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Evaluating the robustness of management procedures for the Sablefish (*Anoplopoma fimbria*) fishery in British Columbia, Canada for 2017-18

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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

Fisheries and Oceans Canada (DFO) and the British Columbia (B.C.) Sablefish (*Anoplopoma fimbria*) fishing industry have collaborated on a management strategy evaluation (MSE) process since 2009. This process is used to develop and implement a transparent and sustainable harvest strategy for the multi-gear Sablefish fishery. The underlying operating model used to generate hypotheses about Sablefish stock and fishery dynamics as part of the MSE was recently updated to include several structural changes that improved model fit to data and resulting estimates of historical recruitment. This paper updates the Sablefish MSE by incorporating these improvements to the operating model, and then tests the existing and alternative management procedures for robustness to uncertain stock dynamics. The current management procedure (MP) uses a harvest control rule with a maximum harvest rate (HR) set at the estimated harvest rate at maximum sustainable yield (U_{MSY}), as well as a minimum TAC floor of 1,992 tonnes and a minimum size limit of 55 cm. Nine alternative MPs were also evaluated that differed in their use of TAC floors, maximum harvest rates within the harvest control rule, phase-in periods to a new MP, and sub-legal release regulations. We based our five operating model scenarios on plausible hypotheses about productivity (i.e., the steepness parameter of the spawner-recruit relationship) and current spawning stock biomass. MP performance was ranked within scenarios, as well as weighted across operating model scenarios. Our results show that the current MP was unable to meet conservation objectives under any of the five operating model scenarios. Based on the weighted-average performance across the five scenarios, MPs that included TAC floors were not able to achieve conservation objectives while MPs without a TAC floor were able to achieve these objectives. The length of the phase-in period to a lower maximum harvest rate did not have a large effect on MP performance relative to conservation objectives. MPs that include the addition of full retention (here meaning all sub-legal (< 55 cm) and legal fish caught are counted against the TAC) resulted in better performance against conservation objectives relative to the identical MPs without full retention. In the absence of full retention of Sablefish, an MP with a phase-in to a new maximum target harvest rate of 5.5% over 5 years was able to achieve two of the conservation objectives while providing 10-year average catch of 1,690 t, which is below the current TAC floor of 1,992 t.

1 INTRODUCTION

Fisheries and Oceans Canada (DFO) and the British Columbia (B.C.) Sablefish (*Anoplopoma fimbria*) fishing industry collaborate on a management strategy evaluation (MSE) process intended to develop and implement a transparent and sustainable harvest strategy. This process has been in place since 2009 (Cox et al. 2009) with updates occurring in 2011 (Cox et al. 2011) and 2014 (DFO 2014). This current update to the Sablefish MSE incorporates improvements to the underlying operating model used to generate hypotheses about Sablefish stock and fishery dynamics (DFO 2016, Cox et al.[1]) and tests the existing and alternative management procedures for robustness to uncertain stock and fishery dynamics.

MSE is an approach to fisheries management in which the consequences of a set of alternative management procedures are compared in a manner that exposes trade-offs in performance across a range of conflicting management objectives (Smith 1993, Smith et al. 1999). Management procedures (MP) evaluated as part of an MSE include three main components: data collection, an assessment of stock status, and fishery management decisions based on assessment results. Closed-loop simulation analyses are used within an MSE process to quantify performance of alternative management procedures across a range of operating models, with each operating model representing a different hypothesis about underlying stock and fishery dynamics.

Throughout the British Columbia Sablefish MSE process, consultation among industry participants and fishery managers has been used to develop measurable fishery objectives, identify candidate management procedures, identify key uncertainties, and evaluate acceptable trade-offs in performance across conflicting objectives (Cox and Kronlund 2008, Cox and Kronlund 2009, Cox et al. 2009, Cox et al. 2011, DFO 2014). Candidate management procedures evaluated for Sablefish have covered a wide range of management approaches, including data-based decision rules, catch-at-age assessment models, surplus production assessment models, constraints on annual changes in TAC, regulations aimed at reducing at-sea releases of sub-legal Sablefish by multiple gear types, and the addition of a catch floor to harvest decision rules (Cox and Kronlund 2009, Cox et al. 2011, DFO 2014). Similarly, operating model scenarios for Sablefish have focused on representing a wide range of uncertainties, including productivity, the level of spawning stock depletion, natural mortality, at-sea release mortality, individual growth rate, and recruitment autocorrelation (Cox and Kronlund 2009, Cox et al. 2011).

An updated Sablefish operating model was developed in January 2016 (DFO 2016, Cox et al.[1]). The revised operating model includes structural changes that improve the fit to age-composition and at-sea release data compared to the previous operating model structure, including the inclusion of ageing error and an expansion to a two-sex model that allows for differences in growth, mortality, and maturation of male and female Sablefish. These changes improved the time series of age-1 Sablefish recruitment by reducing the unrealistic autocorrelation present in the previous model results. The revised estimates of recruitment indicate strong year classes of Sablefish that are similar in timing and magnitude to estimates for the Gulf of Alaska. The improved recruitment time series also help better explain the temporal pattern of at-sea releases, which suggests that it may be possible to improve the evaluation of regulations aimed at reducing at-sea releases in all fisheries that was undertaken as part of the 2011 Sablefish MSE review (Cox et al. 2011).

2 METHODS

2.1 OBJECTIVES AND PERFORMANCE MEASURES

2.1.1 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, 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 the $0.4B_{MSY}$ 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}, or (b) 0.8 B_{MSY} when rebuilding from the Cautious zone, in 50% of the years measured over 2 Sablefish generations;
4. P(Catch>1,992): Maximize probability that annual catch levels remain above 1,992 tonnes measured over two Sablefish generations.
5. AveCatch: Maximize the average annual catch over 10 years subject to Objectives 1-4.

Objective 4 [*P*(Catch>1,992)] is proposed for this MSE to reflect the current minimum industry-acceptable catch level of 1,992 tonnes (DFO 2014). The current management procedure for B.C. Sablefish uses a 1,992 TAC floor to ensure such an objective is met with 100% certainty, essentially acting as an economic safeguard to the fishery. However, given new estimates of recruitment and sub-legal at-sea release mortality, such an objective may not be feasible 100% of the time.

2.1.2 Performance Measures

Evaluating management procedures by simulation requires a quantitative performance indicator for each fishery objective. Stock status indicators are all measured using the true operating model female spawning stock biomass. We use two Sablefish generations (36 years) as the "reasonable" time frame required by the DFO PA Framework, and 10 years as the short-term to reflect industry economic interests.

Performance statistics corresponding to each of Objectives 1-5, as well as other quantities of interest are listed in Table 1. Each statistic is calculated for a simulation replicate, and the expected performance for a management procedure is summarized by the mean (or median) of 100 replicates of each simulation.

2.2 MANAGEMENT PROCEDURES

We define a management procedure (MP) as a combination of monitoring data, stock assessment method, harvest control rule, and measures governing at-sea release of sub-legal Sablefish. In this section, we describe the current management procedure used for the British Columbia Sablefish fishery (DFO 2014) as well as nine additional candidate management procedures.

When describing management procedures, we use the terminology B_{lower} and B_{upper} to describe the biomass-based operational control points (OCPs) used within the Sablefish harvest control rule. OCPs represent the stock status level at which management response is taken, and differ from the biomass-based reference points (LRP and Target) used to define Sablefish management objectives in Section 2.1. The OCP values of $B_{lower} = 0.4B_{MSY}$ and $B_{upper} = 0.6B_{MSY}$ are used to trigger changes in target harvest rates (HR) within the harvest control rule, while management objectives are expressed relative to a LRP = $0.4B_{MSY}$ and Target = B_{MSY} or Target = 0.8 B_{MSY}.

All MPs use the same data and stock assessment method, with the exception of a small change made to tuning of the prior distributions for stock assessment model parameters for some MPs (described below). The alternatives to the current management procedure differed in their use of TAC floors, maximum harvest rates within the harvest control rule, phase-in periods to new target harvest rates, as well as sub-legal release regulations.

Sablefish captured below the legal size limit of 55 cm must be released by regulation in all B.C. fisheries. This limit was originally determined via yield-per-recruit analyses that assumed (i) a single-fleet fishery and (ii) an ability to either completely avoid Sablefish smaller than the size limit or to release sub-legal sized fish at-sea without associated mortality.

Neither of these conditions is actually true for B.C. Sablefish. The three Sablefish fleets comprising the fishery each have different size-selectivity and fishing intensities. During the period for which we have direct estimates via observers or video-audited logbooks, the three fleets combined have accounted for sub-legal releases ranging from 307 to 646 tonnes per year, representing 11-24% of the landed catch. Current estimates of release mortality for trap (15%), longline hook (30%), and trawl (80%) fisheries suggest that at-sea releases could substantially affect the Sablefish population growth rate and yield available at legal sizes above 55 cm.

An initial evaluation of full retention of all sizes was undertaken as part of the 2011 Sablefish MSE (Cox et al. 2011). As an alternative to the current 55 cm size limit regulation, the "full retention" option required all fisheries to retain all Sablefish captured, regardless of size. While results of the 2011 MSE simulation analyses showed that management procedures based on full retention of Sablefish achieved better overall fishery performance compared to options that maintained the current 55cm legal size limit, benefits were smaller than expected. Structural limitations of the 2011 operating model were identified as a possible explanation for these small differences. The recent update to the operating model addressed several of these limitations, resulting in improved model fits to age composition data and at-sea releases from the trawl fishery (Cox et al.[1]). Updated estimates of exploitation rates of sub-legal Sablefish are considerably higher than previous estimates, suggesting that re-evaluation of full retention may produce different results than were seen in 2011. Given the improvements in model fit with the new operating model, results from the current analyses are expected to be more realistic than the 2011 evaluation.

The sections below first describe the current management procedure, followed by descriptions of the nine alternative management procedures we evaluated that each contained variations on the harvest control rule and sub-legal retention regulation applied.

[1] Cox, S.P., Kronlund, A.R., Lacko, L, and Jones, M. A revised operating model for Sablefish in British Columbia, Canada. CSAP Working Paper 2014GRF03. *In revision*.

2.2.1 Current Management Procedure: currMP

Data requirements for the current management procedure include total Sablefish landings from all B.C. fisheries and three catch per unit effort (CPUE) indices of abundance. The stock assessment model component of the MP ignores at-sea releases and release mortality, so the simulated total catch data are based on total landings aggregated over all gear types. Note that the at-sea release process and mortality continues to exist within the operating model.

The three simulated indices of abundance are:

1. commercial trap fishery CPUE (1979-2009),
2. standardized trap survey CPUE (1991-2009), and
3. stratified random trap survey CPUE (2003-present).

Abundance indices based on the commercial fishery and the standardized trap survey are not simulated past 2009. From 2009 onwards, the stratified random trap survey is the only abundance index generated from the operating model. Previous MSE analyses for the B.C. Sablefish fishery have shown that management procedures using only the stratified random trap survey after 2009 provide similar conservation performance to procedures using both the stratified random trap survey and the standardized trap survey (Cox et al. 2011).

For all surveys, the above CPUE observations are simulated as bias-corrected log-normally distributed observations

$$I_{g,t} = q_g B_{g,t}^{exp} e^{\sigma_g \varepsilon_{g,t} - \sigma_g^2/2}$$

where *g* is an index denoting the survey series (*g* = 1, 2, or 3), *t* is year, $q_g B_{g,t}^{exp}$ is the expected CPUE for survey *g* in year *t*, which is survey exploitable biomass (B^{exp}) scaled by survey catchability (q), $\epsilon_{g,t}$ is a standard normal deviation, and σ_g is the standard log-deviation of the observations. Observation error standard deviations σ_g and catchability parameters q_g are estimated during operating model conditioning.

The stock assessment component of the management procedure involves fitting a state-space surplus production model to the above data series (Appendix A). The assessment model estimates current exploitable biomass ($\hat{B}_T$), the exploitation rate and biomass at maximum sustainable yield ($\hat{U}^{\mathrm{MSY}}$ and $\hat{B}^{\mathrm{MSY}}$, respectively), and the exploitable biomass forecast for the coming year ($\hat{B}_{T+1}$). Note that the exploitable biomass, $\hat{B}_T$, estimated in the assessment does not correspond to any particular survey because the catch data are landings only.

Parameter estimates are then used in a two-step harvest control rule (Table 2) in which the first step sets a preliminary TAC given the forecasted exploitable biomass ($\hat{B}_{T+1}$). The target exploitation rate used in this step is set at a maximum of $\hat{U}^{\mathrm{MSY}}$ when forecasted biomass is above the upper operational control point ($\hat{B}_{\mathrm{upper}} = 0.6\hat{B}^{\mathrm{MSY}}$) and decreases linearly from $\hat{U}^{\mathrm{MSY}}$ to zero as forecasted biomass declines from $\hat{B}_{\mathrm{upper}}$ to the lower operational control point ($\hat{B}_{\mathrm{lower}} = 0.4\hat{B}^{\mathrm{MSY}}$). The second step modifies the preliminary TAC to be at or above the minimum TAC floor corresponding to the 2013/14 TAC of 1,992 tonnes. Catch floors provide a means of incorporating minimum annual catch objectives directly into the harvest control rule. The application of a catch floor can also reduce annual catch variability, which is another important fishery performance measure. Under the current management procedure, all Sablefish captured below the minimum legal size limit of 55 cm fork length are released at sea and subject to at-sea release mortality in the operating model. We label the current management procedure **currMP**.

2.2.2 Alternative Management Procedures

Preliminary simulations indicated that the current MP may not be robust in the long-term under the new operating model, especially given uncertainty in productivity. Improving long-term conservation performance usually involves trade-offs between short-term and long-term yield; however, the current TAC floor limits the scope for adjusting current MP performance in any time period. In this section, we derive nine alternative MPs based on combinations of TAC floors, maximum target exploitation rates ($U_{\max}$), phase-in periods over which new, lower maximum exploitation rates are gradually introduced, and a full retention regulation for Sablefish under 55 cm in length (explained in next section).

For all the MP alternatives described below (numbered MP2 – MP10), we include a new constraint on upward TAC changes in which TACs remain at a particular level until the recommended TAC increase is at least 200 t. This change was requested by industry to limit unnecessary upward movement in TACs. In addition, all nine alternative MPs differed from the current MP in the level of tuning used to define prior distributions for F_{MSY} and *MSY* in the simulated stock assessment. MP2 – MP10 were given tighter and slightly more precise prior distributions for these parameters to reflect the corresponding reductions in these values for the updated operating model. The largest difference among prior distributions between the currMP and all other MPs was in the standard deviation of F_{MSY}. While the currMP used a prior distribution of *Normal*(0.08, 0.04) on F_{MSY}, MP2-MP10 used a prior distribution of *Normal*(0.07, 0.005). Differences in the prior distributions of MSY were negligible in comparison. Sensitivity analyses on the effects of the prior distribution of F_{MSY} on currMP performance showed that while the more precise priors did reduce the average TACs by about 1%, the relative ranking of currMP didn't change when using the newer prior distribution parameters for F_{MSY} (results not shown). This is as expected, because preliminary analyses showed that the issue with the current MP was not the accuracy of the assessment, but the catch floor creating a positive feedback effect that led to sustained overfishing. We chose to maintain the less informative prior distributions on F_{MSY} and MSY that had been used in previous MSE analyses for the currMP so that results from our current evaluation would be comparable with those obtained using the old formulation of the operating model for this MP.

MP2 - FI1.992_HR5.5: We combined the 1,992 t floor with a fixed input exploitation rate U_{max} = 0.055 instead of the U^{MSY} estimated annually as part of the current management procedure's stock assessment. This has the effect of keeping current catches at or above the floor, while also allowing catch to track upward changes in the stock over time. The particular value 0.055 was chosen by trial and error as the target harvest rate value from the MP that produced a realized exploitation on legal-sized Sablefish near the operating model's optimal legal harvest rate. We provide graphical examples of this effect in the Results section.

MP3-FI1.992_HR5.5_frt: This procedure adds a full retention option to MP2. Here, all Sablefish are landed regardless of size.

MP4-FI1.80_HR5.5: This procedure is the same as MP2 but with a 1,800 t floor.

MP5-FI1.80_HR5.5_frt: Same as MP4 with full retention regulation.

MP6-FI0.00_HR5.5: Same as MP2, but without a TAC floor.

MP7-FI0.00_HR5.5_ph3: Same as MP6, but with the maximum target harvest rate changing from 0.08 in 2017 to 0.055 in 2019 (3-year phase in to lower target harvest rate). This is an alternative form of safeguard for industry that does not carry the risks of constant catch policies. The gradual phase-in is aimed at maintaining minimum viable TACs while the stock recovers.

MP8-FI0.00_HR5.5_ph4: Same as MP7, but with 4-year phase-in period.

MP9-FI0.00_HR5.5_ph5: Same as MP7, but with 5-year phase-in period.

MP10-FI0.00_HR5.5_ph5_frt: Same as MP9, but with full retention regulation.

A summary of all 10 candidate management procedures considered is provided in Table 3.

2.3 OPERATING MODEL AND SCENARIOS

The updated Sablefish operating model developed in January 2016 (DFO 2016, Cox et al.[1]) implements a two-sex age-structured model to account for differences in growth, mortality, and maturation of male and female sablefish. This model replaces the combined-sex model used for 2011 and 2014 Sablefish MSE analyses (Cox et al. 2011, DFO 2014). Three additional structural changes that were made to the 2016 model include: an ageing error matrix applied to the model age proportions, a revised multivariate-logistic age composition likelihood that reduces model sensitivity to small age proportions, and the ability to model time-varying selectivity. These changes improved model fit to age composition and at-sea release data compared to the previous operating model, and reduced the unrealistic recruitment autocorrelation present in the previous model estimates. We refer readers to Cox et al.[1] for a description of the updated operating model, including a thorough evaluation of model fit to data and retrospective patterns.

We used the data scenario “D2: Base with ageing error correction – Long” from Cox et al. [1] to condition operating models for our simulation analyses. Under this scenario, the operating model is fit to:

1. time series of retained catch between 1965 and 2016, including three commercial fishery gear-types (trap, longline, and bottom trawl) and two research surveys;
2. time series of at-sea releases between 1996 and 2016 for trawl and between 2006 and 2016 for trap and longline hook fisheries;
3. indices of relative abundance from commercial CPUE (1979-2009), standardized trap survey (1991-2009), and stratified random trap survey (2003-2015);
4. age composition data from the commercial Sablefish trap fishery, standardized trap survey, and stratified random trap survey.

Detailed descriptions of these data sets are provided in Cox et al.[1] For the present analysis, we update the operating model data to include an additional year (Appendix B). Model fit diagnostics using updated data to the end of 2016 are shown in Appendix C. A Bayesian estimation approach using Markov Chain Monte Carlo (MCMC) simulation was used to generate posterior parameter estimates for the operating model scenarios described below. Size-selectivity for trawl was assumed dome-shaped and constant among years based on estimates derived from Sablefish tag release-recovery data (Appendix E of Cox et al.[1]). Size-selectivity was also dome-shaped and constant over time for trap and longline fisheries, although the degree of doming was small for longline hook fisheries.

We use five operating model scenarios to test the candidate management procedures, dividing these into an expected case scenario derived from the posterior mean parameter values and four robustness scenarios (Rademeyer et al. 2007, Cox et al. 2013, Punt et al. 2016). The expected case scenario represents the most plausible hypothesis about stock and fishery dynamics, and is intended to be used as the primary basis for evaluating candidate management procedure performance (Punt et al. 2016). Robustness scenarios are considered less likely than the base case scenario, but still plausible, and thus are important for determining sensitivity under potentially extreme conditions (Cox et al. 2013, Punt et al. 2016).

We based our operating model scenarios on plausible hypotheses about productivity (i.e., the steepness parameter of the spawner-recruit relationship) and current spawning stock biomass. The base case operating model used the posterior mean (i.e., expected) value of steepness and $fSSB_{2016}$. The remaining four scenarios were selected by fitting a multivariate normal distribution to the joint posterior distribution for these two variables, and selecting four points on the same percentile ellipse that captured the marginal central 80th percentiles of each parameter's posterior (Figure 1a). For each of the five steepness – $fSSB_{2016}$ pairs defined, the MCMC posterior point that laid closest to the pair was identified, and the corresponding MCMC samples for all other leading parameters and error terms were used to condition the operating model for each scenario. The four alternatives to the base case represented the following combinations:

1. high productivity and mean $fSSB_{2017}$ (hiProd);
2. low productivity and mean $fSSB_{2017}$ (loProd);
3. mean productivity and high $fSSB_{2017}$ (hiSSB); and
4. mean productivity and low $fSSB_{2017}$ (loSSB).

This approach allowed us to capture uncertainty about both stock-recruitment steepness and current spawning stock biomass without simulating all the possible parameter combinations from the operating model posterior distribution. While the posterior correlation between current spawning biomass and stock-recruitment steepness is itself quite weak, fitting a bivariate normal distribution to approximate the posterior captures this correlation (Figure 1b). Leading model parameters for each operating model scenario are provided in Table 4.

2.4 FEEDBACK SIMULATIONS

We use the following closed-loop simulation algorithm to evaluate each candidate management procedure (e.g., Walters 1986, de la Mare 1998, Cooke 1999, Punt and Smith 1999, Sainsbury et al. 2002, Butterworth 2007):

1. Define a management procedure based on the harvest control rule TAC floor and sub-legal regulation;
2. Initialize a pre-conditioned operating model scenario for the period (1965 – 2016) based on historical data;
3. Project the operating model population and fishery one time step into the future. At each step apply the following:
    a. Generate the catch and survey data available for stock assessment;
    b. Apply the stock assessment method to the data to estimate quantities required by the harvest control rule;
    c. Apply the harvest control rule to generate a catch limit;
    d. Update the operating model population given the fishing mortality rate generated by the catch limit and sub-legal regulation, and new recruitment;
    e. Repeat Steps 3.i-3.iv until the projection period ends.
4. Calculate quantitative performance statistics for the replicate;
5. Repeat Steps 2-4 for 100 replicates.

3 SIMULATION RESULTS

3.1 EXAMPLE SIMULATION REPLICATES

In this section, we demonstrate operating model outcomes for the base scenario under the current MP (currMP) and the Fl0.00_HR5.5_ph5_frt MP, which is probably the best overall-performing MP. The latter features both a 5-year phase-in to a lower 5.5% target harvest rate and a full retention regulation. All other MPs generally fall between these two extremes. Under the base scenario, operating model female spawning biomass (fSSB) is projected to increase over the 2016-2026 period, regardless of the management procedure. This occurs primarily because of recent high age-1 recruitment already present in the operating model population (Figure 2) that is expected to fuel strong growth in fSSB. During the growth phase, currMP maintains TACs at the current floor of 1,992 t, while the Fl0.00_HR5.5_ph5_frt MP first reduces the TAC and then follows the growth over time. Both procedures maintain high, or even increasing, TACs as the fSSB begins to decline in the late 2020's when the high 2013-14 recruitment cohorts die off. The key difference between the two MPs begins to appear around 2035 when currMP returns to the TAC floor, while Fl0.00_HR5.5_ph5_frt continues to reduce TACs until fSSB shows signs of recovery. This general pattern drives most of the differences in long-term conservation performance; that is, most of the effect of different harvest strategies comes after the 2013-14 recruitment has passed through the population. Variability in projected future Sablefish recruitment appears similar to the historical recruitment patterns based on a visual comparison of historical and projected time periods (Figure 2; bottom panels).

The simulated stock assessments differ between the two MPs because prior distributions on F_{MSY} and MSY in the Fl0.00_HR5.5_ph5_frt MP have lower and more precise prior distributions compared to the currMP. The assessments under Fl0.00_HR5.5_ph5_frt end up less variable than those under currMP, as shown by the tighter distribution of retrospective model fits *grey lines) in Figure 3. However, the two MPs are similar in overall biomass levels. As shown by the retrospective estimation patterns in Figure 3, the simulated assessments are biased with respect to both fSSB and exploitable biomass in the operating model. In both cases, the biomass time series estimated by the surplus production model tends to be less than the legal biomass and greater than the fSSB in the operating model (Figure 3). This bias occurs because (i) the production models assume a single spawning/exploitable stock and (ii) the assessment only accounts for landed catch, which has a negative effect on the bias leading to under-estimation of exploitable biomass.

Differences in operating model outcomes and simulated assessment performance lead to different patterns in the harvest rule components for both currMP and Fl0.00_HR5.5_ph5_frt (Figure 4). First, the tighter prior distributions in the Fl0.00_HR5.5_ph5_frt assessments, lead to less variability in the harvest control rule operational control points (i.e., B_{lower} and B_{upper}). Both assessments estimate the biomass to be near B_{MSY} for most of the simulation time period. The realized harvest rates decline in the short-term under both MPs as the stock grows; but, after 2018 the two MPs produce very different harvest rate outcomes. Near the end of the simulation time horizon for currMP, the precautionary harvest control rule recommends dropping the target harvest rate to zero (bottom panel), but the floor keeps the TAC at 1,992. As a consequence, the currMP procedure leads to a continuously increasing harvest rate to over double the optimal rate of U_{MSY} for the operating model. In contrast, Fl0.00_HR5.5_ph5_frt procedure maintains a lower realized harvest rate after 2035 and then reduces these further in response to the stock decline. The realized harvest rate on the operating model stock actually remains close to the value estimated by the assessment and the downward adjustments reverse the decline. Note that in all these simulations, the Fl0.00_HR5.5_ph5_frt MP has the advantage of full retention so there is (i) an exact match between the landed catch and the total catch-related mortality, which helps the assessment model and (ii) lower overall mortality of small fish, which leaves more production available to support stock growth and recovery.

3.2 MANAGEMENT PROCEDURE PERFORMANCE

This section presents projected distributions of fSSB depletion, catch, and harvest rate for selected MPs. We expand the list of MPs used to present results in the previous section (currMP and FI0.00_HR5.5_ph5_frt) to also include two variants of the latter: one without a phase-in period or full retention (FI0.00_HR5.5) and one with a 5-year phase-in only (FI0.00_HR5.5_ph5). Projected distributions for all 10 MPs and 5 scenarios are given for depletion and catch in Appendix D and for legal harvest rate in Appendix E.

3.2.1 MP Performance: Base Scenario

The projected fSSB distribution under the currMP applied to the base scenario reflects the single replicate presented in the previous section; that is, the stock grows over the first ten years, after which the risk of decline below the LRP increases for the remainder of the projection period (Figure 5). When currMP is applied to the base scenario, fSSB < LRP about 7% of the time (Table 5), while the median fSSB begins stabilizing just below the Healthy Zone (where, the Healthy Zone is > $0.8B_{MSY}$; note reference lines in Figure 5 are only shown for LRP and B_{MSY}). Landed catch for currMP increases for the first ten years while the stock is growing, and then stabilized over the latter part of the simulation period, although the TAC is mainly limited to less than 2,600 t (Figure 5; Table 5).

The FI0.00_HR5.5 MP (i.e., no floor, a lower target harvest rate, no phase-in period, and no full retention) leads to continued stock growth over the entire simulation period and essentially no chance of fSSB < LRP (Table 5). The median level of stock depletion approaches $0.80B_{MSY}$ near the end of the projected period (Figure 5). The cost for this level of conservation performance is an initial TAC reduction in 2017 to approximately 1,500 t, a 10-year average catch near 1,900 t, but possible catches greater than 2,100 t during the first 10 projection years. As with any feedback management procedure, catch tends to track upward changes in stock biomass, but TACs rarely reach over 3,000 t (Figure 5).

Applying the 5-year phase-in period for adjusting to the new, lower target harvest rate of 5.5% has no measurable effect on long-term conservation performance, essentially maintaining fSSB > LRP 100% of the time (Table 5) and allowing the stock to grow toward $0.8B_{MSY}$ in the long-term (Figure 5). The phase-in period leads to a projected 2017 TAC of 2,150 t, with the median dropping for a short time to just under 2,000 t by the end of the first 5 years. Long-term catch performance is then identical to the corresponding MP without the phase-in period.

Finally, the full FI0.00_HR5.5_ph5_frt MP has the conservation benefits of a precautionary harvest control rule (i.e., allowing catch variation with abundance) plus the added benefit of greatly reduced sub-legal Sablefish mortality. As a result, the stock grows continuously toward B_{MSY} and, in fact, achieves a median fSSB of B_{MSY} by the end of the simulation. This particular result shows that sub-legal Sablefish mortality could prevent even an ideal precautionary harvest control rule from achieving B_{MSY}. All of the FI0.00_HR05.5 MPs could produce B_{MSY} outcomes in the absence of sub-legal Sablefish mortality. The FI0.00_HR5.5_ph5_frt MP also produces the highest 10-year average catch of 2,033 t. This MP thus produces a "win-win" option in both conservation and landed catch for Sablefish.

3.2.2 MP Performance: High Productivity Scenario (hiProd)

The high stock-recruitment productivity scenario is defined mainly by a steepness parameter of h = 0.63. The optimal legal harvest rate for this operating model (0.050;Table 4) is about 14%

higher than the expected productivity scenario (0.044). However, the slightly smaller current stock size for the hiProd scenario leads to a higher initial exploitation rate and consequent negative impact of short-term catches (Figure 6). The 1,992 floor for currMP, in particular, leads to a wide range of outcomes for female spawning biomass over the first decade of the simulations (Figure 6). The short-term conservation performance of currMP is actually worse for the hiProd scenario than for the base scenario. Over the two generation simulation time horizon, fSSB was < LRP approximately 10% of the time, while the probability of decline over the first 10-years was 29% (Table 6).

Given higher than average stock productivity, all procedures except currMP resulted in fairly rapid stock growth to B_{MSY}, or higher, by the end of the simulation period (Figure 6; Appendix D). All of the probabilities of fSSB > LRP were within requirements for Objective 1 and probabilities of fSSB decline over the first 10 years were 2% or less (Table 6). However, unlike the base case, all of the alternative MPs had lower 10-year average catch than currMP. In the long-term, most had greater average catch over the latter part of the simulation period than currMP due to higher stock biomass.

3.2.3 MP Performance: Low Productivity Scenario (loProd)

The low stock-recruitment productivity scenario is defined mainly by a steepness parameter h = 0.48. The optimal legal harvest rate for this operating model (0.036;Table 4) is about 18% lower than the expected productivity scenario. At this level of productivity, fSSB is very near the LRP as of 2016, which results in relatively higher risks of decline in the short-term (Figure 7).

For the loProd scenario, currMP results in a 59% chance that fSSB is < LRP over two Sablefish generations and a 62% chance of decline over the first 10-years (Table 7). Average 10-year catch is the same as other scenarios, but in the long-term, TACs drop for currMP in some simulation replicates when fSSB drops below 5% of the unfished level. When this happens, the floor 1,992 t can no longer be taken as catch.

The alternative MPs without TAC floors all maintain 94% or greater chances of maintaining fSSB > LRP and probabilities of decline over 10 years of 8% (with full retention) or 15% (without full retention), both of which are greater than the acceptable probability of decline of 6% (Table 7). Over the long term, these non-floor procedures result in stock growth above the LRP and toward B_{MSY}, although none result in more than an 18% chance of reaching 0.8 B_{MSY} over two generations. By the end of the simulation period, all of these non-floor MPs have median fSSB in the middle of the Cautious Zone (Figure 7). Average 10-year catch in for these MPs are highly uncertain, ranging from lows of 780 t to highs of 2,000 t with medians approximately 1,300-1,400 t.

Under the low productivity scenario, management procedures without TAC floors maintained negative feedback between operating model biomass and realized operating model harvest rates, thus allowing the stock to grow to larger sizes in response to good recruitment. Fluctuations in stock size are compensated by lower target harvest rates when stocks are low and high target harvest rates when stock are high. In general, these harvest rates fluctuate around the optimal harvest rate for the operating model (Figure 10, bottom panel).

In contrast, procedures with TAC floors (Figure 10, top and middle panels) result in poor long-term conservation performance because holding catch constant creates a positive feedback in which realized harvest rates increase whenever the stock declines. This generally begins to happen around the middle of the simulation time horizon (e.g., 2027-2037) as the recent high recruitments die off and the future recruitment more closely resembles the average stock-recruitment relationship. In some cases, very large recruitment(s) occur to offset declines; however, in most cases, harvest rates increase over time to well-above U_{MSY}.

3.2.4 MP Performance: High Spawning Biomass (hiSSB)

We defined the high fSSB (hiSSB) scenario by a posterior female spawning biomass level of 11.5 tonnes in 2017 (Table 4). While fSSB in 2017 is larger for this scenario compared to the base scenario, the 2017 depletion level was similar ($fSSB_{2017} / B_0 = 0.21$ for hiSSB and 0.20 for base). The steepness parameter for this scenario is 0.56, which is close to the value of 0.57 used in the base case. As a result, MSY-related quantities, including U_{MSY} and B_{MSY}, are also close to the base case (Table 4).

