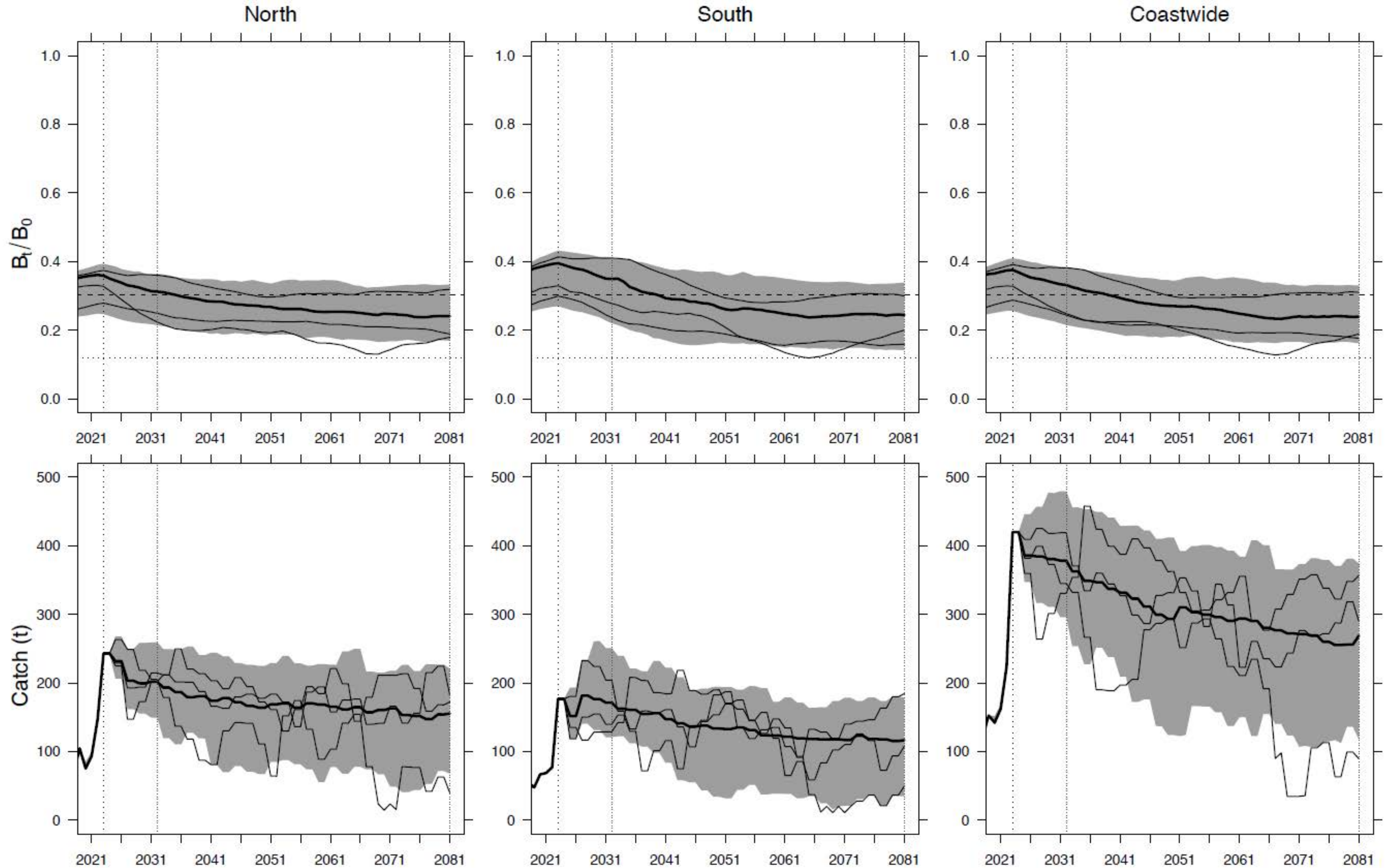

Figure 11. Weighted projection distributions for spawning biomass depletion (i.e., B_t/B_0) (top) and total catch (bottom) for 4 operating models from ***2021-2081*** *in the* ***North, South, and Coastwide*** *from the* ***HBLL 3YR*** *simulated MP tuned to a* ***0.8B_{MSY} TRP****. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical dashed line indicates start of projection period (2023), while vertical dotted lines indicate short-term (10 years) and long-term (59 years) projection periods used to generate MP performance metrics.*

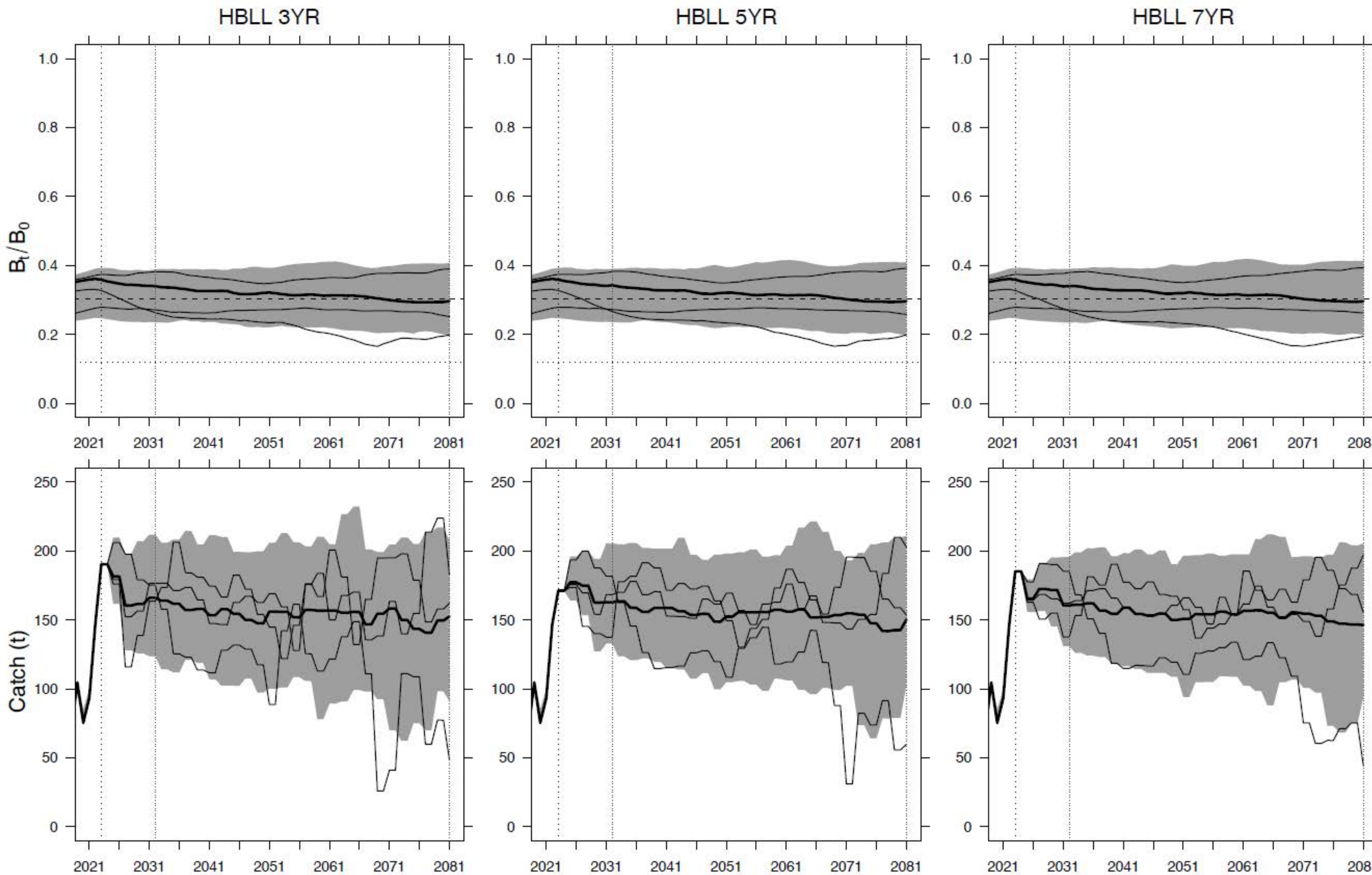

Figure 12. Weighted projection distributions for spawning biomass depletion (i.e., B_t/B_0) (top) and total catch (bottom) for 4 operating models in the ***North*** *from the simulated MPs (**HBLL 3YR, HBLL 5YR, HBLL 7YR**) with **TRP of B_{MSY}**. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical dashed line indicates start of projection period (2023), while vertical dotted lines indicate short-term (10 years) and long-term (59 years) projection periods used to generate MP performance metrics.*

