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conservation law foundation

For a thriving New England

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Dear Sirs:

Conservation Law Foundation ("CLF") submitted a petition for rulemaking to end overfishing and rebuild Atlantic cod on February 13, 2020 under 5 U.S.C. § 553(e) of the Administrative Procedure Act. We also submitted a supplement to that petition, which included three attached documents, on June 24, 2020. Given that a final decision on the merits of our petition has not yet been made, we submit a second supplement for inclusion in the record of your review of CLF's petition containing scientific information not previously available.[1]

Please consider the attached draft report from Kerr, *et. al.* titled "Evaluating the Impact of Inaccurate Catch Information on New England Groundfish Management" as an additional

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[1] CLF submitted its petition for rulemaking and now this additional supplement under 5 U.S.C. § 553(e) of the Administrative Procedure Act. We are seeking to compel the National Marine Fisheries Service to end overfishing of Atlantic cod immediately and rebuild the two stocks in this fishery in as short a time as possible as required by the Magnuson-Stevens Fishery Conservation and Management Act. *See* 16 U.S.C. §§ 1853(a)(1)(A) and 1854(e)(3) & (4).

supplement to our February 13, 2020 petition and as part of the basis for your final agency action on the petition. This report, while still in draft form, is critical to understanding the impacts that lack of monitoring and accountability in New England's groundfish fishery have had on the management of Atlantic cod stocks as pursuant to the Magnuson-Stevens Fishery Conservation and Management Act ("MSA"). The draft report states:

> The goal of [the] analysis was to simulation-test a range of underestimated catch scenarios and evaluate the impact on the performance of the stock assessment and management. This analysis focused on Gulf of Maine cod as a representative species in the groundfish complex because it has had discard incentives, potentially underestimated catch, and uncertainties in its stock assessment . . . **[The analysis] demonstrated that inaccurate catch information has the potential to impact stock trajectories, assessment and management performance of Gulf of Maine cod**.[2]

While the draft report does not quantify the amount of "missing catch," it is clear that bias in catch estimates—bias that is known to exist in the New England groundfish fishery due to observer effects and economic incentives to discard[3]—negatively affects science and management. On the other hand, the draft report demonstrates that fully accounting for catch can lead to faster rebuilding, more accurate stock assessments, greater landings, and more effective management.

In the design of the simulation test, Kerr, *et. al.* relied on analysis by the Groundfish Plan Development Team ("PDT") included in the Amendment 23 Draft Environmental Impact Statement.[4] Please also consider this analysis titled "Magnitude of potential 2018 missing Gulf of Maine cod discards" (attached) as part of the basis for your final agency action on the petition. Using Gulf of Maine cod as an example, the PDT's analysis[5] is an investigation into the possible missing catch for the stock in 2018 due to illegal discards and concludes:

> [T]he results of the analysis indicate a possible upper bound multiplier of 2.3 times GOM cod landings, roughly 1,100 thousand pounds (~498mt) of missing

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[2] Kerr LA, Weston AE, Mazur M, and Cadrin SX. *Evaluating the Impact of Inaccurate Catch Information on New England Groundish Management* (DRAFT). Available at: https://s3.amazonaws.com/nefmc.org/2.-Report_-Eval_of_Inaccurate-Catch_7.15.20.pdf (emphasis added).

[3] *See* CLF petition for rulemaking for more details.

[4] *See* NEFMC. *Draft Amendment 23 to the Northeast Multispecies Fishery Management Plan including a Draft Environmetnal Impact Statement.* Formal Submission Draft dated March 4, 2020. Available at: https://s3.amazonaws.com/nefmc.org/200304_Draft_Groundfish_A23_DEIS_formal_submission_corrected_200312.pdf.

[5] *Id.* at 300-304; The analysis uses data from large-mesh trawl gear sector trips or sub-trips.

landings (or missing legal-sized discards), with an uncertainty range of 1.5 to 2.5,[6] or about 700 thousand pounds to 1,200 thousand pounds (~317mt to 544mt).[7]

Overall, this science reinforces the need for the agency to assert direct controls over the cod fishery, which has failed for so long to achieve the MSA's minimum requirements. Thank you for taking this supplementary information under consideration. Please do not hesitate to reach out to us with any questions you may have.

Sincerely,

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[6] In fact, the maximum multiplier calculated was as high as 3.24x.

[7] *Id.* at 304.

DRAFT

Evaluating the Impact of Inaccurate Catch Information on New England Groundfish Management

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1. Executive Summary

Underestimation of catch is a common problem in fisheries globally and has been an issue in the New England groundfish fishery. In response to this problem, the New England Fishery Management Council is considering increasing monitoring of the fishery to improve the accuracy of catch information. The goal of our analysis was to simulation-test a range of underestimated catch scenarios and evaluate the impact on the performance of the stock assessment and management. This analysis focused on Gulf of Maine cod as a representative species in the groundfish complex because it has had discard incentives, potentially underestimated catch, and uncertainties in its stock assessment. We examined the impact of a range of catch bias scenarios under two operating models with alternative natural mortality assumptions, two harvest control rules (sliding and constant fishing mortality), and two assumptions of the period of catch bias and (constant and a change over time). Through simulation testing, we demonstrated that inaccurate catch information has the potential to impact stock trajectories, assessment and management performance of Gulf of Maine cod. Scenarios with no catch bias exhibited accelerated rebuilding of the Gulf of Maine cod stock and were characterized by accurate stock assessment performance and effective management. Scenarios that assumed Gulf of Maine cod have higher natural mortality did not achieve the same rebuilding and management outcomes as observed under the lower natural mortality assumption. Under scenarios of constant catch bias, assessments exhibited consistent underestimation of recruitment and spawning stock biomass, and the magnitude of underestimation increased with increased bias in catch. However, fishing mortality estimates remained unbiased because they were informed by unbiased age composition. Under scenarios with a changepoint in catch bias, assessments initially performed well for 10-15 years after the changepoint and then performance increasingly degraded. Retrospective patterns the stock assessment (i.e., a systematic decrease in updated estimates of spawning stock biomass and increase in updated estimates of fishing mortality) resulted from changepoint catch bias scenarios, but not from constant catch bias scenarios. Estimated stock status was similar to “true” stock status determinations under constant catch bias scenarios, but changepoint catch bias scenarios exhibited instances of misperceived stock status. Results suggest that high to extreme bias in catch reporting was detrimental to sustainable management, however, catch reporting bias <50% had more limited impacts on assessment and management performance in the context of risk averse management. In general, the impacts of catch bias scenarios were similar across alternative harvest control rules with key differences in the

performance of the constant harvest control rules in the short-term (1-5 projection years) due to higher fishing mortality during this period. It is important to recognize the caveats and limitations of this analysis and that the results are contingent on the specification of the models and scenarios. This study provides a demonstration of the potential impact of underestimation of catch that can provide guidance to managers on the magnitude and direction of the impact of bias in catch reporting.

2. Background

Fisheries management decisions are informed by stock assessments which incorporate catch and survey time series, as well as biological information, to estimate the exploitable biomass of stocks. Accurate catch data, as well as correct specification of models (i.e., valid model assumptions, Francis 2011), are critical to ensuring that fish stocks are assessed accurately and that catch limits prevent overfishing. Misreported catch is a problem for many fisheries globally because of common problems with monitoring, enforcement, and the economic incentives driving this behavior (Agnew et al. 2009). The approach to monitoring fisheries is one aspect of a fisheries management procedure that can be evaluated to assess its impact on the goals of sustainable fisheries management (Rudd and Branch 2016). Management strategy evaluation can be used to evaluate the impact of misreported catch on stock assessment results and management recommendations.

Groundfish stocks in New England are managed under the Northeast multispecies groundfish federal fishery management plan (FMP) by the New England Fishery Management Council (NEFMC). The current groundfish monitoring program includes catch reports from fishermen and dealers, as well as estimates of discards based on data provided by at-sea observers on a portion of trips (10-35% of trips; Demarest 2019). The use of observed trips to infer total discards for the fishery assumes that these trips are representative of unobserved trips. Recent analyses suggest that this assumption may not be valid, resulting in underestimation of the total catch (McNamee et al. 2019). The NEFMC is considering adjusting the groundfish monitoring program through Amendment 23 to the Northeast Multispecies FMP with the aim of improving the reliability and accountability of catch reporting and to ensure a precise and accurate representation of catch (landings and discards; NEFMC 2020). In considering this action, the NEFMC reviewed analyses conducted by the Groundfish Plan Development Team (PDT) relevant to Amendment 23 issues.

The Groundfish PDT conducted a series of analyses of groundfish monitoring that evaluated the assumption that observed trips are representative of unobserved trips and that the current approach to quantifying fishery discards enables accurate accounting of total catch. Henry et al. (2019) identified changes in discard incentives by stock and fishing year and documented positive incentives to discard certain species within the groundfish fishery in certain years (e.g., Atlantic cod). Demarest (2019) documented significant differences in the operation of fishing vessels in the groundfish fishery between observed and unobserved trips, suggesting that fishing behavior is altered when a human observer is onboard. Linden (2019) used a predictive model based on observed trips to predict catch on unobserved trips and identified differences between the predicted and reported catch. Finally, Nitschke (2019a) compared the stock landings to effort and total catch ratios on observed and unobserved trips and found differences between observed and unobserved trips that support the presence of an observer effect. These analyses provide evidence of an observer effect on groundfish trips and suggest that estimating discards on unobserved trips based on observed trips may not be accurate and could result in an underestimation of total discards (McNamee et al. 2019). The analyses did not provide a precise quantification of the magnitude of underestimated discards, making it challenging to understand the potential impact on stock status determination and catch advice for groundfish stocks.

In response to this issue, the NEFMC is considering increasing monitoring in the groundfish fishery to improve the accuracy of catch information. One of the potential benefits of increased monitoring (e.g., observer or electronic monitoring) is improvement in the accuracy of stock assessments and the effectiveness of catch advice. However, increased monitoring is costly and there are limited analyses that demonstrate the impact of underestimated catch on fisheries management performance (e.g., Rudd and Branch 2016).

The goal of this analysis was to simulation test a range of underestimated catch scenarios and evaluate the impact on the performance of the stock assessment and fisheries management. This analysis focused on Gulf of Maine cod as a representative species in the groundfish complex for which discard incentives and accuracy of catch information are thought to be an issue as it is a constraining stock in the fishery (Nitschke 2019b). We examined the impact of catch bias, simulating different levels and timing scenarios, in the context of Gulf of Maine cod operating models with alternative natural mortality assumptions and management under two alternative harvest control rules (i.e., sliding and constant fishing mortality).

3. Methods

We used a closed-loop simulation model framework to test alternative scenarios of underestimated catch. The approach involves simulating the natural and human aspects of the managed fishery resource system. In this context, the perceived status of the resource triggers action based on a management procedure, and subsequent management decisions in-turn affect fishing activities and feedback on the resource (Punt et al. 2016). The framework consists of: 1) operating models, designed to emulate stock dynamics, and 2) management procedures that include an observation model (i.e., designed to emulate generation of survey and harvest data), a stock assessment fit to simulated fishery and survey data, estimated biological reference points, and a harvest control rule that determines catch advice. Using this framework, we simulated a range of underestimated catch scenarios through introduction of bias in catch reporting (i.e., observation bias) and bias in the implementation of catch advice, such that catch exceeded levels prescribed by catch advice (i.e., implementation bias). Models were written in the R statistical programming language (R Core Team, 2019) and code was version controlled through a GitHub repository that included technical documentation.

3.1. Operating models

We developed two operating models that emulated the two accepted stock assessment models for Gulf of Maine cod (NEFSC 2019). These models differed in their assumption of natural mortality, the M = 0.2 model (i.e., natural mortality = 0.2) and the M-ramp model (i.e., natural mortality increased from 0.2 to 0.4 during the time series). The operating models were age-structured (ages 1-9+) stochastic models designed to emulate the population dynamics of Gulf of Maine cod. In the context of the simulation framework, the operating models represented versions of the “true” dynamics of the resource and provide “perfect” knowledge of the resource from which we can evaluate the performance of stock assessment and management. Abundance of fish at age over time was calculated based on exponential survival (Eqn. 1, Table 1). Spawning stock biomass was a function of abundance-at-age, weight-at-age, and maturity-at-age of fish (Eqn. 2, Table 1). Recruitment was modeled using an empirical cumulative distribution function with a linear decline to zero at zero spawning stock (Eqn. 3, Table 1). Catch by the fishery was calculated as a function of the Baranov catch equation (Eqn. 4, Table 1).

The models were parameterized based on the most recent stock assessment update and benchmark assessment for Gulf of Maine cod (NEFSC 2013, NEFSC 2019, Table 2). Growth was modeled using a time invariant weight-at-age vector and maturity-at-age followed a logistic pattern. These values were consistent with the specification of growth and maturity used in stock assessment projections (Table 3, NEFSC 2019). We modified the stock-recruit relationship used in stock assessment projections of Gulf of Maine cod (NEFSC 2013) to utilize the last 20 years of observed recruitment (1998-2018) in the cumulation distribution function. The original fitting of the stock-recruit relationship used all historically observed recruitments, including extreme high values from the 1980s. This resulted in periodic extreme high recruitment in operating model simulations which were not consistent with moderate to low values of recruitment observed in recent decades. In addition to sampling from this distribution of recruitment, we incorporated a small amount of stochasticity (i.e., process error, Table 2). We modeled the harvest of cod by the fishery as a single fleet (i.e., recreational and commercial combined) consistent with the current stock assessment. Fishery selectivity-at-age was informed by the selectivity-at-age in the most recent stock assessment for the most recent selectivity block (Table 3). The selectivity curve represents the combined recreational and commercial catch.

Historic estimates of fishing mortality and recruitment (1982-2014) from the stock assessments (M = 0.2 scenario and M-ramp scenario) were used to condition the models and emulate estimated stock trajectories (NEFSC 2019). The historic period of the operating models spanned 1982-2014 and served to initialize forward projections starting from the current stock status of Gulf of Maine cod (i.e., overfished and overfishing is occurring; NEFSC 2019). The models were projected forward 36 years, from 2015 to the year 2050, under alternative management procedures.

3.2. Management Procedures

We aimed to emulate the current fishery management procedure of Gulf of Maine cod. The management procedure included: 1) data collection, 2) fitting a stock assessment, 3) estimating biological reference points, and 4) determining catch advice from a harvest control rule. The management procedure was applied starting in 2015.

Observation models

Observation models were designed to simulate collection of fishery dependent and fishery independent data with the characteristics and quality (i.e., uncertainty and bias) that typically inform the Gulf of Maine cod stock assessment. The fishery-dependent data generated included total catch and catch-at-age information. Fishery independent survey data included a survey index of abundance and an index of abundance-at-age.

We simulated data to emulate the Northeast Fisheries Science Center (NEFSC) bottom trawl survey. We modeled the survey index of abundance-at-age and an aggregated index of abundance (summed across ages) as a function of the total abundance available to the survey (i.e., resource abundance in the operating model), catchability of the survey, selectivity-at-age, and observation error (Eqn. 5, Table 4). We assumed lognormal error for the index of abundance and multinomial error for the index of abundance-at-age (Table 2). Survey selectivity-at-age followed a logistic pattern based on stock assessment fit values for the NEFSC spring bottom trawl (Table 3).

We modeled the fishery catch in number as described previously (Eqn. 4, Table 1) and calculated catch and catch-at-age in weight as described in Eqn. 5 and 6 (Table 4). We assumed lognormal observation error on total catch and multinomial errors on catch-at-age (Table 2). We assumed an observation error for the combined commercial-recreational catch based on values used in the Gulf of Maine cod assessment (i.e., CV = 5%). We modeled underestimation in catch reporting as a function of the true catch and a bias term described in detail in the *Underestimated catch scenarios* section (Eqn. 7, Table 4).

Stock Assessment Model

We integrated the current stock assessment model for Gulf of Maine cod, the Age-Structured Assessment Program (ASAP, Legault and Restrepo 1998), into the simulation framework. Model parameters in the estimation model were generally equivalent to those specified in the operating model, such that the assessment model was not mis-specified, except for the assumption of accurate catch for the catch bias scenarios. The weight-at-age, maturity-at-age, natural mortality, number of fleets (Fleets = 1), and selectivity blocks (blocks = 1) modeled were consistent between the operating model and estimation model. Fishery selectivity and survey selectivity-at-age were estimated in the assessment. Index observation error and recruitment process error were set to 0.5 and the CV on catch was consistent between the operating and estimation model (CV = 0.05, Table 2). The assessment accumulated an additional year of data each year the simulation loop was run such that the first assessment was comprised of 33 years of data and the final assessment included 68 years of data. Further detail on specification of ASAP are provided as dat files for the M=0.2 and M-ramp models (Supplementary files).

Biological Reference Points

Biological reference points (BRP) are the criteria by which we determine stock status and inform triggers for management actions in the context of harvest control rules. In the case of Gulf of Maine cod, a F_{MSY} proxy was calculated using a spawning potential ratio approach (Eqn. 8, Table 5). Spawning potential ratio was calculated at 40% and the value of F^* that results in the given ratio is the F_{MSY} proxy reference point (i.e., $F_{40\%}$, the fishing mortality expected to conserve 40% of the maximum spawning potential; Eqn. 9, Table 5). The associated biomass proxy was calculated through projection of the stock to an equilibrium spawning stock biomass, with recruitment drawn from the 1998-2018 time-series. Reference points for both the M = 0.2 and M-ramp models were calculated using M = 0.2 in accordance with the Gulf of Maine cod stock assessment (NEFSC 2019). Reference points were recalculated every two years to emulate the frequency which Gulf of Maine cod is reassessed for management purposes. We calculated both the “true” F_{MSY} and SSB_{MSY} proxy reference points values for M=0.2 and M-ramp models and estimated values under catch bias based on the stock assessments.

Harvest Control Rule

Two harvest control rules were tested: 1) a sliding harvest control rule, and 2) a constant harvest control rule. The sliding harvest control rule changed fishing mortality rate in response to biomass and was designed to emulate the Acceptable Biological Catch (ABC) control rule that is applied to groundfish species managed by the NEFMC. The ABC control rule dictates that the ABC is determined as the catch associated with fishing at either 75%F_{MSY} (based on the F_{MSY} proxy $F_{40\%}$ in the case of Gulf of Maine cod) or the mortality rate associated with rebuilding by a target rebuilding date ($F_{rebuild}$), whichever is less. For stocks that cannot rebuild to B_{MSY} in the specified rebuilding period, even with no fishing, the ABC should be based on incidental bycatch, including a reduction in bycatch rate. We emulated this using a sliding harvest control rule whereby the F-based advice decreased linearly when stock biomass was estimated to be less than the overfished threshold (i.e., 0.5 SSB_{MSY}). In addition, we modeled a constant fishing mortality control rule (F_{target} = 75%$F_{40\%}$) which removed the same fraction of the stock regardless of abundance. In simulating these harvest control rules, we assumed the Annual Catch Limit (ACL) was set to equal to the ABC. We modeled bias in achieving F_{target} through implementation error in the form of positive bias on total catch (i.e., catch exceeding catch advice; Eqn. 10, Table 5).

