

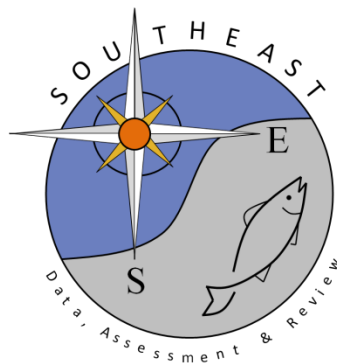
# Evaluating the risks of misspecifying red tide mortality within Gulf grouper stock assessments

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# **Evaluating the consequences of misspecifying red tide mortality within Gulf grouper stock assessments**

Alexandra N. Moller, Lisa Ailloud, Skyler R. Sagarese, Nathan R. Vaughan, and Katie Siegfried

## **Introduction**

The most recent Gulf Gag (SEDAR 72; SEDAR 2021 and SEFSC 2022) and Red Grouper (SEDAR 88; SEDAR 2025) stock assessments use the ‘bycatch fleet’ option in Stock Synthesis (SS) to model episodic red tide mortality. The bycatch fleet acts as a pseudo discard-only fishing fleet with an associated selectivity pattern, which can be configured to operate exclusively in specified years. The stock assessment model then freely estimates the magnitude of annual mortality in the specified non-zero years based on the signal in the input data (e.g., indices, compositions, etc). Previous simulation testing concluded that the bycatch fleet accurately estimates red tide mortality with low error when it is designated in the correct years (Sagarese and Harford 2022). The specific red tide years used for the bycatch fleet have typically been determined using a combination of quantitative and qualitative information. Gulf Grouper assessments have recognized 2005 as the most extreme red tide event in recent history (SEDAR 33; SEDAR 2014, 42; SEDAR 2015). The severity of the 2005 red tide has been consistently supported by the binary index of red tide severity (Walter et al. 2013, Sagarese et al. 2018) and estimates of red tide mortality derived from the West-Florida Shelf (WFS) Ecospace model (Vilas et al. 2023). According to the Ecospace indices, none of the subsequent red tide events in 2014, 2018, and 2021 reached the severity of the 2005 event. However, results from Karnauskas et al.’s (SEDAR61-WP20) and Turley et al.’s (SEDAR72-WP-09) Local Ecological Knowledge (LEK) work showed that fishermen consistently identified 2005, 2014, and 2018 as major red tide events for red and gag grouper mortality. Turley et al. demonstrated that the hypoxia associated with the 2005, 2014, and 2018 red tide events could cause additional mortality that was seen in the LEK research (2022). During the review of SEDAR 72 projections in 2021 (and later in 2022), 2021 was identified as a potentially important red tide year and was modeled as a “medium red tide” for projection purposes, largely informed by results from the WFS Ecospace model (SEDAR 2021 and SEFSC 2022). In 2024, SEDAR 88 established 2021 as a fourth red tide event year based on Topical Working Group (TWG) discussions focused on red tide (SEDAR 2025).

In addition to specifying the years where red tides were severe, the selectivity of the red tide bycatch fleet is typically assumed flat, targeting all ages equally. Estimates of red tide selectivity have been provided at previous red tide TWGs (Vilas et al. 2023), and these age-specific red tide mortalities were used to define year-specific red tide bycatch fleet selectivities for SEDAR 88 (SEDAR 2025). Sensitivity analysis confirmed that the introduction of multiple red tide bycatch fleets with differing selectivities did not substantially change the population estimates or management advice, however it increased model complexity and required additional modifications for running projections.

This study uses simulation to quantify the bias introduced by misspecifying red tide mortality in Gulf grouper stock assessments and the impact of that bias on fishery landings and population abundance estimates. Specifically, we evaluate the consequences of incorrectly identifying event years and determine whether allowing Stock Synthesis to estimate red tide mortality freely in all years serves as an improved

alternative. We also alternated red tide selectivity assumptions to determine how much error is introduced when selectivity is incorrectly parameterized. We used the Management Strategy Evaluation for Stock Synthesis (SSMSE) R-package (Doering et al. 2023) to conduct simulation tests on the SEDAR 61 Red Grouper stock assessment (SEDAR 2019). Using this approach, a known population is simulated using an Operating Model (OM). This OM population is then sampled to produce simulated data sets that inform an Estimation Model (EM) that sets fishery landing targets which are then fed back into the OM in an iterative cycle. The OM parameters were conditioned on the original stock assessment to represent the historical period (1986–2017). The iterative MSE feedback period evaluated in the analyses presented herein spans a 51-year future simulation period (2018–2068).

Simulation testing various red tide event assumptions helps us understand how our assessment models perform by identifying errors from misspecification. Collectively, these experiments aimed to identify the red tide year and selectivity configurations that minimize misspecification bias and error. We then explored the management implications of this error by identifying whether management objectives are realized. By highlighting the potential risks of misspecification, this research supports management with the best available science on how to parameterize red tide mortality (and other episodic events) in stock assessment models.

## Methods

### *SSMSE and Scenarios*

SSMSE is an R-package designed to test management strategies in Stock Synthesis (Doering et al. 2023). It can utilize an existing Stock Synthesis model (such as a base model run from an accepted stock assessment) as the OM, which serves as the simulated truth. The OM consists of a fixed historic period conditioned on the original stock assessment as well as a future simulation period. During the future simulation period SSMSE iterates forward in 3 year steps (user-defined), at each step:

- 1) Past data from the OM is sampled with error and fed into the EM (i.e. the simulated stock assessment model) that can be identical to the OM or differ in structure.
- 2) The EM is fit to this OM sampled data with error and used to estimate management targets (e.g. catch limits).
- 3) These management targets are then fed back into the OM as achieved landings to calculate the population structure for the next 3 years.
- 4) The process is repeated until the end of the simulation period.

Throughout this paper, scenarios are defined by the true OM settings crossed with the assumed EM settings (e.g. no red tide crossed with no red tide (no\_rt\_x\_no\_rt)). We refer to the realized OM, biological response after it has been subjected to the catch limits dictated by our EM, as the achieved OM value or outcomes. While the EM outcomes show us what managers *think* is happening to the stock as a result of our assessment model, the OM outcomes show us what is *actually* happening to the stock. Changes to the EM included altering estimated or fixed parameters. When an OM and an EM match, parameters and fishery reference points are estimated with high mean accuracy and a precision subject to

data sampling uncertainty. When they mismatch, we can quantify the mean bias or error that results from our assumptions not matching reality.

We used the SEDAR 61 Gulf Red Grouper Stock Synthesis model, refit to the expected data, as our base OM (SEDAR 2019). To maintain model consistency, we fixed SigmaR to the value estimated in the stock assessment (0.811). This model was chosen over the Gulf Gag Grouper (SEDAR 72; SEDAR 2021 and SEFSC 2022) and recently completed Gulf Red Grouper (SEDAR 88; SEDAR 2025) models for its efficient runtime and relative simplicity (i.e. its use of a single bycatch fleet with flat selectivity). Red tide events are implemented as a bycatch fleet in Stock Synthesis with flat selectivity where all ages (including age-0) are equally vulnerable to red tide. The historic modeled period (1986-2017) had severe red tide events in 2005 and 2014 and the future simulation period spanned 51 years from 2017 to 2068. For assessment projection purposes, where projections are run following the completion of the historical assessment within the EM, the past 15 years of estimated red tide mortality was averaged and the red tide mortality in the projection was held constant at this value (SEDAR105-WP09). The base OM was manipulated with three frequency assumptions (no red tide, 17 years of red tide, and all years) and four selectivity assumptions (young, mid, old, and flat) to create alternative OMs and EMs. We crossed the OM and EMs in a model matrix illustrated by **Figure 1** resulting in a total of 45 scenarios.