Under the hiSSB scenario, currMP has a 10% chance of fSSB < LRP over two Sablefish generations, and a 25% chance of decline over the first 10 years (Table 8). As expected, the average 10-year catch of 2060 t is about 4% higher than the other scenarios, which is caused by the higher absolute biomass in this scenario. Similarly, the maximum catch is higher than other scenarios at 2270t (Table 8). However, the median catch stays close to the TAC floor over the projection period, indicating slow growth of the biomass under currMP (Figure 8).

Similar to the hiProd scenario, all MPs except currMP and Fl1.992_HR5.5 passed Objective 1 [P(*fSSB* > LRP] and Objective 2 [P(decline)] (Table 8). Procedures with full retention of juvenile fish performed the best regardless of the TAC floor, with higher average catch and higher probability of climbing out of the cautious zone. Those MPs without full retention of juveniles grew more slowly. The 10-year average TAC for the currMP was 13 to 19% higher than those of MPs with no floors or a floor set at 1,800 t. Despite the remaining MPs having lower 10-year average TACs than currMP, median TACs for those MPs climbed away from the floor over the course of the projection period (Figures D-3 to D-10 in Appendix D).

3.2.5 MP Performance: Low Spawning Biomass in 2016 (loSSB)

The low fSSB (loSSB) scenario is defined by a female spawning biomass level of 8.72 tonnes in 2017 (Table 4), which corresponds to a 2017 depletion level of $fSSB_{2017} / B_0 = 0.16$. The steepness parameter for this scenario is 0.56, which is close to the value of 0.57 used in the base case. As with the hiSSB case, MSY-related quantities, including U_{MSY} and B_{MSY}, are close to the base case (Table 4).

Under the loSSB scenario, currMP had a 56% chance of fSSB < LRP, and a 46% chance of decline over the first 10 years (Table 9). The average 10-year catch is equally high for currMP and the two MPs with floors set at 1,992 t and maximum harvest rates set at 5.5% (Fl1.992_HR5.5 and Fl1.992_HR5.5_frt); however, none of these MPs were able to meet Objective 1 [P(*fSSB* > LRP] or Objective 2 [P(decline)] than currMP.

None of the 10 MPs evaluated were able to Objective 1 [P(*fSSB* > LRP] in the lowSSB scenario with the required 95% probability; however, all MPs without a TAC floor maintained fSSB > LRP at least 90% of the time. Moreover, the same MPs all achieved acceptable probabilities of decline (Table 9). Despite starting the projection period at the lower end of the cautious zone, all MPs without TAC floors were able to grow median biomass to at least halfway through the cautious zone over the projection, with median TACs exceeding the floor in the latter half of the projection period (Figures E6 to E-10 in Appendix E). This behavior is due to the same negative feedback effect observed in the loProd scenario, where lower TACs reduced the effective harvest rate, which allowed the MP to reach the optimal rate in nearly 50% of simulations by the end of the projection.

In contrast, the use of TAC floors without full retention of juveniles promoted positive feedbacks in the harvest rate. By keeping TACs constant, these MPs effectively eliminated surplus production at the lower biomass level. This effect resulted in flat median biomass at the LRP, indicating a 50% probability of zero or negative growth. This positive feedback effect was mitigated by full retention options, where the reduced fishing pressure on older age classes resulted in higher stock growth. However, median TACs for MPs with floors and full retention (i.e., FI1.992_HR5.5_frt and FI1.80_HR5.5_frt) did not begin to grow until the last 10 years of the projection (Figures D-3 and Figure D-5 in Appendix D).

3.3 SUMMARY OF MP PERFORMANCE AGAINST OBJECTIVES

Table 10 provides MP performance weighted by scenario. Weights were assigned to scenarios based on probability densities calculated at each associated productivity-fSSB$_{2017}$ point from the bivariate normal distribution fit to the joint posterior distribution, which resulted in a 36% probability to the expected base case scenario and probabilities of 16%, 16%, 15%, and 17% to the hiProd, loProd, hiSSB, and loSSB scenarios, respectively.

Based on the weighted-average performance across the five OM scenarios, MPs that included TAC floors were not able to achieve conservation objectives (Objective 1 [P(fSSB > LRP) and Objective 2 [P(decline)]), while MPs without a TAC floor were able to achieve these objectives (Table 10). MPs that included the addition of full retention usually performed better relative to conservation objectives than identical MPs without full retention.

The current management procedure was unable to meet the three conservation objectives under any of the five productivity-spawning biomass OM scenarios and was consistently ranked last in conservation performance. Under the new operating model, currMP had a probability of fSSB > LRP = 0.76 based on weighted performance, which violated Objective 1.

The alternative FI1.992_HR5.5 MP, which combines the currMP floor with the new, lower maximum target harvest rate, performed second worst across conservation objectives (Table 10). When the FI1.992_HR5.5 MP was combined with full retention (FI1.992_HR5.5_frt), conservation performance ranked third best in the base and hiSSB scenarios (Table 5 and Table 8, respectively); however, overall weighted performance for this MP was poor due to poor performance in the loProd and loSSB scenarios (Table 7 and Table 9).

The FI0.00_HR5.5_frt MP performed best based on weighted performance over the two conservation objectives and catch Objective 4 (probability of TAC > 1,992 = 0.52). This MP was in the top half of MPs for Objective 5 (maximize catch; 10-year average catch = 1,730 t), however, the 10-year average catch for this MP was 18% less than that of currMP, which was the best performing MP for Objective 5.

Of the MPs that were able to meet Objective 1 [*P*(fSSB > LRP)] and Objective 2 [P(decline)] without requiring full retention, FI0.00_HR5.5_ph5 had the highest probability of TAC > 1,992 and the highest 10-year average catch. Shorter phase-in periods to the new, lower harvest rate had only small effects on Objective 3b [i.e., *P*(fSSB > 0.8B_{MSY})]. Like the other MPs without a floor, there is a 44% chance that FI0.00_HR5.5_ph5 could deliver TACs below the current 1,992 t floor over the first 10 projection years with the bottom 5th percentile in the 1,270 t range (Table 10, Min *C*). On the other hand, FI0.00_HR5.5_ph5 could also deliver TACs well above the current floor over the first 10 projection years with the top end in the 2,150 t range (Table 10, Max *C*). Overall, the level of interannual variability in TACs was just under 13% for this MP.

No MP was able to meet Objective 3b, which is to maintain fSSB > 0.8B_{MSY} more than 50% of the time over two Sablefish generations. Under all productivty scenarios, full retention MPs such as FI0.00_HR5.5_ph5_frt allow median fSSB > 0.8B_{MSY} by the final year.

4 DISCUSSION

4.1 PERFORMANCE RELATIVE TO OBJECTIVES

In this paper, we used a new operating model to evaluate the conservation and yield performance of alternative management procedures for setting annual harvest levels in the B.C. Sablefish fishery. Based on weighted-average performance across five scenarios, management procedures with TAC floors were not able to meet fishery conservation Objective 1 [P(*fSSB* > LRP)] regardless of whether they were combined with full retention of all Sablefish < 55 cm in length. In the absence of both TAC floors and full retention, an MP that phased-in a new maximum target harvest rate of 5.5% over 5 years was able to meet both Objective 1 [P(*fSSB* > LRP) and Objective 2 [P(decline)] while providing 10-year average catch of 1, 690 t. This procedure (Fl0.00_HR5.5_ph5) carries some risk of TACs in the 1,200 – 1,300 t range over the first 10 years, which would be well below the industry's current TAC floor.

None of the MPs evaluated were able to meet Objectives 3a [P(*fSSB* > B_{MSY})] and 3b [P(*fSSB* > 0.8B_{MSY})] with the required certainty under any of the operating model scenarios. Meeting these objectives requires spawning biomass to remain above B_{MSY} (Objective 3a), or 0.8B_{MSY} (Objective 3b) if the stock is rebuilding from the cautious zone, in 50% of the years measured over two Sablefish generations. In the context of a rebuilding stock, this objective requires spawning stock biomass to reach these target levels by mid-way through the projected trajectory (e.g., within 18 years). Several of the MPs evaluated were able to promote stock growth towards B_{MSY} by the end of the 36 year projection period (e.g. those with maximum harvest rates of 5.5% and those that required full retention of sub-legal fish). However, none were able to reach this level and remain above by year 18. This result differs from previous MSE analyses which have shown greater potential for biomass growth under MPs similar to those tested here. The inability of any MPs in our current evaluation to meet objectives 3a [P(*fSSB* > B_{MSY})] and 3b [P(*fSSB* > 0.8B_{MSY})] is due to a combination of current stock status being around 0.45B_{MSY} and the lower productivity of Sablefish represented in the updated operating model compared to the previous version (e.g. U_{MSY} is now estimated to be 5.5% compared to 6% in the 2011 operating model). If Objectives 3a and 3b are to be achieved, alternative MPs will need to be considered that allow for further catch reductions than the ones presented here. Alternatively, if there is a recognition that rebuilding slow-growing stocks such as Sablefish requires longer than one generation, objectives and performance related to rebuilding stocks back towards target reference points such as B_{MSY} could be structured in such a way that they require a 50% probability of reaching the target by year 36, instead of requiring that the target be achieved in 50% of years. Previous iterations of the Sablefish MSE predicted higher probabilities of reaching these objectives using the old operating model, due to the higher productivity estimates produced by the previous combined-sex model.

The new B.C. Sablefish operating model addressed two documented limitations of previous models. In particular, the new sex-structured operating model (i) accounted for differences in natural mortality, growth, and selectivity of male and female Sablefish and (ii) included greater variability in recruitment after accounting for ageing errors in the model conditioning step. The lower overall Sablefish productivity estimated by the new operating model suggests greater sensitivity of future stock sizes to TAC floors used to safeguard the fishery and greater sensitivity to at-sea release mortality of Sablefish < 55 cm in length. Sensitivity to the TAC floors is generally not expressed until 10 years into the projection period (for the base scenario) as Sablefish from recent high recruitments pass through the population. Unlike our previous MSE simulations, a full retention regulation is projected to offset higher mortality associated with TAC floors, and ultimately provide greater safeguarding of the fishery and the future spawning stock.

We present MP performance ranked within scenarios, as well as a weighted ranking across operating model scenarios. Experience over the past 5 years with the current management procedure suggests that the original scenarios may have been somewhat optimistic in basing MP decisions on the most likely scenario. In previous MSE work for this fishery, MPs were mainly chosen based on the most likely operating model scenario with other scenarios serving as stress tests. One condition, however, was that no MP would be acceptable if it did not pass Objective 1 [P(*fSSB* > LRP)] under any scenario, including stress tests. Although the current MP passed those original tests (DFO 2014), here it failed to meet Objective 1 (i.e., the probability that *fSSB* > LRP was less than 95%) under any productivity scenario. Performance in the low productivity case was particularly poor with > 60% chance of spawning biomass decline over 10-years and an only 41% chance of spawning biomass above the LRP. Using the weighted average performance across scenarios takes these risks into account in proportion to their credibility in the operating model.

4.2 MANAGEMENT STRATEGY IMPLICATIONS FOR THE 2017/2018 FISHERY

Although the management procedure that maximized catch performance while ensuring that conservation objectives were met used full retention of Sablefish (Fl0.00_HR5.5_ph5_frt), full retention as a management tool is likely not feasible to implement for the 2017/2018 fishing year. Among the remaining management procedure options, the four harvest control rules with no floor and a maximum harvest rate of 5.5% (Fl0.00_HR5.5, Fl0.00_HR5.5_ph3, Fl0.00_HR5.5_ph4, and Fl0.00_HR5.5_ph5) do the next best in terms of Objective 1 [P(*fSSB* > LRP], Objective 2 [P(decline)], and Objective 3b [P(*fSSB* > $0.8B_{MSY}$] based on weighted performance across all five productivity scenarios. All of these MPs were able to meet Objectives 1 and 2 with the required level of certainty, while none of them were able to achieve Objectives 3b. Among these four MPs, increasing the number of years of phase-in from zero to five years resulted in small decreases in probability of meeting Objective 3b, but improved performance relative to the two catch objectives (Objective 4 [Pr(Catch > 1,992) and Objective 5 [AveCatch]). While one of these four procedures is most likely the best option out of the non-retention MPs evaluated here, final selection will depend on a trade-off in risk preferences between Objectives 3b, 4, and 5. Improvement in the performance measure for Objective 3b (probability of spawning biomass being greater than $0.8B_{MSY}$ in any given year) range from 31% at 0 years to 28% at 5-years), while the corresponding changes in the 10-year median catch level (TACs) range from 1,600 t at 0 years phase-in to 1,690 t at 5-year phase-in.

Predicted TACs for the 2017/2018 fishery, based on the 2015 survey index being used as a proxy for the 2016 survey index, are 1,380 t for the Fl0.00_HR5.5 MP with no phase-in and 2,000 t for the other three MPs that use a phase-in period to introduce the lower maximum harvest rate regime.

4.3 LIMITATIONS

The Sablefish operating model presents several uncertainties and challenges originating from data limitations and tenuous population dynamics assumptions. Abundance index and age composition data are lacking for any gear type during the early part of the fishery (i.e., in the 1960s-1970s). In addition, age and size composition data are lacking for both trawl and longline hook fisheries, which means that we continue to rely heavily on tag release-recovery data for estimating the size-selectivity of these fisheries. Biological sampling in the trap fishery continues to be voluntary, although recent data seem to be improving relative to the 1980s-1990s. The influence of assumed prior distributions on natural mortality and steepness parameters within the operating model have not yet been thoroughly explored for the updated operating model, so future MSE analyses should consider conducting robustness testing of these prior distributions.

Lack of population closure for B.C. Sablefish is well documented based on decades of tag release-recovery data in both the USA and Canada. Although the majority of tagged Sablefish are recaptured within B.C., we have yet to examine the relative role of local production via spawning versus net movement into B.C. from Sablefish habitat in the Gulf of Alaska (GOA) in the north and the U.S. west coast (USWC) to the south. To date, the age-/sex-structured models or basic production models don't seem to show systematic lack-of-fit or retrospective patterns indicative of model failure to the magnitude observed for historical Pacific halibut stock assessments (prior to merging all areas into a single coastwide model). However, the assumption of a closed population is a key uncertainty in our analysis. Further work could be directed towards better quantifying movement rates between Canada and the U.S. using tagging data and considering options for a more coastwide view of the stock.

We continue to assume that the B.C. Sablefish population was at the unfished equilibrium biomass as of 1965 because there is essentially no hope of freely estimating a non-equilibrium starting condition for this model given the lack of data during that time. Although reported catch was low during the 1960s, thus supporting the unfished hypothesis, the fishing industry feels that considerable catch went unreported prior to the 1970s. Indeed, a non-equilibrium starting condition would be consistent with the current stock assessment for Gulf of Alaska in which spawning biomass starts near $0.75B_0$ in 1960. Future MSE work should consider alternative hypotheses for exploitation prior to the 1960s. Initial stock abundance and composition hypotheses could be represented in the operating model either as fixed parameters or estimated with highly informative priors.

Size-selectivity for B.C. Sablefish continues to be challenging to estimate. In particular, size-selectivity in the stratified random Sablefish trap survey could be over-estimated for age 1-2 fish (Appendix C, Figure C-3). We have not yet evaluated the implications of biased selectivity, but speculate that over-estimation for age 1-2 fish might lead to positively biased future survey indices. This would have the effect of simulating higher TACs than would occur in the presence of unbiased survey selectivity, although the magnitude is uncertain. On the other hand, realized legal harvest rates in the operating model are generally maintained near U_{MSY}, so perhaps the bias is compensated by a lower maximum target harvest rate of 5.5%, which we obtained via trial-and-error.

Decreasing abundance for B.C. Sablefish is consistent with recent assessments for both the Gulf of Alaska (GOA) and the U.S. West Coast (Hanselman et al. 2015, Johnson et al. 2015). Similarly, target harvest rates in B.C. of 7-8% are similar to those estimated for the GOA. Projections of spawning stock biomass for the GOA population show similar patterns to those presented here. It is therefore possible that harvest rates in this range are too high for Sablefish as suggested by our new operating model estimates of 4-5%. At-sea release mortality, and additionally depredation in the GOA, represent production losses that should be further investigated for B.C. and hopefully minimized in the future. Our results showing that a full retention fishery performs better in both conservation and catch should encourage discussion and research on the value of reducing non-landed mortality rates.

4.4 CONCLUSIONS

The B.C. Sablefish management strategy evaluation process was originally established to develop a transparent set of decision rules for setting sustainable TACs (Cox and Kronlund 2008). Since 2011, annual harvest decisions have closely followed recommendations from simulation-tested management procedures despite known limitations of the operating models underlying those tests. Recent revisions to the operating model, which are simulation tested for the first time here, appear to improve estimates of recruitment and mortality, but they also add complexity and uncertainty to the whole management strategy evaluation process. Under the new operating model scenarios, the current management procedure for the Sablefish fishery was not able to meet the highest-level conservation objective that guided historical choices. We present several alternative new management procedures that could meet performance standards for the two highest-level conservation objectives (Objectives 1 and 2), while also attempting to safeguard the economic performance of the fishery. Although all of these procedures lead to continuous stock growth in the future, none meets the specific probabilistic requirement for rebuilding spawning biomass to $0.8B_{\mathrm{MSY}}$ within one generation. For the highest ranked procedures, actually meeting this third objective would require a trade-off between fairly drastic short-term reductions in yield on the order of 500-700 t/yr against a change in probability of spawning biomass being greater than $0.8B_{\mathrm{MSY}}$ from 31-42% to 50%.

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7 TABLES

Table 1. Performance statistics calculated for each simulation replicate of a management procedure/scenario combination. Note that fSSB denote female spawning stock biomass and that the interval t = t_1, t_2 defines the time period over which each statistic is calculated. The probability P(decline) differs among scenarios depending on operating model stock status. The indicator function I(x is TRUE) = 1 or I(x is FALSE) = 0.

No.	Objective	Description	Probability or Statistic	Definition
P.1	Objective 1: *P*(fSSB > LRP)	Proportion of projection years where *fSSB* exceeds the LRP of 0.4B^{MSY}. (Period: t_1 = 2017, t_2 = 2052)	$P(fSSB > LRP)$	$P(B > LRP) = \frac{\sum_{t_2}^{t_1} \mathrm{I}(fSSB_t > LRP)}{t_2 - t_1 - 1}$
P.2	Objective 2: P(decline)	Proportion of 10-year trends that are declining (Period: t_1 = 2017, t_2 = 2026)	$P(\beta < 0) < P(decline)$	$P(\beta > 0) = \frac{1}{100}\sum_{1}^{100} \mathrm{I}(\beta < 0)$
P.3a	Objective 3a: *P*(fSSB>B_{MSY})	Proportion of projection years where *fSSB* exceeds B^{MSY} (Period: t_1 = 2017, t_2 = 2052)	$P(B > B_{MSY})$	$P(B > B_{\mathrm{MSY}}) = \frac{\sum_{t_2}^{t_1} \mathrm{I}(B_t > B^{MSY})}{t_2 - t_1 - 1}$
P.3b	Objective 3b: *P*(fSSB>0.8B_{MSY})	Proportion of projection years where spawning biomass exceeds 0.8B^{MSY} (Period: t_1 = 2017, t_2 = 2052)	$P(B > 0.8B_{MSY})$	$P(B > 0.8B_{\mathrm{MSY}}) = \frac{\sum_{t_2}^{t_1} \mathrm{I}(B_t > 0.8B^{MSY})}{t_2 - t_1 - 1}$
P.4	Objective 4: *P*(Catch>1,992)	Proportion of projection years where catch is above 1,992 tonnes (Period: t_1 = 2017, t_2 = 2052)	$P(C^L > 1{,}992\ t)$	$P(C^L > 1{,}992\ t) = \frac{\sum_{t_2}^{t_1} \mathrm{I}(C > 1{,}992\ t)}{t_2 - t_1 - 1}$

No.	Objective	Description	Probability or Statistic	Definition
P.5	Objective 5: AveCatch	Mean of annual landed catch (Period: t_1 = 2017, t_2 = 2026)	$\overline{C^L}$	$\overline{C^L} = \frac{1}{t_2 - t_1 + 1} \sum_{t_1}^{t_2} C_t^L$
P.6	Min and Max	Minimum and Maximum landed catch (Period: t_1 = 2017, t_2 = 2026)	Min *C* Max *C*	$\min(C_{2017}^L, C_{2018}^L, \ldots C_{2026}^L)$ $\max(C_{2017}^L, C_{2018}^L, \ldots C_{2026}^L)$
P.7	Industry preference	Average annual absolute change in the landed catch (Period: t_1 = 2017, t_2 = 2026)	*AAV*	$AAV = \sum_{t=t_1}^{t_2} \left\lvert C^L{}_t - C^L{}_{t-1} \right\rvert \Big/ \sum_{t=t_1}^{t_2} C^L{}_t$

Table 2. Harvest control rule component of the Sablefish management procedure. Parameters of the rule are derived from the TAC floor (Q_{min}), the maximum harvest rate (U_{max}), and surplus production stock assessment model estimates (listed in H1). Surplus production model estimates include the optimal harvest rate U_{MSY} , the biomass producing maximum sustainable yield B^{MSY}, and multipliers (0.4, 0.6) of B^{MSY} that define the bounds B_{lower} and B_{upper}, respectively. These parameters define a precautionary target harvest rate, U_{T+1} (H2), that multiplies the exploitable biomass forecast ($\hat{B}_{T+1}$) to determine a recommended total quota Q_{T+1} of legal-size fish using either H3 (if no minimum TAC increase) or H3a (if minimum TAC increase of 200 t used). The current management procedure uses U_{max} set at $\hat{U}^{MSY}$ and equation H3 with Q_{min}= 1,192 tonnes.

No.	Definition
H1	$\Psi = \left(\hat{U}^{MSY}, \hat{B}_{lower}, \hat{B}_{upper}, \hat{B}_{T+1}\right)$
H2	$U_{T+1} = \begin{cases} 0 & \hat{B}_{T+1} < \hat{B}_{lower} \\ U_{max}\left(\dfrac{\hat{B}_{T+1} - \hat{B}_{lower}}{\hat{B}_{upper} - \hat{B}_{lower}}\right) & \hat{B}_{lower} \le \hat{B}_{T+1} \le \hat{B}_{upper} \\ U_{max} & \hat{B}_{T+1} \ge \hat{B}_{upper} \end{cases}$
H3	$Q_{T+1} = \max\left(Q_{min}, U_{T+1}\hat{B}_{T+1}\right)$
H3a	$Q_{T+1} = \begin{cases} \max\left(Q_{min}, U_{T+1}\hat{B}_{T+1}\right) & (Q_{T+1} - Q_T) \ge 200 \\ Q_T & (Q_{T+1} - Q_T) < 200 \end{cases}$

Table 3. Candidate management procedures evaluated for the B.C. Sablefish fishery. Values in U_{max} and Q_{min} columns are the maximum harvest rates and TAC floors used in equations H2 and H3, respectively (see Table 2). The Minimum TAC Increase column indicates smallest allowable TAC increase; in the current MP (MP1), the TAC was calculated using equation H3 from Table 2, while all others used equation H3a instead. The Phase-in yrs indicates the number of years over which the maximum target harvest rate will ramp down from the 2017 value of 0.08 to U_{MAX}. Sub-legal regulations are either the status quo "Release < 55 cm" or "Full Retention" where no size limit is applied to all gears/sectors. The final column shows the labels used to identify each MP in graphics and tables. For reference, the acronyms used to construct the MP labels are given in parentheses within the column headers.

Management procedure	**U_{max+} (HR)**	**Q_{min} (FI)**	**Minimum TAC Increase**	**Phase-in yrs (ph)**	**Sub-legal Reg. (frt)**	**Label**
MP1	$\hat{U}_{MSY}$	1,992 t	0	0	Release < 55 cm	currMP
MP2	0.055	1,992 t	200	0	Release < 55 cm	FI1.992_HR5.5
MP3	0.055	1,992 t	200	0	Full retention	FI1.992_HR5.5_frt
MP4	0.055	1,800 t	200	0	Release < 55 cm	FI1.80_HR5.5
MP5	0.055	1,800 t	200	0	Full retention	FI1.80_HR5.5_frt
MP6	0.055	0.000	200	0	Release < 55 cm	FI0.00_HR5.5
MP7	0.055	0.000	200	3	Release < 55 cm	FI0.00_HR5.5_ph3
MP8	0.055	0.000	200	4	Release < 55 cm	FI0.00_HR5.5_ph4
MP9	0.055	0.000	200	5	Release < 55 cm	FI0.00_HR5.5_ph5
MP10	0.055	0.000	200	5	Full retention	FI0.00_HR5.5_ph5_frt

Table 4. Distinguishing features of operating model productivity scenarios S1-S5. Leading model parameters for each scenario are stock-recruitment steepness (h), the natural mortality rate (M) for males (top) and females (bottom), the unfished female spawning biomass (B_0), and female spawning biomass in 2017 ($fSSB_{2017}$). Equilibrium characteristics include the maximum sustainable yield (MSY), optimal legal harvest rate (U_{MSY}), spawning biomass (B_{MSY}), spawning biomass depletion (D_{MSY}), and depletion at the limit reference point $0.4B_{MSY}$ (D_{LRP}).

Scenario	***h***	***M***	B_0	$fSSB_{2017}$	**MSY**	U^{MSY}	B^{MSY}	D^{MSY}	D^{LRP}	$fSSB_{2017}/B_{MSY}$
S1:Base	0.57	0.041 0.079	56.76	10.45	2.84	0.044	23.01	0.41	0.16	0.45
S2:hiProd	0.63	0.041 0.079	56.91	10.40	3.09	0.050	22.42	0.39	0.16	0.46
S3:loProd	0.48	0.041 0.081	55.15	9.90	2.49	0.036	23.71	0.43	0.17	0.42
S4:hiSSB	0.56	0.041 0.078	57.19	11.50	2.78	0.043	23.34	0.41	0.16	0.49
S5:loSSB	0.56	0.041 0.079	56.62	8.72	2.81	0.043	23.21	0.41	0.16	0.38

Table 5. Management procedure performance against objectives for the base operating model scenario. For objectives 1 to 3, the symbol (●) is used to show that a management procedure satisfies an objective. Numerical values appear instead of the (●) symbol only when an objective is not satisfied. A procedure meets Objective 1 if the stock remains above the LRP in 95% of years, on average, over two generations. Objective 2 is met if the proportion of declining stock trajectories over the first 10 projection years is smaller than the acceptable probability of decline [P(decline)],where P(decline*) is based on spawning biomass in 2016. When this objective is not met, the projected proportion of declining stock trajectories along with P(decline*) for reference. Note that P(decline*) differs among scenarios. Objective 3a is met if spawning biomass is greater than B_{MSY} in 50% of years over 2 generations, while objective 3b is met if spawning biomass is greater than $0.8B_{MSY}$ in 50% of years over 2 generations. Objective 4 shows the average proportion of years in which annual landed catch is above 1,992 tonnes. Values under Objective 5 are median average catch (000s t) in the first 10 years of the projections. Additional performance measures shown that do not link directly to objectives include: "Min C" and "Max C" (the medians of minimum and maximum catch, respectively, over the first 10 projection years), AAV (the average absolute annual variation in catch), D_{2016} (average spawning biomass depletion for 2016), and C_{2017} (average projected legal catch for 2017).*

Scenario S1: Base	**Objective**										
Management procedure	**1** P(fSSB > LRP)	**2** P(decline)	**3a** P(fSSB > B_{MSY})	**3b** P(fSSB> $0.8B_{MSY}$)	**4** P(C > 1,992)	**5** Ave Catch	Min *C*	Max *C*	*AAV*	D_{2017}	C_{2017}
FI1.80_HR5.5_frt	●	●	0.23	0.45	0.69	1.93	1.79	2.19	3.95	0.20	1.79
FI0.00_HR5.5_ph5_frt	●	●	0.22	0.43	0.73	2.03	1.77	2.31	6.47	0.20	2.15
FI1.992_HR5.5_frt	●	●	0.22	0.43	0.65	2.02	1.98	2.16	1.39	0.20	1.98
FI0.00_HR5.5	●	●	0.15	0.37	0.61	1.87	1.52	2.17	7.59	0.20	1.48
FI1.80_HR5.5	●	●	0.14	0.34	0.58	1.91	1.79	2.14	3.79	0.20	1.79
FI0.00_HR5.5_ph3	●	●	0.14	0.34	0.61	1.95	1.67	2.29	7.39	0.20	2.15
FI0.00_HR5.5_ph4	●	●	0.14	0.33	0.61	1.98	1.72	2.29	6.91	0.20	2.15
FI0.00_HR5.5_ph5	●	●	0.14	0.32	0.62	2.01	1.75	2.30	6.65	0.20	2.15
FI1.992_HR5.5	●	●	0.13	0.32	0.53	2.00	1.98	2.09	1.02	0.20	1.98
currMP	0.93	●	0.07	0.18	0.73	2.30	1.98	2.59	5.00	0.20	2.05

Table 6. Management procedure performance against objectives for the high productivity (hiProd) operating model scenario. See Table 5 caption for definition of notation.

Scenario S2: hiProd	**Objective**										
	1	**2**	**3a**	**3b**	**4**	**5**					
Management procedure	P(fSSB > LRP)	P(decline)	P(fSSB > B_{MSY})	P(fSSB> $0.8B_{MSY}$)	P(C > 1,992)	Ave Catch	Min *C*	Max *C*	*AAV*	D_{2017}	C_{2017}
FI0.00_HR5.5_ph5_frt	•	•	0.29	0.48	0.54	1.62	1.11	2.12	13.13	0.19	1.95
FI1.80_HR5.5_frt	•	•	0.27	0.45	0.47	1.79	1.79	1.79	1.21	0.19	1.79
FI0.00_HR5.5	•	•	0.22	0.42	0.44	1.51	1.09	1.72	12.94	0.19	1.34
FI0.00_HR5.5_ph3	•	•	0.22	0.41	0.44	1.53	1.02	2.04	14.03	0.19	1.95
FI0.00_HR5.5_ph4	•	•	0.22	0.40	0.45	1.55	1.02	2.08	14.13	0.19	1.95
FI0.00_HR5.5_ph5	•	•	0.22	0.40	0.45	1.57	1.04	2.11	14.80	0.19	1.95
FI1.992_HR5.5_frt	•	0.12>0.10	0.24	0.41	0.43	1.98	1.98	1.98	0.13	0.19	1.98
FI1.80_HR5.5	•	0.14>0.10	0.18	0.33	0.36	1.79	1.79	1.79	1.21	0.19	1.79
FI1.992_HR5.5	0.90	0.28>0.10	0.15	0.27	0.31	1.98	1.98	1.98	0.13	0.19	1.98
currMP	0.90	0.29>0.10	0.09	0.22	0.48	1.99	1.98	2.09	1.08	0.19	2.01

Table 7. Management procedure performance against objectives for the low productivity (loProd) operating model scenario. See Table 5 caption for definition of notation.

Scenario S3: loProd	**Objective**										
Management procedure	**1** P(fSSB > LRP)	**2** P(decline)	**3a** P(fSSB > B_{MSY})	**3b** P(fSSB> $0.8B_{MSY}$)	**4** P(C > 1,992)	**5** Ave Catch	Min *C*	Max *C*	*AAV*	D_{2017}	C_{2017}
FI0.00_HR5.5_ph5_frt	●	0.08>0.06	0.06	0.18	0.24	1.40	0.85	2.04	18.72	0.18	1.90
FI0.00_HR5.5	●	0.15>0.06	0.04	0.13	0.16	1.31	0.88	1.62	16.80	0.18	1.31
FI0.00_HR5.5_ph3	●	0.15>0.06	0.04	0.12	0.16	1.34	0.78	1.97	19.13	0.18	1.90
FI0.00_HR5.5_ph5	0.94	0.15>0.06	0.04	0.12	0.17	1.35	0.78	2.03	19.81	0.18	1.90
FI0.00_HR5.5_ph4	0.94	0.15>0.06	0.04	0.12	0.17	1.34	0.79	2.01	19.25	0.18	1.90
FI1.80_HR5.5_frt	0.72	0.41>0.06	0.04	0.11	0.15	1.79	1.79	1.79	1.21	0.18	1.79
FI1.992_HR5.5_frt	0.62	0.53>0.06	0.02	0.08	0.13	1.98	1.98	1.98	0.13	0.18	1.98
FI1.80_HR5.5	0.56	0.56>0.06	0.00	0.04	0.07	1.79	1.79	1.79	1.21	0.18	1.79
FI1.992_HR5.5	0.42	0.62>0.06	0.00	0.02	0.04	1.98	1.98	1.98	0.13	0.18	1.98
currMP	0.41	0.62>0.06	0.00	0.01	0.11	1.98	1.98	1.98	0.13	0.18	2.00

Table 8. Management procedure performance against objectives for the high fSSB$_{2017}$ (hiSSB) operating model scenario. See Table 5 caption for definition of notation.

