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Accounting for episodic mortality events in the estimation of fishery reference points for groupers in the Gulf of America

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Abstract

Stock assessments for red grouper (*Epinephelus morio*) and gag grouper (*Mycteroperca microlepis*) in the Gulf of America (Gulf) routinely account for red tide mortality in the assessment period (i.e., the historic period fitted to observed data) and in short-term projections for deriving catch advice where necessary. However, it remains unclear how to account for red tide events in the longer term when estimating reference points. In this simulation exercise we evaluate how reference points for Gulf red grouper and gag grouper are affected by episodic events of severe red tides causing mass mortality. Given the uncertainty surrounding future red tide events in both space and time (and intensity), various scenarios of red tide mortality occurrence and severity are simulated with bounds derived from previous stock assessment estimates of red tide mortality. Simulation results suggest that ignoring future red tide mortality in stock assessment projections will result in the overestimation of sustainable fishing mortality rates and long-term depletion of the stock below targeted spawning stock biomass (SSB) thresholds. Importantly this overexploitation results in negligible increases in long term landings due to the reduced population abundance counteracting the increased fishing mortality rates. Our results also suggest that, due to the significant impact of red tide mortality, the population actually needs to spend a significant amount of time above target SSB levels in order to provide a buffer for episodic mortality events. We demonstrate this approach using the 2025 Gulf red grouper assessment, and thereby provide guidance for fisheries managers on the important tradeoffs and dynamics to consider when determining reference points in the context of episodic mortality events.

Introduction

Fishery stock assessments are quantitative analyses that use available data to assess the health of a stock and determine sustainable yields. The stock assessment modeling process can be divided into two phases: (1) historical reconstruction of stock dynamics by fitting an assessment model to available data; and (2) projecting the assessment model forward in time under assumed stock, fishery, and environmental conditions (i.e., simulation analysis). While most of the analytical time is spent on phase one via model building and diagnostics (e.g., Carvalho et al. 2021; Karp et al. 2022), arguably the most important outcomes of stock assessments are derived from phase two including stock status determination and forecasted catch advice. Biological reference points are used to determine stock status, with current estimates of stock biomass and fishing mortality from the assessment model compared to established management objectives based on achieving maximum sustainable yield (MSY) or its proxy in the long-term (Lynch et al. 2018). Overfished stocks are those where current biomass drops below the minimum stock size threshold (MSST), often specified as a fraction of the biomass attained when fishing at MSY (B_{MSY}). Stocks undergoing overfishing are those where the current fishing mortality rate is above the maximum fishing mortality threshold (MFMT = F_{MSY}). Determining stock status allows fisheries managers to adjust their harvest policies to ensure rebuilding of overfished stocks or to reduce overfishing if it is occurring.

Reference points based on MSY are achievable for fishery stocks that have an informative spawner-recruitment relationship and when the steepness parameter is well-estimated by the assessment model (e.g., as demonstrated through diagnostics), which reflects the preferred approach were feasible (Methot et al. 2025). Unfortunately, the spawner-recruitment relationship for many Gulf reef fish is uninformative due in part to the lack of contrast stemming from short time-series (<50 years). For these stocks, reference points are based on a proxy for MSY that uses the spawning potential ratio (SPR), or the stock biomass relative to its unfished state. Estimates of SPR range from 26% for red snapper (*Lutjanus campechanus*) and gray snapper (*Lutjanus griseus*) to more conservative estimates of 40% SPR for hermaphroditic groupers including red grouper (Gulf Council 2026b), gag grouper (GMFMC 2023), scamp (*Mycteroperca phenax*; Gulf Council 2025), and yellowedge grouper (*Hyporthodus flavolimbatus*; Gulf Council 2026a). Their life history characteristics (e.g., long-lived, slow to mature) and reproductive strategies (i.e., sperm limitation or limited understanding of reproductive behavior) make them more vulnerable to fishing pressure. Simulations conducted by Harford et al. (2019) suggest that SPRs of 40% or 50% led to the highest probabilities of achieving long-term MSY for hermaphroditic stocks. More conservative fishing mortality proxies were required in simulations to achieve MSY-based fishery objectives when steepness was “least certain” (i.e., specified by a uniform prior; Harford et al. 2019).

By definition, MSY is “the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological, environmental conditions” (50 CFR 600.310(e)(1)(i)(A)). However, a key challenge for stock assessments is how to establish biological reference points when ecosystems are changing with environmental and oceanographic conditions (Lynch et al. 2018). For example, Ianelli et al. (2011) developed climate-based stock projections which better tracked productivity for Eastern Bering Sea walleye pollock (*Gadus chalcogrammus*) under warming conditions. Status quo management for the stock would have led to reduced catches and more fishery closures. An area that has received the most attention is the inclusion of recruitment-environmental relationships. Haltuch et al. (2019) identified nine (out of 12) studies on opportunistic strategists (e.g., short pre-recruit survival window) and three (out of 11) studies on periodic strategists where inclusion of an environmental driver improved prediction capability of recruitment (Haltuch et al. 2019). The authors cautioned against using direct mechanistic relationships within stock assessment models which can break down over time (e.g., wind and Atlantic cod *Gadus morhua*; Hare et al. 2015), and highlighted examples of environmentally based harvest control rules or where environmental thresholds were incorporated into reference points. More recent research has emphasized the potential for dynamic reference points to account for environmental changes (Sharma et al. 2019), although their use requires careful consideration (Berger 2019; Methot et al. 2025). O’Leary et al. (2020) simulation tested both dynamic and moving-average biological reference points, and found that the dynamic approach using a climate-linked natural mortality model produced the least variable reference points for summer flounder (*Paralichthys dentatus*) on the Northeast U.S. continental shelf.

Estimation of red tide mortality has been an integral part of base assessment model development for Gulf gag and red grouper since 2009 (SEDAR 2009a, 2009b). Major advancements for considering red tide mortality have occurred using the Stock Synthesis assessment modeling framework (Methot and Wetzel, 2013), with multiple severe red tide events having negatively impacted these species across the eastern Gulf (Turley et al. 2026). The current approach to accounting for red tide mortality treats red tide as a discard-only bycatch fleet (Sagarese et al. 2021; Sagarese and Harford 2022), with negative effects, i.e., red tide mortality, only occurring during severe red tides. Red grouper stock assessments have estimated red tide kills between 3-23% of abundance (3-30% of biomass; Table 1, SEDAR 2019, SEDAR 2025). The most recent gag grouper stock assessment estimated even larger kills ranging between 6% and 48% of estimated population abundance (SEFSC 2022). Strong year classes tend to follow red tide events, suggesting that grouper populations may have a greater capacity to recover from stock declines than previously thought.

The spatio-temporal nature of red tides has continued to challenge the assessment process, particularly the development of short-term catch advice when red tides occur in the first few years of projections. A red tide event of unknown severity occurred during the first few years of projections in assessments for both red grouper (SEDAR 2019) and gag grouper (SEFSC 2022). In the absence of data regarding the severity of the 2018 red tide event for red grouper, which was ongoing at the time of the assessment, several projection scenarios varying levels of 2018 red tide mortality were conducted in an effort to provide a range of forecasted catch advice for the Gulf Council to consider (Sagarese et al. 2021). For gag grouper, a novel index of red tide mortality was derived from an Ecopath with Ecosim and Ecospace model of the West Florida Shelf (Vilas et al. 2021, 2023) and was available during gag grouper projection development (SEFSC 2022). Several projection scenarios were run for gag grouper which varied levels of 2021 red tide mortality based directly on the red tide mortality estimates obtained from the Ecospace model, making this application the first where an ecosystem model directly affected catch advice for a Gulf fishery stock. While the availability of this data stream is promising for adjusting short-term catch advice in almost real-time, it remains unclear how to account for red tide events in the longer term when estimating reference points.

The impacts of regulated fishing fleets and by-catch fleets (e.g., shrimp) are routinely incorporated into the calculation of reference points; however, environmentally induced episodic mortality has not to date been addressed for Gulf reef fish. The potential impact of these unpredictable events should be considered when developing reference points and stock rebuilding timelines where warranted, which has been supported by explicit inclusion in Terms of Reference for research track stock assessments in the region. The objective of this study was to evaluate how reference points for Gulf red grouper and gag grouper are affected by episodic events of severe red tides causing mass mortality using simulation analysis. Given the uncertainty surrounding future red tide events (frequency and severity), various scenarios of red tide mortality are simulated with bounds derived from assessment model red tide mortality estimates. We then implement this approach using the 2025 Gulf red grouper assessment to demonstrate the impacts on the outcome of the stock assessment. Changing oceanographic conditions may increase the frequency of harmful blooms (Hallegraeff 2010), may exacerbate red tides (Heil and Muni-Morgan 2021), and may cause both direct (e.g., temperature effects on cell metabolism or range expansion) and indirect effects (e.g., hurricanes) on harmful algal blooms. However, much uncertainty remains regarding the exact impacts of changing oceanographic conditions on *Karenia brevis* red tide blooms (reviewed in Turley et al. 2022).

Methods

Base assessment model structure

The assessment models for both red grouper and gag grouper start in a fished state, with red grouper starting in 1986 and gag grouper starting in 1963 (Table 1; Figure S1). Commercial fishing fleets include vertical line, longline, and trap (red grouper only), and recreational fishing fleets for gag grouper include charter, private/shore, and headboat while red grouper only considers a single combined recreational fleet (Figure S1). Associated data inputs for fishing fleets include landings, discards, catch-per-unit-effort indices, retained age compositions, retained length compositions, and discard length compositions where available (Figure S1). Multiple fishery-independent surveys with indices of relative abundance and length compositions are included for both species which track different age classes (Figure S1).

Age-specific natural mortality (M) was configured for each species based on Lorenzen (2000), with point estimates of M obtained from maximum age-based proxies (Table 1). Models for both species assume a Beverton-Holt spawner-recruitment model, with steepness fixed at 0.99 for red grouper and 0.85 for gag grouper. Length-based selectivity was estimated for all fishing fleets and surveys, with time-varying retention used to allow for varying discards at size due to the impacts of fishery minimum size limits and bag limits.

The target SPR% percentage reference points used for management in these assessments were 30% for red grouper and 40% for gag grouper (Table 1). Both species were determined to have a terminal spawning biomass below their respective targets with red grouper at 25% in 2017 and gag grouper at 3% in 2019. Base assessment models produced projections for management advice that included zero long term red tide mortality, recent landings estimates for 3 years prior to management being implemented and all fishery selectivity and biology being the average of the estimated values in the last 3 years of the assessment model.

For both species, red tide mortality was implemented using the bycatch fleet approach, with severe red tide events incorporated into the model based on a combination of quantitative and qualitative data (reviewed in Sagarese et al. (2021) for red grouper). Three red tide events (2005, 2014, and 2018) were incorporated into the model for gag grouper based on a combination of quantitative (Vilas et al. 2021) and qualitative data (Turley et al. 2021). Selectivity of the red tide fishing fleet was assumed constant at age (i.e. = 1) due to the lack of data on age- or size-specific red tide mortality. While a similar assumption was made for gag grouper in the base assessment model, other assumptions were considered during sensitivity runs but warranted further review of modeled dynamics and behavior (SEDAR 2021).

Additional details on data inputs, model development, diagnostics, and projections can be found in their respective assessment reports (red grouper: SEDAR 2019; gag grouper: SEDAR 2021, SEFSC 2022).