The three red tide frequency assumptions represented two realities and three alternative stock assessment approaches. Our first assumption was no red tide (no\_rt), which would represent a future reality with no red tide events (OM) or a stock assessment assumption of no red tide events (i.e., no bycatch fleet) (EM). Our second assumption had 17 random red tide events over the 51 year simulation period. The average magnitude of the red tide mortality assumed in the OM was 0.1 which is considered a moderate red tide event (SEDAR 88; SEDAR 2025). In the EM, the same 17 red tide years are specified, but the magnitude is estimated. The final assumption allowed the EM to estimate red tide mortality in all years of the future simulation period. Matching red tide frequency assumptions in the OM and EM allowed us to quantify the effects of the selectivity assumptions and vice versa.

We developed four red tide selectivity assumptions that were applied to both OMs and EMs. To test alternative selectivity assumptions, we reran the base OM with age-based selectivity curves that target young, middle (mid), or old individuals as illustrated in **Figure 2**. The mid selectivity represented a domed curve where all ages could be targeted by red tide but ages 1–4 are more impacted than ages 0 and 5+. The young and old selectivity assumptions target ages 4 and under or 5 and up, respectively. The flat selectivity represented the status quo as the current selectivity assumed for red tides for gag grouper and the SEDAR 61 red grouper model (SEDAR 2018).

We ran 100 iterations for each of the 45 scenarios. To ensure comparability, the random seed for red tide event years and magnitudes for a given iteration was fixed across scenarios. If any of the model runs within an iteration had a gradient greater than 1, the entire iteration for that specific scenario was removed to prevent poorly converged runs from skewing results. There were 79 iterations removed across 12 scenarios as listed in **Table 1**.

### *Residual Error & SSB Ratio*

To compare scenarios, we used the same error metrics for all experiments: Residual Error (RE), Percent Residual Error, and Total Removals as a percentage. Error was evaluated across three removal types – total catches from the recreational and commercial sectors and dead discards from the red tide. The vertical line and longline fleets were summed to get the commercial fleet total removals. The recreational fleet total removals were already represented by a single fleet in the stock assessment and is composed of headboat, charterboat, private and shore modes. The trap fleet was closed in 2007 and therefore was not active in our simulation period. We calculated the residual error (in million of tons, MT) for each removal type using the equation:

$$\text{Residual error} = \text{OM}_{\text{removal\_type}} - \text{EM}_{\text{removal\_type}}$$

Next we calculated the percent residual error, or percent bias using the equation:

$$\% \text{ Residuals} = (\text{OM}_{\text{removal\_type}} - \text{EM}_{\text{removal\_type}}) / \text{OM}_{\text{removal\_type}} * 100$$

To allow us to compare scenarios with all removals included in the % error, we used this equation:

$$\text{Total Removals \%} = \sum(\text{OM}_{\text{removal\_type}} - \text{EM}_{\text{removal\_type}}) / \sum \text{OM}_{\text{removal\_type}} * 100$$

All three error metrics were calculated over the 2018-2022 time period to demonstrate short term effects from the first five years on the fishery.

For each scenario, we extracted the achieved SSB Ratio (annual SSB/ unfished SSB) from the OM and plotted the median SSB Ratio with 95% confidence intervals over time to explore management implications. In SSMSE, the management benchmarks were estimated using a maximum sustainable yield (MSY) proxy of 30% spawning potential ratio (SPR30%) which would produce an equivalent 0.3 SSB Ratio given that steepness is assumed equal to 1.

## **Results**

SSMSE accurately simulated red tide mortality in matched scenario self-tests, providing a baseline to quantify bias in mismatched scenarios (**Figure 3**). In mismatched scenarios, the impact depended on the nature of the mis-specification: assuming no red tide when they actually existed caused severe underestimation of mortality, whereas assuming red tides when none occurred resulted in negligible mortality estimates (**Figure 4**). When the OM specified 17 red tide years, allowing the EM to estimate red tide mortality across all years yielded average red tide mortality estimates that were nearly identical to when the EM was correctly specified (**Figures 5**).

### *No Red Tide*

When there is no red tide in the OM, the closest scenario to achieving the target SSB Ratio (0.3) is the matching EM where there is no red tide (no\_rt). The achieved SSB Ratio over time for all scenarios when

there are no red tide events in the OM are presented in **Figure 6**. All red tide selectivity scenarios exceed the SSB Ratio target, which may result in foregone yield. Old, mid and flat selectivities fall closest to the target ( $\sim 0.32$ ), with young selectivity achieving SSB ratios close to 0.35.

When there are no red tide events in the OM and we assume there are in the EM, there are minimal errors. For the scenarios listed in **Table 2** there are no red tide events in the OM and all of the scenarios have very similar errors regardless of their red tide selectivity or frequency assumptions in the EM. The commercial and recreational removals all have a similar level of bias to the matching scenarios ( $\sim 1\%$  commercial; 1.2-3.9% recreational). The total removals all have positive error suggesting an overestimation of red tide, which is expected because red tide does not exist in reality, so when estimating any, it will be more than expected. The overestimation of total removals ranges from 1.2-6.6%, with most scenarios within 5%.

The most error occurs in the scenarios where there are red tide events in the OM but not in the EM (**Table 3**). Red tides selecting for older fish in the OM but assessing the stock as if red tide did not occur (old\_x\_no\_rt) was the worst case scenario, and all of the scenarios with no red tide in the EM followed that trend. Total removal errors for these scenarios range from -6.1% when red tides select younger fish in the OM to -8.8% when red tides select older fish in the OM. In all of these scenarios, the EM attempted to explain the increased mortality due to red tide by overestimating recreational removals by 7.7% to 10.5%. Despite being able to explain the additional depletion by overestimating recreational removals, all these scenarios failed to reach the target SSB Ratio of 0.3 as this additional mortality could not be accounted for in EM OFL projections (**Figure 7**).

### *Selectivity*

When the red tide selectivity is matching between the OM and the EM, we see minimal error in estimated values between the EM and OM and achieve target stock status in the OM (**Table 4**). Low error is displayed for commercial ( $\sim 0.6\%$ ), recreational (1.7 to 4.6%), and total removals (0.1-3.1%). Error in red tide removals is more variable and ranges from -32.6% to 3.2%. Between the two frequency assumptions of 17 random red tide years (rt\_17) vs. the EM estimating red tide in all years (all\_yrs), the all years scenarios estimated red tide removals with higher accuracy, unless the red tide selected for younger fish. In the young\_x\_young\_all\_yrs scenario, the red tide removals were overestimated by  $\sim 20\%$ , potentially because of the number of iterations removed for non-convergence. The achieved SSB Ratios for all of the matching scenarios tend to be closest to the target SSB Ratio of 0.3 for the 17 random red tide years (**Figure 8**) and for red tide in all years (**Figure 9**). The least total removals error, across all 45 scenarios, is in the flat\_x\_flat\_all\_yrs scenario (0.1%). The nearly zero error comes from an overestimation of recreational removals at 3.3% and an underestimation of commercial and red tide removals at -0.6% and -5.4%, respectively.