3.3. Underestimated catch scenarios

Underestimated catch scenarios were constructed through: 1) applying observation bias to fishery catch information going into the stock assessment (i.e., emulating underreporting; Eqn. 7, Table 4) and 2) applying implementation bias to catch advice (i.e., “true" catch is the intended catch plus unreported catch) in the operating model (Eqn. 10, Table 5). We assumed that missing catch consisted of discarded legal-sized cod (Nitschke 2019b). The same fishery selectivity curve was used to represent reported and unreported catch. Simulations assume 100% mortality of unaccounted for catch. Each catch bias scenario was projected for a period of 36 years and 100 simulations were run of each unique scenario.

Catch bias scenarios were designed to encompass a potential range of unaccounted for catch levels, because we do not know all sources and the magnitude of catch bias (Table 6). Although a quantification of unaccounted for catch was not possible across stocks, the groundfish PDT attempted to approximate the magnitude of unaccounted for catch in the commercial fishery for Gulf of Maine cod (Nitschke 2019b). This analysis suggested that missing catch for Gulf of Maine ranged from 150 to 250% times the total commercial catch. We used the upper limit of this range to inform one of the discard scenarios and encompassed the lower limit within the range of simulated scenarios. For integration in the simulation model framework, which models a combined commercial and recreational fleet, we adjusted the groundfish PDT estimate of bias in catch reporting to account for the proportional representation of recreational and commercial catch of Gulf of Maine cod which is estimated to be 50:50 over the years 2011-2018. Thus, the estimated upper limit value of 250% was adjusted to 125% to represent unaccounted for commercial catch as a proportion of total catch. The full range of our scenarios was extended to a maximum value of 200% to account for other potential sources of unaccounted for catch (e.g., recreational discards). Overall, four levels of catch bias were simulated (0, 50, 125, and 200% bias). The base case scenario was modeled with perfect observation of fishery catch and no implementation bias on fishing mortality. The simulated catch data input to the assessment was negatively biased and catch advice generated from the stock assessment was positively biased to influence the operating model dynamics and represent these levels of increasing bias in catch.

In addition to the magnitude of catch bias, the timing and duration of these issues are important to consider. The year in which bias in catch reporting started for Gulf of Maine cod is unknown and we explored two alternative scenarios. We ran scenarios under “constant bias” where bias was applied across all years of the simulation and a “changepoint in bias” in which bias was initiated in 2015 with no bias prior to 2015 (Table 6). During the historical period of the constant bias scenario, observation bias is applied as described above, but implementation bias is not as fishing mortality is input from the stock assessment during this period. The observed high fishing mortality rates during this period are assumed to reflect implementation bias. The changepoint in bias scenario was informed by NEFMC groundfish PDT work that supported a change in discard incentives in 2015 for Gulf of Maine cod (Henry et al. 2019).

3.4. Performance metrics

Sustainability, stock assessment, and management performance metrics were evaluated for each scenario. These included operating model time series (i.e., spawning stock biomass, recruitment, fishing mortality and catch) to evaluate how scenarios affect "true" stock dynamics. We also characterized trajectories of spawning stock biomass, recruitment, fishing mortality and catch over the short (1-5 years), medium (6-15 years), and long-term (15-36 years) of the projection period.

We quantified stock assessment time series, including estimated spawning stock biomass, recruitment, fishing mortality and catch, to evaluate how scenarios affect the estimated or perceived stock dynamics. To evaluate stock assessment performance, we compared the "true" operating model time series values (i.e., spawning stock biomass, recruitment, and fishing mortality) to estimated assessment values over the span of each stock assessment. Percent relative error estimates (*%REE*) of spawning stock biomass, recruitment, and fishing mortality was calculated:

$$\%REE_t = \frac{x_{est,t-} \, x_{true,t}}{x_{true,t}} \times 100$$

where $x_{est,t}$ was the stock assessment estimated value for quantity x at time t and $x_{true,t}$ was the operating model value of quantity x at time t. Values were summarized as averages for each stock assessment during the projection period and the median of 100 simulations was reported. We also evaluated retrospective patterns in stock assessment results through retrospective peels every five years over the span of projection period (2015-2050).

Management performance was evaluated through quantification of stock status over time. We compared the "true" biological reference point proxies for each operating model (M=0.2 and M-ramp) to biological reference points estimated under catch bias scenarios. We evaluated both the perceived stock status (estimated values from the stock assessment compared to estimated biological reference points) and "true" stock status (operating model values compared to 'true" biological reference points). Overfishing was characterized as $F_t > F_{40\%}$, overfished status was calculated as $SSB_t < SSB_{threshold}$ where $SSB_{threshold}$ was 0.5 $SSB_{F40\%}$ and a stock was considered rebuilt when $SSB_t > SSB_{F40\%.}$

3.5. Collaboration with NEFMC Groundfish PDT

We collaborated with the NEFMC Groundfish PDT to define and prioritize the range and number of scenarios for testing the performance of catch bias scenarios. The Groundfish PDT also provided input on the catch bias scenarios, parameterization of operating models, estimation model settings, and management procedures employed in simulation testing. This collaboration was conducted through a series of virtual meetings.

4. Results

The main body of this report summarizes results for scenarios simulated under the sliding harvest control rule. Results of simulations run under the constant fishing mortality harvest control rule are reported in Appendix A.

4.1. Operating model dynamics

Historical Period

The historical trajectory and magnitude of the Gulf of Maine cod stock was reconstructed by incorporating recruitment and fishing mortality time series (1982-2014) from the most recent stock assessment realizations (M = 0.2 and M-ramp) and calculating spawning stock biomass and catch as emergent properties. Historically, estimated recruitment decreased over time under both natural mortality scenarios from relatively strong recruitment in the late 1980s to the lowest estimated values in recent years (Figure 1). In M = 0.2 scenarios, recruitment was estimated to be lower and less variable from 1990 onward compared to the M-ramp assessment realization. Fishing mortality was estimated to be high during the 1990s and peaked in the mid-2010s at values close to (i.e., M-ramp assessment estimates) or exceeding F = 2.0 (i.e., M=0.2 assessment estimates; Figure 1). The simulated spawning stock biomass and catch trajectories emulated the trends estimated from the most recent stock assessments with spawning stock biomass and catch declining from highs in the early 1990s (NEFSC 2019). At the end of the historical time period reconstructions for both M=0.2 and M-ramp models, Gulf of Maine cod were at historically low values and stock status was overfished and overfishing was occurring. Thus, simulated cod stock trajectories differed between operating models with alternative natural mortality assumptions (i.e., M=0.2 and M-ramp), but within these scenarios the historical period was consistent across catch bias scenarios.

No Catch Bias

In scenarios that assumed perfect catch reporting (i.e., no bias), spawning stock biomass of Gulf of Maine cod was projected to steadily increase from historic low levels and reached a plateau after 15 years at approximately 33,389 mt in M = 0.2 models and 20,844 mt in M-ramp models (Table 7, Figure 2). The rebuilding response was a function of the significant reduction in advised fishing mortality under the sliding harvest control rule relative to historical levels, as well as the expectation of steady levels of recruitment in the future. For example, under no catch bias scenarios fishing mortality was less than or equal to 0.14 (75% of $F_{40\%}$) based on M=0.2 and 0.13 based on M-ramp operating models which is considerably lower than historical fishing mortality values which ranged from 0.4 to 2.2 for these models (Figure 1). The stock-recruit relationship drew from estimated recruitment during the last 20 years, which projects steady levels of recruitment unless spawning stock biomass was below the spawning stock biomass hinge point value (M=0.2 hinge point = 6,300 mt, M-ramp hinge point = 7,900 mt). M-ramp scenarios had higher expected future recruitment compared to M=0.2 scenarios based on the differences in estimated recruitment values that informed the stock-recruit relationship (Figure 1). The “true” catch of Gulf of Maine cod was also projected to increase over time under the no catch bias scenario, reaching an asymptote of approximately 3,614 mt in M=0.2 models and 1,840 mt in M-ramp models (Table 7, Figures 2).

Constant Catch Bias

Across constant catch bias scenarios, spawning stock biomass increased over the projection period, but the magnitude of the asymptote in biomass decreased with increasing levels of catch bias (Figure 2). For example, the asymptote of spawning stock biomass in the no bias scenario was 2.6 times greater than in the extreme bias scenario (200%) in the M=0.2 model. The catch bias scenarios in the M-ramp model exhibited a similar pattern, however the relative difference across scenarios was not as great. Projections of recruitment were similar across catch bias scenarios in M=0.2 models, but were higher and more variable in M-ramp model scenarios. In general, recruitment expectations were lower in the initial projection years (0-5 years) when spawning stock biomass was below the hinge point value in the stock-recruit relationship and subsequently increased to steady levels over the remaining projection period (Figure 2). “True” fishing mortality rates in the operating models increased across scenarios with increasing levels of catch bias, reflecting fishing above target levels prescribed by the harvest control rule (Figure 2). Values were consistent after the initial projection years in M=0.2 models, however, fishing mortality rates in M-ramp model catch bias scenarios declined slightly after peaking. Across catch bias scenarios, “true” catch (reported plus unreported) was low in the initial years of the projection period (0-5 yrs) under the sliding harvest control rule (Figure 2 and 3). In general, “true” catch was higher in scenarios with higher catch bias, however the magnitude of differences in catch across scenarios evolved over time as the impact of overfishing influenced the resource and ultimately impacted potential yield (Figures 3 and 6). For example, in M=0.2 scenarios, median “true” catch was highest in the scenario with extreme bias (200%) in the short (0-5 yrs) and medium (5-15 yrs) term, but in the long term catch was similar across catch bias scenarios based on the interaction between increasing fishing mortality and decreasing spawning stock biomass trajectories (i.e., a larger portion of the stock was caught under higher bias scenarios, Table 7, Figures 3 and 6).

Changepoint in Catch Bias

There was little difference in Gulf of Maine cod operating model trajectories simulated under constant and changepoint catch bias based on M = 0.2 operating models. The main difference in these scenarios was assessment performance and the perception of stock status (described in corresponding sections below). M-ramp operating models exhibited differences between constant and changepoint bias scenarios at higher catch bias levels and at medium to long time scales. In changepoint scenarios, there was a tendency for higher fishing mortality and “true catch” under these circumstances (Figures 2 and 3).

4.2. Assessment performance

No Catch Bias

Stock assessment trajectories of spawning stock biomass, recruitment, fishing mortality, and catch provided insight on the perceived stock dynamics of Gulf of Maine cod across catch bias scenarios (Figure 4). Comparison of the perceived stock trajectories estimated from the stock assessment and "true" operating model trajectories enabled us to quantify the relative error in assessment performance (Figure 5). Under the scenario of perfect catch reporting, the assessment models were fit to unbiased catch data and the assessment model was specified in a similar manner to the operating model. This represented a "self-test" wherein an estimation model has similar structural assumptions to the operating model, as compared to a "cross test" where there is a misspecification of the model (Deroba et al. 2015). Spawning stock bias, recruitment, and fishing mortality estimates from the assessment demonstrated good agreement with the "true" operating model values with percent relative error near zero (Figure 5). The assessment demonstrated similar accurate performance in estimating the "true" stock trajectories for M = 0.2 and M-ramp operating models (Figure 5).

Constant Catch Bias

Under scenarios of constant catch bias, stock assessments were fit to biased total catch information, as well as information that more accurately reflected stock dynamics (i.e., the survey index of abundance and age composition information from the survey and catch). Estimated stock trajectories differed from the "true" stock trajectories of the operating model in constant catch bias scenarios (Figure 4). Across scenarios with increased levels of bias, the assessment tended to increasingly underestimate spawning stock biomass and recruitment (Figure 5). For example, estimated spawning stock biomass was considerably lower than "true" operating model values under the extreme bias scenario, with the estimated trajectory remaining close to historic low levels over the projection period (Figure 4). The relative error estimates of the stock assessment were constant over time and similar in magnitude between M=0.2 and M-ramp operating models (Figure 5). Percent relative error estimates of recruitment and spawning stock biomass ranged from underestimation on the order of -32% in scenarios of moderate bias to -67% in scenarios with extreme bias. Across scenarios, the stock assessment exhibited little bias in the estimation of fishing mortality. This suggests that the age composition information provided to the assessment was sufficient to estimate fishing mortality, despite misreporting of the magnitude of total catch. High weighting of the index age composition within our scenarios, which provided accurate magnitude and age composition information, contributed to this outcome. These scenarios simulated constant bias in catch information and resulted in constant bias in assessment performance over the projection period. The estimated catch in the stock assessment was considerably lower than "true" catch in the operating model reflecting the difference between reported and unaccounted for catch (Table 7, Figure 6). Because unaccounted for catch was assumed to reflect discarding, reported catch can be considered that catch which provides economic value to the fishery as compared to unaccounted for catch which is discarded (Figure 1 and 4). Over the medium to long-term of the projection period, lower catch bias scenarios ultimately exhibited higher reported catch due to long-term impacts of greater than intended catch on stock biomass and potential yield (Figure 6). Retrospective analysis of stock assessment results at fiver year intervals over the span of the projection period provided insight on issues with retrospective patterns. Retrospective inconsistencies were negligible under scenarios of constant catch bias (Figure 7).

Changepoint in Catch Bias

Assessment performance differed under the changepoint catch bias scenarios compared to constant catch bias scenarios. Implementing a changepoint in catch bias in 2015 introduced a trend in assessment error, with little error in the estimation of recruitment and spawning stock biomass early in the projection period (i.e., years 1-10) followed by subsequent increasing levels of assessment error (Figure 5). Scenarios with higher bias in catch reporting exhibited the highest levels of underestimation in spawning stock biomass and recruitment by the end of the projection period (Figure 5). The same trends were observed for scenarios based on the $M = 0.2$ and M-ramp operating models, but the trend in underestimation of spawning stock biomass and recruitment started slightly later in M-ramp models (Figure 5). The lag in the impact of imposed catch bias on spawning stock biomass and recruitment relates to age structure and the time it takes for all extant year-classes to transition from partially biased catch histories to entirely biased catch histories. In the initial years of the projection, fishing mortality was increasingly underestimated as bias in catch reporting scenarios increased, but relative error subsequently decreased after 10-15 years (Figure 5). Similarly, this pattern relates to age structure as the introduction of bias causes an initial discontinuity in the progression of age classes, however, estimation of fishing mortality improves with the transition to an entirely biased catch history (i.e., similar to constant catch bias scenarios).

Relative error measures characterized the overall agreement between estimated and “true” stock trajectories (Figure 5), however, because this metric integrated bias over the span of each assessment time series it can obscure more subtle patterns that may exist within assessments, such as trends in terminal years of the assessment. Estimated stock trajectories for the final assessment in the projection period showed patterns of increasing spawning stock biomass and decreasing fishing mortality in the last several years of the projection period (Figure 4). A retrospective analysis of stock assessments over the projection period provided insight on large inconsistencies in the terminal years of the assessment (i.e. 5-10 years). In scenarios that assumed a changepoint in catch bias, retrospective analysis revealed consistent increases in updated estimates of fishing mortality and consistent decreases in updated estimates of spawning stock biomass in these scenarios (Figure 8).

4.3. Management performance

No Catch Bias

In scenarios that assumed perfect catch reporting (i.e., no bias), biological reference points provide insight as to the "true" $F_{40\%}$ and $SSB_{F40\%}$ for Gulf of Maine cod. The F_{MSY} proxy was similar between M = 0.2 and M-ramp ($F_{40\%}$ ~ 0.18) operating models, however, $SSB_{F40\%}$ values were higher for M-ramp compared to M = 0.2 operating models (Table 7, Figure 9). This pattern was driven by the lower recruitment assumptions that informed the M=0.2 operating model. Note the subtle differences in true biological reference points between constant and changepoint scenarios reflect that these were calculated from recruitment realizations simulated from the true stock-recruit relationship (Figure 7). Interestingly, deterministic calculation of MSY-reference points for M=0.2 and M-ramp operating models indicate that the $F_{40\%}$ and $SSB_{F40\%}$ are considerably less than the deterministic F_{MSY} and SSB_{MSY} (M=0.2: F_{MSY}=0.3, SSB_{MSY} =13,751 mt, and MSY =2,804 mt; M-ramp: F_{MSY}=0.3, SSB_{MSY}=26,548 mt, and MSY = 5,413 mt).

Stock status determination was equivalent between the "true" operating model and stock assessment perception in the no catch bias scenario due to the accuracy of the assessment under these scenarios. Scenarios without bias in catch did not exhibit overfishing at any point during the projection period due to the prescribed fishing mortality target at 75% of $F_{40\%}$, or less, as defined in the sliding harvest control rule (Figure 10). Comparison of the "true" spawning stock biomass to the "true" $SSB_{F40\%}$ in M=0.2 scenarios demonstrated rebuilding above the SSB_{MSY} proxy under the no catch bias scenario in the medium to long term. However, biomass remained overfished ($<SSB_{threshold}$) and below the SSB_{MSY} proxy in M-ramp operating model scenarios which related to the higher expected future recruitment and SSB_{MSY} proxy (Figure 10).

Constant Catch Bias

Bias in reported catch has the potential to impact the realization of sustainable fisheries management goals through impacts on the stock assessment and biological reference point estimates that inform determination of catch advice through harvest control rules. Estimation of the F_{MSY} proxy remained essentially the same across constant catch bias scenarios and operating models (Table 7, Figure 9). This was expected based on the approach to calculation. However, estimation of $SSB_{F40\%}$ differed across catch bias scenarios for each operating model. Estimated $SSB_{F40\%}$ values decreased with increasing bias in catch and were lower in M = 0.2 compared to M-ramp model scenarios (Table 7, Figure 9). This pattern was driven by increased underestimation of recruitment with increased catch bias and the recruitment assumptions of the different operating models. The decreasing trend in estimates of the SSB_{MSY} proxy with increasing catch bias resulted in a lower bar for measuring overfished status of the stock and can lead to a misperception of the productivity of the stock (e.g., MSY perceived to be lower; Figure 7).

