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Southwest Nova Scotia/Bay of Fundy Herring: Management Strategy Evaluation Framework

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Foreword

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

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ABSTRACT

An approach for conditioning operating models (OMs) for the southwest Nova Scotia/Bay of Fundy (SWNS/BoF) Atlantic Herring (*Clupea harengus*) management strategy evaluation (MSE) was developed in 2020 (Carruthers et al. 2023). This document completes the MSE framework that will be used to evaluate the performance of candidate management procedures (MPs) for the SWNS/BoF Herring fishery by defining: 1) the MSE objectives and associated performance metrics for evaluating the objectives, 2) the reference set of OMs that will serve as a testbed for evaluating the performance of MPs, 3) the closed-loop simulation approach used for the evaluation of MPs, 4) the exceptional circumstance criteria for triggering an evaluation of the suitability of the advice from an MP, and 5) the proposed frequency and timing of interim-year updates to be provided between full peer-reviewed frameworks, and the recommended timing of the next framework. The application of the MSE framework is demonstrated in this document using a set of candidate MPs. Candidate MPs can continue to be developed and evaluated using this MSE framework.

INTRODUCTION

A management strategy evaluation (MSE) framework has been developed to identify candidate management procedures (MPs) for the southwest Nova Scotia/Bay of Fundy (SWNS/BoF) Atlantic Herring (*Clupea harengus*) fishery that are consistent with national policy guidance based on Fisheries and Oceans Canada's (DFO) Precautionary Approach (PA) policy (DFO 2009). The MSE framework includes a set of operating models (OMs) that are conditioned on fishery data and are used to characterize the dynamics of the fishery. The general OM conditioning approach is described in Carruthers et al. (2023). Each OM represents an alternative hypothesis for the fishery dynamics. The MSE framework uses closed-loop simulations to evaluate the performance of candidate MPs against a set of objectives. The MSE objectives do not include all objectives for the fishery (additional objectives are defined in the Integrated Fisheries Management Plan for the stock; DFO 2020a) but consist of a conservation objective (defined by DFO, based on the PA policy) and a set of objectives defined by stakeholders that can be quantitatively evaluated in the framework. The MP evaluation is conducted on a reference set of OMs that consists of the most plausible hypotheses. Candidate MPs are eliminated from consideration when they do not meet a minimum performance standard for the conservation objective. MP selection involves exploring trade-offs in performance among the remaining objectives. The application of the MSE framework is demonstrated using a set of candidate MPs. Candidate MPs can continue to be developed and evaluated using this MSE framework

Atlantic Herring (herein referred to as Herring) is a coastal pelagic species found on both sides of the North Atlantic Ocean. Herring are a schooling fish that form predictable aggregations for feeding, over-wintering, and spawning. The fishery for Herring in SWNS/BoF, in Northwest Atlantic Fisheries Organization (NAFO) area 4VWX, is one of the largest and oldest fisheries in the region. SWNS/BoF Herring are harvested by multiple gear types: purse seine (more than 80% of the current total landings), gillnet, weir, shutoff (nearshore seining), and trap nets.

The 4VWX Herring fishing area contains a number of spawning areas, separated to various degrees in space and time. Spawning areas in close proximity with similar spawning times, and which share a larval distribution area, are considered part of the same component. The stock structure is complicated as Herring migrate long distances and mix outside of the spawning period both with members considered part of the same component and with members of other components (Stephenson et al. 2009). For the purposes of evaluation and management, the 4VWX Herring fisheries are divided into four components: the SWNS/BoF spawning component, the offshore Scotian Shelf spawning component, the coastal Nova Scotia spawning component, and the Southwest New Brunswick (SWNB) migrant juveniles. The SWNB migrant juvenile (weir) fishery occurs within the spatial bounds of the SWNS/BoF stock area but are considered a separate management component and the weir fishery lands a mixture of Herring from different spawning areas. The SWNS/BoF spawning component is the largest management unit and this fishery is managed by an annual total allowable catch (TAC). The main spawning areas are German Bank, Scots Bay, Seal Island, and Trinity Ledge, but fishing also occurs on aggregations outside of these spawning locations.

The SWNS/BoF Herring stock has been without a modeling framework for approximately two decades and management decisions have been based on trends in an acoustic index of spawning stock biomass (SSB). The SWNS/BoF Herring management component was last assessed in 2018 (DFO 2018) as part of the assessment of 4VWX Herring. Stock status updates for SWNS/BoF Herring were provided in 2019, 2020, and 2021 (DFO 2020b,c, 2021) and the stock was below its limit reference point (LRP) and in the critical zone of DFO's PA policy framework (DFO 2009) in 2018, 2019, and 2020. The stock status for 2021 has not yet been determined. Although a rebuilding plan (DFO 2013) has been developed for the stock, the lack of an analytical modeling approach to provide short term projections has prevented Science from providing advice on harvest levels. The Science advice for the last three years has been to keep exploitation to the lowest possible level until the stock is out of the critical zone (DFO 2020b,c, 2021).

MSE OBJECTIVES

The following conservation objective was defined by DFO to be consistent with DFO's PA policy (DFO 2009) and serves as a minimum performance standard for MP selection:

1. Maintain the stock above the LRP with at least 75% probability in each year in years 10–25 of the projection period for each OM in the reference set.

Additional MSE objectives were defined by stakeholders:

2. Maintain SSB above a target biomass in the long-term.
3. Maximize short-term yield.
4. Maximize long-term yield.
5. Minimize variability in catch.
6. Limit the removal of small fish.

ANALYSIS

PERFORMANCE METRICS

Performance metrics are used to quantitatively assess the ability of MPs to meet the MSE objectives. For the primary conservation objective (objective 1), a minimum performance standard is defined as:

- P(model estimated SSB > mean model estimated SSB from 2005–2010) > 0.75 in each year in years 10–25 of the projection period for each OM in the reference set.

MPs that do not meet the minimum performance standard are eliminated from further consideration. The LRP for the stock is the mean value of the acoustic index of SSB from 2005–2010 (Clark et al. 2012) so the same time period was used for model estimated SSB to reflect this period of low biomass. The probability value of 0.75 represents the lower end of the range for a "high probability" defined in the PA policy (DFO 2009). The 10 year time period was defined as approximately two generations for SWNS/BoF Herring (upper end of the 1.5–2 generation range defined as a reasonable timeframe in the PA policy; DFO 2009). Although the least conservative values from the ranges defined in the PA policy were chosen for a "high probability" and "reasonable time frame", the performance standard must be met for each OM in the reference set.

The other performance metrics are used only to rank the relative performance of MPs and are used to evaluate trade-offs among MPs. A minimum performance value is not defined for these metrics and they are not used to eliminate MPs from consideration. The time periods used for the performance metrics were defined based on an approximate median response from a survey completed by stakeholders. An upper stock reference point has not been formally defined for the stock so target biomass values of the acoustic index of SSB of 425 kt and 500 kt are used to evaluate objective 2. Since the performance of MPs relative to objectives 2–6 is used only to rank the performance of MPs, the target value of the acoustic index of SSB and the specific time frames chosen for the performance metrics for these objectives will influence the magnitude of the performance metric, but should not influence the relative ranking of MPs under similar target biomass values and similar time frames. The performance metrics for objectives 2 to 6 are defined as:

2. a. P(3-yr moving average index of SSB > 425 kt) over years 16–25.

   b. P(3-yr moving average index of SSB > 500 kt) over years 16–25.
3. Maximum yield over years 1–5.
4. Maximum yield over years 6–25.
5. Average interannual variability in yield over years 1–25.
6. Percent of small fish by number (< 23 cm) over years 1–15.

Performance metrics for each MP were calculated separately by OM across simulations and years for the entire time period stated.

DATA

Key uncertainties for the population dynamics and the fishery were identified by stakeholders during a workshop held January 23–24, 2020. The fishery population dynamics were modeled for the MSE framework using a multi-fleet stock reduction analysis with an initial 36 OMs (revised from Carruthers et al. 2023). These OMs result from a cross of all levels of four axes of uncertainty: natural mortality rate (*M*), future growth, resilience, or steepness of the stock recruitment relationship (*h*), and inclusion of the weir catch and composition data (Table 1). The models assume a constant Beverton-Holt stock recruitment relationship parameterized with an initial (over the first five years) *h* of 0.65 or 0.95 to represent low and high scenarios of resilience at low SSB. Herring was assumed to have a relatively high *h* and the range of *h* values was selected based on likelihood profiles (Carruthers et al. 2023). The *M* scenarios were a constant *M* = 0.35 and a low and high age-varying *M* (Table 1). The models were conditioned to catch (1968–2020) and age (1970–2019) composition data, an acoustic index of SSB (1999–2020) with age composition data for the index (1999–2019), and a larval survey used as an index of spawning stock abundance (1972–1998, 2009) using the rapid conditioning model in SAMtool package (Huynh et al. 2022) in R (R Core Team 2021). The model fleet structure consisted of a purse seine fleet (generally > 90% of landings) with logistic selectivity, a gillnet fleet with dome shaped selectivity, and an “other” fleet that consists of all other gear types with dome shaped selectivity. The weir catch axis of uncertainty involves the addition of a fourth “weir” fleet that consists of weir and shut-off (near shore seining) catch and age composition data from SWNB. The weir catches are currently not considered as part of the SWNS/BoF stock; however, there are data to suggest connectivity between the SWNS/BoF stock and the Herring caught in the weir fishery (DFO unpublished tagging data). This weir fleet is modeled assuming dome shaped selectivity and historical catch proportions are variable, with the 5^{th}, 50^{th}, and 95^{th} percentiles of the weir catch from 1968 to 2018 being 4%, 18%, and 27% of the total catch for all four fleets.

Significant changes in Herring growth have been observed over time (Figure 1). Three future growth scenarios are considered in the OM projections:

- A: Future weight-at-age is the mean of the last three years.
- B: Future weight-at-age is a continuation of the change in mean weight-at-age observed over time based on the regression of $\log_{10}$(weight) vs. year by age.
- Binv: Future weight-at-age is a reversal of the magnitude change in weight-at-age in B.

OPERATING MODELS

A reference set of OMs was defined as a subset of the initial 36 OMs to represent plausible alternative hypotheses that are used as a testbed for MP evaluation. The remaining OMs from the initial 36 that converged were assigned to a robustness set. The robustness sets of OMs represent hypotheses that are less likely or lack support and are used for evaluating MP performance, but MPs are not eliminated from consideration if they don't meet the minimum performance standard for robustness OMs.