Scenario S4: hiSSB	**Objective**										
	1	**2**	**3a**	**3b**	**4**	**5**					
Management procedure	P(fSSB > LRP)	P(decline)	P(fSSB > B_{MSY})	P(fSSB> 0.8B_{MSY})	P(C > 1,992)	Ave Catch	Min *C*	Max *C*	*AAV*	D_{2017}	C_{2017}
FI0.00_HR5.5_ph5_frt	•	•	0.21	0.40	0.52	1.80	1.50	2.21	8.72	0.21	2.08
FI1.80_HR5.5_frt	•	•	0.20	0.38	0.46	1.80	1.79	1.86	1.79	0.21	1.79
FI1.992_HR5.5_frt	•	•	0.18	0.35	0.42	1.98	1.98	1.98	0.13	0.21	1.98
FI0.00_HR5.5	•	•	0.15	0.33	0.40	1.66	1.40	1.86	8.42	0.21	1.43
FI0.00_HR5.5_ph3	•	•	0.14	0.32	0.41	1.73	1.42	2.19	9.32	0.21	2.08
FI0.00_HR5.5_ph4	•	•	0.14	0.31	0.41	1.75	1.47	2.19	9.29	0.21	2.08
FI0.00_HR5.5_ph5	•	•	0.14	0.31	0.42	1.78	1.45	2.20	9.16	0.21	2.08
FI1.80_HR5.5	•	•	0.13	0.28	0.35	1.79	1.79	1.80	1.35	0.21	1.79
FI1.992_HR5.5	0.91	0.22>0.13	0.10	0.24	0.29	1.98	1.98	1.98	0.13	0.21	1.98
currMP	0.90	0.25>0.13	0.06	0.17	0.51	2.06	1.98	2.27	3.08	0.21	2.03

Table 9. Management procedure performance against objectives for the low fSSB$_{2017}$ (loSSB) operating model scenario. See Table 5 caption for definition of notation.

Scenario S5: loSSB	**Objective**										
	1	**2**	**3a**	**3b**	**4**	**5**					
Management procedure	P(fSSB > LRP)	P(decline)	P(fSSB > B_{MSY})	P(fSSB> 0.8B_{MSY})	P(C > 1,992)	Ave Catch	Min *C*	Max *C*	*AAV*	D_{2017}	C_{2017}
FI0.00_HR5.5_ph5_frt	0.92	•	0.14	0.28	0.38	1.39	0.79	1.94	20.07	0.16	1.76
FI0.00_HR5.5	0.93	•	0.08	0.21	0.28	1.32	0.80	1.63	18.67	0.16	1.21
FI0.00_HR5.5_ph3	0.91	•	0.08	0.21	0.28	1.32	0.73	1.87	20.61	0.16	1.76
FI0.00_HR5.5_ph4	0.90	•	0.08	0.21	0.28	1.33	0.73	1.91	20.74	0.16	1.76
FI0.00_HR5.5_ph5	0.90	•	0.08	0.21	0.28	1.33	0.72	1.94	21.04	0.16	1.76
FI1.80_HR5.5_frt	0.74	0.17>0.05	0.09	0.21	0.28	1.79	1.79	1.79	1.21	0.16	1.79
FI1.992_HR5.5_frt	0.64	0.31>0.05	0.07	0.17	0.24	1.98	1.98	1.98	0.13	0.16	1.98
FI1.80_HR5.5	0.58	0.34>0.05	0.03	0.11	0.16	1.79	1.79	1.79	1.21	0.16	1.79
FI1.992_HR5.5	0.45	0.46>0.05	0.01	0.06	0.12	1.98	1.98	1.98	0.13	0.16	1.98
currMP	0.44	0.46>0.05	0.00	0.04	0.21	1.98	1.98	1.98	0.13	0.16	1.99

Table 10. Management procedure performance averaged (weighted) over five operating model scenarios with weights equal to 36% on the expected productivity scenario, 16% on the hiProd scenario, 16% on the loProd scenario, 15% on the hiSSB scenario, and 17% on the loSSB scenario. Descriptions for each performance measure are the same as those given for Table 5, with the exception of Objective 2. Performance for objective 2 was calculated using the weighted average of the difference between the observed probability of decline and the acceptable probability of decline (observed – acceptable), such that the objective was met if the difference was <0.

	Objective										
	1	**2**	**3a**	**3b**	**4**	**5**					
Management procedure	P(fSSB > LRP)	P(decline)	P(fSSB> B_{MSY})	P(fSSB> $0.8B_{MSY}$)	P(C > 1,992)	Ave Catch	Min *C*	Max *C*	*AAV*	D_{2017}	C_{2017}
FI0.00_HR5.5_ph5_frt	●	●	0.19	0.37	0.54	1.73	1.32	2.16	12.02	0.19	2.00
FI0.00_HR5.5	●	●	0.14	0.31	0.43	1.60	1.21	1.87	11.83	0.19	1.38
FI0.00_HR5.5_ph3	●	●	0.13	0.29	0.43	1.65	1.24	2.11	12.75	0.19	2.00
FI0.00_HR5.5_ph4	●	●	0.13	0.29	0.43	1.67	1.26	2.13	12.62	0.19	2.00
FI0.00_HR5.5_ph5	●	●	0.12	0.28	0.44	1.69	1.27	2.15	12.75	0.19	2.00
FI1.80_HR5.5_frt	0.91	0.09	0.18	0.35	0.47	1.84	1.79	1.95	2.30	0.19	1.79
FI1.992_HR5.5_frt	0.87	0.23	0.16	0.32	0.43	1.99	1.98	2.04	0.59	0.19	1.98
FI1.80_HR5.5	0.84	0.17	0.11	0.25	0.36	1.83	1.79	1.92	2.17	0.19	1.79
FI1.992_HR5.5	0.78	0.27	0.09	0.21	0.31	1.99	1.98	2.02	0.46	0.19	1.98
currMP	0.76	0.26	0.05	0.14	0.48	2.11	1.98	2.26	2.52	0.19	2.02

8 FIGURES

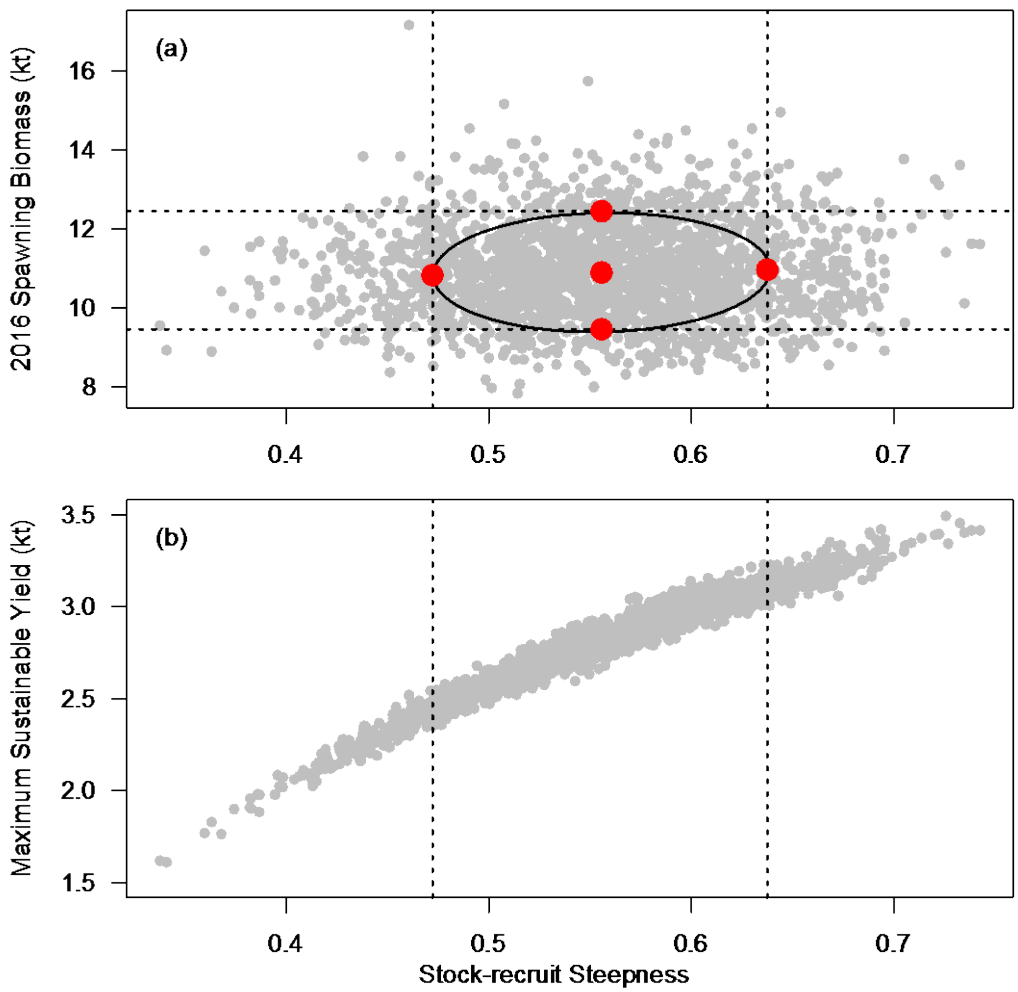

Figure 1. Joint posterior distributions for stock-recruitment steepness versus (a) 2016 female Sablefish spawning biomass or (b) maximum sustainable yield. The grey points are joint posterior Markov chain Monte-Carlo samples. In plot (a) OM productivity and biomass scenarios are defined by the red points at the joint posterior mean (centre) and intersections of the marginal central 80th percentiles (dashed lines) and the ellipse defining the central 57% of the joint marginal posterior distribution for steepness and 2016 female spawning biomass.

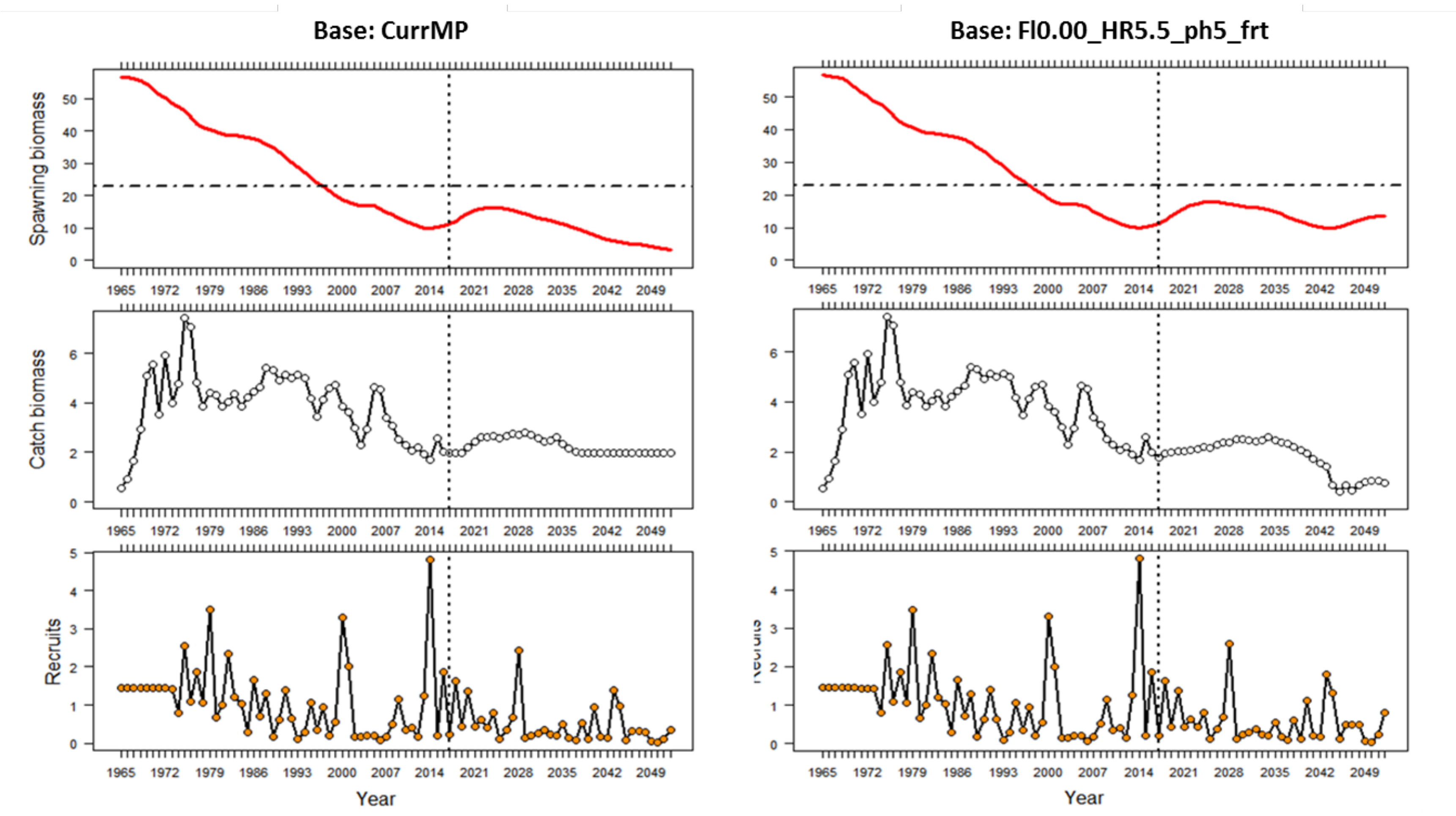

Figure 2. Operating model female spawning biomass, catch, and recruitment under the base scenario for two management procedures: (i) the current management procedure (currMP; left) and (ii) an alternative MP with no TAC floor, maximum target harvest rate of 0.055, 5-year phase-in period to the new target harvest rate, and full retention (Fl0.00_HR5.5_ph5_frt; right). The vertical dashed line separates the historical and projection periods.

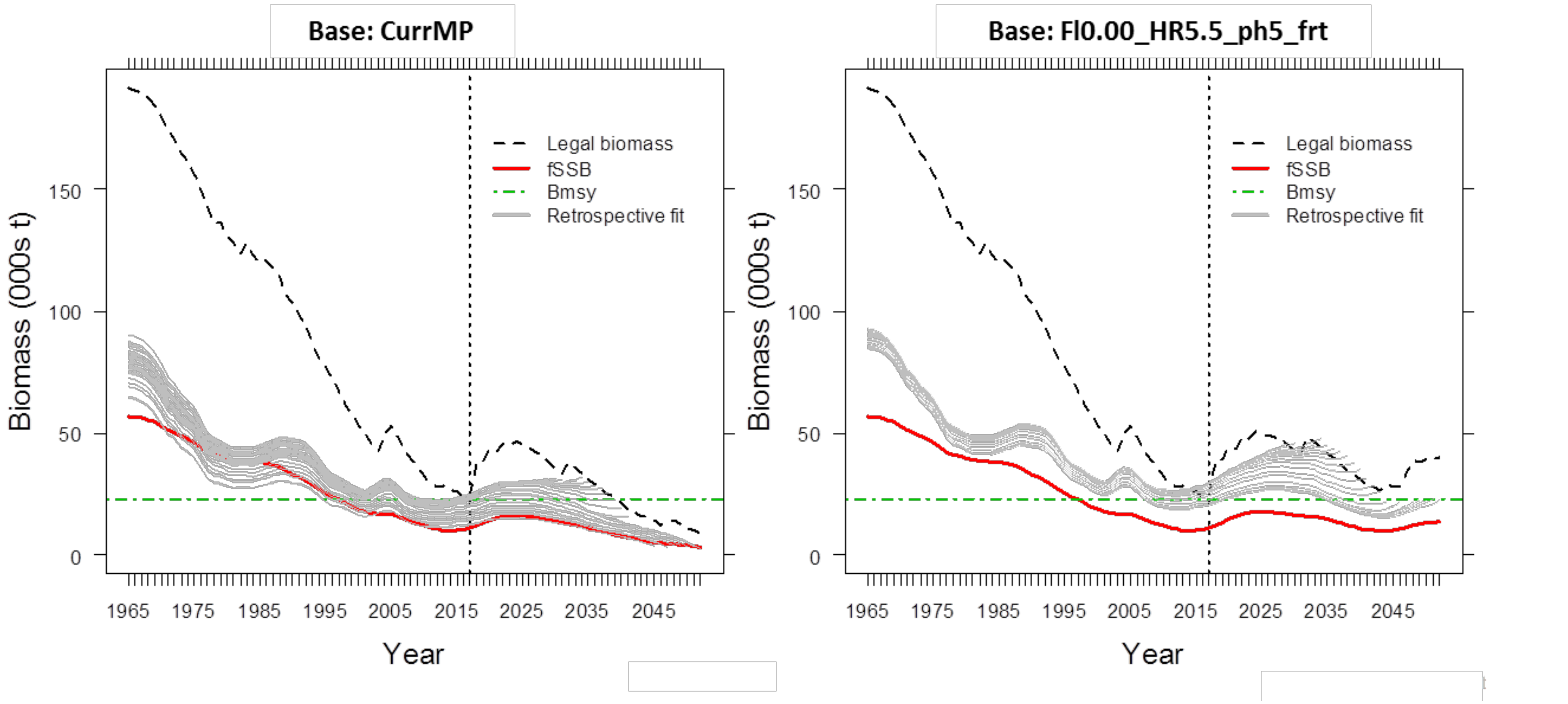

Figure 3. Example of retrospective patterns in biomass estimates from stock assessment model fits in two alternative management procedures applied to the base operating model:(i) the current management procedure (currMP; left) and (ii) an alternative MP with no TAC floor, maximum target harvest rate of 0.055, 5-year phase-in period to the new target harvest rate, and full retention (Fl0.00_HR5.5_ph5_frt; right). The solid red line and black dashed line show spawning biomass and total legal biomass in the operating model, respectively, while the grey lines show annual retrospective estimates of spawning. The vertical dashed line separates the historical and projection periods.

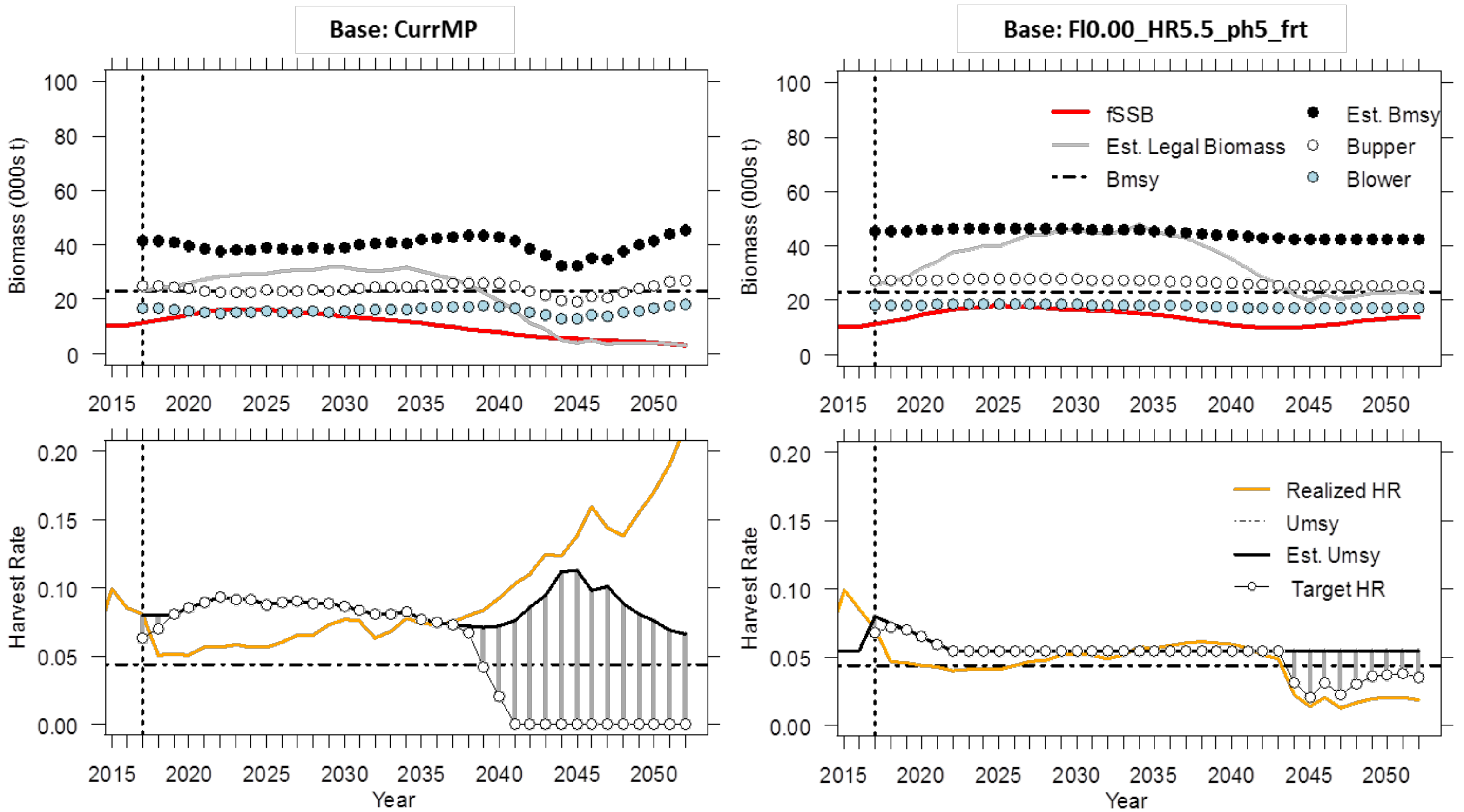

Figure 4. Harvest control rule components for the current management procedure (currMP; left) and an alternativeMP with no TAC floor, maximum target harvest rate of 0.055, 5-year phase-in period to the new target harvest rate, and full retention (Fl0.00_HR5.5_ph5_frt; right). Top panels show estimated B_{MSY}, the upper and lower operational control points used in the HCR (Bupper = $0.6B_{MSY}$ and Blower = $0.4B_{MSY}$, respectively), and a 1-year ahead projection of total exploitable biomass (Est. Legal Biomass). Female spawning biomass (fSSB) and B_{MSY} from the operating model are shown for reference. Bottom panels show the maximum target harvest rate from the operating model (U_{MSY}), annual estimates of U_{MSY} from the management procedure (Est. U_{MSY}), the annual target harvest rates based on annual application of the harvest control rule (Target HR), and the realized harvest rate experienced by the operating model population. Annual harvest rate adjustments in the bottom panel occur as the estimated exploitable stock in the top panel falls between harvest control rule points $0.4B_{MSY}$ and $0.6B_{MSY}$.

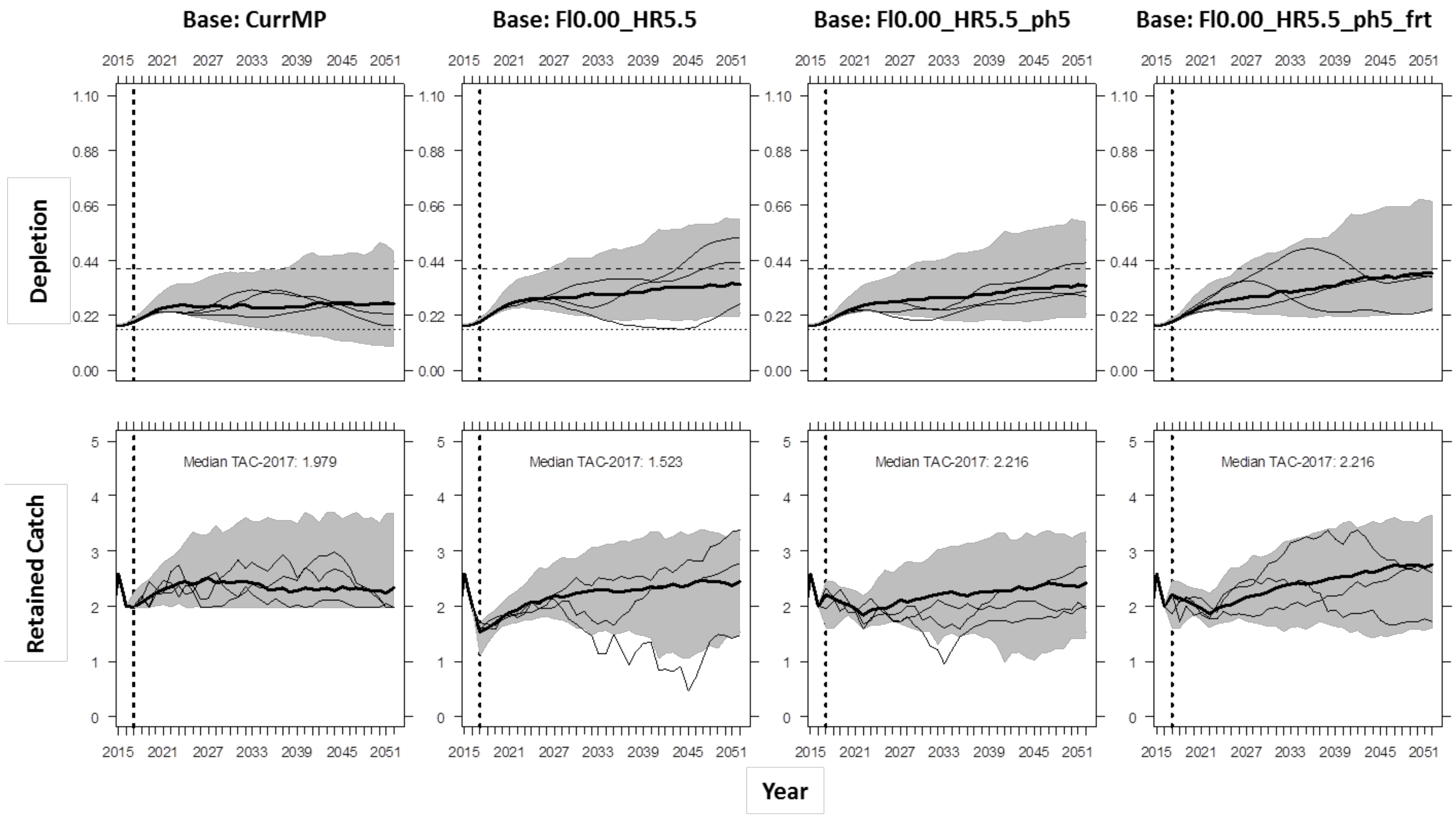

Figure 5. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated management procedures (bottom) under the ***base scenario****. From left to right, the currMP procedure is the most constrained in terms of catch, Fl0.00_HR5.5 is the least constrained, Fl0.00_HR5.5_ph5 uses a 5-year phase-in to a new, lower maximum harvest rate, and Fl0.00_HR5.5_ph5_frt implements a full retention regulation. Distributions represent the central 80% of 100 simulation replicate outcomes, medians (thick black lines), and randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

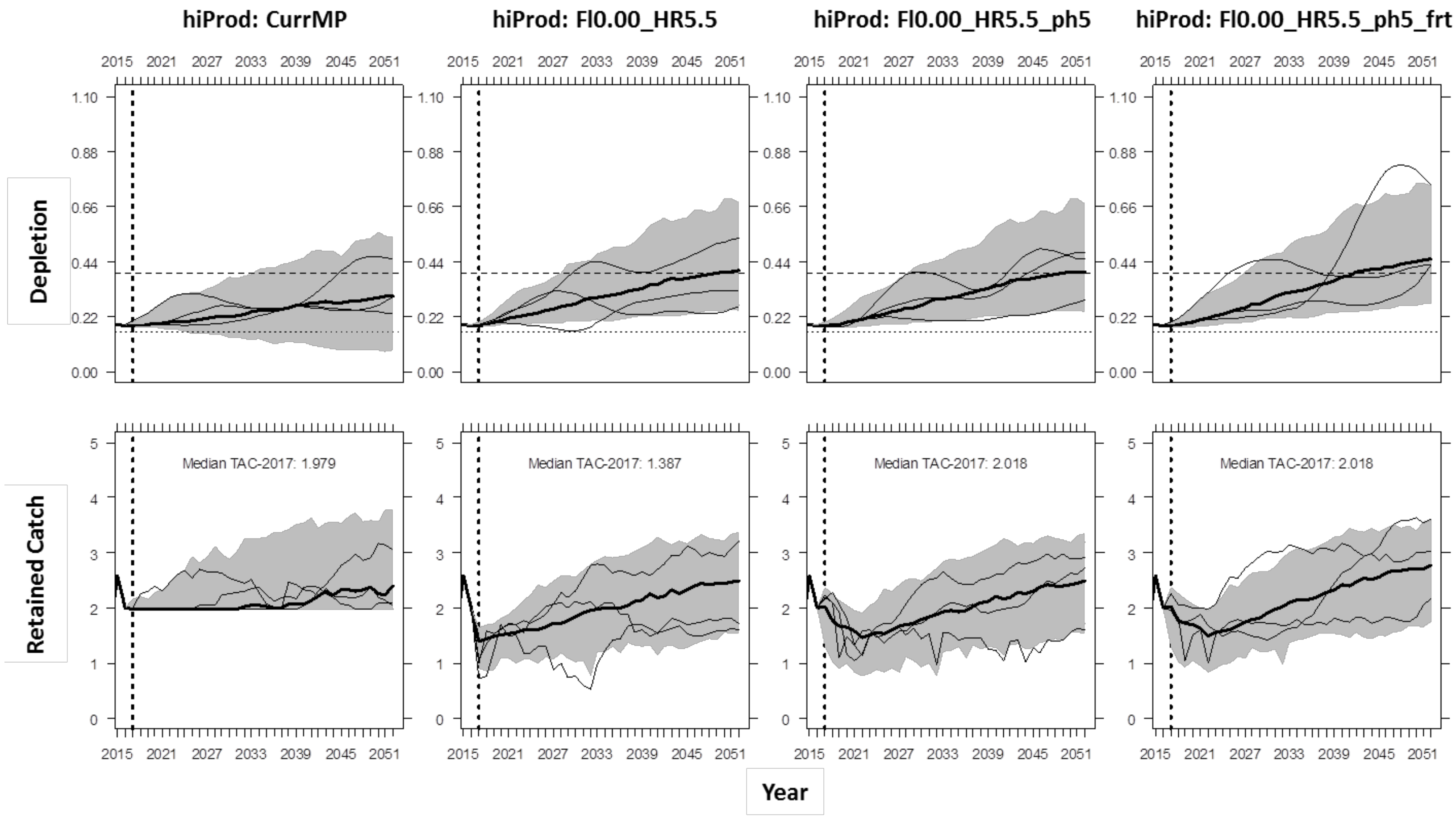

Figure 6. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated management procedures (bottom) under the ***high productivity scenario****. From left to right, the currMP procedure is the most constrained in terms of catch, FI0.00_HR5.5 is the least constrained, FI0.00_HR5.5_ph5 uses a 5-year phase-in to a new, lower maximum harvest rate, and FI0.00_HR5.5_ph5_frt implements a full retention regulation. Distributions represent the central 80% of 100 simulation replicate outcomes, medians (thick black lines), and randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

