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EVALUATING THE ROBUSTNESS OF CANDIDATE MANAGEMENT PROCEDURES IN THE BC SABLEFISH (*ANOPLOPOMA FIBRIA*) FOR 2019-2020.

Context

Since 2008, Fisheries and Oceans Canada (DFO) and the British Columbia (BC) groundfish fishing industry have collaborated on a management strategy evaluation (MSE) process intended to maintain a transparent and sustainable harvest strategy for sablefish fisheries in BC. Transparency and potential sustainability of candidate management procedures (MPs) are demonstrated by simulating MP performance against a set of pre-agreed conservation and socio-economic objectives. Operating models underlying the simulations are intended to represent key uncertainties related to sablefish stock status and productivity. The sablefish MSE process has been reviewed in several Canadian Science Advisory Secretariat processes, Canadian Science Advisory Secretariat Science Responses, and independent peer-reviewed scientific journals and books since 2008 (Cox and Kronlund 2008; Cox et al. 2011, 2013, 2019; DFO 2014). Canadian sablefish harvest advice derived from simulation-tested MPs has been adopted and subsequently approved by the Minister of Fisheries every year since 2011.

The sablefish MSE aims to follow a 3-year cycle in which the operating model is re-fitted to updated fishery and survey biomass indices, catch-at-age, at-sea releases, and tag release-recoveries. Each 3-year update also offers an opportunity to revise the conservation and fishery objectives, as well as to propose new candidate MPs.

Previous BC sablefish assessment and MSE work demonstrated that low recruitment, on average over the past three decades, has contributed to a long-term decline in spawning stock biomass and harvest opportunities. Stakeholder and management consultations identified at-sea release mortality of sub-legal sablefish (i.e., fish smaller than 55 cm size limit) as a potential source of mortality that, if reduced or avoided, may improve production of over-55 cm sablefish, spawning stock biomass, and, ultimately, future harvest opportunities (Cox et al. 2019). While some voluntary tactics aimed at reducing sub-legal mortality have been identified (e.g., improved fleet communication, informal move on rules, and increased electronic monitoring), to date management tactics aimed at reducing sub-legal mortality have not been formally evaluated through the sablefish MSE process. Indeed, closed-loop simulations suggest that both full avoidance and full retention of sub-legal sablefish may improve both average annual sablefish yield in directed fisheries as well as the probability of stock rebuilding to BMSY (Cox et al. 2011, 2019). Unfortunately, full avoidance may not be feasible, especially in trawl fisheries, which encounter sub-legal sablefish as part of fishing operations for other species, while full retention may involve lost fishing opportunities (particularly for the trawl sector) and lower profitability for directed fisheries, because sub-legal sablefish are worth less per-kilogram than legal-sized fish. In consultations, industry stakeholders suggested that an ideal solution would involve incentives that shift fishing behaviour toward higher avoidance of sub-legal sablefish.

The DFO Fisheries Management Branch has, therefore, requested that the Science Branch (i) update the Sablefish operating model to include the most recent data available (up to 2018); (ii) update advice about expected performance of the current MP; and (iii) evaluate alternative MP and/or regulation options aimed at reducing productivity losses to sub-legal mortality. The key issue in (iii) is identifying MPs that minimize the impact of such regulations on fishing opportunities in non-directed fisheries (i.e., bottom trawl) where sub-legal sablefish are captured incidentally.

Advice arising from this Canadian Science Advisory Secretariat Science Response will be used to select a new MP for BC Sablefish for years 2020-2022 that is compliant with the DFO Sustainable Fisheries Framework and A fishery decision-making framework incorporating the Precautionary Approach policy (Fisheries and Oceans Canada 2009). In addition, this Science Response informs fishery managers and stakeholders about the fishery implications of limiting productivity losses due to sub-legal sablefish releases at-sea.