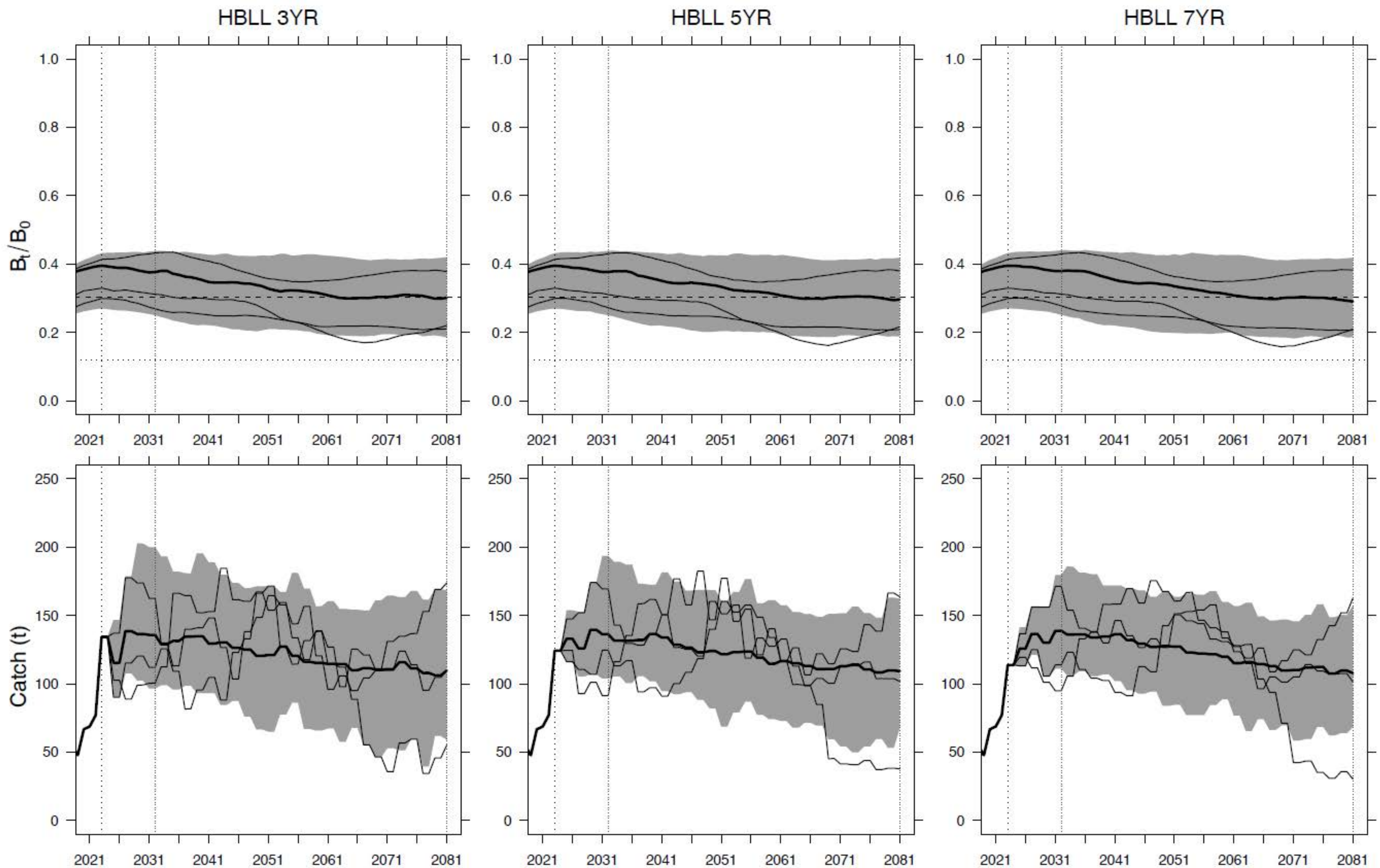

Figure 13. Weighted projection distributions for spawning biomass depletion (i.e., B_t/B_0) (top) and total catch (bottom) for 4 operating models in the ***South*** *from the simulated MPs (**HBLL 3YR, HBLL 5YR, HBLL 7YR**) with **TRP of B_{MSY}**. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical dashed line indicates start of projection period (2023), while vertical dotted lines indicate short-term (10 years) and long-term (59 years) projection periods used to generate MP performance metrics.*

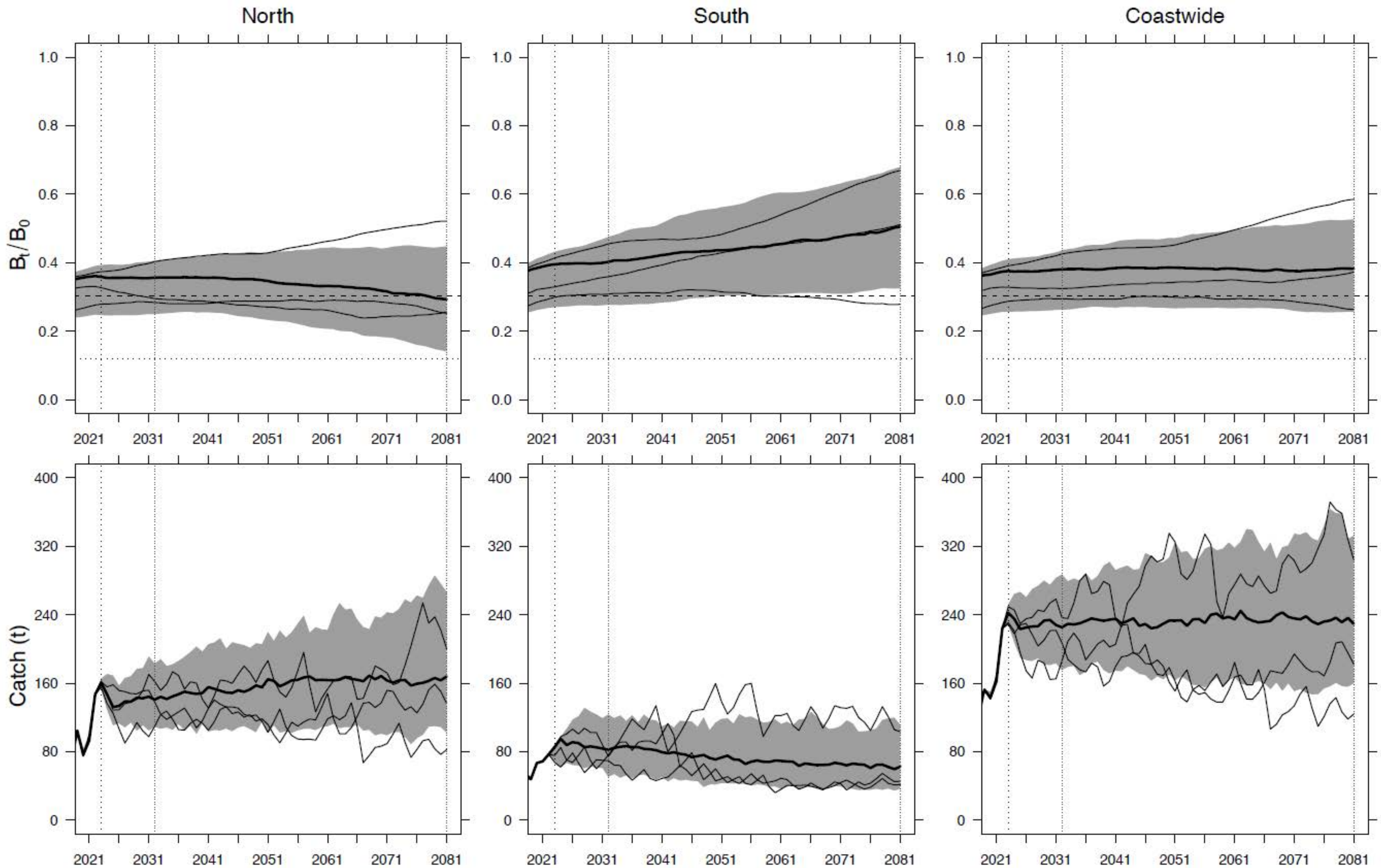

*Figure 14. Weighted projection distributions for spawning biomass depletion (i.e., B_t/B_0) (top) and total catch (bottom) for 4 operating models from **2021-2081** in the **North, South, and Coastwide** from the **idxSmuv** simulated management procedure. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical dashed line indicates start of projection period (2023), while vertical dotted lines indicate short-term (10 years) and long-term (59 years) projection periods used to generate MP performance metrics.*

Research Priorities and Timelines for Outside Yelloweye Management System

The next operating model update and assessment of stock status will begin in 2024/25 with plans for completion in 2025/26, after which there will be a new evaluation of management procedures via closed-loop simulation. Simulation results will be used to inform the selection of an MP for application to the fishery beginning in the 2027/28 fishing year until the next cycle of operating model and MP updates. In the interim, other key priorities for OYE management research are:

1. broader consultation with stakeholders and First Nations groups on OYE management objectives;
2. the impact of large-scale marine spatial planning on OYE management plan;
3. evaluate the utility of age sampling data (e.g., sample size, sample frequency, sampling allocation) from surveys, commercial fisheries (no age data since 2001), and recreational fisheries (no age data);
4. assess the proportion of OYE habitat in HBLL survey strata to identify potential sources of bias and alternative strata weightings (e.g., Recommendation 4 in Doherty et al. 2019; Forrest et al. 2020); and
5. evaluate how non-directed OYE catch rates associated with alternative TRPs might affect quota access for other target species (e.g., Pacific Halibut).