Comparison of the "true" fishing mortality and spawning stock biomass to the "true" biological reference points for the operating model provided an accurate perception of stock status.

Overfishing did not occur in the short-term across catch bias scenarios and natural mortality realizations. However, overfishing occurred after approximately 5-10 years in M = 0.2 models with moderate to extreme catch bias and in M-ramp models with large to extreme catch bias (Figure 10). Comparison of the "true" spawning stock biomass to the "true" $SSB_{F40\%}$ in M=0.2 scenarios demonstrated rebuilding to the SSB_{MSY} proxy under the moderate catch bias (50%) scenario in the medium term. Biomass increased above the $SSB_{threshold}$ under the large catch bias scenario (125%) in M=0.2 scenarios, but was consistently less than the SSB_{MSY} proxy. Spawning stock biomass was generally at or below the $SSB_{threshold}$ under the extreme catch bias scenario (200%) in M=0.2 scenarios. Stock status remained overfished (i.e., below $SSB_{threshold}$) under all M-ramp scenarios (Figure 10).

Comparison of the estimated fishing mortality and spawning stock biomass to the estimated biological reference points provided insight on perceived stock status. For scenarios of constant catch bias, estimated stock status was generally the same as the "true" stock status. This consistency was due to the combined effect of underestimated assessment values and underestimated biological reference points under constant catch bias scenarios which resulted in similar ratios (e.g. estimated F/F_{MSY} proxy) and stock status determination to operating models (Figure 9 and 10).

Changepoint in Catch Bias

Similar to the constant catch bias scenarios, estimation of the F_{MSY} proxy did not change across levels of catch bias or natural mortality realizations ($F_{40\%}$= 0.18; Figure 9). However, SSB_{MSY} values differed between M = 0.2 and M-ramp models, with higher values estimated under the M-ramp assumption. SSB_{MSY} values demonstrated a similar decline with increasing catch bias, but were generally higher across changepoint catch bias scenarios compared to constant catch bias scenarios (Table 7, Figure 9).

Comparison of the "true" fishing mortality and spawning stock biomass to the "true" biological reference points for the operating model revealed similarities with stock status under constant catch bias scenarios. Overfishing generally did not occur in the short-term across catch bias scenarios but occurred across scenarios with catch bias after approximately 5-10 years in M = 0.2 and M-ramp models (Figure 10). In the M = 0.2 model, rebuilding to the SSB_{MSY} proxy occurred in the moderate catch bias scenario (50%) in the medium term. Biomass increased above the overfished threshold under the large catch bias scenario (125%) and remained close to the threshold under the extreme catch bias scenario (200%) in M=0.2 scenarios, but neither scenario rebuilt to the SSB_{MSY} proxy. All of the catch bias scenarios based on the M-ramp model remained overfished over the projection period.

Comparison of estimated fishing mortality and spawning stock biomass to the estimated biological reference points for changepoint catch bias scenarios revealed differences from the "true" stock status. The biggest differences were at the end of the projected time period, when there was a change in perception of stock status in M=0.2 models to no overfishing across scenarios and a change in status to rebuilt in moderate catch bias scenario and not overfished in the extreme catch bias scenario (Figure 10). Because of the retrospective pattern under the changepoint scenarios, there was a tendency for updated estimates of spawning stock biomass to decrease and for updated estimates of fishing mortality to increase, which impacted estimated $F/F_{MSY\ proxy}$ and $SSB/SSB_{MSY\ proxy}$ ratios and lead to an overly optimistic perception of stock status at the end of the time series. This same pattern is observed in M-ramp models, however, the perception of overfished status did not change due to the high $SSB_{threshold}$ values in these scenarios.

5. Discussion

Through simulation testing, we demonstrated that inaccurate catch information has the potential to impact stock assessment and management performance of Gulf of Maine cod with resulting impacts on stock trajectories. Under scenarios of no bias in catch reporting, we find that rebuilding the Gulf of Maine cod stock was accelerated and reached a higher magnitude. The no catch bias scenarios were characterized by accurate stock assessment performance and effective management as evidenced by the stock transitioning from overfished and overfishing status to a rebuilt stock with no overfishing over the projection period in M=0.2 operating models. It is also important to note that scenarios with no bias in catch attained the highest level of reported catch which is the component of direct economic relevance to the fishery (Figure 6). We recognize that the no catch bias scenarios underestimate the true uncertainty in the Gulf of Maine cod assessment, because it assumes that the population dynamics are perfectly known, the estimation model is perfectly specified, and all catch components, including recreational catch, are well-estimated. Despite these assumptions, the no catch bias scenarios offer a reference for comparing the performance of biased catch scenarios. Scenarios of increasing catch bias generally exhibited lower spawning stock biomass, lower reported catch, and higher “true” catch (i.e., reported and unreported catch).

Scenarios that assumed Gulf of Maine cod have higher natural mortality (M-ramp), did not achieve the same rebuilding and management outcomes as observed under the M=0.2 assumption, because of the inconsistency in the assumed natural mortality rate projected forward in the operating model (M = 0.4) and the natural mortality rate assumed in the reference point model (M = 0.2). These scenarios exhibited lower spawning biomass and catch levels related to the higher overall mortality experienced by cod under these scenarios, despite higher expectations of recruitment. In addition, the assumed higher recruitment in M-ramp scenarios resulted a higher SSB_{MSY} proxy and $SSB_{Threshold}$ value for determination of overfished status, resulting in the stock consistently determined to be overfished.

We found that assessment performance was unbiased under the perfect catch reporting scenarios (i.e., no catch bias). Under scenarios of constant catch bias, assessments increasingly underestimated recruitment and spawning stock biomass with increasing catch bias while fishing mortality estimates remained unbiased. Constant catch bias scenarios simulated a constant level of bias in catch information, such that the trends in stock dynamics were captured accurately, but the magnitude was not. Under scenarios with a changepoint in catch bias, assessments initially performed well for 10-15 years after bias was introduced and then performance increasingly degraded. The impact of bias in catch information on assessment performance is consistent with other studies (Rudd and Branch 2016) which have shown constant under-reporting results in consistent underestimation of biomass, but that trends in reporting can result in more complex patterns of assessment error.

Constant catch bias scenarios did not demonstrate significant retrospective patterns, but changepoint catch bias scenarios exhibited retrospective patterns with a tendency to decrease updated estimates of spawning stock biomass and to increase updated estimates of fishing mortality. Retrospective patterns were evident from the beginning of the projection period in the changepoint scenarios (Figure 8). Our simulation results align with previous simulations that indicate changes in the level of catch accounting in the assessment is a known factor contributing to retrospective patterns (e.g., Legault 2009). The retrospective patterns produced in the changepoint scenarios are similar to those observed for many groundfish stocks in recent years, including Gulf of Maine cod (e.g., decrease in updated estimates of SSB; Weidenmann and Jensen 2018, 2019). However, the biases in SSB derived from these simulation analyses are generally opposite of the 'bias' that is often erroneously inferred from retrospective patterns (Cadrin 2020). SSB was underestimated when compared to the "true" values in the operating model but interpreting retrospective patterns as bias would suggest that SSB is overestimated. Our simulation results are similar to those from Hurtado-Ferro et al. (2015), who concluded that the direction and magnitude of retrospective patterns are not related to true bias. It is important to note that this model framework allows us to make inferences about biased assessment estimates from our simulations due to our ability to compare estimated and "true" values, but we cannot draw the same type of inference from retrospective analyses which compare across assessments. The management procedure that we simulated does not include the retrospective adjustments that are applied to many groundfish stock assessments and catch projections (e.g., NEFSC 2019). Based on the retrospective analysis and the simulation testing, the underestimation of SSB would be even greater if a retrospective adjustment was applied.

These simulations illustrate that, in some cases, the effectiveness of management measures can be compromised by inaccurate catch information. We observed how biased assessment performance can influence estimated biomass-based reference points and stock estimates, potentially influencing the perception of stock status. Constant catch bias scenarios exhibited bias in the estimation of the magnitude of both spawning stock biomass and the $SSB_{F40\%}$, which effectively resulted in unbiased estimates of stock status as the ratio of $SSB/SSB_{F40\%}$ remained the same. However, changepoint catch bias scenarios introduced a trend in catch bias, which impacted this ratio and resulted in differences between the "true" and estimated stock status.

Scenarios with higher bias in catch reporting were more likely to exhibit overfishing and overfished status during the projection period. However, our scenarios would suggest that low catch bias (<50%) would achieve reasonable management performance, largely because of the precautionary management procedure (e.g., the proxy reference point is considerably less than the true F_{MSY} value, and target catch is 75% of $F_{40\%}$). Thus, these scenarios might be viewed as a conservative assessment of the potential impact of catch bias in catch reporting. We tested a harvest control rule with a precautionary fishing mortality target (F_{target} = 75% of $F_{40\%}$) that decreased when the stock became overfished. The sliding harvest control rule used here is close to what is used for Gulf of Maine cod, but may allow for lower catch levels than would be deemed acceptable by management. It is important to note, that the levels of fishing mortality projected under even extreme catch bias (F ~ 0.47) are considerably lower than observed values estimated in recent years for the Gulf of Maine cod stock (Figure 1).

Alternatively, the expectations of future productivity of Gulf of Maine cod could be viewed as overly optimistic, conferring a high degree of resilience to the impacts of catch misreporting in these scenarios. We projected moderate levels of recruitment into the future across scenarios which are higher than the most recent estimates over the past 5-10 years which are the lowest in the time series. The parameterization of the stock-recruit relationship for Gulf of Maine cod was such that there was little influence of declining spawning stock biomass on production of recruits. In addition, a recent analysis suggests lower reproductive potential of the Gulf of Maine cod stock due to associations between recruitment and warming waters in the region which we have not been accounted for here (Fogarty et al. 2008, Pershing et al. 2015).

We applied the same selectivity curve in modeling both reported and unreported catch in these simulations. This implies there was no change in the size/age composition of the total catch as catch bias increased. We anticipate that significant changes in selectivity would introduce error to estimation of fishing mortality rates. Highgrading, the act of selecting larger fish and discarding smaller fish, is one potential scenario that could be occurring for Gulf of Maine cod. A shift in size/age composition toward larger reported and smaller unreported catch would likely lead to error in the estimation of fishing mortality (Hurtado-Ferro et al. 2014). Currently, we don’t have information to support a change in selectivity, but this could be explored in the future using this modeling framework.

It is important to recognize the caveats and limitations of this analysis. We sought to understand the impact of misreported catch by isolating this factor as a key determinate of the structure of our scenarios. We know many other factors have potential to influence assessment and management performance. For example, we tested the impact of catch bias in the context of a correctly specified assessment models. Estimation model misspecification has the potential to introduce misperception of population dynamics and management advice (e.g., Deroba et al. 2015, Hurtado-Ferro et al. 2015, Weston 2018). In addition, further testing of the impact of catch bias scenarios could include other aspects of imperfect management implementation and different perceptions of stock dynamics (e.g., operating models with different perceptions of recruitment). Furthermore, future work could include enhanced simulation of fleets to allow for explicit modeling of the uncertainty and bias associated with catch reporting by fleet (e.g., commercial vs. recreational fleets). This would require partitioning catch, and approximating uncertainty and bias by fleets across years. The limited uncertainty captured in these scenarios may emphasize the signal of bias in catch reporting. It is important to note that low levels of catch bias may have minimal impact in the context of other uncertainties in the system.

Simulations of the impact of bias in catch reporting focused on a constraining stock, Gulf of Maine cod, known to have incentives for discarding (NEFMC 2020). Thus, these simulations can provide insight on the impact of unaccounted for catch on other groundfish stocks with similar low stock status and considered to have discard incentives (e.g., Eastern Georges Bank cod, yellowtail flounder). Furthermore, scenarios run without bias in catch reporting can provide insight on the performance of the stock assessment and management process in the context of accurate catch information and thus can provide insight on fishery management performance for stocks with low or no discard incentives (e.g., haddock, pollock, redfish). Undoubtedly, there would be differences based on specific aspects of groundfish life history. For example, stocks with higher productivity expectations would exhibit higher resilience to catch misreporting.

These simulations demonstrate the potential impact of bias in catch accounting and can provide guidance to managers on the anticipated magnitude and direction of the impact of this factor in isolation. Our analysis suggests that improvement of catch reporting has the potential to improve stock assessment and management performance and contribute to achieving rebuilding plans. Results suggest that high to extreme bias in catch reporting was detrimental to sustainable fisheries management. However, catch reporting bias <50% had more limited impacts on assessment and management performance because of risk averse management (e.g., target fishing mortality at 75% of $F_{40\%}$). Thus, the costs of improved monitoring need to be weighed against the desired level of improvement in assessment and management outcomes. However, improved catch reporting does not ensure improved biological, assessment, and management performance due to all the other factors described above.

Summary of Findings

- Scenarios with no catch bias exhibited accelerated rebuilding of the Gulf of Maine cod stock and were characterized by accurate stock assessment performance and effective management as evidenced by the stock transitioning to no overfishing and rebuilding during the projection period.
- Scenarios that assumed Gulf of Maine cod have higher natural mortality (M-ramp), did not achieve the same rebuilding and management outcomes as observed under the M=0.2 assumption. This related to the higher overall mortality experienced by cod under these scenarios and the inconsistency in the assumed natural mortality rate in the operating model and the reference point model.
- Under scenarios of constant catch bias, assessments exhibited consistent levels of underestimated recruitment and spawning stock biomass with underestimation increasing with increased bias in catch reporting. Fishing mortality estimates remained unbiased because they were informed by unbiased age composition data.

- Under scenarios with a changepoint in catch bias, assessments initially performed well for 10-15 years and then performance increasingly degraded.
- Retrospective inconsistency (i.e., decrease in updated estimates of spawning stock biomass and increase in updated estimates of fishing mortality) resulted from changepoint catch bias scenarios.
- Estimated stock status reflected true stock status determinations under constant catch bias scenarios. However, changepoint catch bias scenarios exhibited frequent instances of misperception of stock status.
- Results suggest that large to extreme bias in catch reporting was detrimental to sustainable management, however, catch reporting bias <50% had more limited impacts on assessment and management performance in the context of risk averse management.
- It is important to recognize the caveats and limitations of this analysis and that the results are contingent on the specification of the models and scenarios.
- These simulations demonstrate the potential impact of bias in catch accounting and can provide guidance to managers on the anticipated magnitude and direction of the impact of this factor.

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Tables

Table 1. Description of equations and symbols used in simulating the population dynamics of Gulf of Maine cod in an age-structured operating model.

Eqn. 1	$N_{a,t} = \begin{cases} N_{1,t} & \text{if } a = 1 \\ N_{a-1,t-1}e^{-[\mathrm{M}+F_t(s_{a-1})]} & \text{if } 1 < a < x \\ N_{a-1,t-1}e^{-[M+F_t(s_{a-1})]} + N_{a,\mathrm{t}-1}e^{-[\mathrm{M}+F_t(s_a)]} & \text{if } a = x \end{cases}$	
Eqn. 2	$SSB_t = \sum_{a=1}^{a=x} N_{a,t}W_{a,t}P_{a,t}$	
Eqn. 3	$N_{1,t} \begin{cases} c_R \times ecdf(R_{obs}) & \text{if } SSB_t \geq SSB_* \\ c_R \times \frac{SSB_t}{SSB_*}\left(ecdf(R_{obs})\right) & \text{if } SSB_t < SSB_* \end{cases}$	
Eqn. 4	$C_{a,t}^N = \frac{\Phi_{a,t}^F F_t}{\Phi_{a,t}^F F_t + M} N_{a,t}(1 - e^{-\Phi_{a,t}^F F_t - M})$	
Symbols used in equations	$N_{a,t}$	abundance of fish at age *a* at time *t*
	M	natural mortality
	F_t	time-varying fishing mortality at time *t*
	s_a	selectivity to the fishery at age *a*
	x	plus group
	SSB_t	spawning stock biomass at time *t* (mT)
	$W_{a,t}$	average weight-at-age, *a* of fish at time *t*
	$P_{a,t}$	fraction of fish of age, *a* that are mature at time *t*
	c_R	conversion coefficient for input recruitment to absolute numbers
	SSB_*	spawning stock biomass hinge value
	$ecdf(R_{obs})$	sample from empirical cumulative distribution of historic observed recruitments (R_{obs}) 1998-2018
	$C_{a,t}^N$	catch of age, *a* fish in time *t* in numbers
	$\Phi_{a,t}^F$	selectivity of age, *a* in time *t*

Table 2. Associated parameter names, symbols and input values used in the Gulf of Maine code operating model.

Parameter	**Symbol**	**Value**	**Source (model)**
Natural mortality (M = 0.2 scenarios)	M	0.2	NEFSC 2019 (ASAP)
Natural mortality (M-ramp scenarios)	M	0.2-0.4	NEFSC 2019 (ASAP)
Conversion coefficient	c_R	1000	NEFSC 2019 (AGEPRO)
Spawning stock biomass hinge value (M = 0.2 scenarios)	SSB_*	6300	NEFSC 2019 (AGEPRO)
Spawning stock biomass hinge value (M-ramp scenarios)	SSB_*	7900	NEFSC 2019 (AGEPRO)
Fishery catchability	q^F	1	Assumed
Survey catchability	q^I	1	NEFSC 2019 (ASAP)
Survey timing	st	0.5	Assumed
Catch weight observation error		0.05	NEFSC 2019 (ASAP)
Index observation error		0.05	NEFSC 2019 (ASAP)
Recruitment process error		0.01	Assumed

Table 3. Gulf of Maine cod operating model parameter input vectors at age.

	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9+	Source (model)
Initial numbers-at-age	15000	17000	6000	3500	2000	200	300	150	100	NEFSC 2019 (ASAP)
Weight-at-age	0.057	0.365	0.908	1.662	2.426	3.307	4.09	5.927	10.375	NEFSC 2019 (ASAP/AGEPRO)
Maturity-at-age	0.087	0.318	0.697	0.919	0.982	0.996	0.999	1	1	NEFSC 2019 (AGEPRO)
Fishery selectivity-at-age	0.013	0.066	0.271	0.663	0.912	0.982	0.997	1	1	NEFSC 2019 (AGEPRO)
Fishery selectivity-at-age (M-ramp)	0.009	0.051	0.241	0.651	0.917	0.985	0.997	1	1	NEFSC 2019 (AGEPRO)
Survey selectivity-at-age	0.038	0.134	0.289	0.531	0.778	1	1	1	1	NEFSC 2019 (ASAP)

Table 4. Description of equations and symbols in the observation model to generate simulated catch and index data.