Simulation analysis structure

For our simulation study the population biology and fishery selectivity dynamics were handled the same as in the base stock assessments. The simulation design for this study was a two-stage process comprised of calculating:

1) Equilibrium benchmark projection simulations to determine fleet specific annual fishing mortality rate targets estimated to achieve fishery allocation and population status targets under one of 11 constant red tide mortality rate assumptions. These simulations replicate the projection approach used in management to determine overfishing limit estimates. To avoid issues with premature stock collapse, these equilibrium simulations assumed zero fishing and red tide mortality rates in the first 4 years of the simulation. These zero values for years 1 through 4 are then replaced with the estimated rates from year 5 for the phase 2 randomized simulations.

2) Randomized episodic red tide mortality projections consisting of 500 replicates at each of three average red tide mortality magnitudes while utilizing the equilibrium target fishing mortality rates from phase 1 for targeted fishing fleets but implementing randomized episodic red tide mortality series to replace the constant equilibrium rates assumed in phase 1. These simulations determined how the target fishing mortality rates estimated in phase 1 could be expected to perform under real world red tide variability.

This resulted in each of the 11 fishing mortality time-series estimated in stage 1 being applied to all 1500 randomized episodic red tide scenarios. Fishery landings and stock status outcomes were then compared to evaluate the impact of the 11 differing projection assumptions. To avoid

Equilibrium benchmark projection simulations

For each species, equilibrium projection simulations were run for 100 years beyond the assessment's terminal year using the same parameter values and population dynamics as their respective base assessment models. Selectivity, discard mortality, retention, and relative fishing mortality rate between fleets within a sector were assumed to persist at the average associated with the last three years of the assessment. Sector-specific allocations of landings between commercial and recreational fishing fleets were maintained annually in the projection period, under the assumption that allocations would be achieved in each year. Allocations assign 59.3% of red grouper landings to commercial (GMFMC 2021) and 61% of gag grouper landings to recreational (GMFMC 2023). Forecast recruitment values were derived from the assessment model-estimated Beverton-Holt spawner-recruitment relationship. SPR-based reference point targets, as a proxy for MSY, were implemented for both as specified in the based assessment models. Total harvest rate (total biomass killed / total biomass) was constant across all years from year 5 onwards. The optimization of annual fishing mortality rates subject to relative effort, allocation, harvest rate, and SPR reference point constraints used in this analysis was the same method as the base stock assessments with the only change being the exclusion of fishing mortality in the first 4 years of the projection simulation.

For equilibrium projections, red tide mortality was held constant across all projection years from year 5 of the simulation onwards. Target fishing mortality vectors were estimated for 11 magnitudes of red tide mortality. Values from 0 to 0.1 in 0.01 increments were tested in order to span the range of average mortality magnitudes observed in the fisheries and tested in the randomized episodic simulations described below. The results of each of these projections was used to produce a time series of target fishing mortality rate for each fleet which was then implemented within the random red-tide simulations.

Random episodic red-tide scenario replicates

Given the inability to forecast red tides in the long-term, we selected a range of low (0.01), medium (0.03), and high (0.06) plausible average red tide mortality estimates based on the historical values estimated in the base red grouper and gag grouper stock assessments.

Historic values used to estimate the range were the average red tide mortality values estimated over the entire modeled time series of 0.018 for red grouper (1986-2017) and 0.03 for gag grouper (1963-2019; Figure 2). The average mortality estimate over a representative subset of the time series for which quantitative estimates of red tide severity were available (i.e., circa 1998 using SeaWiFS satellite data; described in Walter et al. 2013) were 0.03 for red grouper and 0.08 for gag grouper. The recent average red tide mortality over the last 5 years of the stock assessment were 0.05 for red grouper and 0.015 for gag grouper.

These low, medium, and high magnitudes were then used to define "true values" of average annual red tide mortality in the simulations with 500 replicate simulations produced for each magnitude level. For each replicate, red tide events were simulated to occur randomly in time and magnitude, with between five and 20 events occurring randomly throughout the 100-year projection period. The magnitude of each event was drawn from a uniform distribution with a maximum possible value 4 times greater than the minimum and the absolute magnitude determined by scaling mortality values so the average over all 100 years matched the low, medium, or high target average (i.e., the true value).

These random episodic mortality values were then used to replace the constant values used in each of the 11 equilibrium projection scenarios producing new simulations of achieved landings and population biomass under the different simulated target fishing mortality rates.

In addition to all of the assumed dynamics in the projections described above, this analysis assumes that the overfishing limit (OFL) is estimated without error and that the annual fishing mortality rate targets were achieved perfectly in each year of the simulation (e.g., from stock assessment updates and annual interim analyses). Fleet specific fishing mortality rate was maintained at the equilibrium target levels rather than landings in order to test a best case scenario for implementation over a long time horizon. This avoided compounding effects of stock abundance deviations leading to severe over or under exploitation without needing to explicitly define stock assessment update frequency and implement the full feedback simulation of a management strategy evaluation.

Metrics

For each true red tide scenario (minimum, average, and maximum), the results of the various baseline red tide projection scenarios were compared based on landings estimates (i.e., achieved overfishing limits), the SSB ratio (SSB/unfished SSB), total biomass, and the biomass killed by red tide. The various metrics were averaged within each baseline scenario for ease of comparison amongst baseline red tide mortality estimates within a true red tide mortality value. Individual simulation trajectories are presented (all inclusive or as a random subset) in addition to summary trajectories identifying the median values and confidence intervals based on the 2.75th and 97.5th percentiles (95% confidence interval) and the 25th and 75th percentiles (50% confidence interval).

For each baseline red tide mortality projection, stock status was determined based on status determination criteria for red grouper (GMFMC 2017) and gag grouper (GMFMC 2023). Target values were obtained from the base projection for each baseline red tide mortality value and compared to each baseline-true value scenario to determine what each simulation achieved relative to its target. The maximum fishing mortality threshold (MFMT) was equivalent to the harvest rate (F_{MSY} proxy; total biomass killed / total vulnerable biomass) that achieved SSB at the MSY proxy, and was used to assess whether overfishing was occurring in a given year. The minimum stock size threshold (MSST) was determined by multiplying the reference spawning stock biomass, SSB at the MSY proxy, by 0.5 for both species (GMFMC 2017). A stock was considered overfished if $SSB_{Current} < MSST$ and undergoing overfishing if $F_{Current} > MFMT$, where $F_{Current}$ was defined as the geometric mean of the fishing mortality over the most recent three years of the assessment.

Case Study: 2025 Red grouper application

The proposed approach for incorporating red tide mortality into the estimation of benchmarks was tested using the 2025 Gulf red grouper stock assessment (SEDAR 2025). This assessment model included a number of data changes that were significant improvements upon the 2019 assessment model, such as the use of the Florida-caught private recreational landings and discard estimates from the Florida State Reef Fish Survey, better accounting for uncertainty within landings and discards, including mean-length-at-age data for fishing fleets, and fitting to the mean weight of recreational landings. Model configuration was also modified considerably to implement better practices regarding natural mortality, steepness, growth, and age-specific selectivity by severe red tides (Table 1). Additional details on model configuration are provided in SEDAR (2025). Baseline levels of red tide mortality were based on historical averages from the 2025 assessment model, and reference points were determined using an SPR40% with recruitment derived from the Beverton-Holt spawner-recruitment curve.

Results

Red grouper

Deterministic scenarios

When red tide events occurred randomly and produced a true average red tide mortality rate of 0.03 in the 100-year projection, assuming various baseline levels of red tide mortality led to similar landings when assumed average mortality was ≤ 0.03 but very different SSB ratio outcomes (Figure 3). With the exception of the first few years of the projection, the landings estimates were nearly identical for the 0 and 0.01 baseline red tide mortality values and only marginally lower at the 0.03 baseline, suggesting that including low baseline levels of red tide mortality in the projection would not negatively impact projected yields. When assuming a baseline red tide mortality estimate of 0.06, projected yields were consistently lower because this baseline value was higher than the true red tide mortality in this simulation (0.03). Notable differences were evident across baseline red tide mortality scenarios for the SSB ratio and total biomass (Figure 3). Assuming no annual red tide mortality (i.e., baseline of 0) led to annual SSB ratios consistently below the target of 0.3, with a few years approaching the minimum stock size threshold defining an overfished state. This period overlapped with a cluster of severe red tides occurring every few years between the 2070s and 2080s in the simulation period. Assuming higher baseline red tide mortality rates led to SSB ratios generally closer to the target, with a baseline of 0.03 being closest to the true red tide value (0.03). When assuming a baseline level of 0.06 red tide mortality, which was larger than the true red tide level of 0.03 for this simulation, SSB ratio was substantially above the target level of 0.03 in most years, indicative of being underfished. Assuming higher baseline red tide mortality values led to larger red tide fish kills throughout the projections, with some nearly as large as the historical events in 2005 and 2014 for red grouper (Figure 3).

True vs baseline red tide mortality simulations

When averaged within baseline scenarios for each true red tide mortality estimate, results were similar to the trends identified in the deterministic projection. Projected landings after five years were very similar between the baseline scenarios assuming no red tide mortality (i.e., the status quo approach) and a baseline red tide mortality of up to 0.03 for all future true red tide scenarios (Figure 4). Assuming substantially higher baseline red tide mortality levels led to reduced landings and subsequently higher SSB ratios and total biomass estimates. For red grouper, simulated dynamics showed greater variability when true future red tide mortality was higher (Figures S2-S3). Some simulations at high average red tide mortality rates of 0.06 estimated SSB ratio and total biomass at very low levels crashing the stock (Figures S2-S3). Red tide fish kills over the projection period were very variable, due to variation in the frequency and magnitude of red tide mortality (Figure S4).

Stock status determination

Stock status in terms of overfished status did not change amongst baseline red tide mortality levels for red grouper (projections by design equilibrate at the target SPR of 30%). The ratio of current SSB to minimum stock size threshold remained at 0.82 for red grouper across baseline values. In contrast, the probability of overfishing occurring did vary considerably across baseline red tide mortality rates. For red grouper, baseline levels of red tide mortality of 0.02 or higher led to overfishing status ($F_{current}$/MFMT range: 1.06 - 6.99).

Gag grouper

Deterministic scenarios

The results for gag grouper were similar in trend to those for red grouper, although noticeable differences in projected landings were evident (Figure 5). Under the baseline red tide mortality rates of 0 and 0.01, the cluster of severe red tides occurring in the projection period led to the stock dropping below the minimum stock size threshold in a few years. When assuming a baseline level of 0.06 red tide mortality, which was larger than the true red tide level of 0.03 for this simulation, SSB ratio remained well above the target level of 0.4 in most years but oscillated around the target during the cluster of severe and frequent red tide events. Assuming higher baseline red tide mortality values led to larger red tide fish kills throughout the projections, with a few exceeding the largest historical event for gag grouper in 2005 due to the extremely depleted status of gag grouper at the time of all historic red tide mortality events (Figure 5).

True vs baseline red tide mortality simulations

For gag grouper, there was a strong decline in landings as baseline red tide mortality estimates increased across true red tide mortality values. Equilibrium projections estimated no sustainable level of landings for any scenarios with greater than 0.07 average red tide mortality (Figure 6).

Simulated dynamics for gag grouper also showed greater variability when true future red tide mortality was higher, and for this species many high mortality rate simulations led to stock collapse as evidenced by very low SSB ratios (Figures S5-S6). Red tide fish kills over the projection period were highly variable, with magnitudes substantially larger than historic mortality events due to predicted population rebuilding (Figure S7).