Research priorities 1 and 2 are discussed in more detail below.

Management objectives for OYE

Further consultations with all stakeholders and First Nations in BC are required to explore management objectives for OYE. Additional work on alternative target reference points may follow future consultations if there is interest in adjusting the target objective. There may also be interest in finer-scale spatial objectives or population age-structure objectives that could be considered. It would be beneficial to identify any changes to OYE management objectives prior to the next operating model update, to allow sufficient time for operating model changes, should they be required to evaluate new management objectives.

Accounting for fisheries closures in OYE management plan

Rockfish conservation areas implemented in 2007 have closed fisheries in up to 20% of Outside Yelloweye Rockfish habitat in British Columbia (Yamanaka and Logan 2010). In recent years, additional fisheries closures have been implemented in southern Haida Gwaii as part of the Gwaii Haanas National Marine Conservation Reserve and Haida Heritage Area with more closures expected in the future as part of large-scale marine planning underway for the Northern Shelf Bioregion. It remains unclear how these areas will affect assessment and management performance of OYE. For example, the HBLL survey sampling frame was designed to cover OYE habitat in BC to provide coastwide abundance indices, and more recently a post-stratification approach was used to generate indices for North and South stocks (Doherty et al. 2019; Cox et al. 2020). If fisheries closures also restrict scientific surveys, this will bias future indices of abundance for OYE, whereby new data collection will only represent abundance trends for OYE that are available to commercial fisheries harvest (i.e., ‘Harvestable portion of stock’) and will not capture OYE abundance trends in closed areas that are no longer fished or only have FSC fishing (i.e., ‘non-harvestable portion of the stock’).

Future work could simulation test different MPs on the harvestable and non-harvestable portions of OYE stocks. Performance metrics could be generated for a combination of the harvestable and non-harvestable stocks, and alternative reference points, to evaluate consequences of marine spatial planning for OYE management. This approach might involve developing new OYE operating models at finer spatial scales to provide spatial estimates of biomass and population dynamics for OYE operating models in closed and open fishing areas.

Conclusions

This Science Response identifies new candidate management objectives and empirical management procedures (HBLL MPs) that meet key policy for DFO's Sustainable Fisheries Framework (SFF), specifically the Precautionary Approach (PA) and Fish Stock Provisions (FSP) policies (Compliance Summary Table 1). This includes clarifying rebuilding objectives, rebuilding plan exit criteria, and the 2018 stock status, which indicate a rebuilding plan is not currently required for OYE.

HBLL MPs were developed and simulation tested using the Outside HBLL survey index with different choices for moving averages (3 YR, 5 YR, 7 YR), all of which meet OYE objectives with similar performance for the candidate TRPs ($0.8B_{MSY}$, B_{MSY}, $1.2B_{MSY}$). The results of the closed-loop simulation can be used to inform the selection of an MP to set TACs for 2023/24-2026/27 fishing seasons. A candidate TRP of B_{MSY} was recommended by the OYE Science Response Technical Working Group (SR TWG) following an evaluation of catch vs conservation trade-offs associated with alternative TRPs ($0.8B_{MSY}$, B_{MSY}, $1.2B_{MSY}$).

Contributors

Roles (A:Author, R:Reviewer, SC:Steering Committee TWG:Technical Working Group) and tasks (A:analysis, D:data acquisition, I:idea generation, W:writing) for Science Response contributors.

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Tables

Table 2. Management objectives for Outside Yelloweye Rockfish Management Plan. Conservation objectives are adapted from Cox et al. 2020.

General intent	Current or aspirational objective	Measure	Probability	Time	Performance Statistic
Avoid low abundance where recruitment could be impaired (DFO)	Long-term conservation (C.1) Maintain spawning stock biomass (B) out of the critical zone (i.e., above the LRP of $0.4B_{MSY}$), where B_{MSY} is the operating model biomass at MSY, with a very high (95%) probability, measured after 1.5 generations.	Long-term spawning biomass below LRP	Very high (95%)	1.5 gen (59 yrs)	Proportion of simulation trials where B > LRP at the end of the 1.5 generation projection period
Adjust level of precaution depending on stock status (DFO SFF Table 1)	Short-term conservation (C.2) When the spawning stock biomass (B) is between the LRP ($0.4B_{MSY}$) and USR ($0.8B_{MSY}$), limit the probability of decline over the next 10 years from very low (5%) at the LRP to moderate (50%) at the USR. At intermediate stock status levels, define the tolerance for decline by linearly interpolating between these probabilities.	Short-term spawning biomass status and trend	Probability of decline Very Low (5%) at LRP to Neutral (50%) at USR	10 yrs	Proportion of simulation trials where B after 10 years is less than B at the beginning of projection period
Identify rebuilt state and maintain stock status in desirable range (i.e., 'Healthy Zone') (DFO SFF, DFO Fish Stock Provisions)	Long-term target (T.1) Maintain spawning stock biomass (B) in the healthy zone (i.e., above the TRP of B_{MSY}), where B_{MSY} is the operating model biomass at MSY, with a neutral (50%) probability of further decline, measured after 1.5 generations.	Spawning biomass above TRP	Probability of decline Neutral (50%) at the TRP	1.5 gen (59 yrs)	Proportion of simulation trials where B > TRP at the end of the 1.5 generation projection period

General intent	Current or aspirational objective	Measure	Probability	Time	Performance Statistic
Provide stable inter-annual TACs (Fishing objective)	Variability Fishery Objective (F.1) Avoid large inter-annual changes in TAC.	Absolute (up or down) annual change in TAC	NA	2023-2032	Proportion of simulation trials where maximum absolute annual change in TAC is greater than (20%) or up to (30 t)
Maintain quota access for other species (Fishing objective)	TAC Fishery Objective (F.2) Maintain catch above a threshold.	Minimum annual TAC	NA	2023-2032	Proportion of simulation trials where minimum TAC is less than 2017 catch (200 t Coastwide [a], 125 t in North, 75 t in South)

[a] based on 2017 catches (123 t in North, 75 t in South)

Table 3. MLE estimates with 95% CIs() for biological parameter and management reference point estimates for operating models (OMs), by area. Spawning Stock Biomass (B) and MSY units in kt. Values used to estimate current status (B_{2018}, B_{2018}/B_{MSY}, P>LRP, P>USR) are approximated from posterior samples from a multivariate normal distribution using the covariance matrix from MLEs.

Area	OM	Unfished Biomass		Natural Mortality		Reference Points			Current Status (2018)					
		B0	95% CI	M	95% CI	B_{MSY}	F_{MSY}	MSY	B_{2018}	95%CI	B_{2018}/B_{MSY}	95% CI	P(B_{2018} > LRP)	P(B_{2018} > USR)
Coastwide														
	baseOM	25.5	22.1 - 29.6	0.035	0.034 - 0.037	7.5	0.038	0.31	9.9	6.2 - 15	1.29	0.78 - 2.17	1	0.96
	om2	19.6	16.4 - 23.5	0.036	0.034 - 0.037	6.1	0.034	0.22	7.2	3.8 - 13.2	1.17	0.60 - 2.33	1	0.87
	om3	27.2	24 - 30.9	0.030	0.030 - 0.031	8.6	0.029	0.26	7.6	3.9 - 13.9	0.88	0.45 - 1.76	0.99	0.61
	om4	16.5	14.4 - 18.9	0.035	0.034 - 0.037	5.0	0.037	0.20	5.5	3.3 - 8.7	1.09	0.65 - 1.91	1	0.87
	wt	23.3	20.2 - 27	0.034	0.033 - 0.036	7.0	0.036	0.27	8.3	4.9 - 13.5	1.17	0.67 - 2.08	1	0.87
North														
	baseOM	14.5	12.8 - 16.6	0.035	0.034 - 0.037	4.3	0.038	0.18	5.4	3.4 - 8.6	1.24	0.73 - 2.16	1	0.96
	om2	11	9.3 - 13	0.036	0.034 - 0.037	3.4	0.034	0.12	4.1	2.3 - 7.2	1.18	0.63 - 2.29	1	0.90
	om3	15.8	14.1 - 17.8	0.030	0.030 - 0.031	5.0	0.029	0.15	4.5	2.6 - 7.7	0.90	0.49 - 1.69	1	0.66
	om4	9	8 - 10.1	0.035	0.034 - 0.037	2.7	0.037	0.11	3.0	2.0 - 4.6	1.11	0.67 - 1.89	1	0.91
	wt	13.2	11.6 - 15.1	0.034	0.033 - 0.036	4.0	0.036	0.15	4.6	2.9 - 7.6	1.15	0.66 - 2.06	1	0.89
South														
	baseOM	11	9.3 - 13	0.035	0.034 - 0.036	3.2	0.038	0.13	4.3	2.3 - 7.7	1.33	0.68 - 2.51	1	0.92
	om2	8.6	7.1 - 10.5	0.035	0.034 - 0.037	2.7	0.034	0.10	3.0	1.3 – 7.0	1.11	0.45 - 2.66	0.99	0.77
	om3	11.4	9.9 - 13.1	0.030	0.030 - 0.031	3.6	0.029	0.11	2.9	1.2 – 7.0	0.83	0.32 – 2.00	0.91	0.52
	om4	7.5	6.4 - 8.8	0.035	0.034 - 0.036	2.3	0.037	0.09	2.4	1.1 - 4.8	1.05	0.48 - 2.20	1	0.75
	wt	10.1	8.6 - 11.9	0.034	0.033 - 0.035	3.0	0.036	0.12	3.5	1.8 – 7.0	1.16	0.55 - 2.40	0.98	0.80

Table 4. Estimated observation model (OM) standard errors for different operating models for HBLL survey, IPHC FISS, commercial longline (LL), and commercial trawl index and age composition data for North (N), South (S), and Queen Charlotte Sound (QCS).