Eqn. 5	$I^{N}_{a,t} = \Phi^{I}_{a,t} e^{(-\Phi^{I}_{a,t}F_t - M)st}$	
Eqn. 6	$C^{W}_{a,t} = C^{N}_{a,t} W_a$	
Eqn. 7	$\hat{C}^{W}_{t} = C^{W}_{t} \omega$	
Symbols used in equations	$I^{N}_{a,t}$	survey catch in numbers for age *a* in time *t*
	$\Phi^{I}_{a,t}$	survey selectivity at age, *a* in time *t*
	st	survey timing, given as proportion of the year that has elapsed
	$\Phi^{F}_{a,t}$	fishery selectivity of age, *a* in time *t*
	C^{W}_{a}	catch weight at age *a*
	$\hat{C}^{W}_{t}$	adjusted catch weight-at-age with bias at time *t*
	ω	observation bias on catch weight

Table 5. Description of equations and symbols used to calculate biological reference points from the stock assessment in the management procedure.

Eqn. 8		$\frac{SSB}{R}_{F^*} = \sum_{a=0}^{a=A} e^{-\Phi_a^F F^* - M}\,\theta_a W_a$
Eqn. 9		$SPR_{F^*} = \frac{[\frac{SSB}{R}_{F=0}]}{[\frac{SSB}{R}_{F=F^*}]}$
Eqn. 10		$\hat{C}_t = C_t^W + (C_t^W \beta)$
Symbols used in equations	$\frac{SSB}{R}_{F^*}$	estimated spawning stock biomass per recruit at fishing mortality level F^* for an average individual
	W_a	weight at age
	θ_a	maturity at age
	SPR_{F^*}	spawning potential ratio ($F^* = 0.4$)
	$\frac{SSB}{R}_{F=0}$	spawning stock biomass per recruit when $F = 0$
	$\hat{C}_t$	adjusted total catch weight with bias at time t
	C_t^W	total catch weight at time t
	β	Implementation bias on total catch

Table 6. Scenario testing specifications.

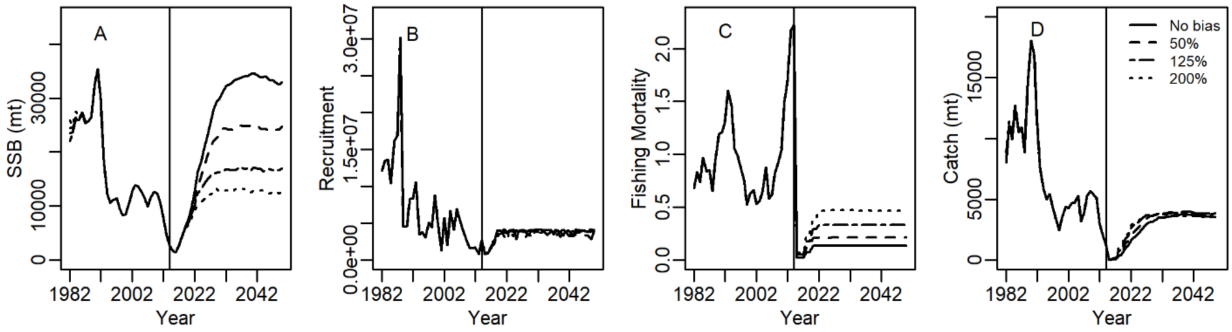
OM/assessment natural mortality	Timing of catch bias	MP start year	HCR	Catch bias scenarios
M = 0.2	Constant bias over time	2015	Sliding	No bias Moderate bias (50%) Large bias (125%) Extreme bias (200%)
M-ramp				No bias Moderate bias (50%) Large bias (125%) Extreme bias (200%)
M = 0.2	Changepoint where bias is 0 prior to 2015, then ranges from 0-200% into future	2015	Sliding	No bias Moderate bias (50%) Large bias (125%) Extreme bias (200%)
M-ramp				No bias Moderate bias (50%) Large bias (125%) Extreme bias (200%)
M = 0.2	Constant bias over time	2015	Constant	No bias Moderate bias (50%) Large bias (125%) Extreme bias (200%)
M-ramp				No bias Moderate bias (50%) Large bias (125%) Extreme bias (200%)
M = 0.2	Changepoint where bias is 0 prior to 2015, then ranges from 0-200% into future	2015	Constant	No bias Moderate bias (50%) Large bias (125%) Extreme bias (200%)
M-ramp				No bias Moderate bias (50%) Large bias (125%) Extreme bias (200%)

Table 7 Summary of median operating model and estimation model values for spawning stock biomass, recruitment, fishing mortality and catch across short (1-5 years), medium (6-15), and long (16-36) time scales of the projection period (2015-2050). Biological reference point proxies ($SSB_{F40\%}$ and $F_{40\%}$) are reported for "no bias" scenarios which represent the "true" biological reference point proxies for operating models and for biased catch scenarios.

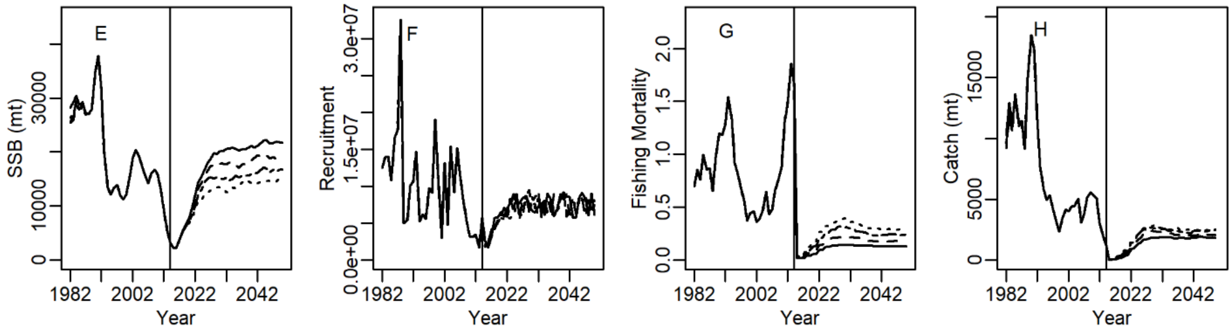
Scenarios	Operating Model Values												Stock Assessment Model Values													
	Median SSB			Median Recruitment			Median F			Median Catch			Median SSB			Median Recruitment			Median F			Median Catch			Biological Reference Points	
	Short	Med.	Long	Short	Med.	Long	Short	Med.	Long	Short	Med.	Long	Short	Med.	Long	Short	Med.	Long	Short	Med.	Long	Short	Med.	Long	$SSB_{40\%}$	$F_{40\%}$
Constant catch bias, sliding harvest control rule																										
M = 0.2																										
No bias	2843	19500	33389	1919850	3931682	4050602	0.02	0.14	0.14	70	2248	3614	2973	19895	35095	2054401	3903036	4050240	0.02	0.13	0.13	71	1987	3585	26632	0.18
Moderate bias	2826	16454	24330	1808146	3858570	3941042	0.04	0.21	0.21	114	2771	3883	1958	11241	16841	1167508	2571887	2597604	0.04	0.21	0.21	75	1669	2605	17435	0.18
Large bias	2838	13638	16799	1721631	3860380	3806988	0.06	0.34	0.34	157	3198	3838	1259	5993	7486	763422	1639883	1611111	0.05	0.33	0.33	69	1311	1691	11309	0.18
Extreme bias	2817	11017	12861	1871676	3928808	3907216	0.07	0.47	0.47	205	3290	3740	929	3718	4253	632102	1220745	1254345	0.07	0.46	0.46	68	1041	1228	8474	0.18
Mramp																										
No bias	3858	16155	20844	3265188	7668253	7775012	0.02	0.13	0.13	53	1375	1840	4154	16691	21813	3449855	7534137	7425541	0.01	0.11	0.13	53	1138	1859	54822	0.19
Moderate bias	3823	14877	18385	3934389	6738670	7607981	0.02	0.18	0.18	77	1757	2088	2696	10475	12512	2770527	4358923	5217020	0.02	0.15	0.18	52	985	1397	36142	0.19
Large bias	3778	13732	15972	4221748	6922611	7931987	0.04	0.26	0.24	117	2218	2410	1744	6130	7110	1898661	3149525	3303294	0.04	0.22	0.24	52	797	1065	23500	0.19
Extreme bias	3814	11699	14338	3450310	6094533	7878026	0.05	0.32	0.30	156	2162	2482	1291	3927	4729	1237871	1993563	2422260	0.05	0.29	0.29	51	621	823	17482	0.19
Changepoint bias, sliding harvest control rule																										
M = 0.2																										
No bias	2874	19235	33325	1624279	3985338	3799949	0.02	0.14	0.14	74	2233	3619	2968	19819	34698	1687589	3708393	3868610	0.02	0.13	0.13	73	1951	3552	26330	0.18
Moderate bias	2855	17530	23945	1788832	3485835	3792604	0.04	0.21	0.21	104	2933	3787	2051	12158	18304	1230337	2471302	2825097	0.03	0.20	0.19	70	1772	2519	23572	0.18
Large bias	2834	13653	17330	1830815	3888752	3935338	0.05	0.33	0.33	157	3201	3916	1411	6428	8511	793628	1683110	1921510	0.05	0.31	0.29	68	1306	1722	19278	0.18
Extreme bias	2810	10758	13087	1700121	4020223	3923885	0.07	0.47	0.46	202	3215	3740	1307	3929	4719	576646	1270517	1375509	0.05	0.41	0.41	67	1010	1239	15733	0.18
M ramp																										
No bias	3841	16572	20463	3997027	7230148	7501452	0.02	0.13	0.13	52	1447	1765	4057	16836	20909	3964504	7267831	7656873	0.01	0.11	0.13	41	1199	1791	54742	0.19
Moderate bias	3820	15461	17739	4170649	7718805	7739959	0.02	0.19	0.21	80	1895	2281	3081	11442	13966	2666312	5114974	6424120	0.02	0.15	0.17	43	1053	1509	48660	0.18
Large bias	3802	13377	14551	4059534	6497978	7840662	0.04	0.31	0.33	118	2417	2666	2095	6644	7525	1939082	3057595	4137185	0.03	0.22	0.26	41	913	1161	42134	0.18
Extreme bias	3773	11714	11997	3411726	6938872	7018307	0.05	0.42	0.44	151	2700	2757	1660	4349	4820	1229800	2258890	2948847	0.04	0.30	0.35	40	745	908	39155	0.18
Constant catch bias, constant F harvest control rule																										
M = 0.2																										
No bias	2757	17963	32406	1813266	3819987	3749459	0.14	0.14	0.14	388	2119	3532	2841	18368	34847	1813957	3795508	3885254	0.13	0.13	0.13	387	1800	3522	26197	0.18
Moderate bias	2682	14065	24870	1204347	4025061	3932761	0.21	0.21	0.21	544	2420	3940	1823	9777	17025	869635	2728804	2554017	0.21	0.21	0.21	367	1402	2621	17185	0.18
Large bias	2592	10439	16902	1241207	3834926	3869306	0.33	0.33	0.34	758	2592	3858	1143	4589	7523	568721	1633643	1640972	0.33	0.33	0.33	331	991	1686	10939	0.18
Extreme bias	2477	7505	13160	1412547	3800248	4071749	0.46	0.47	0.47	910	2320	3832	817	2520	4315	448558	1128940	1303809	0.46	0.47	0.46	298	684	1251	8088	0.18
M ramp																										
No bias	3726	13719	21078	2856463	5996744	8351844	0.14	0.14	0.14	399	1305	1928	3888	14443	21725	3040095	6376929	8078436	0.13	0.13	0.13	402	1167	1915	54702	0.19
Moderate bias	3567	11210	16951	3454123	6655706	6791926	0.21	0.22	0.22	553	1540	2238	2499	7640	11479	2175057	4071038	4592176	0.21	0.21	0.21	375	914	1504	35267	0.19
Large bias	3448	8411	13822	3729471	6258392	6605893	0.33	0.34	0.34	767	1670	2601	1540	3761	6095	1570687	2802819	3036133	0.33	0.33	0.34	341	663	1147	22508	0.19
Extreme bias	3369	7104	11098	3415208	5494714	6265484	0.47	0.47	0.47	953	1790	2669	1113	2370	3682	1093347	1728486	2109339	0.46	0.47	0.47	318	525	872	15790	0.19
Changepoint bias, constant F																										
M = 0.2																										
No bias	2729	17070	32452	1748268	3889186	3933803	0.14	0.14	0.14	384	2015	3519	2789	17327	33812	1744015	3824139	3911901	0.13	0.13	0.13	388	1984	3494	25978	0.18
Moderate bias	2696	14173	24715	1667258	3959138	4038400	0.21	0.21	0.21	548	2410	3902	1892	10042	18075	1088772	2640009	2939418	0.20	0.20	0.19	366	1633	2626	22997	0.18
Large bias	2581	10405	17211	1717525	3726750	3880403	0.33	0.33	0.33	746	2572	3854	1374	4922	8197	799125	1606126	1952773	0.29	0.30	0.28	332	1110	1706	17619	0.18
Extreme bias	2448	7641	12932	1552774	3217493	3847276	0.46	0.46	0.45	902	2334	3672	1248	2736	4702	487234	1056880	1372514	0.38	0.41	0.40	299	779	1207	14418	0.18
M ramp																										
No bias	3677	13622	20258	3045233	6582255	6760788	0.14	0.14	0.14	393	1304	1847	3859	14108	20827	3112142	6854629	6890137	0.13	0.13	0.13	484	1424	1847	54477	0.19
Moderate bias	3613	11372	17478	4136873	6904089	8059737	0.21	0.21	0.21	560	1585	2296	2630	8329	13576	2957538	4891732	6147636	0.19	0.19	0.18	452	1144	1546	47187	0.18
Large bias	3461	8439	14139	2797547	5680496	7791125	0.34	0.33	0.33	772	1644	2648	1733	4124	7111	1321584	2582232	3907300	0.30	0.30	0.28	386	798	1161	33768	0.18
Extreme bias	3375	6628	11232	2513535	5677377	6155019	0.47	0.46	0.46	952	1644	2668	1517	2315	4211	939490	1887357	2821601	0.41	0.40	0.40	338	592	890	27249	0.18

Figures

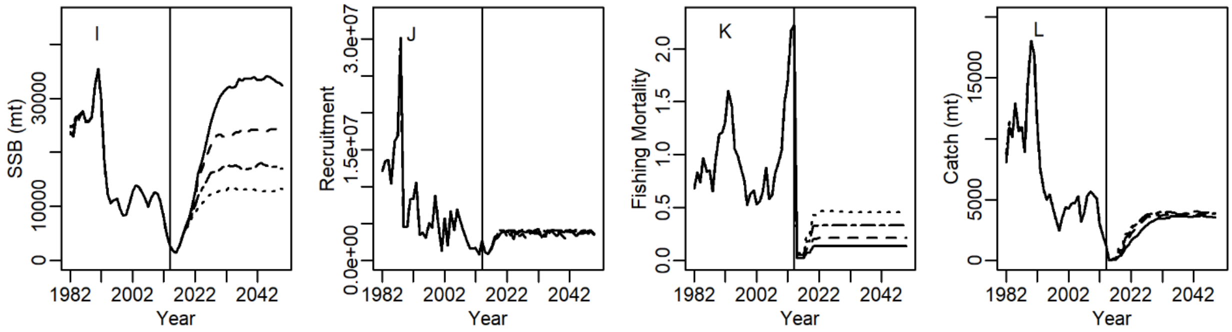
Constant catch bias, M = 0.2, sliding harvest control rule



Constant catch bias, M-ramp, sliding harvest control rule



Changepoint catch bias, M = 0.2, sliding harvest control rule



Changepoint catch bias, M-ramp, sliding harvest control rule

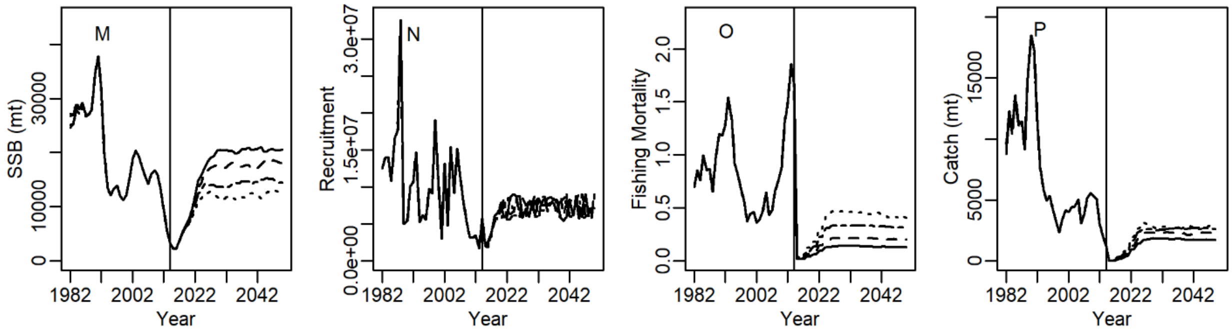
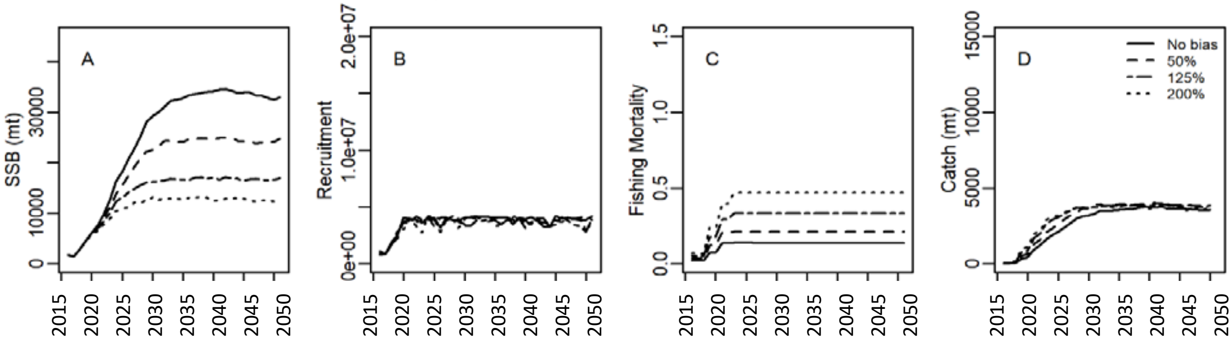
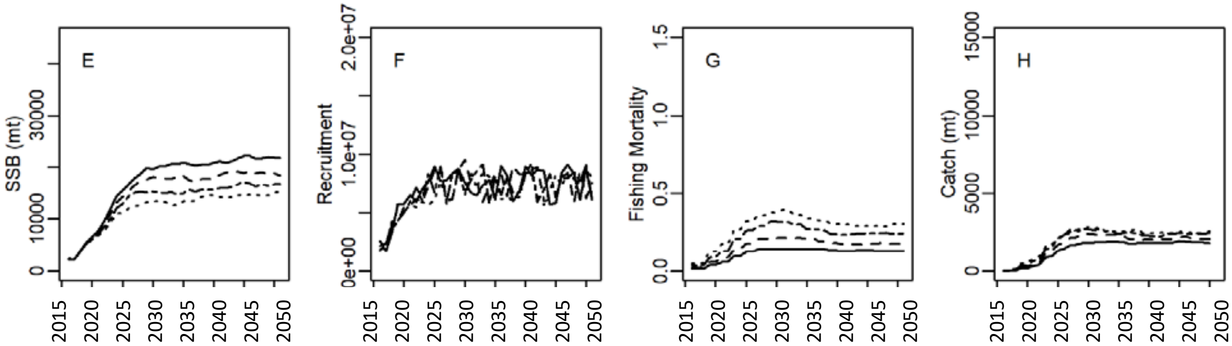


Figure 1. Time series of median operating model spawning stock biomass, recruitment, fishing mortality, and catch from 100 simulations of scenarios with no catch bias, moderate bias (50%), large bias (125%), and extreme bias in catch reporting (200%) under M = 0.2 with constant bias (A-D), M-ramp with constant bias (E-H), M = 0.2 with 2015 changepoint bias (I-L), and M-ramp with 2015 changepoint catch bias (M-P). Vertical black line indicates the start of the projection period (2015).