This Science Response Report results from the Science Response Process of September 2019 on evaluating the robustness of candidate management procedures in the BC sablefish (Anoplopoma fibria) fishery for 2019-2020.

Analysis and response

This Science Response uses a closed-loop simulation approach to evaluate the relative performance of candidate MPs for the BC sablefish fishery, using identical methodology to that presented in the previous MSE cycle (Cox et al. 2019). The following sub-sections provide brief descriptions of the updated data provided for conditioning the sablefish operating model, the changes required to fit that data, and the new management procedure elements that were tested. Additional details of the simulation procedures, diagnostic checks, and performance measure calculations are given in Cox et al. (2019).

Objectives

The specific objectives of this Science Response are to:

1. Describe operating model fits and inferences after fitting (conditioning) to updated biomass indices, catch-at-age, and new catch-at-age data derived from length-composition sampling of sablefish in the trawl fishery;
2. Derive a grid of 5 reference operating models and 5 robustness trial operating models based on uncertainties about Sablefish stock status and productivity (reference OMs) and year 2016 recruitment (robustness OMs);
3. Simulate and rank candidate MPs under the reference and robustness OMs based on performance against Fishery Objectives (see below).

Methods

Updates to the operating model

Data updated to 2018 included biomass indices and catch-at-age for the stratifed random trap survey (StRS), catch-at-age for the commercial longline trap fishery, catch and total at-sea releases (in biomass units) for the commercial longline trap, longline hook, and trawl fisheries.

New catch-at-age and catch-at-length datasets were obtained for the trawl fishery to help estimate trawl selectivity, which is the key determinant of sub-legal sablefish catch in trawl fisheries. The full trawl catch-at-age dataset (with some missing years) was derived from an age-length key given age and length data from 1972 to 2017.

A number of small changes were made to the operating model as part of routine attempts to improve fits to various data. These included (i) changing the functional form of trawl selectivity to a gamma density function, (ii) reducing the youngest model age class from age-3 to age-2 for all age composition series to better reflect the range of age-composition observations, (iii) adding new commercial trawl age-composition data (Appendix A), (iv) adding an estimated recruitment deviation in 2016, rather than using the expected recruitment off the stock-recruit curve, (v) updating the ageing-error matrix to use a simpler normal approximation a recommended in the previous CSAS review (Cox et al. 2019); and (vi) imposing a standard deviation of $\sigma = 0.1$ (on the log-scale) on trawl at-sea release observation errors to force a better fit to those data. Previous models avoided estimating recruitment in the 3 most recent years, mainly because (i) this would have been the first age-at-entry to the observations provided to the model and (ii) there is typically little information to support those estimates because fish are too small to be selected by the fisheries or surveys. However, for this update, we made change (iv) because we needed to improve fits to recent (very high) trawl at-sea release observations. Otherwise, we would be simulating effects of at-sea releases based on a model that could not adequately fit historical at-sea releases. This change has a potentially large impact on simulated MP performance and, therefore, is a focus of the robustness OMs (described below).

Operating model scenarios

Reference OMs

The reference OMs were derived using the same method as the previous MSE cycle (Cox et al. 2019). Briefly, we derive 5 OMs defined by the joint posterior distribution of 2018 spawning stock biomass (to reflect short-term biological risk) and stock-recruitment steepness (to reflect long-term stock productivity risk). The 5 combinations are chosen to represent the joint marginal mean of 2018 biomass and steepness and 4 outer points lying at the intersection of the mean of one variable, and the 10th and 90th percentiles of the marginal density of the other variable (Figure 1). For each of the 5 posterior points, the operating model was conditioned on a sample of 100 posterior draws constrained to lie within a Mahalanobis distance of 0.75 units from that point. We then used an empirical estimate of the posterior density at each of the 5 centres as a plausibility score for weighting MP performance across the 5 OMs within each of the reference and robustness sets (Table 2).