	Biomass index observation errors					Age composition observation errors						
OM	**HBLL_N**	**HBLL_QCS**	**HBLL_S**	**IPHC_N**	**IPHC_S**	**HBLL_N**	**HBLL_QCS**	**HBLL_S**	**IPHC_N**	**IPHC_S**	**LL**	**TRAWL**
North												
base	0.20	0.30	-	0.24	-	0.31	0.47	-	0.32	-	0.58	0.57
OM2	0.21	0.30	-	0.26	-	0.33	0.49	-	0.35	-	0.59	0.51
OM3	0.20	0.30	-	0.23	-	0.34	0.49	-	0.36	-	0.60	0.52
OM4	0.23	0.31	-	0.25	-	0.31	0.47	-	0.32	-	0.58	0.57
South												
base	-	-	0.26	-	0.40	-	-	0.40	-	0.48	0.58	-
OM2	-	-	0.25	-	0.38	-	-	0.40	-	0.51	0.59	-
OM3	-	-	0.25	-	0.38	-	-	0.41	-	0.52	0.60	-
OM4	-	-	0.25	-	0.36	-	-	0.40	-	0.48	0.58	-

Table 5. Annual TACs for longline, trawl and recreational sectors from 2021/22-2022/23 fishing seasons (DFO IFMPs 2021, 2022) and mean proportions used to allocate annual surplus TAC (after removal of 18.9 t for FSC and 15.8 t for surveys) in simulations for the 3 fishing fleets in operating models. Recreational TAC is not allocated spatially in IFMPs and is assumed to be allocated evenly among North and South for simulation work.

Area	**Fisheries**	**2021**		**2022**		**Mean %**
		t	**%**	**t**	**%**	
North	longline	73	79	80	80	79.2
	recreational	16.6	18	17.1	17	17.5
	trawl	3	3	3	3	3.1
South	longline	46	72	42	70	70.9
	recreational	16.6	26	17.1	28	27.2
	trawl	1	2	1	2	1.6

Table 6. Performance statistics calculated for simulation replicates for conservation objectives (first 2 rows), target objectives, long-term depletion, and catch. The B denotes spawning stock biomass and statistics are calculated for either long-term (1.5 generations, 59 years), or short-term (10 years) projection periods. The indicator function I(x is TRUE) = 1 or I(x is FALSE) = 0, and the Q_2() function calculates the median performance statistic across i replicates.

Performance Measure	Description	Period	Definition
Long-term Conservation Objective $P(B_{2081} > LRP)$	Proportion of simulation trials where B > LRP of $0.4B_{MSY}$ at the end of the 1.5 generation projection period	Long-term 59 yrs	$P(B_{2081} > 0.4B_{MSY}) = \frac{1}{100}\sum_{i=1}^{100} \mathrm{I}(B_{2076} > 0.4B_{MSY})$
Short-term Conservation Objective $P(B_{2032} < B_{2023})$	Proportion of simulation trials where B in 2032 is less than B at beginning of projection period	Short-term 10 yrs	$P(B_{2032} < B_{2023}) = \frac{1}{100}\sum_{i=1}^{100} \mathrm{I}(B_{2032} < B_{2023})$
Target Objective	Proportion of simulation trials where B > TRP at the end of the 1.5 generation projection period	Long-term 59 yrs	$P(B_{2081} > B_{MSY}) = \frac{1}{100}\sum_{i=1}^{100} \mathrm{I}(B_{2081} > TRP)$
Final Depletion $\widetilde{B_{2081}/B_0}$ $\widetilde{B_{2081}/B_{MSY}}$	Median biomass depletion across replicates relative to unfished biomass and B_{MSY} at end of projection period	Long-term 59 yrs	$\widetilde{B_{2081}/B_0} = Q_2(\frac{B_{2081,i}}{B_{0,i}})$ $\widetilde{B_{2081}/B_{MSY}} = Q_2(\frac{B_{2081,i}}{B_{0,i}})$
Average Catch $\tilde{C}$	Median of average annual landed catch across replicates	Short-term 10 yrs t_1 =2023 t_2 =2032	$\tilde{C} = Q_2\left(\frac{1}{t_2 - t_1 + 1}\sum_{t_1}^{t_2} C_{t,i}\right)$
Catch Variability $\widetilde{AAV}$	Median of average annual absolute change in the landed catch across replicates	t_1 =2023 t_2 =2032	$\widetilde{AAV} = Q2\left(\sum_{t=t_1}^{t_2} \lvert C_{i,t} - C_{i,t-1}\rvert \middle/ \sum_{t=t_1}^{t_2} C_{i,t}\right)$

Performance Measure	Description	Period	Definition
Minimum Catch $P(C_t>minC_p)$	Proportion of projection years where catch is greater than 125 t in the North and 75 t for the South, considered minimum totals to maintain quota access for other species	t_1 =2023 t_2 =2032	$\boldsymbol{P(C_t > minC_p) = \frac{\sum_{i=1}^{100}\sum_{t_1}^{t_2} I(C_{i,t} > minC_p)}{100(t_2 - t_1 + 1)}}$
Change in TAC $P(\Delta C_t > 30t)$	Proportion of projection years where annual change in TAC is greater than 30t	t_1 =2024 t_2 =2032	$P(C_t > 30t) = \frac{\sum_{i=1}^{100}\sum_{t_1}^{t_2} \mathrm{I}(\Delta C_{i,t} > 30)}{100(t_2 - t_1 + 1)}$
Change in TAC $P(\Delta C_t > 0.20)$	Proportion of projection years where annual % change in TAC is greater than 20%	t_1 =2024 t_2 =2032	$P(C_t > 0.2) = \frac{\sum_{i=1}^{100}\sum_{t_1}^{t_2} \mathrm{I}(\lvert \Delta C_{i,t}/C_{i,t} \rvert > 0.2)}{100(t_2 - t_1 + 1)}$

Table 7. Weighted-average management procedure performance over 4 operating model scenarios for the North and South. Note we use TRP=B_{MSY} and F_{REF}=F_{MSY} for summarizing performance for the interim index MP idxSmuv since TRP and F_{REF} were not specified for the interim management strategy.

MP	TRP	Long-term biomass objectives and depletion				Fishing objectives (10 years)						TAC Forecast	
		P(B_{2081}>LRP)	P(B_{2081}>TRP)	B_{2081}/B_0	B_{2081}/B_{MSY}	Median TAC (t)	P(C_t^{North}>125t) P(C_t^{South}>75t)	AAV	P(|ΔC$_t$|>30t)	P(|ΔC$_t$|>20%)	P(F<F_{REF})	2023-24	2025-26
North													
idxSmuv	B_{MSY}	0.99	0.49	0.29	0.98	144	0.82	9	0	0	0.94	154	136
HBLL 3YR	B_{MSY}	1	0.50	0.30	0.99	173	0.96	7	0.03	0.02	0.75	190	185
HBLL 5YR	B_{MSY}	1	0.50	0.30	1.00	170	0.98	4	0.01	0.01	0.77	171	180
HBLL 7YR	B_{MSY}	1	0.50	0.30	1.01	172	0.99	5	0.00	0.00	0.74	185	167
HBLL 3YR	1.2B_{MSY}	1	0.50	0.36	1.19	140	0.78	5	0.02	0.03	0.77	152	148
HBLL 5YR	1.2B_{MSY}	1	0.50	0.36	1.19	139	0.85	3	0.00	0.01	0.80	138	145
HBLL 7YR	1.2B_{MSY}	1	0.50	0.36	1.20	139	0.88	3	0.00	0.00	0.77	149	134
HBLL 3YR	0.8B_{MSY}	1	0.51	0.24	0.80	217	0.99	9	0.04	0.02	0.70	243	236
South													
idxSmuv	B_{MSY}	1	0.95	0.50	1.65	89	0.80	10	0	0	1.00	86	91
HBLL 3YR	B_{MSY}	1	0.50	0.30	1.00	135	1.00	10	0.06	0.08	0.92	134	120
HBLL 5YR	B_{MSY}	1	0.50	0.30	1.00	133	1.00	8	0.03	0.04	0.93	124	136
HBLL 7YR	B_{MSY}	1	0.50	0.30	1.00	130	1.00	6	0.02	0.04	0.94	114	128
HBLL 3YR	1.2B_{MSY}	1	0.50	0.36	1.21	108	0.98	9	0.04	0.08	0.93	106	95
HBLL 5YR	1.2B_{MSY}	1	0.50	0.36	1.20	106	0.99	6	0.01	0.05	0.95	98	108
HBLL 7YR	1.2B_{MSY}	1	0.50	0.36	1.20	103	1.00	5	0.01	0.04	0.96	90	101
HBLL 3YR	0.8B_{MSY}	0.99	0.52	0.24	0.81	176	1.00	12	0.08	0.07	0.89	177	158