When the red tide selectivity is mismatching between the OM and the EM, we see minimal error but some management implications. Overall, the commercial and recreational errors were generally within 1% and 5%, at similar levels to the matching scenarios (**Tables 5 and 6**). Two exceptions were young\_x\_old\_rt\_17 which had 7.2% recreational error and old\_x\_young\_rt\_17 which had -7.5% total error (**Table 5**). Because both scenarios represent completely opposite selectivity assumptions, these

results suggest that severe mis-specification of red tide selectivity can meaningfully increase error in removal estimates.

Error in red tide removals was more variable when the red tide selectivity was mismatched between the OM and EM. In every scenario with the all\_yrs EM assumption and the OM selecting younger fish, the red tide removals were overestimated by more than 43.3% (**Table 6**). These scenarios all had high total error relative to the matching scenarios, ranging from 7.1%-8.2% (**Table 6**). Since red tide removal error varies depending on the OM, it would suggest that the selectivity assumption is important, especially in the absence of red tide frequency information.

Evaluating the achieved SSB Ratio of the different red tide selectivity scenarios under two EM frequency assumptions reveals slightly different trends. **Figure 8** illustrates the SSB Ratio over time for the 17 random red tide year scenarios when the EMs only estimated red tide mortality in the correct 17 random years. Across all OMs, matched OM-EM selectivity configurations and assuming young selectivity in the EM consistently maintained the median SSB ratio closest to the target SSB Ratio of 0.3. Assuming flat or middle selectivity in the EM yielded intermediate performance, closely tracking the target across panels. Conversely, assuming old selectivity or omitting red tide entirely consistently failed to reach the SSB target across all operating models.

Similar trends emerged when the EM is allowed to estimate red tide mortality across all years (**Figure 9**). Across all OMs, assuming mid or flat selectivity in the EM maintained median SSB ratios consistently close to the target SSB Ratio of 0.3, with matched OM-EM configurations again providing the most accurate results. The EMs assuming young selectivity consistently result in an SSB ratio of nearly 0.4, which is ~30% above the target, suggesting foregone yield, even in the scenario where the OM and EM match. Assuming old selectivity or omitting red tide entirely resulted in a persistent downward bias, consistently failing to reach the 0.30 target.

## Discussion

Evaluating red tide assumptions within a simulation framework provides critical insight into assessment model performance, helping quantify bias from misspecification to ultimately improve management advice. Our findings demonstrate that excluding red tide mortality from the stock assessment model when events did in fact occur consistently resulted in overestimated recreational removals and SSB ratios below target levels. Similar trends were identified in Sagarese and Harford 2022, and our results emphasize the importance of accounting for red tide mortality in our Gulf grouper assessments. Not accounting for red tide mortality in the assessment model when events did occur was the worst-case scenario for management because it resulted in the stock being consistently depleted below target SSB levels and incorrectly estimated recreational fishery overages to be the cause. This is likely to result in lower true yields for both recreational and commercial fisheries and potential penalties on the recreational sector for overages that did not actually occur.

Allowing stock assessments to estimate red tide mortality freely in all years alleviates one of the biggest concerns with the current fixed year approach - the need to identify years where red tides were severe enough to cause mass mortality. When red tide was estimated in all years, the commercial removals and

total removals bias were consistent with their respective known years cases when selectivities were matching, and the red tide and recreational removals had less bias for all selectivity assumptions except for young. This may have been due to the instability of the models with young selectivity like young\_x\_young\_all\_yrs having the most iterations removed from the analysis. One potential explanation for instability in the young selectivity cases could be due to lack of sufficient contrast in the data to estimate recruitment and red tide mortality on age zero individuals simultaneously. Under the all years frequency assumption, excluding the young selectivity assumption in the OM, red tide estimates were improved in the short-term, with more accurate estimates of the amount of fish removed by red tide events without having to designate the years. Considering that flat\_x\_flat\_all\_yrs scenario (0.1%) has the least error, it suggests that Stock Synthesis largely balances an underestimation of red tide mortality with an overestimation of recreational removals, which is possible because of the higher and more flexible CV on the recreational fleet. This result is encouraging for the simpler assumption of flat red tide selectivity, currently the status quo for the gag grouper stock assessment, where all of these errors are close to or within 5%. Additionally, the mid and flat selectivities had the same achieved SSB Ratio near 0.3 under both the 17 random red tide years and all years frequency assumptions scenarios, suggesting that estimating red tide mortality in all years does not significantly affect the SSB which would lead to similar management reference points.

Our all years simulations differ from the results of Sagarese and Harford, where their alternative historical model with estimated red tide mortality in all years (1986-2017) had highly biased estimates of terminal fishing mortality and SSB. The EMs in our simulation analysis only estimated red tide in the correct years during the historic conditioning period, and our EM scenarios only differed in which years red tide mortality was estimated during the simulation period (2018-2047). This restricted “all years” estimation may have allowed the historic period to provide sufficient contrast to estimate critical stock productivity values like  $R_0$ . It is also possible that the SSMSE data sampling method may have made the EMs more robust at estimating the magnitude of the red tide mortality than could be expected in a real stock assessment due to increased contrast in the bootstrapped values that only included observation error in the data streams. It would be beneficial for SEDAR 105 to consider multiple scenarios where red tide mortality is estimated in different ranges of historical years to see whether the assessment model picks up on past red tide events, particularly in earlier years before satellite data were available to identify red tides (see Blake et al. 2022 for a reconstructed timeline). The red grouper assessment model covers a more limited but data-rich time series from 1986-2017, so additional investigation is likely needed on which historical years to allow estimation of red tide mortality given the longer time series for gag grouper (1963-2024).

Assessing the scenarios with matching and mismatching selectivity confirmed that red tides targeting specific age groups could change management advice and highlighted a need for additional research on selectivity trends. Mismatching scenarios had much higher error than the matching scenarios, with the most extreme mismatches (i.e. young\_x\_old\_rt\_17 and old\_x\_young\_rt\_17) having higher recreational (7.2%) or higher red tide removals (-56.8%) than expected. Interpreting these red tide error results between selectivity scenarios is difficult, as removals in weight are not equivalent between ages (i.e. If the OM had 10,000 age zero to two fish die but the misspecified EM selectivity assigned that to age three to four fish it would require a significantly larger mortality by weight to result in the correct abundance of age five and six fish in future years). In general however, when the OM selected for younger fish, the red

tide removals were overestimated and their respective SSB Ratios exceeded 0.3, suggesting underexploitation and foregone yield. Based on these extreme cases and the sensitivity of young selectivity, we would recommend continuing the status quo of a flat selectivity curve.

While turning on the bycatch fleet in all years allows Stock Synthesis to account for red tide mortality, it also inherently accounts for any other source of episodic mortality currently unaccounted for in the stock assessment. This capacity may account for the past limitations observed in attempting to utilize externally derived red tide magnitude estimates directly within stock assessments (SEDAR 88; SEDAR 2025).

While active blooms produce toxins harmful to Gulf Groupers, the subsequent hypoxia associated with these events can also lead to mass mortality events. Turley et al. found that hypoxic conditions were seen in 2005, 2008-2011, 2014-2016, and 2019, in coastal regions that could affect Gulf Gag and Red Groupers (2022, SEDAR 72-WP-10). Because previously mentioned indices and bycatch fleet configurations have focused exclusively on parameterizing red tide mortality, these hypoxic events, which occur in years without modeled red tide mortality, may be poorly accounted for in previous stock assessments or be confounded with red tide mortality in the years it is estimated. Similarly, mass mortality events have been documented following cold snaps (e.g. 2010) for Goliath Groupers (SEDAR 47; SEDAR 2016). If the red tide fleet is turned on in all years, it may be appropriate to call it an “extra mortality” fleet. Large mortality events estimated in future assessments using this extra mortality fleet would need to be validated from observations, Ecospace model results, or LEK.