OMs 20, 23, and 35 with low *M* (level 2), low *h* (level L), and weir catches included (level +) did not converge. These OMs would converge if the likelihood weighting for the survey age composition data was increased. An evaluation was conducted to assess the correlation between the model estimated SSB and the acoustic index (1999–2020). The model estimated SSB was negatively correlated with the acoustic index of SSB for the revised OMs 20, 23, and 35 so these OMs were eliminated based on plausibility. The historical trajectories of SSB/SSB_{MSY} (SSB relative to SSB at maximum sustainable yield) and F/F_{MSY} (fishing mortality rate relative to fishing mortality rate at maximum sustainable yield) were evaluated for each OM using equilibrium MSY assumptions with annual growth, maturity, and selectivity estimates. OMs with high *M* and high *h* (OMs 3, 6, 15, 18, 27, and 33), as well as models with low *M* and low *h* (remaining OMs 8, 11, 29) had historical F/F_{MSY} ratios that implied that stock had either been overexploited or underexploited over nearly the entire time series, suggesting the assumed combinations of *M* and *h* are extreme and not likely for SWNS/BoF Herring. These OMs were moved to a robustness set of OMs. A set of 24 OMs remained for consideration to include in the reference set. Projections of $F = 0$ (no fishing) for these 24 OMs were conducted to evaluate the range of future productivity scenarios captured by these OMs. OMs with high *M* and low *h* resulted in very low productivity such that SSB increased slightly in the first few years and plateaued over the long term and decreased beyond 15 years for growth scenario B (e.g., OM 12). Given the extreme productivity scenarios (both high and low) generated by the OMs with high and low *M*, the reference set of OMs was defined using only OMs with $M = 0.35$, resulting in a reference set with 12 of the initial 36 OMs defined (Table 2).

An evaluation of temporal changes in recruitment and surplus production over time (Figure 2 and 3) revealed a change point for all OMs in the reference set after 1989 for recruitment and after 1985 for surplus production. The change point analysis was conducted using the *cpt.mean* function in the *changepoint* package in R (Killick et al. 2016) with the default parameters to identify step changes in the mean in the time series. The future (projected) recruitment for the reference set of OMs was therefore estimated with statistical properties (mean, variance, and autocorrelation) determined by the recruitment deviations from 1990–2017.

Additional uncertainties are captured in a set of robustness OMs (Table 3). These uncertainties include higher future recruitment and higher future weir catches. The future recruitment scenarios are based on mean recruitment deviations over the historical time series (1968–2017) and future recruitment based on the lower 90% of historical recruitment deviations (Table 3). The higher future weir catch scenarios are 40%, 50%, and 60% of the SWNS/BoF TAC, compared to the assumed 20% in the reference set of OMs (Table 3). Four robustness OMs are defined for each of these uncertainties using $M = 0.35$ from the reference set, the B and Binv future growth scenarios, high and low *h*, and the − and + levels of the weir uncertainty (Table 1) to capture a range of productivity states (Table 3).

CLOSED-LOOP SIMULATIONS

The MSE framework evaluates MP performance using closed-loop simulations using the MSEtool package (Hordyk et al. 2022) in R (R Core Team 2021). The simulation analysis is conducted on each OM/MP combination and involves simulating fishery data for replicate (n = 1,000) simulations from the OM. The choice of 1,000 simulations was based on stability in performance metrics (e.g., 25th, 50th, and 75th percentiles of the projected SSB) across various n values (e.g., Figure 4). Increasing n to greater than 1,000 didn't provide any benefit (e.g., Figure 5). An initial 1,000 replicates are sampled from the OM and in some cases a fishing mortality rate could not be estimated and these replicates are dropped by the software as non-converged iterations. The number of iterations that converged (for the four OMs with unique historical fits in the reference set) were 1,000, 994, 1,000, and 945 for OMs 1, 7, 13, 19, respectively. Each simulation varies in the estimated process error and observation error. Simulated fishery data are generated by applying an observation model (step 1 in Figure 6) with observation error and uncertainty designed to replicate the fishery.

The projected acoustic index is estimated assuming proportionality with the model estimated SSB, with observation error that is estimated based on the statistical properties (variance and autocorrelation) of the acoustic index used in the conditioning of the OM. The estimated hyperstability parameter β estimated from the acoustic index and model estimated SSB (1999–2020) was generally < 1 (Figure 7); however, in the projection period β was assumed equal to 1 (i.e., the acoustic index of SSB proportional to model estimated SSB). The projected values of the acoustic index of SSB are used in a performance metric for objective 2, as the monitoring data in candidate MPs, and used to set trigger values in the exceptional circumstances (Appendix A).

A candidate MP is applied to the simulated data (step 2 in Figure 6) and the MP generates a TAC recommendation. The TAC is implemented (step 3 in Figure 6) using an implementation model which can include a multiplier to account for catches being higher or lower than the TAC. For the OMs with no weir catch included, the multiplier was set to 1 (i.e., catch = TAC). For the OMs with weir catch included, the multiplier was set to 1.2 to account for catches from the weir fleet that are not counted towards the TAC for the SWNS/BoF Herring stock. The assumed 1.2 multiplier represents the approximate ratio of the weir catch relative to the catch for the other three fleets (i.e., the SWNS/BoF stock) over the last three years. This results in removals equal to the TAC for the purse seine, gill net, and "other" fleets (i.e., the SWNS/BoF stock) and additional removals equal to 20% of the TAC advice of the MP for the weir fleet.

The final step of the simulation loop (step 4 in Figure 6) is to remove the catch from the fishery (using the mean selectivity of the last three historical years) by updating the OM. This process is repeated until the end of the 25-year (approximately five generations for SWNS/BoF Herring) projection period. At the end of the projection period, the performance of the MPs can be evaluated.

The assumption of future weir catches being 20% of the SWNS/BoF TAC was evaluated in the robustness set of OMs by defining alternative OMs with catch multipliers of 1.4, 1.5, and 1.6 (Table 3). Higher future weir catches lowered the probability of SSB being above the mean SSB from 2005–2010 for the weir OMs (Figure 8). The higher catch from the weirs did not influence the *minimum probability* of being above the mean SSB from 2005–2010 when the catch multiplier was 1.4 (i.e., the probabilities for OM R3d are greater than OM 10 = OM R3b) or 1.5, but did influence the *minimum probability* for the multiplier of 1.6 (Figure 8).

CANDIDATE MANAGEMENT PROCEDURES

Candidate MPs were defined to provide annual TAC advice as a function of either the annual or the three-year moving average of the acoustic index of SSB. The general shape of the MPs were fixed TACs, fixed harvest rates, hockey stick harvest rate MPs consistent with the provisional harvest control rule in the PA policy (DFO 2009), and step functions (Table 4; Figure 9).

Additional MPs were defined that would separate the allocation of the TAC for the purse seine fleet into two parts: a) catches of juvenile fish, and b) catches of adult fish. These MPs were defined by modifying the OM future selectivity of the purse seine fleet in the projections. The assumed selectivity for the purse seine fleet for juveniles was assumed to be the model estimated selectivity for the weir fleet using the OM with the same *h* assumption; however, the weir fleet selectivity was forced to be zero for age-1 because age-1 Herring are rarely caught by the purse seine fleet. The assumed selectivity for the purse seine fleet for adults was assumed to be the maturity ogive (mean of the last three historical years of data). The overall purse seine fleet selectivity with a TAC allocation of *p*% for juvenile catches was then estimated as a weighted average (*p*% juvenile and (100-*p*)% adult) of the two selectivity curves, then standardized to a maximum selectivity-at-age of 1 (Figure 10).

MANAGEMENT PROCEDURE PERFORMANCE

Candidate MPs were first tested against the conservation objective (objective 1). MPs that did not have a probability of being above the mean SSB from 2005–2010 in each year in years 10–15[1] of the projection period for each OM in the reference set were modified until an MP met this minimum performance standard. The candidate MPs that met the minimum standard (i.e., MPs that met objective 1; Figure 11) were evaluated against objectives 2–6 (Figure 12; Table 5). The relative ranking of MPs for objective 2 is the same using a target biomass of 425 kt and 500 kt. The *fix12.5* MP has the highest short-term yield but the lowest long-term yield and no variability in yield (Figure 12). The hockey stick MPs (*HS_PA_f11.8* and *HS_PA_f13.1a*) have the lowest short-term yield and highest long-term yield and highest variability in yield (Figure 12). These trade-offs among MPs are contrasted in Figure 13. The percent of catch (by number) < 23 cm is similar among MPs unless the future selectivity is specifically changed. Two fixed harvest rate MPs were compared to demonstrate the trade-offs in the harvest of juvenile Herring. The *P3.5* MP has a fixed harvest rate of 3.5% and the *P3.7_20_80* MP has a fixed harvest rate of 3.7%, but with only 20% of the purse seine TAC allocated to juvenile fish. This reduction in percentage of the catch of juvenile Herring results in a median drop among reference set OMs from 51% to 39% in the percent of catch (by number) < 23 cm and the magnitude of the harvest rate that meets the minimum performance standard increases from 3.5% to 3.7% and increases both short-term and long-term yield (Figure 12; Figure 13; Table 5).

EXECPTIONAL CIRCUMSTANCES

Once an MP is adopted, it is used each year to provide the TAC advice. Exceptional circumstances are commonly defined in MSE frameworks to address situations outside the range for which the MP was simulation tested or when the data required to apply the MP are not available. The exceptional circumstance protocol for this MSE framework is attached as Appendix 1 and was developed in collaboration with DFO Resource Management and stakeholders. The reasons for triggering exceptional circumstances are:

A. There is evidence that the stock is in a state that is not considered in the range of hypotheses in the reference set of OMs.

[1] MP performance is displayed using a time period of 10–15 years for objective 1 in this document, based on a request from DFO Resource Management.

B. The data required to apply the MP are no longer available or no longer appropriate.

Specific actions when an exceptional circumstance is triggered have not been formally defined. Exceptional circumstances will be evaluated in annual CSAS update documents and the specific action will be provided in the annual science advice. The indicators, evaluation criteria, frequency of evaluation, and some Science considerations for each of these seven exceptional circumstances are provided in Appendix 1:

1. The acoustic index of SSB is outside the projected range for the MP.
2. Weight-at-age is outside the range of values used in the projections.
3. Weir landings are higher than the range used in the projections.
4. Future catch for the SWNS/BoF stock area is higher than the TAC.
5. New data become available to suggest that the data inputs or model assumptions are no longer valid.
6. The acoustic index of SSB is not available to apply the MP.
7. Estimates of SSB from secondary spawning grounds in the SWNS/BoF stock area become significant in magnitude.

PROPOSED FREQUENCY AND TIMING OF INTERIM-YEAR UPDATES AND FRAMEWORKS

The proposed time frame for using an MP selected from this MSE framework is five years. Annual updates will continue on the status quo schedule of approximately March of each year and will involve applying the MP using the acoustic index of SSB estimated from the previous year and an evaluation of the exceptional circumstances protocol.

CONCLUSIONS

The MSE framework for evaluating MPs against the six MSE objectives for the SWNS/BoF Herring fishery has been described using the reference set of 12 OMs and a set of candidate MPs. This framework can be used to identify candidate MPs that meet the minimum performance standard for the conservation objective to maintain the stock above the LRP with at least 75% probability in each year in years 10–25 of the projection period for each OM in the reference set. MP performance was displayed using a time period of 10–15 years for this objective in this document, based on a request from DFO Resource Management. Trade-offs among MPs can be assessed by comparing performance against the other MSE objectives. The two robustness sets of OMs can be used to further discriminate among candidate MPs. Candidate MPs can continue to be developed and evaluated using this MSE framework.

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Table 1. Operating model factors and levels.