Appendix A. Historical and Projected Biomass Depletion and Catch

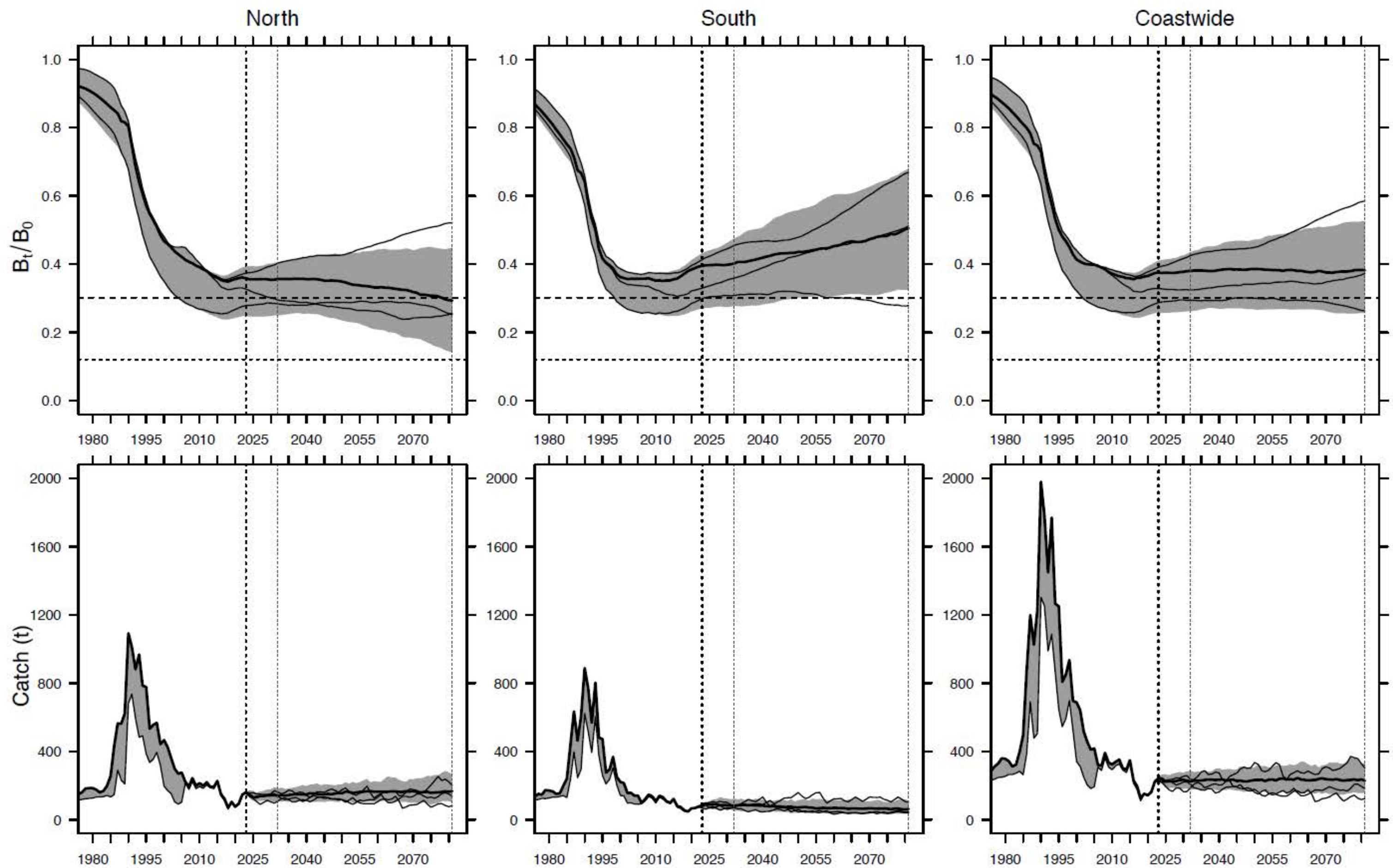

*Figure A.1. Weighted projection distributions for spawning biomass depletion (i.e., B_t/B_0) (top) and total catch (bottom) for 4 operating models from **1960-2081** in the **North, South, and Coastwide** from the **idxSmuv** simulated management procedure. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical dashed black line indicates start of projection period (2023), while grey lines indicate short-term (10 years) and long-term (59 years) projection periods used to generate MP performance metrics.*

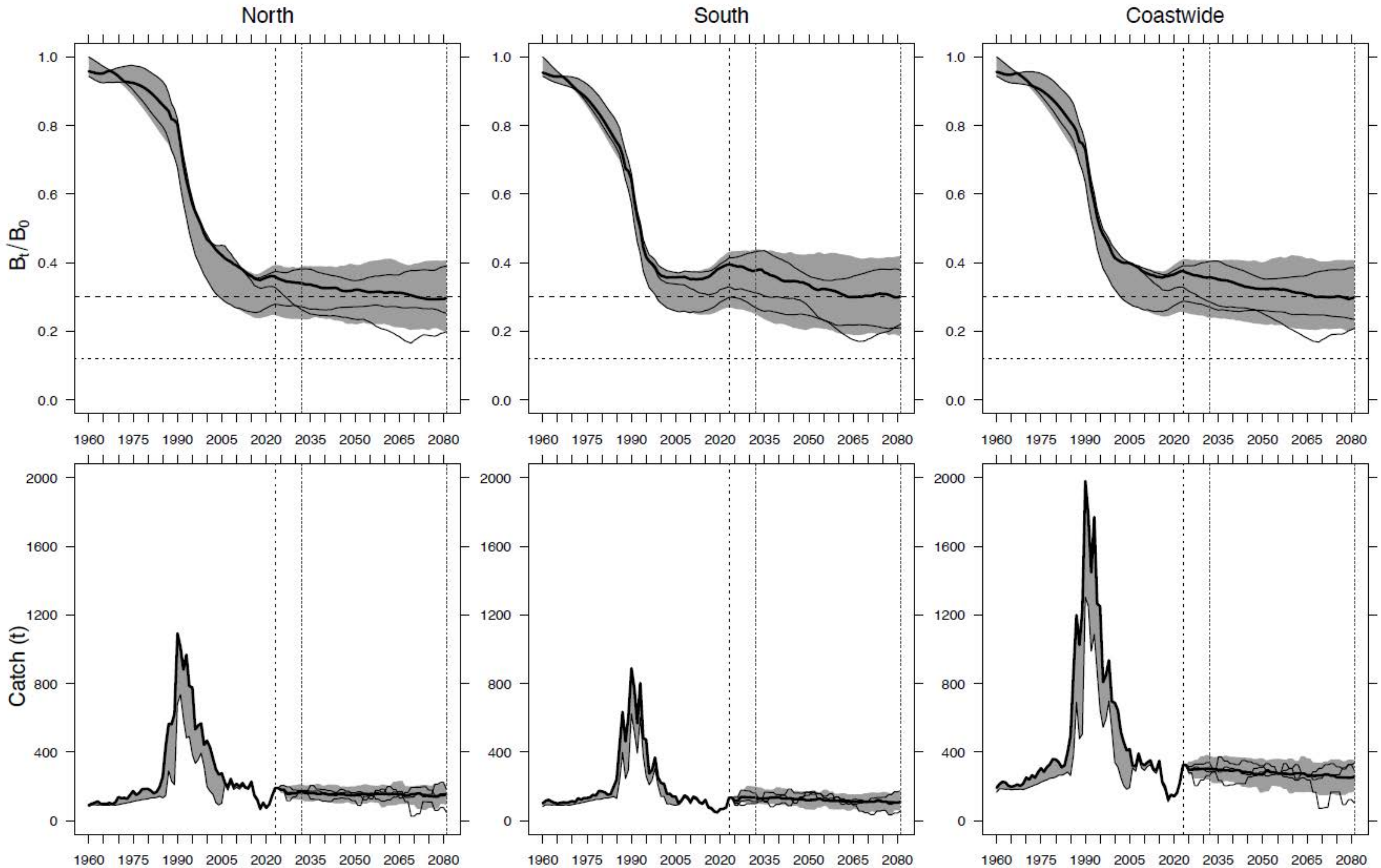

Figure A.2. Weighted projection distributions for spawning biomass depletion (i.e., B_t/B_0) (top) and total catch (bottom) for 4 operating models from ***1960-2081*** *in the* ***North, South, and Coastwide*** *from the* ***HBLL 3YR*** *simulated MP with* $\boldsymbol{B_{MSY}}$ ***TRP****. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of* $0.4B_{MSY}$ *(bottom, dotted line) and* B_{MSY} *(top, dashed line). Vertical dashed black line indicates start of projection period (2023), while grey lines indicate short-term (10 years) and long-term (59 years) projection periods used to generate MP performance metrics.*