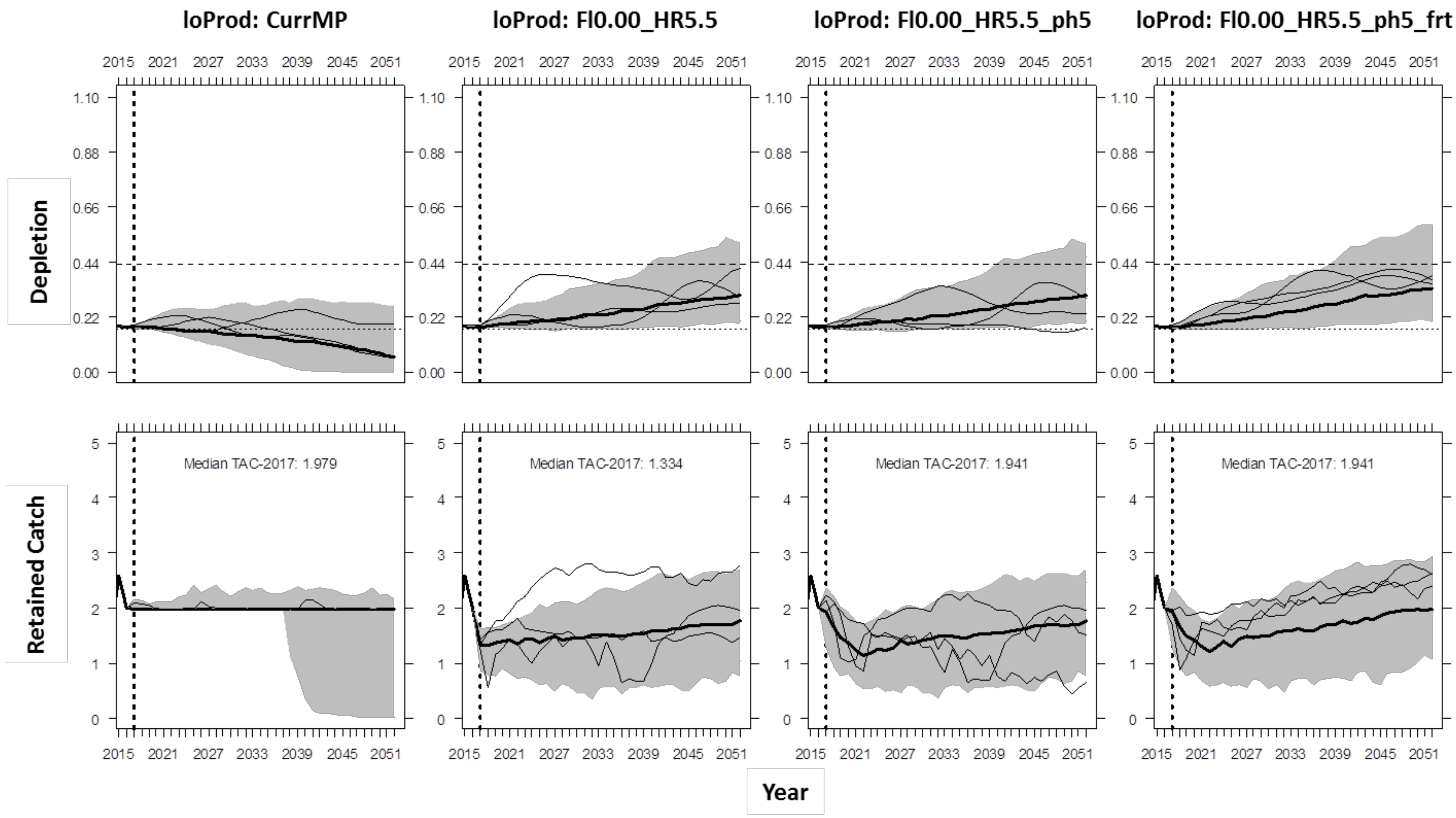

*Figure 7. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated management procedures (bottom) under the **low productivity scenario**. From left to right, the currMP procedure is the most constrained in terms of catch, Fl0.00_HR5.5 is the least constrained, Fl0.00_HR5.5_ph5 uses a 5-year phase-in to a new, lower maximum harvest rate, and Fl0.00_HR5.5_ph5_frt implements a full retention regulation. Distributions represent the central 80% of 100 simulation replicate outcomes, medians (thick black lines), and randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

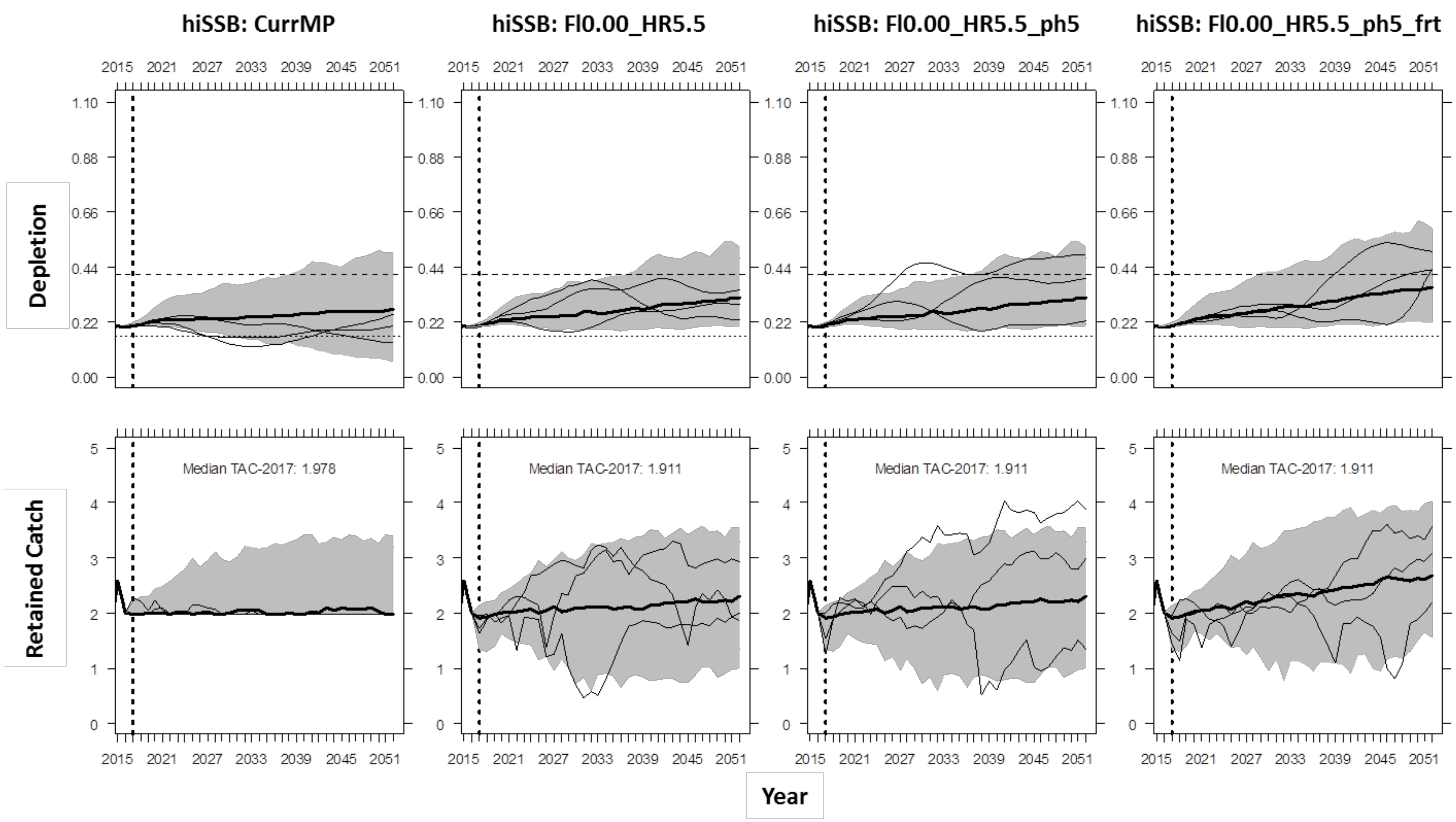

*Figure 8. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated management procedures (bottom) under the **high fSSB scenario**. From left to right, the currMP procedure is the most constrained in terms of catch, Fl0.00_HR5.5 is the least constrained, Fl0.00_HR5.5_ph5 uses a 5-year phase-in to a new, lower maximum harvest rate, and Fl0.00_HR5.5_ph5_frt implements a full retention regulation. Distributions represent the central 80% of 100 simulation replicate outcomes, medians (thick black lines), and randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

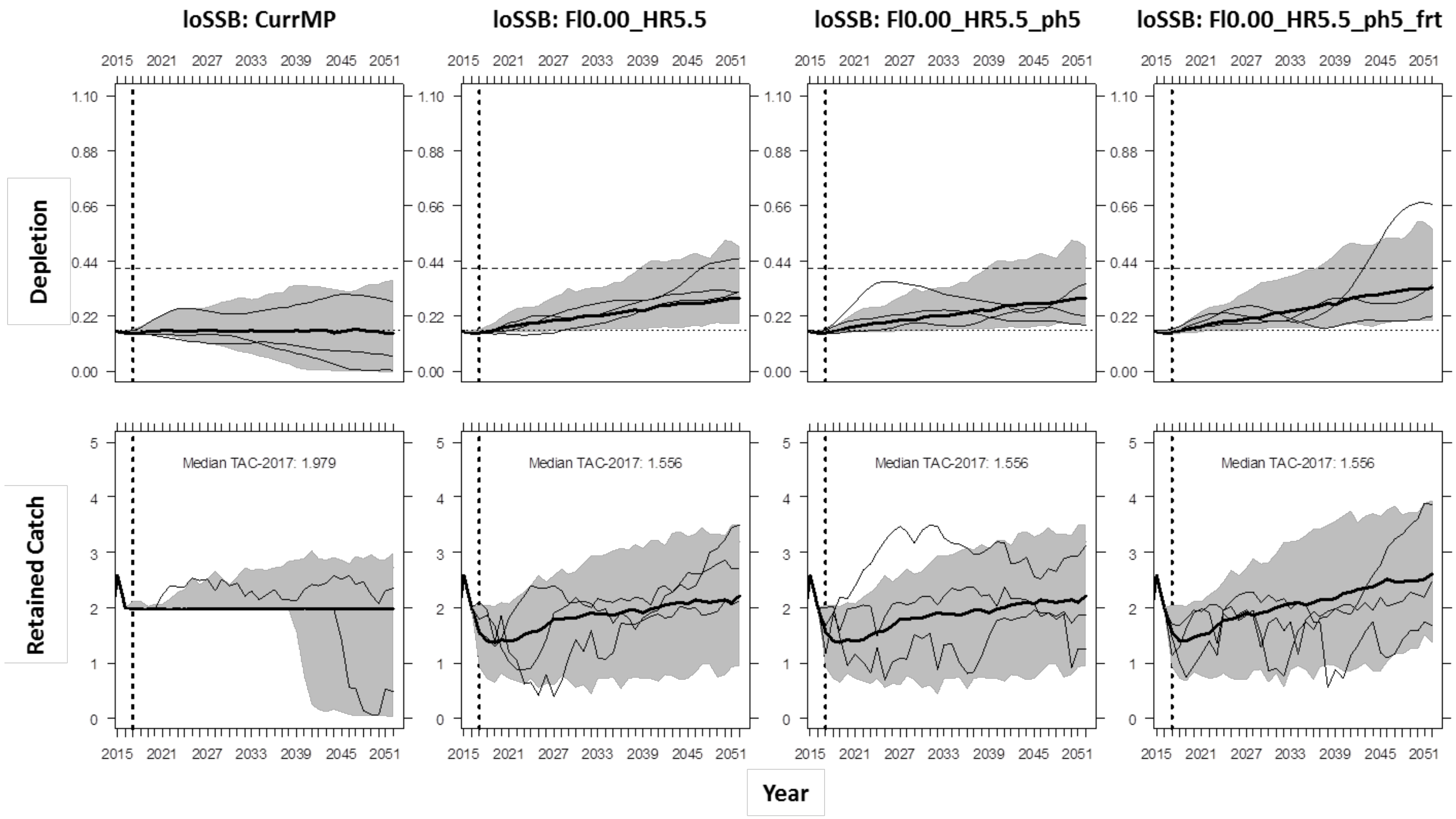

*Figure 9. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated management procedures (bottom) under the **low fSSB scenario**. From left to right, the currMP procedure is the most constrained in terms of catch, Fl0.00_HR5.5 is the least constrained, Fl0.00_HR5.5_ph5 uses a 5-year phase-in to a new, lower maximum harvest rate, and Fl0.00_HR5.5_ph5_frt implements a full retention regulation. Distributions represent the central 80% of 100 simulation replicate outcomes, medians (thick black lines), and randomly chosen individual replicates (thin lines). Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

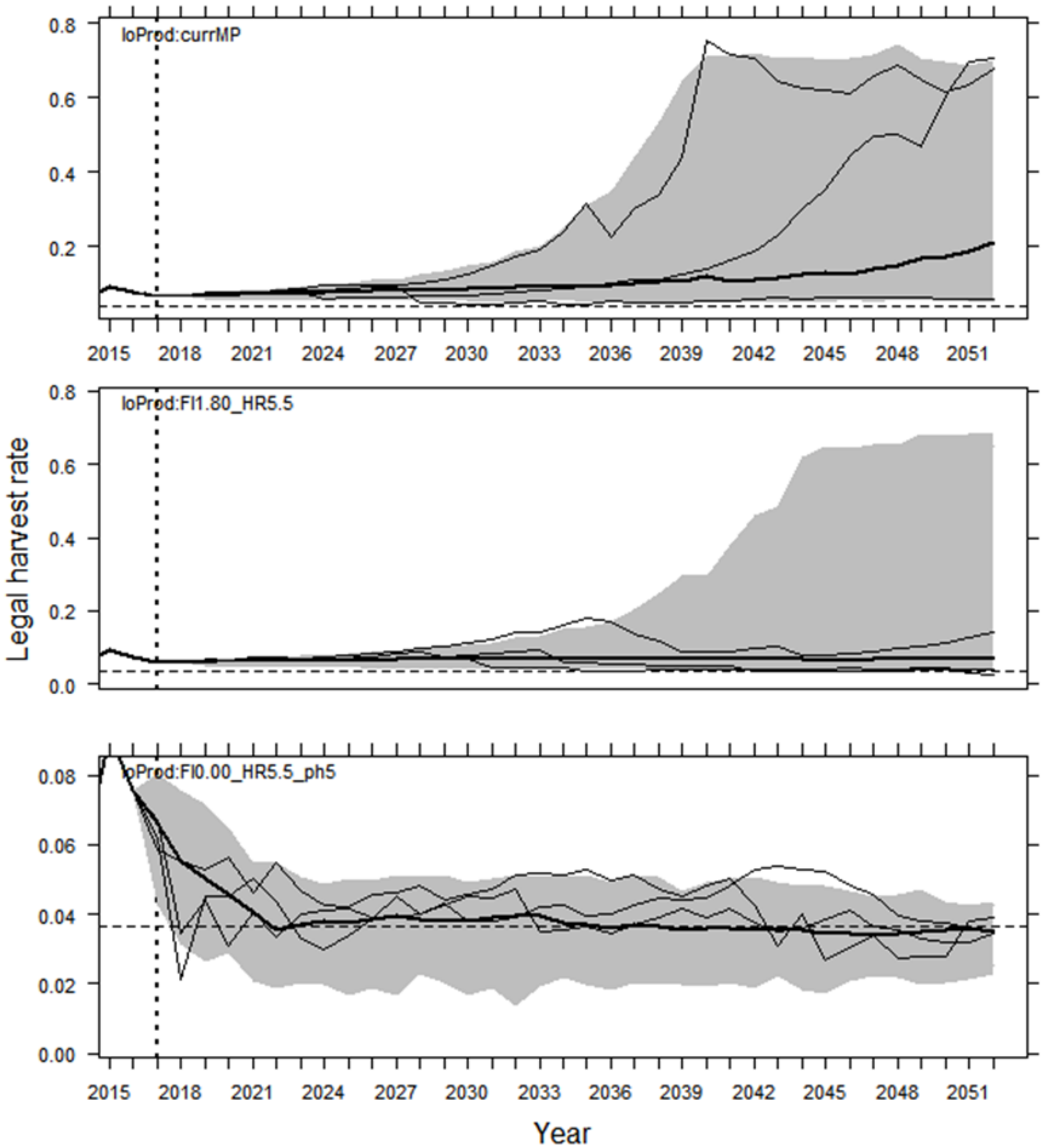

Figure 10. Projection distributions for realized legal harvest rates in the operating model under the low productivity scenario and the current MP with floor of 1,992 t (top), an MP with lower floor at 1,800 t and lower maximum harvest rate (middle), and an MP with no floor, a lower maximum harvest rate, and a 5-year phase-in (bottom). Note the order of magnitude difference in scale of the Legal Harvest Rate axis for the top panel. Horizontal dashed lines show the maximum target harvest rate from the operating model (U_{MSY}).

APPENDIX A: PRODUCTION MODEL USED IN MANAGEMENT PROCEDURES

Model Structure

We use a Schaefer surplus production model for the annual stock assessment component of management procedures. Model notation and equations are listed in Table A- 1 and Table A-2, respectively. The production model derives inferences about management parameters from time-series observations of total landed catch, and any combination of trap fishery CPUE, standardized trap survey CPUE, and stratified random trap survey CPUE. The assessment takes no account of legal and sub-legal discarding, even though both processes occur within the operating model.

Production models pool the effects of recruitment, growth, and natural mortality into a single production function to predict biomass in each year Bt+1 based on four components: (i) the predicted stock present in the previous year Bt, (ii) an average production function f(Bt) that depends on biomass, (iii) total landed catch Ct, and (iv) a random deviation ω_t from the average production relationship (Punt 2003). These components can be written into a production model of the form

(1) $$B_{t+1} = \left(B_t + rB_t \left(1 - B_t / K \right) - C_t \right) e^{\omega_t} \; ,$$

Where B_t (tonnes) and C_t (tonnes) are the stock biomass at the start of year t $(t = 1,2, \ldots, T+1)$ and catch biomass during year *t*, respectively and (*r*,*K*) are the usual logistic population dynamics growth rate and carrying capacity. The catch is assumed to be taken instantaneously and after production. The random production anomaly term ω_t is assumed independent of stock biomass and may represent, for example, the net result of (i) Sablefish immigration into B.C. from Alaska or the lower west coast U.S., (ii) emigration out of the stock that is present in B.C. at any moment, and/or (iii) random deviations from the average production relationship within B.C. We assumed that production deviations, however they arise, are independent and identically distributed (Eq E2.1).

The Schaefer form assumes that fish production is a symmetric, dome-shaped function of existing stock biomass so that $U^{MSY} = r/2$ and $Y^{MSY} = rK/4$ define the optimum exploitation rate and maximum sustainable yield, respectively. The maximum sustained yield biomass level is $B^{MSY} = K/2$. These quantities can be used by “passive adaptive” management strategies that attempt to steer fisheries exploitation toward theoretically optimal levels (c.f. Walters 1986 for full description of adaptive harvest policies). We re-parameterized equation (1) so that two management parameters, U^{MSY} and Y^{MSY}, are estimated directly. The resulting production model is given by equation E.2.6.

Indices of relative abundance for sources $g = 1, \ldots, G$ are used in estimating production model parameters via a linear observation model of the form

(2) $$I_{t,g} = q_g B_t e^{\xi_{t,g}} \; ,$$

where q_g is a constant catchability coefficient and $\xi_{t,g}$ is a normally distributed random observation error in year *t* for index *g*.

Likelihood Function

Different assumptions about how to allocate random deviations in the data to the stock dynamics (ω_t) or the observations ($\xi_{t,g}$) give different production model estimators. Assigning the total model error to the observations leads to an "observation error" estimator in which the stock dynamics are assumed to be non-random and exactly equal to that predicted by Equation 1 with $\omega_t = 0$ for all values of t. Thus, observation error models ignore inter-annual changes in stock biomass that may occur via unmodelled processes like natural mortality, immigration, emigration, or environmental influences on production. On the other hand, assigning all random error to the underlying stock dynamics by setting $\xi_{t,g} = 0$ in the observation model (Equation 2) for all values of *t* and *g* leads to a "process error" estimator in which the observations are assumed to be exact, i.e., $I_{t,g} = q_g B_t$, and thus inter-annual fluctuations in the data indicate changes in true stock biomass. For the process error estimator, the variance and individual terms ω_t must be estimated.

Inferences about the dynamics of fish stocks depend upon uncertainty in both the observations and the underlying population dynamics processes. Admitting both observation and process errors in the stock assessment model leads to errors-in-variables estimators in which some proportion ρ of the total error variance is assigned to the observations and the remainder 1- ρ is assigned to unmodelled changes in the underlying stock dynamics. Formally, errors-in-variables estimators define the total error variance, κ^2, as

(5) $$\kappa^2 = \tau^2 + \sigma^2 .$$

If the observation error proportion $\rho = \tau^2 \big/ \left(\tau^2 + \sigma^2\right)$ is assumed known, the individual variance components can then be expressed as

(6) $$\tau^2 = \rho\kappa^2, \quad \sigma^2 = \left(1-\rho\right)\kappa^2 ,$$

for observation and process errors, respectively. For our analysis, ρ is considered to act as a control or tuning parameter in the estimation procedure. As ρ approaches 0, the emphasis on process error will tend to allow for relatively large random changes in the estimated stock biomass from year to year, provided, of course, that possibly multiple abundance indices suggest the same direction and magnitude of change. Conversely, values of ρ near 1 will cause the model biomass to change deterministically in response to changes in fishery impacts; that is, the stock will only increase if catches are less than the deterministic surplus production. Experience gained through simulation of production model assessments (Cox et al. 2009) suggests that high values of ρ performed adequately for longer-lived species such as Sablefish, so we set $\rho = 0.95$. The resulting negative log-likelihood function is given by E2.10.

Prior Distributions

We used informative prior distributions on U^{MSY} and Y^{MSY} to tune the behaviour of the production model. Priors were both based on the normal distribution with means (μ^U, μ^Y) and standard deviations(σ^U, σ^Y), respectively. Specifying informative priors for the assessment model component of management procedures is similar to the approach taken in the International Whaling Commission's Catch Limit Algorithm (Cooke 1999).

Table A- 1. Notation for the surplus production stock assessment model.

Indices and index ranges

Symbol	Description
T	Year in which stock assessment is performed
t	Year, where $t=1,\ldots,T$
g	Stock index (fishery or survey), where $g=1,\ldots,G$
n_g	Number of non-missing observations for the index g
i	Index for non-missing survey observations $i=1,\ldots,n_g$

Data

Symbol	Description
$C_{t,g}$	Catch biomass removed during year t by gear type g
$I_{t,g}$	Stock relative abundance observation for year t

Leading model parameters

Symbol	Description
Y^{MSY}	Maximum sustainable yield
U^{MSY}	Optimal exploitation rate

Nuisance parameters

Symbol	Description
q_g	Catchability coefficient for abundance index g
κ^2	Total error variance
ρ	Observation error proportion of total variance (assumed known)

State variables

Symbol	Description
B_t	Biomass at the beginning of year t

Derived reference points

Symbol	Description
B^{MSY}	Maximum sustainable yield biomass level

Prior distributions

Symbol	Description
$N\left(\mu^Y,\sigma^Y\right)$	Normal prior on Y^{MSY}
$N\left(\mu^U,\sigma^U\right)$	Normal prior on U^{MSY}

Statistical error distributions

Symbol	Description
$\xi_{t,g} \sim N\left(0,\rho\kappa^2\right)$	Observation error in year t for index g
$\omega_t \sim N\left(0,(1-\rho)\kappa^2\right)$	Process error in year t

Table A-2. Mixed-error surplus production model used for annual stock assessments within management procedure simulations.

Model parameters

No.	Description
E2.1	$\Theta = \left(U', Y', \{\omega_t\}_{t=1}^{t=T-1} \right)$

Parameter transformations

No.	Description
E2.2	$U^{\text{MSY}} = \exp\left(U'\right)$
E2.3	$Y^{\text{MSY}} = \exp\left(Y'\right)$

Biomass dynamics model

No.	Description
E2.4	$B_1 = 2Y^{\text{MSY}} / U^{\text{MSY}}$
E2.5	$B^{\text{MSY}} = Y^{\text{MSY}} / U^{\text{MSY}}$
E2.6	$B_{t+1} = \begin{cases} \left(B_t + 2U^{\text{MSY}} B_t \left(1 - \dfrac{B_t}{2B^{\text{MSY}}} \right) - \sum_{g=1}^{G} C_{t,g} \right) e^{\omega_t} & 1 \le t \le T-1 \\ B_t + 2U^{\text{MSY}} \left(1 - \dfrac{B_t}{2B^{\text{MSY}}} \right) - \sum_{g=1}^{G} C_{t,g} & t = T \end{cases}$

Residuals

No.	Description
E2.7	$\xi_{t,g} = \log_e \left(I_{t,g} / B_t \right)$

Conditional maximum likelihood estimates

No.	Description
E2.8	$\widehat{\log q_g} = \dfrac{1}{n_g} \sum_{1}^{n_g} \xi_{i,g}$
E2.9	$\hat{\kappa}^2 = \dfrac{1}{n. + T - 1} \left(\dfrac{1}{\rho} \sum_{g=1}^{G} \sum_{i=1}^{n_g} \left(\xi_{i,g} - \widehat{\log q_g} \right)^2 + \dfrac{1}{1-\rho} \sum_{t=1}^{T-1} \omega_t^2 \right)$

Negative log-likelihood and objective function

No.	Description
E2.10	$\ell(\mathbf{I}\|\Theta) = \dfrac{n. + T - 1}{2} \left(log_e \dfrac{1}{\rho} \sum_{g=1}^{G} \sum_{i=1}^{n_g} \left(\xi_{i,g} - \widehat{log q_g} \right)^2 + \dfrac{1}{1-\rho} \sum_{t=1}^{T-1} \omega_t^2 \right)$
E2.11	$G\left(\Theta \| \mathbf{I}\right) \propto \ell\left(\mathbf{I} \| \Theta\right) + \dfrac{1}{2\left(\sigma^Y\right)^2} \left(Y^{\text{MSY}} - \mu^Y \right)^2 + \dfrac{1}{2\left(\sigma^U\right)^2} \left(U^{\text{MSY}} - \mu^U \right)^2$

APPENDIX B: DATA TABLES

The history of Sablefish (*Anoplopoma fimbria*) fishery management and data collection was recently summarized by Cox et al.[1]) when describing parameterization of the revised Sablefish operating model. In this appendix we give only a brief overview of the types of data used to parameterize the operating model for the current MSE and refer readers to Cox et al.[1] for a detailed overview of this history, including management tactics, regulations, catch reporting systems, and available abundance indices.

In this appendix we provide up-to-date (end of 2016) data tables below for retained catch, released catch, and abundance index values. These data differ slightly from the data used to condition operating models in Cox et al.[1]; an extra year of data has become available since this time and minor updates to pre-2016 data have occurred due to the completion of the 2015 calendar year. Age composition data for 2015 have also become available since Cox et al.[1] and are used to condition operating models. These data are shown in Appendix C when assessing operating model fits to data.

Catches are summarized by calendar year rather than fishing year because of the various changes in the definition and duration of fishing years over the history of Sablefish management. The current fishing year definition of Feb 21 to Feb 20 is not used in anticipation of possible future adjustments and because there is little difficulty caused by applying stock assessment modelling on a calendar year time step.

RETAINED CATCH

The time series of Sablefish retained fishery catch used to parameterize the operating model extends from 1965 to present (Table B - 1) and includes three commercial fishery gear-types (trap, longline hook (“longline”), and bottom trawl). In addition, retained catch from two Sablefish research surveys are used: the standardized trap survey (1990 and 2010) and the stratified random trap survey (2003-present). Longline fishery catch values include Canadian domestic fisheries and foreign fleets from Japan, the US, the USSR and the Republic of Korea that operated in Canadian waters prior to 1980. Data sources used to compile retained catch records are summarized in Cox et al.[1].

RELEASED CATCH

We use released catch values from at-sea observer (trawl sector 1996-2016) and electronic video monitored (non-trawl sectors 2006-2015) logbook data to parameterize operating models (Table B - 2).

Prior to 1996, at-sea releases of Sablefish were reported in logbooks on a voluntary basis for all groundfish fishery sectors. In 1996 the trawl fishery (Option A only) implemented an at-sea observer program, at which time fishery-independent estimates of Sablefish releases become available. Other groundfish sectors relied on fishery-dependent logbooks until 2006 when electronic video monitoring was introduced to audit fishery logbooks. The pre-1996 (all sectors) and pre-2006 (non-trawl sectors) logbook data were not used to estimate the absolute amount of released Sablefish for our analyses as their accuracy cannot be independently verified.

ESTIMATION OF CATCH FOR THE REMAINDER OF 2016

Data tables for MSE analyses were compiled using database queries conducted on October 28, 2016. The steps used to estimate the incomplete retained and released catch for the remainder of the 2016 calendar year are as follows:

1. Assume 2016 retained catch will be approximately 2,000 t. This assumption is based on the amount of Sablefish quota available to the groundfish fisheries for the current year. An assumption of 2000 t leaves 474 t of retained catch to be caught after October 28, 2016;
2. Allocate the 474 t of retained catch to the commercial gear types by the average of the retained catch proportions observed from 2013 to 2015. This calculation yields estimated retained catches of 747.5, 1134.5, and 118.0 t for trap, longline hook and trawl gears, respectively;
3. Assume Sablefish in the remainder of 2016 are released at the rate observed during the first 10 months of 2016, i.e., the ratios of observed released catch to retained catch by gear type for January 1 – October 28, 2016;
4. Apply the ratios in step (3) to the estimated retained catch by gear in step (2) to estimate releases by gear type. This calculation yields releases of 139.8, 112.5, and 244.5 t for trap, longline and trawl gears, respectively;
5. Add the estimated retained and released catches to the catches observed to date to estimate commercial fishery catches by gear;
6. Assume the 2016 stratified random trap survey will incur the same retained catches as in 2015 (40.7 t).

ABUNDANCE INDICES

Three different relative abundance indices based on annual Sablefish catch-per-unit effort (CPUE) were used to fit operating models (Table B - 3). The first of these was a fishery-dependent index,

1. commercial nominal trap fishery CPUE (1979 – 2009),

while the remaining two were derived from fishery-independent research surveys that targeted Sablefish,

2. standardized trap survey CPUE (1990-2009); and,
3. stratified random sampling survey CPUE (2003-2015).

All three indexing series use longline trap gear (hereafter “trap” gear). Catch per unit effort (CPUE) is calculated in units of kg/trap for each set. Descriptions of each of these stock indices, including survey design and estimation method, are available in Cox et al.[1]

Table B-1. Annual Sablefish retained catch (t) aggregated by gear as input to simulation analyses. Data in italics for 2016 are based on catch totals available on October 6, 2016. Catches for the remainder of the 2016 calendar year (October 7 to December 31) were estimated (see text). The year designation 2016 indicates estimated 2016 retained catch used for the simulations (see text below for estimation method).*

Year	Time Step	Trap	Longline Hook	Trawl	Standardized Trap Survey	StRS Trap Survey	Total
1965	1	0	193.2	353.9	0	0	547.1
1966	2	0	499.7	406.9	0	0	906.6
1967	3	0	1441.9	203.6	0	0	1645.5
1968	4	0	2682.3	232	0	0	2914.3
1969	5	0	4882.3	191.3	0	0	5073.6
1970	6	0	5284.1	269.9	0	0	5554
1971	7	0	3173	350.3	0	0	3523.3
1972	8	0	4635.7	1270.3	0	0	5906

Year	Time Step	Trap	Longline Hook	Trawl	Standardized Trap Survey	StRS Trap Survey	Total
1973	9	745.8	3069.8	170.8	0	0	3986.4
1974	10	327.1	4036.3	413.8	0	0	4777.2
1975	11	469.4	6117.2	820.8	0	0	7407.4
1976	12	303.4	5918.4	855	0	0	7076.8
1977	13	214.6	3224.1	1357.5	0	0	4796.2
1978	14	634.6	2160.2	1078.5	0	0	3873.3
1979	15	1480.1	1388.8	1512.1	0	0	4381
1980	16	3210.8	447.6	652.3	0	0	4310.7
1981	17	3275.3	326.1	228.8	0	0	3830.2
1982	18	3437.8	343.6	245.9	0	0	4027.4
1983	19	3610.5	451.4	274.1	0	0	4336
1984	20	3275.4	365.1	187	0	0	3827.4
1985	21	3501.3	458.3	233.1	0	0	4192.7
1986	22	3277.1	619.2	551.8	0	0	4448.1
1987	23	2954.3	1268.6	406.9	0	0	4629.8
1988	24	3488.5	1273.6	637.3	0	0	5399.4
1989	25	3772	928.6	623.4	0	0	5324
1990	26	3072.4	1371.8	460.7	10.1	0	4915
1991	27	3494.4	1179.2	438.8	6	0	5118.4
1992	28	3710.2	848.6	448.7	9.5	0	5016.9
1993	29	4142.4	424.2	543.1	8.2	0	5117.9
1994	30	4050.7	467.7	483.1	7	0	5008.5
1995	31	3282.2	474.3	427.4	4.8	0	4188.7
1996	32	2984.3	280.4	190.9	4.9	0	3460.6
1997	33	3553.6	431.1	156.3	4.1	0	4145.1
1998	34	3772	443.6	376.1	5.6	0	4597.3
1999	35	3677.3	627.9	403	4.7	0	4713
2000	36	2745.3	752.4	326.1	7.3	0	3831.1
2001	37	2742.8	564.5	299.6	3.4	0	3610.4
2002	38	2161.9	564.4	267.1	16.2	0	3009.5
2003	39	1419.2	640.5	227.6	19.9	22.4	2329.5
2004	40	2128.5	467.4	344.7	16.2	8.6	2965.4
2005	41	3196.5	1146.7	277.1	13.6	8.3	4642.3
2006	42	2773.5	1306.3	441.8	12	10.7	4544.2
2007	43	2140	971.5	288.9	9.1	10.5	3419.9
2008	44	1487	1246.5	352.9	9.6	12.4	3108.5
2009	45	1174.4	1107.7	223.2	6.4	12	2523.6
2010	46	975.7	1095.3	208.7	7.3	11.4	2298.4
2011	47	803.9	1082.4	175.7	0	11.1	2073
2012	48	891.6	1150.4	154.7	0	11.3	2207.9
2013	49	841.4	877.3	184	0	32.1	1934.8
2014	50	570.6	984.9	132.4	0	22.9	1710.8
2015	51	1110.9	1328.6	132.8	0	40.7	2613.0
2016	*52*	*556.2*	*888.1*	*82.2*	*0*	*0*	*1526.5*
2016*	52	747.5	1134.5	118.0	0	40.7	2040.7

Table B-2. Annual Sablefish released catch (t), aggregated by gear, as input to simulation analyses. Releases values are available starting in 1974 for all gears; however, only values obtained from the at-sea trawl observers program (1996-2016 for trawl fishery) and the at-sea electronic monitoring program (2006-2016 for trap and longline fisheries) were used to fit operating models (see text for explanation). Data in italics for 2016 are complete to October 6, 2015. The year designation 2016 indicates estimated 2016 releases used for the simulations (see text below for estimation method).*

Year	Time Step	Trap	Longline	Trawl	Total
1996	32	--	--	353.4	353.4
1997	33	--	--	452.9	452.9
1998	34	--	--	387.5	387.5
1999	35	--	--	422.7	422.7
2000	36	--	--	468.1	468.1
2001	37	--	--	341.8	341.8
2002	38	--	--	531.5	531.5
2003	39	--	--	362.2	362.2
2004	40	--	--	278.2	278.2
2005	41	--	--	189.2	189.2
2006	42	148.2	365.9	132.0	646.1
2007	43	173.7	164.6	126.8	465.1
2008	44	152.7	145.0	71.8	369.5
2009	45	87.2	136.2	83.7	307.1
2010	46	125.4	154.7	174.7	454.8
2011	47	130.7	176.4	133.7	440.8
2012	48	161.3	195.2	133.5	490.0
2013	49	186.4	147.4	126.4	460.2
2014	50	108.0	91.8	128.9	328.7
2015	51	148.1	147.0	218.4	513.5
2016	*52*	*104.0*	*88.1*	*170.3*	*362.4*
2016*	52	139.8	112.5	244.5	496.8

Table B-3. Sablefish relative stock indices: nominal trap fishery CPUE, standardized survey CPUE, and stratified random survey CPUE.