Factor	Level	Description
Natural Mortality	1	*M* = 0.35 (all ages)
	2	*M* = 0.49 (ages 0-2); *M* = 0.26 (ages 3+)
	3	*M* = 0.72 (ages 0-2); *M* = 0.45 (ages 3+)
Future Growth	A	Future growth = mean of last three historical years (2018–2020)
	B	Future growth determined by a linear extrapolation of the temporal trend in $\log_{10}$(weight-at-age)
	Binv	Future growth is a reversal of the magnitude change in weight-at-age from level B
Resilience	H	Initial steepness of Beverton-Holt stock recruitment relationship *h* = 0.95
	L	Initial steepness of Beverton-Holt stock recruitment relationship *h* = 0.65
Weir Catches	-	Southwest New Brunswick weir and shutoff catch and size composition data are excluded from the SWNS/BoF stock
	+	Southwest New Brunswick weir and shutoff catch and size composition data are included from the SWNS/BoF stock

Table 2. Assumed natural mortality rate (M), future growth, steepness (h) and weir catches ("-" = excluded; "+" = included) for the initial set of 36 OMs and the classification (Ref = reference set; Rob = robustness set, X = removed) for the OMs.

OM	*M*	Growth	*h*	Weir	Set	OM	*M*	Growth	*h*	Weir	Set
1	1	A	H	-	Ref	19	1	A	L	+	Ref
2	2	A	H	-	Rob	20	2	A	L	+	X
3	3	A	H	-	Rob	21	3	A	L	+	Rob
4	1	B	H	-	Ref	22	1	B	L	+	Ref
5	2	B	H	-	Rob	23	2	B	L	+	X
6	3	B	H	-	Rob	24	3	B	L	+	Rob
7	1	A	L	-	Ref	25	1	Binv	H	-	Ref
8	2	A	L	-	Rob	26	2	Binv	H	-	Rob
9	3	A	L	-	Rob	27	3	Binv	H	-	Rob
10	1	B	L	-	Ref	28	1	Binv	L	-	Ref
11	2	B	L	-	Rob	29	2	Binv	L	-	Rob
12	3	B	L	-	Rob	30	3	Binv	L	-	Rob
13	1	A	H	+	Ref	31	1	Binv	H	+	Ref
14	2	A	H	+	Rob	32	2	Binv	H	+	Rob
15	3	A	H	+	Rob	33	3	Binv	H	+	Rob
16	1	B	H	+	Ref	34	1	Binv	L	+	Ref
17	2	B	H	+	Rob	35	2	Binv	L	+	X
18	3	B	H	+	Rob	36	3	Binv	L	+	Rob

Note: Reference OMs shaded in grey

Table 3. Robustness OMs (in addition to those identified in Table 2).

OM	*M*	Growth	*h*	Weir	Future Recruitment	Future Weir Catch
R1a	1	Binv	H	-	68–17	20% of SWNS/BoF TAC
R1b	1	B	L	-	68–17	20% of SWNS/BoF TAC
R1c	1	Binv	H	+	68–17	20% of SWNS/BoF TAC
R1d	1	B	L	+	68–17	20% of SWNS/BoF TAC
R2a	1	Binv	H	-	90%	20% of SWNS/BoF TAC
R2b	1	B	L	-	90%	20% of SWNS/BoF TAC
R2c	1	Binv	H	+	90%	20% of SWNS/BoF TAC
R2d	1	B	L	+	90%	20% of SWNS/BoF TAC
R3a	1	Binv	H	-	90–17	40% of SWNS/BoF TAC
R3b	1	B	L	-	90–17	40% of SWNS/BoF TAC
R3c	1	Binv	H	+	90–17	40% of SWNS/BoF TAC
R3d	1	B	L	+	90–17	40% of SWNS/BoF TAC
R4a	1	Binv	H	-	90–17	50% of SWNS/BoF TAC
R4b	1	B	L	-	90–17	50% of SWNS/BoF TAC
R4c	1	Binv	H	+	90–17	50% of SWNS/BoF TAC
R4d	1	B	L	+	90–17	50% of SWNS/BoF TAC
R5a	1	Binv	H	-	90–17	60% of SWNS/BoF TAC
R5b	1	B	L	-	90–17	60% of SWNS/BoF TAC
R5c	1	Binv	H	+	90–17	60% of SWNS/BoF TAC
R5d	1	B	L	+	90–17	60% of SWNS/BoF TAC

Notes:
90–17 = future recruitment based on mean recruitment deviations from 1990–2017 (from reference set assumption)
68–17 = future recruitment based on mean recruitment deviations from 1968–2017
90% = future recruitment based on the lower 90% of historical recruitment deviations
OM names ending in “a” = OM 25 and OM names ending in “b” = OM 10 from the reference set

Table 4. Candidate management procedures (MPs) that meet the minimum performance standard for the conservation objective for the reference set of 12 OMs.

MP	MP Description SI = smoothed index (3-yr moving average) in kt I = annual index in kt u = harvest rate defined in terms of SI	Minimum Annual $P(SSB > SSB_{2005–2010})$ across all 12 OMs [Years 10–15]
NFref	No fishing reference (u = 0)	0.883
fix12.5	Fixed TAC of 12.5 kt	0.752
P3.5	Fixed u of 3.5%	0.752
P3.7_20_80	Fixed u of 3.7%, 20% of purse seine TAC for juvenile fish; 80% for adult fish	0.753
HS_PA_f11.8	Hockey stick with (SI, u) control points at (0,0%), (318,0%), (425,5.57%), and (∞,5.57%)	0.751
HS_PA_f13.1a	Hockey stick with (I, u) control points at (0,0%), (318,0%), (425,6.14%), and (∞,6.14%)	0.751
STEP1a	Step function with (I, TAC in kt) line segments joining points: (0,5) to (200,5), (200,9) to (250,9), (250,11) to (300,11), (300,13) to (350,13), (350,15) to (400,15), (400,17) to (450,17), and (450,19) to (∞,19)	0.757

Table 5. Performance (minimum, median, and maximum across OMs in the reference set) of MPs for each of the MSE objectives.

Objective	Metric	Statistic	NFref	fix12.5	P3.5	P3.7_20_80	HS_f11.8	HS_PA_f13.1a	STEP1a
1	Minimum annual P(SSB>$SSB_{2005–2010}$) [10–15 yrs]	min	0.883	0.752	0.752	0.753	0.751	0.751	0.755
		med	0.962	0.881	0.878	0.878	0.845	0.850	0.884
		max	0.992	0.956	0.958	0.956	0.899	0.926	0.959
2	P(3-Yr Index > 425 kt) [16–25 yrs]	min	0.796	0.627	0.586	0.586	0.546	0.540	0.611
		med	0.934	0.837	0.776	0.777	0.708	0.709	0.815
		max	0.983	0.951	0.890	0.891	0.809	0.826	0.932
2	P(3-Yr Index > 500 kt) [16–25 yrs]	min	0.692	0.532	0.480	0.479	0.435	0.419	0.508
		med	0.872	0.758	0.676	0.677	0.601	0.592	0.725
		max	0.959	0.908	0.821	0.822	0.726	0.732	0.879
3	Short-Term Yield (kt) [1–5 yrs]	min	0	12.5	11.0	11.6	5.3	10.1	12.0
		med	0	12.5	11.9	12.5	7.6	13.9	12.8
		max	0	12.5	12.8	13.5	9.6	17.5	13.5
4	Long-Term Yield (kt) [6–25 yrs]	min	0	12.4	20.3	21.5	26.2	27.3	15.5
		med	0	12.5	27.1	28.6	36.8	38.2	17.2
		max	0	12.5	32.9	34.7	45.3	47.7	18.1
5	Annual variability in yield (%) [1–25 yrs]	min	-	-	12	12	32	30	13
		med	-	-	16	17	69	102	24
		max	-	-	21	21	135	200	35
6	% Catch < 23 cm by # [1–15 yrs]	min	-	44	46	31	47	47	45
		med	-	50	51	39	53	53	50
		max	-	57	58	45	59	59	57

Notes:

"-" = no variability in yield or no catch.
blue shading for probabilities ≥ 0.75, > 0.85, and > 0.95 (darker = higher probability)
orange shading for interannual variability in yield > 20% and > 40% (darker = higher probability)
green shading for "% catch < 23 cm" < 40%.

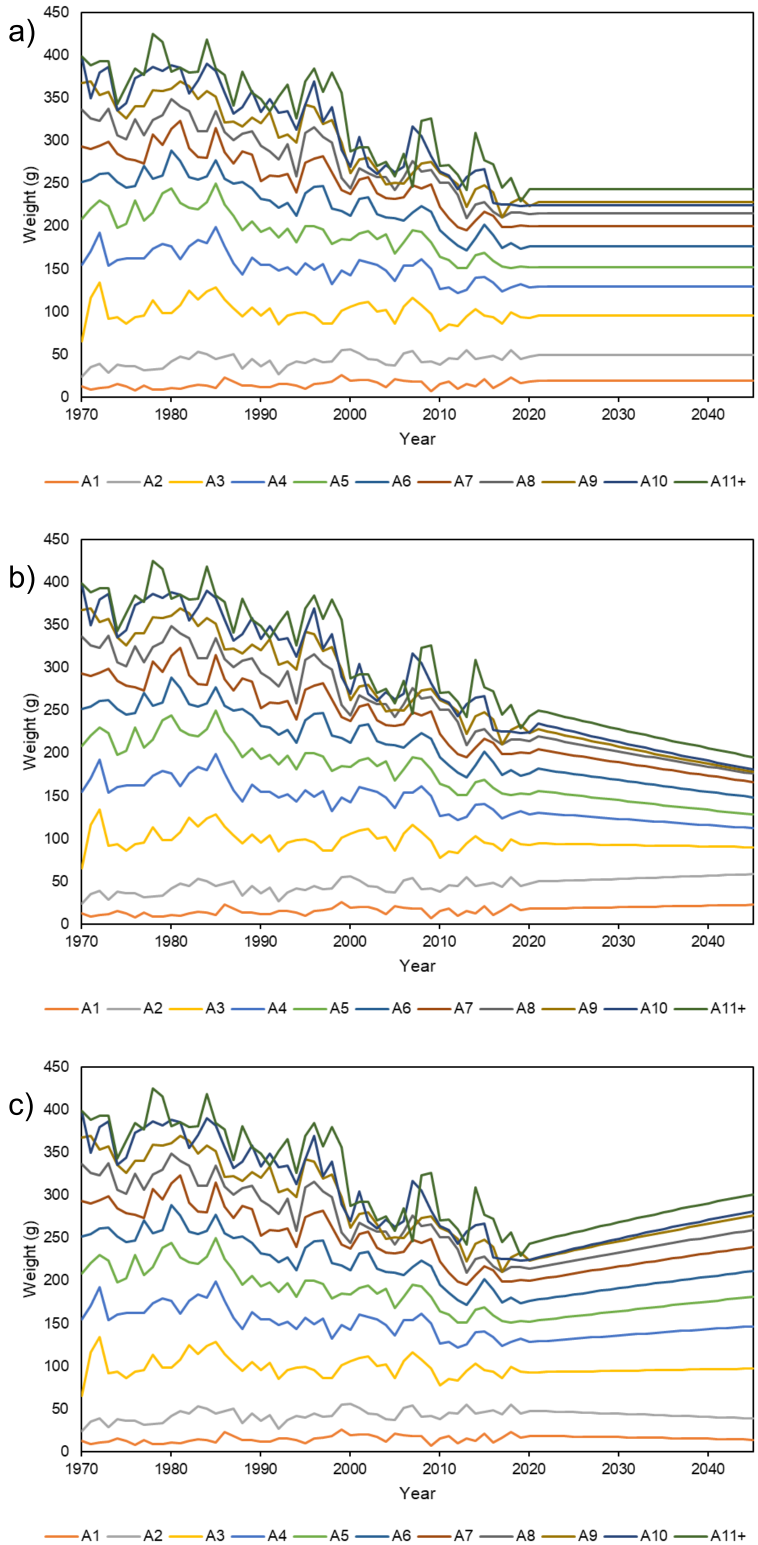

Figure 1. Empirical weight-at-age 1970–2020 with a) 25-year projections based on the mean weight-at-age for 2018–2020 (scenario A); b) 25-year projections based on the regressions of $\log_{10}$(weight) vs. year by age (scenario B), and c) 25-year projections based on a reversal of the magnitude of changes from the regressions of $\log_{10}$(weight) vs. year by age (scenario Binv).