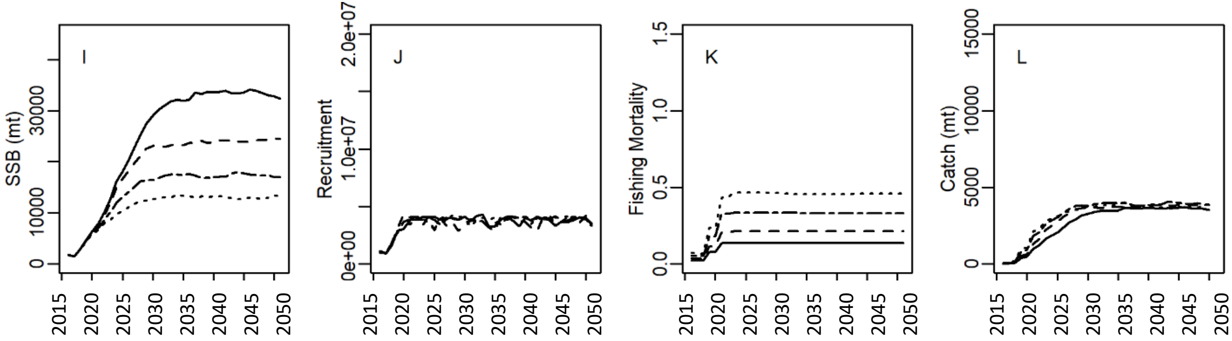
Constant catch bias, M = 0.2, sliding harvest control rule



Constant catch bias, M-ramp, sliding harvest control rule



Changepoint catch bias, M = 0.2, sliding harvest control rule



Changepoint catch bias, M-ramp, sliding harvest control rule

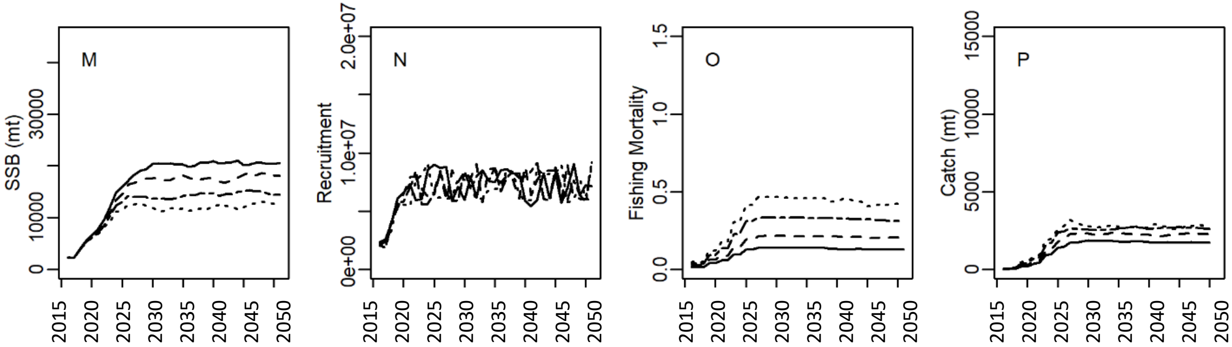
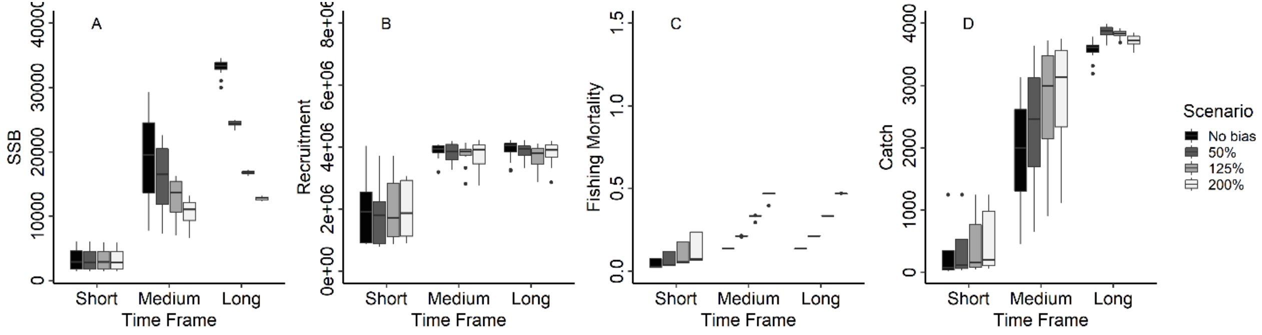
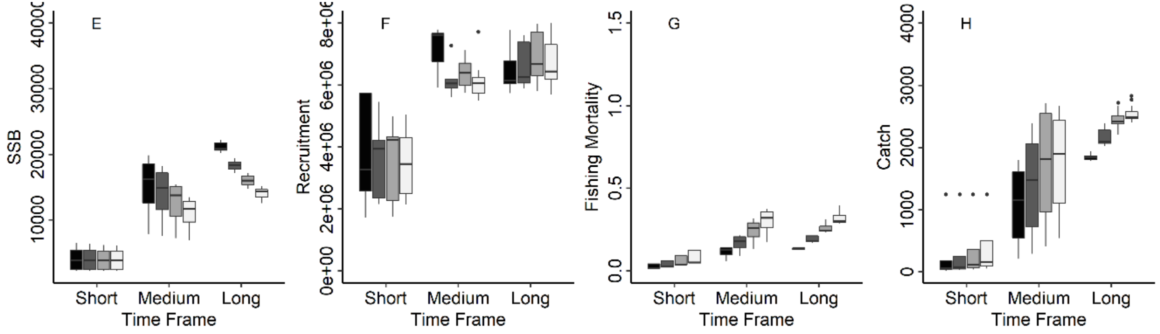


Figure 2. Time series of projected (2015-2050) median operating model spawning stock biomass, recruitment, fishing mortality, and catch from 100 simulations of scenarios with no catch bias, moderate bias (50%), large bias (125%), and extreme bias in catch reporting (200%) under M = 0.2 with constant bias (A-D), M-ramp with constant bias (E-H), M = 0.2 with 2015 changepoint bias (I-L), and M-ramp with 2015 changepoint catch bias (M-P).

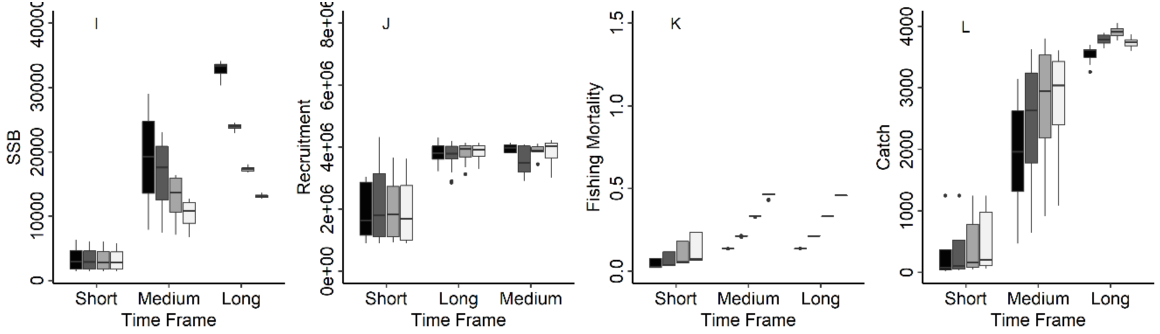
Constant catch bias, M = 0.2, sliding harvest control rule



Constant catch bias, M-ramp, sliding harvest control rule



Changepoint catch bias, M = 0.2, sliding harvest control rule



Changepoint catch bias, M-ramp, sliding harvest control rule

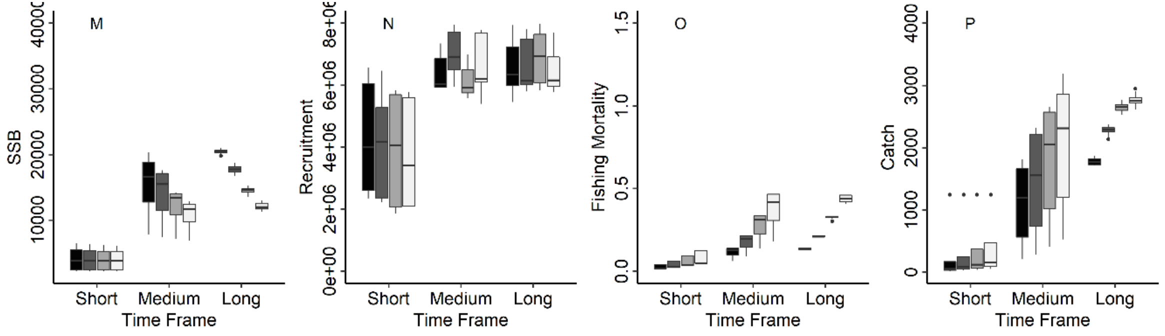
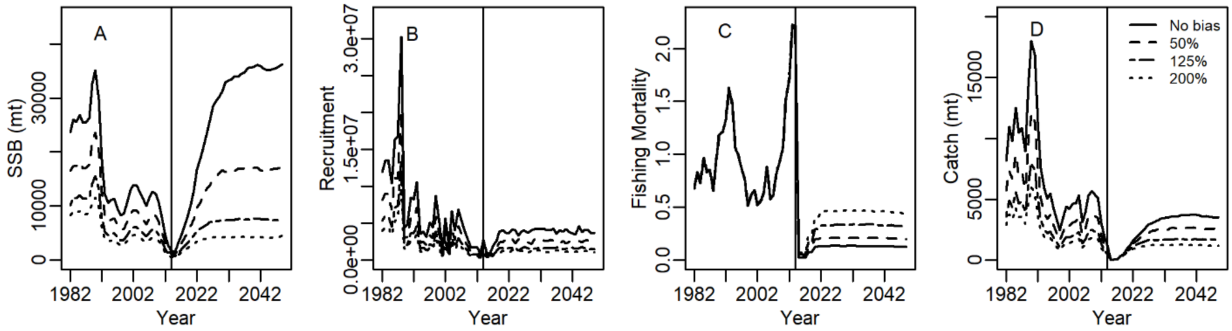
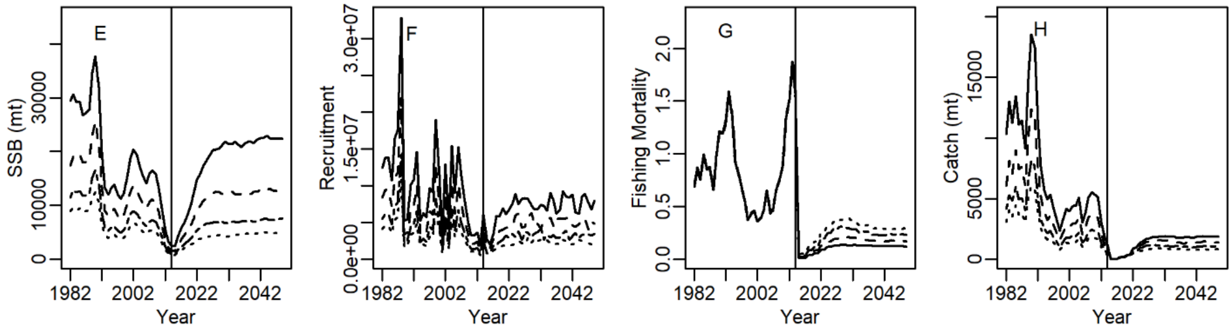


Figure 3. Boxplots of operating model spawning stock biomass, recruitment, fishing mortality, and catch (mt) across 100 simulations for each scenario under constant catch bias with M = 0.2 (A-D), constant bias with M-ramp (E-H), changepoint catch bias with M = 0.2 (I-L) and changepoint catch bias with M-ramp (M-P) in the short term (1-5 projected years), medium term (6-15 projected years), and long term (16-36 projected years).

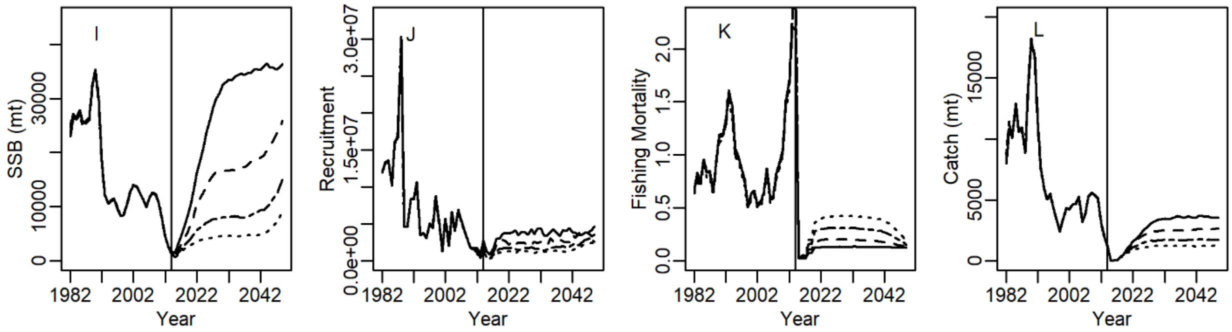
Constant catch bias, M = 0.2, sliding harvest control rule



Constant catch bias, M-ramp, sliding harvest control rule



Changepoint catch bias, M = 0.2, sliding harvest control rule



Changepoint catch bias, M-ramp, sliding harvest control rule

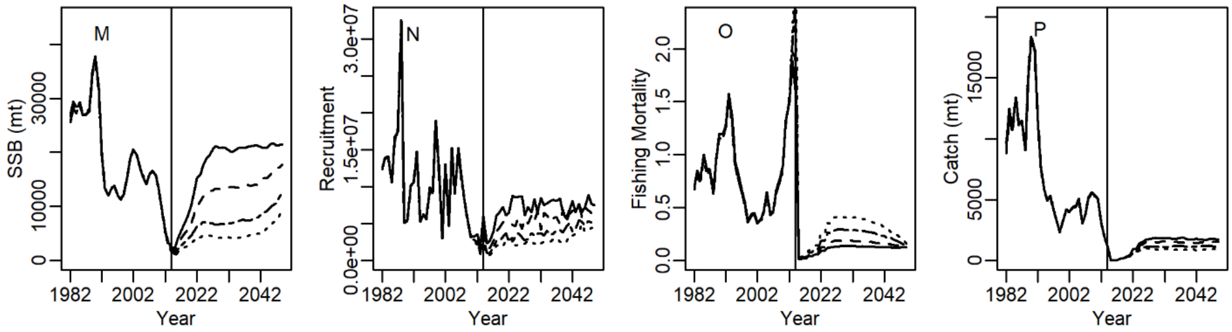
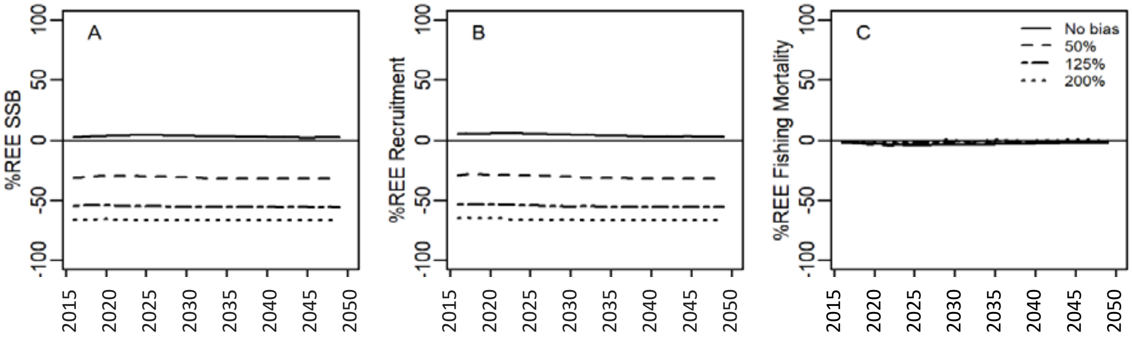
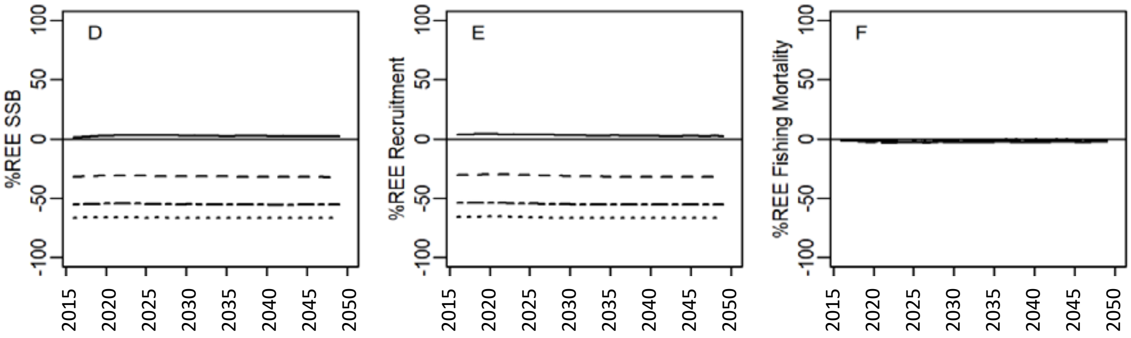


Figure 4. Median of estimated spawning stock biomass, recruitment, fishing mortality, and catch from last stock assessment in the projected time series (100 simulations). Scenarios were simulated with no catch bias, moderate bias (50%), large bias (125%), and extreme bias in catch reporting (200%) under M = 0.2 with constant bias (A-D), M-ramp with constant bias (E-H), M = 0.2 with 2015 changepoint catch bias (I-L), and M-ramp with 2015 changepoint catch bias (M-P). Vertical black line indicates the start of the projection period (2015).

