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PRELIMINARY MANAGEMENT STRATEGY EVALUATION TO EVALUATE THE IATTC INTERIM REFERENCE POINTS AND PROPOSED HARVEST CONTROL RULE

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ABSTRACT

Harvest control rules (HCRs) and reference points (RPs) have become common in the management of many fish stocks. The IATTC has operated for many years under the unofficial HCR of fishing at F_{MSY}, and recently adopted interim target (TRP) and limit (LRP) reference points. We use management strategy evaluation (MSE) to evaluate the HCR and RPs using bigeye tuna as an example. Stock Synthesis is used as both the operating model (OM) and the assessment model. The analysis is repeated under misspecification of the steepness of the stock-recruitment relationship, the asymptotic length, and natural mortality. Random recruitment deviations are applied for projection of the OM when testing the management procedure (MP). The results show that the probability of recruitments dropping below 50%R_0, which is used to define the LRPs, is generally lower than 10% for the 9-year management period. An over-assumed steepness in the MP can increase the probability of dropping below 50%R_0, and an over-assumed steepness or natural mortality can increase the probability of exceeding the fishing mortality-based LRP. Overall, the MP applied in this study works effectively to manage the stock at the MSY level, and avoid a high risk of recruitment being seriously impacted. However, these results are only preliminary, and more analyses are needed.

1. INTRODUCTION

Harvest control rules (HCRs) and reference points (RPs) have become common in the management of many fish stocks. They are an essential component of the guidelines for adopting the precautionary approach to fisheries management outlined in Annex II of the United Nations Straddling Fish Stocks Agreement (UNFSA 1995). There is mounting pressure from a variety of organizations and certification bodies for regional fisheries management organizations (RFMOs) to test and adopt RPs and HCRs. Management Strategy Evaluation (MSE) is seen as the gold standard for developing HCRs.

The Inter-American Tropical Tuna Commission (IATTC) has recently adopted interim target (TRP) and limit (LRP) reference points (see the minutes of the IATTC 2014 October meeting). The target reference points are the biomass (B) and fishing mortality rate (F) corresponding to maximum sustainable yield (B_{MSY} and F_{MSY}, respectively) which have been the unofficial target reference points used in managing tuna in the eastern Pacific Ocean (EPO). The limit reference points are those associated with a 50% reduction in recruitment under a conservative assumption of the stock-recruitment relationship (steepness, or h = 0.75; see Maunder and Deriso 2014), which is based on biological grounds to protect a stock from serious, slowly reversible, or irreversible fishing impacts. In general, this is interpreted as ensuring that recruitment is not substantially impacted.

The IATTC has operated under the unofficial HCR of fishing at F_{MSY}, or more accurately, reducing the fishing mortality to F_{MSY} if fishing mortality on bigeye or yellowfin exceeds their respective F_{MSY} as estimated by the base case stock assessments. This HCR does not take uncertainty into consideration, nor the probability of exceeding the LRP, and the action taken if the LRP is exceeded has not been defined. The HCR and RPs have not been tested to determine whether they meet the management goals, and the management goals have not been explicitly defined, except in broad terms as outlined in the Antigua Convention (*e.g*. "maintain or restore the populations of harvested species at levels of abundance which can produce the maximum sustainable yield").

We develop a preliminary MSE for bigeye tuna in the EPO to test the proposed HCR and interim LRPs. Bigeye tuna was chosen for this initial attempt at an MSE because it is the species that often dictates management of the purse-seine fishery in the EPO. The operating model (OM) for the MSE is based on a recent bigeye tuna stock assessment model, and is therefore conditioned to the data, but ignores several sources of uncertainty. The approach follows that suggested by Maunder (2014) and illustrated using bluefin tuna in the northern Pacific Ocean, which is based on the Stock Synthesis (SS) general stock assessment program (Methot and Wetzel 2013). The stock assessment model (SAM) used in the management procedure (MP) is based on a simplified version of the original stock assessment model in order to reduce the computational demands of the MSE. The MP is tested under different SAM misspecifications to investigate uncertainty. The probability of exceeding the LRPs is used as the main performance measure.

2. METHODS

2.1. Operating model

The OM is based on a recent assessment model used for bigeye tuna in the EPO (Aires-da-Silva and Maunder 2014). This ensures that the OM is conditioned on the data, which means that the dynamics represented by the OM are consistent with the observed data and avoids the inclusion of extreme dynamics. However, stock assessment models typically do not include all the possible sources of uncertainty, because parameter estimation would not be possible. Therefore, we conduct several model structure sensitivity analyses, as discussed below, to investigate the impact of additional uncertainty. The approach follows that outlined by Maunder (2014) using SS (Methot and Wetzel 2013).

The OM and the data used to estimate the parameters were configured following Aires-da-Silva and Maunder (2014). The data include catch, indices of abundance based on catch-per-unit-of-effort (CPUE), and size-composition data for January 1975 through December 2012. All data were summarized and analyzed on a quarterly basis. Twenty-three fisheries were defined for the stock assessment on the basis of gear type, time period, length-frequency sampling area or latitude, and unit of longline catch. The CPUE-based indices of abundance used in the model were from purse-seine fisheries on fish associated with floating objects and from longline fisheries. Detailed descriptions of the data used can be found in Aires-da-Silva and Maunder (2014). Biological and demographic information, including stock structure, growth, natural mortality, and maturity, were parameterized as presented in Aires-da-Silva and Maunder (2014).