Year	Nominal Trap Fishery CPUE (kg/trap)	Std. Trap Survey CPUE (kg/trap)	Stratified Random Survey CPUE (kg/trap)
1979	17.661	-	-
1980	15.312	-	-
1981	15.056	-	-
1982	16.973	-	-
1983	16.819	-	-
1984	13.059	-	-
1985	17.687	-	-
1986	15.602	-	-
1987	16.160	-	-
1988	24.736	-	-
1989	25.695	-	-
1990	19.222	20.017	-
1991	24.600	19.594	-
1992	24.363	25.603	-
1993	20.380	37.020	-

Year	Nominal Trap Fishery CPUE (kg/trap)	Std. Trap Survey CPUE (kg/trap)	Stratified Random Survey CPUE (kg/trap)
1994	18.397	15.565	-
1995	15.020	13.882	-
1996	14.087	11.413	-
1997	12.956	7.879	-
1998	13.020	12.176	-
1999	13.426	7.768	-
2000	12.667	9.394	-
2001	10.082	3.141	-
2002	9.899	8.487	-
2003	19.222	29.228	28.363
2004	14.009	26.811	24.941
2005	11.615	19.799	23.789
2006	10.034	17.702	28.889
2007	9.705	10.270	20.476
2008	10.042	10.889	26.243
2009	10.090	7.229	18.299
2010	-	8.322	21.402
2011	-	-	19.851
2012	-	-	15.210
2013	-	-	19.729
2014	-	-	13.443
2015	-	-	22.638
2016	-	-	-

APPENDIX C: OPERATING MODEL FIT DIAGNOSTICS

Figures C-1 to C-12 in this appendix show the operating model fit to data.

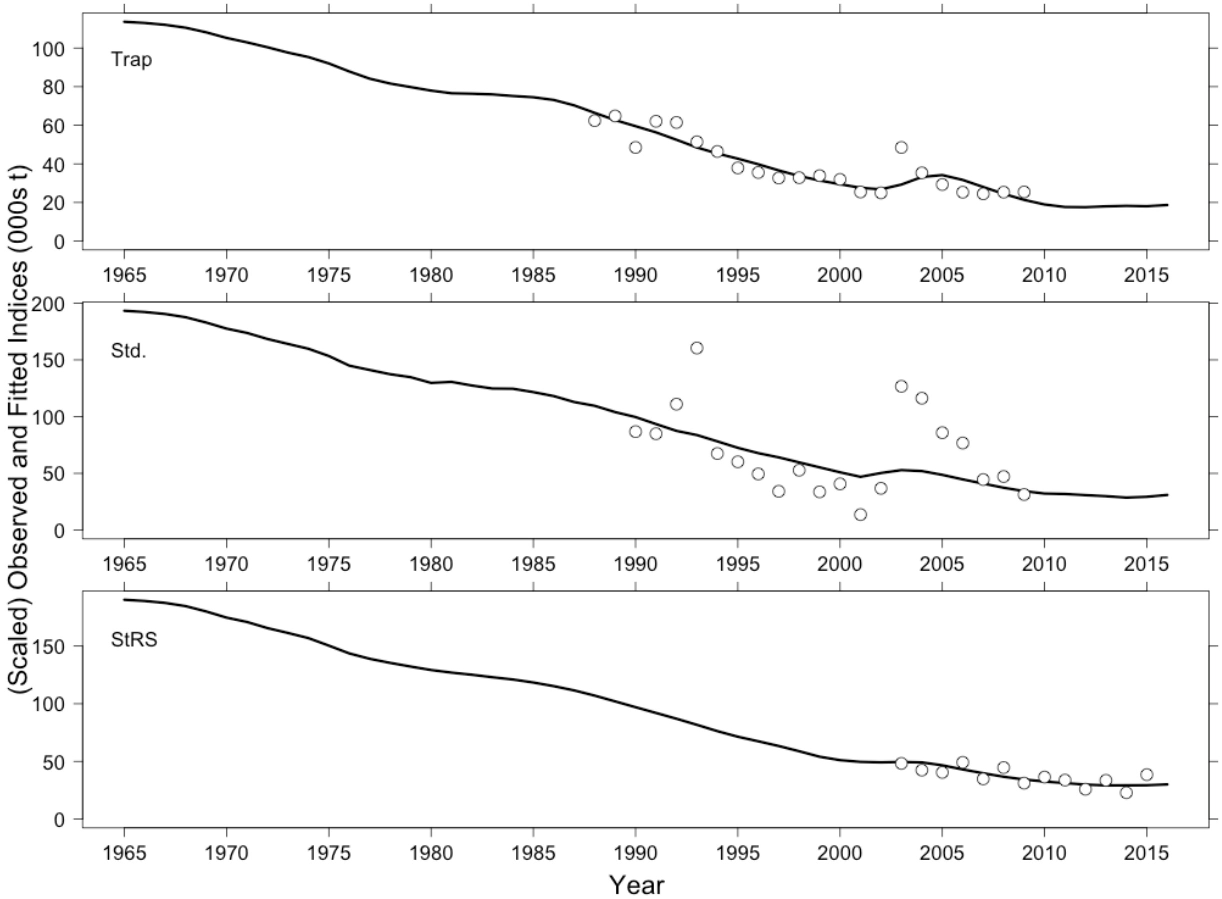

Figure C-1. Fit to annual Sablefish stock indices scaled to biomass units by catchability estimates for commercial trap gear index (upper panel), standardized survey index (centre panel), and stratified random survey index (lower panel). Scaled observations are indicated by open circles, the solid line in each figure panel shows the model estimates. Result is for the base case operating model.

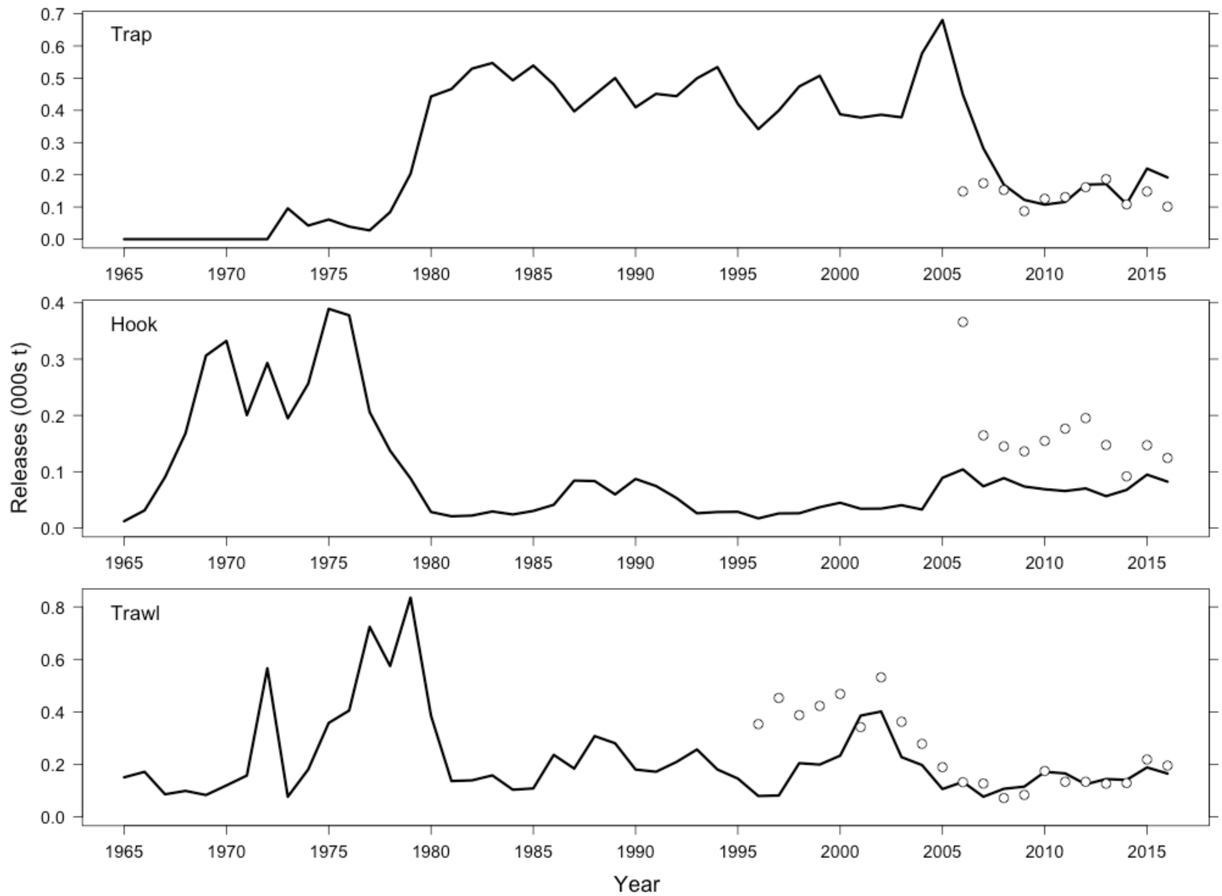

Figure C-2. Fit to annual Sablefish releases for commercial trap gear index (upper panel), longeline hook gear (centre panel), and trawl gear (lower panel) for the base case operating mode scenario. Observed releases are shown as open circles, the solid line in each figure panel shows the model estimates.

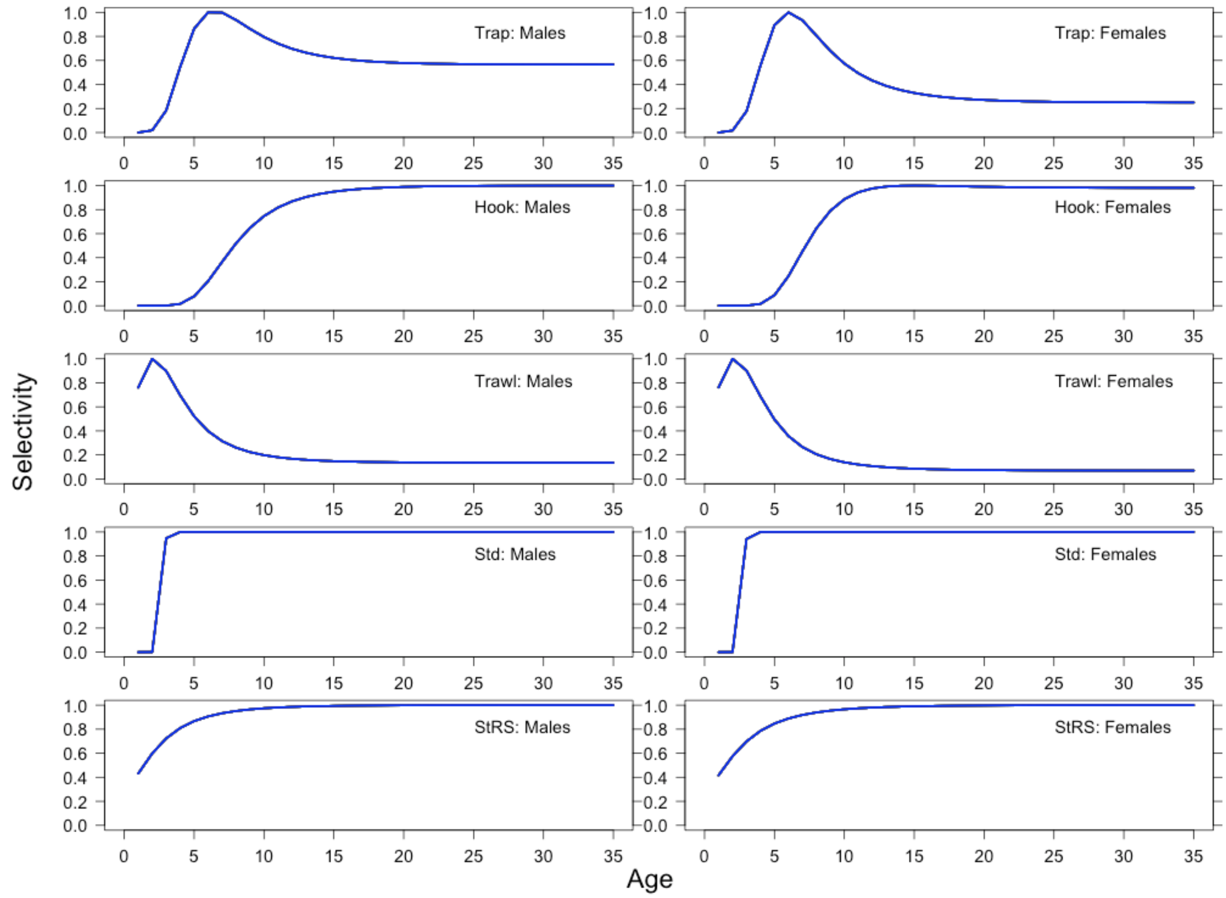

Figure C-3. Maximum probability density estimates of age-based selectivity by each gear type for male and female Sablefish for the base case operating model scenario. The top three rows show selectivity for the three different commercial fisheries: trap gear, longline (hook) gear, and trawl gear. The bottom two rows show selectivity for the standardized trap survey (Std) and the stratified random trap survey (StRS).

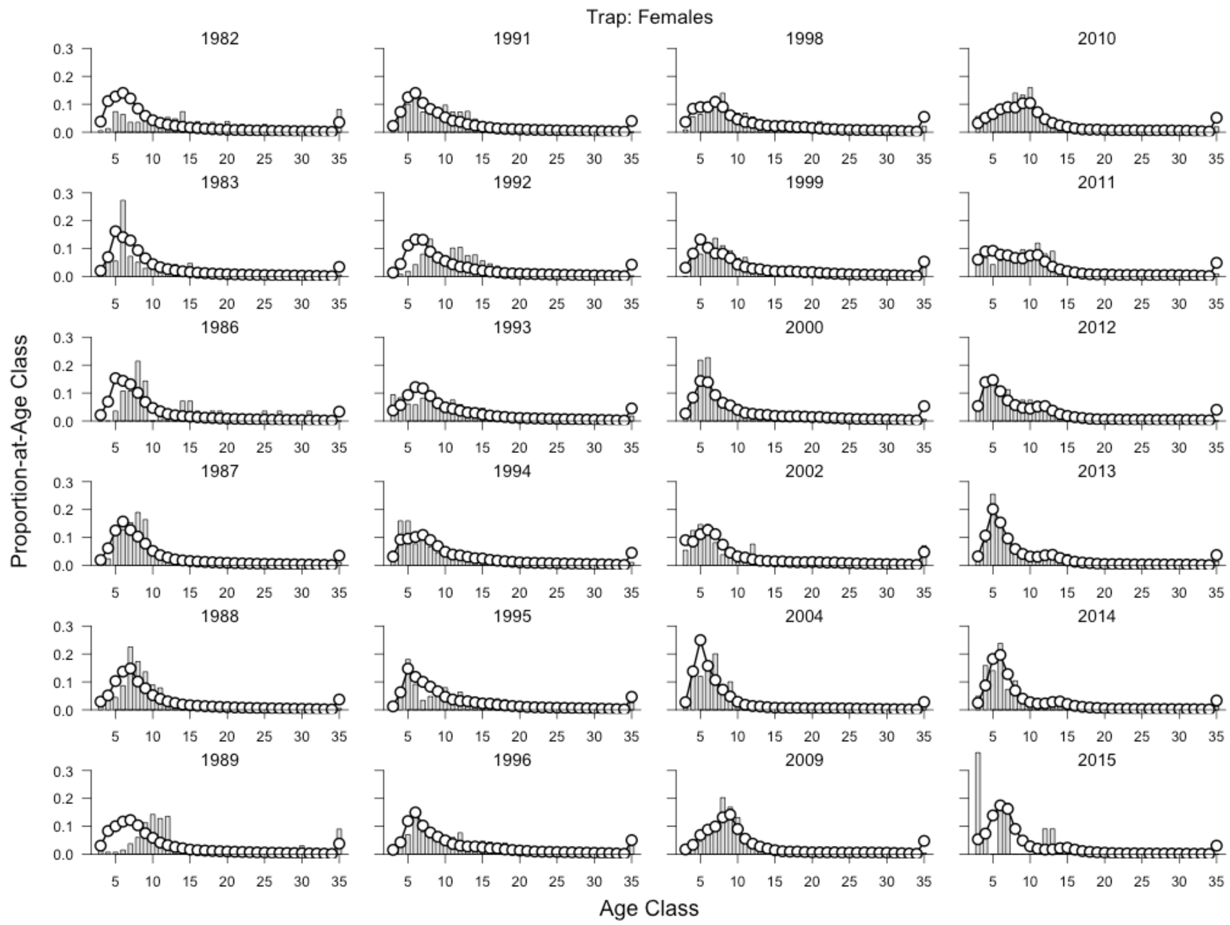

Figure C-4. Annual observed (bars) and predicted (lines and circles) proportions-at-age of female Sablefish for the commercial trap gear fishery for the base case operating model scenario. Age proportions 3 to 25 were fitted; observed proportions age 26 and greater did not enter the likelihood calculations or age composition samples prior to 1990.

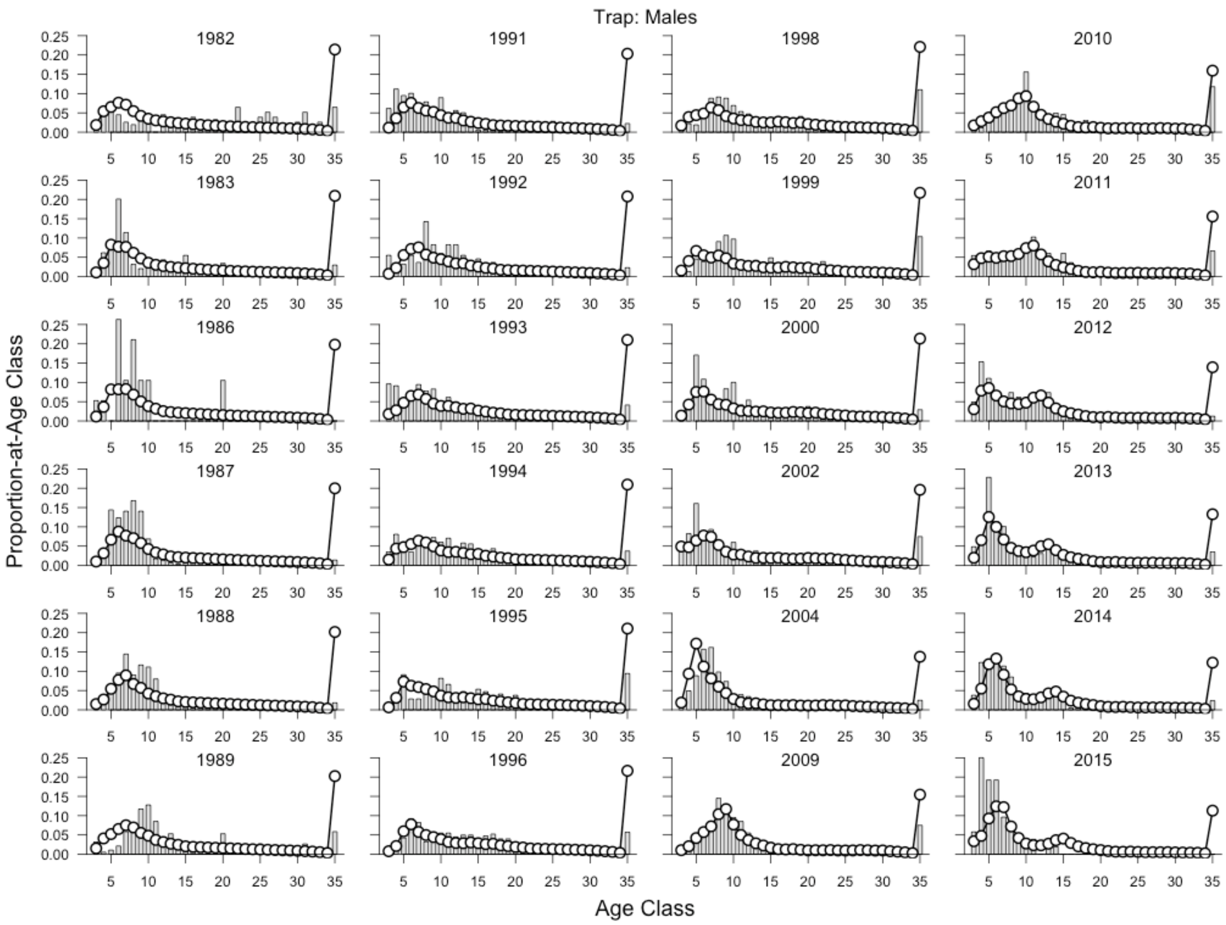

Figure C-5. Annual observed (bars) and predicted (lines and circles) proportions-at-age of male Sablefish for the commercial trap gear fishery for the base case operating model scenario. Age proportions 3 to 25 were fitted; observed proportions age 26 and greater did not enter the likelihood calculations or age composition samples prior to 1990.

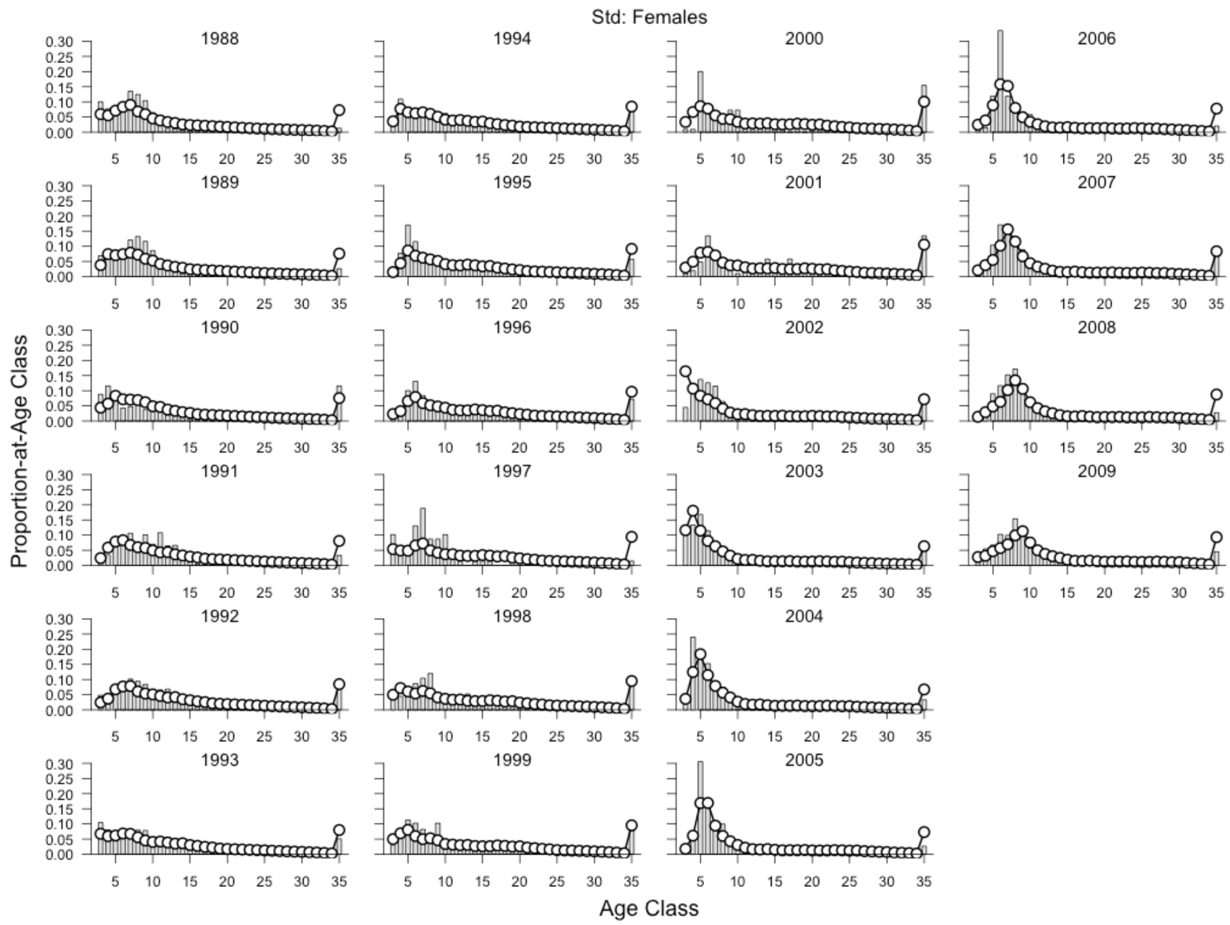

Figure C-6. Annual observed (bars) and predicted (lines and circles) proportions-at-age of female Sablefish for the standardized trap gear survey year for the base case operating model scenario. Age proportions 3 to the plus group at age 35 were fitted.

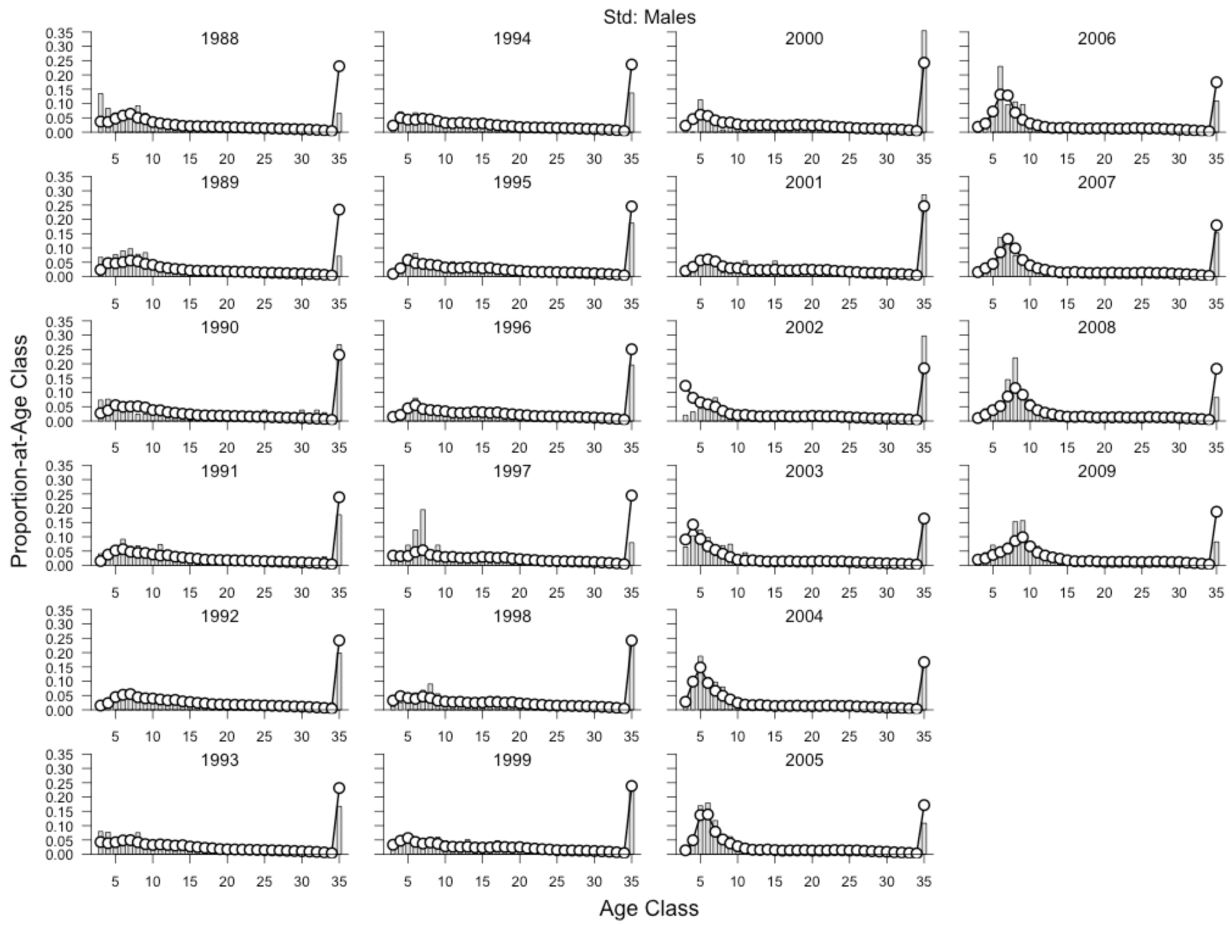

Figure C-7. Annual observed (bars) and predicted (lines and circles) proportions-at-age of male Sablefish for the standardized trap gear survey year for the base case operating model scenario. Age proportions 3 to the plus group at age 35 were fitted.