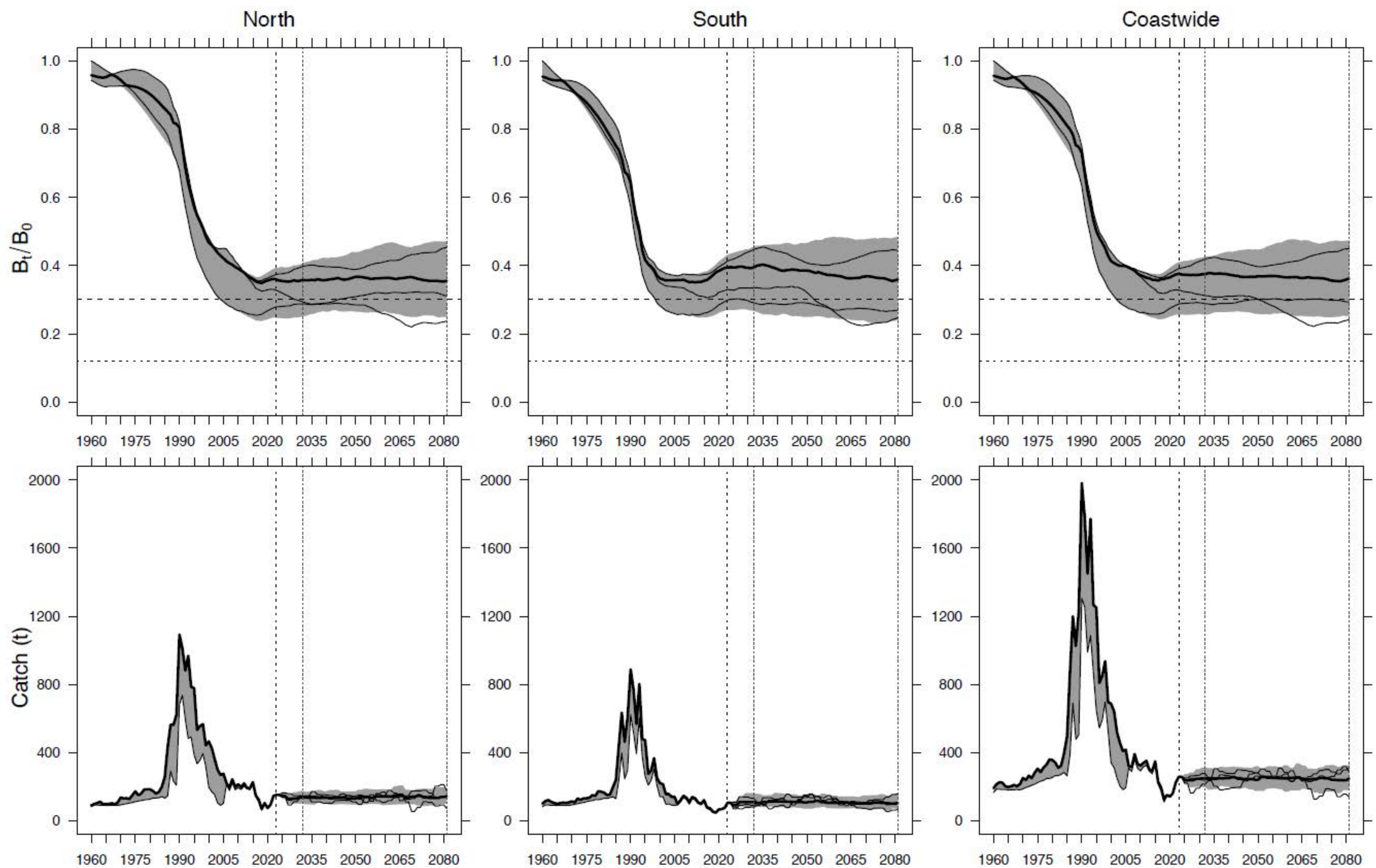

*Figure A.3. Weighted projection distributions for spawning biomass depletion (i.e., B_t/B_0) (top) and total catch (bottom) for 4 operating models from **1960-2081** in the **North, South, and Coastwide** from the **HBLL 3YR** simulated MP with **$1.2B_{MSY}$ TRP.** Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical dashed black line indicates start of projection period (2023), while grey lines indicate short-term (10 years) and long-term (59 years) projection periods used to generate MP performance metrics.*

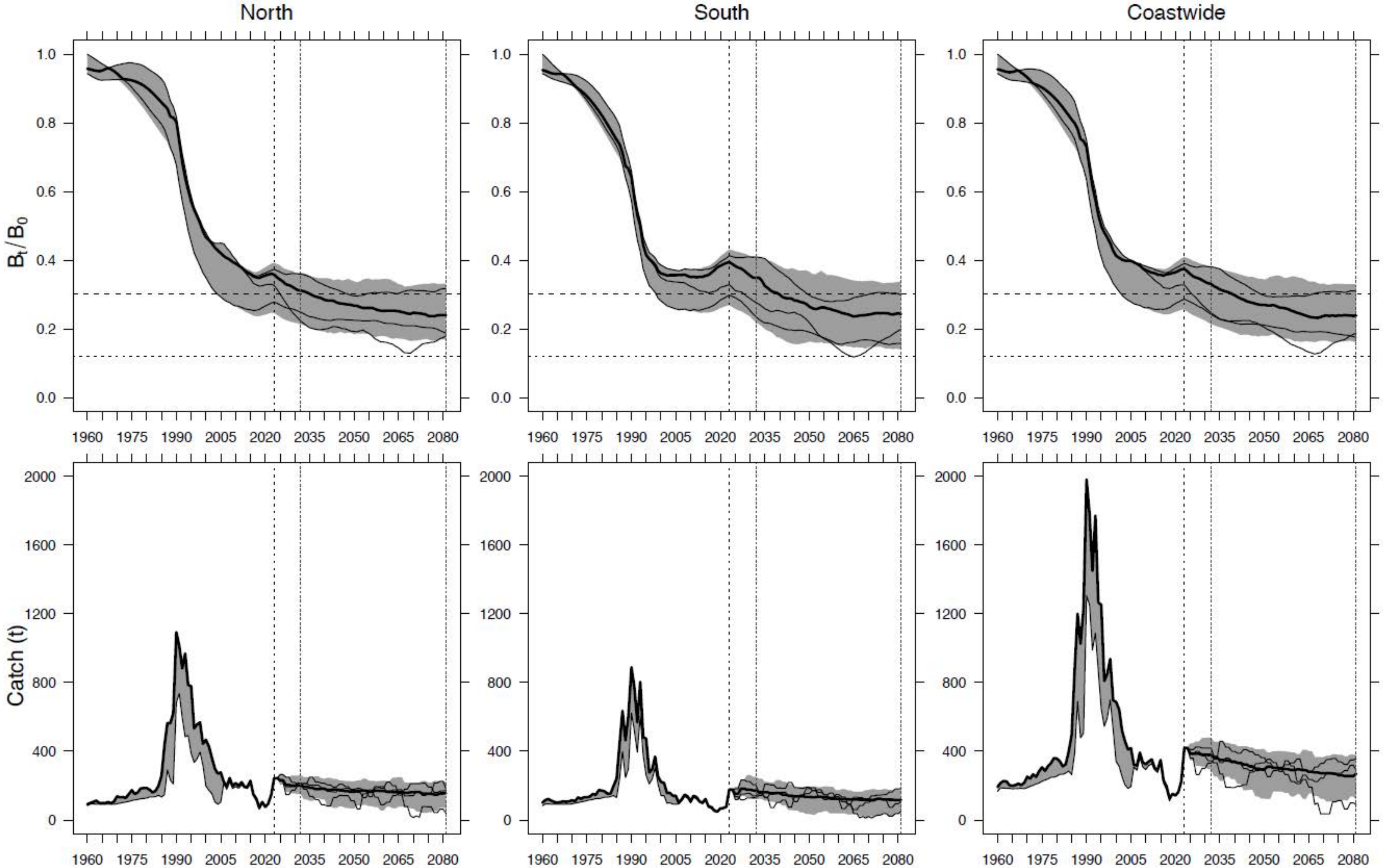

*Figure A.4. Weighted projection distributions for spawning biomass depletion (i.e., B_t/B_0) (top) and total catch (bottom) for 4 operating models from **1960-2081** in the **North, South, and Coastwide** from the **HBLL 3YR** simulated MP with **$0.8B_{MSY}$ TRP.** Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical dashed black line indicates start of projection period (2023), while grey lines indicate short-term (10 years) and long-term (59 years) projection periods used to generate MP performance metrics.*