The stock assessment model is fitted to the historical data to estimate the model parameters. These parameters are then fixed when using the operating model, to represent the underlying "true" population dynamics in the future when applying the HCR. Random quarterly recruitment deviates are added to the model to incorporate stochastic future population dynamics. The log-transformed recruitment deviates are assumed to follow a normal distribution with mean 0 and standard deviation 0.6, consistent in both in the OM and in the SAM. The bootstrap functionality of SS is used to generate the observed data used in the MP.

2.2. Management procedure

The MP is a combination of the HCR and the SAM. The HCR is simply to set the fishing mortality at the estimated F_{MSY}. The SAM is a simple two-fishery version of the stock assessment model used for the OM. The first fishery combines the catch for all the purse-seine fisheries (fisheries 1-11; see Aires-da-Silva and Maunder (2014) for fishery definitions), but uses only length-composition data from the floating-object fisheries (fisheries 1-5). The second fishery aggregates the catch for all the longline fisheries (fisheries 12-23), but uses only the index of abundance and length-composition data for the main southern longline fisheries (fisheries 16-17). The length-composition data are combined by weighting them by sample size. Time-invariant dome-shaped selectivity is used for the first fishery, and time-invariant asymptotic selectivity for the second fishery. The historical data are the same as those as used in the OM, and the data are updated for the future. The SAM is applied and fishing mortality updated every three years. The dynamics are projected 9 years into the future. Implementation error is not considered.

We defined the recruitment-based LRP as 50% of the virgin recruitment (R_0), notated as $R_{0.5}$ (*i.e.* $R_{0.5}$= 50%R_0). We tested $R_{0.5}$ and the corresponding LRPs associated with fishing mortality and spawning biomass (SSB), notated as $F_{0.5R0}$ and $d_{0.5R0}$ (the depletion level of SSB), respectively. $d_{0.5R0}$ is calculated by assuming a conservative h = 0.75, using the equation described by Maunder and Deriso (2014), despite the "true" h differing among scenarios. $F_{0.5R0}$ is estimated by finding the equilibrium fishing mortality corresponding to $d_{0.5R0}$, with the "true" h for the specific scenario.

2.3. Scenarios

The MSE is repeated for four versions of the OM. The scenarios differ in the specification of the parameter h of the Beverton-Holt stock-recruitment relationship, the average size of the oldest individuals (*L2*), or the natural mortality (*M*) level (see **Table 1** for scenario configurations). In all scenarios, the SAM assumes that h = 1, *L2* = 185.5 cm, and *M* equal to the values in the base case of Aires-da-Silva and Maunder (2014). Thus, we mimic the stock assessment in the MP by all these parameters perfectly assumed (Scenario 1), *L2* under-assumed (Scenario 2), h over-assumed (Scenario 3), and *M* over-assumed (Scenario 4) (**Table 1**).

2.4. Algorithm

The basic structure of the MSE is shown in **Figure 1**. The process includes the following steps:

1. Fit base case bigeye tuna assessment model to the historical data (1975-2012). This provides the parameters of the OM that will be fixed for the analysis;
2. Compile the historical data and structure of the OM to be used by the two- fishery SAM. Fit the SAM to the data and estimate F_{MSY};
3. Project the OM forward 3 years (12 quarters) using the estimated F_{MSY} and random recruitment deviation (process error). This updates the stock trajectory for 3 years;
4. Change the data files of the updated OM by a) adding 3 years to the model end year; b) put the catch calculated from the projected years from (3) in as catch of the updated 3 years; c) put the random recruitments used in the projected period into the updated 3 years; and d) add dummy data (CPUE, length composition, and last five years' average of sample size for the length composition) to the data file for the 3 new years;
5. Run bootstrap to generate "perceived" observations of catch, CPUE, and length composition for the whole time period (historical and forecast period). Update the fishery data by replacing the catch and dummy data with bootstrapped data for the forecast period in (3);
6. Repeat (2) - (5) for as many times as desired (3 times in our example, which equals 9 years);
7. Repeat (2) - (6) for as many times as desired with different random recruitment deviations (100 times in our example);
8. Repeat (1) - (7) for each scenario. The random recruitment deviations should be the same for each scenario to eliminate the impact of random recruitments when making comparisons between

different scenarios.

The simulation is coded by R (R Core Team, 2014) and associated package r4ss (Taylor *et al*., 2014).

2.5. Performance measures

Several quantities are calculated to determine how well the MP performs.

1. The frequency with which the fishing mortality dropped below $F_{0.5R0}$;
2. The frequency with which the spawning biomass depletion level dropped below $d_{0.5R0}$;
3. The probability (uses frequency as proxy) that recruitment dropped below $R_{0.5}$;
4. The average catch and coefficient of variation (CV) of catch from the multiple simulations.

