# 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 [@cox2019evaluating]. The following sub-sections provide

brief descriptions of the updated data used to condition the

Sablefish OM, the changes required to fit that data, and

the new MP elements that were tested. Additional

details of the simulation procedures, diagnostic checks, and

performance measure calculations are given in @cox2019evaluating.

In this Science Response we specifically:

1. Describe OM 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 five reference OMs and five

robustness trial OMs based on uncertainties about

Sablefish stock status and productivity (reference OMs) and

year 2015 recruitment (robustness OMs); and

3. Simulate and rank candidate MPs under the reference and

robustness OMs based on performance against Fishery Objectives

(see below).

## Methods

### Updates to the OM

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. We also obtained new

catch-at-age and catch-at-length datasets 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 OM 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 (Figure A5), (ii) reducing the youngest modelled

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

2015, rather than using the expected recruitment off the

stock-recruit curve, (v) updating the ageing-error matrix to use

a simpler normal approximation recommended in the previous CSAS

review [@cox2019evaluating]; 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 three most recent years,

mainly because this would have been the first age-at-entry

observations provided to the model and 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) above (i.e., estimated recruitment deviation in 2015)

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 [@cox2019evaluating]. Briefly, we derived five 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 five combinations were chosen to

represent the joint marginal mean of 2018 biomass and steepness and four

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). This set of five OMs was chosen to maintain

consistency with the previous MSE cycle [@cox2019evaluating]. For each

of the five 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 five centres as a

plausibility score for weighting MP performance across the

five OMs within each of the reference and robustness sets.

#### Robustness OMs

The robustness OMs were identical to the five 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 recruitment

based on the stock-recruitment relationship resulting in an

expected 2015 year class that was more similar

to the long-term average ($\sim 2.63$ million).

### Fishery Objectives

Objectives for the B.C. Sablefish fishery have been developed

iteratively over the past decade via consultations between

fishery managers, scientists, and industry stakeholders

[@cox2009evaluation; @cox2011management; @dfo2014performanc;

@cox2019evaluating]. 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 OM 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(TAC < 1,992 t)\*\*: Minimize probability that annual TAC levels

are below 1,992 tonnes measured over two Sablefish

generations; and

5. \*\*MaxCatch\*\*: Maximize the average annual catch over 10 years

subject to Objectives 1-4.

Performance measures corresponding to Fishery 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

@cox2019evaluating.

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 management measures

that require landing small Sablefish (e.g., no size limit). Therefore,

in addition to presenting catch performance statistics (e.g., Fishery Objective 5), we

also computed cumulative revenue over 10 years and average revenue

per tonne by fleet (because the size composition of the catch also differs by

fleet).

### Management procedures

A management procedure 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 2011 and revised in two subsequent MSE iterations. Generally, the

MP consists of (i) \_\_data\_\_ - landed catch and three biomass indices;

(ii) \_\_assessment method\_\_ - a surplus production model with

observation and process errors for estimating stock biomass from the biomass

indices and landings; (iii) \_\_harvest control rule\_\_ - a 60:40 harvest control rule

(HCR) in which the target harvest rate is adjusted from 0% when the estimated biomass

is below 40% of $B\_{MSY}$ to a maximum value when estimated biomass is

above 60% of estimated $B\_{MSY}$; (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 2017 to 5.5% in 2021. Total

TACs are allocated among the three sectors according to

40.37% for longline trap, 50.90% for longline hook, and 8.75%

for trawl, with the remaining quota being reserved for

surveys. The trawl allocation is based on negotiations between

the sectors that fixed trawl allocation in previous MSE work

[@cox2011management], while the trap and hook split is calculated

based on the average proportion of catch in each sector over the

years 2009 - 2018.

For this Science Response, we evaluated performance of the current MP for

Sablefish, a no fishing reference case, and 15 variations of the current MP

that only vary in their at-sea release management measures. The MP variants are

constructed by combining three 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

464 t of at-sea releases that occurred between 2006 and 2018. The

current MP involves no cap (unlimited at-sea releases without penalty),

while a no size limit (\*\*NSL\*\*) case allows no at-sea

releases (all fish brought on-board vessels must be landed and

counted against the TAC).