Robustness OMs

The robustness OMs were identical to the 5 reference OMs with the exception of how the recruitment from the 2015 year class was treated in the OM historical conditioning and projections. The reference OM used draws from the joint posterior distribution (as defined above) for the 2015 year class, which is approximately 22 million fish or about 8 times the historical average. For the robustness OMs, we simulated the recruitment off the stock-recruitment relationship resulting in an expected 2015 year class that was more similar to the long-term average (~ 2.63 million).

Fishery Objectives

Objectives for the B.C. Sablefish fishery have been developed iteratively via consultations between fishery managers, scientists, and industry stakeholders (Cox and Kronlund 2009; Cox et al. 2011, 2019; DFO 2014). The five primary objectives guiding this fishery are:

1. **P(fSSB > LRP)**: Maintain female spawning stock biomass (fSSB) above the limit reference point $LRP = 0.4B_{MSY}$, where B_{MSY} is the operating model female spawning biomass at maximum sustainable yield (MSY), in 95% of years measured over two sablefish generations (36 years);
2. **P(decline)**: When female spawning stock biomass is between $0.4B_{MSY}$ and $0.8B_{MSY}$, limit the probability of decline over the next 10 years from very low (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 these probabilities;
3. **P(fSSB > B_{MSY})**: Maintain the female spawning biomass above a target level of (a) B_{MSY} when inside the healthy zone, or (b) $0.8B_{MSY}$ when rebuilding from the Cautious zone, in the year 2052 with a probability of 50%;
4. **P(Catch > 1,992 t)**: Minimize probability that annual catch levels are below 1,992 tonnes measured over two sablefish generations.
5. **MaxCatch**: Maximize the average annual catch over 10 years subject to Objectives 1-4.

Performance measures corresponding to Objectives 1-4 (in bold) are read as "Probability of (condition)". Performance measures are calculated for each simulation replicate, and the expected performance for a management procedure is summarized by the mean (or median) over the 100 replicates of each simulation. Full details of performance measures and calculations are given in Cox et al. (2019).

As noted above, there is a price premium for larger size classes of sablefish, which means that the same tonnage of landed catch may yield widely different dockside values if the underlying size distributions of individual fish are substantially different. This may have consequences for sub-legal regulation options that require landing small sablefish (e.g., full retention). Therefore, in addition to presenting catch performance statistics (e.g., Objective 5), we also computed cumulative landed value over 10 years and average landed value per tonne by fleet (because the size composition of the catch also differs by fleet).

Management procedures

A management procedure (MP) represents a specific, repeatable algorithm for computing annual total allowable catches (TACs) in a fishery. In most cases, MPs involve monitoring data, assessment methods for processing data and estimating stock status, harvest control rules for translating assessment outputs into catch limits, and meta rules that may include constraints on TAC changes, as well as conditions (e.g., exceptional circumstances) for triggering deviations from the standard MP harvest advice.

The MP currently used to set annual sablefish TACs was initially developed in Year 2011 and revised in two subsequent MSE iterations. Generally, the MP consists of (i) 3 biomass indices; (ii) a surplus production model with observation and process errors for estimating stock biomass from the biomass indices; (iii) a 60:40 harvest control rule (HCR) in which the maximum target harvest rate is adjusted from 5.5% when estimated biomass is above 60% of estimated B_{MSY}, and 0% when the estimated biomass is below 40% of B_{MSY}; (iv) a meta rule stating that TAC

increases are 0 unless the HCR recommended increase is more than 200 tonnes (TAC decreases are always adopted); and (v) a meta rule adjusting the maximum target fishing mortality rate from 9.5% in Year 2017 to 5.5% in Year 2021. Complete details of the current MP specifications are given in Cox et al. (2019).