3. RESULTS

The candidate LRPs based on 50%R_0 for each scenario are shown in **Table 2**. The probability of recruitments dropping below the $R_{0.5}$ in a particular year is lower than 10% for the projected 9 years, except for one year when the *h* in SAM is over-assumed (Scenario 3) (**Figure 2**). An over-assumed *h* results in a higher probability of exceeding the $R_{0.5}$. There are one or two years in the historical period in which the recruitments are also lower than $R_{0.5}$ level, depending on the scenario (**Figure 2**).

The probability of fishing mortality exceeding $F_{0.5R0}$ is zero for the projected years when the *h*, *L2*, and *M* are perfectly specified in the SAM (Scenarios 1). $F_{0.5R0}$ is also not exceeded when *L2* is under-assumed (Scenarios 2). Both over-assumed *h* and over-assumed *M* result in $F_{0.5R0}$ being exceeded for a few years in the projection period, but the probability of exceeding $F_{0.5R0}$ is very low (lower than 5% in any particular year) (Scenarios 3-4; **Figure 3**). The probability of the SSB depletion level being below the $d_{0.5R0}$ is zero for all the scenarios. **Figure 4** shows the SSB depletion time series of the OM. The SSB depletions corresponding to MSY for scenarios 1-4 are 0.2081, 0.2125, 0.2529, and 0.2427.

The time series of catch and CV of catch are shown in **Figures 5-6**. For each scenario, the catch rises to the level around MSY estimated from the OM (*i.e*. the true MSY) when the stock is projected using F_{MSY} estimated by the SAM (**Figures 5**). The true MSY is 96,382 t, 94,401 t, 95,600 t, and 92,140 t for Scenarios 1-4, respectively. The CVs of catch are 5-20% for the projected periods, and there is no obvious difference among scenarios.

4. DISCUSSION

We have shown that it is feasible to conduct MSE for bigeye tuna in the EPO using the existing stock assessment model as the operating model. This ensures that the possible states of nature are consistent with the observed data and avoids the inclusion of extreme cases. We included additional uncertainty in the operating model by conducting multiple MSEs with different model assumptions. However, these assumptions were arbitrarily chosen, and a more quantitative method is needed to determine the assumptions and their weight in the analysis. The MSE is computationally intensive, even though a simplified stock assessment model is used as part of the management procedure. Therefore, we were limited in the number of simulations in this study. Additional simulations should be conducted to improve the precision of the analysis and ensure that the results are not just a function of the limited random data generated, and to increase the number of years for which the MSE is carried out.

LRPs are generally considered to have a low (but not zero) probability of being exceeded if management is implemented to achieve the TRPs (*i.e*. MSY for bigeye tuna). We found that the proposed $R_{0.5}$ might be an appropriate LRP for bigeye tuna, since the probability of exceeding this LRP is low (**Figure 2**). We also found that an over-assumed steepness in the SAM of the management procedure can increase the risk of high depletion of recruitments (Scenario 3 in **Figure 2**). $R_{0.5}$ is exceeded most probably because of high recruitment variability. The over-assumed *h* or *M* in the SAM has a larger impact on the fishing mortality than *L2*, resulting in increase of risk of exceeding the *F*-based LRP (**Figure 3**), but although further sensitivity analysis needs to be conducted. An operating model with $h = 0.9$ was used because fitting a model with h = 0.75 to condition the OM was problematic. Further analysis is needed to better investigate the impact of the steepness of the stock-recruitment relationship.

The assessment model we have used is a simplification of the currently used assessment model. However, it captures a significant amount of the model structure. In future MSE work the assessment model should be constructed to better represent the model that will be used for assessing the stock. For example, the simplified model combined all the purse-seine fisheries into a single fishery, but modelled selectivity as time-invariant. It is unlikely that selectivity remains constant when fisheries are combined, because changes in the relative catch among fisheries will change the effective selectivity. Modelling time-varying selectivity for the purse-seine fishery would improve the analysis.

Overall, the MP used for bigeye tuna in this case study is effective for maintaining the stock biomass at the level corresponding to MSY and ensure that recruitment is not substantially decreased. This MP can also support sustainable catch around the MSY, although the variability of catch can be high due to the potential variability of recruitment in the future. The catch level around MSY is maintained even when the SAM is misspecified, presumably because the yield curve is flat. However, the MSE needs to be conducted over more years to confirm this result.

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TABLE 1. Key parameters in operating model and stock assessment model for different scenarios

<table>
<tr><th></th><th colspan="3">Operating model</th><th colspan="3">Stock assessment model</th></tr>
<tr><th></th><th>h</th><th>$L2$ (cm)</th><th>M</th><th>h</th><th>$L2$ (cm)</th><th>M</th></tr>
<tr><td>Scenario 1</td><td>1</td><td>185.5</td><td>base level</td><td rowspan="4">base level
(h=1)</td><td rowspan="4">base level
(185.5)</td><td rowspan="4">base level</td></tr>
<tr><td>Scenario 2</td><td>1</td><td>195.0</td><td>base level</td></tr>
<tr><td>Scenario 3</td><td>0.9</td><td>185.5</td><td>base level</td></tr>
<tr><td>Scenario 4</td><td>1</td><td>185.5</td><td>25% lower of base level</td></tr>
</table>

Note: base level – the level used in the base case by Aires-da-Silva and Maunder (2014);
Scenario 1 – perfectly assumed in SAM;
Scenario 2 – under-assumed *L2* in SAM;
Scenario 3 – over-assumed *h* in SAM;
Scenario 4 – over-assumed *M* in SAM.