2. \_\_fixed allocation among fleets\_\_ (i.e. trap, longline hook, trawl) of

the total at-sea release cap. 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.

In this Science Response, MPs are named by combining the three at-sea

management measures detailed above: CAP\_ALLOCATION\_AMORTIZATION. For example,

the \*\*cap.5\_hstAl\_am5\*\* MP involves a total at-sea

release cap that is 50% (0.5) of the historical average (\*\*cap.5\*\*), a cap

allocation among fleets that is based on the historic (2006-2018),

fleet-specific average proportions (\*\*hstAl\*\*), and a 5-year amortization

period for at-sea release overages (\*\*am5\*\*). The two special cases to this

naming convention are the current MP (\*\*noCap\*\*), which has no cap,

and no size limit MP (\*\*NSL\*\*), which has no releases (all fish are landed,

regardless of size). For 0% caps, only the amortization period for overages

would apply (e.g. \*\*cap0\_am5\*\*) with all at-sea releases counted as overages.

#### A worked example at-sea release management measures for \*\*cap.5\_hstAl\_am5\*\*.

To illustrate how we simulated the implementation of the at-sea release

management measures, below 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, $t$ is year, $g$ is fleet, and $p(g)$ is proportion

of releases allocated to fleet $g$.

1. Calculate 50% at-sea release CAP for year and fleet (464 t is the

2006 - 2018 average):

\begin{equation\*}

CAP(t,g) = 0.5 \cdot 0.464 \cdot p(g).

\end{equation\*}

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 $CAP(t,g)$: \tabularnewline

\begin{equation\*}

o(t,g) = R(t,g) - CAP(t,g).

\end{equation\*}

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:

\begin{equation\*}

O(t + k,g) = O(t+k,g) + o(t,g)/5, \mbox{ for } k = 1, ..., 5.

\end{equation\*}

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 management measures):

\begin{equation\*}

TAC(t,g) = TAC'(t,g) - O(t,g).

\end{equation\*}

This approach aims to create an incentive to avoid sub-legal Sablefish via

future TAC reductions (assuming 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 quantifies MP performance

against performance statistics representing each of the the Fishery

Objectives. The first three performance statistics are represented by 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 ones 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 performance statistics while only differing on one. If

this were the case, then the decision on which MP is preferred would be

straightforward – choose the MP with better performance on the fifth statistic.

Unfortunately, MPs typically differ on all five performance statistics simultaneously, which

makes it difficult to compare performance without, at least, establishing some

equivalency between conservation probabilities (Fishery Objectives 1-3) and

short-term average catch (Fishery Objectives 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. Fishery 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 Fishery Objective 3 would

require severe short-term catch restrictions for highly uncertain long-term

benefits. Over the past year, the Sablefish industry and DFO agreed to revise

Fishery 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 Fishery Objective 3 performance from, say,

$P(B\_{2052} \geq B\_{MSY}) = 0.5$ to $P(B\_{2052} \geq B\_{MSY}) = 0.55$? The probability

difference of only five percentage points could mean a difference of several

hundred tonnes in average annual catch, which would cumulatively add up

to tens of millions of dollars in revenue. MPs that perform better

under Fishery Objective 3 almost always do so at the expense of performance

under Fishery Objectives 4 and 5.

We aimed to simplify interpretation of MP performance by tuning all MPs to

a standard $P(B\_{2052} \geq B\_{MSY}) = 0.5$, which ensured that all MPs meet

Fishery Objectives 1-3.Tuning was achieved by iteratively adjusting $F\_{2021}$,

which is the maximum target fishing mortality rate scheduled for

Year 2021 (as part of 5-year phase-in period for the current MP)

[@cox2019evaluating], until each MP satisfied Objective 3, i.e.,

$P(B\_{2052} \geq B\_{MSY}) = 0.5$. These $F\_{2021}$ target maximum

harvest rates then replace the scheduled maximum target harvest rate

of 5.5% for Year 2022 and beyond.