Stock status determination

Stock status in terms of overfished status did not change amongst baseline red tide mortality levels for gag grouper (projections by design equilibrate at an SPR of 40%). The ratio of current SSB to minimum stock size threshold remained very low at 0.07 for gag grouper. For gag grouper, all baseline levels of red tide mortality led to overfishing status ($F_{current}$/MFMT range: 2.56 - 37.7).

Case Study: Red grouper 2025

Over the entire modeled time period of 1986 through 2022 for the 2025 red grouper stock assessment, four severe red tides were estimated to have occurred (2005, 2014, 2018, 2021), resulting in an average red tide mortality estimate of 0.01. Between 1998 and 2017 (i.e., where red tide severity was quantified using satellite data), the assessment model estimated an average red tide mortality rate of 0.02 (doubled to 0.04 for the worst case scenario). Landings estimates throughout the projection period and at equilibrium were reduced when assuming higher baseline red tide mortality estimates (Figure 7). Assuming higher baseline red tide mortality in the near-term led to lower ratios of SSB and SPR. Regardless of the baseline red tide mortality scenario, all projections equilibrated at an SPR of 40% (by design) and at the same equilibrium SSB ratio, which led to no change in overfished status (Table 2). Changes in reference points related to fishing mortality were evident, as assuming higher baseline red tide mortality estimates throughout the projections resulted in lower equilibrium fishing mortality estimates (Table 2). While none of the red tide projection scenarios led to determinations that overfishing was occurring in recent years, higher baseline red tide mortality estimates assumed throughout the projection period resulted in a ratio of current F to the maximum fishing mortality threshold closer to the limit of 1 defining overfishing (Table 2). The equilibrium yields projected by each scenario, assuming they accurately reflect the true future average mortality rate, suggest that ongoing red tide mortality could result in a 9-36% reduction in the sustainable productivity of the red grouper fishery (Table 2). It is important to note that our simulation results show that underestimating the true future average red tide mortality rate in reference point projections results in significantly reduced population biomass and increased risk of stock collapse with minimal increase in long term yields.

Discussion

Recent emphasis on managing fisheries in the face of rapidly changing ocean conditions by the NOAA Fisheries' Changing Ecosystems and Fisheries Initiative (CEFI) program has pushed stock assessments towards providing climate-informed catch advice. While ecosystem considerations are rarely incorporated directly into stock assessments (Marshall et al. 2019; Karp and Vieser 2024), the red tide-grouper linkage within the Gulf has been a successful case study. Initial work focused first on historical incorporation into the assessment model and more recently on short-term catch advice which decremented recommended catch levels to account for red tide removals during the first few years of projections (Sagarese et al. 2021). Here we used simulation analyses to help address the last remaining questions: (1) should we account for episodic mortality when estimating reference points and (2) how to do so. Overall, our results provide guidance to managers for how to incorporate episodic mortality events into the decision making process in the face of uncertain future red tide events.

Our results provide support for accounting for episodic mortality when estimating reference points. Simulation results suggest that ignoring future red tide mortality in stock assessment projections may result in the overestimation of sustainable fishing mortality rates and long-term depletion of the stock below targeted spawning stock biomass (SSB) thresholds. Importantly this overexploitation results in negligible increases in long term landings due to the reduced population abundance counteracting the increased fishing mortality rates. Additionally, these results highlight the significant risk of population collapse due to episodic mortality events particularly when stocks are already depleted to low levels. Our results also suggest that, due to the significant impact of red tide mortality, managers should expect populations to be estimated at above target SSB levels in the majority of years in order to provide the buffer needed to withstand episodic mortality events. Given this justification for inclusion, and in the absence of future forecasts of red tide events, we recommend that a baseline level of red tide mortality be included for each year throughout the projection period. This baseline value could be derived from the average red tide mortality throughout the modeled time period or a subset of years where red tide events were quantifiable, as done in this study. This approach is similar to assuming a fixed level of mortality for shrimp bycatch in some Gulf stock assessments, which is often based on the average from the most recent five years. Alternatively, managers could achieve similar outcomes by incorporating a buffer on reference point SPR proxies. Our simulations suggest that increasing SPR proxies by around 10% to 40% for red grouper and 50% gag grouper could have a similar result to assuming an average red tide mortality rate of 0.03 in the projection period. Similarly, the dynamic stock status trajectories seen in our results suggest that this approach would enable the range between target SPR and the minimum stock size threshold to truly reflect the range of abundance levels expected from a sustainably managed fishery.

Stock Synthesis has recently included an option to treat red tide (and other episodic events) as a predator fleet, removing the confusion over labeling red tide mortality as a component of fishing mortality because it is treated as dead bycatch (Methot et al. 2024). For red tides, and other episodic mortality events, the question becomes how should red tide mortality be incorporated into fished vs unfished equilibrium population targets. Do these events reflect extra un-natural mortality pressure that compete with directed fishery catch, which are better treated as a “bycatch fleet”, or should they be linked to natural mortality and incorporated into baseline levels such that they reduce fished and unfished biomass. Part of the justification for including red tide only during severe years is that natural mortality estimates input into the stock assessment model are generally longevity-based proxies (e.g., Hoenig 1983; Hamel and Cope 2022) in the absence of more direct estimation, and likely already capture baseline levels of episodic mortality (SEDAR 2019). While the chosen approach to incorporating red tide mortality within stock assessment models remains debatable, the reality is that how to account for red tide in projections is arguably the most important question for fishery managers. If red tide is treated as extra natural mortality, treating it as natural mortality would decrement unfished SSB through time. In contrast, treating red tide as a “fishing fleet” would lead to unfished SSB calculated in a world without red tide. A stark example of the impacts of this seemingly simple decision is seen in our simulation of the high true red tide scenario simulated for gag grouper. In this scenario the bycatch fleet approach estimated zero sustainable fishery landings, a complete closure, and population still being depleted to less than twenty percent of the spawning biomass expected under no red tide mortality. If however a predator fleet approach was used that incorporated red tide mortality into both fished and unfished, the twenty percent spawning biomass state would be considered the unfished level suggesting a target ratio of as low as 8% of the virgin biomass expectation.

Incorporating environmental drivers into short-term projections of catch advice or long-term equilibrium projections for the estimation of reference points is particularly difficult because of the need to predict future patterns or ensure “prevailing conditions” persist into the future. The complex nature of *Karenia brevis* blooms in the Gulf has challenged the ability to make long-term projections regarding red tide occurrence, frequency, and magnitude (Tominack et al. 2020). Recent advancements have focused on projecting blooms in the near-term, between 3-4 days, for use by governmental agencies (Liu et al. 2023). Additional efforts are planned to predict seasonal blooms, with the goal of assisting fishermen during their fishing operations and identifying areas affected by blooms (Turley et al. 2022).

Forecasting harmful algal blooms composed specifically of *Karenia brevis* will likely be difficult if not impossible to operationalize in the face of changing oceanographic conditions. For example, the index of red tide severity developed using SeaWIFS satellite data (Walter et al. 2013) was based on eight derived products (Chlorophyll concentration, Chlorophyll anomaly, Morel, Carder, CMbbp, remote sensing reflectance at 670 nm, spectral shape at 490 nm, and the HAB_ensemble). An independent effort aimed at developing an index of red tide mortality using an ecosystem modeling approach (Vilas et al. 2023) relied on fluorescent line height (FLH) which was specific to the MODIS satellite platform. The continuity of these approaches has been complicated because some of these derived quantities are not measured by more recent satellite platforms (e.g., spectral shape and FLH by VIIRS), and therefore new methods for detecting *Karenia brevis* and quantifying severity will be required. Further, there has been some discussion regarding how hypoxia affects red tides (Turley et al. 2022), which has not yet been accounted for in ecosystem models focused on red tides on the West Florida Shelf. While future forecasts of some environmental drivers are possible (e.g., sea surface temperature), it seems unlikely that all of the various environmental drivers of red tides can be confidently predicted.

There are a number of important caveats for these long-term projections which are based on a myriad of assumptions. First, these calculations do not account for the highly variable nature of recruitment events nor the fundamental relation between adult spawners and subsequent recruits. Specifically for red grouper simulations using the 2019 stock assessment model, projections are based on the assumption that future recruitment will remain constant at recent averages (i.e., steepness is approximately 1.0). In addition, long-term equilibrium conditions are unlikely to hold for any resource given environmental conditions and management changes. This analysis showed that even if the OFL was extracted perfectly from the stock, just environmental conditions alone (i.e., a red tide) could drive the stock below the biomass threshold and potentially even result in stock collapse under extreme scenarios. While this analysis focused on red tide mortality as the environmental stressor, many other potential sources of mortality are known to impact fish populations including other environmental events (e.g., cold snaps, hypoxia, hurricanes) and non-fishing anthropogenic disturbances (e.g., oil spills).

The incorporation of ecosystem considerations into fisheries management in general remains a key area of research. The most direct means of operationalizing their inclusion in stock assessment is first obtaining a good foundation of understanding environmental drivers impacting stock dynamics and incorporating them into the assessment model (i.e., direct linkage of environment to stock dynamics). However, there are other places in the management process where ecosystem and socioeconomic considerations could be incorporated (Lynch et al. 2018). For example, harvest control rules could be designed to take into account red tide events and buffer against scientific uncertainty (Harford et al. 2018). Also, scientific advisory bodies to the Fishery Management Councils have the authority to recommend reduced Acceptable Biological Catch limits to account for more scientific uncertainty, as was done following the SEDAR 61 stock assessment for red grouper (GMFMC 2021). Fishery Management Councils themselves also have the ability to set precautionary targets by reducing Annual Catch Limits to levels below the estimated Acceptable Biological Catch limits. This study serves to highlight the substantial long-term risks and limited short-term benefits associated with ignoring episodic mortality effects when managing fishery quotas. While additional research will help identify optimal adjustment values, these results suggest that incorporating moderate buffers immediately should provide significant biological benefits with limited economic costs.

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Tables

Table 1. Summary of assessment model configurations and key details for the red and gag grouper stock assessment models used during simulations and for the case study (2025 red grouper assessment only). *Age-based selectivity used for fishing fleets in 2025 red grouper model.