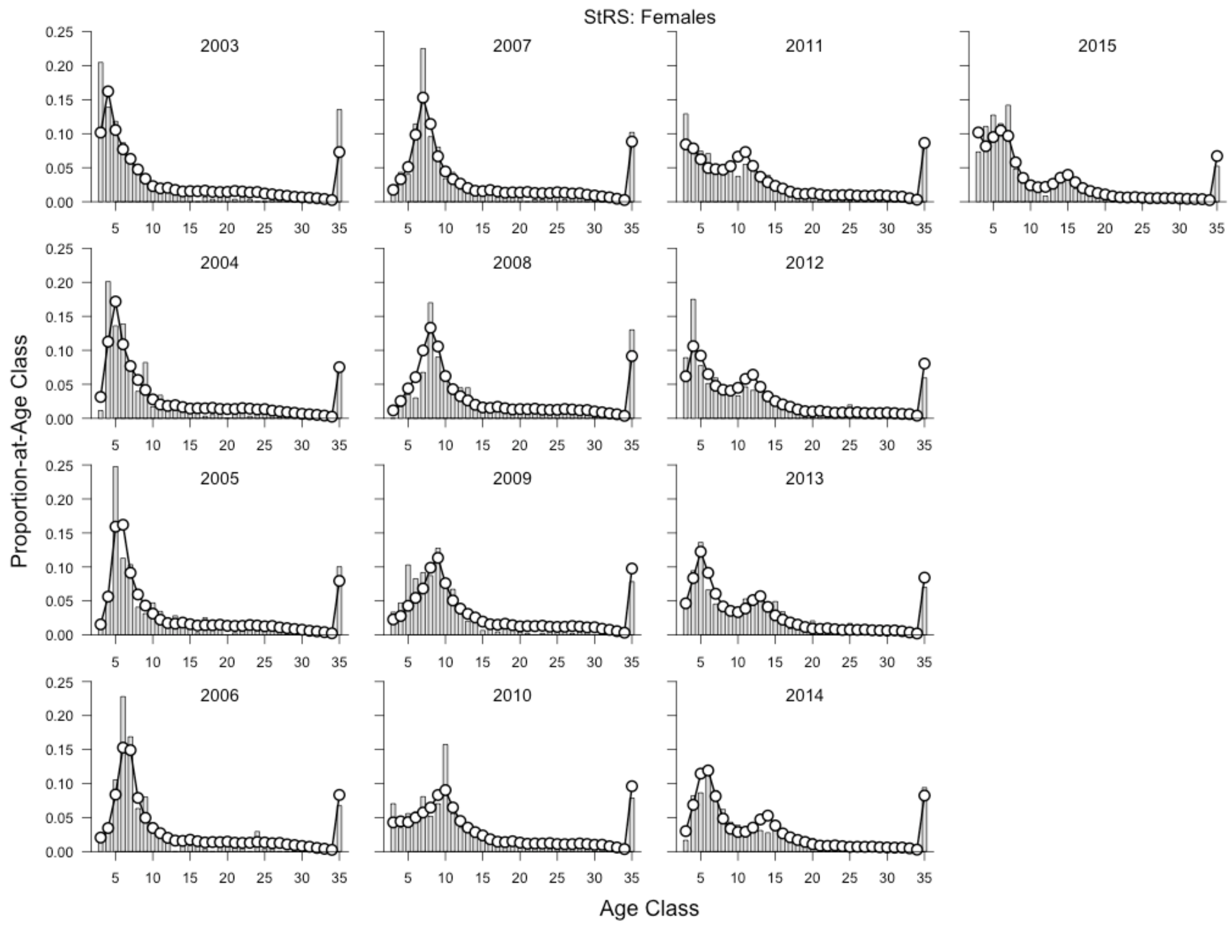

Figure C-8. Annual observed (bars) and predicted (lines and circles) proportions-at-age of female Sablefish for the stratified random trap gear survey for the base case operating model scenario. Age proportions 3 to the plus group at age 35 were fitted.

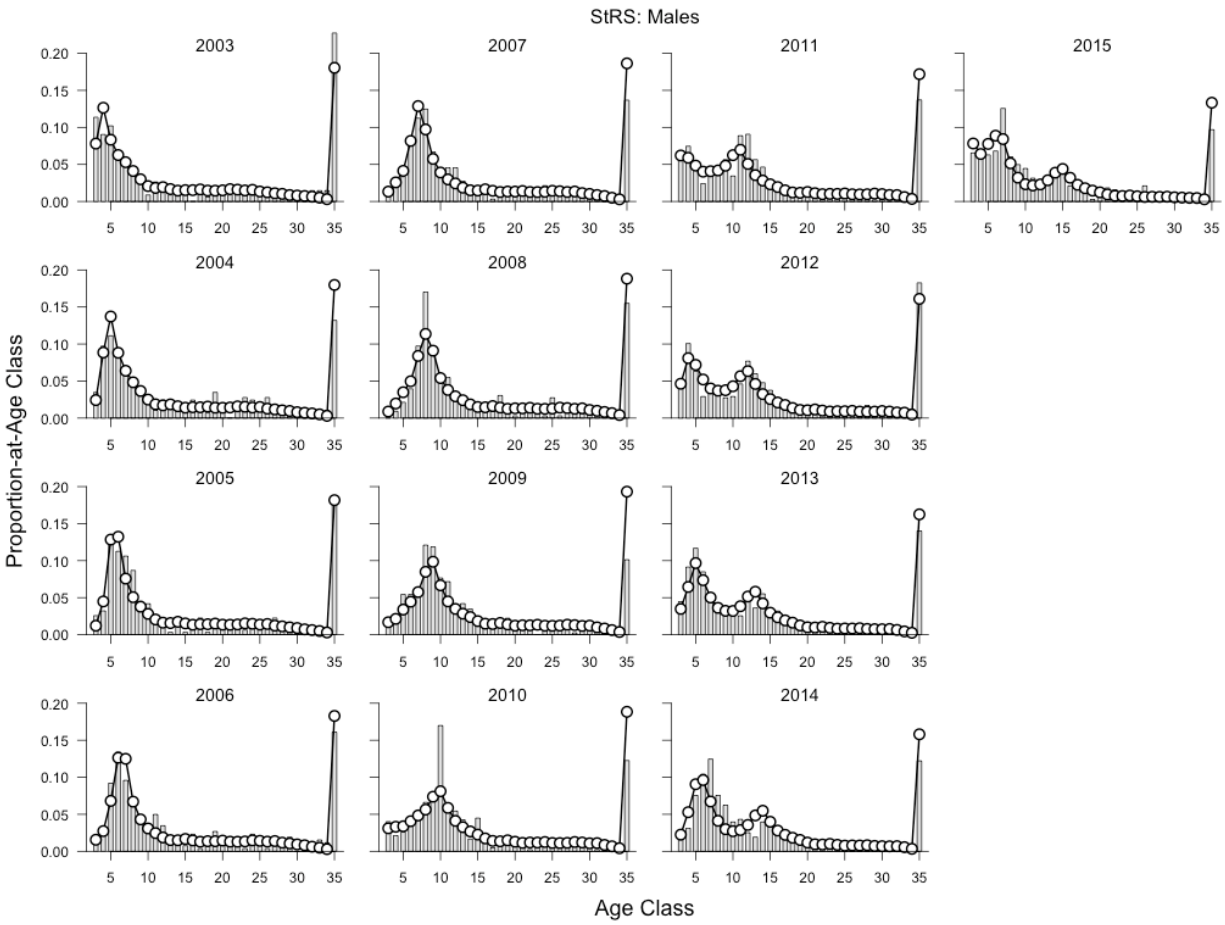

Figure C-9. Annual observed (bars) and predicted (lines and circles) proportions-at-age of male Sablefish for the stratified random trap gear survey for the base case operating model scenario. Age proportions 3 to the plus group at age 35 were fitted.

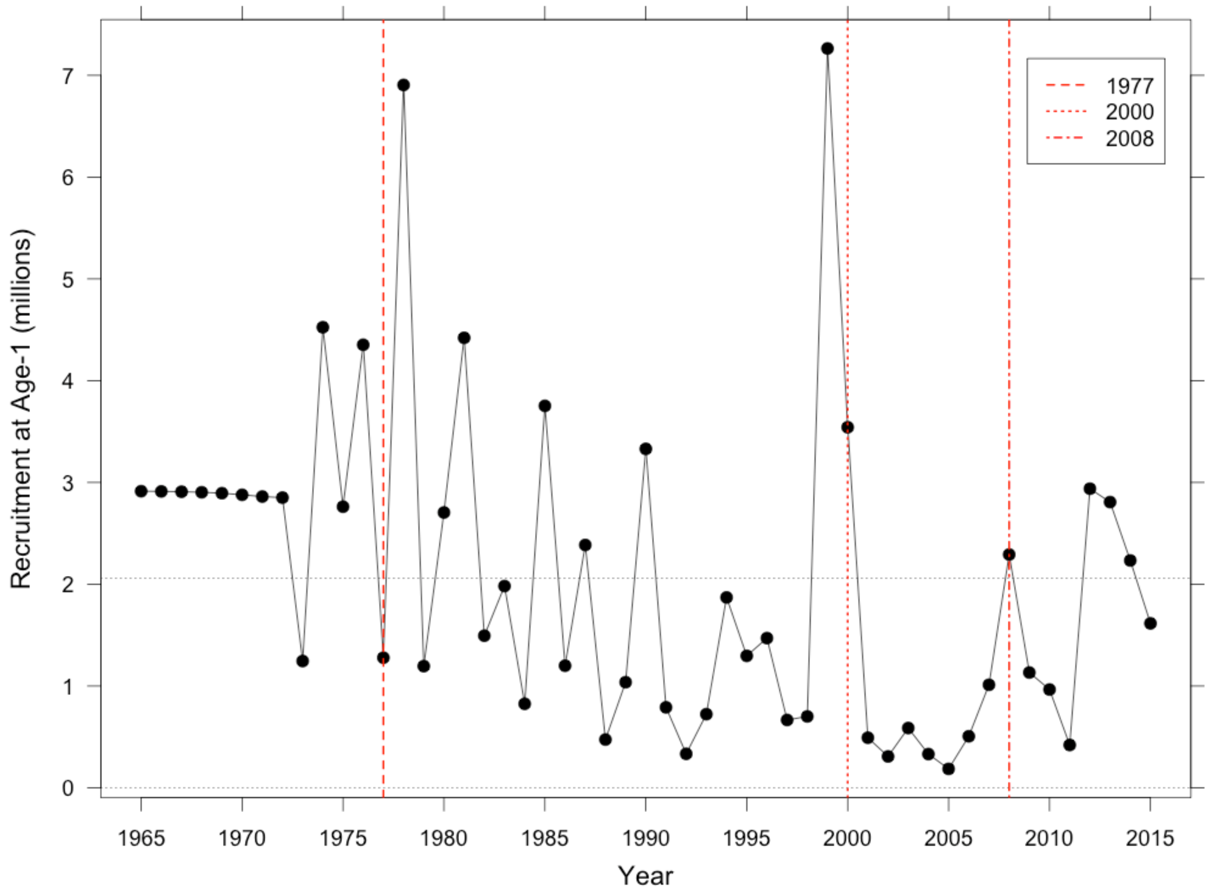

Figure C-10. Annual estimates of Sablefish age-1 recruitment for the base case operating model scenario. The average recruitment is indicated by the horizontal dashed line, excluding 2013-2015. Reference lines are provided for 1977, 2000, and 2008 brood years when influential recruitments are presumed to have occurred in the Gulf of Alaska, B.C., and the U.S. west coast.

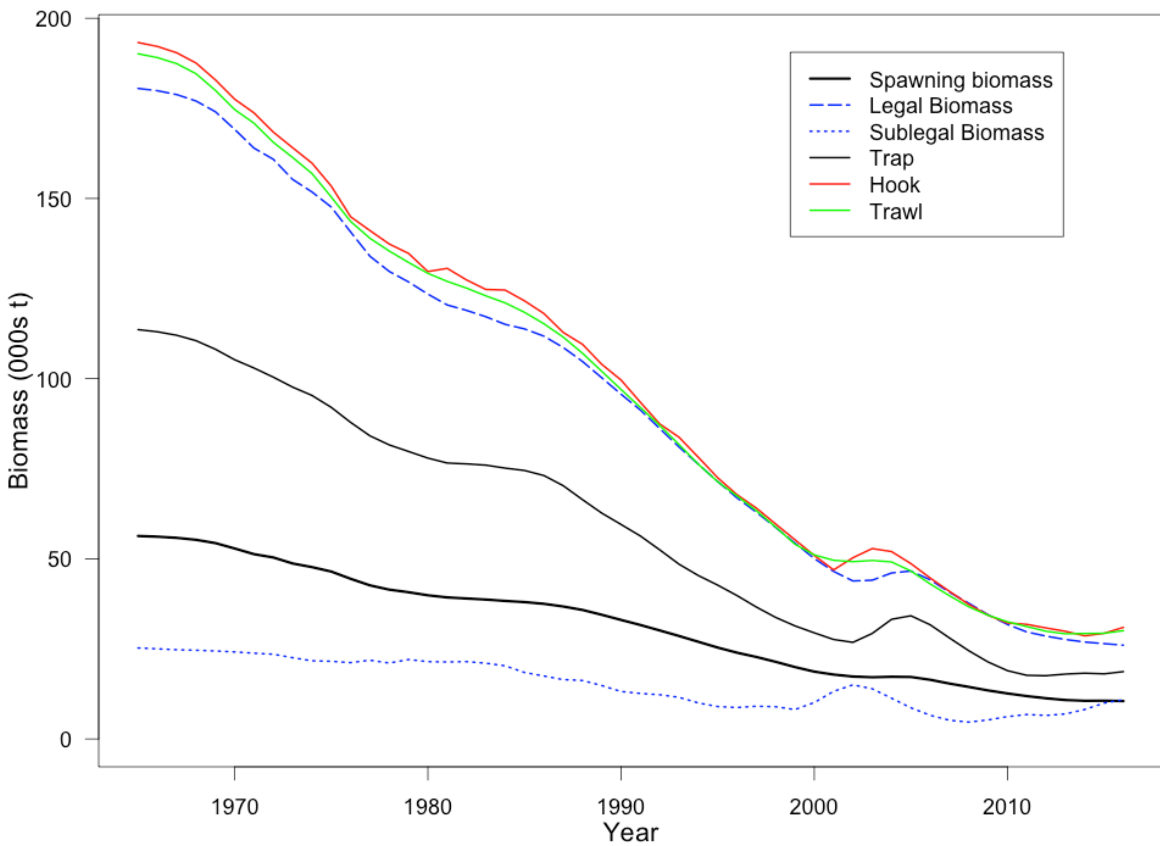

Figure C-11. Estimated annual Sablefish biomass (000s t) trajectories for the base case operating model scenario. Female spawning biomass is shown by the thick solid black line. Exploitable biomass is shown for longline trap, longline hook, and trawl gears. Sublegal biomass refers to the biomass of fish less than 55 cm fork length.

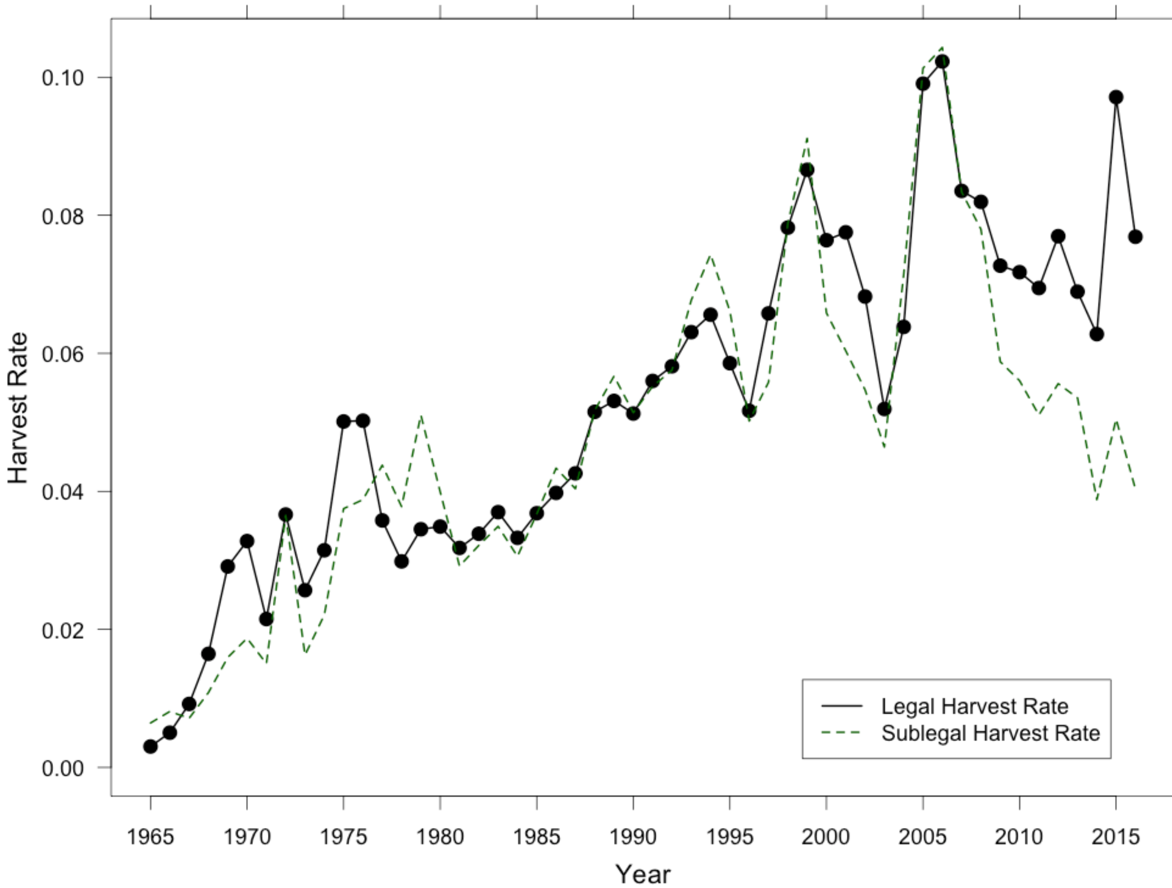

Figure C-12. Estimated annual harvest rates for legal size and sublegal Sablefish for the operating model scenario.

APPENDIX D: SIMULATION RESULTS – DEPLETION AND CATCH SERIES

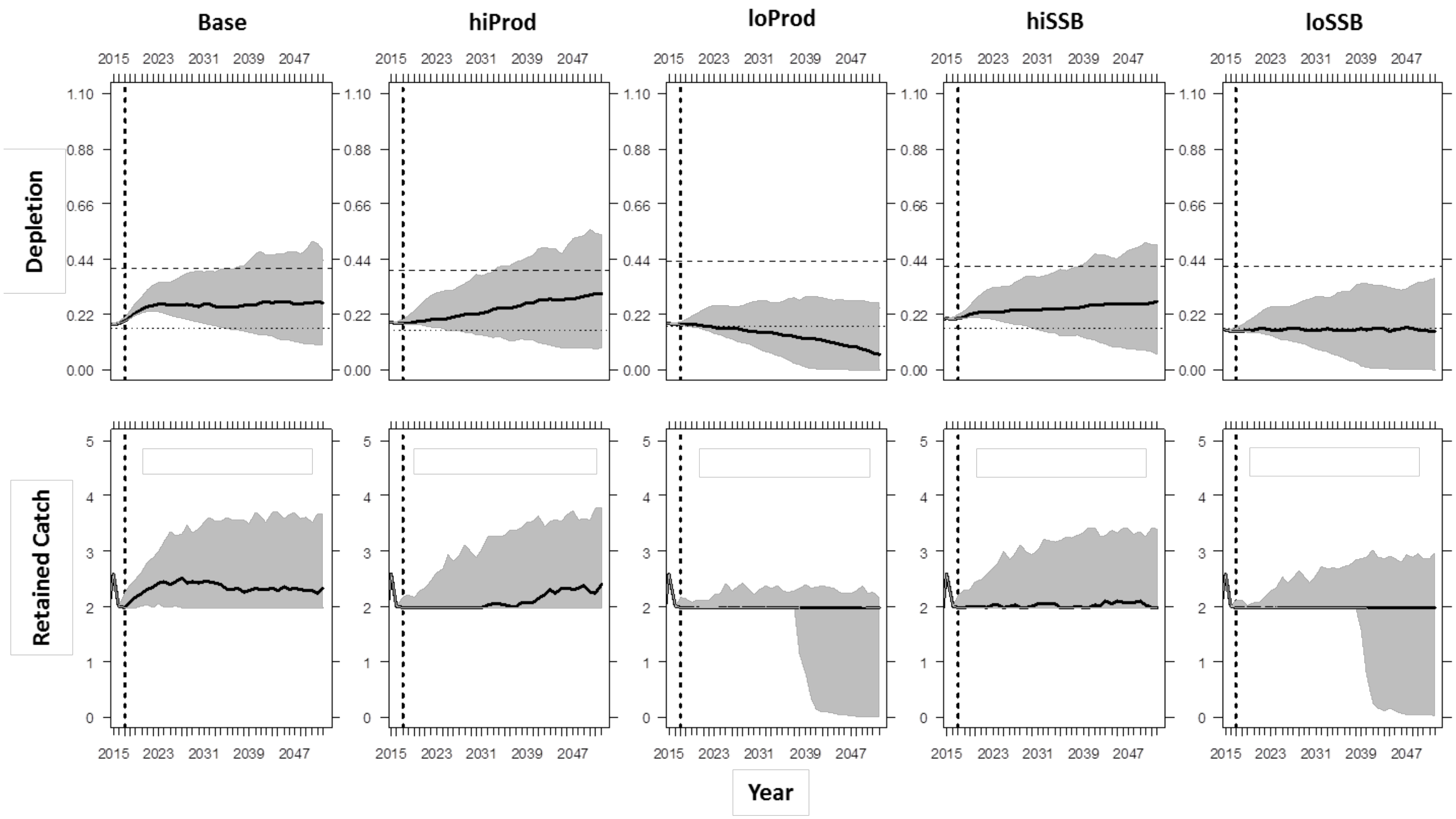

*Figure D-1. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated **currMP** management procedure under five different productivity scenarios (left to right columns: base, high productivity, low productivity, high initial fSSB, low initial fSSB). Grey shading represents the central 80% of 100 simulation replicate outcomes and the thick black lines show the median over all replicates. Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

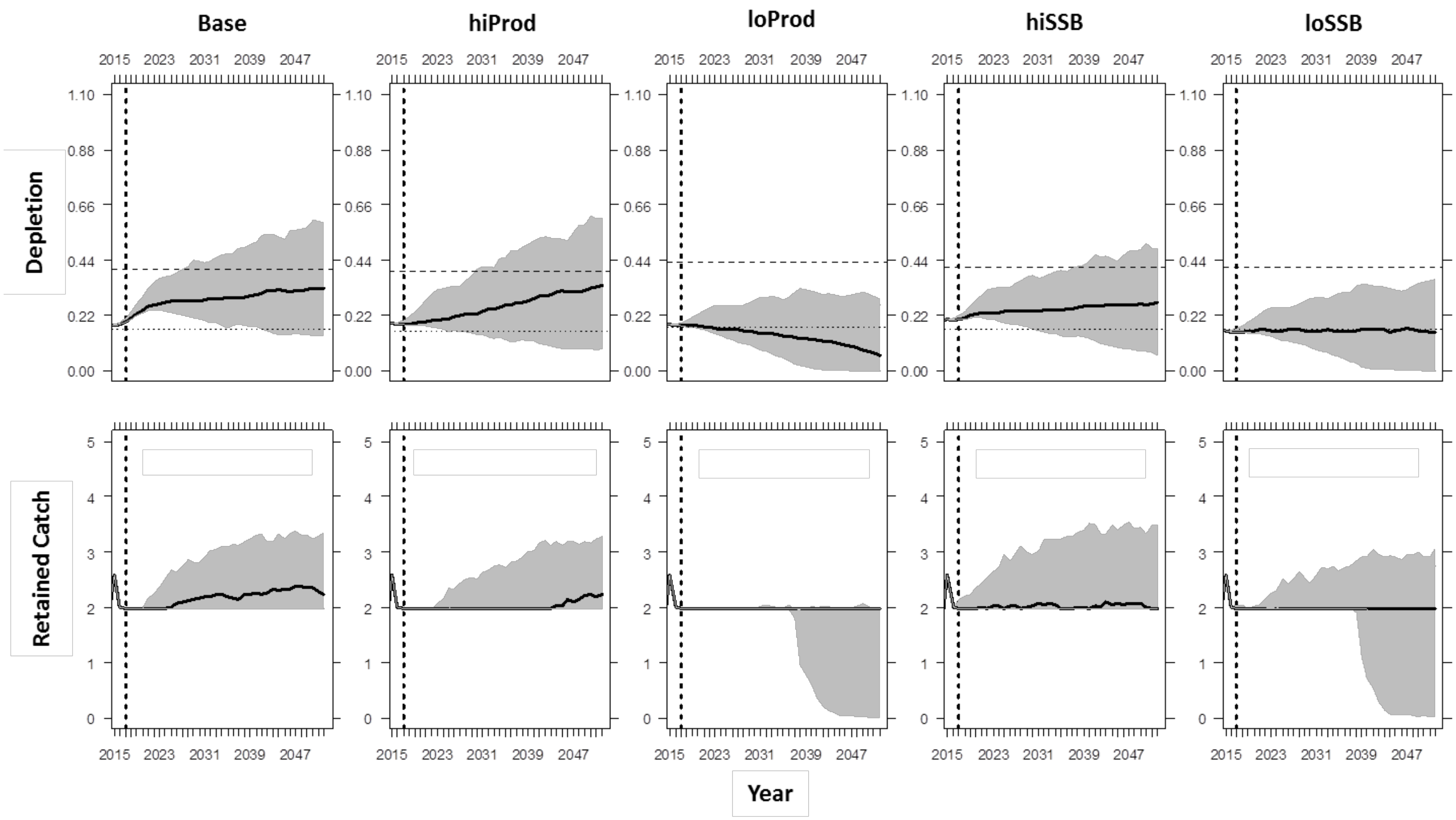

*Figure D-2. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated **FI1.992_HR5.5** management procedure under five different productivity scenarios (left to right columns: base, high productivity, low productivity, high initial fSSB, low initial fSSB). Grey shading represents the central 80% of 100 simulation replicate outcomes and the thick black lines show the median over all replicates. Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

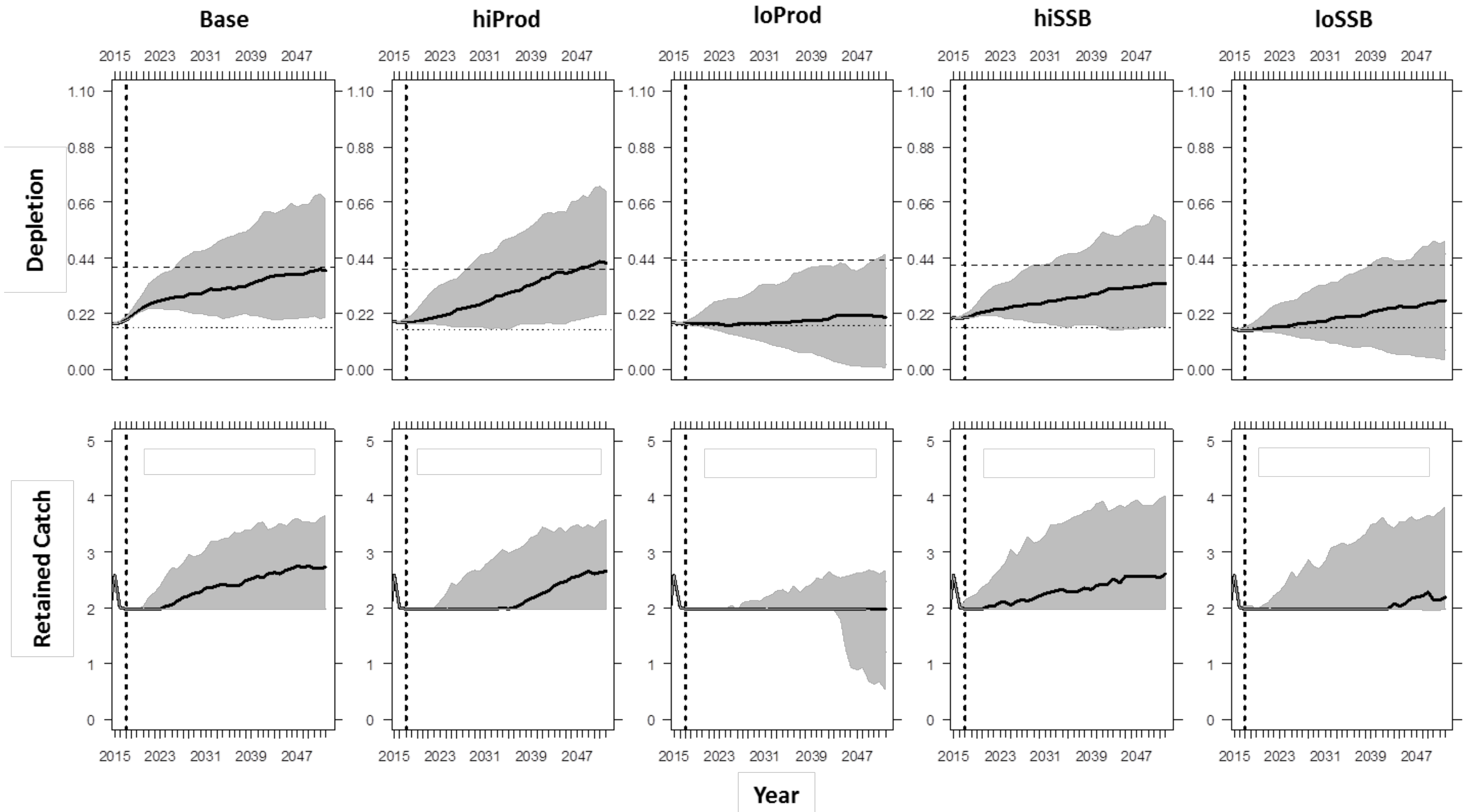

*Figure D-3. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated **FI1.992_HR5.5_frt** management procedure under five different productivity scenarios (left to right columns: base, high productivity, low productivity, high initial fSSB, low initial fSSB). Grey shading represents the central 80% of 100 simulation replicate outcomes and the thick black lines show the median over all replicates. Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

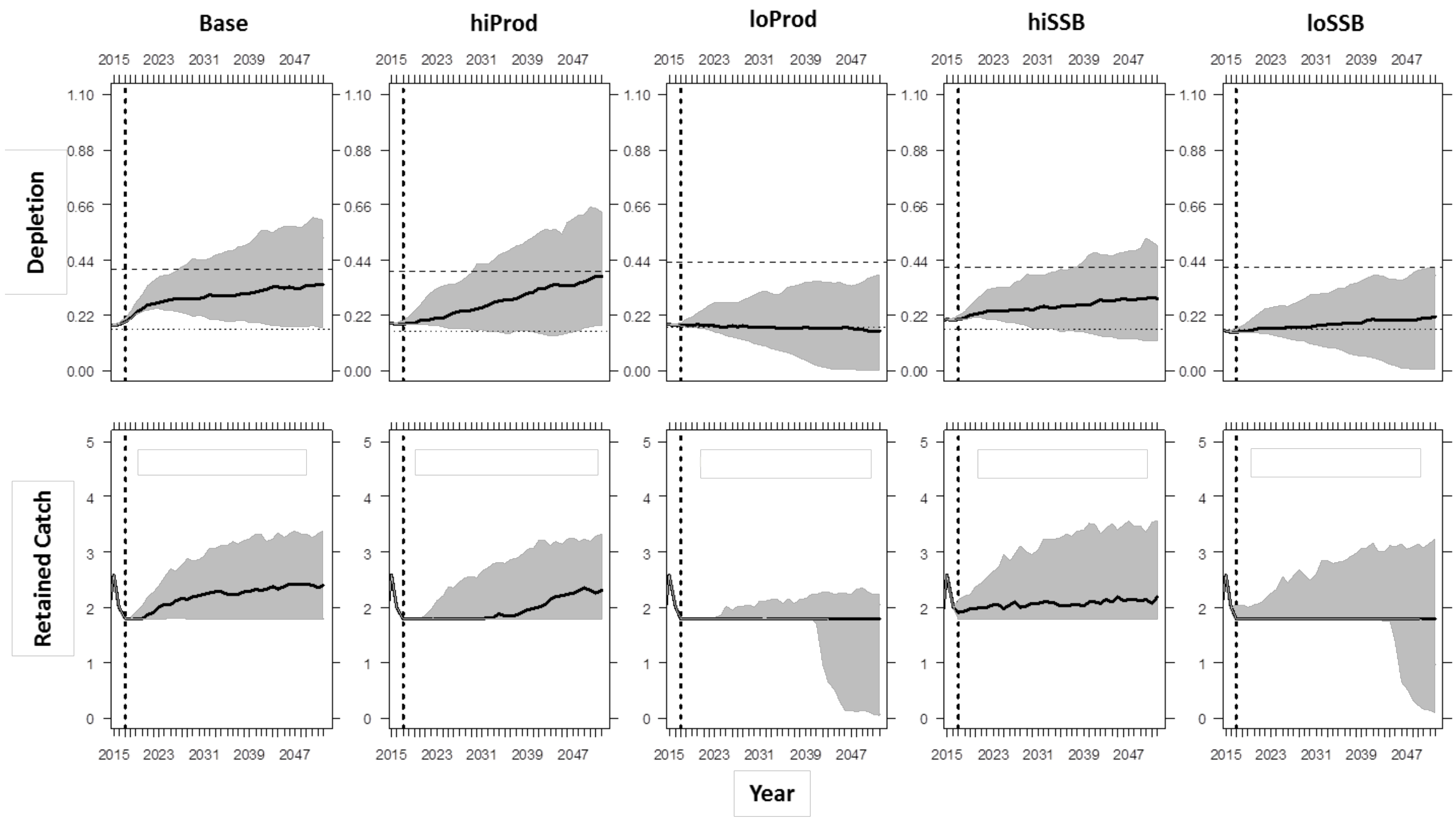

*Figure D-4. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated **FI1.80_HR5.5** management procedure under five different productivity scenarios (left to right columns: base, high productivity, low productivity, high initial fSSB, low initial fSSB). Grey shading represents the central 80% of 100 simulation replicate outcomes and the thick black lines show the median over all replicates. Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