Each MP was tuned seperately to the reference and robustness OM scenarios,

leading to different $F\_{2021}$ values for each MP (i.e., once for each

OM). We then simulated a cross-test in which $F\_{2021}$ values tuned

under the reference OM were applied in MPs for the robustness OM and

vice versa. The cross-test reveals the potential biological and catch

consequences of using the wrong $F\_{2021}$ values.

## Results

### Operating model update and implications for stocks status

Operating model fits to survey and fishery biomass indices were similar to

previous versions, where both the model and data showed a long-term steady

decline. The most recent two stratified random survey (StRS) data points

(2017 and 2018) were substantially higher than the preceding 15 years,

suggesting potential increases in the offshore stock biomass (Figure 2).

In general, the age-structured OM fit the age-composition data

reasonably well (Figure 3). Fits to the trap fishery age-composition

continued to show a large positive residual at the plus-group age 35+ for males, and to a more neglibale extent for females (Figure 3, Trap:). Fits to the trawl age-composition also also showed a large

positive residual for age-2 males, which appeared to arise from the 2017 and

2018 samples that were large and, therefore, tended to drive the average to have

what appeared to be a large positive residual at age-2. This was

a potential contributing factor to the estimated size the estimated 2015 year-class.

Model fits to the standardized survey were similar to previous OM versions —

patterns lie somewhere between the fishery age-composition fits (worst)

and StRS fits (best) (Figures 2 and 3). The OM continued to fit StRS very well,

which probably arose because the StRS is specifically designed for

monitoring the offshore Sablefish population (unlike all other data

series).

The updated stock status of Canadian Sablefish depended on the absolute size

of the 2015 year-class (age-3 in assessment Year 2018). The raw

estimate of this year-class was about eight times the historical average (see

Robustness OMs section above; Figure 4, bottom row), which created the

impression of the largest recorded recruitment from one of the

lowest spawning biomasses ever observed. Such a high recruitment at low

spawning biomass had cascading effects on the model parameter estimates,

biological reference points, and estimated current biomass. These effects

included: (i) the estimated stock productivity (i.e., stock-recruitment

steepness parameter) was adjusted upwards; (ii) the most productive stock

size ($B\_{MSY}$) was adjusted downwards, because the stock is apparently more

productive at low biomass; (iii) the optimal fishing mortality rate

($F\_{MSY}$) was adjusted upwards because the more productive stock can

sustain higher fishing pressure; and (iv) current spawning biomass was

adjusted upwards because about 20-25% of age-3 fish were maturing. Although

these were positive and encouraging signs that Sablefish status is improving,

there was some risk in tuning future MPs to substantial

model changes that arose from a small number of observations. Other

Pacific groundfish fisheries (e.g., Pacific Hake [\*Merluccius productus\*]

and Gulf of Alaska Sablefish) have treated initial large estimated

recruitments with caution until the data used to estimate them

more fully materialize. Here, we dealt 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

MPs.

Under the large 2015 year class, the OM fit showed

the Sablefish stock status as generally good (Table 1, 2018 Fit).

Spawning biomass in 2018 was about twice the limit reference point

(LRP), up from about 1.5 times the LRP, which

was itself revised from the 2016 fit of about 1.17 times the LRP . This

change indicated that the BC Sablefish stock might have moved

out of an overfished state. Similarly, the posterior probability

of the last year's biomass being above the limit

reference also improved from 2016 to 2018, increasing

from 93% (2016 fit) to 100% (2018 fit).

### Management procedure evaluation results

#### Reference OM set under reference $F\_{2021}$ tuning

As expected, recruitment from the 2015 year class was the primary driver

of projected spawning biomass and fishery outcomes in the reference

OM simulations. Spawning biomass increased rapidly over the first

five years of the projection period as age-3 (i.e., 2015

year class) fish became fully recruited to the fisheries and then the

spawning biomass (Figures 4 and 5, top row). Spawning biomass then trended

downward toward $B\_{MSY}$ over the long-term as the 2015 year class was fished down

and recruitments returned to expected values around the stock-recruitment

relationship (i.e., recruitments for 2016 onward are all simulated off the

stock-recruitment relationship).