Parameter	Red grouper	Red grouper 2025	Gag grouper
Stock Synthesis version	3.30.16	3.30.21	3.30.16_05
Reference	SEDAR 61 (2019)	SEDAR 88 (2025)	SEDAR 72 (2022)
Start year (condition)	1986 (fished)	1986 (fished)	1963 (fished)
Terminal year	2017	2022	2019
Terminal year depletion (SSB/SSBunfished)	0.25	0.41	0.03
Fishing mortality (F)	Annual and initial F for each fleet	Annual and initial F for each fleet	Annual for each fleet, initial F for commercial handline and recreational private/shore
Growth parameters estimated	Length at minimum age (LAmin), von Bertalanffy growth rate (K)	LAmin, K, Von Bertalanffy asymptotic length (Linf)	LAmin, K, Linf
Natural mortality	Fixed age-specific vector; Hoenig (1983) point estimate (maximum age of 29 years) scaled using Lorenzen (2000)	Lorenzen scaling implemented within Stock Synthesis using the Hamel and Cope (2022) point estimate (maximum age of 29 years)	Fixed age-specific vector; Then et al. (2015) regression re-calculated for Serranid data point estimate (maximum age of 33 years) scaled using Lorenzen (2000)
Recruitment parameters estimated	R0, sigmaR, rec devs 1993-2017	R0, sigmaR, steepness, rec devs 1993-2022	R0, regime parameter, rec devs 1963-2019
Reproductive potential units	Relative number of eggs	Relative number of eggs	Male and female SSB combined
Length-based Selectivity			
Commercial handline	Dome shaped	Dome shaped*	Logistic
Commercial longline	Dome shaped	Logistic*	Logistic
Commercial trap	Dome shaped	Dome shaped	
Recreational (combined)	Dome shaped	Dome shaped*	
Recreational charter			Dome shaped
Recreational headboat			Dome shaped
Recreational private/shore			Dome shaped

Parameter	Red grouper	Red grouper 2025	Gag grouper
Length-based Selectivity			
Age-0 seagrass survey	Dome shaped		Age-0 only
Summer trawl survey	Logistic	Dome shaped	
Bottom longline survey	Dome shaped	Logistic	
Charter/private survey	Logistic		
FWRI vertical line survey	Logistic		
Combined video survey		Logistic	Logistic
SEAMAP video survey			Dome shaped
Panama City video survey			
Time-varying Retention	Commercial handline Commercial longline Commercial trap Recreational	Commercial handline Commercial longline Commercial trap Recreational	Commercial handline Commercial longline Recreational charter Recreational headboat Recreational private/ shore
Catchability	8 indices	6 indices	7 indices
Dirichlet multinomial	N/A	7	10
Red tide mortality rate (coefficient of variation)			
2005	0.34 year^{-1} (0.31)	0.17 year^{-1} (0.53)	0.74 year^{-1} (0.16)
2014	0.26 year^{-1} (0.43)	0.20 year^{-1} (0.46)	0.91 year^{-1} (0.22)
2018	N/A	0.04 year^{-1} (2.04)	0.07 year^{-1} (3.30)
2021	N/A	0.10 year^{-1} (1.61)	N/A
Red tide kill in numbers (%); in biomass (%)			
2005	35.9 million (23%); 7,137 metric tons (30%)	5.9 million (12%); 4,741 metric tons (14%)	7.8 million (41%); 7,426 metric tons (52%)
2014	13 million (19%); 5,292 metric tons (21%)	5.0 million (6%); 3,918 metric tons (13%)	4.8 million (48%); 4,723 metric tons (63%)
2018	N/A	2.1 million (3%); 733 metric tons (3%)	0.3 million (6%); 281 metric tons (7%)
2021	N/A	6.7 million (6%); 1,539 metric tons (5%)	N/A

Table 2. Comparison of stock status across red four projection scenarios incorporating different assumed baseline red tide mortality rates of 0, 0.01, 0.02, and 0.04 within the projections for the 2025 Gulf Red Grouper assessment model. Spawning stock biomass units are in relative number of eggs.

Definition	Base (Red Tide = 0)	Red Tide = 0.01	Red Tide = 0.02	Red Tide = 0.04
Mortality Rate Criteria				
Equilibrium F that achieves an SPR of 40% ($F_{MSYproxy}$ = MFMT)	0.156	0.142	0.128	0.1
$F_{current}$ (geometric mean of 2020-2022; excludes red tide mortality in 2021)	0.073	0.073	0.073	0.073
$F_{current}$/MFMT	0.473	0.518	0.574	0.733
Biomass Criteria				
Equilibrium SSB when fishing at $F_{SPR40\%}$ ($SSB_{MSYproxy}$)	504,435	504,428	504,435	504,439
MSST = 0.5 * $SSB_{SPR40\%}$	252,218	252,214	252,218	252,220
$SSB_{current}$ (SSB in 2022)	660,063	660,063	660,063	660,063
$SSB_{current}$/MSST	2.62	2.62	2.62	2.62
Yield				
Equilibrium Yield (million pounds gutted weight)	6.886	6.269	5.654	4.428

Figures

Figure 1. Example simulation of baseline (yellow) and true red tide mortality estimates (purple) in the future for the 100-year equilibrium projection. In this instance, the true red tide mortality estimates average out to 0.01 over the entire projection period, with 15 red tides occurring randomly (simulated range of 5 to 20) and being drawn from a uniform distribution. The baseline red tide mortality value is held constant at a fixed rate of 0.01 throughout the projection period in this scenario.

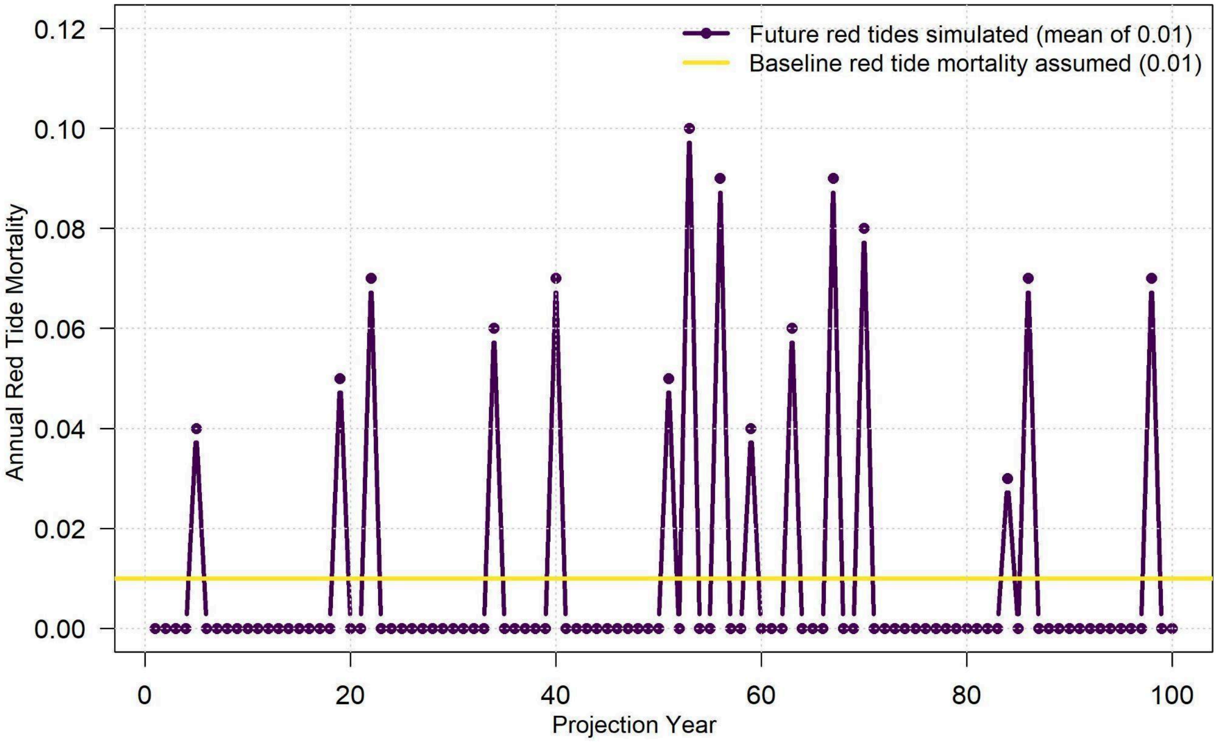


Figure 2. Estimated instantaneous mortality rates for red grouper (left panels) and gag grouper (right panels) by fishing fleet and by severe red tide events (yellow lines). The bottom panels show alternate average red tide mortality rates calculated for each species and used to determine simulation ranges (note that the y-axis is abbreviated; the full extent of red tide mortality is shown in the top panels).

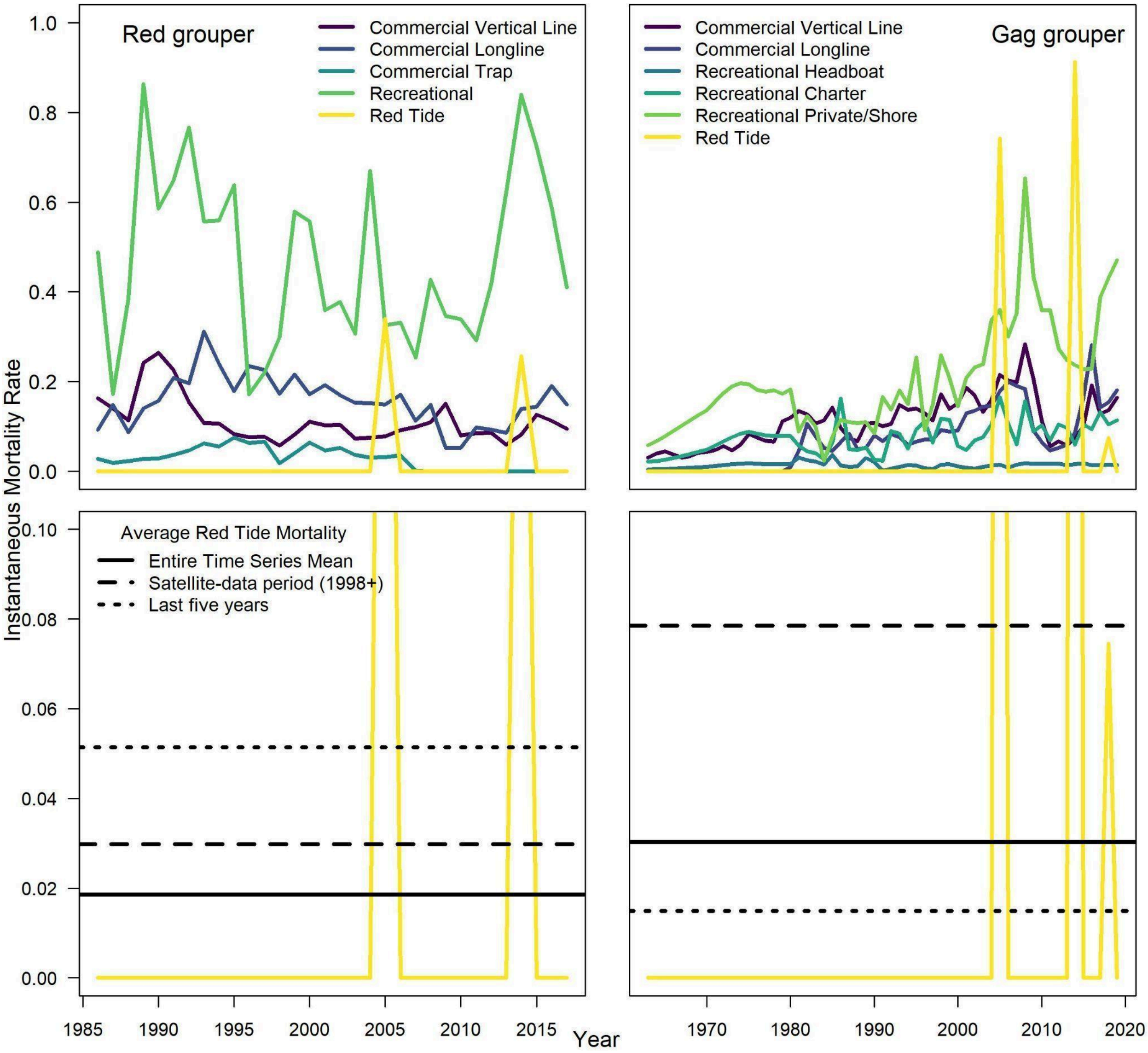


Figure 3. Historic (1986-2017; black line) and simulated red grouper fishery outcomes under four projection scenarios incorporating different assumed baseline red tide mortality rates of 0, 0.01, 0.03, and 0.06. In this instance, true future red tide mortality occurred randomly with an average annual rate of 0.03.