For this Science Response, we evaluated performance of the current MP for sablefish, a NoFishing reference case, and 15 variations of the current MP that only change at-sea release regulations. The MP variants are constructed by combining 3 features:

1. at-sea sub-legal release cap in which all at-sea releases below the cap may be released without penalty and amounts exceeding the cap go to overages. Caps are noCap, 0%, 50%, 100%, and 150% over the average 464t of at-sea releases that occurred between 2006 and 2018. The current MP involves no cap (unlimited at-sea releases without penalty), while a full retention (frt) case allows no at-sea releases (all fish brought on-board vessels must be landed and counted against the TAC).
2. fixed allocations of the total at-sea release cap to each fleet (i.e., trap, longline hook, trawl). Allocations are computed based on either recent (rct = $(23\%, 18\%, 59\%)$, 2016 - 2018) or historical (hst = $(30\%, 37\%, 33\%)$, 2006-2018) fleet-specific average proportions of the total annual at-sea releases.
3. amortization period of either 5 (am5) or 10 (am10) years over which to spread at-sea release overages to future TACs.

The naming convention we followed for MPs attempts to describe the at-sea release regulations by concatenating CAP_ALLOCATION_AMORTIZATION settings. For example, the **cap.5_hstAl_am5** MP involves a total at-sea release cap that is 50% of the historical average (**cap.5**), a cap allocation among fleets that is computed from the historical, fleet-specific average proportions (**hstAl**), and a 5-year amortization period for at-sea release overages (**am5**). The two special cases are the current MP (**noCap**), which has no cap, and full retention (frt), which has no releases. Note that the allocation is irrelevant for the 0% cap, as all fleets would have a cap of 0t, and only the amortization period for overages would apply.

A worked example at-sea release regulation for cap.5_hstAl_am5.

Here we provide the sequence of calculations used to establish annual at-sea release caps and then how they affect future TAC allocations. In the computations below, the following notation applies: t is year, g is fleet, and $p(g)$ is proportion of releases allcoated to fleet g.

1. Calculate 50% at-sea release CAP for year and fleet:
$$CAP(t, g) = 0.5 \cdot 0.464 \cdot p(g).$$
2. Run simulation for year t to get actual at-sea releases: $R(t, g)$.
3. Calculate overage $o(t, g)$ for the year as the difference between actual releases $R(t, g)$ and the $CAP(t, g)$: $o(t, g) = R(t, g) - CAP(t, g)$
4. Amortization period is 5 years, so add 1/5th of this year's overage. to the accumulated overage account $O(t + k, g)$ in each of the next 5 years:
$$O(t + k, g) = O(t + k, g) + o(t, g)/5, \text{ for } k = 1, ..., 5.$$
5. Get adjusted legal-sized sablefish TAC for next year by subtracting overage account for that year from initial TAC' (TAC' set by the MP prior to at-sea regulations):
$TAC(t, g) = TAC'(t, g) - O(t, g).$

This approach aims to create an incentive to avoid sub-legal sablefish via future TAC reductions (using a one-for-one accounting of sub-legal biomass to legal sized sablefish biomass), while also allowing some flexibility year-to-year for unpredictably large at-sea releases in any given year. Note that the overage account can never be less than zero, so that TACs cannot be increased above the initial TAC set by the first stage MP (i.e., banking of TAC cannot occur).

Management procedure tuning

The Sablefish management strategy evaluation considers five primary dimensions of MP performance against objectives. The first three represent biomass conservation performance against the LRP, short-term probability of decline, and achieving a long-term target at or near B_{MSY}, while the fourth and fifth dimensions relate to maintaining catch levels above an industry-preferred floor and short-term average catch. It is rare that two MPs would have comparable performance across four of these objectives while only differing on one. If this were the case, then MP decisions would be straightforward – choose the MP with better performance on the fifth criterion. Unfortunately, MPs typically differ on all 5 dimensions simultaneously, which makes it difficult to compare performance without, at least, establishing some equivalency between conservation probabilities (performance dimensions 1-3) and short-term average catch (performance dimension 5).