Under these conditions, all MPs met all the biological criteria

defined by Fishery Objectives 1-3 (Table 2). All tuned MPs were able to meet Fishery

Objective 3, where median spawning biomass (top row of Figure 5) achieves

$B\_{MSY}$ (horizontal dashed line with green dots at end points) by the

final year (2052). Some MPs are able to achieve $B\_{MSY}$ 15-20 years prior to

the final year, while others just make $B\_{MSY}$ by the final year.

Tuning MPs to meet Fishery Objectives 1-3, and specifically

treating Fishery Objective 3 as a target, focuses MP performance

differences on average annual catch over the next 10 years (Table 2; Fishery Objective

5). As expected, MPs with more restricted at-sea release

management measures ranked higher in terms of 10-year average catch (Table 2)

with the values ranging from 4,530 t per year for no size limit (MP17 \*\*NSL\*\*)

to 3,710 t per year for management measures with a cap 150% higher than average,

recent cap allocation among fleets (i.e., allocating 59% to trawl), and 5-year

amortization (MP14 \*\*cap1.5\_rctAl\_am5\*\*). This difference was attributable

to two factors. First, the key assumption here was that fishing activity

stops once the TAC is reached, so no size limit results in less mortality

of sub-legal fish over all fleets. This led to a large reduction in

growth overfishing for the no size limit MP — gains in Sablefish

body growth were 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 could operate at higher

fishing mortality rates because survival over sub-legal size classes

was higher and therefore more fish recruit to fisheries and the

spawning stock. Indeed, the apparently conservative current MP

maximum target $F=5.5\%$/yr was largely the result of lower survival

through sub-legal size classes, which inhibited MPs from meeting

the future spawning biomass Fishery Objective 3. In contrast, the no

size limit MP almost met Fishery Objective 3 despite a maximum target

$F=7.5\%$/yr on legal-sized fish (Table 2; $F\_{2021}$).

Differences in average annual catch were smaller among at-sea management measures

that involved a size limit. A 0% at sea-release cap and five year

amortization (MP6) resulted in catches about 400 t higher than the

current MP (MP15; Table 2), while the gain was 300 t for a 10-year

amortization (MP5).

An at-sea release cap of 50% of the historical average resulted in average

annual catch levels 160 t and 300 t higher than the current MP, depending on the allocation

and the amortization period (MP3 and MP4 vs. MP15; Table 2). Interestingly,

a 10-year amortization with a 0% cap gives identical 10-year average catch

to a 50% cap with a historical allocation and 5-year amortization period

(MP5 vs MP6; Table 2).

An at-sea release cap equal to 100% of the historical average also produced

200 t more average annual catch than the current MP, as long as the

cap was allocated according to the historical at-sea release proportions

and amortized over five years (MP8 vs MP15, Table 2). The similarity to the

lower 50% caps described above mainly reflects cap allocation to the trawl

fleet, where the recent allocation (59%) is approximately twice the historical

(33%), so switching to the lower, historical allocation allowed for doubling

the cap, i.e., the total at-sea release amounts allocated to the trawl fleet

were 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

(MP13 vs 15; Table 2). 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 decoupled

at-sea releases and recruitment to some (small) degree and allowed trawl

fishing to continue past current sub-legal catch rates.

As caps increased under recent at-sea release allocation,

the effect of amortization switched from 5 years being better (under low

caps) to 10 years being better (under high caps). Although the differences

were small (MP12 vs MP3; Table 2), the switch

probably occured 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

had a direct effect on TACs, with longer amortization periods having less

impact because overages spread over the longer period have less

impact on annual TAC adjustments.

We initially expected that a no size limit and/or lower cap management measures

would negatively affect fishery revenue because the landed catch

would consist of higher proportions of sub-legal fish. Price premiums

for Sablefish (Table 3; C. Acheson per comm., Spring 2019) may result

in several dollars per pound difference between sub-legal (< 3 lbs) and

large (4/5+) legal-sized Sablefish.

Indeed, the average revenue per

tonne was approximately $170 lower for a no size limit trap fishery

compared to noCAP (Table 4), while revenue was approximately $20

and $1,070 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. Cumulative revenues over ten years were

$47 million, $18 million, and $15 million higher for trap, longline

hook, and trawl fisheries under the no size limit MP compared to

the next best MP from an average annual catch perspective (i.e., MP6,

\*\*cap0\_am5\*\*; Table 4).