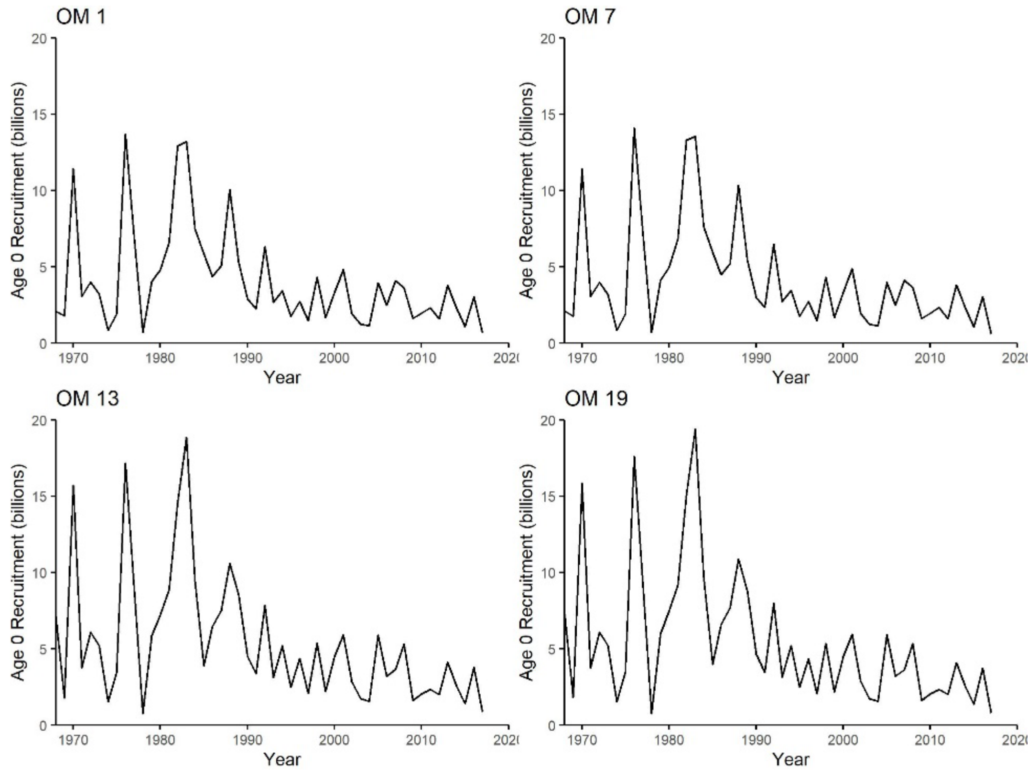

Figure 2. Time series plot of model estimated recruitment (1968–2017) for the reference set of OMs with unique historical model fits.

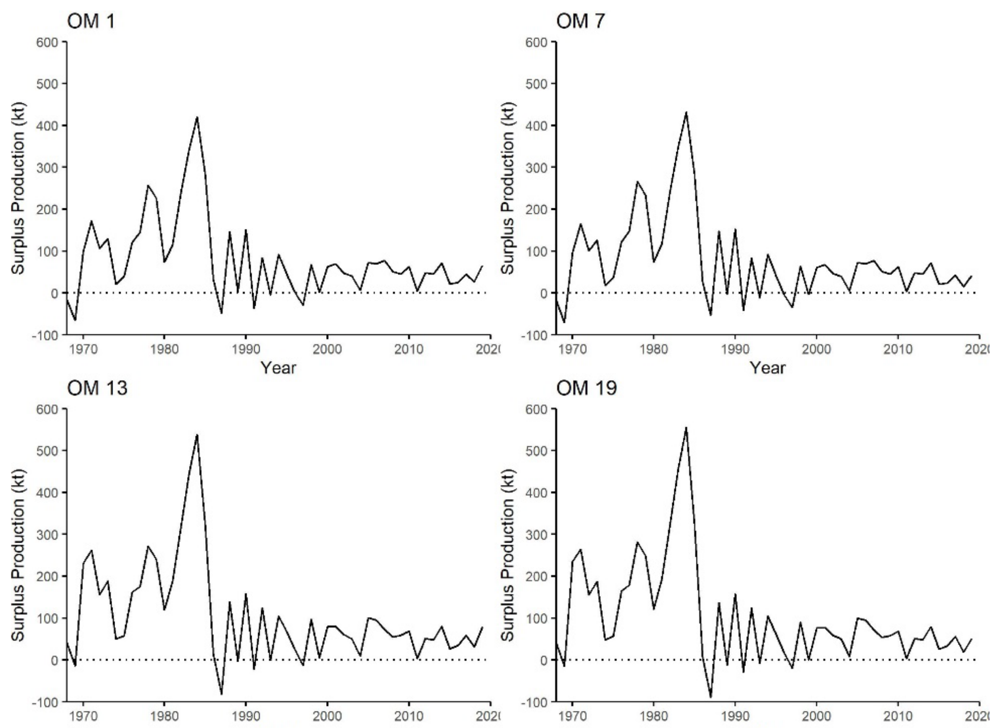

Figure 3. Time series plot of surplus production (1968–2019) for the reference set of OMs with unique historical model fits. Surplus production was estimated for year t as: $P_t = B_{t+1} - B_t + C_t$ where P is surplus production, B is model estimated total biomass, and C is total catch (Hilborn 2001).

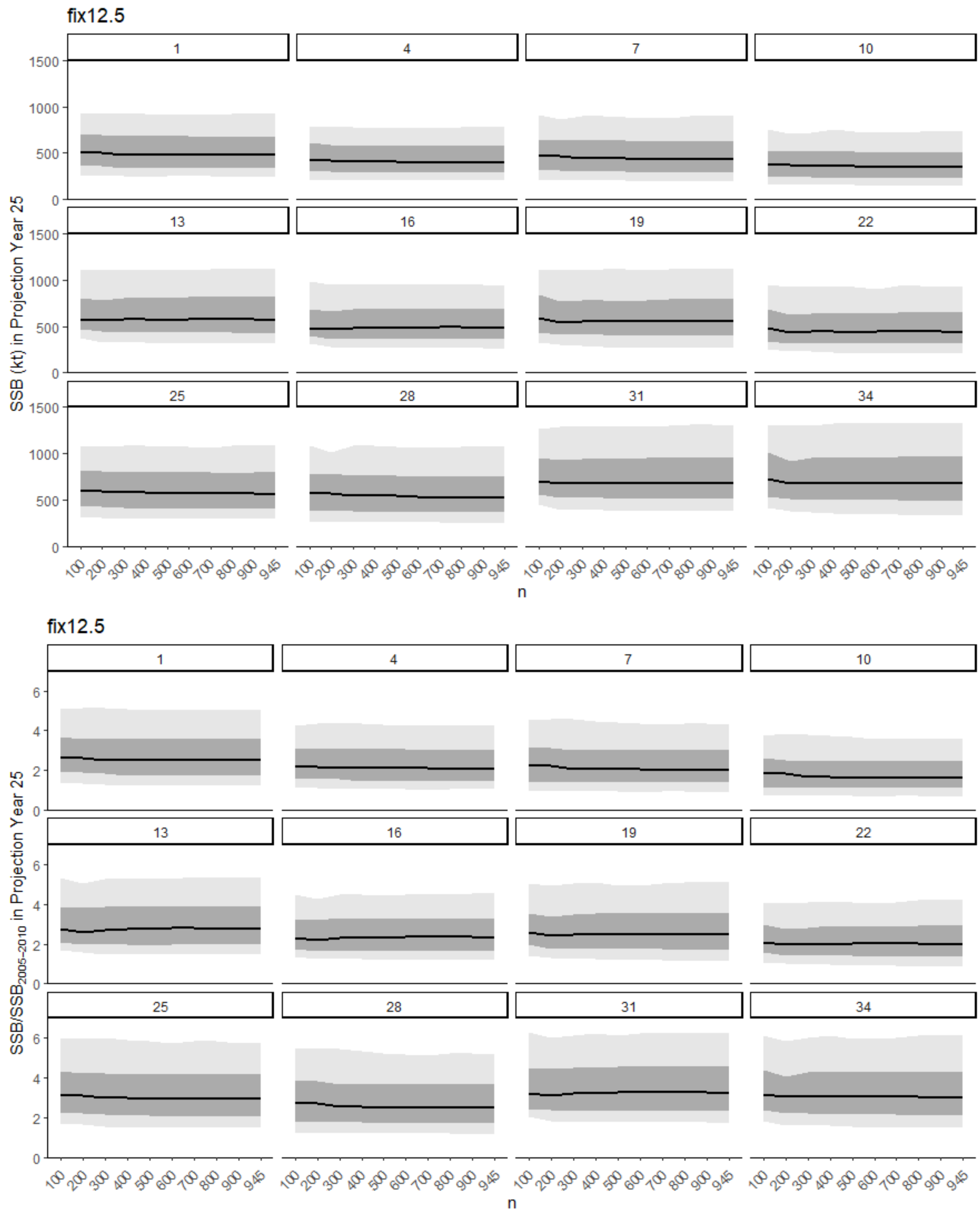

Figure 4. Estimates of model estimated SSB (top) and ratio of SSB to mean SSB in 2005–2010 (10th, 25th, 50th, 75th, and 90th percentiles) in projection year 25 for each OM in the reference set for MP fix12.5 for various n (number of simulations).