Management procedure tuning provides a means of establishing equivalent MP performance against objectives for which the values and probabilities are well established. For example, maintaining the sablefish stock above the LRP ($0.4B_{MSY}$) with high probability has not been openly debated since it is an overarching Canadian policy directive in the sablefish fishery context (at least not debated over the 10+ year history of the sablefish MSE). Similarly, maintaining a low probability of short-term decline has also not been debated, probably because avoiding further decline has been the key overriding objective of the sablefish fishing industry since the inception of the MSE process. Objective 3 – spawning biomass in the healthy zone within 2 generations – has been debated over the years for practical reasons. Specifically, there is concern that achieving Objective 3 would require severe short-term catch restrictions for highly uncertain long-term benefits. Over the past year, the sablefish industry and DFO Science and Management agreed to revise Objective 3 to achieve biomass in the healthy zone by a specific end-year (2052) with at least 50% probability, i.e., median fSSB at, or above, B_{MSY}. As we demonstrate below, this objective is now feasible given sablefish dynamics and also achievable for a range of realistic MPs. However, this raises a new question: how much is it worth (i.e., in catch) to improve Objective 3 performance from, say, $P(B_{2052} \geq B_M SY) = 0.5$ to $P(B_{2052} \geq B_M SY) = 0.55$? The probability difference of only 5 percentage points could mean a difference of several hundred tonnes in average annual catch, which would cumulatively added up to tens of millions of dollars in landed value. MPs that perform better under Objective 3 almost always do so at the expense of performance under Objectives 4 and 5.

We aimed to simplify interpretation of MP performance by tuning all MPs to a standard $P(B_{2052} \geq B_M SY) = 0.5$, which ensured that all MPs under consideration meet all the stated conservation objectives. We applied the tuning in a cross test design, where MPs were tuned to meet Objective 3 under both the reference and the robustness OMs, and the performance of tuned MPs on both sets of OMs were reported. This tuning ensured that all MPs met the conservation objectives of the OMs that they were tuned to, and only differed in catch performance on those OM sets. This simplification was needed in the current context, because

the at-sea regulations we evaluated had catch and fishing opportunity implications across fishing sectors.

Tuning was achieved by iteratively adjusting Year 2022 phased-in maximum target fishing mortality rates F_{2022} until each MP met the lower limit of Objective 3, i.e., $P(B_{2052} \geq B_{MSY}) = 0.5$. We tuned the surplus production model management procedures separately to the reference OM and robustness OM scenarios, leading to different F_{2022} values under each recruitment scenario. Note that this target maximum harvest rate replaces the final maximum target rate of 5.5% after the 5-year phase-in from 2017 (Cox et al. 2019). The most critical, and perhaps unrealistic in some cases, assumption in the above is that fleets stop fishing when their fleet-specific TACs are fully landed.

Results

Operating model update and implications for stocks status

Operating model fits to survey and fishery biomass indices are similar to previous versions, where both the model and data show a long-term steady decline. The most recent two stratified random survey (StRS) data points are substantially higher than the preceding ones, suggesting potential increases in the offshore stock biomass (Figure 2).

In general, the age-structured operating model fit the age-composition data reasonably well (Figure 3). Fits to the trap fishery age-composition continue to show a large residual at the plus-group age 35+. The plus-group residual is also positive, but considerably smaller for females (Figure 3, Trap:Females). The trawl age fits show a large positive residual at age-2 for males, which appears to arise from the 2017 and 2018 samples that are large and, therefore, tend to drive the average to have what appears to be a large residual at age-2. This could be a contributing factor, or at least contributing to the uncertainty, regarding the estimated 2015 year-class.

Model fits to the standardized survey are similar to previous OM versions — error patterns in these lie somewhere between the fishery data fits (worst) and StRS fits (best) (Figure 2). The OM continues to fit StRS very well, which probably arises because the StRS is specifically designed for monitoring the offshore sablefish population (none of the other data series do that).