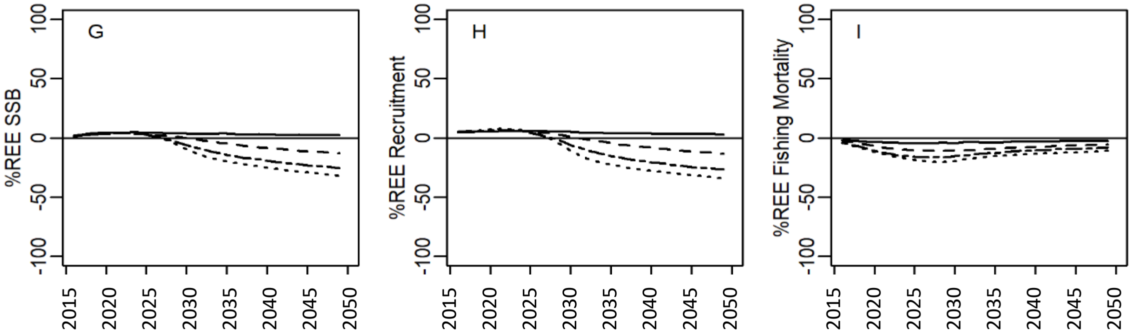
Constant catch bias, M = 0.2, sliding harvest control rule



Constant catch bias, M-ramp, sliding harvest control rule



Changepoint catch bias, M = 0.2, sliding harvest control rule



Changepoint catch bias, M-ramp, sliding harvest control rule

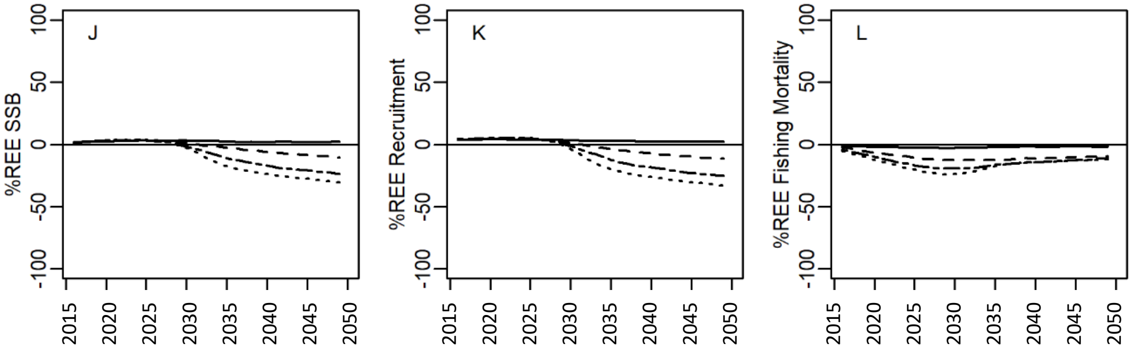


Figure 5. Time series of median percentage relative error estimates (%REE) comparing assessment estimates to operating model values for spawning stock biomass, recruitment, and fishing mortality across 100 simulations for each scenario under constant catch bias with M = 0.2 (A-C), constant bias with M-ramp (D-F), changepoint catch bias with M = 0.2 (G-I) and changepoint catch bias with M-ramp (J-L). The horizontal black line is to reference zero bias.

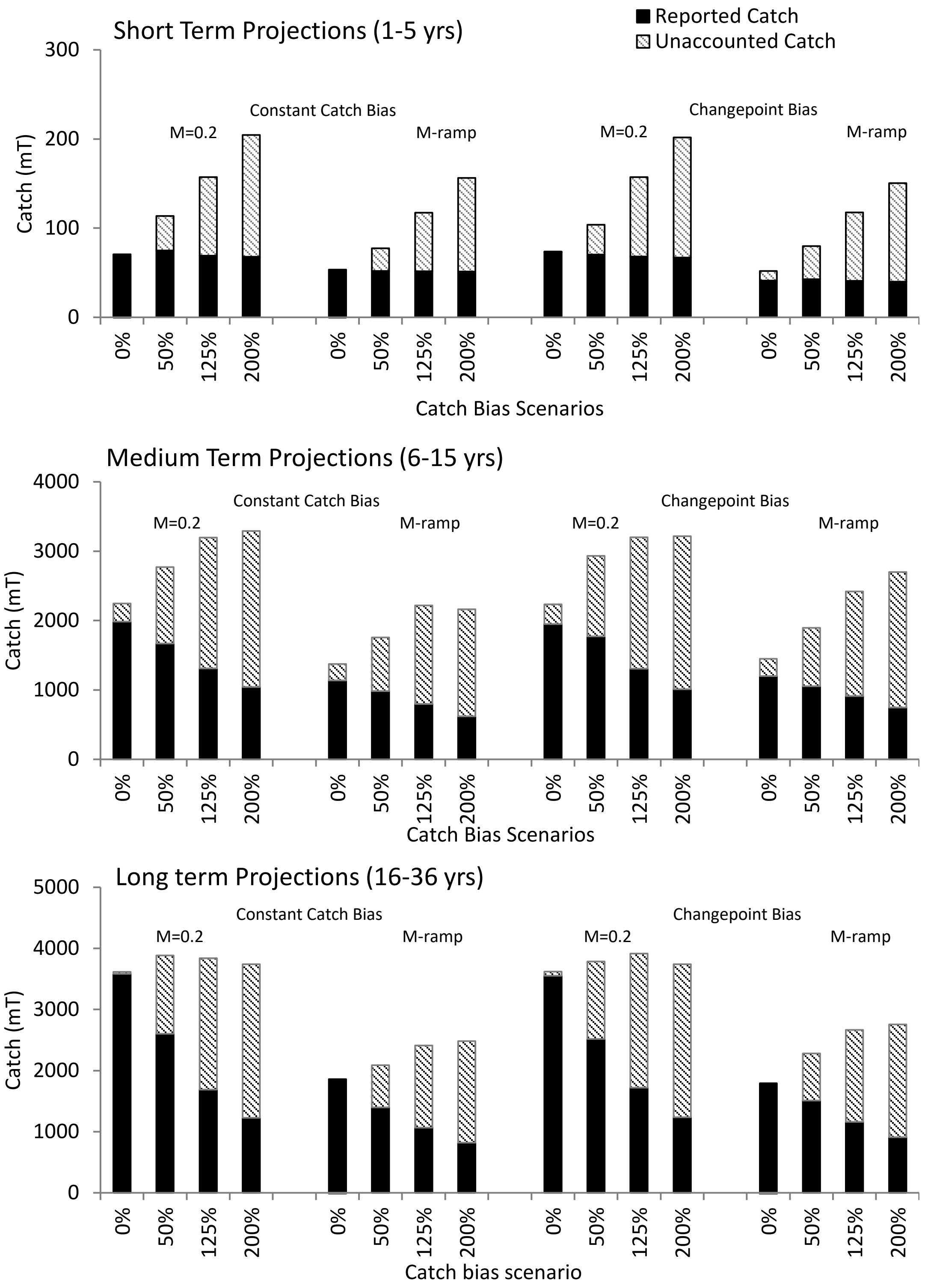


Figure 6. Median reported and unaccounted catch (together equating to "true" catch) across 100 simulations of catch bias scenarios for each scenario under constant and changepoint catch bias for M = 0.2 and M-ramp operating models in the short term (1-5 projected years), medium term (6-15 projected years), and long term (16-36 projected years).

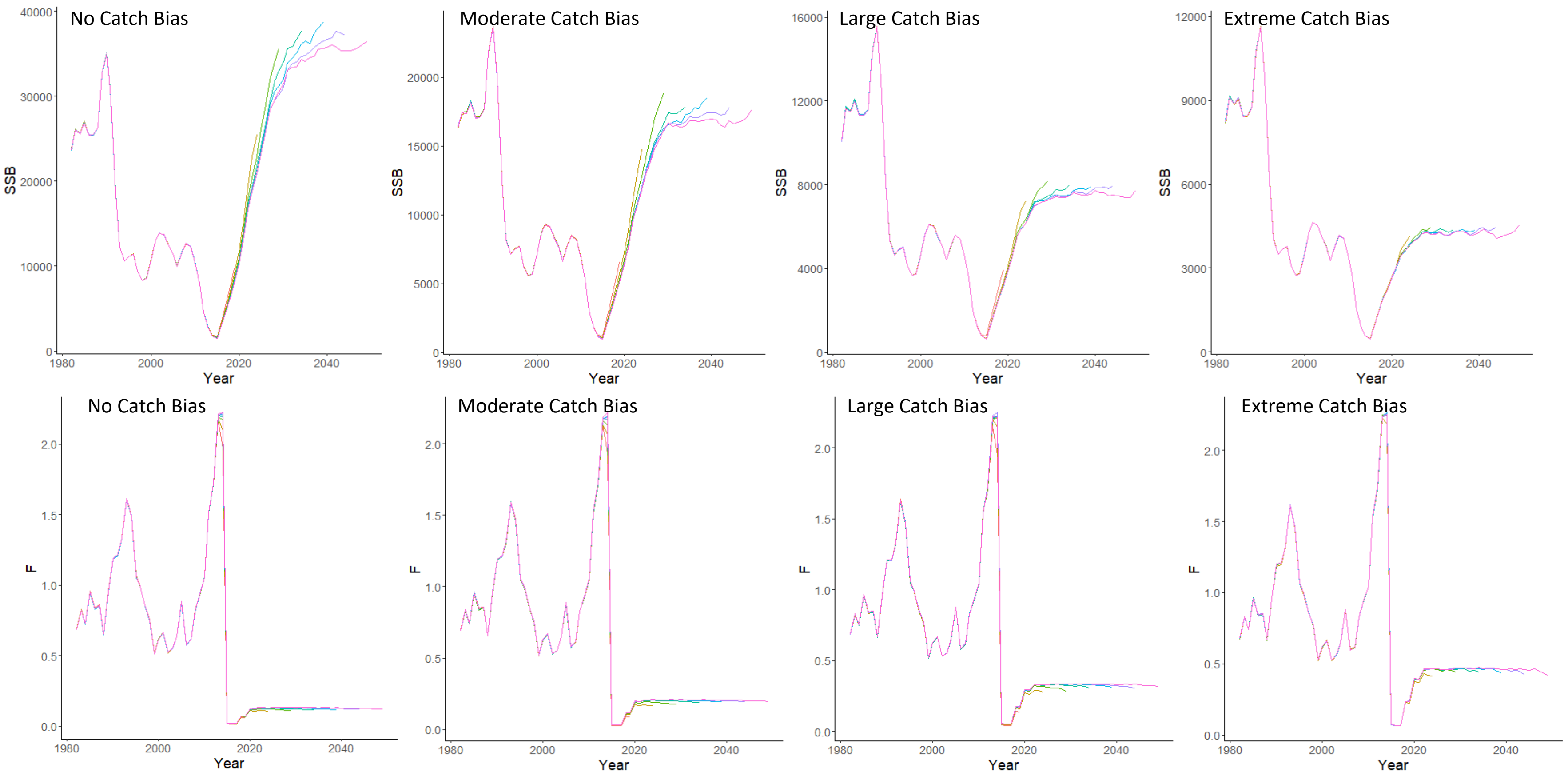


Figure 7: Retrospective evaluation of stock assessment results every five years over the span of projection period (2015-2050) assuming constant catch bias under M=0.2 operating models and a sliding harvest control rule. Panels from left to right show results for scenarios with increased catch bias**.**

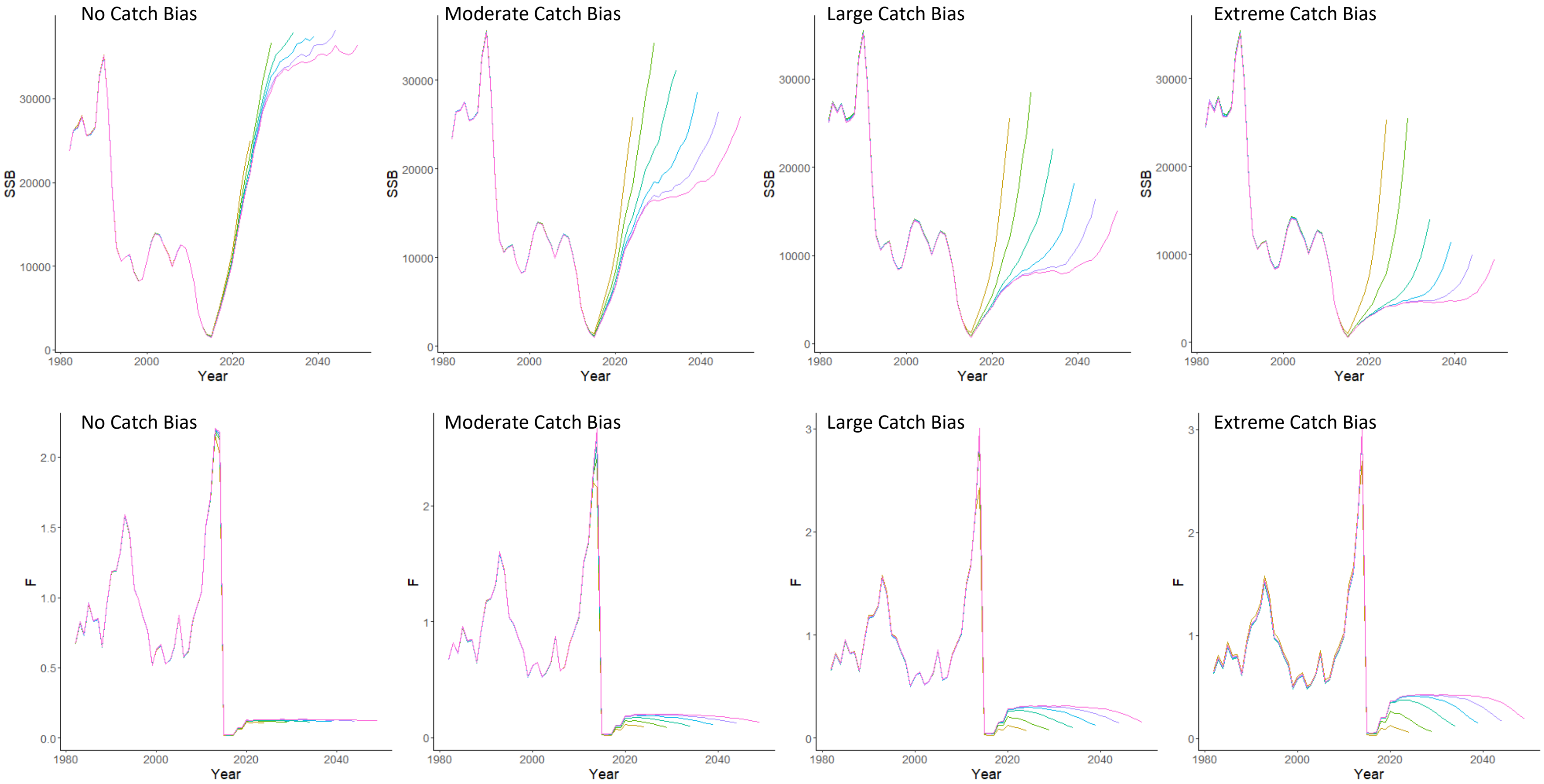
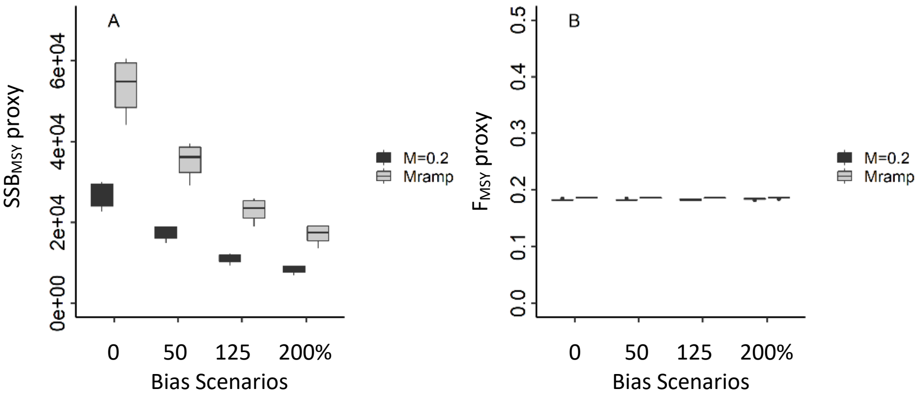


Figure 8: Retrospective evaluation of stock assessment results every five years over the span of projection period (2015-2050) assuming a changepoint in catch bias under M=0.2 operating models and a sliding harvest control rule. Panels from left to right show results for scenarios with increased catch bias**.**