TABLE 2. Candidate limit reference points for recruitments, SSB depletion, and fishing mortality corresponding to 50%R_0

<table>
<tr><th></th><th>R_0
(1000s fish per quarter)</th><th>SSB_0
(t per year)</th><th>$R_{0.5}$
(1000s fish per quarter)</th><th>$F_{0.5R0}$
(per quarter)</th><th>$d_{0.5R0}$</th></tr>
<tr><td>Scenario 1</td><td>6321.86</td><td>320,592</td><td>3160.93</td><td>0.4029</td><td rowspan="4">0.077</td></tr>
<tr><td>Scenario 2</td><td>5381.16</td><td>314,059</td><td>2690.58</td><td>0.3962</td></tr>
<tr><td>Scenario 3</td><td>6967.88</td><td>353,353</td><td>3483.94</td><td>0.3434</td></tr>
<tr><td>Scenario 4</td><td>3783.28</td><td>430,145</td><td>1891.64</td><td>0.3485</td></tr>
</table>

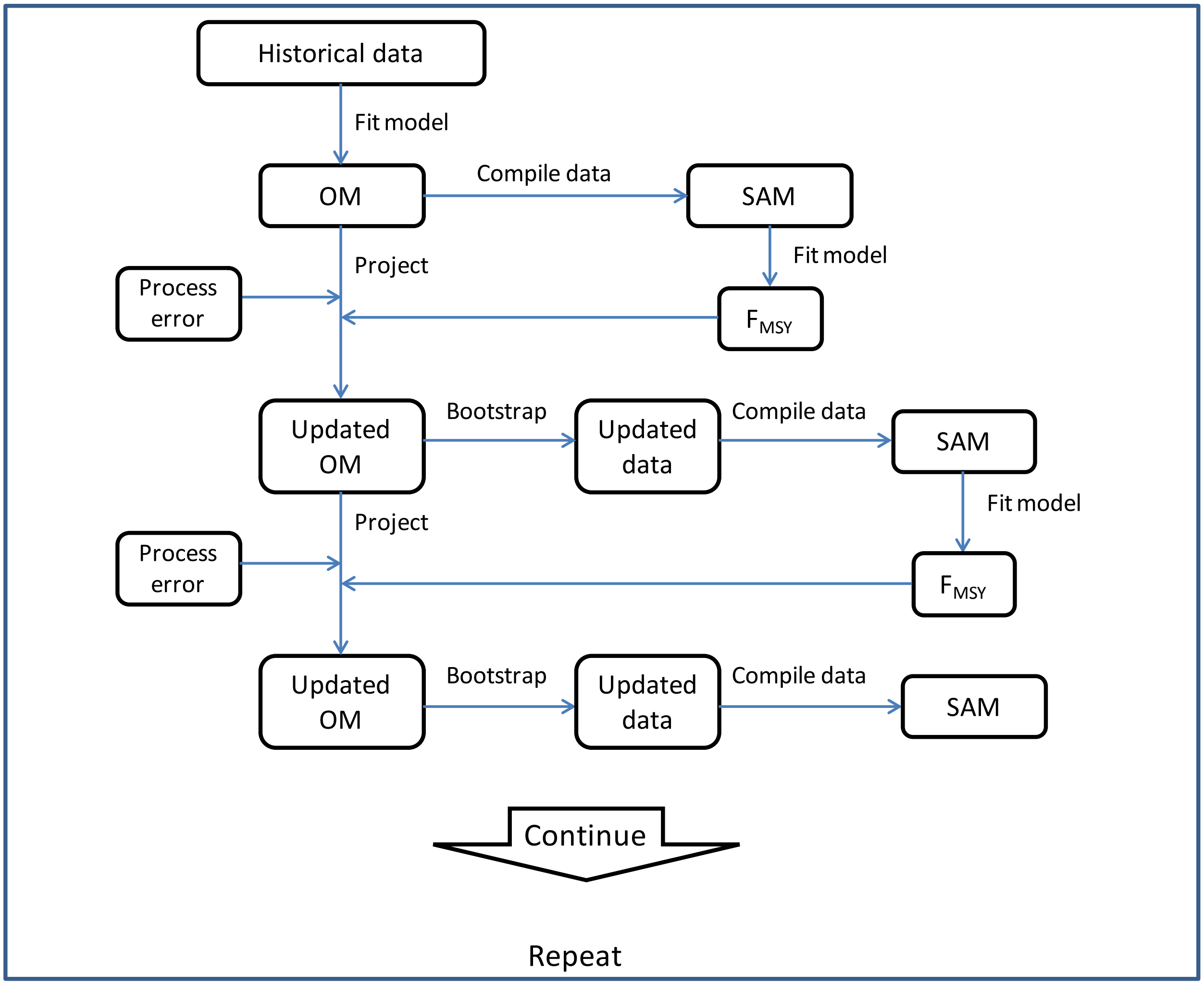

FIGURE 1. Flowchart of the simple MSE used for bigeye tuna

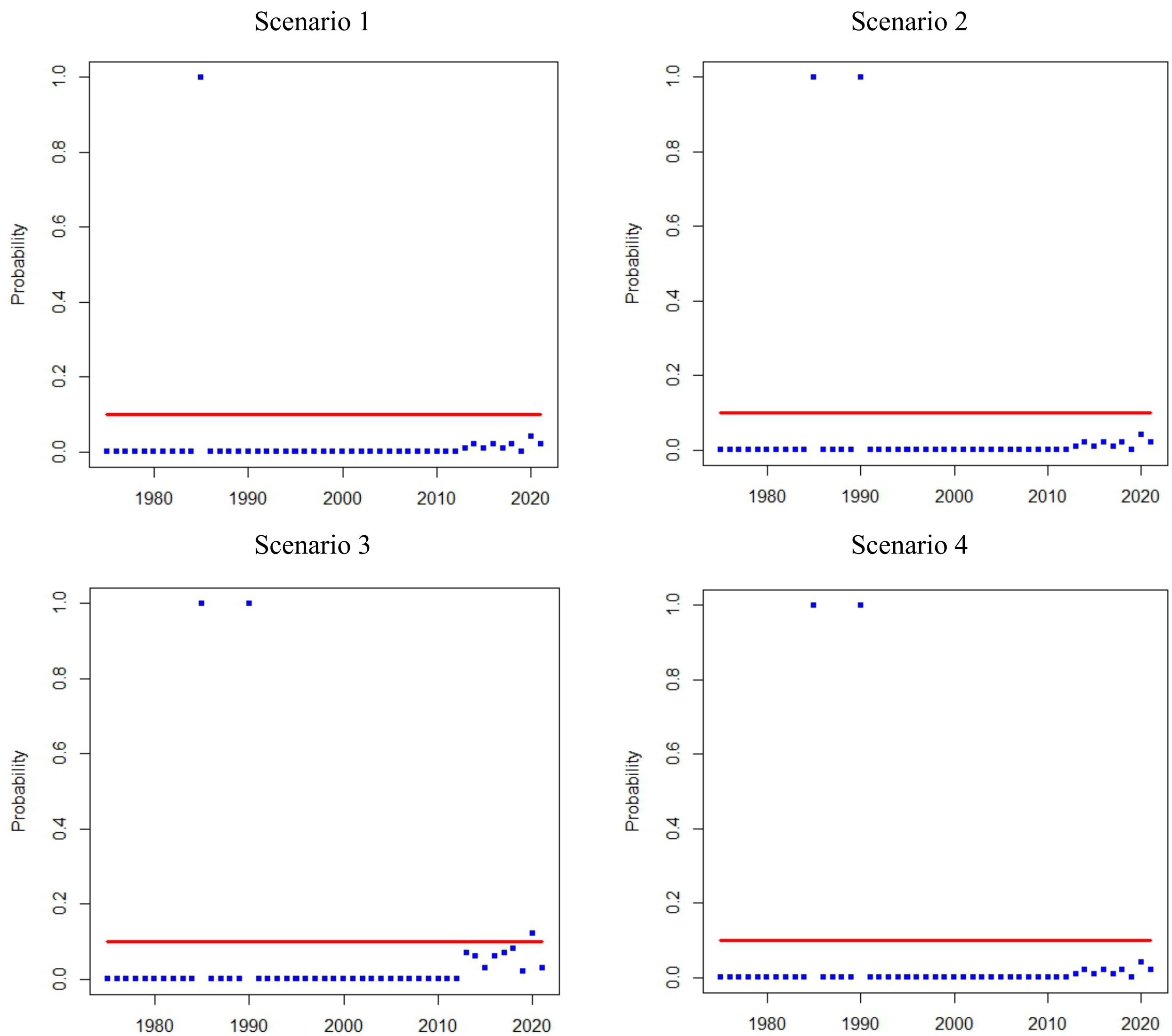

FIGURE 2. Probability (represented by frequency) of the recruitment LRP ($R_{0.5}$) being exceeded. The red line indicates the probability of 0.1. There is only a single recruitment value for the historical period (1975-2012), so the probability is equal to one or zero.