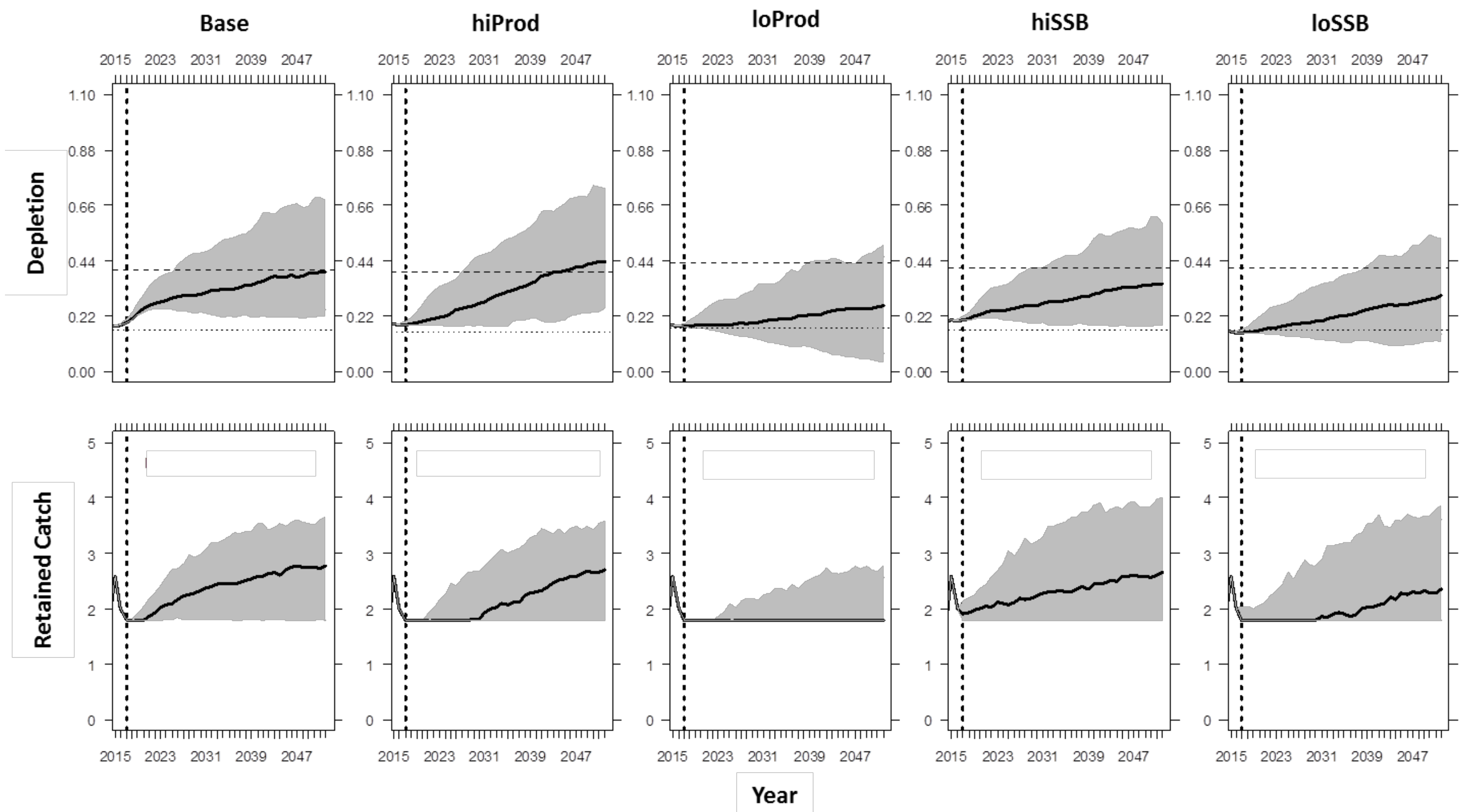

*Figure D-5. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated **FI1.80_HR5.5_frt** management procedure under five different productivity scenarios (left to right columns: base, high productivity, low productivity, high initial fSSB, low initial fSSB). Grey shading represents the central 80% of 100 simulation replicate outcomes and the thick black lines show the median over all replicates. Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

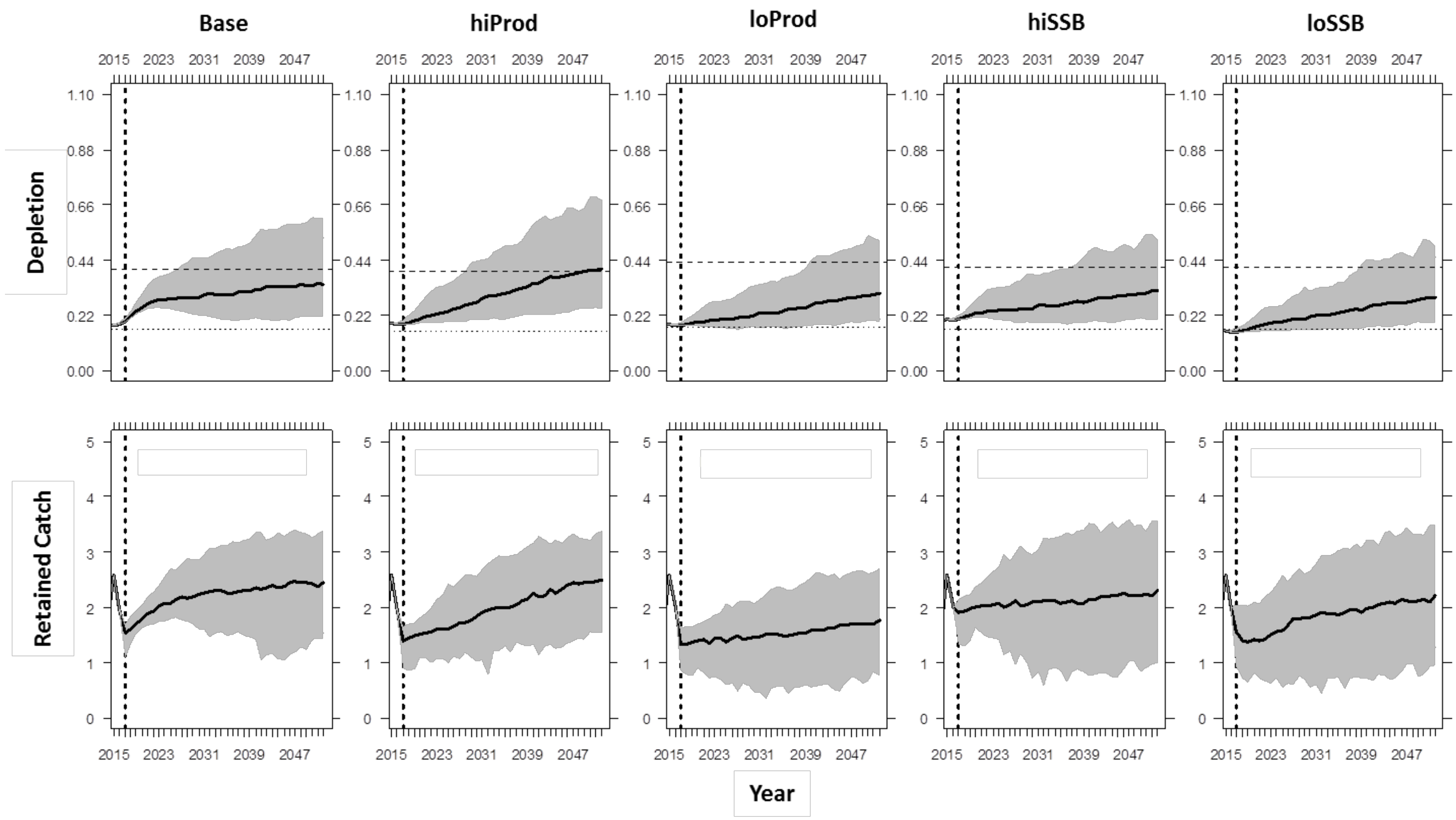

*Figure D-6. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated **FI0.0 0_HR5.5** management procedure under five different productivity scenarios (left to right columns: base, high productivity, low productivity, high initial fSSB, low initial fSSB). Grey shading represents the central 80% of 100 simulation replicate outcomes and the thick black lines show the median over all replicates. Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

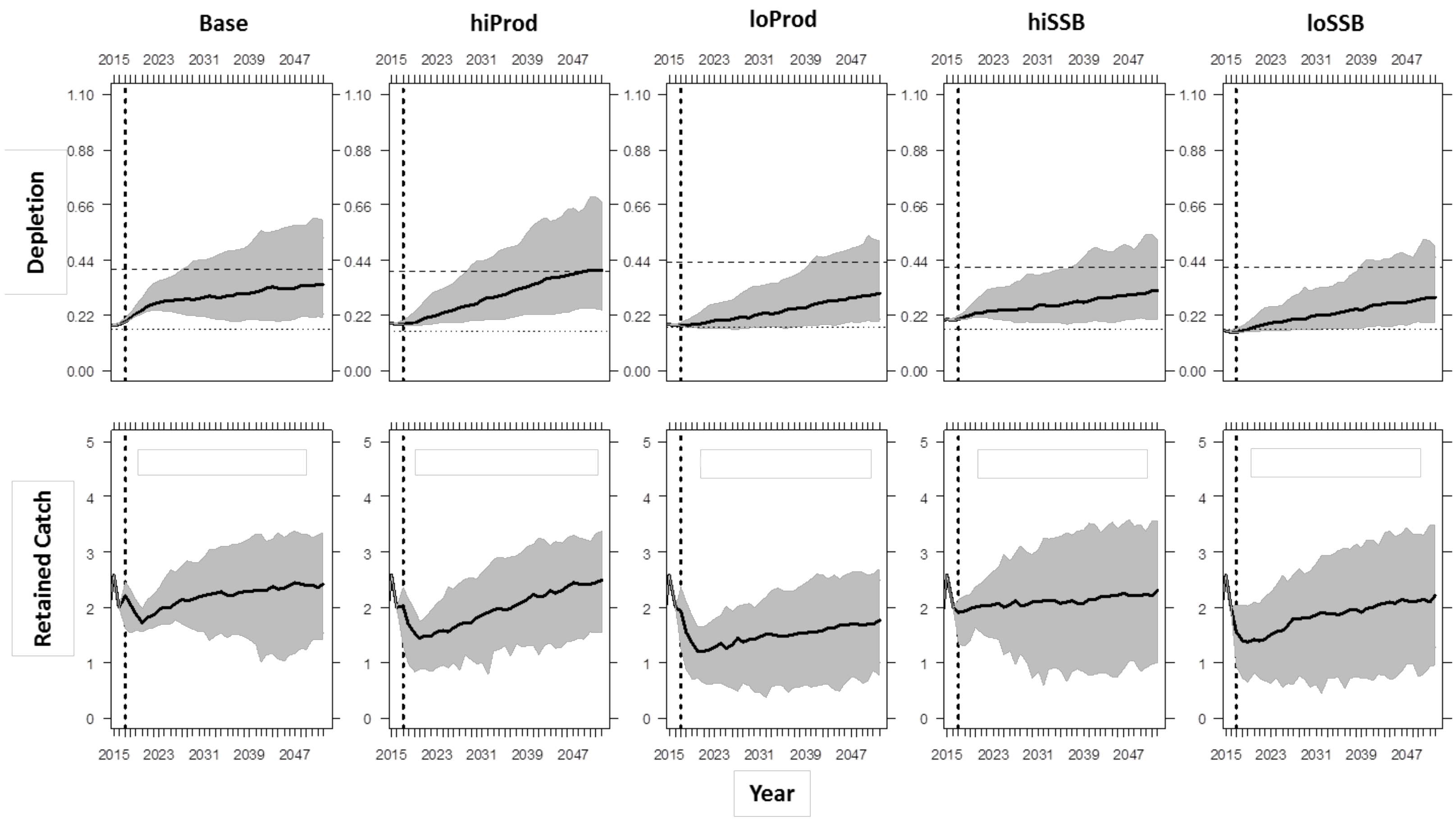

*Figure D-7. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated **FI0.00_HR5.5_ph3** management procedure under five different productivity scenarios (left to right columns: base, high productivity, low productivity, high initial fSSB, low initial fSSB). Grey shading represents the central 80% of 100 simulation replicate outcomes and the thick black lines show the median over all replicates. Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

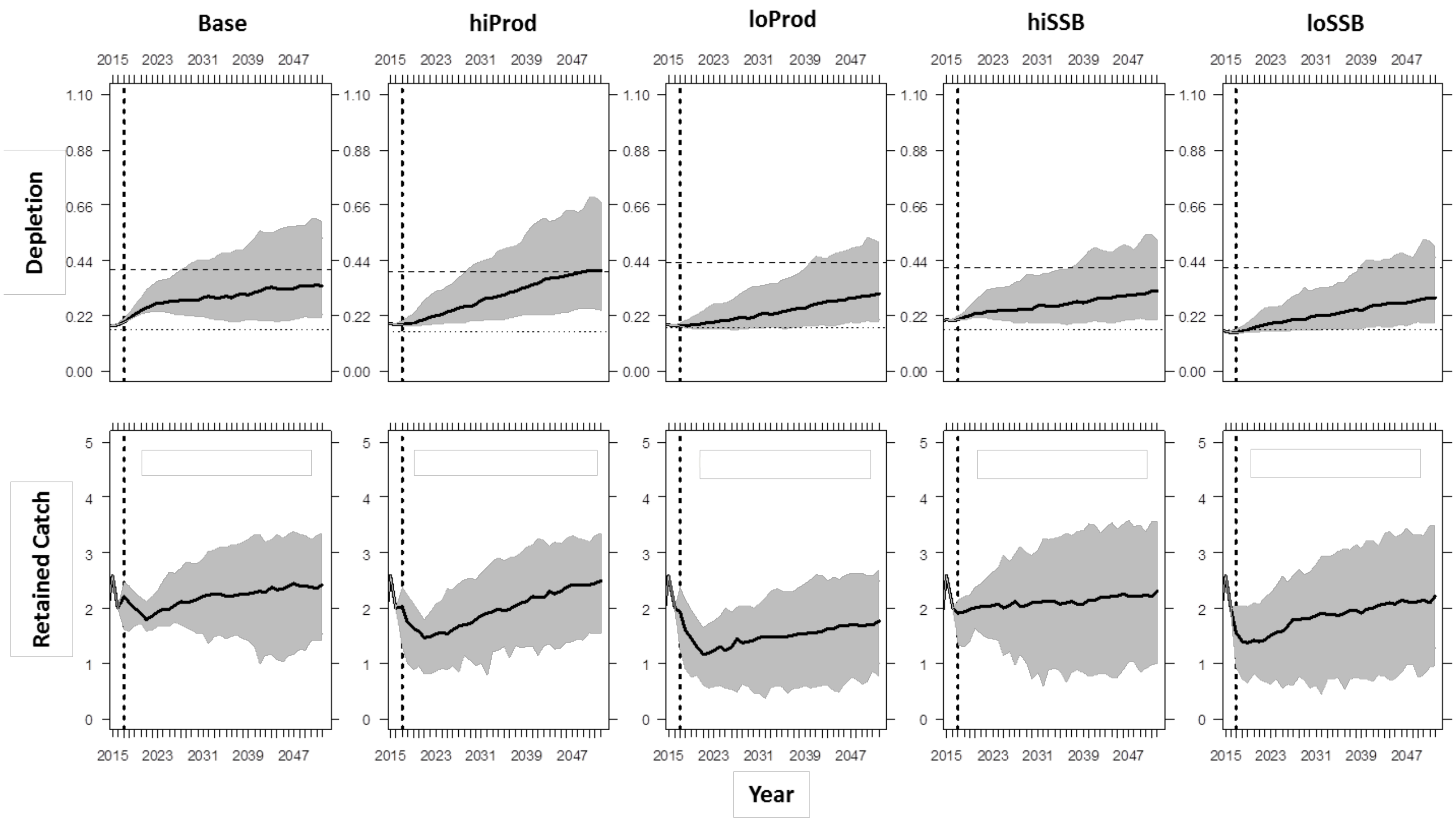

*Figure D-8. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated **FI0.00_HR5.5_ph4** management procedure under five different productivity scenarios (left to right columns: base, high productivity, low productivity, high initial fSSB, low initial fSSB). Grey shading represents the central 80% of 100 simulation replicate outcomes and the thick black lines show the median over all replicates. Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

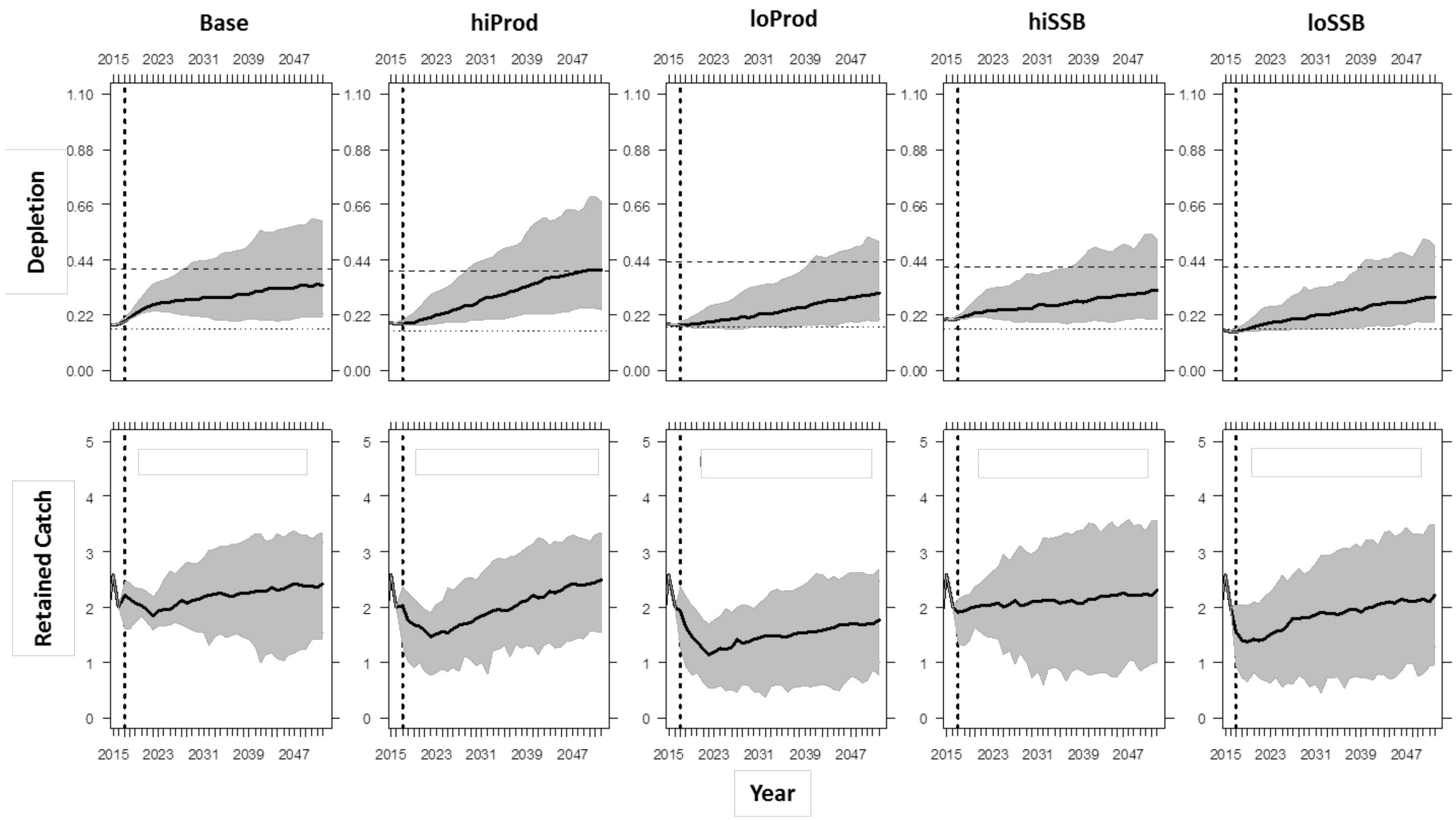

*Figure D-9. Projection distributions for operating model female spawning biomass depletion (i.e., $fSSB_t/fSSB_0$) (top) and retained catch (TACs) from the simulated **FI0.00_HR5.5_ph5** management procedure under five different productivity scenarios (left to right columns: base, high productivity, low productivity, high initial fSSB, low initial fSSB). Grey shading represents the central 80% of 100 simulation replicate outcomes and the thick black lines show the median over all replicates. Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

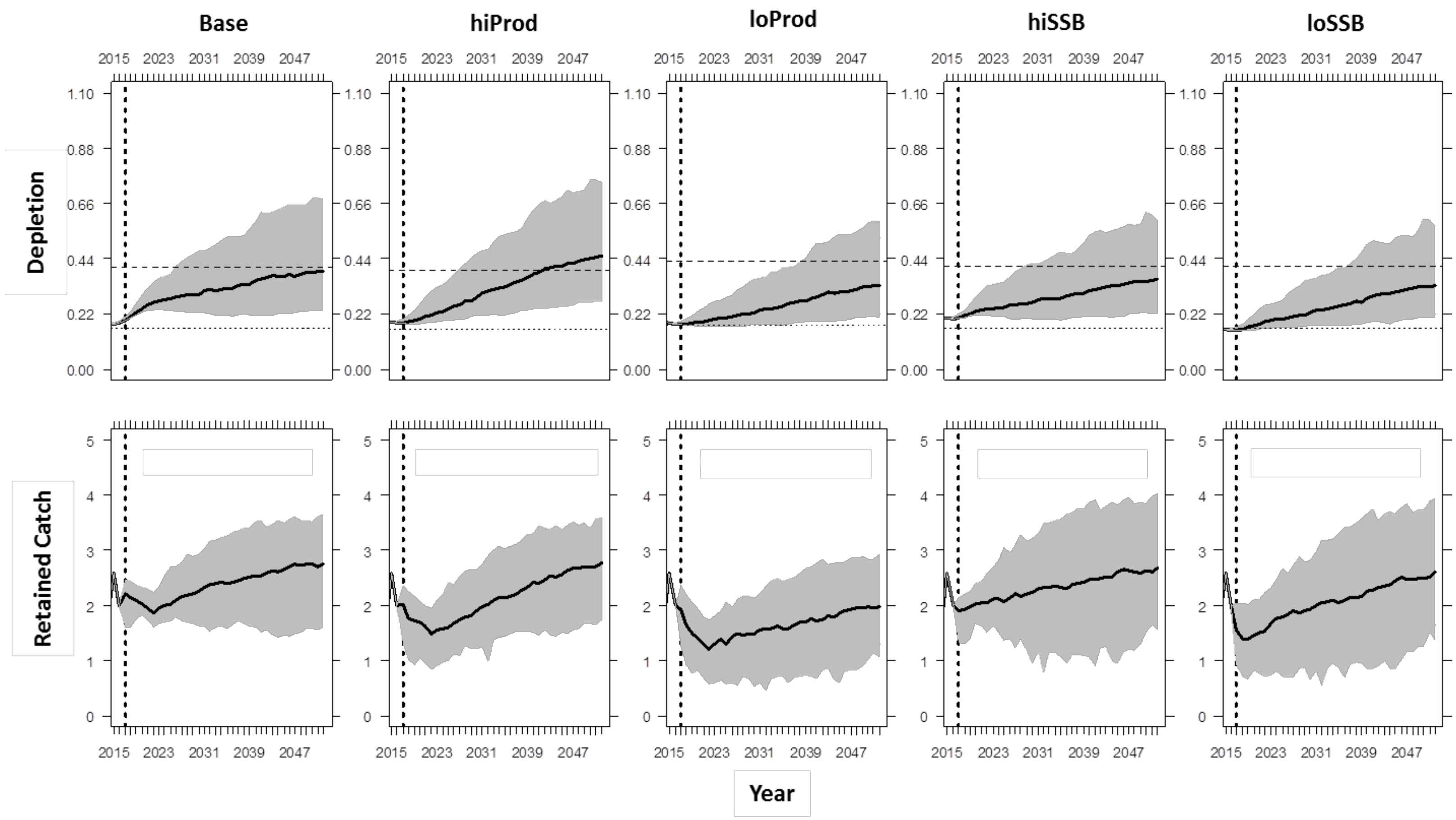

*Figure D-10. Projection distributions for operating model female spawning biomass depletion (i.e., fSSBt/fSSB0) (top) and retained catch (TACs) from the simulated **FI0.00_HR5.5_ph5_frt** management procedure under five different scenarios (left to right columns: base, high productivity, low productivity, high initial fSSB, low initial fSSB). Grey shading represents the central 80% of 100 simulation replicate outcomes and the thick black lines show the median over all replicates. Horizontal lines in the top panels mark the biomass limit reference point (bottom, dotted line) and B_{MSY} (top, dashed line).*

APPENDIX E: SIMULATION RESULTS – HARVEST RATES

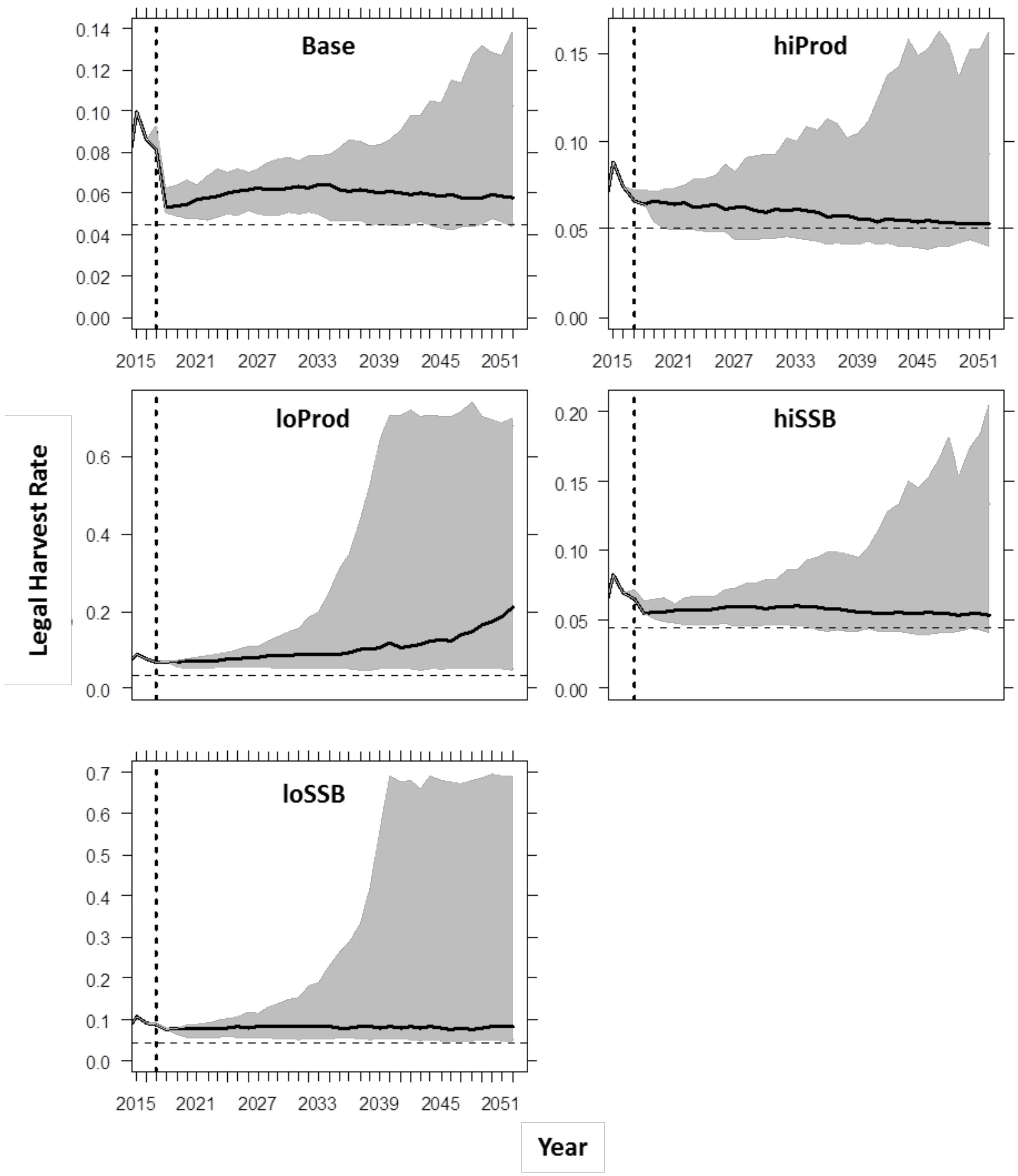

*Figure E-1. Projection distributions for realized legal harvest rates in the operating model for the **currMP** management procedure under five different scenarios: base, high productivity, low productivity, high initial fSSB, low initial fSSB. Note the scale of the Legal Harvest Rate axis differs for the five panels.*

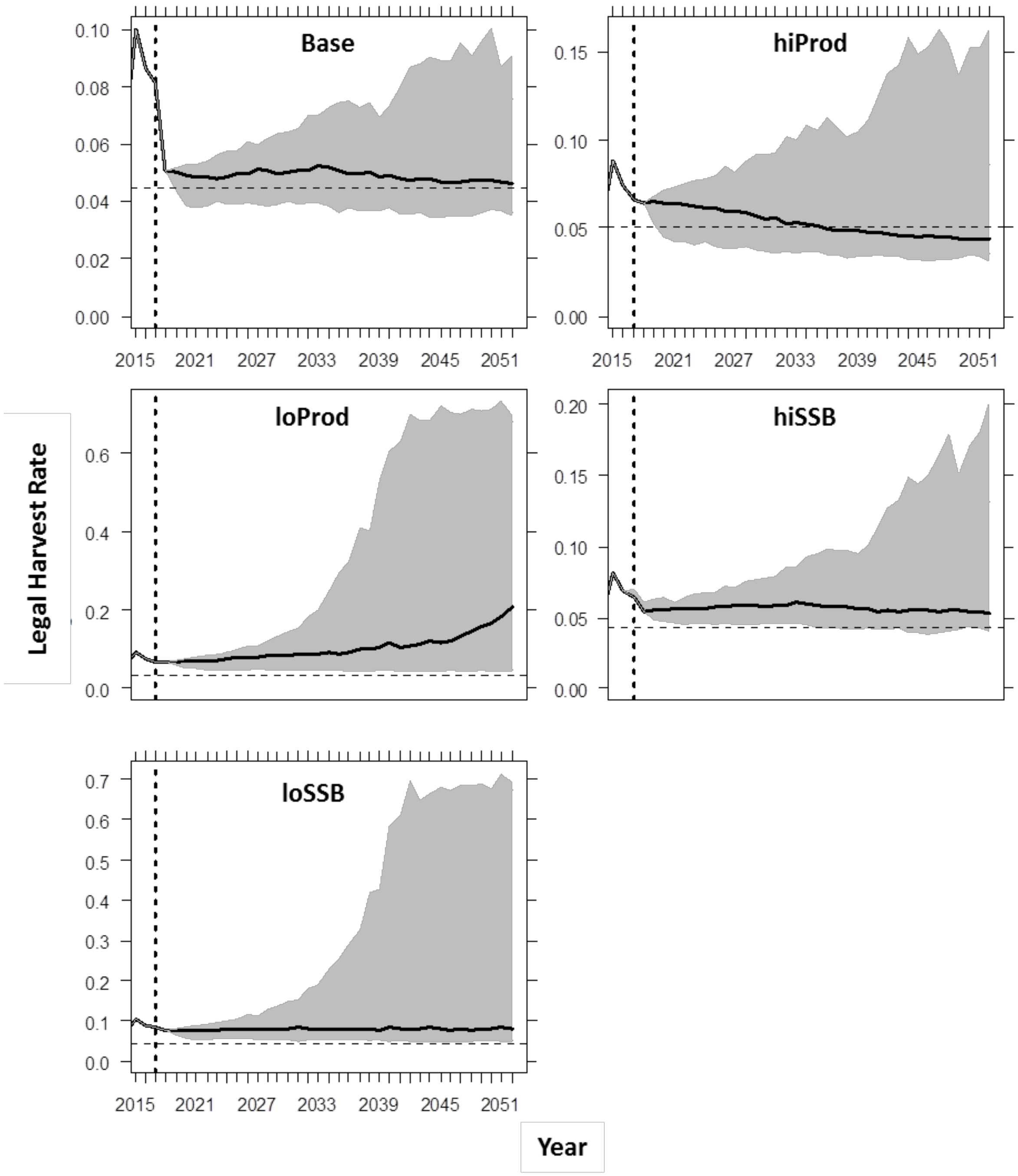

*Figure E-2. Projection distributions for realized legal harvest rates in the operating model for the **FI1.992_HR5.5** management procedure under five different scenarios: base, high productivity, low productivity, high initial fSSB, low initial fSSB. Note the scale of the Legal Harvest Rate axis differs for the five panels.*