Constant catch bias, sliding harvest control rule



Changepoint catch bias, sliding harvest control rule

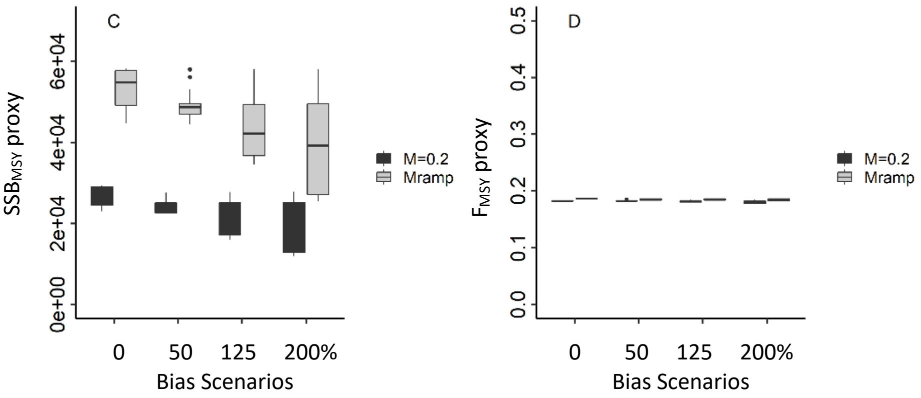
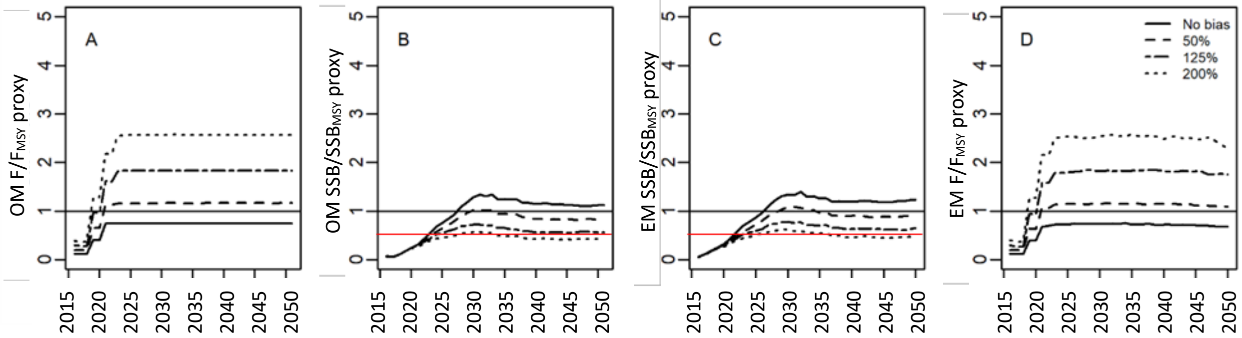
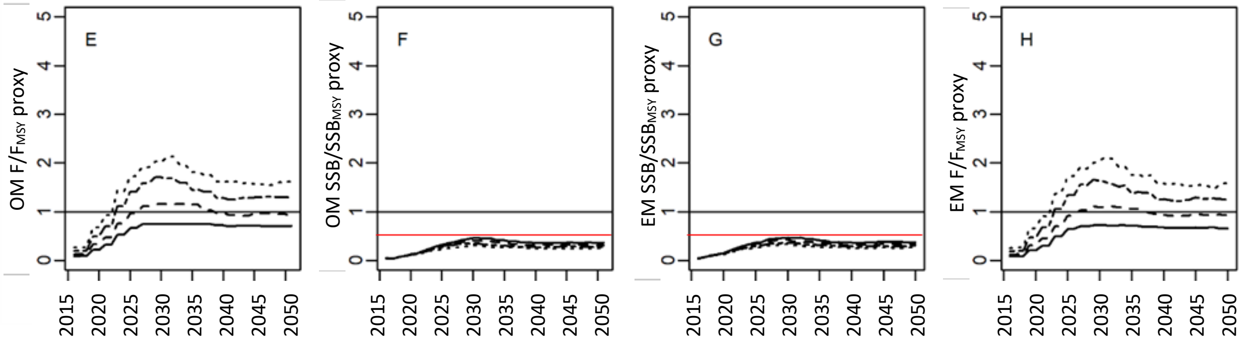


Figure 9: Boxplots of spawning stock biomass ($SSB_{F40\%}$) and fishing mortality ($F_{40\%}$) biological reference point values for M = 0.2 and M-ramp realizations under contant catch bias (A, B) and changepoint catch bias (C, D) across catch bias scenarios. Note that M-ramp biological reference points were calculated assuming M= 0.2.

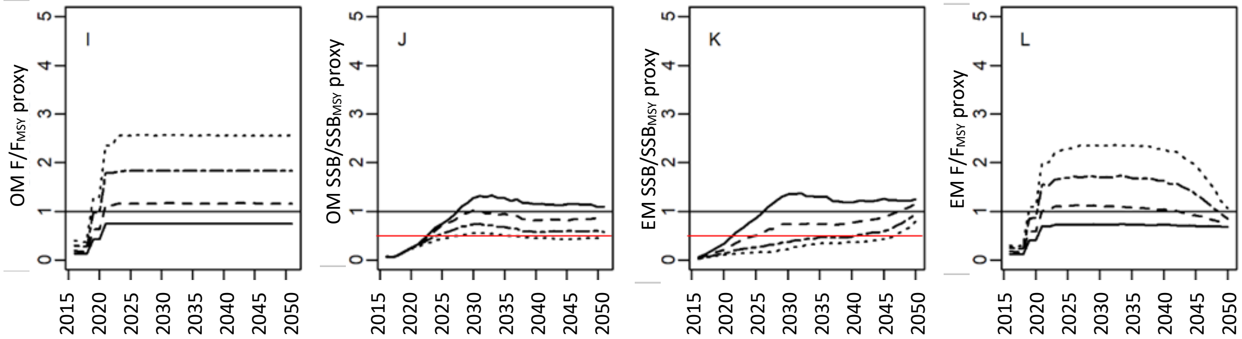
Constant catch bias, M = 0.2, sliding harvest control rule



Constant catch bias, M-ramp, sliding harvest control rule



Changepoint catch bias, M = 0.2, sliding harvest control rule



Changepoint catch bias, M-ramp, sliding harvest control rule

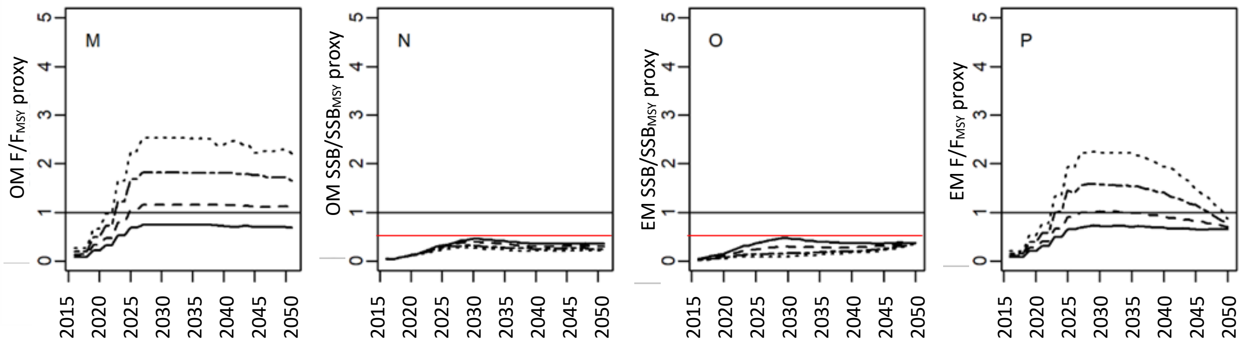


Figure 10: Left panels: Operating model (OM) fishing mortality and spawning stock biomass values relative to "true" proxy reference points (Black lines are relative to $F_{40\%}$ and $SSB_{F40\%}$, red line is relative to 0.5 $SSB_{F40\%}$. **Right panels:** Stock assessment estimates (EM) of spawning stock biomass and fishing mortality relative to the estimated biological reference point proxies. Results are from 100 simulations of scenarios.

Appendix A: Constant F harvest control rule simulation results

To understand the implications of underestimated catch scenarios under an alternative harvest control rule, we ran all catch bias scenarios under a constant fishing mortality harvest control rule (75% $F_{40\%}$, Figure A1). These simulations also included testing under alternative operating models (M = 0.2 and M-ramp) and alternative bias structure (constant and changepoint catch bias). The sliding harvest control rule reduced fishing mortality target values with lower spawning stock biomass, whereas the constant harvest control rule maintained the same level of fishing mortality regardless of stock size (Figure A1). In general, the impacts of catch bias scenarios were similar across the alternative harvest control rules with some key differences in the performance of the sliding and constant harvest control rules in the short-term (1-5 projection years). Under the constant fishing mortality harvest control rule, operating models exhibited higher fishing mortality and catch, and lower spawning stock biomass in the short term compared to simulations under the sliding harvest control rule. This led to slightly lower spawning stock biomass and catch levels in the medium term, but similar values over the long term. The patterns of assessment and management performance under the constant fishing mortality harvest control rule were consistent with the performance observed under the sliding harvest control rule. The similar outcomes of testing catch bias scenarios across alternative harvest control rules support the robustness of our findings.

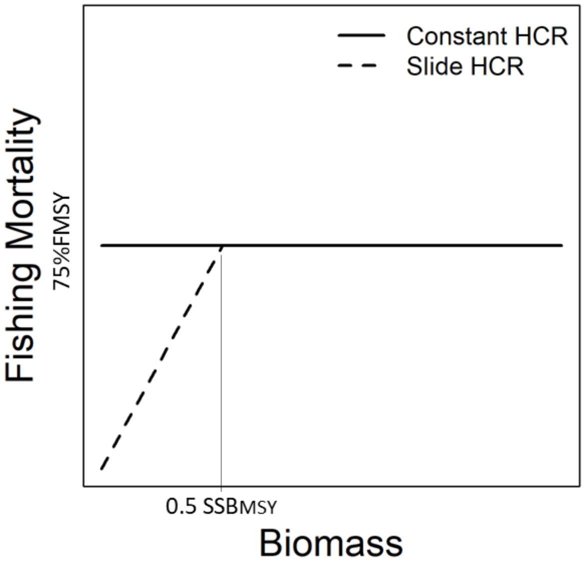
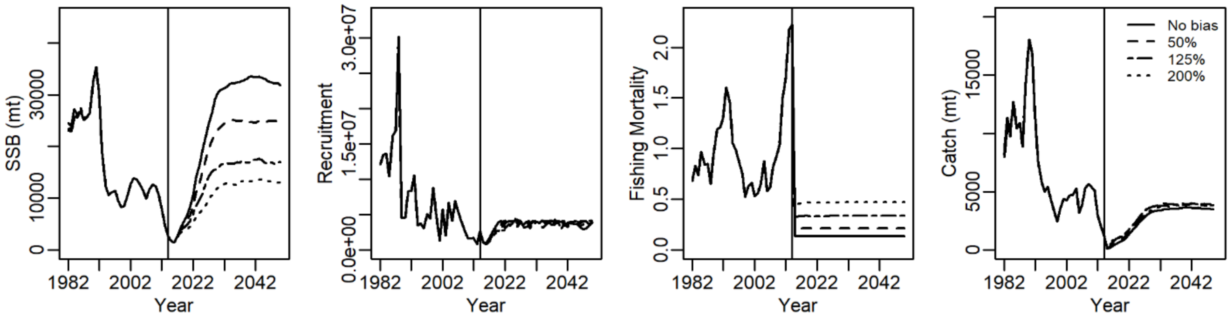
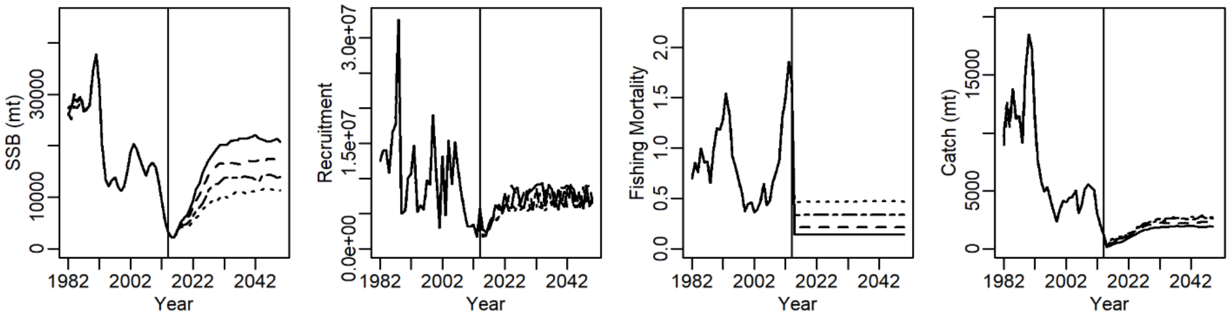


Figure A1: Depiction of sliding harvest control rule and constant fishing mortality harvest control rule used in analysis.

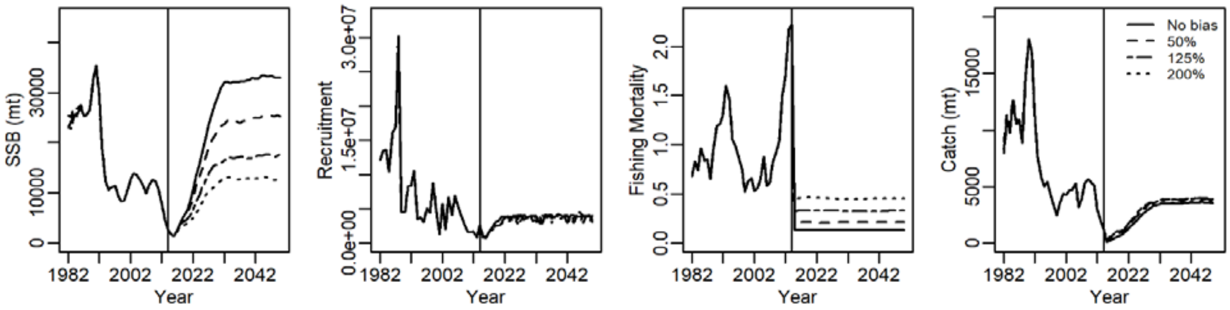
Constant catch bias, M = 0.2, constant F harvest control rule



Constant catch bias, M-ramp, constant F harvest control rule



Changepoint catch bias, M = 0.2, constant F harvest control rule



Changepoint catch bias, M-ramp, constant F harvest control rule

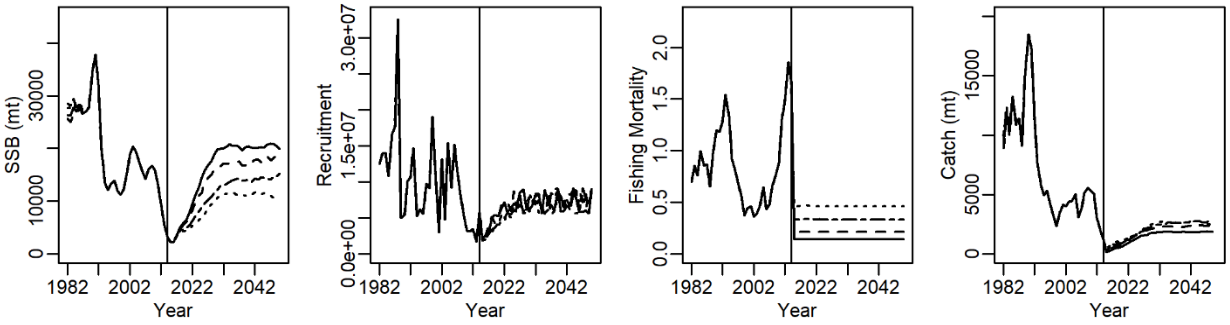
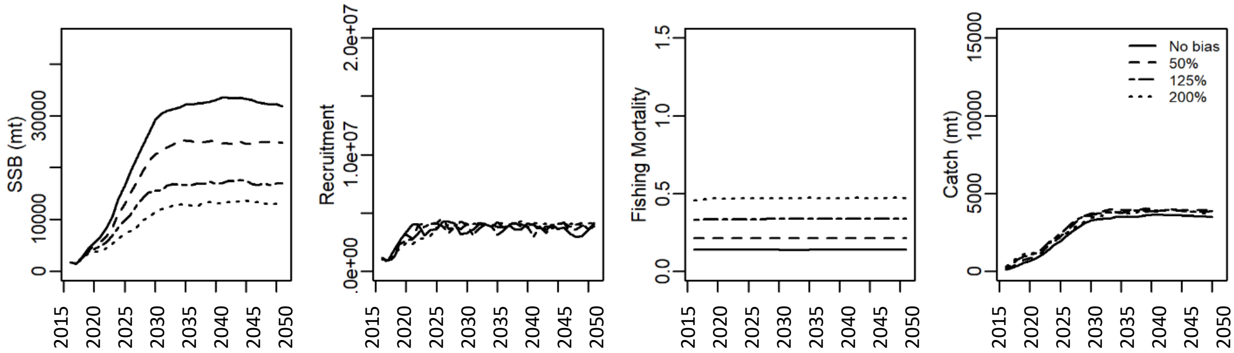
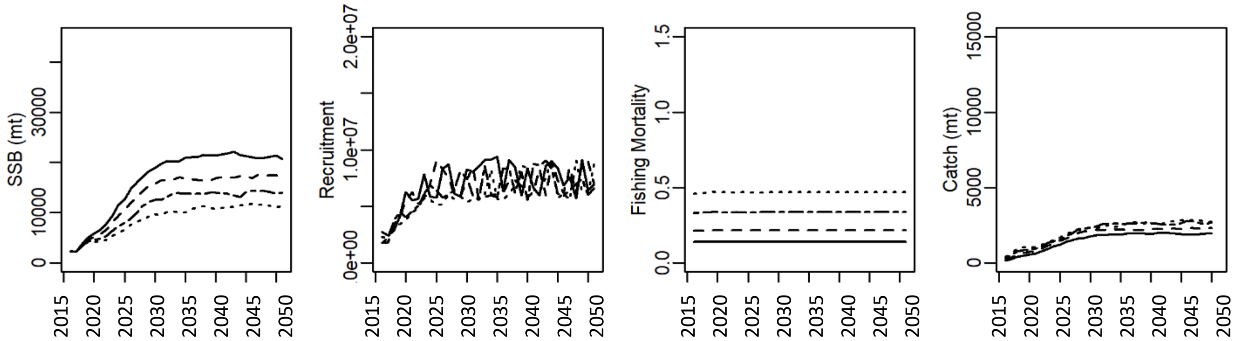


Figure A2. Time series of median operating model spawning stock biomass, recruitment, fishing mortality, catch from 100 simulations of scenarios with no catch bias, moderate bias (50%), large bias (125%), and extreme bias in catch reporting (200%) under M = 0.2 and M-ramp with constant and changepoint catch bias using a constant fishing mortality harvest control rule.