The updated stock status of Canadian sablefish depends on the absolute size of the 2015 year-class (age-3 in assessment Year 2018) (Table 1). The raw estimate of this year-class is about 5 times the historical average, which creates the impression of the largest recorded recruitment from one of the lowest spawning biomasses ever observed. Such a high recruitment at low spawning biomass has cascading effects on the model parameter estimates, biological reference points, and estimated current biomass. These effects include: (i) the estimated stock productivity (i.e., stock-recruitment steepness parameter) is adjusted upwards; (ii) the most productive stock size (B_MSY) is adjusted downwards, because the stock is apparently more productive at low biomass; (iii) the optimal fishing mortality rate (F_{MSY}) is adjusted upwards because the more productive stock can sustain higher fishing pressure; and (iv) current spawning biomass is adjusted upwards because about 20-25% of age-3 fish are maturing. Although these are positive and encouraging signs that sablefish status is improving, there is some risk in tuning future management procedures to substantial models changes that arise from a small number of observations. Other fisheries for Pacific groundfish (e.g., Pacific Hake, Gulf of Alaska Sablefish [*Merluccius productus*]) have treated large recruitments with caution until the data more fully

materialize. Here, we deal with the uncertainty in 2015 year-class size by developing reference (using age-3 data) and robustness (ignoring age-3 data) OMs for use in evaluating management procedures.

Management Procedure Evaluation Results

Reference oeprating model set

Recruitment from the 2015 year class is a main driver of projected spawning biomass and fishery outcomes in the reference OM simulations. Given the high 2015 recruitment, spawning biomass increases rapidly over the first 5 years of the projection period as these fish become fully recruited to the fisheries and then the spawning biomass (Figure 4 and 6). Spawning biomass then trends downward toward B_MSY in the long-term as this large year class is fished down. Under these conditions, all MPs met all the conservation criteria defined by Objectives 1-3. The probability of catch below the 1,992 t floor was 2.6% or less across all MPs. Tuning MPs to meet Objectives 1-3, and specifically treating Objective 3 as a target, highlights MP performance differences in average annual catch over the next 10 years.

As expected, management procedures with more restricted at-sea release regulations ranked higher in terms of 10-year average catch (Table 2) with the values ranging from 4,510 t per year for full retention (**frt**) to 3,700 t per year for a cap 150% higher than average, recent cap allocation among fleets (i.e., allocating 59% to trawl), and 5-year amortization (MP13 **cap1.5_rctAl_am5**). This difference is attributable to two factors. First, the key assumption here is that fishing activity stops once the TAC is reached, so full retention involves less mortality of sub-legal fish over all fleets. This leads to a large reduction in growth overfishing for the full retention regulation — gains in sablefish body growth are much higher than losses due to natural mortality in sub-legal size classes — and, therefore, average weight of legal-sized fish in the catch is larger. Second, the fishery can operate at higher fishing mortality rates because survival over sub-legal size classes is higher and therefore higher survival to fisheries and the spawning stock. Indeed, the current MP maximum target $F = 5.5\%$ is largely the result of lower survival through sub-legal size classes, which inhibits MPs from meeting the future spawning biomass Objective 3. In contrast, the full retention MP meets Objective 3 despite a maximum target $F = 7.4\%$ (Table 2).

Differences in average annual catch were smaller among at-sea regulation options not involving full retention. An at-sea release cap of 50% of the historical average resulted in average annual catch levels approximately 200 t higher than the current MP (**noCap**), regardless of how the cap in the former was allocated among fleets (MP3 and MP5 vs. MP15; Table 2).

An at-sea release cap equal to 100% of the historical average also produced 200 t more average annual catch compared to the current MP, as long as the cap was allocated according to the historical at-sea release proportions and amortized over 5 years. The similarity to the lower 50% caps described above mainly reflects cap allocation to the trawl fleet, where the recent allocation (57%) is approximately twice the historical (29%), so switching to the lower, historical allocation allows for doubling the cap, i.e., the total at-sea release amounts allocated to the trawl fleet are similar. In general, the historical allocation options ranked higher than the recent allocations because the historical allocation involves lower at-sea releases by the trawl fleet. The amortization period did not have as noticeable an effect as the overall cap and allocation options, in that order.