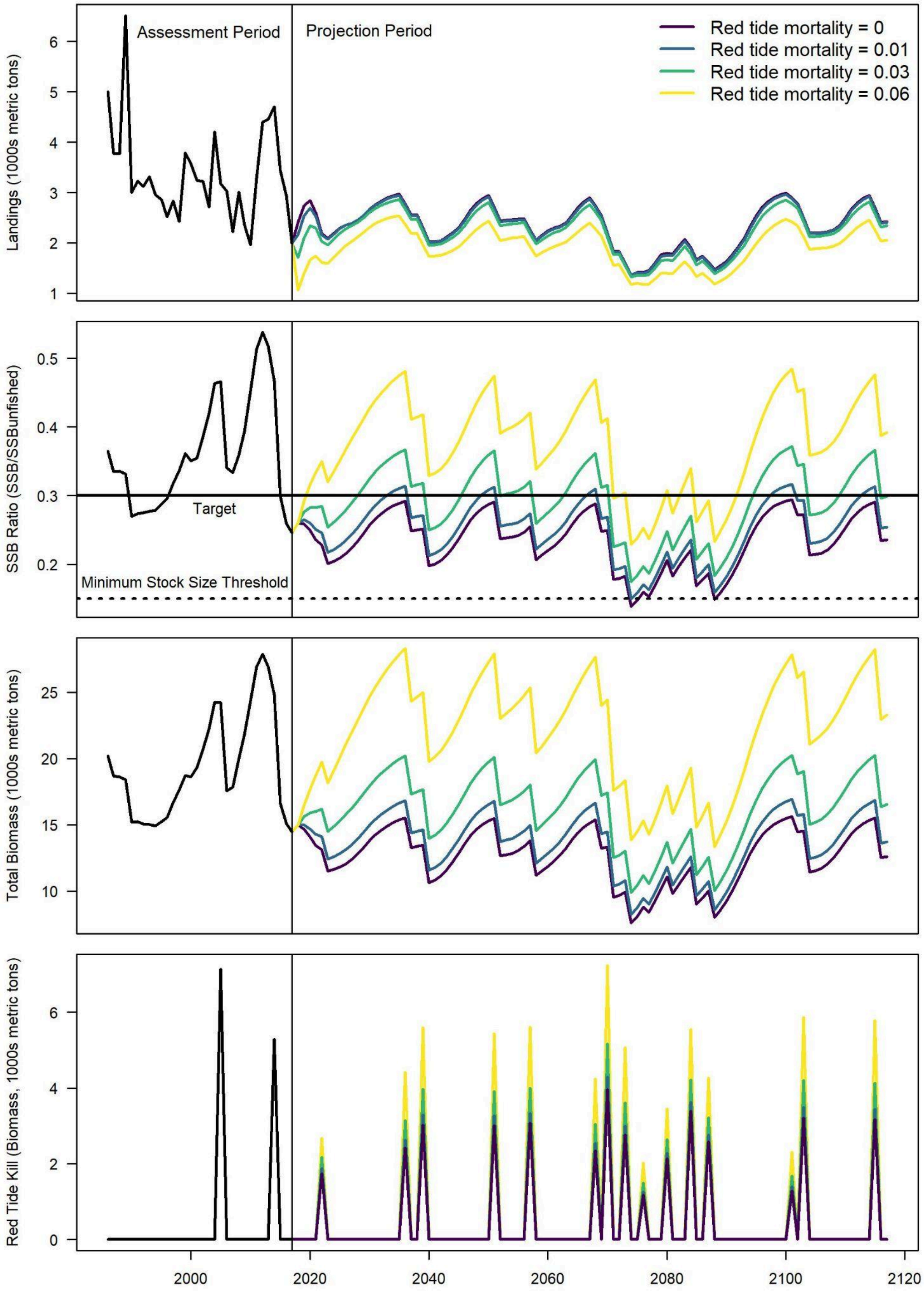


Figure 4. Comparison of simulated trajectories (averaged within each baseline red tide mortality level shown in the legend in the top-right panel) for red grouper for the 100-year projection period across three true red tide mortality values (RTM). Outputs shown include landings (in 1000s of metric tons), SSB ratio (SSB/SSBunfished), total biomass (in 1000s of metric tons), and the biomass killed by red tide (in 1000s of metric tons). Colors gradually change from the lowest (purple) to the highest (yellow) baseline red tide mortality levels.

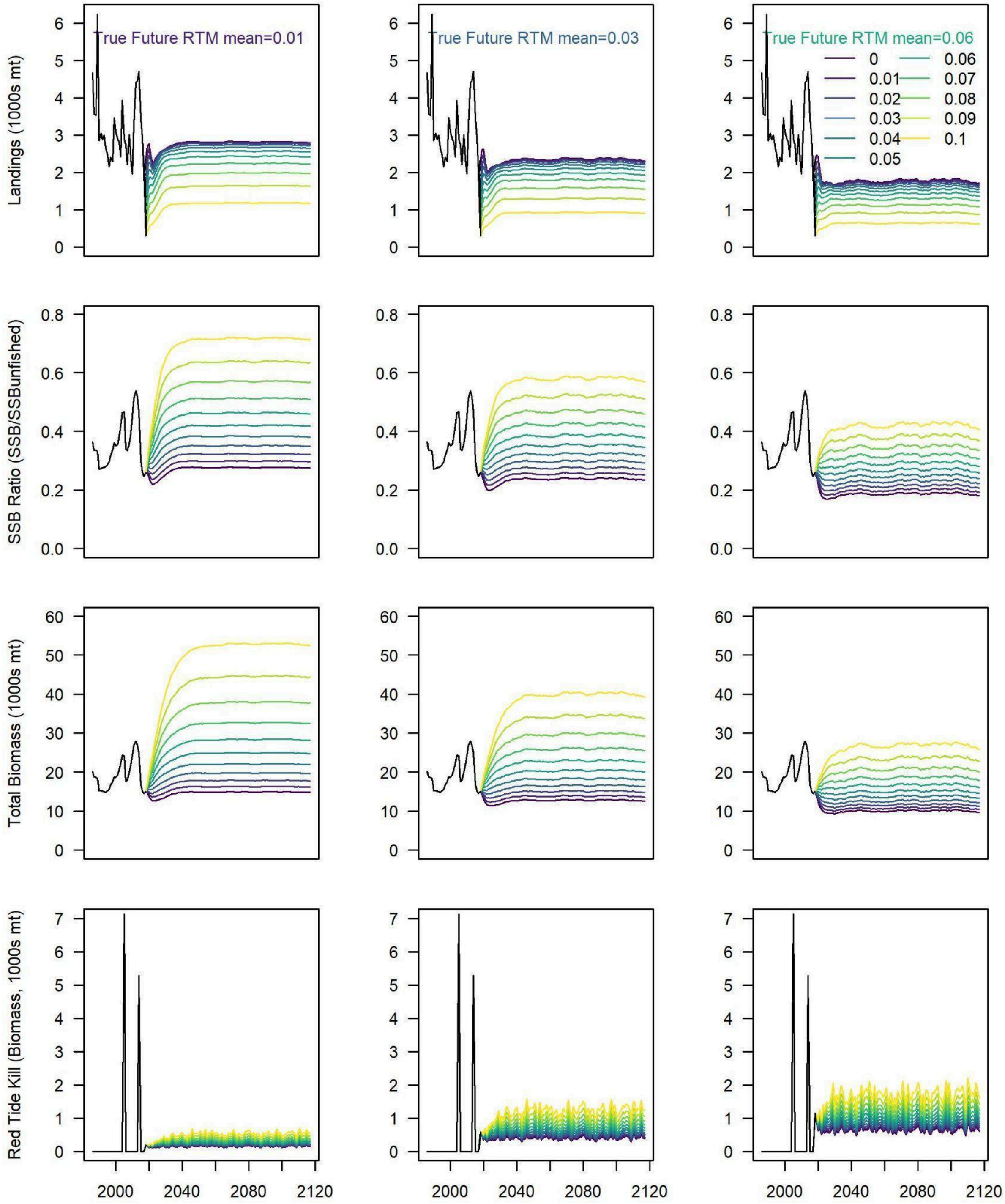


Figure 5. Historic (1962-2019; black line) and simulated gag grouper fishery outcomes under four projection scenarios incorporating different assumed baseline red tide mortality rates of 0, 0.01, 0.03, and 0.06. In this instance, true future red tide mortality occurred randomly with an average annual rate of 0.03.

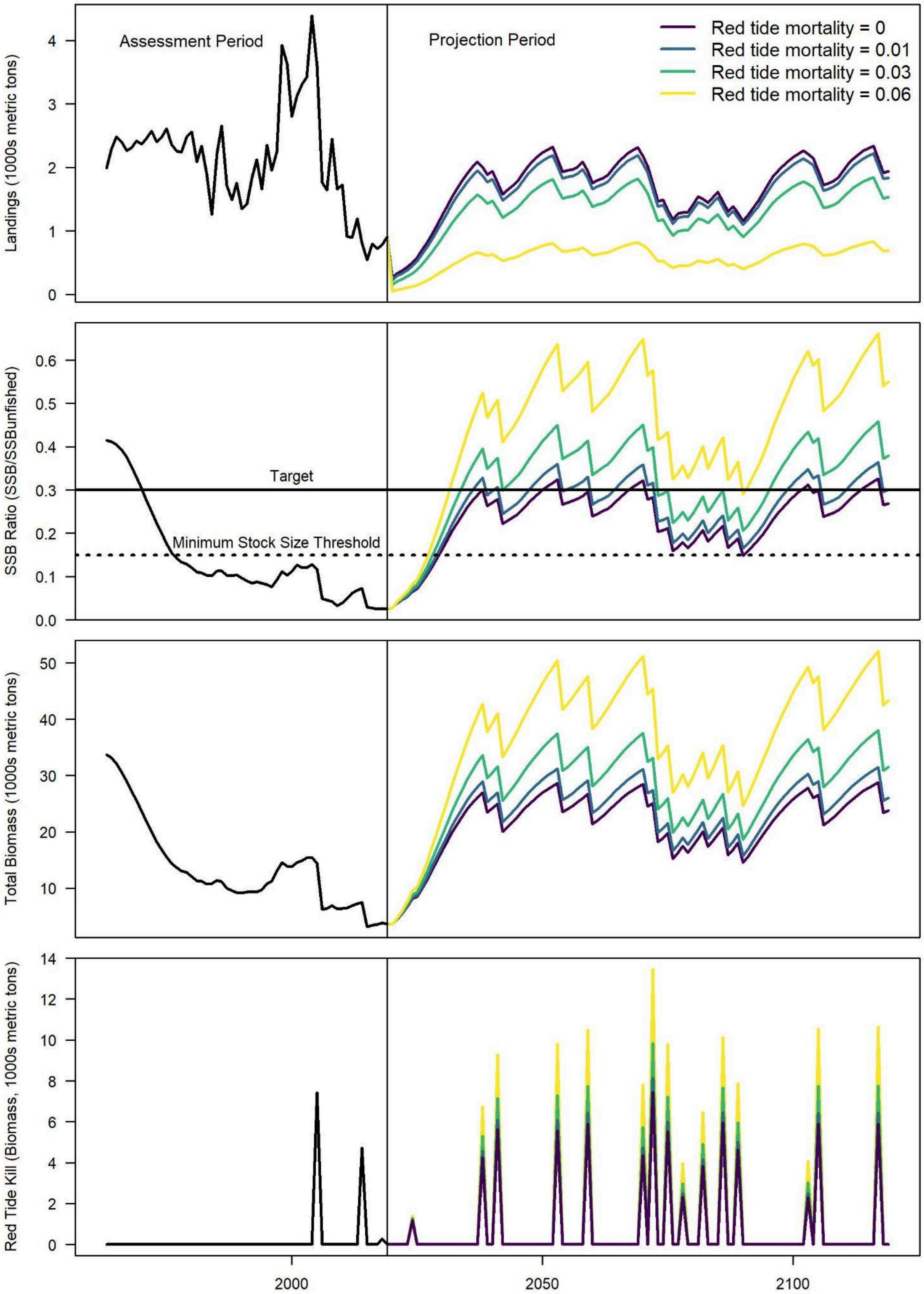


Figure 6. Comparison of simulated trajectories (averaged within each baseline red tide mortality level shown in the legend in the top-right panel) for gag grouper for the 100-year projection period across three true red tide mortality values (RTM). Outputs shown include landings (in 1000s of metric tons), SSB ratio (SSB/SSBunfished), total biomass (in 1000s of metric tons), and the biomass killed by red tide (in 1000s of metric tons). Colors gradually change from the lowest (purple) to the highest (yellow) baseline red tide mortality levels.