Our tentative recommendations for SEDAR 105 are to consider running the Gag Grouper stock assessment with red tide turned on in all years and validating the red tide magnitude and frequency with external observations. This will allow Stock Synthesis to estimate external environmental mortality in all years and may capture die-offs that were not previously considered. Specifically, the Ecospace red tide mortality index (Chagaris 2025) and LEK of red tides (Turley et al. 2021) could help validate red tide events. Additional resources would likely need to be reviewed as well to validate other potential drivers of mortality not attributed to red tides, such as the Gulf Ecosystem Status Report (Karnauskas et al. 2017). Future analysis should focus on applying this work to the Gag Grouper Stock Synthesis model to see whether similar outcomes are obtained.

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## Tables and Figures

**Table 1. The list of scenarios with non-converged runs.** Iterations with gradients greater than 1 were removed from the analysis and listed in the table below with the number of iterations removed out of 100.

| Scenario (OM x EM)    | Removed iterations (%) |
|-----------------------|------------------------|
| young_x_young_all_yrs | 26                     |
| young_x_young_rt_17   | 14                     |
| flat_x_young_all_yrs  | 12                     |
| mid_x_young_all_yrs   | 11                     |
| old_x_young_all_yrs   | 5                      |
| mid_x_young_rt_17     | 3                      |
| flat_x_young_rt_17    | 2                      |
| young_x_mid_all_yrs   | 2                      |
| flat_x_no_rt          | 1                      |
| mid_x_mid_all_yrs     | 1                      |
| mid_x_mid_rt_17       | 1                      |
| old_x_young_rt_17     | 1                      |

**Table 2. The proportional bias of commercial, recreational, and red tide removals from 2018-2022 for the scenarios with no red tide in the OM.** Each residual error percentage represents the proportional bias in a negative (red) or positive (green) direction when summed across the first 5 simulation years (2018-2022). The total proportion of removals demonstrates that while the red tide removals could not be calculated, they result in overestimated total removals.

| Scenario              | Commercial Removals Bias (%) | Recreational Removals Bias (%) | Red Tide Removals Bias (%) | Total Removals Bias (%) |
|-----------------------|------------------------------|--------------------------------|----------------------------|-------------------------|
| no_rt_x_flat_all_yrs  | -1.0                         | 1.9                            | -                          | 4.8                     |
| no_rt_x_flat_rt_17    | -0.9                         | 2.6                            | -                          | 3.1                     |
| no_rt_x_mid_all_yrs   | -1.0                         | 1.5                            | -                          | 5.3                     |
| no_rt_x_mid_rt_17     | -0.9                         | 2.5                            | -                          | 3.3                     |
| no_rt_x_no_rt         | -1.0                         | 3.9                            | -                          | 1.2                     |
| no_rt_x_old_all_yrs   | -1.1                         | 1.9                            | -                          | 5.6                     |
| no_rt_x_old_rt_17     | -0.9                         | 2.7                            | -                          | 3.2                     |
| no_rt_x_young_all_yrs | -0.8                         | 1.2                            | -                          | 6.6                     |
| no_rt_x_young_rt_17   | -0.9                         | 2.1                            | -                          | 4.1                     |

**Table 3. The proportional bias of commercial, recreational, and red tide removals from 2018-2022 for the scenarios with no red tide in the EM.** Each residual error percentage represents the proportional bias in a negative (red) or positive (green) direction when summed across the first 5 simulation years (2018-2022). The red tide removal bias was -100% because the red tides were completely underestimated. The total removal bias demonstrated that Stock Synthesis tried to balance out the underestimated red tide removals with increased recreational removals but the total removals were still underestimated.

| Scenario      | Commercial Removals Bias (%) | Recreational Removals Bias (%) | Red Tide Removals Bias (%) | Total Removals Bias (%) |
|---------------|------------------------------|--------------------------------|----------------------------|-------------------------|
| flat_x_no_rt  | 0.1                          | 8.8                            | -100.0                     | -8.1                    |
| mid_x_no_rt   | 0.2                          | 9.1                            | -100.0                     | -8.0                    |
| old_x_no_rt   | -0.1                         | 7.7                            | -100.0                     | -8.8                    |
| young_x_no_rt | 0.6                          | 10.5                           | -100.0                     | -6.1                    |

**Table 4. The proportional bias of commercial, recreational, and red tide removals from 2018-2022 for the scenarios with matching red tide selectivity assumptions.** Each residual error percentage represents the proportional bias in a negative (red) or positive (green) direction when summed across the first 5 simulation years (2018-2022). There was minimal error in the commercial and recreational removals when the red tide selectivity assumptions matched and the two frequency assumptions had similar results. The largest difference was in the young\_x\_young scenarios because they had the most iterations removed for non-convergence.

| <b>Scenario</b>       | <b>Commercial Removals Bias (%)</b> | <b>Recreational Removals Bias (%)</b> | <b>Red Tide Removals Bias (%)</b> | <b>Total Removals Bias (%)</b> |
|-----------------------|-------------------------------------|---------------------------------------|-----------------------------------|--------------------------------|
| flat_x_flat_rt_17     | -0.6                                | 4.1                                   | -20.9                             | -1.8                           |
| mid_x_mid_rt_17       | -0.5                                | 3.7                                   | -14.9                             | -1.1                           |
| old_x_old_rt_17       | -0.5                                | 4.6                                   | -32.6                             | -3.5                           |
| young_x_young_rt_17   | -0.6                                | 3.1                                   | 1.9                               | 1.1                            |
| flat_x_flat_all_yrs   | -0.6                                | 3.3                                   | -5.4                              | 0.1                            |
| mid_x_mid_all_yrs     | -0.6                                | 2.7                                   | 3.2                               | 1.2                            |
| old_x_old_all_yrs     | -0.7                                | 3.4                                   | -11.1                             | -0.8                           |
| young_x_young_all_yrs | -0.8                                | 1.7                                   | 19.8                              | 3.1                            |

**Table 5. The proportional bias of commercial, recreational, and red tide removals from 2018-2022 for the scenarios with mismatching red tide selectivity assumptions and 17 random red tide events.**

Each residual error percentage represents the proportional bias in a negative (red) or positive (green) direction when summed across the first 5 simulation years (2018-2022). The most extreme biased scenarios were old\_x\_young underestimating red tide removals and young\_x\_old overestimating recreational removals. because the OM and EMs targeted opposite fish ages.

| <b>Scenario</b>    | <b>Commercial Removals Bias (%)</b> | <b>Recreational Removals Bias (%)</b> | <b>Red Tide Removals Bias (%)</b> | <b>Total Removals Bias (%)</b> |
|--------------------|-------------------------------------|---------------------------------------|-----------------------------------|--------------------------------|
| flat_x_young_rt_17 | -0.7                                | 3.5                                   | -38.9                             | -4.9                           |
| mid_x_young_rt_17  | -0.6                                | 3.1                                   | -35.3                             | -4.5                           |
| old_x_young_rt_17  | -0.6                                | 4.0                                   | -56.8                             | -7.5                           |
| flat_x_mid_rt_17   | -0.6                                | 3.9                                   | -18.6                             | -1.6                           |
| old_x_mid_rt_17    | -0.6                                | 4.1                                   | -37.6                             | -4.5                           |
| young_x_mid_rt_17  | -0.4                                | 3.8                                   | 28.0                              | 5.0                            |
| flat_x_old_rt_17   | -0.4                                | 5.4                                   | -29.5                             | -2.4                           |
| mid_x_old_rt_17    | -0.3                                | 5.5                                   | -29.2                             | -2.3                           |
| young_x_old_rt_17  | -0.1                                | 7.2                                   | -17.1                             | 0.5                            |
| mid_x_flat_rt_17   | -0.5                                | 4.1                                   | -16.8                             | -1.2                           |
| old_x_flat_rt_17   | -0.6                                | 4.2                                   | -37.2                             | -4.4                           |
| young_x_flat_rt_17 | -0.4                                | 4.4                                   | 21.3                              | 4.2                            |