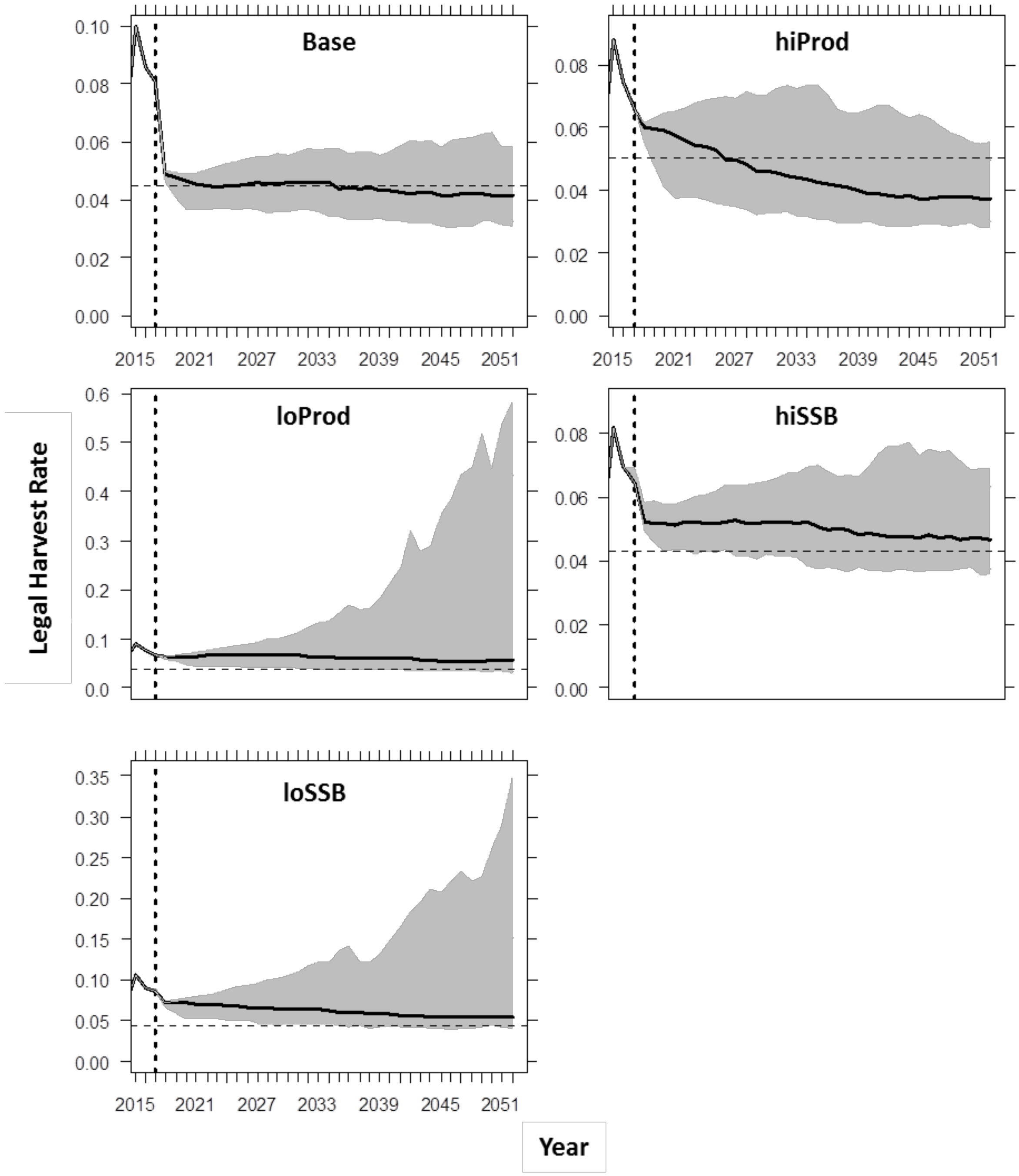

Figure E-3. Projection distributions for realized legal harvest rates in the operating model for the ***FI1.992_HR5.5_frt*** *management procedure under five different scenarios: base, high productivity, low productivity, high initial fSSB, low initial fSSB. Note the scale of the Legal Harvest Rate axis differs for the five panels.*

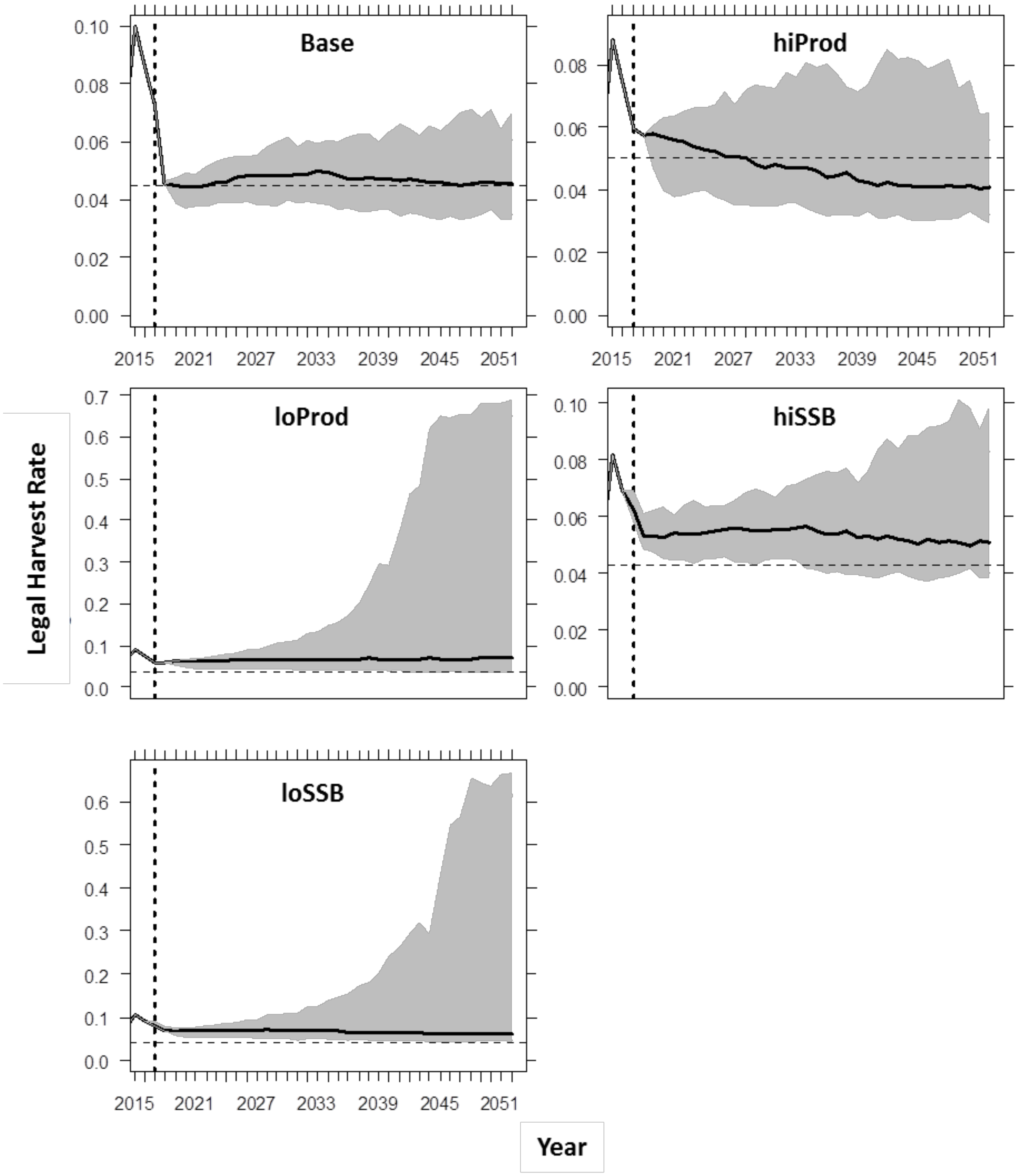

*Figure E-4. Projection distributions for realized legal harvest rates in the operating model for the **FI1.8_HR5.5** management procedure under five different scenarios: base, high productivity, low productivity, high initial fSSB, low initial fSSB. Note the scale of the Legal Harvest Rate axis differs for the five panels.*

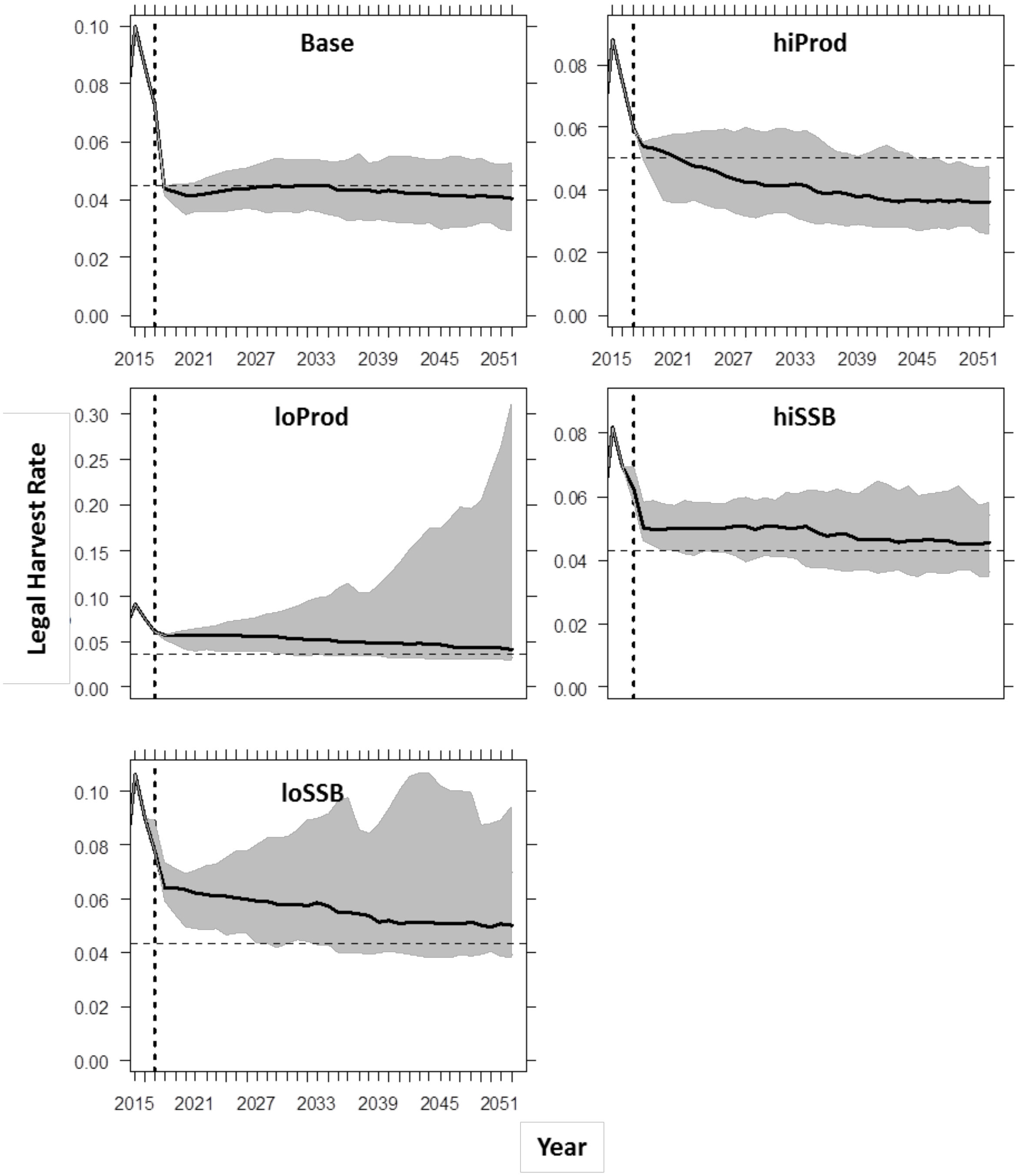

*Figure E-5. Projection distributions for realized legal harvest rates in the operating model for the **FI1.8_HR5.5_frt** management procedure under five different scenarios: base, high productivity, low productivity, high initial fSSB, low initial fSSB. Note the scale of the Legal Harvest Rate axis differs for the five panels.*

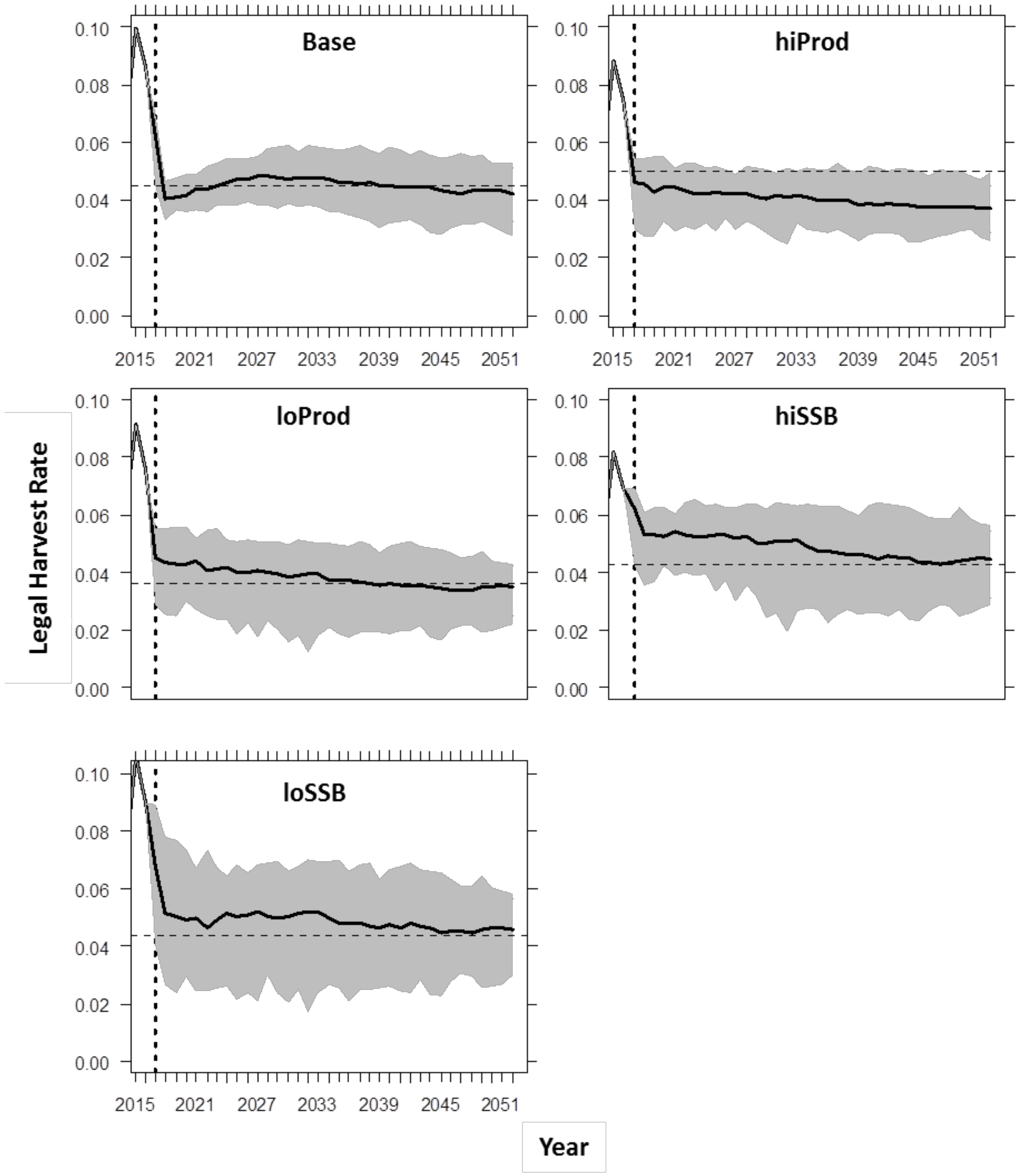

Figure E-6. Projection distributions for realized legal harvest rates in the operating model for the ***FI0.00_HR5.5*** *management procedure under five different scenarios: base, high productivity, low productivity, high initial fSSB, low initial fSSB.*

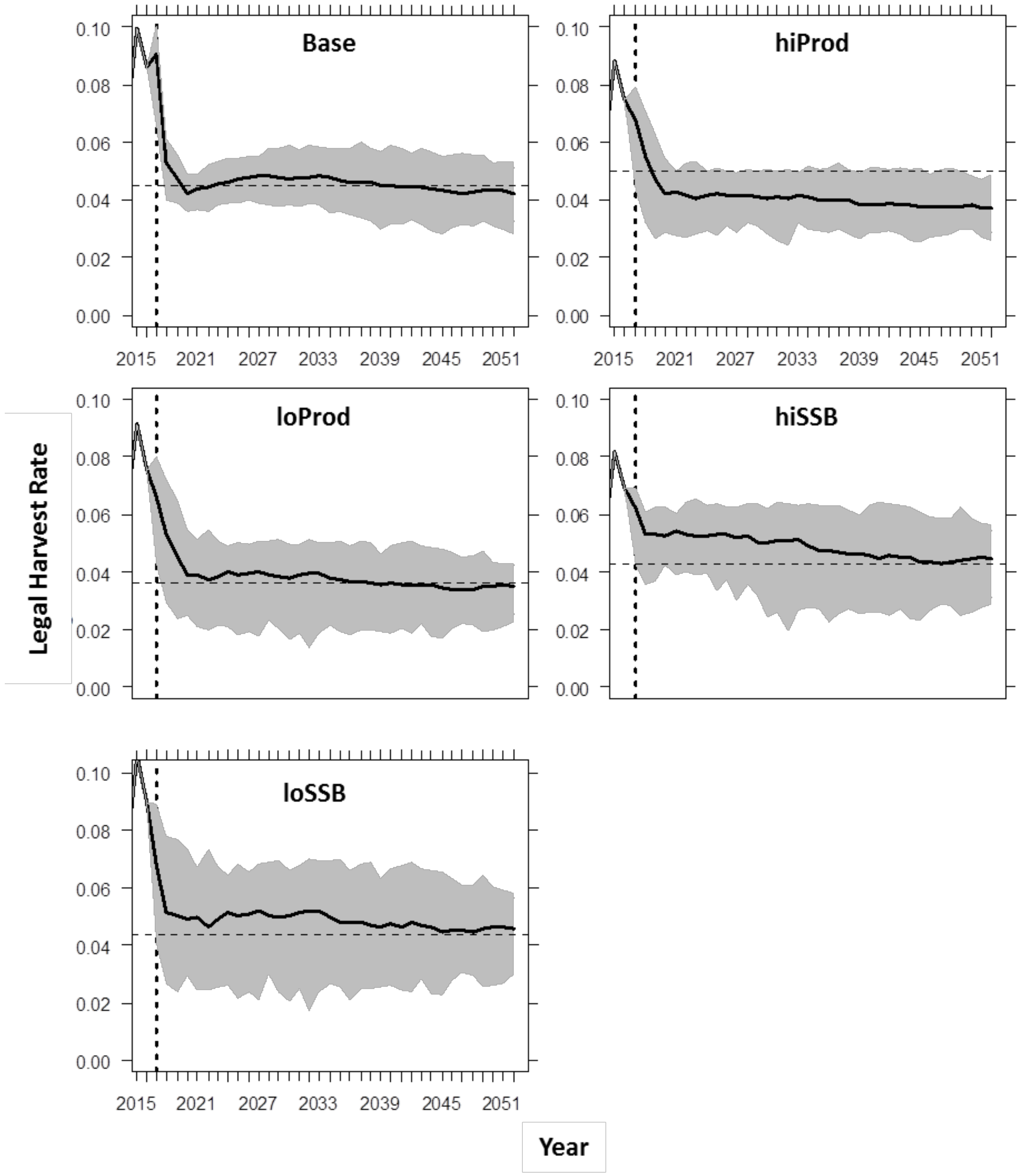

*Figure E-7. Projection distributions for realized legal harvest rates in the operating model for the **FI0.00_HR5.5_ph3** management procedure under five different scenarios: base, high productivity, low productivity, high initial fSSB, low initial fSSB.*

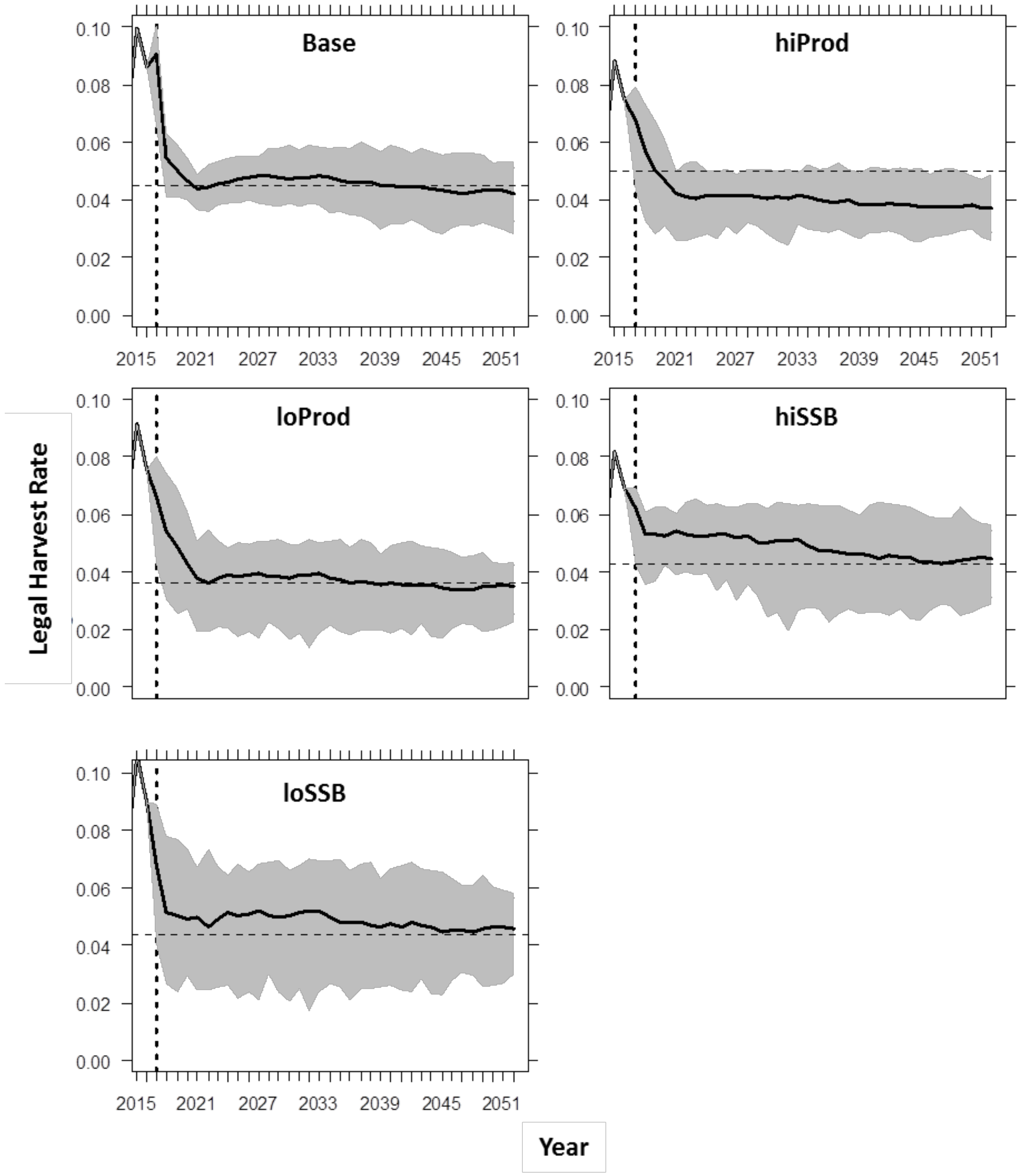

*Figure E-8. Projection distributions for realized legal harvest rates in the operating model for the **FI0.00_HR5.5_ph4** management procedure under five different scenarios: base, high productivity, low productivity, high initial fSSB, low initial fSSB.*

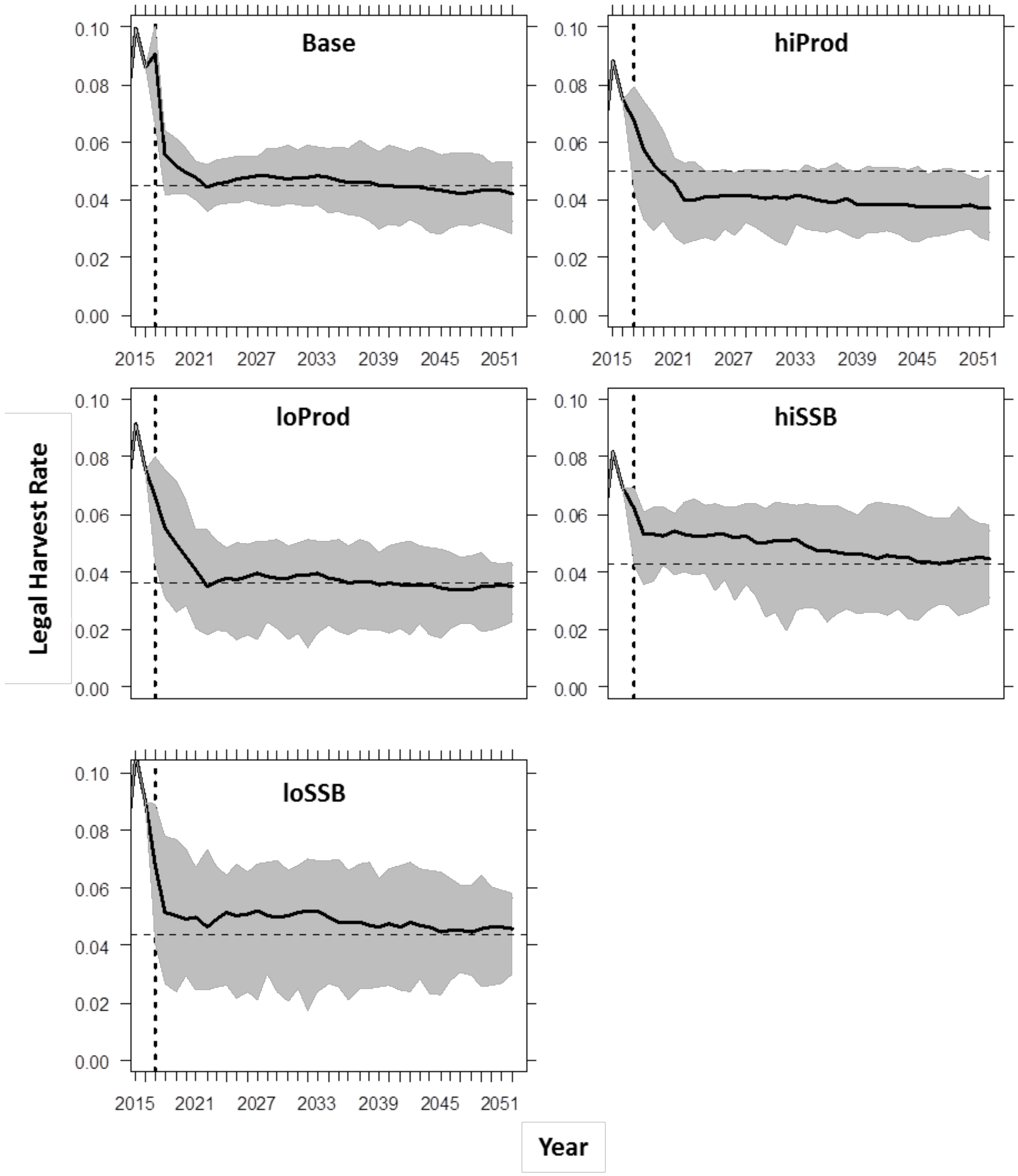

*Figure E-9. Projection distributions for realized legal harvest rates in the operating model for the **FI0.00_HR5.5_ph5** management procedure under five different scenarios: base, high productivity, low productivity, high initial fSSB, low initial fSSB.*

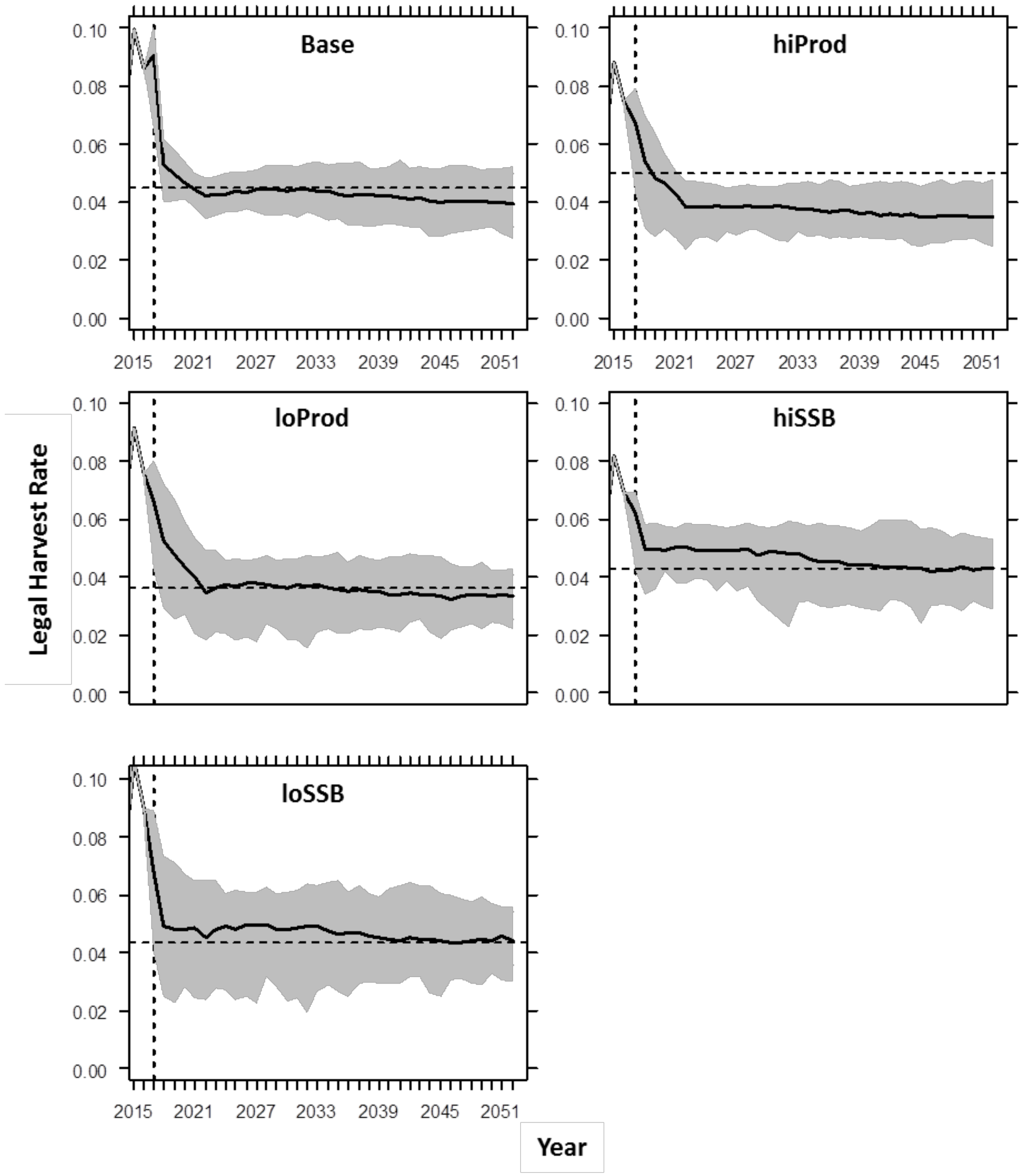

*Figure E-10. Projection distributions for realized legal harvest rates in the operating model for the **FI0.00_HR5.5_ph5_frt** management procedure under five different scenarios: base, high productivity, low productivity, high initial fSSB, low initial fSSB.*