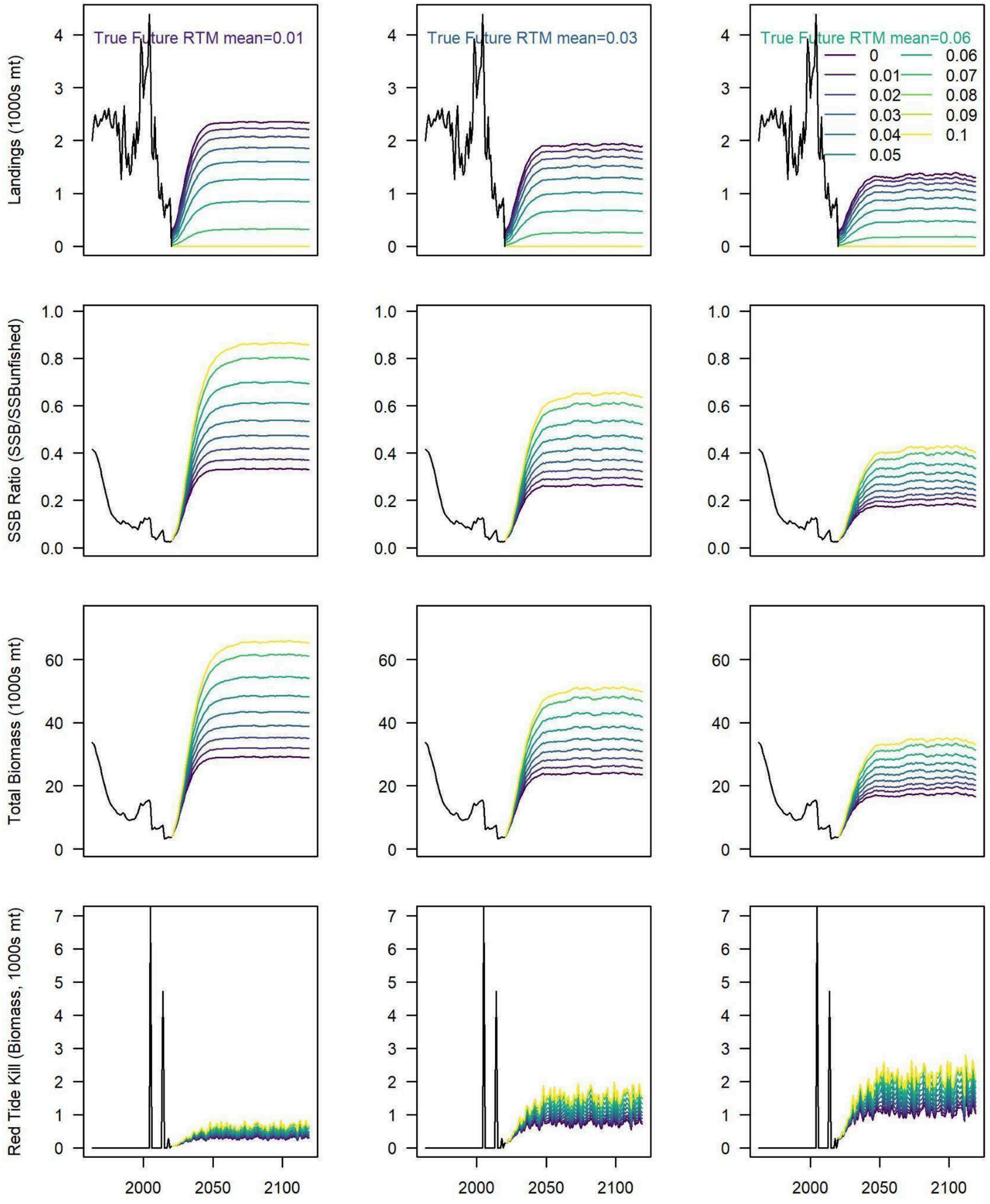
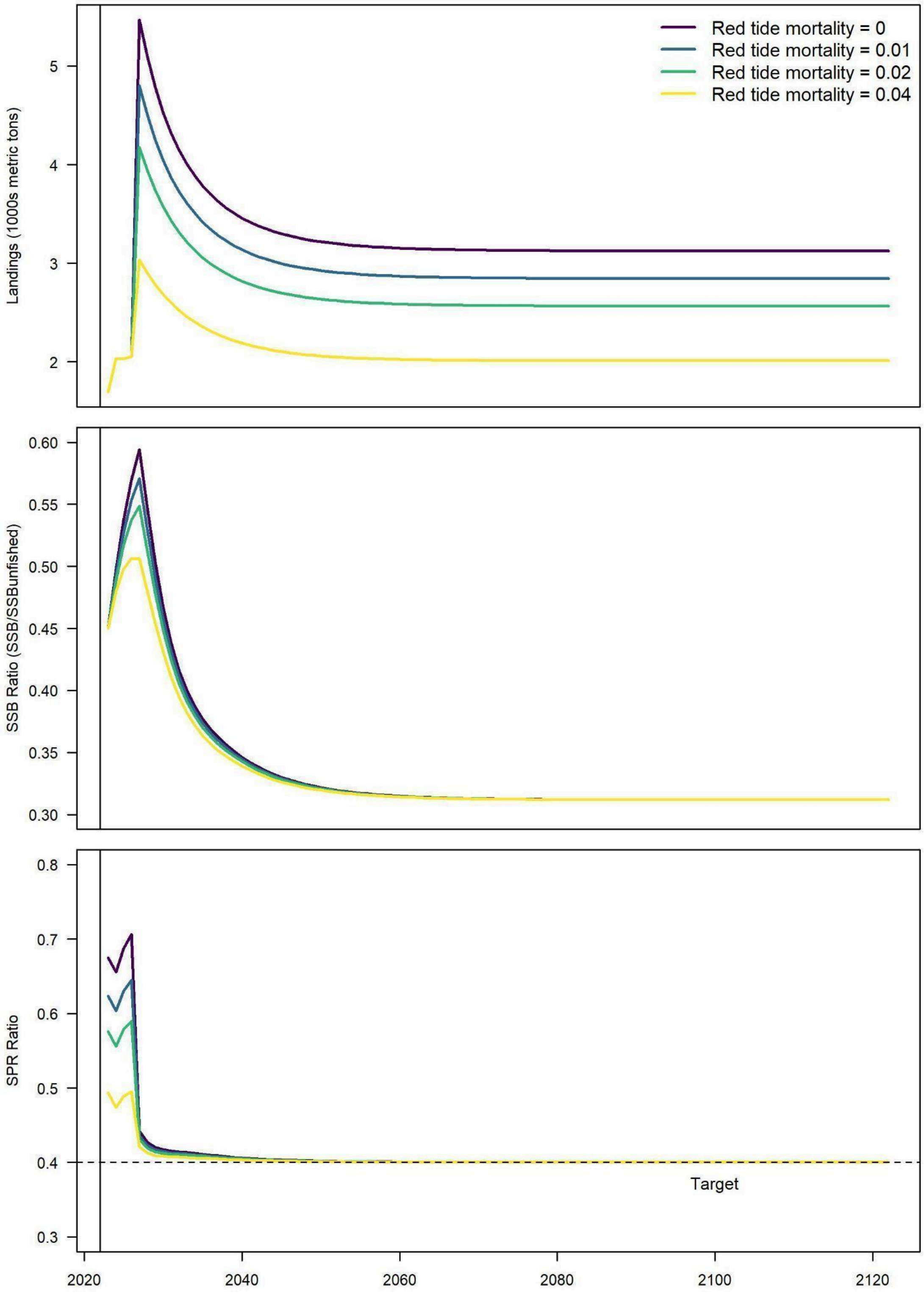


Figure 7. Projected red grouper dynamics from the 2025 assessment under four projection scenarios incorporating different assumed baseline red tide mortality rates of 0, 0.01, 0.02, and 0.04.



Supplemental Material

Figure S1. Data inputs for the red grouper (top) and gag grouper (bottom) assessment models. Circle area is relative within a data type and therefore not comparable between data types. Circles are proportional to total catch for catches; to precision for indices and discards observations; and to total sample size for compositions. Plot produced using the r4ss package (Taylor et al. 2021).

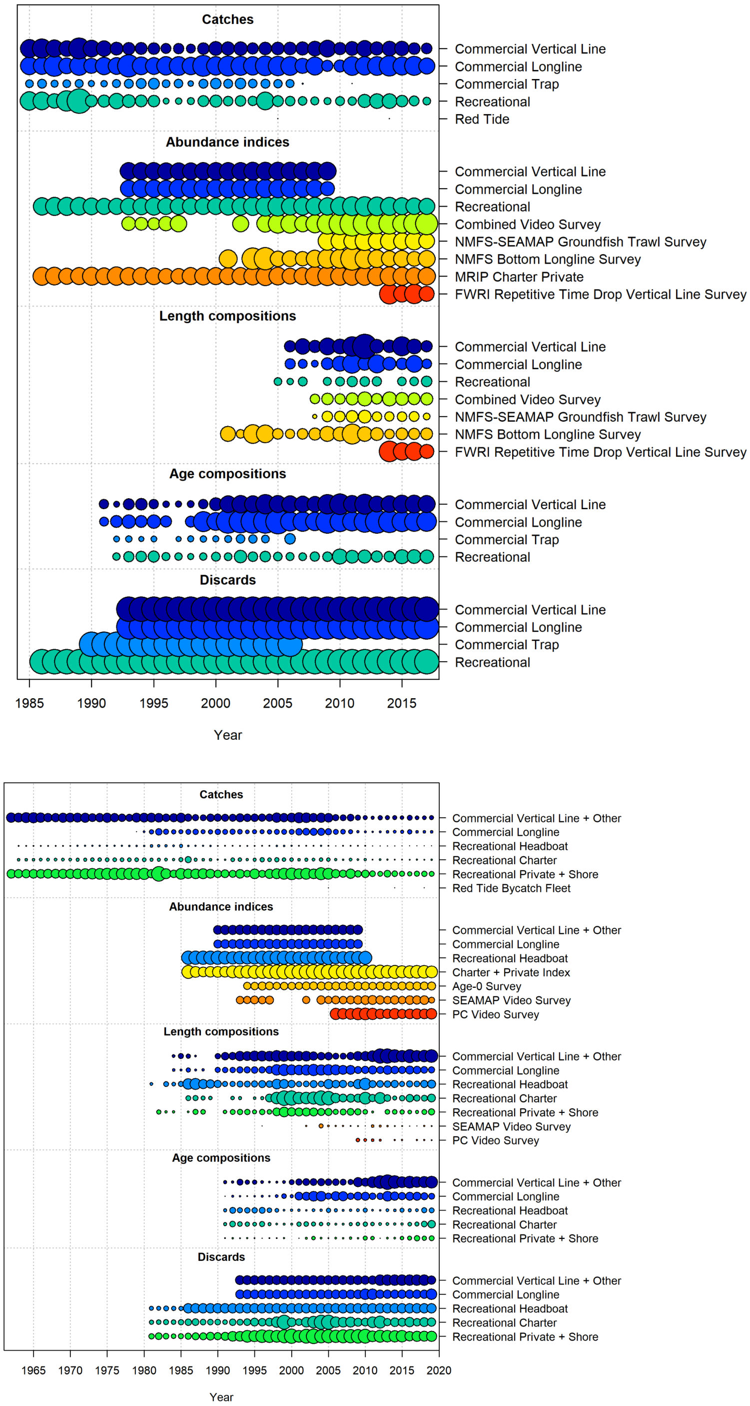


Figure S2. Comparison of all simulated trajectories for red grouper for the 100-year projection period across three true red tide mortality values (RTM). Outputs shown include landings (in 1000s of metric tons), SSB ratio (SSB/SSBunfished), total biomass (in 1000s of metric tons), and the biomass killed by red tide (in 1000s of metric tons).