**Table 6. The proportional bias of commercial, recreational, and red tide removals from 2018-2022 for the scenarios with mismatching red tide selectivity assumptions and red tide events in any year.**

Each residual error percentage represents the proportional bias in a negative (red) or positive (green) direction when summed across the first 5 simulation years (2018-2022). The highest error was in scenarios where red tides selected young fish in the OM, where the red tide removals were overestimated, leading to high total removal bias.

| <b>Scenario</b>      | <b>Commercial Removals Bias (%)</b> | <b>Recreational Removals Bias (%)</b> | <b>Red Tide Removals Bias (%)</b> | <b>Total Removals Bias (%)</b> |
|----------------------|-------------------------------------|---------------------------------------|-----------------------------------|--------------------------------|
| flat_x_young_all_yrs | -1.0                                | 1.7                                   | -19.1                             | -2.9                           |
| mid_x_young_all_yrs  | -1.0                                | 1.8                                   | -15.4                             | -2.3                           |
| old_x_young_all_yrs  | -1.1                                | 2.0                                   | -35.6                             | -5.6                           |
| flat_x_mid_all_yrs   | -0.7                                | 2.9                                   | -0.8                              | 0.6                            |
| old_x_mid_all_yrs    | -0.7                                | 3.2                                   | -22.4                             | -2.7                           |
| young_x_mid_all_yrs  | -0.5                                | 2.0                                   | 55.7                              | 8.2                            |
| flat_x_old_all_yrs   | -0.6                                | 3.7                                   | 1.8                               | 1.4                            |
| mid_x_old_all_yrs    | -0.6                                | 3.8                                   | 4.5                               | 1.8                            |
| young_x_old_all_yrs  | -0.5                                | 4.2                                   | 43.3                              | 7.1                            |
| mid_x_flat_all_yrs   | -0.6                                | 3.2                                   | -0.3                              | 0.8                            |
| old_x_flat_all_yrs   | -0.7                                | 3.4                                   | -25.3                             | -3.0                           |
| young_x_flat_all_yrs | -0.5                                | 2.9                                   | 47.9                              | 7.4                            |

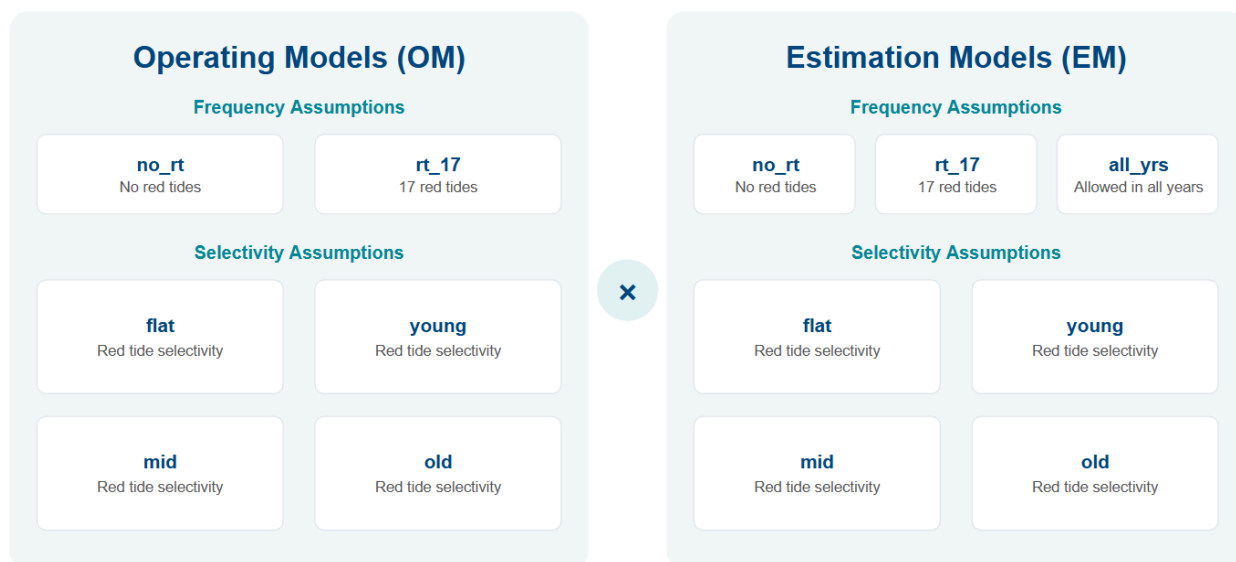


**Figure 1. Diagram of the Frequency and Selectivity assumption options for red tides in the OM and EMs.** Each OM and EM frequency and selectivity assumption were crossed, resulting in 45 total scenarios. Frequency assumptions included no red tide (no\_rt), 17 years of red tide (rt\_17), and estimating red tide in all years (all\_yrs). Red tide selectivity assumptions included flat, young, mid, and old selectivity curves illustrated in Figure 2.

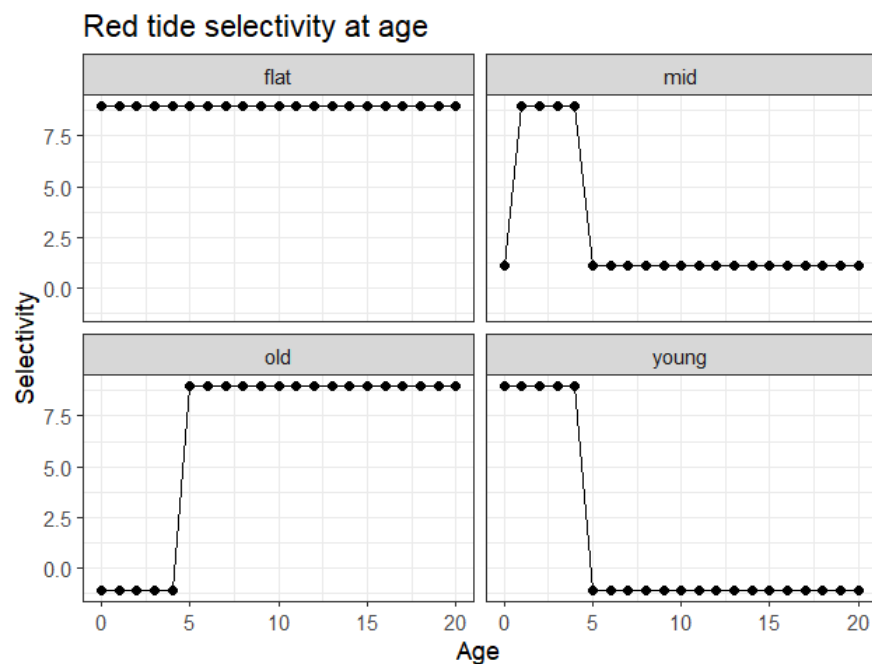


**Figure 2. The four red tide selectivity-at-age curves used as selectivity assumptions.** The flat curve is the current status quo. The mid curve targets primarily middle aged fish from 1-4 years. The old and young curves target older (5+ years) and younger (0-4 years) fish, respectively.