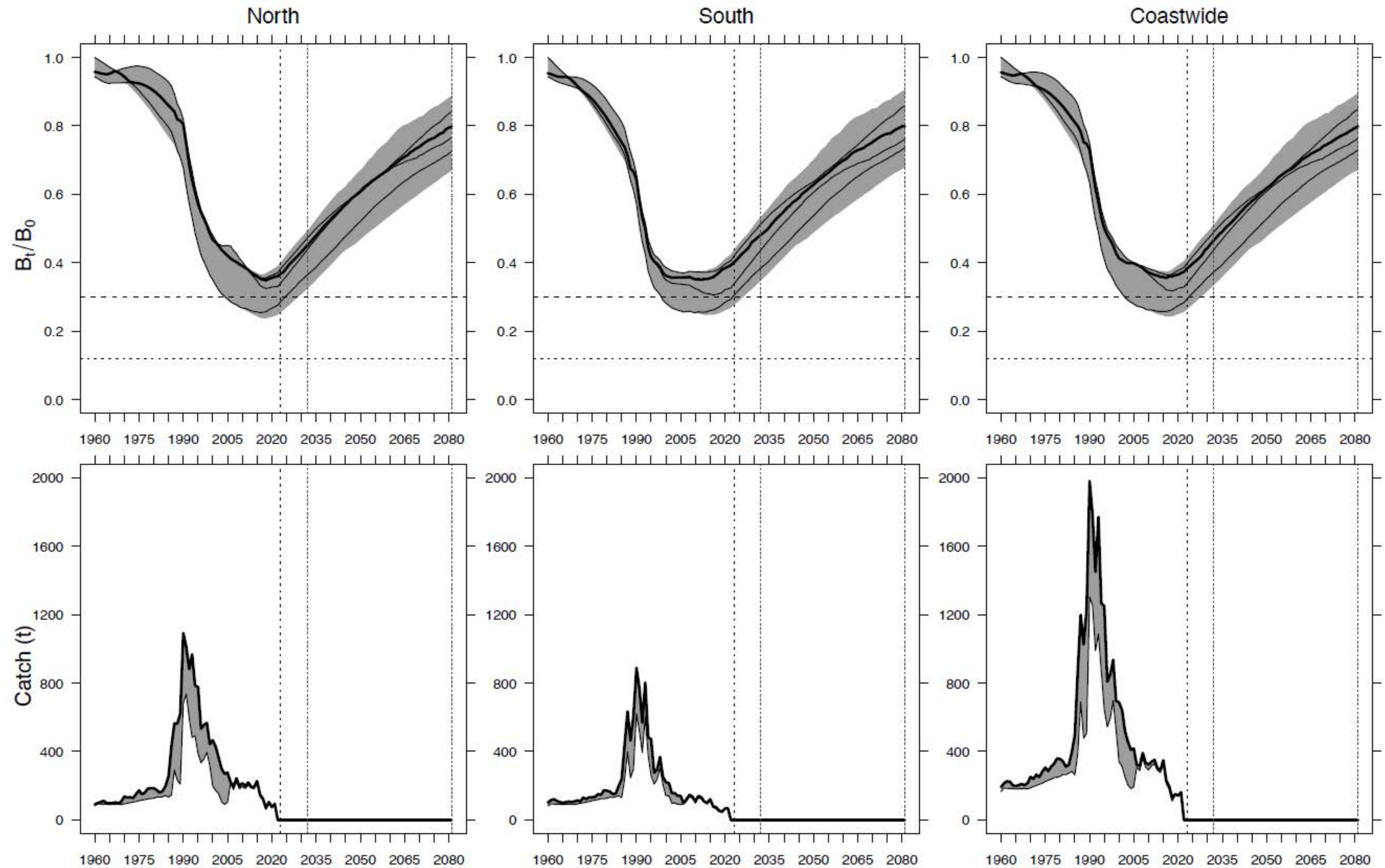

*Figure A.5. Weighted projection distributions for spawning biomass depletion (i.e., B_t/B_0) (top) and total catch (bottom) for 4 operating models from **1960-2081** in the **North, South, and Coastwide** with **No Fishing**. Distributions represent the central 90% of 100 simulation replicate outcomes, medians (thick black lines), and 3 randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the weighted biomass limit reference point of $0.4B_{MSY}$ (bottom, dotted line) and B_{MSY} (top, dashed line). Vertical dashed black line indicates start of projection period (2023), while grey lines indicate short-term (10 years) and long-term (59 years) projection periods used to generate MP performance metrics.*

Appendix B. Clarify Policy Guidance on Choosing a Rebuilding Target Under the Fish Stocks Provisions

Quick refresher on reference points in fisheries

Contemporary fisheries policy and eco-certification around the world focuses on applying the Precautionary Approach to Capture Fisheries (Food and Agriculture Organization 1996; DFO 2009) in which maintaining natural capital (fish stocks) takes precedence over short-term yield. Reference points and harvest control rules are central to the Precautionary Approach as these define the limits and targets for sustainable exploitation. For the majority of exploited species, the stock biomass producing maximum sustainable yield (B_{MSY}) is the only uniquely (i.e., mathematically) identifiable reference point that is consistent with sustainable exploitation, because it is the *only* biomass level that maximizes expected long-term yield. Other reference points, such as the limit reference point (LRP), where stock status warrants preservation over exploitation, are not unique because they are typically chosen based on some combination of expert opinion and risk tolerance.

Canada's Precautionary Approach (DFO 2009) requires three reference points: (i) a limit reference point (LRP) as defined above; (ii) an upper stock reference (USR) delineating a boundary between so-called "cautious" and "healthy" status; and (iii) a target reference point (TRP), generally intended to represent a productive stock size (e.g., B_{MSY}). Although B_{MSY} is the only reference point with a unique solution in fisheries theory, it should be clear that:

Eq B.1 $\quad \text{LRP} < \text{USR} < \text{TRP}$

In other words, the USR and TRP are always at higher stock status levels than the LRP. This is why most LRPs, at least, are defined as a fraction (<1.0) of B_{MSY} (or some proxy thereof) since that guarantees that the above relationship is true. In contrast, one could first choose a LRP (e.g., a low biomass level observed in the past), and then set the TRP to some multiple (>1.0) of that, but this would not guarantee that the TRP was anywhere near B_{MSY}. Ultimately, most reference points are defined as multiples of either B_{MSY} or the unfished biomass (B_0) because that is the only way to ensure that Eq B.1 is always true. For instance, Canada's default policy suggests LRP = $0.4B_{MSY}$, USR = $0.8B_{MSY}$, and TRP = B_{MSY}.

Choosing rebuilding targets for rebuilding plans

Canada's Fish Stocks Provisions require that rebuilding plans be put in place for exploited stocks that are at or below their designated LRP. Specifically, a stock is considered in need of rebuilding if there is a greater than 50% probability that the stock is below its LRP (i.e., $P(B \leq LRP) > 0.5$). A rebuilding target represents the so-called "end point" (as described in the policy) or "off-ramp" (used in TWG discussions) of a rebuilding plan, or the point at which the management process transitions from a rebuilding plan back to a standard fisheries management plan. In a deterministic (i.e., non-random) world, a rebuilding target could represent a milestone along the intended path from the LRP to the TRP; however, fisheries are stochastic and non-linear, and therefore highly uncertain, which means there is no reason to expect that such a smooth path is possible or that a stock can be managed to achieve a TRP. This is why fishery objectives are typically stated in probabilistic terms with a goal, an intended probability, and a time/duration to achieve the goal at the desired probability. As we show below, these three components of objectives are not independent and, therefore, cannot be defined separately.

Under some circumstances (i.e., Case 2 below), the probability component cannot be determined at all *a priori*.

There are two possible circumstances in which we would find ourselves in need of a rebuilding target:

Case 1 – Stock is below the LRP

In this case, available stock assessment information implies the need for a rebuilding plan. At this point, one could simply choose a stock status level such as $0.6B_{MSY}$, $0.8B_{MSY}$, B_{MSY}, or any other stock status reference point (e.g., defined in terms of unfished biomass or various proxies) to serve as the rebuilding target (RT), so long as the rebuilding target is greater than the LRP. In other words,

Eq. B.2 $$\text{LRP} < \text{RT}$$

However, the FSP further requires that rebuilding targets meet the following two conditions[2]:

a. The rebuilding target must be set at a level above the LRP so that there is a very low to low likelihood (<5-25% probability) of the stock being below its LRP, and

b. A rebuilding target has been reached when there is at least a 50% probability that the stock is at or above its rebuilding target.