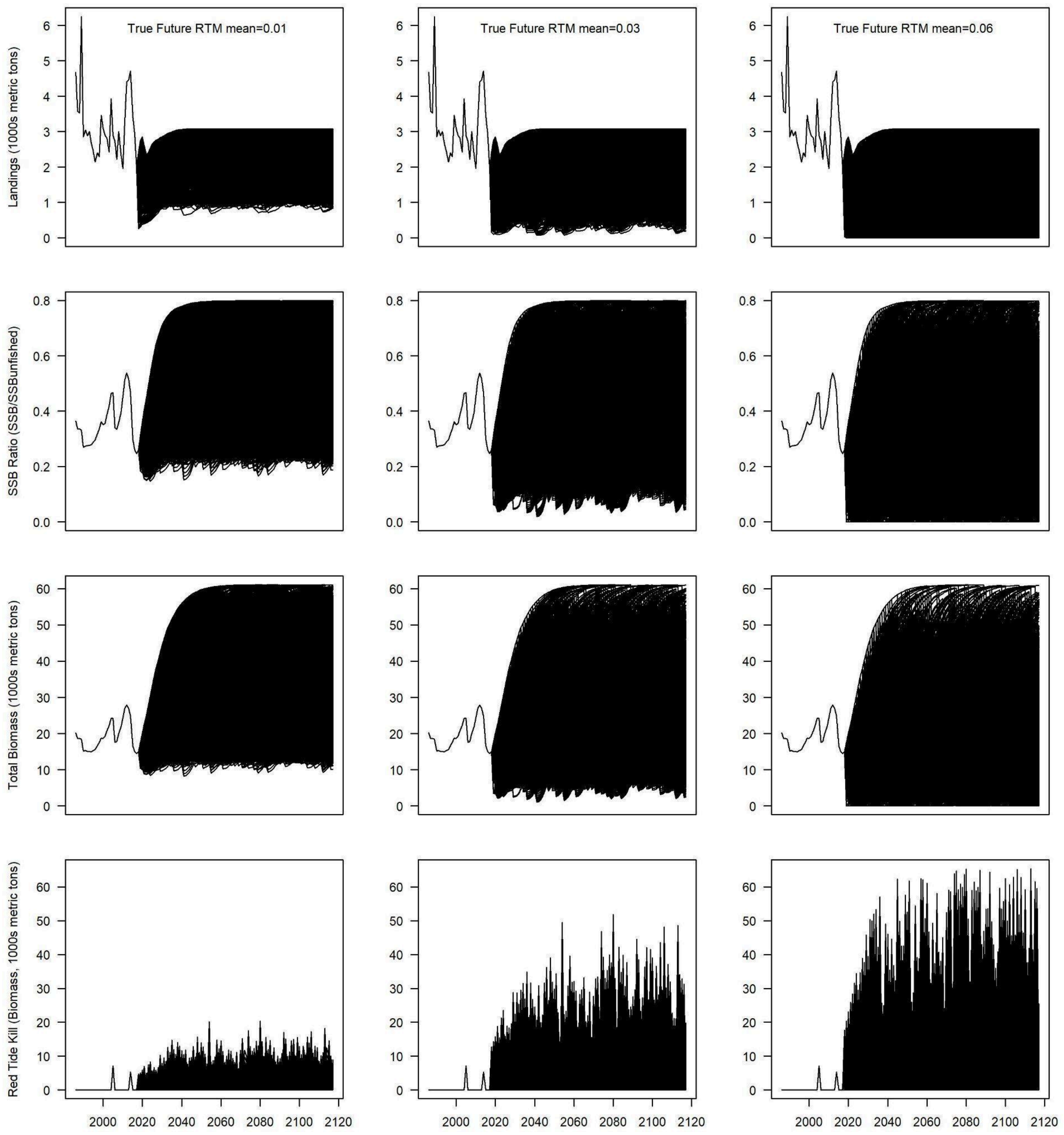


Figure S3. Comparison of a subset of simulated trajectories (five per baseline) for red grouper for the 100-year projection period across three true red tide mortality values (RTM). Outputs shown include landings (in 1000s of metric tons), SSB ratio (SSB/SSBunfished), total biomass (in 1000s of metric tons), and the biomass killed by red tide (in 1000s of metric tons). Colors gradually change from the lowest (purple) to the highest (yellow) baseline red tide mortality levels as shown in the legend in the bottom-left panel.

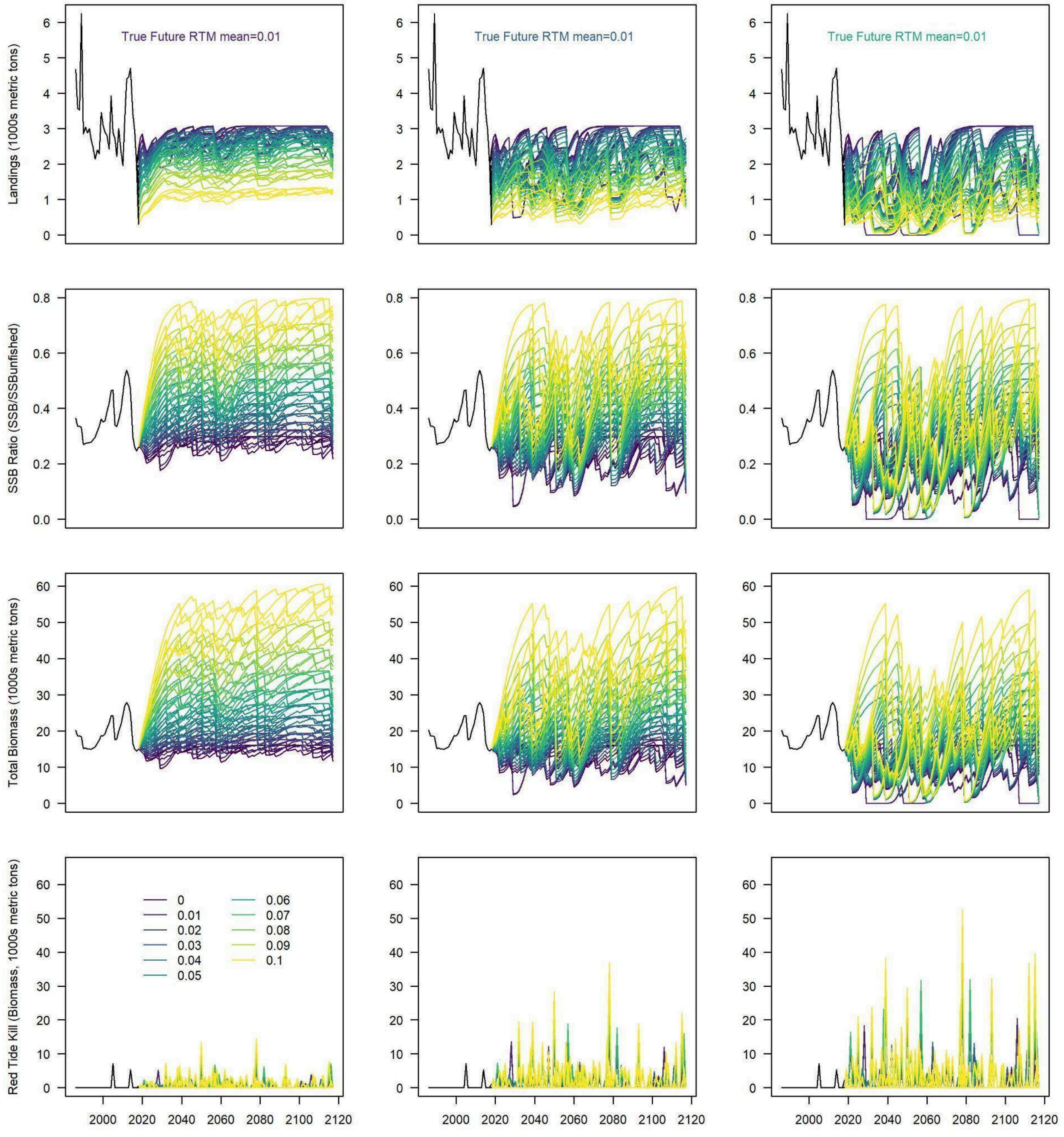


Figure S4. Summary statistics of simulated trajectories for red grouper for the 100-year projection period across three true red tide mortality values (RTM). Outputs shown include landings (in 1000s of metric tons), SSB ratio (SSB/SSBunfished), total biomass (in 1000s of metric tons), and the biomass killed by red tide (in 1000s of metric tons). Solid black lines identify the median across 500 simulations whereas the purple and yellow shaded areas bound the 95% and 50% confidence intervals, respectively.