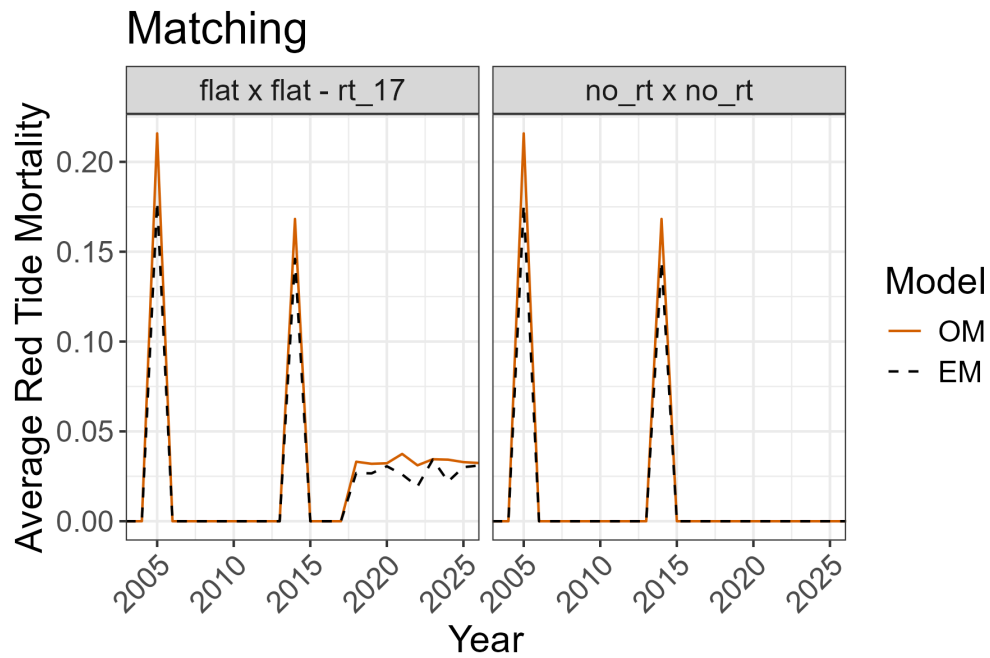


**Figure 3. Average red tide mortality over time for matching scenarios.** Two example scenarios with matching OM and EM frequency assumptions are shown, displaying the average red tide mortality in the OM (orange, solid) and EM (black, dashed).

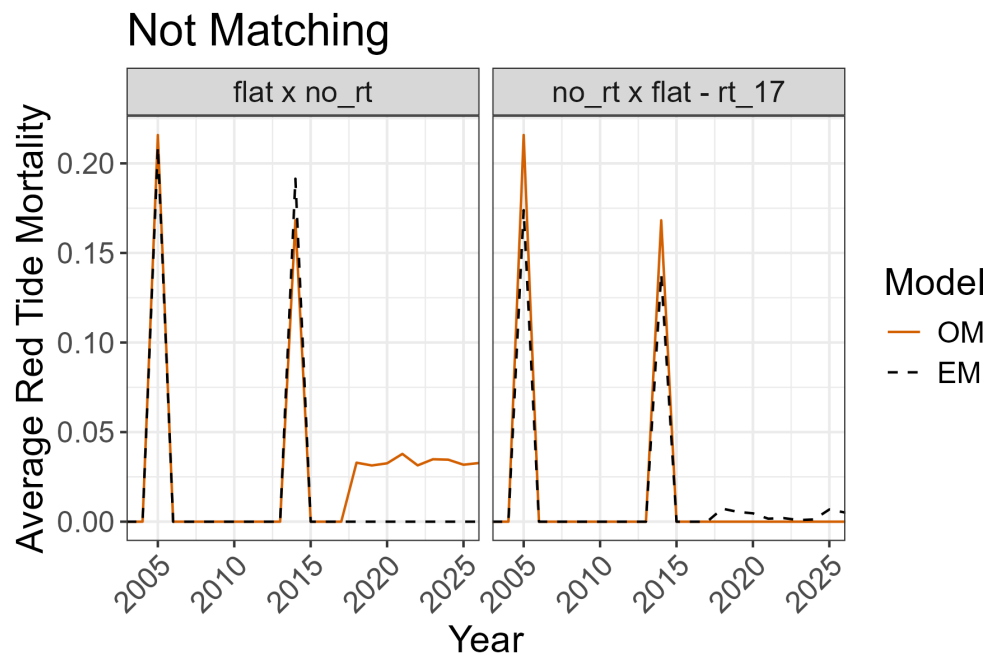


**Figure 4. Average red tide mortality over time for mismatching scenarios.** Two example scenarios with mis-matching OM and EM frequency assumptions are shown, displaying the average red tide mortality in the OM (orange, solid) and EM (black, dashed).

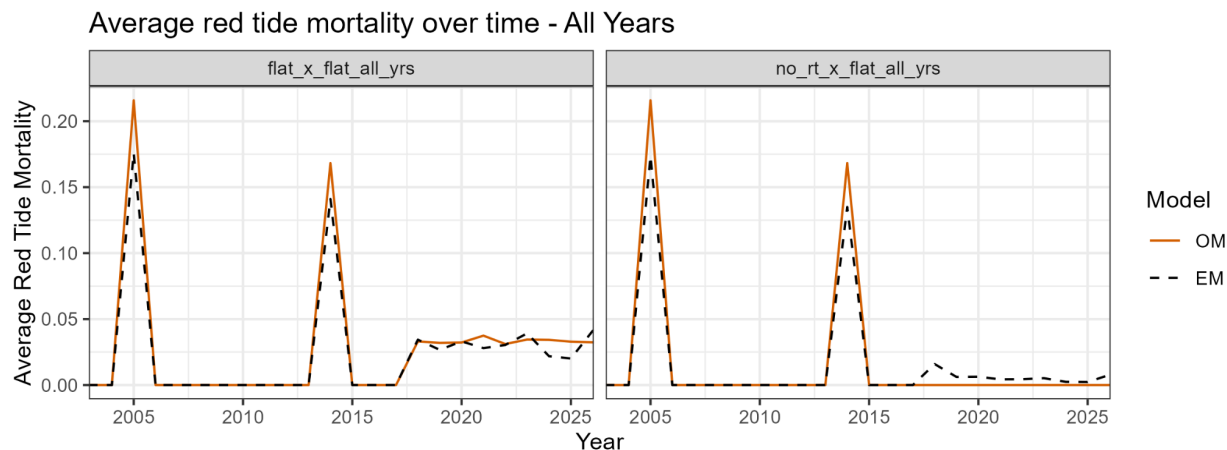


**Figure 5. Average red tide mortality over time for scenarios with the all years frequency assumption.** Two example scenarios with the all years frequency assumption in the EM are shown, displaying the average red tide mortality in the OM (orange, solid) and EM (black, dashed).