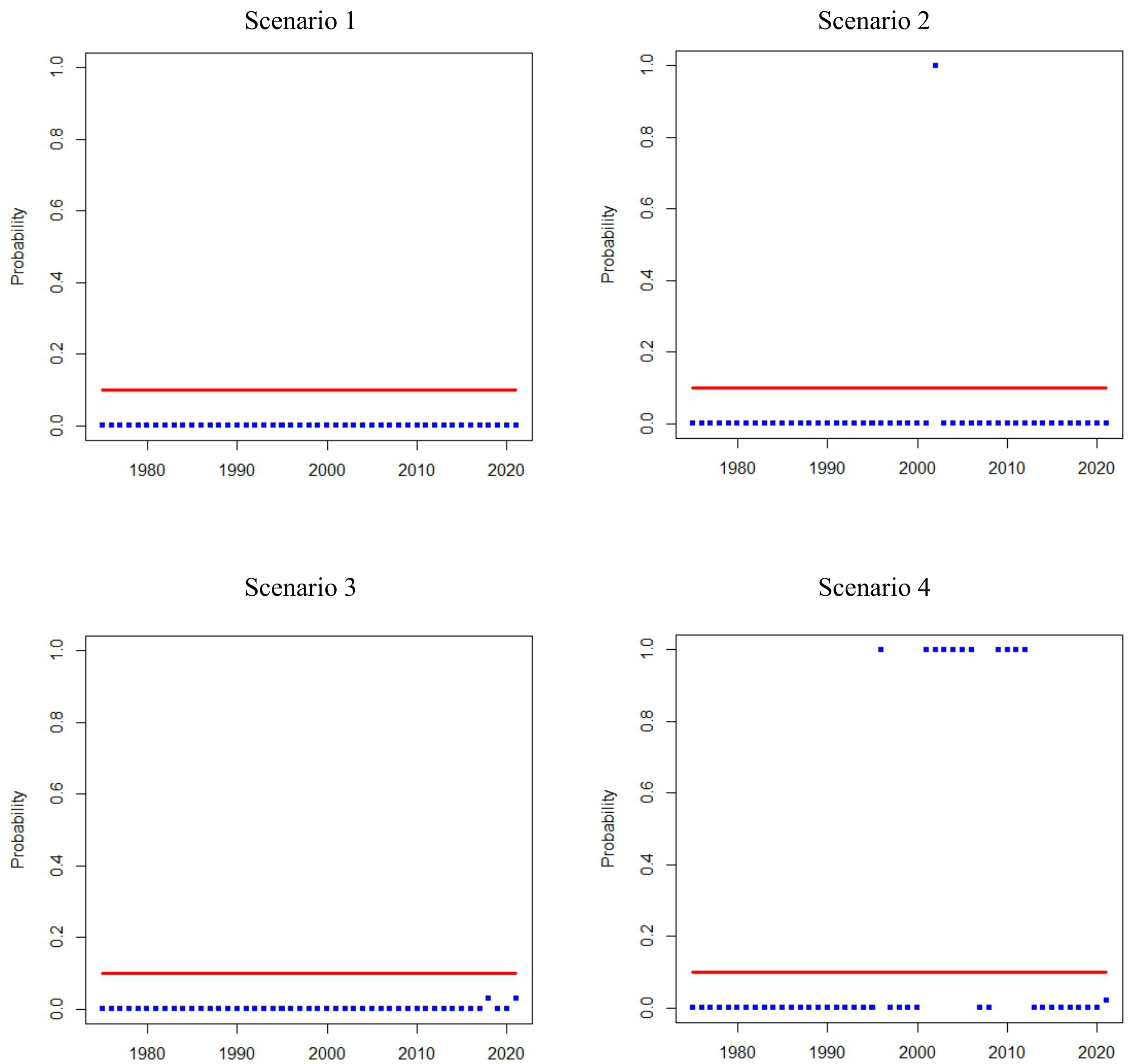

FIGURE 3. The probability (represented by frequency) of the fishing mortality LRP ($F_{0.5R0}$) being exceeded. The red line indicates the probability of 0.1. There is only a single fishing mortality value for the historical period (1975-2012), so the probability is equal to one or zero.