Increasing the cap to 150% of the historical average produced the lowest average annual catch,

despite the current MP having no cap at all. Although average 10-year catches were similar, at-sea releases in the current MP (**noCap**) change mainly with recruitment and therefore have less impact than a 150% cap, which decouples at-sea releases and recruitment to some (small) degree and allows trawl fishing to continue past current sub-legal catch rates.

For higher caps and recent at-sea release allocation, the effect of amortization switched from 5 years being better to 10 years being better. Although the differences were small (MP12 vs MP13; Table 2), the switch probably occurs because there is little to no growth overfishing benefit of amortization at high caps and recent allocations, which would mean higher trawl releases than present. In this case, the amortization period has a direct effect on TACs with longer amortization periods having less impact because any overages are spread over the longer period.

We initially expected that a full retention and/or lower cap regulations would negatively affect fishery landed value because the landed catch would consist of higher proportions of sub-legal fish. Price premiums for sablefish (*see Table X; C. Acheson per comm., Spring 2019*) may result in several dollars per pound differences between sub-legal (< 3 lbs) and legal-sized sablefish.

Indeed, the average landed value per tonne was approximately $170 lower for a full retention trap fishery compared to any of the other at-sea release regulations (Table 4), while landed value was approximately $20 and $90 per tonne lower for longline hook and trawl landings, respectively. Size-selectivity for trap, and especially longline hook, fisheries is shifted far enough toward larger sizes that the impacts of retaining smaller fish are relatively small compared to the benefits of higher average TACs. Indeed, cumulative landed values over ten years were $47 million, $18 million, and $15 million higher for trap, longline hook, and trawl fisheries under full retention fishery compared to the next best average annual catch regulation option (i.e., MP3, **cap.5_hstAl_am5** Table 4).

The next best at-sea release regulation option after full retention was very different between trap and longline hook fisheries and trawl. For instance, as noted above, MP3 (**cap.5_hstAl_am5**) was the next best option for trap and longline hook, in terms of both average annual TAC and cumulative value (Table 4). In contrast, the next best option for trawl landed value was MP13 (**cap1.5_rctAl_am5**), which had the lowest average annual TAC. The value difference for trawl between this option and full retention was only $5 million over 10 years, while the value differences between MP3 and MP13 for trap and longline hook were $33 million and $32 million, respectively. Thus, the results suggest trap and longline hook fisheries would benefit from more restrictive at-sea regulations while trawl would benefit from the least restrictive at-sea regulations, even without considering the implications for trawl's main target fisheries.

Robustness operating model set: under robustness F_{2022} tuning

Unlike the reference OMs, in which biomass and catch increases are large over the next decade, sablefish biomass and catch projections under the robustness OMs increased more gradually and generally required lower fishing rates to meet conservation objectives. In fact, these simulations closely resemble previous sablefish MSE results in suggesting relatively conservative harvest strategies. Tuning MPs to meet Objective 3 under the robustness OMs was more challenging because higher Fs had more noticeable impacts on the short-term decline objective (P(decline); Table 3). MP tuning produced relatively low target fishing mortality rates ranging from 5.24% (current MP) to 6.7% (full retention). Whereas the probability of catches less than 1,992 t