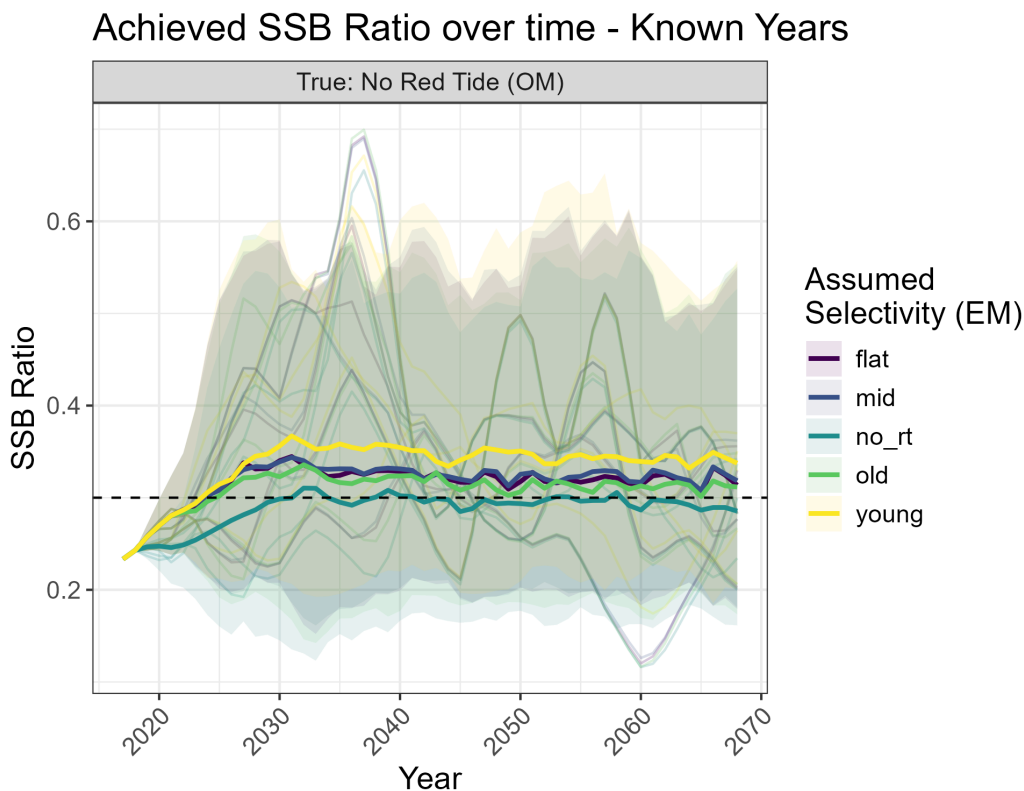


**Figure 6. Achieved SSB Ratio (annual SSB / unfished SSB) over time across scenarios with 17 red tide events.** Thick solid lines show the median SSB Ratio across 100 iterations of the Operating Model (OM), color-coded by the Estimation Model's (EM) assumed red tide selectivity. Thin transparent lines show individual results for the first 5 iterations of each scenario. Shaded regions represent 95% confidence intervals, and the dashed black line indicates the 0.3 SSB Ratio management target.

## Achieved SSB Ratio over time - Known Years

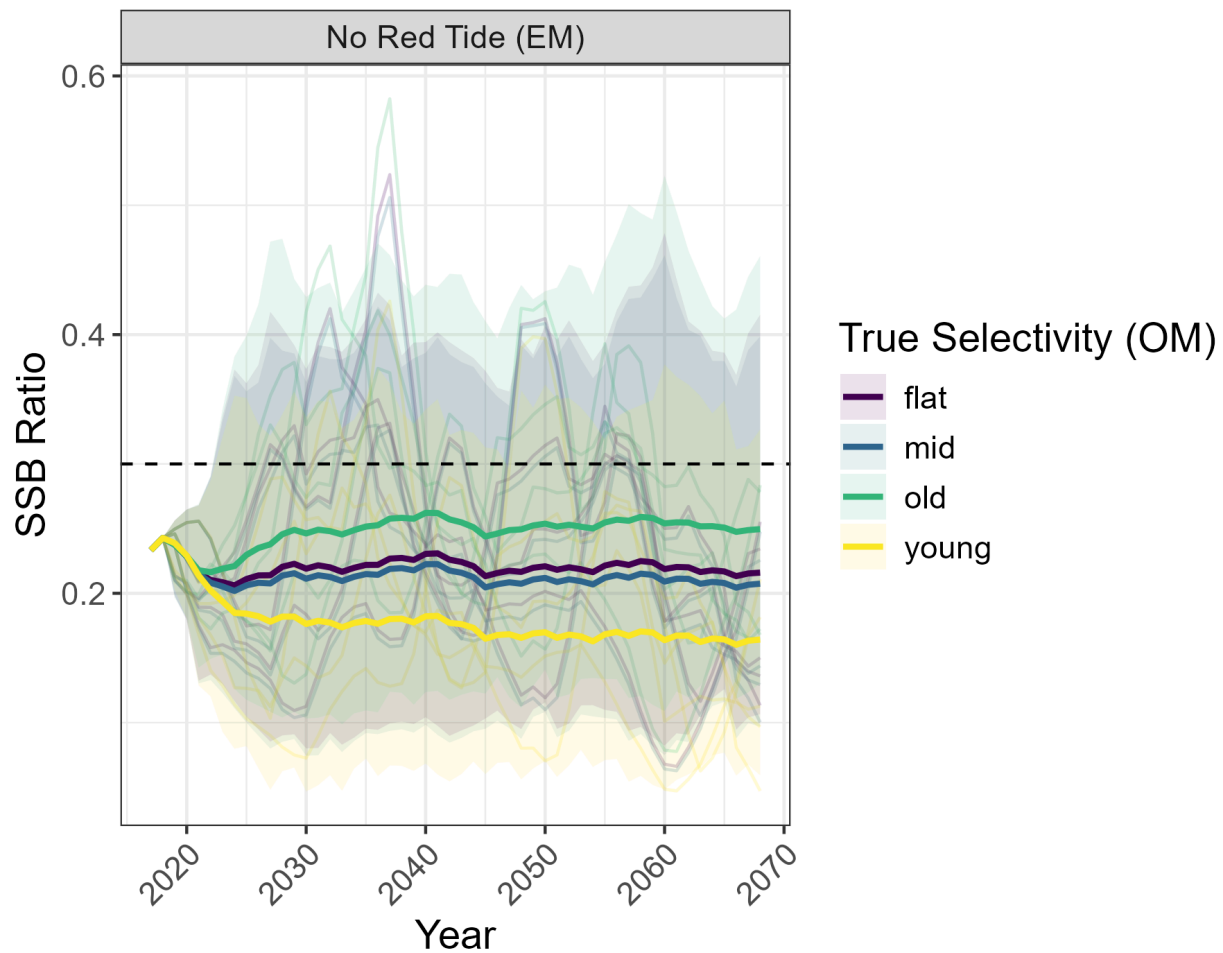


**Figure 7. Achieved SSB Ratio (annual SSB / unfished SSB) over time across scenarios with 17 red tide events.** Thick solid lines show the median SSB Ratio across 100 iterations of the Operating Model (OM) when the EM had no red tide, color-coded by the OM's assumed red tide selectivity. Thin transparent lines show individual results for the first 5 iterations of each scenario. Shaded regions represent 95% confidence intervals, and the dashed black line indicates the 0.3 SSB Ratio management target.