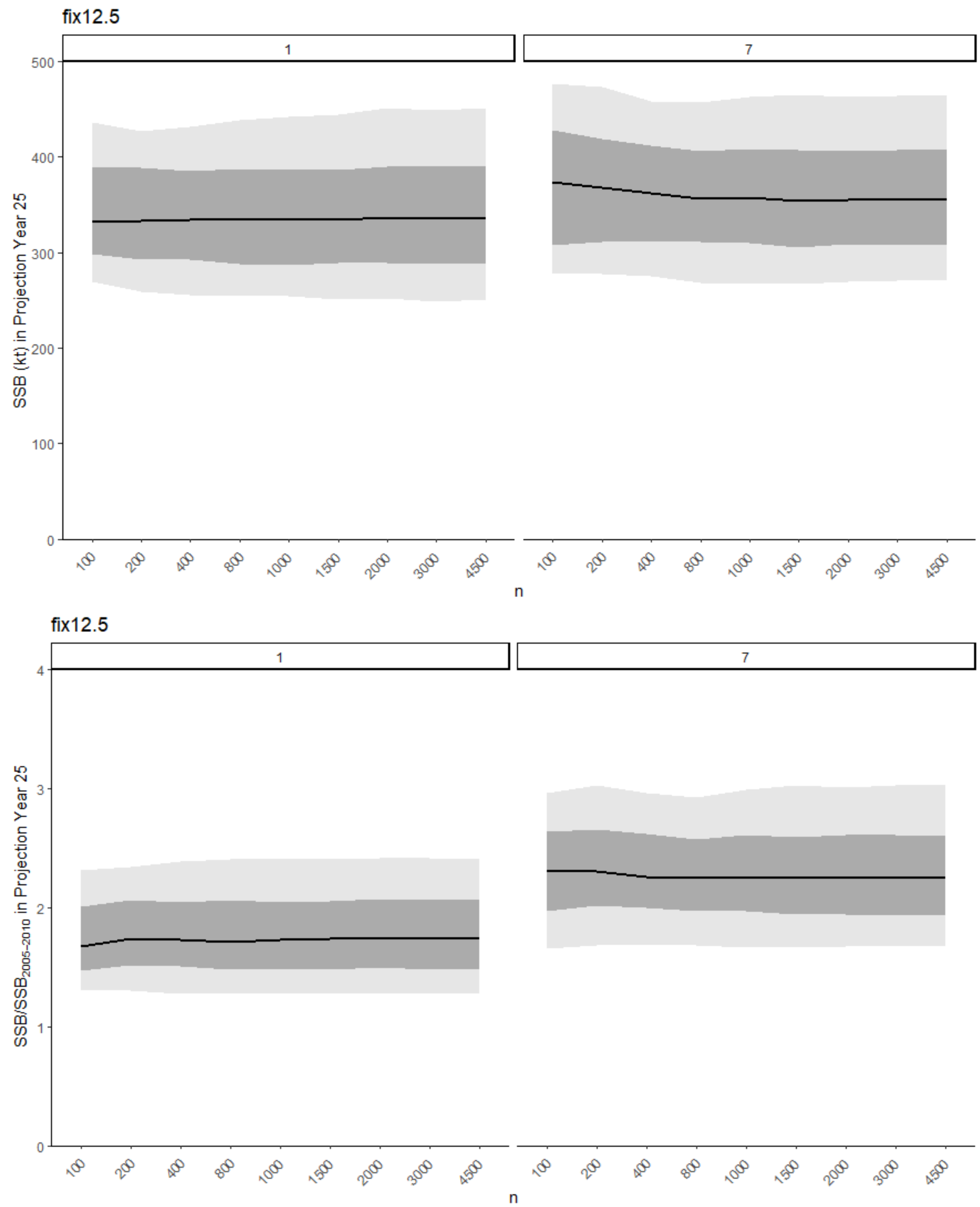

Figure 5. Estimates of model estimated SSB (10th, 25th, 50th, 75th, and 90th percentiles) in projection year 25 for OM 1 and 7 for MP fix12.5 for various n (number of simulations) with some n exceeding 1,000.

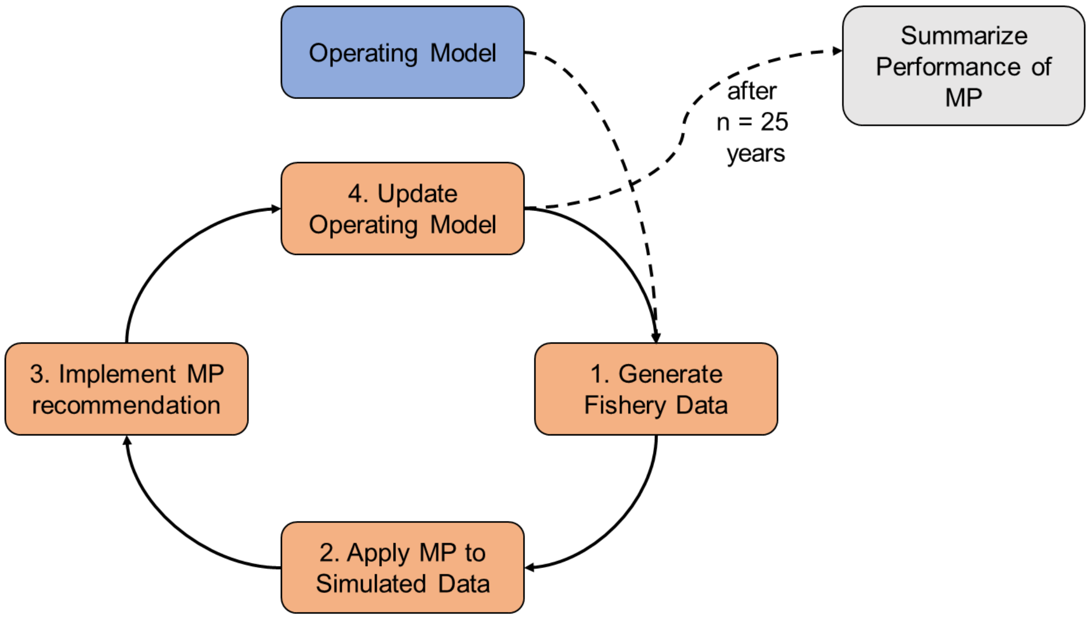

Figure 6. Illustration of the closed-loop simulations. For each OM and MP combination, simulated fishery data are generated by applying an observation model to generate the fishery data (step 1). The MP is applied to the simulated data (step 2) and the MP generates a TAC. The TAC is implemented (step 3) using an implementation model. The final step of the simulation loop (step 4) is to remove the catch from the fishery by updating the OM. This process (steps 1 to 4) is repeated until the end of the 25-year projection period.

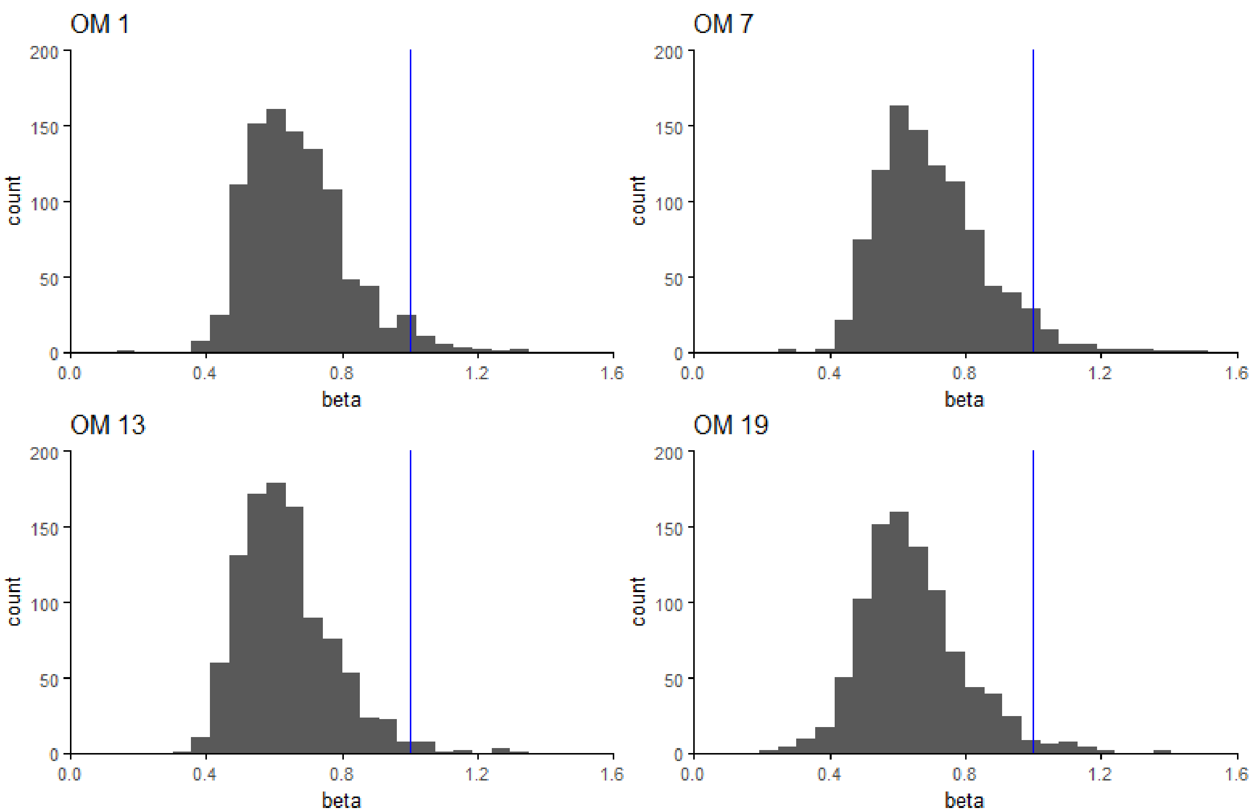

Figure 7. Distribution of the hyperstability parameter β estimated from the acoustic index and model estimated SSB (1999–2020) for the four OMs in the reference set with unique historical fits.