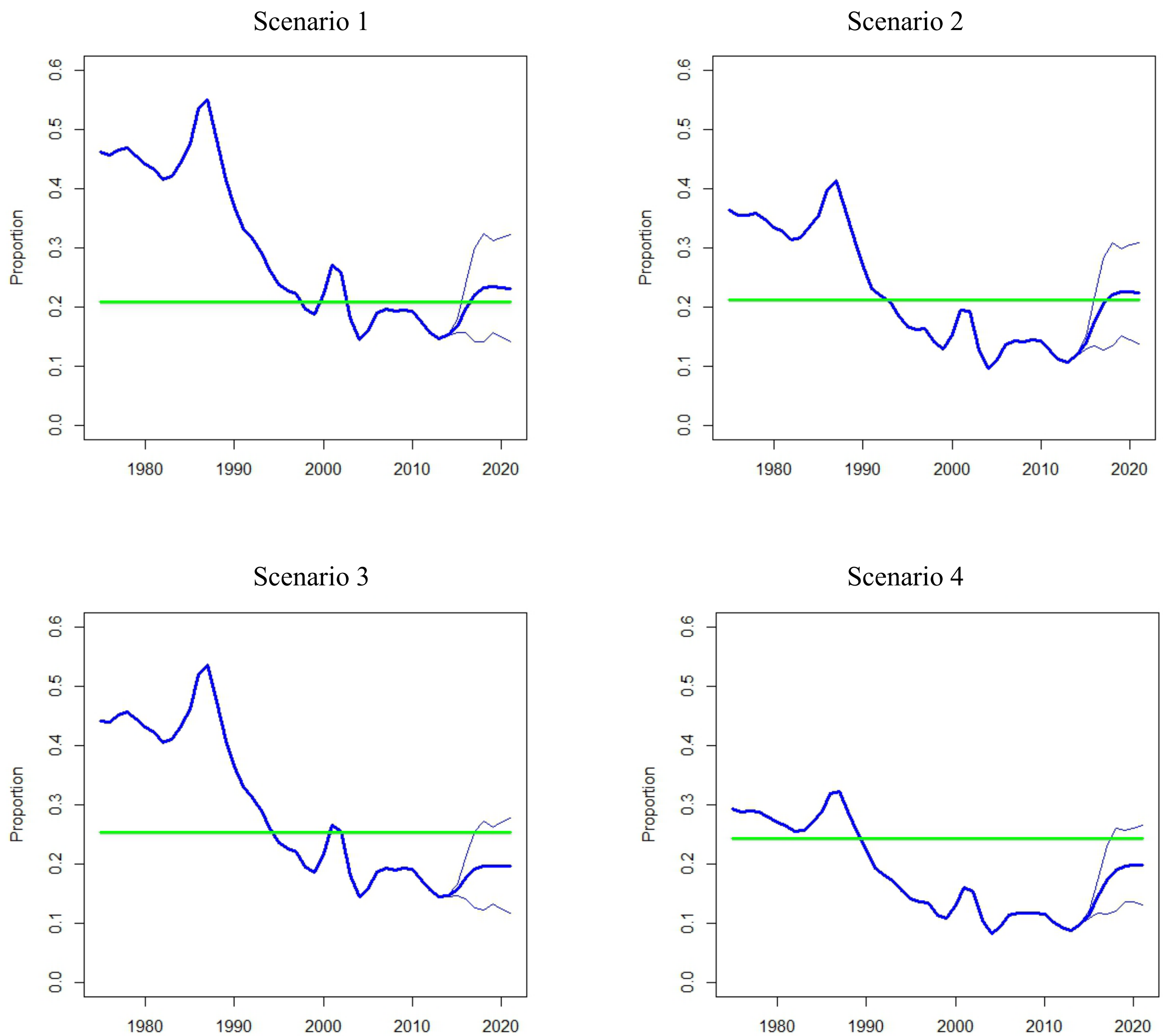

FIGURE 4. Average (thick blue line) and 95% frequency intervals (thin blue line) of the SSB depletion level from the OM. The green line indicates the depletion corresponding to MSY.