The next best at-sea release management measures, from a total catch and

cumulative revenue perspective, after the no size limit MP

were different between trap and longline hook fisheries and trawl.

For instance, as noted above, MP6 (\*\*cap0\_am5\*\*) was the next best

option for trap and longline hook, in terms of both average annual

TAC and cumulative revenue (Table 4). In contrast, the next best option

for trawl revenue was MP14 (\*\*cap1.5\_rctAl\_am5\*\*), which had the

lowest average annual TAC. The revenue difference for trawl between

this option and no size limit was only $5 million over 10 years,

while the revenue differences between MP6 and MP17 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 management measures while trawl would benefit from the

least restrictive at-sea management measures other than the status quo, even

without considering the implications for trawl’s main target fisheries.

#### Robustness OM set under robustness $F\_{2021}$ tuning

Unlike the reference OMs, in which biomass and catch increases were 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 Fishery Objecitives 1-3 (Figures 6 and 7). In fact, these simulations closely

resemble previous Sablefish MSE results, which suggested that relatively

conservative harvest strategies are needed over the long-term to meet

the Fishery Objecitives 1-3 [@cox2019evaluating].

Tuning MPs to meet Fishery Objective 3 under the robustness OMs was more challenging

because higher $F$s had more noticeable impacts on the short-term decline

objective (P(decline); Table 5). MP tuning produced relatively low target

fishing mortality rates ranging from 5.2% (current MP) to 7.2% (cap0).

These low $F$s also had the effect of a higher probability of catches

less than the 1,992 t (Fishery Objective 4); whereas these were

negligible (< 3%) in the reference OMs, they were all greater than

15% in the robustness OMs except under the no size limit MP,

which was 8% (Table 5).

Average annual catch under the robustness OMs ranged from 2,305 t under the

current MP (MP15, noCap) to 2,767 t under no size limit (MP17, NSL). Thus,

the current MP with no limit on at-sea releases performed worse than any

of the cap options by as much as 200 t per year for the top-ranking

cap options (Table 5). There was a slight difference in

the rank order of MPs (ranked by average 10-year catch) under the

robustness OMs compared to the reference OMs, although the absolute

difference among most MPs was small.

Average annual variation in catch (AAV) was 9-11% under the robustness

OMs compared to 7-8% under the reference OMs (Table 5). This probably

occurs because the stock remains below $B\_{MSY}$ for most of the

projection period and is, therefore, assessed below $B\_{MSY}$ at times.

Assessment changes in both stock status and the maximum target fishing

mortality have been relatively common in realized applications of

Sablefish MPs over the past several years and this causes higher

interannual variability in TACs.

Cumulative 10-year revenue under the robustness OMs was approximately

60% of revenue in the reference OMs (Table 6). Although the absolute scales

differ, the cumulative value patterns were similar to the reference

set; that is, no size limit produced the highest overall value, as

well as value in each fleet, and the next best at-sea release management measure

option, from a cumulative revenue perspective, was the most restrictive

for trawl and next-most-restrictive for trap and longline hook (MP6,

\*\*cap0\_am5\*\*; Table 6).

#### Cross tests of OMs under opposite $F\_{2021}$ tuning

As expected, there was considerable asymmetry of risk between

MPs tuned under the robustness OMs and reference OMs. For example,

when MPs were tuned to meet Fishery Objecitives 1-3 under the

reference OMs, but the 2015 year class

failed to materialise as in the robustness OMs, almost all MPs failed to meet

the performance criteria for Fishery Objectives 2 and 3 (Table 7). The benefit

of accepting this conservation risk was approximately 150 t of

extra annual catch, or at most a 6% increase in average annual

catch.

On the other hand, if MPs were tuned to meet Fishery Objecitives 1-3 under

the robustness OMs, but the 2015 year class materialised as expected

under the reference OMs, then, all MPs continued to meet

the Fishery Objecitives 1 - 3 (Table 8). This more risk averse

strategy (from a biological perspective) comes with the cost of

reduced average annual catch of approximately 300 t for all MPs,

or 6.5-8% of the reference-tuned catch.