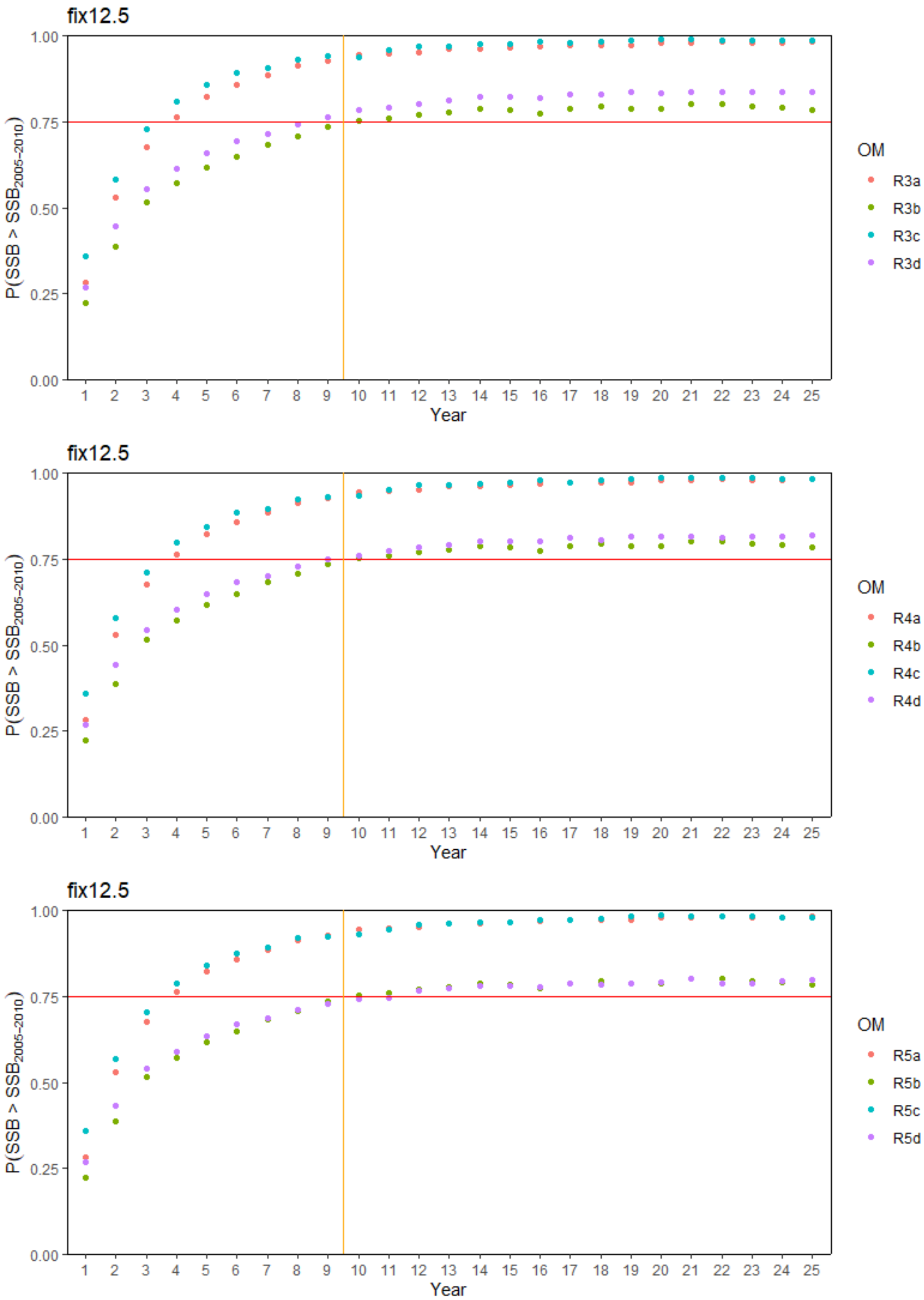

Figure 8. Probabilities of SSB > mean SSB from 2005–2010 (objective 1) by MP for OMs in the robustness sets R3, R4, and R5 of OMs.

Notes: red line = minimum probability of 0.75 for objective 1; orange line = beginning of 10–25 year projection period for objective 1.

OMs R3c and R3d assume future weir catch is 40% of SWNS/BoF TAC
OMs R4c and R4d assume future weir catch is 50% of SWNS/BoF TAC
OMs R5c and R5d assume future weir catch is 60% of SWNS/BoF TAC

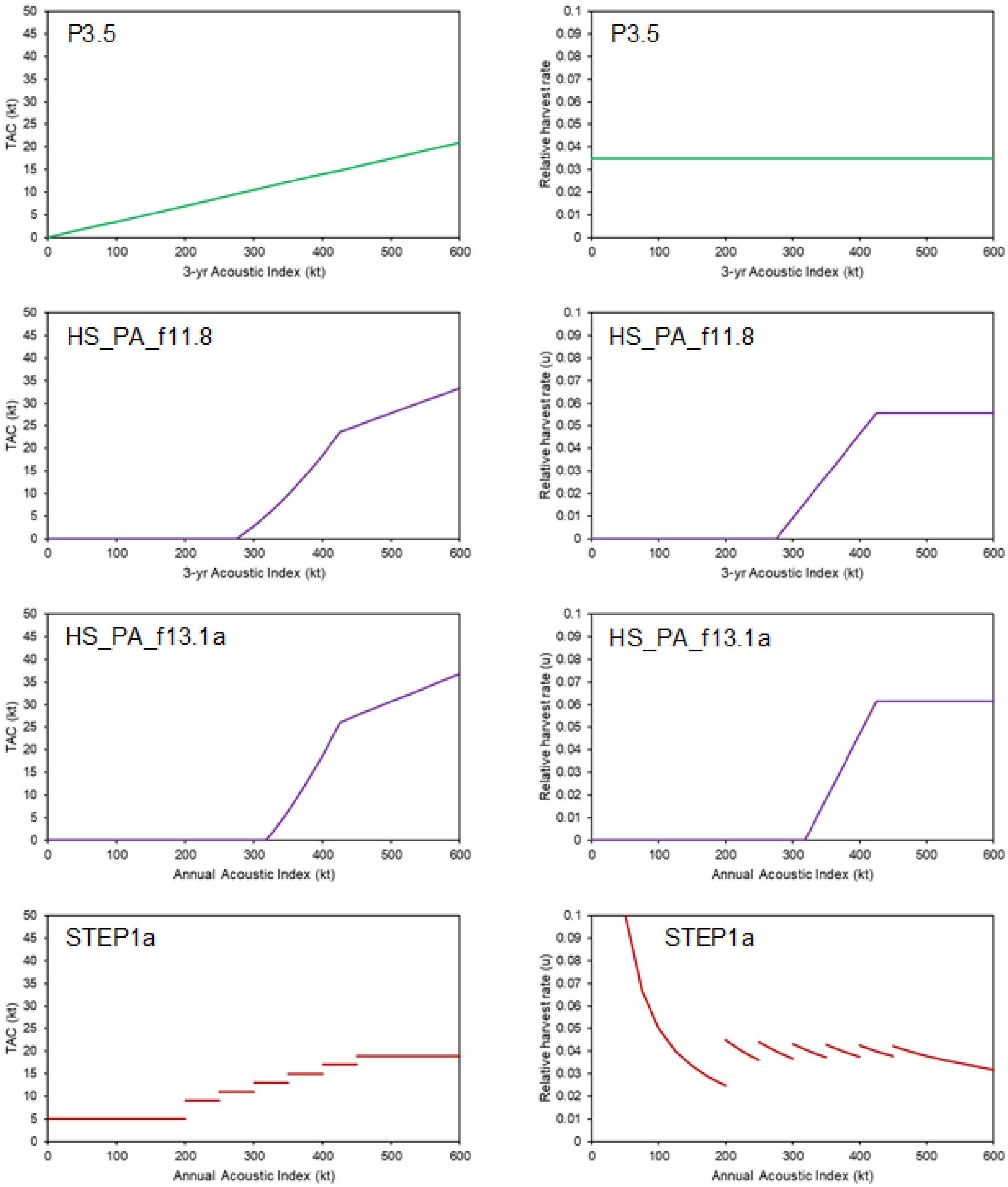

Figure 9. Plots of TAC vs. 3-yr moving average acoustic index of SSB (or annual acoustic index of SSB) and relative harvest rate vs. 3-yr acoustic index (or annual index) for MPs P3.5, HS_f11.8, HS_PA_f13.1a, STEP1a. The fix12.5 and P3.7_20_80 MPs are not plotted.

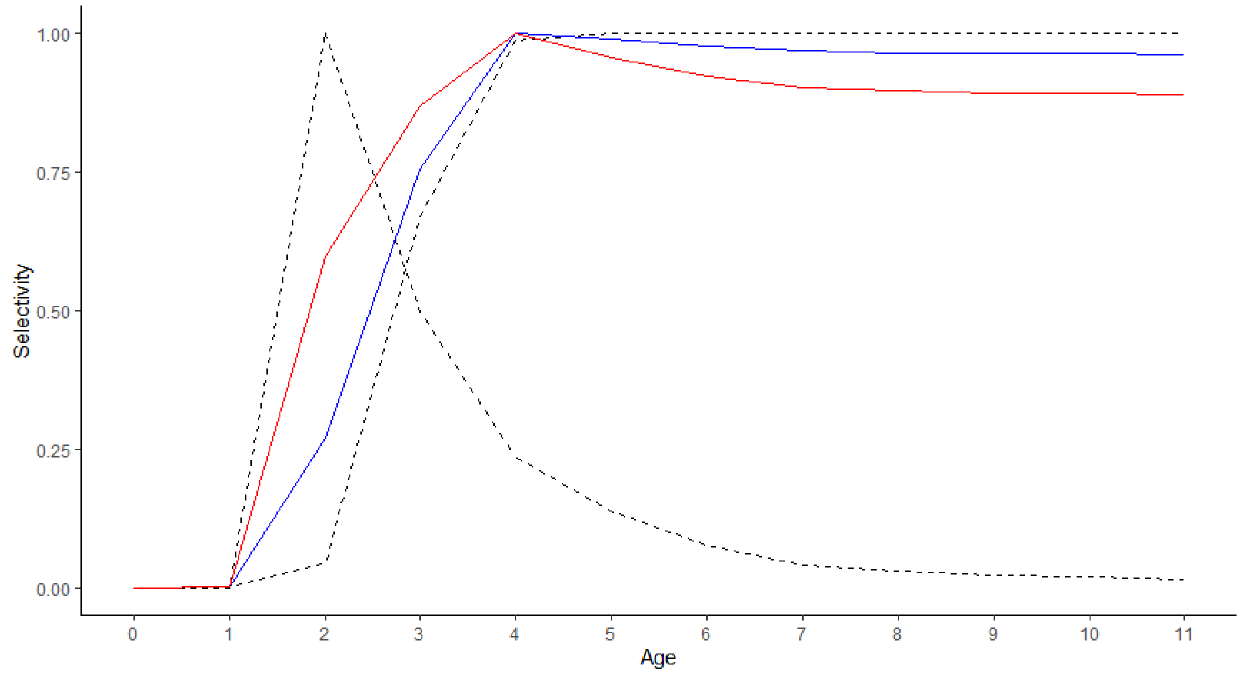

Figure 10. Selectivity curves (mean across simulations) for the purse seine fleet for OM1 assuming 20% juvenile and 80% adult catch (blue), and 40% juvenile and 60% adult catch (red). The curves are estimated as weighted averages of the weir fleet selectivity (setting selectivity at age 1 to zero) from OM 13 (same h assumption as OM1) for juveniles and the maturity ogive (mean over last 2 years) for adults (these curves are dashed lines).