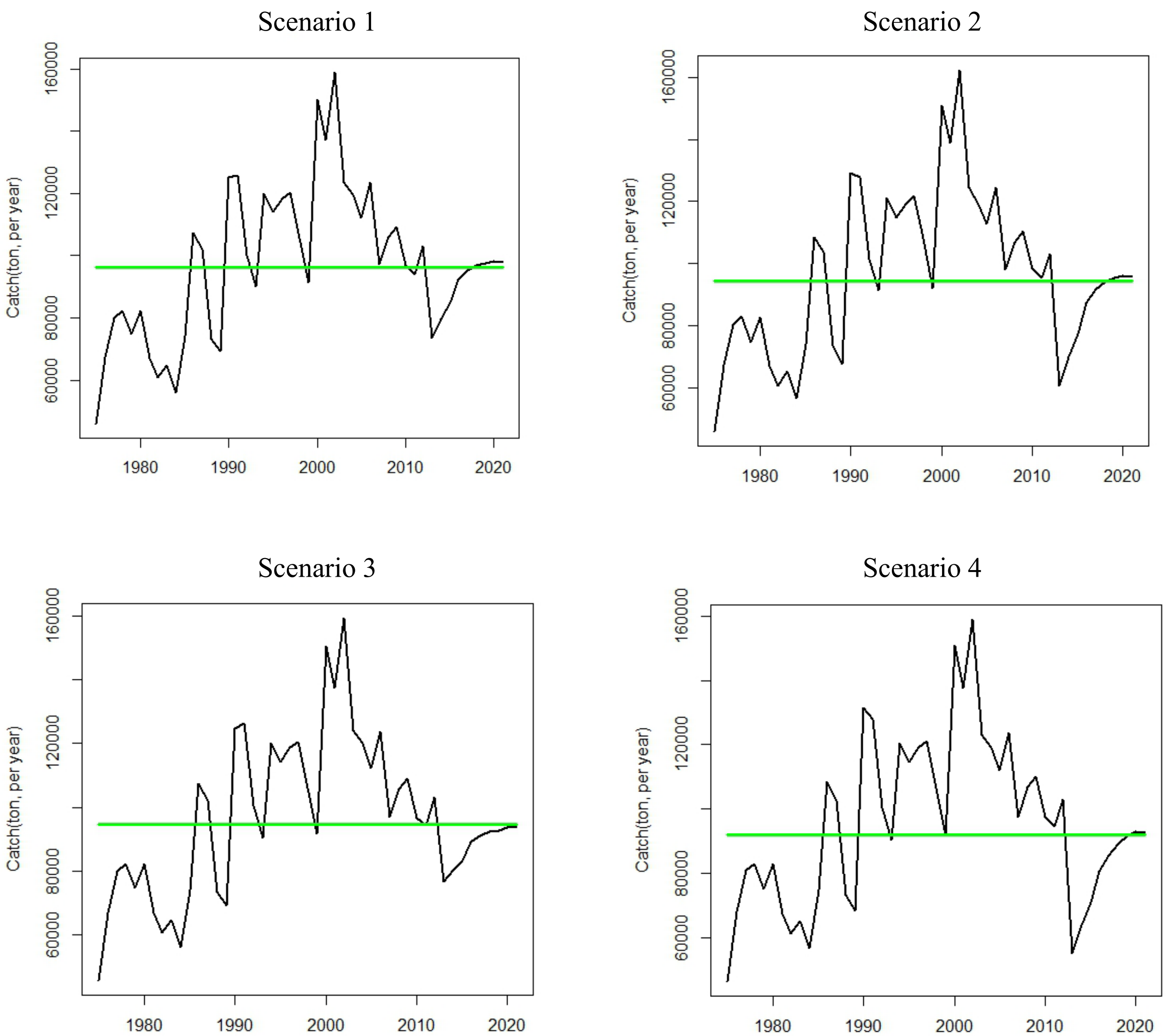

FIGURE 5. Average catch of OM from multiple runs. The green line indicates the MSY level estimated by true F_{MSY} and constant recruitment.

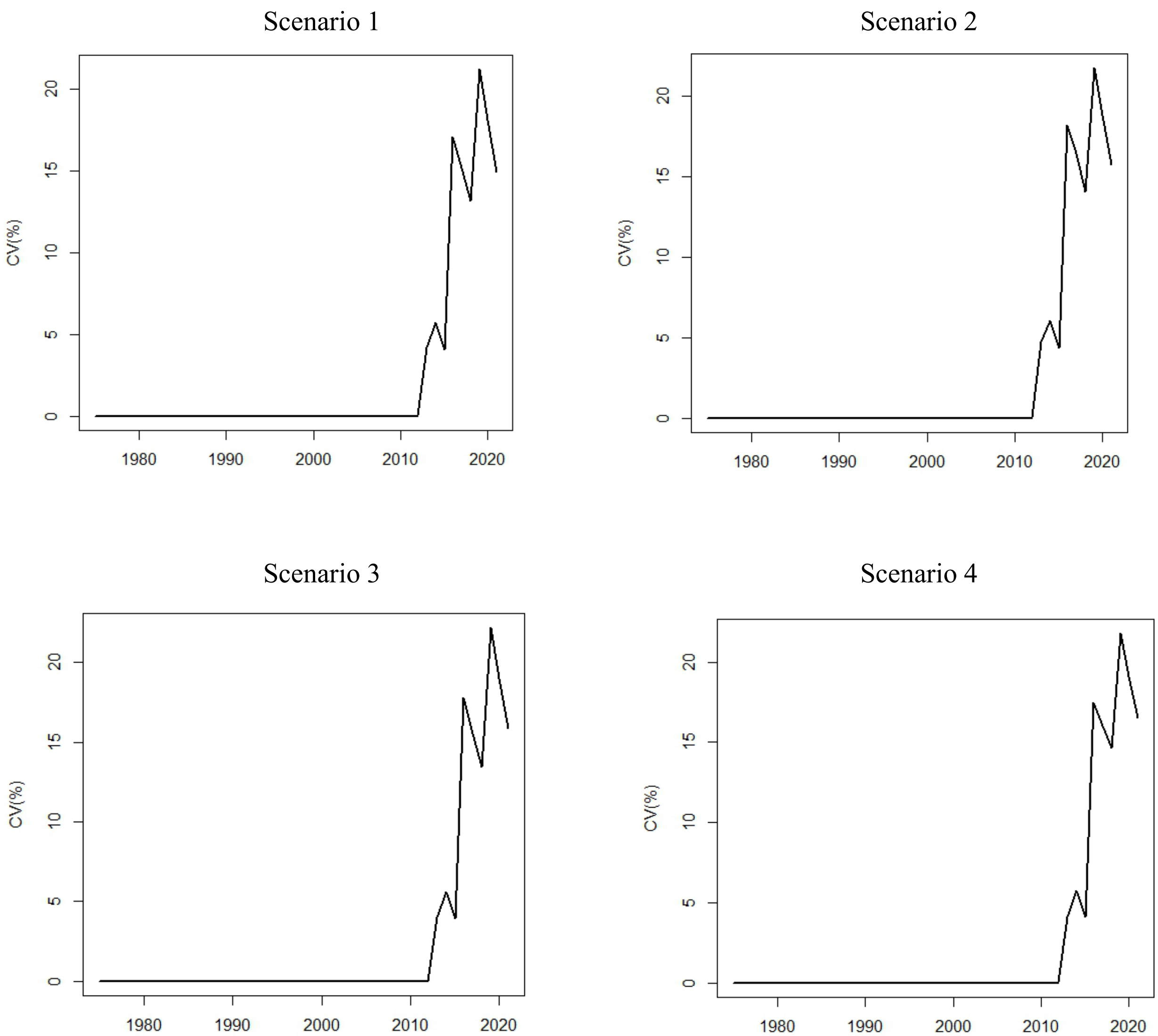

FIGURE 6. Coefficients of variation of catch time series of OM from multiple runs. CV = zero for the historical period because we assume historical data do not change.