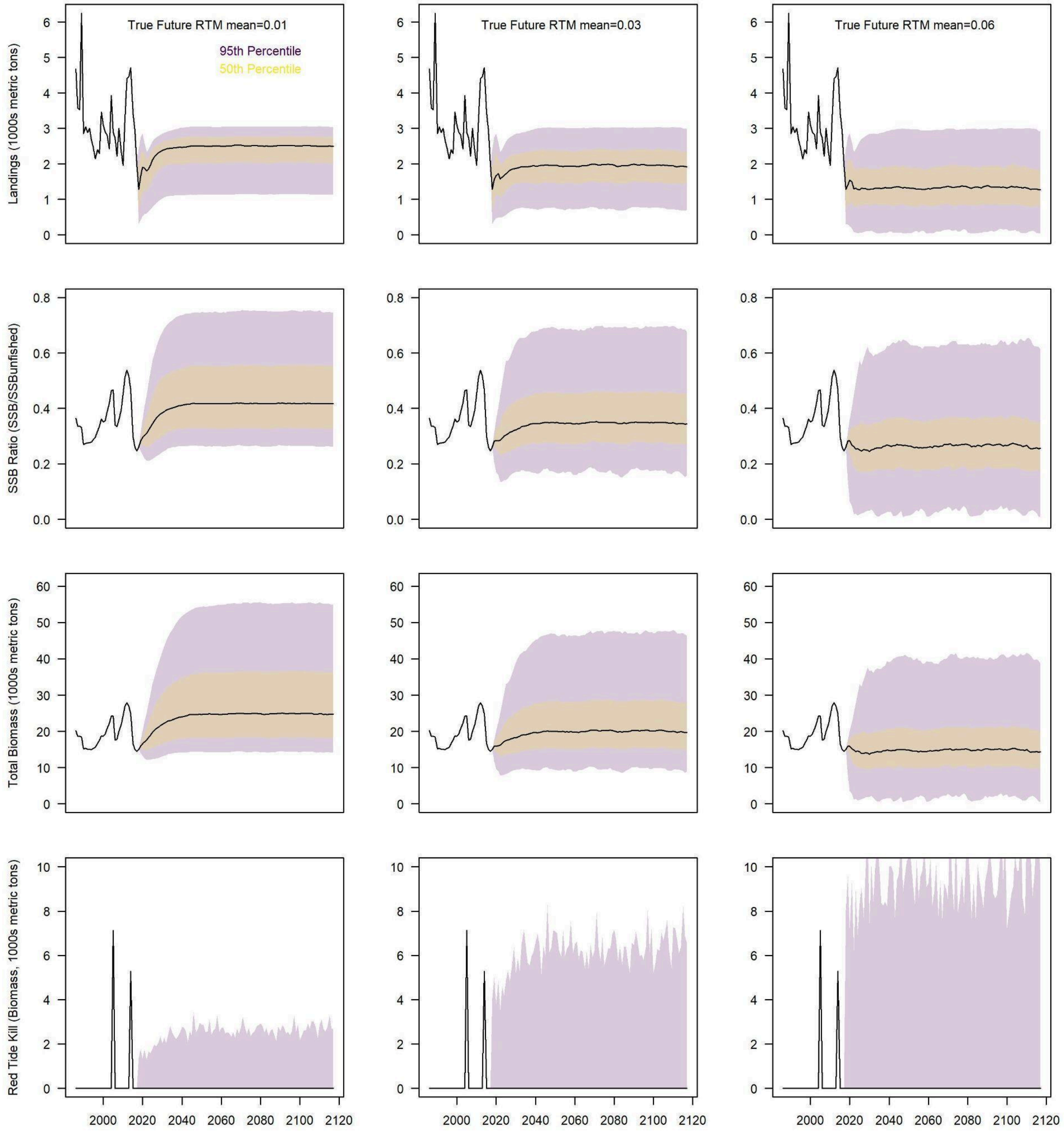


Figure S5. Comparison of all simulated trajectories for gag grouper for the 100-year projection period across three true red tide mortality values (RTM). Outputs shown include landings (in 1000s of metric tons), SSB ratio (SSB/SSBunfished), total biomass (in 1000s of metric tons), and the biomass killed by red tide (in 1000s of metric tons). Note that a few simulations did not converge in the right-most column.

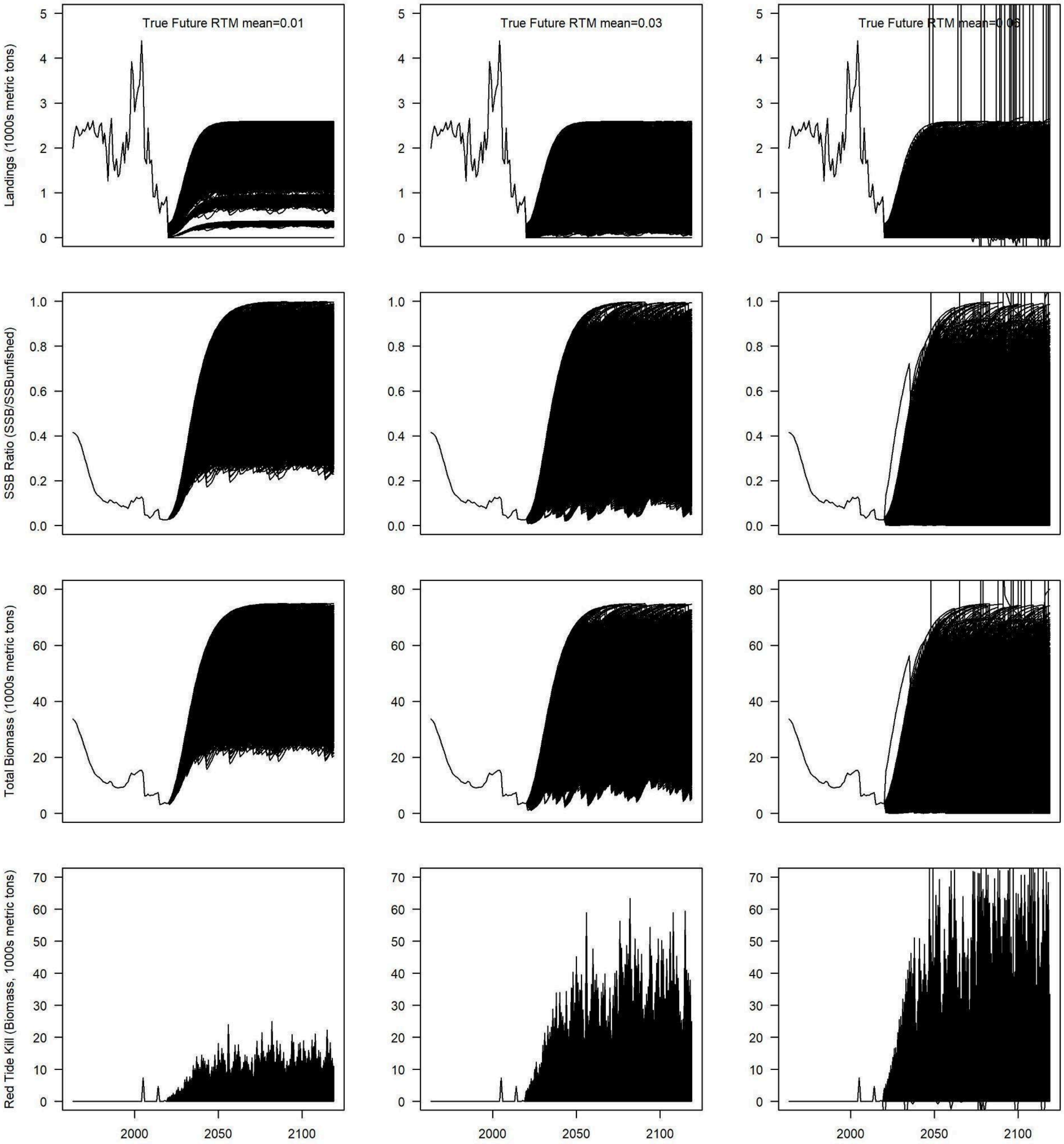


Figure S6. Comparison of a subset of simulated trajectories (five per baseline) for gag grouper for the 100-year projection period across three true red tide mortality values (RTM). Outputs shown include landings (in 1000s of metric tons), SSB ratio (SSB/SSBunfished), total biomass (in 1000s of metric tons), and the biomass killed by red tide (in 1000s of metric tons). Colors gradually change from the lowest (purple) to the highest (yellow) baseline red tide mortality levels as shown in the legend in the top-right panel.

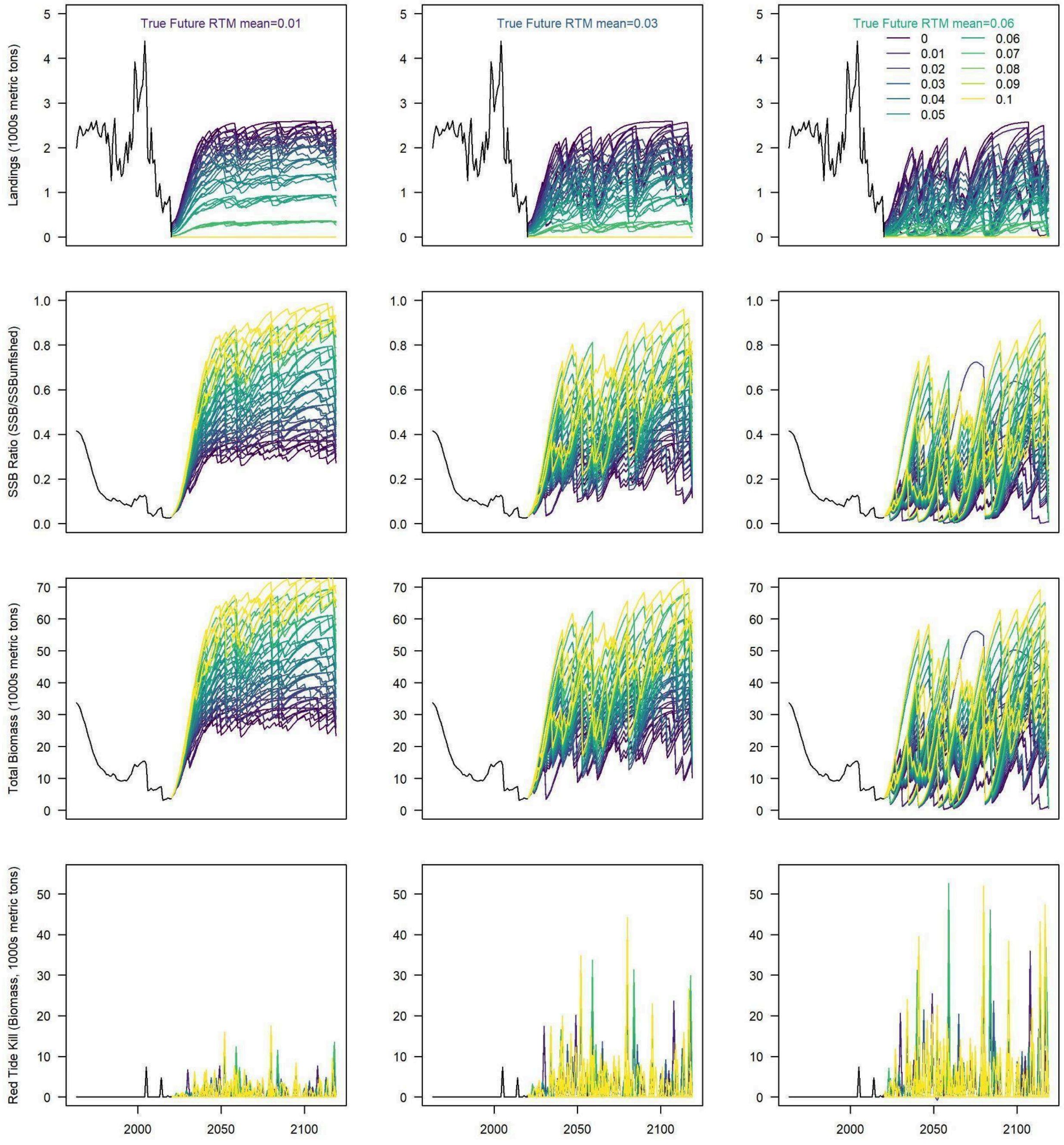


Figure S7. Summary statistics of simulated trajectories for gag grouper for the 100-year projection period across three true red tide mortality values (RTM). Outputs shown include landings (in 1000s of metric tons), SSB ratio (SSB/SSBunfished), total biomass (in 1000s of metric tons), and the biomass killed by red tide (in 1000s of metric tons). Solid black lines identify the median across 500 simulations whereas the purple and yellow shaded areas bound the 95% and 50% confidence intervals, respectively.