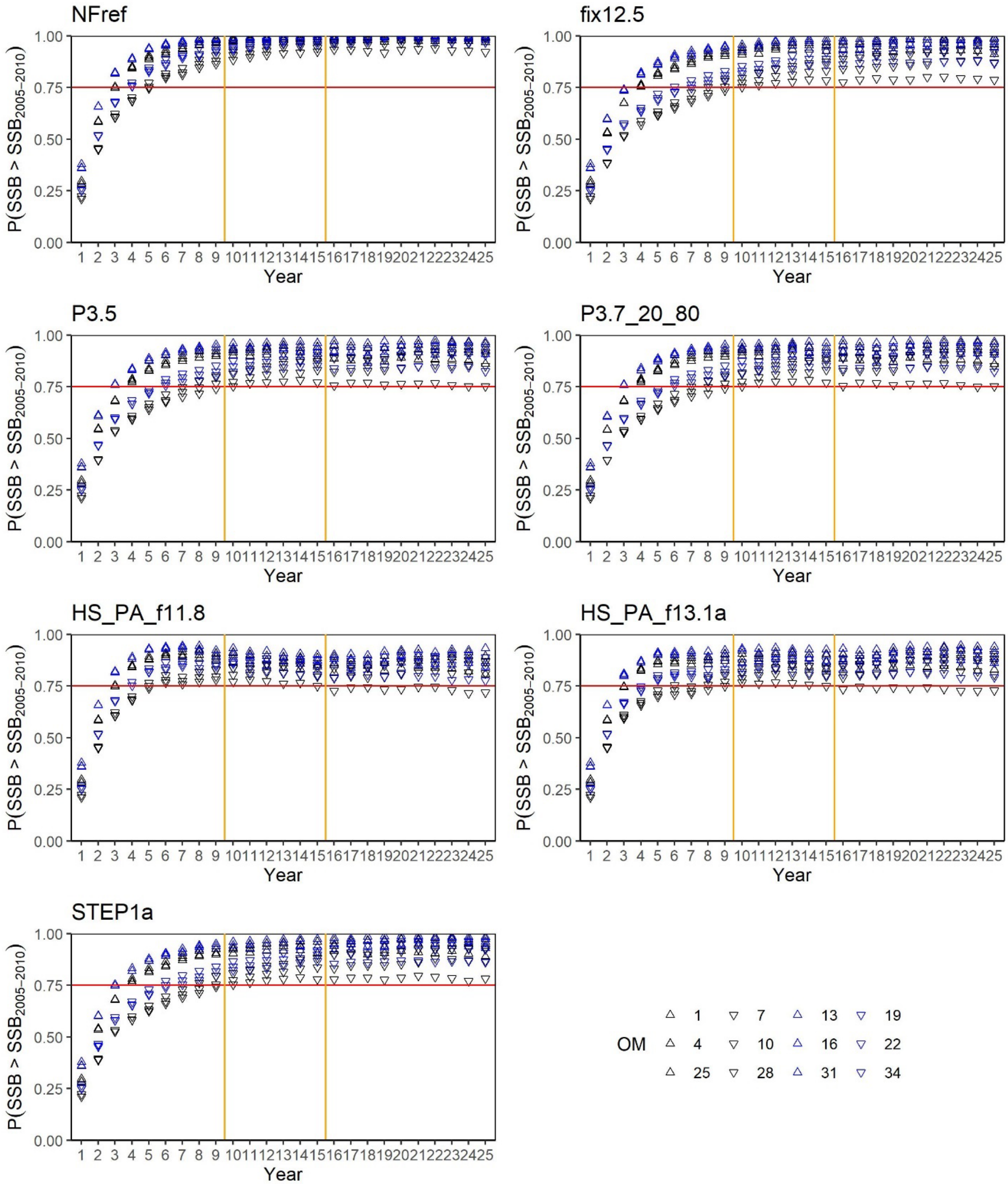

Figure 11. Probabilities of SSB being above mean SSB from 2005–2010 (objective 1) by MP for the reference set of 12 OMs for projection years 1 to 25.

Notes: red line = minimum probability of 0.75 for objective 1; orange lines = beginning of 10-15 year projection period. Symbols: △ = high h; ▽ = low h; black = no weir; blue = weir.

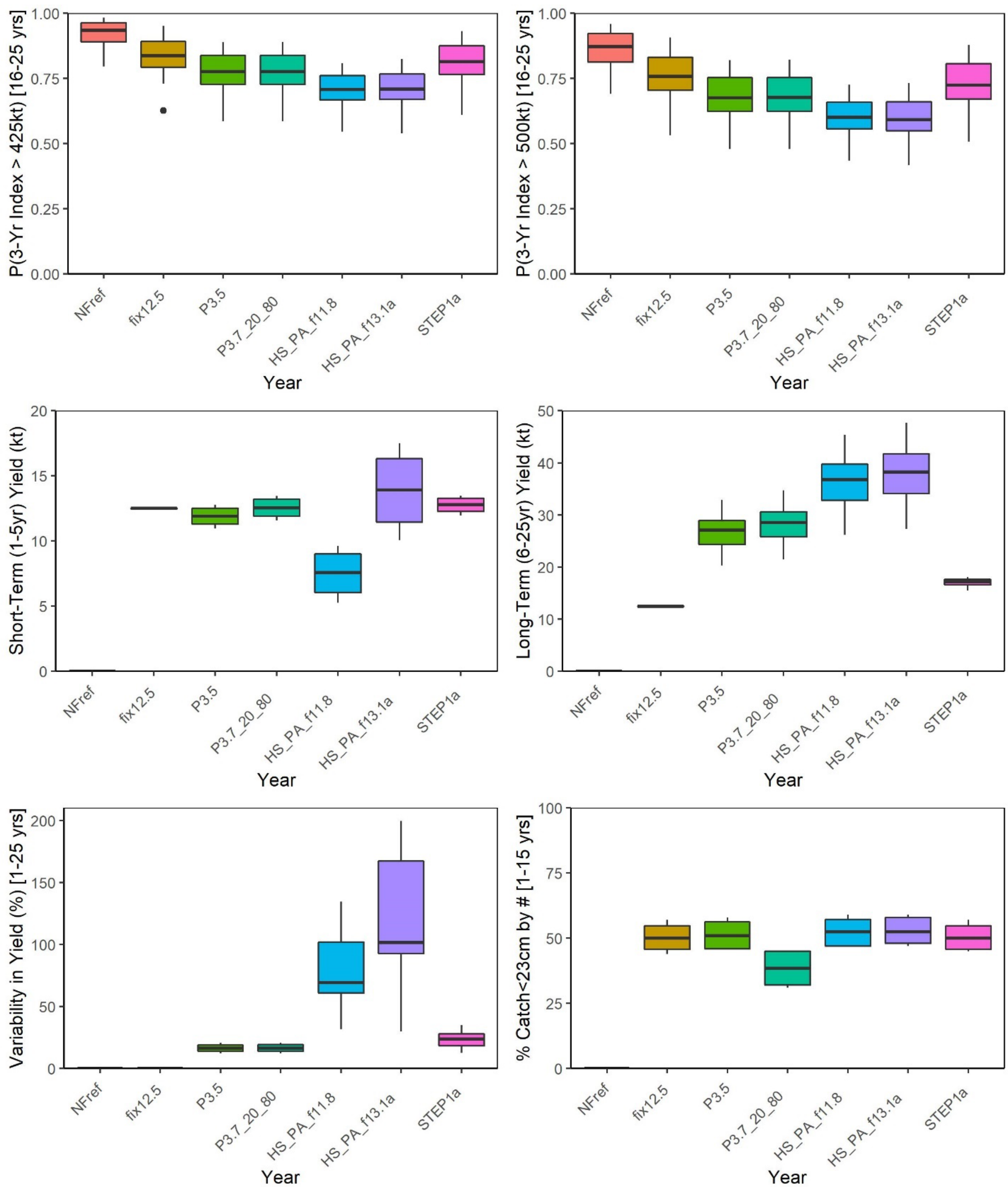

Figure 12. Performance of MPs for the reference set of 12 OMs for objectives 2 to 6. The boxplots display the minimum, 25th, 50th, and 75th percentiles, and maximum values the 12 OMs. Values more than 1.5 times the interquartile range beyond 25th and 75th percentiles are plotted as individual values.

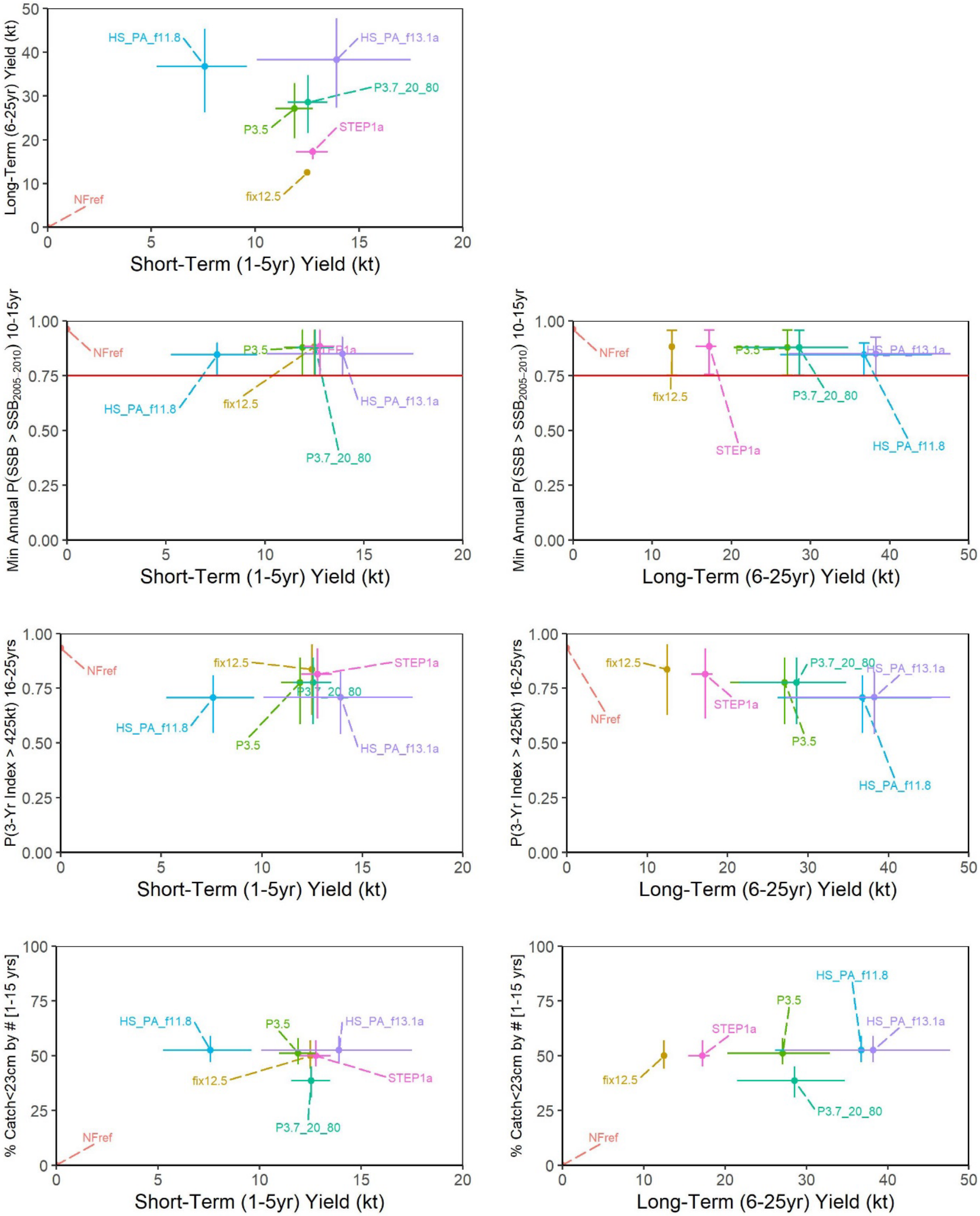

Figure 13. Trade-offs in performance of MPs for the reference set of 12 OMs. The minimum, median, and maximum values among the 12 OMs are plotted as the points and error bars.