## Achieved SSB Ratio over time - Known Years

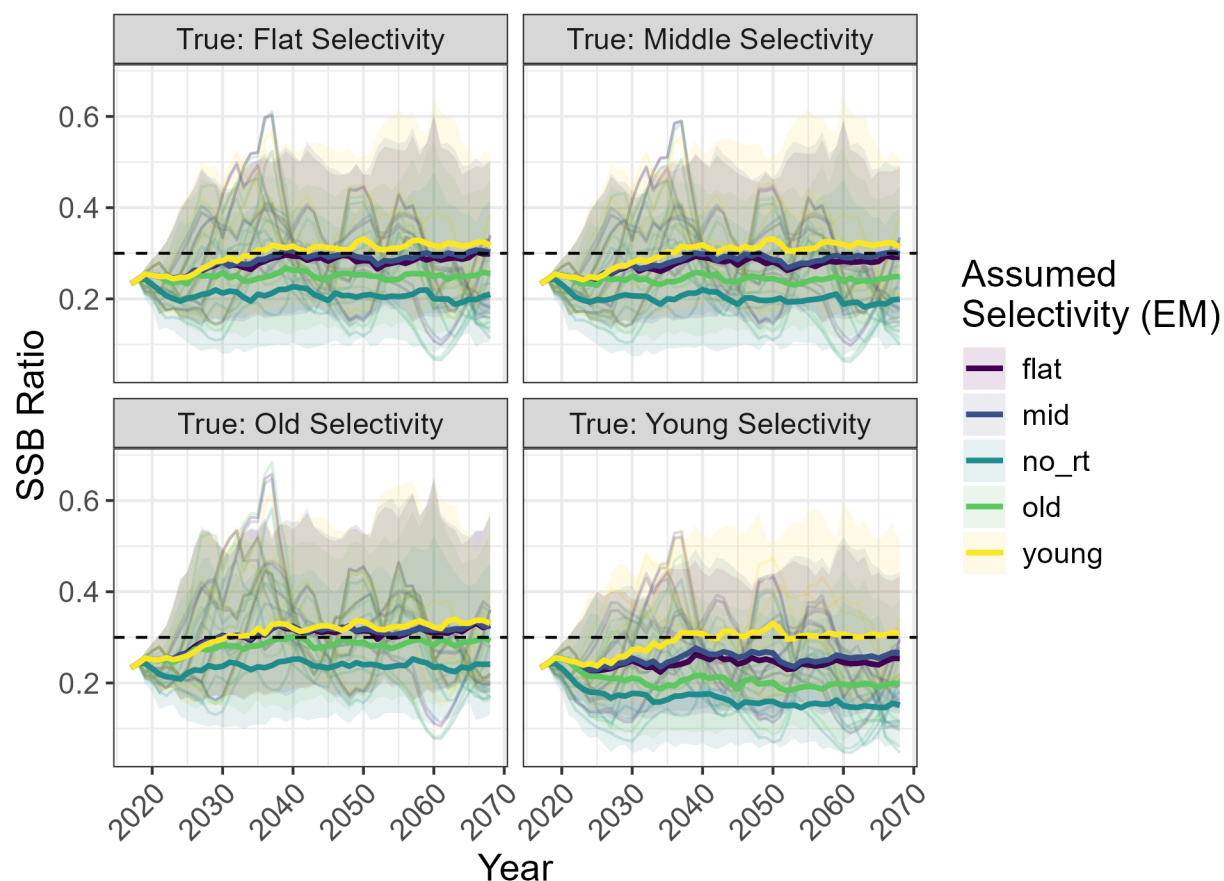


**Figure 8. Achieved SSB Ratio (annual SSB / unfished SSB) over time across scenarios with 17 red tide events for all red tide selectivity combinations.** Thick solid lines show the median SSB Ratio across 100 iterations of the Operating Model (OM), color-coded by the Estimation Model's (EM) assumed red tide selectivity. Thin transparent lines show individual results for the first 5 iterations of each scenario. Shaded regions represent 95% confidence intervals, and the dashed black line indicates the 0.3 SSB Ratio management target.

## Achieved SSB Ratio over time - All Years

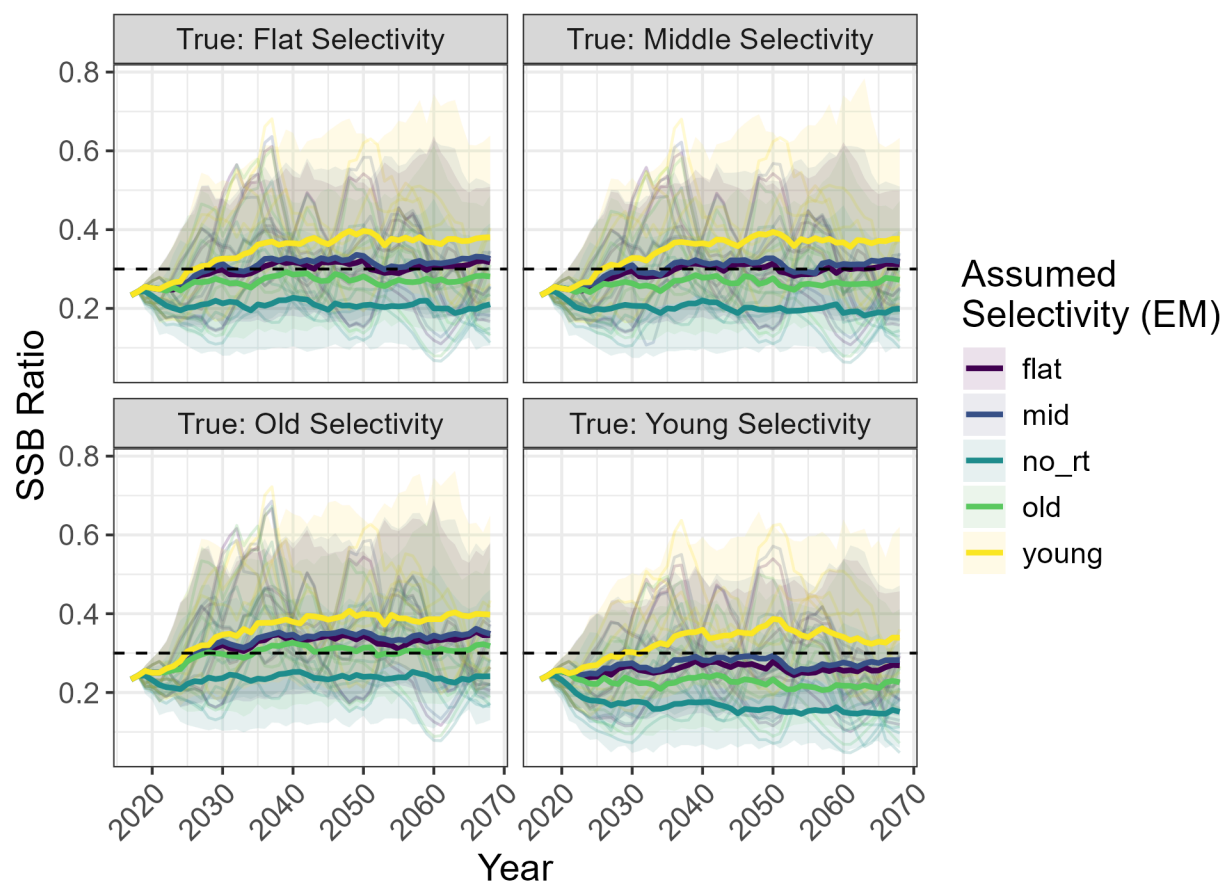


**Figure 9. Achieved SSB Ratio (annual SSB / unfished SSB) over time across scenarios with red tide in all years for all red tide selectivity combinations.** Thick solid lines show the median SSB Ratio across 100 iterations of the Operating Model (OM), color-coded by the Estimation Model's (EM) assumed red tide selectivity. Thin transparent lines show individual results for the first 5 iterations of each scenario. Shaded regions represent 95% confidence intervals, and the dashed black line indicates the 0.3 SSB Ratio management target.