These conditions require that (1) we know the probability distribution around the current and future stock status and (2) the probability statements in *a* and *b* are logically consistent with each other. That is, we need to find a rebuilding target where both probability statements are true.

For stocks in Case 1 (not OYE), a simulation approach would be used to find a rebuilding target that meets those two conditions. This appears to be the situation envisioned in the guidelines for developing rebuilding plans (DFO 2021) and it is commonly employed in practice for stocks in need of rebuilding.

Case 2 – Stock is above the LRP

Here, the stock is above the LRP and, therefore, not in need of rebuilding (applies to OYE at present); however, there may still be a need to define a rebuilding target for future reference. Our main problem here is that we cannot choose a RT that is certain to meet both conditions in *a* and *b* above. This is because of the points made in section B.1; that is, (i) the probabilities and RT are not independent and (ii) we do not even know the probability distribution of future stock status. So, there is no way to simulate a rebuilding stock as we did under Case 1. The only thing we can do is specify condition (*a*) *The rebuilding target must be set at a level above the LRP so that there is a very low to low likelihood (<5-25% probability) of the stock being below its LRP*, since that can be defined by itself without knowledge of future probabilities. The non-independence of conditions (*a,b*) means that defining (*a*) implicitly defines a RT for (*b*). This non-independence is shown graphically in Figure B.1 where the median stock status depends on both the uncertainty in stock status as indicated by the coefficient of variation (CV) and the chosen probability for condition (*a*). IMPORTANT: what is absolutely certain from this graphic (and the laws of probability) is that any choice for condition (*a*) will ensure that condition (*b*) is met, while the reverse (specifying (*b*)) will not.

[2] Note that in the DFO 2021 guidance, the specific wording is: “A rebuilding target should be set at a level that is far enough above the LRP to have a high probability of the stock being above it, taking uncertainties into account. The rebuilding target should also be set far enough above the LRP so that there is a low probability of falling below the LRP in the short to medium term”. Nevertheless, the wording in (*a*), which is based on DFO 2022, is consistent with this for the purpose of this document. Formal definitions of RTs will be stated using this recent guidance.

A second reason to focus mainly on condition (*a*) is that it provides harvesters with an opportunity to invest in improving stock status information that will benefit their fishing opportunity. For example, given a choice for condition (*a*) such as $P(B \leq LRP) \leq 0.25$, a reduction of uncertainty would imply a lower RT and thus greater fishing opportunities without having to wait perhaps decades to achieve an arbitrarily chosen high RT.

In conclusion, specifying rebuilding targets requires three components that are not independent and cannot always be known at the time they are needed. Defining a rebuilding target based on an existing LRP and at a stated probability of being below that LRP will always be possible and will always ensure that both conditions for rebuilding targets are met regardless of the future probability distributions for stock status. Specifying a rebuilding target by picking an arbitrary stock status level that is above the LRP cannot guarantee that both rebuilding target conditions will be true under all circumstances and may even be punitive to fisheries that have the capability to improve stock status information by investing in data collection and assessments. A reasonable option for stocks that are not in need of rebuilding would be to specify a rebuilding target via $P(B \leq LRP)$ and then use a simulation approach to determine the robustness of that choice should the stock end up below its LRP sometime in the future. In fact, those simulations would be needed anyway to ensure that there is “a low probability of falling below the LRP in the short to medium term” (DFO 2021). Such simulations are done routinely as part of management procedure simulations for BC Sablefish if readers need an applied example (Cox et al. 2019).

Appendix B References

Cox, S., Holt, K., and Johnson, S. 2019. Evaluating the robustness of management procedures for the Sablefish (*Anoplopoma fimbria*) fishery in British Columbia, Canada for 2017-18. Can. Sci. Adv. Sec. Res. Doc. 2019/032. vi + 79 p.

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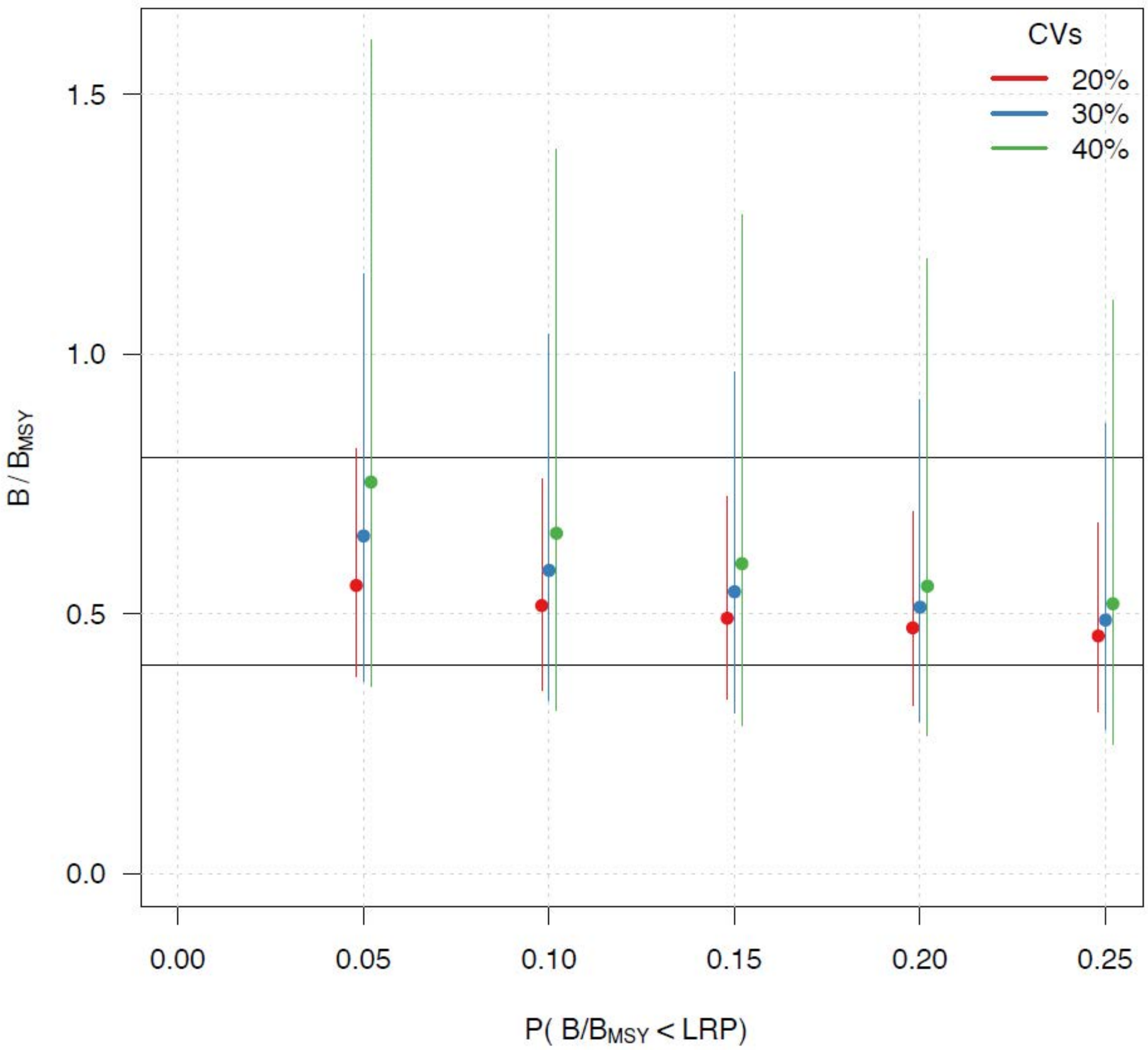

Figure B.1. Relationship between the intended probability of stock status below an LRP (condition a in the text) and the corresponding probability distribution of stock status for three levels of uncertainty (CVs) in stock status. The median stock status is given by the dots, representing condition (b) in the text. The horizontal reference lines are the LRP (lower line, $0.4B_{MSY}$) and the USR (upper line, $0.8B_{MSY}$).

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Centre for Science Advice (CSA)
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ISSN 1919-3769
ISBN 978-0-660-49738-9   Cat No. Fs70-7/2023-037E-PDF

Correct Citation for this Publication:

DFO. 2023. Management Procedures Update and Catch Advice for 2023/24-2026/27 Fishing Seasons for Outside Yelloweye Rockfish (*Sebastes ruberrimus*) in the Pacific Region. DFO Can. Sci. Advis. Sec. Sci. Resp. 2023/037.

Aussi disponible en français :

*MPO. 2023. Mise à jour des procédures de gestion et avis sur les prises pour les saisons de pêche 2023-2024 à 2026-2027 du sébaste aux yeux jaunes (*Sebastes ruberrimus*) des eaux extérieures de la région du Pacifique. Secr. can. des avis sci. du MPO. Rép. des Sci. 2023/037.*