APPENDIX A.
EXCEPTIONAL CIRCUMSTANCES PROTOCOL FOR THE SWNS/BoF HERRING MSE

Reason for triggering exceptional circumstances:

A. There is evidence that the stock is in a state that is not considered in the range of hypotheses in the reference set of OMs.

B. The data required to apply the management procedure are no longer available or no longer appropriate.

The Herring MSE working group decided that instead of defining the planned actions *a priori* for the exceptional circumstances, the evaluation criteria for each circumstance would be set less restrictive and the planned action may depend on the magnitude of the observed indicator relative to the evaluation criteria. For example, an observed index just outside of the 90% prediction interval for one OM would be reported in an annual update document (exceptional circumstance 1; Table A1); however, no specific action may necessarily be taken. Specific planned actions are therefore not defined for each exceptional circumstance and it was agreed that “Science considerations” be defined for each exceptional circumstance in Table A1. The specific action resulting from triggering an exceptional circumstance will be determined by DFO.

Table A1. Indicators, evaluation criteria, frequency of evaluation, and Science considerations for evaluation for the exceptional circumstances.

Number	Reason	Indicator	Evaluation Criteria	Frequency of Evaluation	Science Considerations
1	A	Acoustic index of SSB	Observed index is outside the 90% prediction interval (5th and 95th percentiles) for an OM in the reference set (Figure A1)	Annual	Evaluation of OM hypotheses in the reference set. Exploration of productivity scenarios in the robustness set. Re-evaluate MPs on revised reference set.
2	A	Weight-at-age	Observed weight-at-age 3, 4, 5, 6, or 7 is above the upper 98% (2-tailed) prediction interval for the predicted weight at age for growth scenario Binv OR Observed weight at age 3, 4, 5, 6, or 7 is below the lower 98% (2-tailed) prediction interval for the predicted weight at age for growth scenario B (Figure A2)	Annual	Re-evaluate MPs with revised growth scenarios in the reference set.
3	A	Weir fleet landings	Weir landings > 50% of SWNS/BoF stock TAC	Annual	Re-evaluate MPs with revised weir catch scenarios in the reference set.
4	A	SWNS/BoF landings	Evidence that removals from SWNS/BoF stock area are > 10% more than TAC	Annual	Re-evaluate MPs by updating catch history in the reference set.

Number	Reason	Indicator	Evaluation Criteria	Frequency of Evaluation	Science Considerations
5	A	Data input (e.g., index) or model assumption (e.g., stock structure)	DFO Science identifies new data to suggest that data inputs or model assumptions are no longer valid.	When new data become available	DFO Science reports to the Scotia-Fundy Herring Advisory Committee and provides options for incorporation of the new data in the Science advice.
6	B	Acoustic index of SSB	Insufficient data (< 5 surveys performed in each of GB and SB or less than 8 transects performed per survey) in a single year.	Annual	DFO Science provides options to Resource Management.
7	B	Acoustic index of SSB	Acoustic estimate of SSB on the spawning grounds outside of German Bank and Scots Bay > than the 90th percentile of the overall historical observation error on the index (30.9%) for two consecutive years.	Annual	Re-evaluation of acoustic index of SSB.

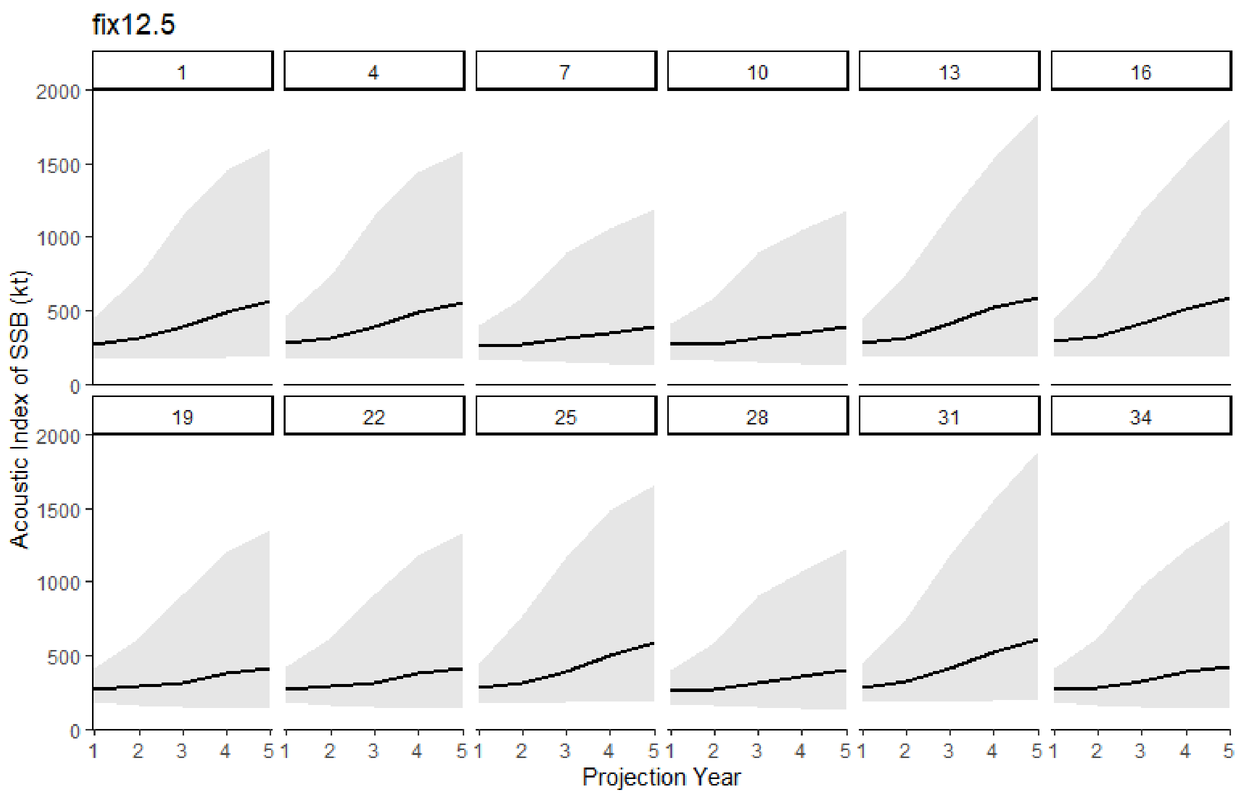

Figure A1. Projections of the acoustic index of SSB (median with 5th and 95th percentile bands) over 5 years for the reference set of OMs with MP fix12.5.

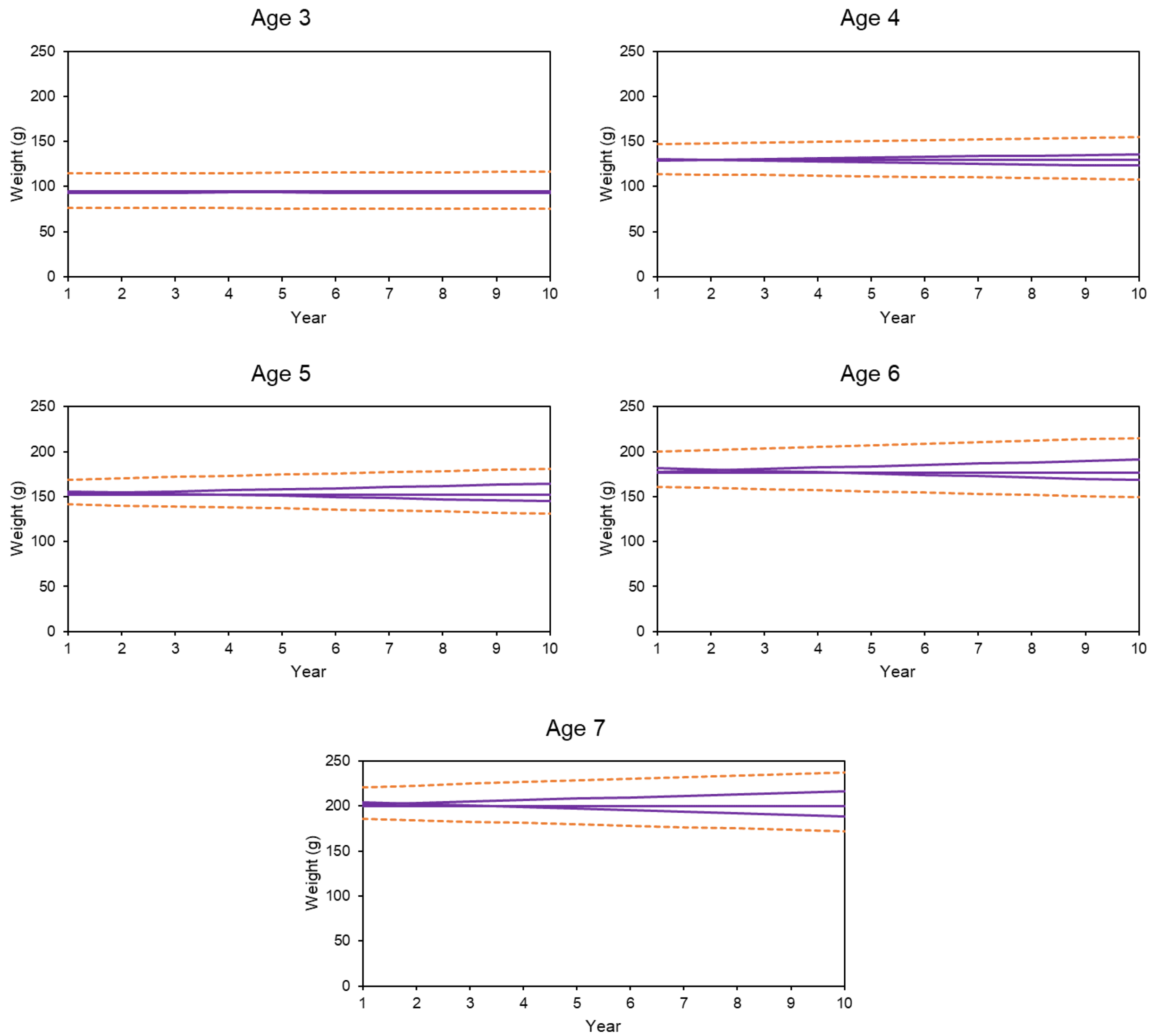

Figure A2. Projections of weight-at-age 3, 4, 5, 6, and 7 over 10 years for growth scenarios A, B, Binv (purple lines) with upper and lower 98% prediction limits for Binv and B (orange lines), respectively.

Note: 98% prediction limits were calculated on the $\log_{10}$-transformed scale as the mean predicted value in each year ± 2.33 SD, where SD = the standard deviation of the regression residuals from the last 10 years of the historical time period. The limits were back-transformed to the original data scale.