(Objective 4) were negligible (< 3%) in the reference OMs, they were all greater than 17% in the robustness OMs except for full retention, which was 8% (Table 3). Average annual catch under the robustness OMs ranged from 2,310 t under the current MP (MP15, noCap) to 2,770 t under full retention. Thus, the current MP with no limit on at-sea releases performed worse than any of the cap options, although most of the differences between cap options and the current MP were 80 t or less (Table 3). There was a slight difference in the rank order of MPs (ranked by average 10-year catch) under the robustness OMs, although the absolute difference among most MPs was small. Annual TACs were also more sensitive to variation in the MP data as indicated by higher average annual variation in catch (AAV), which was 14-16% under the robustness OMs compared to 7-9% under the reference OMs (Table 3). This probably occurs because the stock is sometimes assessed below BMSY, leading to changes in both stock status and the maximum target fishing mortality, which has been relatively common in realized applications of sablefish MPs over the past several years. Cumulative 10-year landed value under the robustness OMs was approximately 60% of landed value in the reference OMs. Although the absolute scales differ, the cumulative value patterns were similar to the reference set; that is, full retention produced the highest overall value, as well as value in each fleet, and the next best at-sea release regulation option was the least restrictive for trawl and next-most-restrictive for trap and longline hook (Table 5).

Robustness operating model set: under reference F_{2022} tuning

TBA: describe results of MP performance using robustness set of OMs but maximum target harvest rates tuned from the reference set of OMs, and visa-versa. This allows us to understand the risks of getting it wrong when it comes to the magnitude of Year 2015 recruitment (Tables 6 and 7)]

Conclusions

The current MP for Canadian sablefish (MP15, noCap), involving no limits on at-sea releases, was able to meet conservation objectives under both reference and robustness OMs, although it ranked near the bottom in terms of catch performance compared to MPs with at-sea release regulations. Of the MPs regulating at-sea releases, MP14 (full retention), MP3 (50% cap, historical allocation, and 5-year amortization), and MP7 (100% cap, historical allocation, and 5-year amortization) ranked among the top-3 under both reference and robustness OMs, provided that maximum target fishing mortality rates were tuned to meet conservation objectives. As indicated in previous MSE work, full retention MPs result in the highest average annual landed catch while still allowing the fishery to meet conservation objectives in both the short- and long-term. Landed value is also greatest for a full retention MP, suggesting that price premiums that place relatively low value on sub-legal sablefish are not that influential. These results held across reference and robustness OMs. The full retention MP produced 500 t and 310 t more average annual landed catch in the reference and robustness OMs, respectively, compared to the next-best performing MP. Given the current (approximate) price structure for sablefish size, these differences equate to approximately $8.5 million/yr in average annual total landed value under the reference OM and $5.3 million/yr under the robustness OM. For MPs not involving full retention, the range of differences in annual average catch among all MPs was only 29 t and 16 t, for reference and robustness OMs, respectively. These equate to approximately $5.6 million/yr in average annual total landed value under the reference OM and $2.4 million/yr under the

robustness OM. The largest conservation risk appears to be tuning an MP to meet conservation objectives under the reference OM only to find out, in the future, that the 2015 year-class was over-estimated, or did not materialize as hoped (which would not be unprecedented in fisheries). We tested the implications of such a scenario by simulating a cross-test of MP performance under the robustness OMs where maximum target fishing mortality was tuned under the reference OMs. As expected, performance against Objective 3 was poor for all MPs in these trials. In addition, most MPs, except full retention, also failed Objective 2 under the robustness OMs by causing relatively high probability of short-term stock declines. Thus, MPs tuned under the reference OMs carry relatively high risks if the 2015 recruitment fails to materialize at 5 times the historical average. On the other hand, the opposite cross-test — robustness-tuned MPs against the reference OMs — showed that robustness-tuned MPs do exceptionally well against conservation objectives under the reference OMs and still produce 10-year average catch in the 3,400 – 4,200 t range or approximately 90% of the annual yield produced by MPs tuned specifically to the reference OMs. Therefore, the cost in yield of adopting a robustness-tuned MP is relatively low given the high additional certainty regarding conservation performance. These annual yields are still considerably larger than present. Revisions to the strategy could be made in the next MSE cycle when the 2015 year-class size should be better estimated as several more years of fishery and survey data accumulate.

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