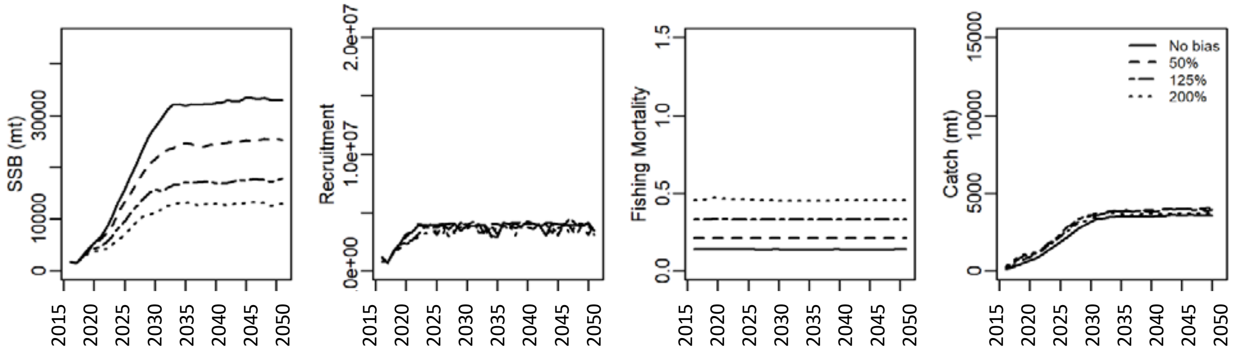
Constant catch bias, M = 0.2, constant F harvest control rule



Constant catch bias, M-ramp, constant F harvest control rule



Changepoint catch bias, M = 0.2, constant F harvest control rule



Changepoint catch bias, M-ramp, constant F harvest control rule

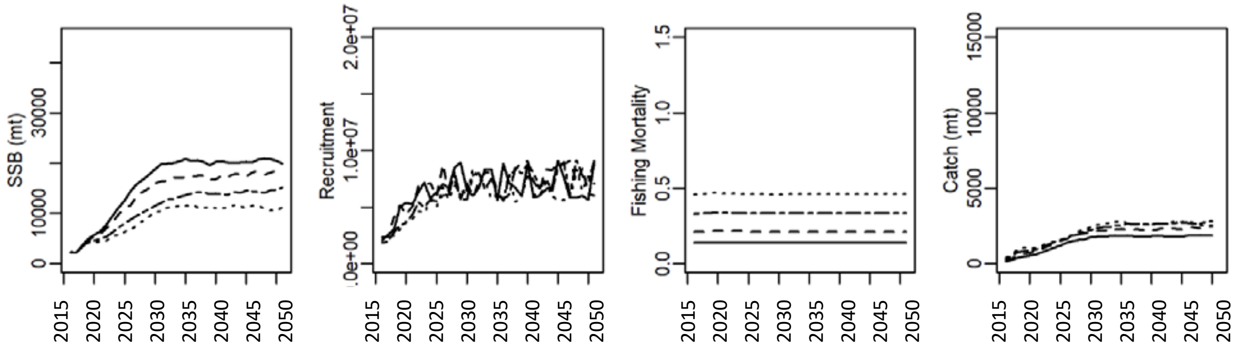
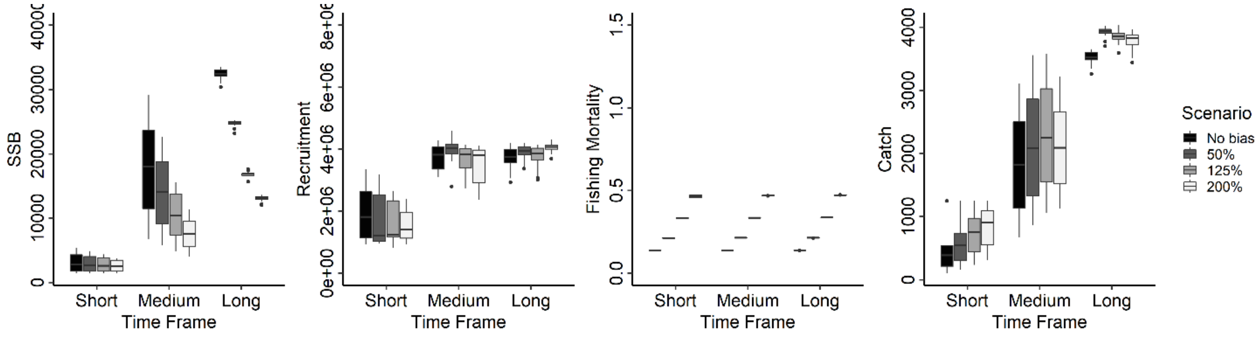
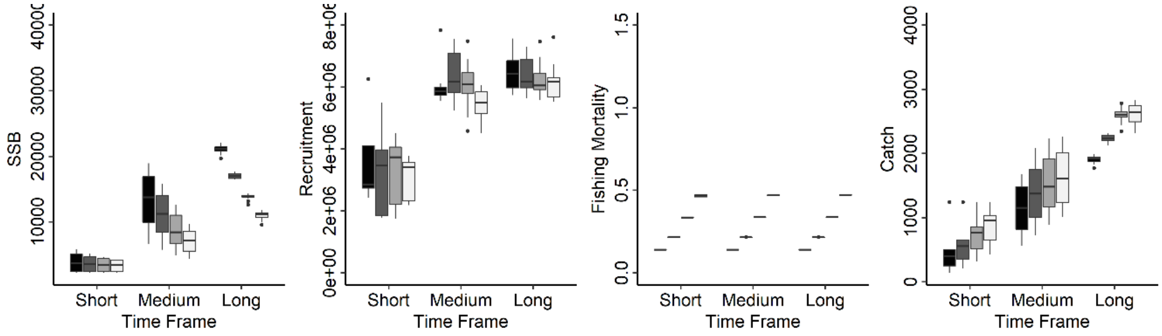


Figure A3. Time series of median operating model spawning stock biomass, recruitment, fishing mortality, and catch from 100 simulations of scenarios with no catch bias, moderate bias (50%), large bias (125%), and extreme bias in catch reporting (200%) under M = 0.2 and M-ramp with constant and changepoint catch bias using a constant fishing mortality harvest control rule.

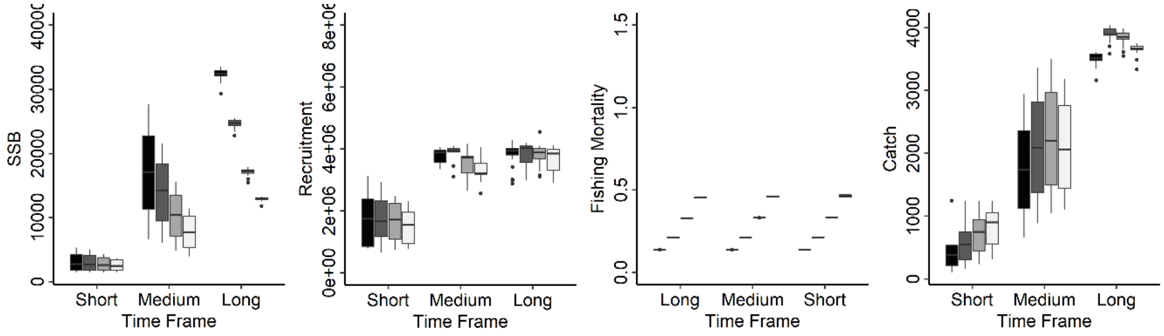
Constant catch bias, M = 0.2, constant F harvest control rule



Constant catch bias, M-ramp, constant F harvest control rule



Changepoint catch bias, M = 0.2, constant F harvest control rule



Changepoint catch bias, M-ramp, constant F harvest control rule

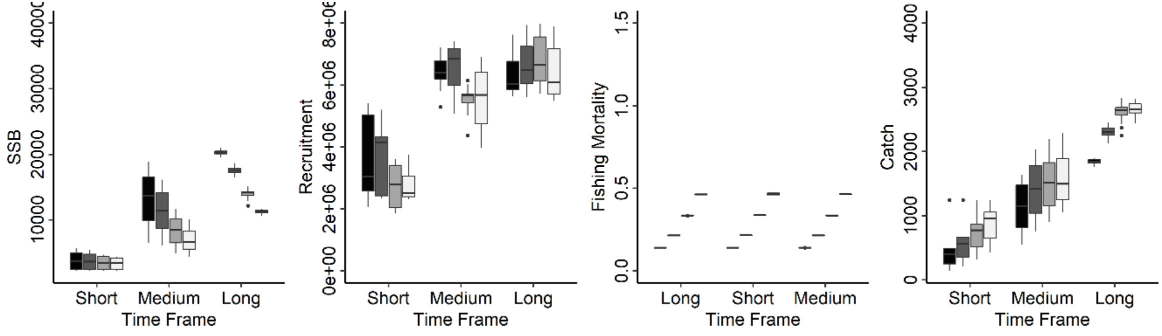
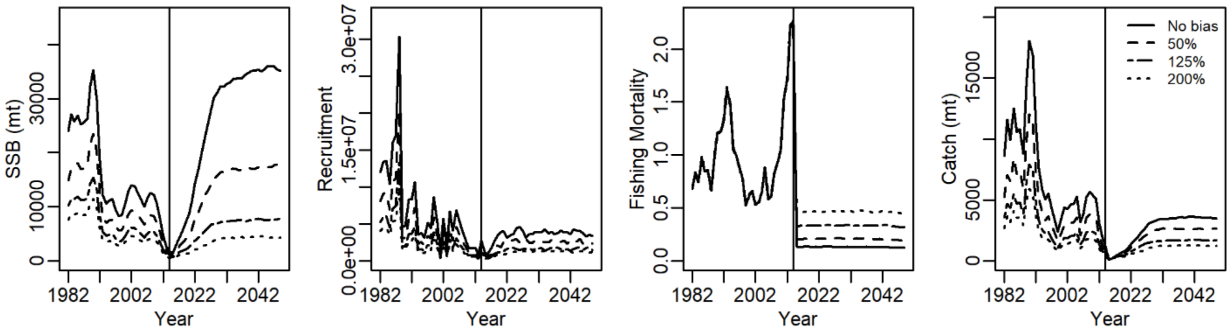
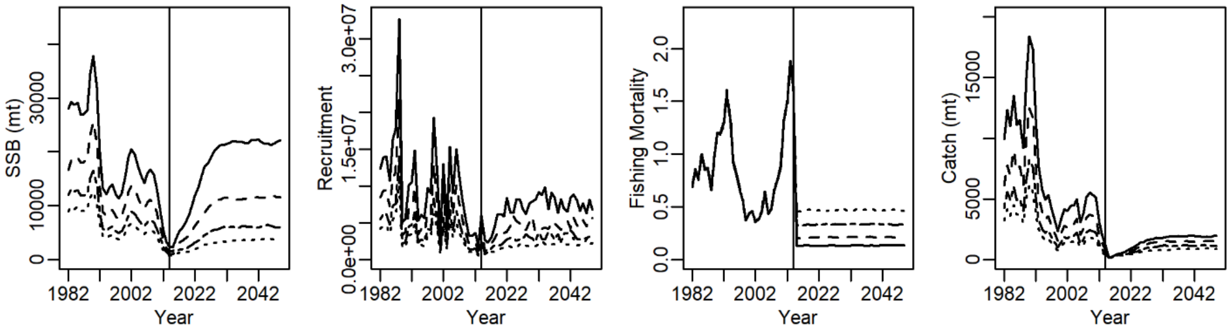


Figure A4. Boxplots of operating model spawning stock biomass, recruitment, fishing mortality, and catch (mt) across 100 simulations for each scenario under constant and changepoint catch bias with M = 0.2 and M-ramp using a constant fishing mortality harvest control rule in the short term (1-5 projected years), medium term (6-15 projected years), and long term (16-36 projected years).

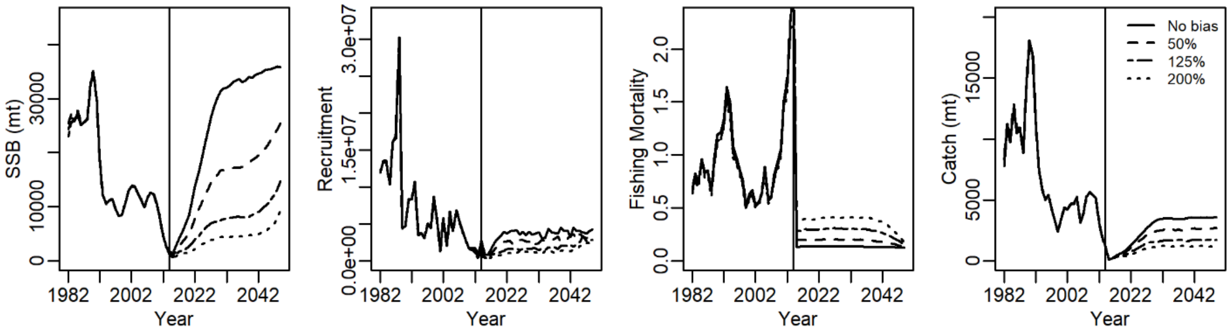
Constant catch bias, M = 0.2, constant F harvest control rule



Constant catch bias, M-ramp, constant F harvest control rule



Changepoint catch bias, M = 0.2, constant F harvest control rule



Changepoint catch bias, M-ramp, constant F harvest control rule

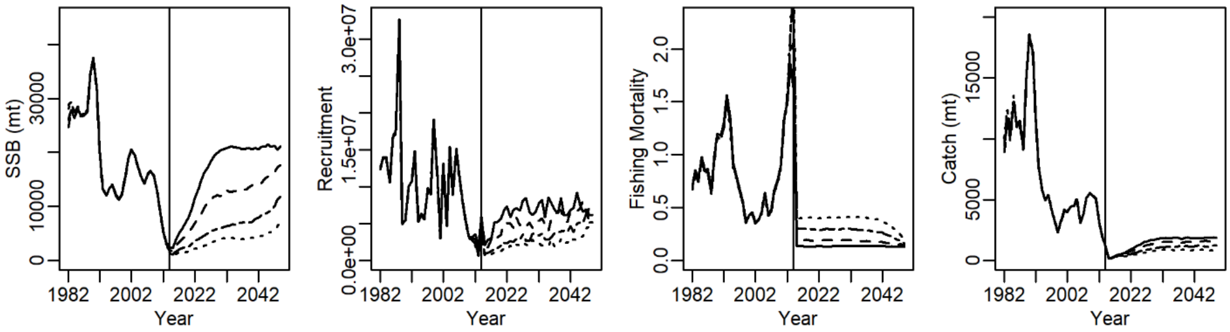
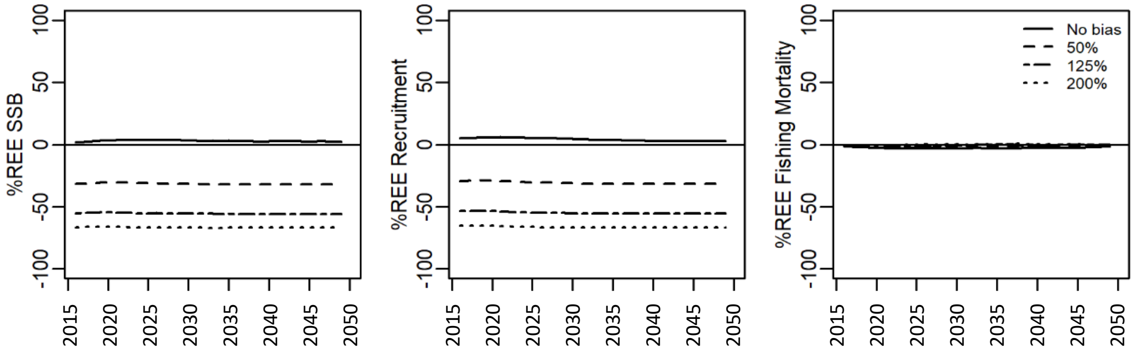
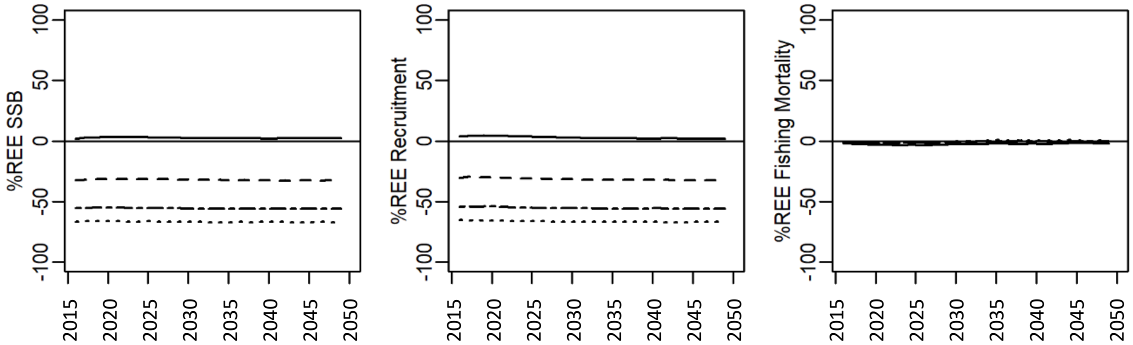


Figure A5. Time series of median estimated spawning stock biomass, recruitment, fishing mortality, and catch from last stock assessment in the projected time series (100 simulations). Scenarios were simulated with no catch bias, moderate bias (50%), large bias (125%), and extreme bias in catch reporting (200%) under M = 0.2 and M-ramp with constant and changepoint catch bias using a constant harvest control rule. Vertical black line indicates the start of the projection period (2015).

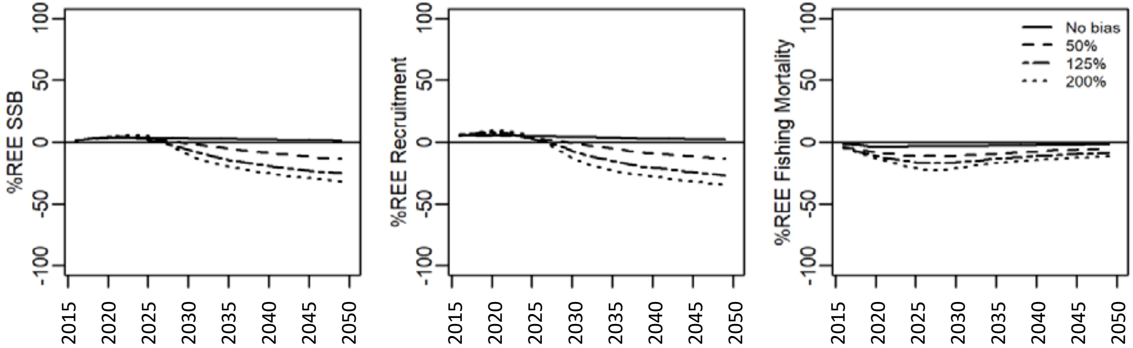
Constant catch bias, M = 0.2, constant F harvest control rule



Constant catch bias, M-ramp, constant F harvest control rule



Changepoint catch bias, M = 0.2, constant F harvest control rule



Changepoint catch bias, M-ramp, constant F harvest control rule

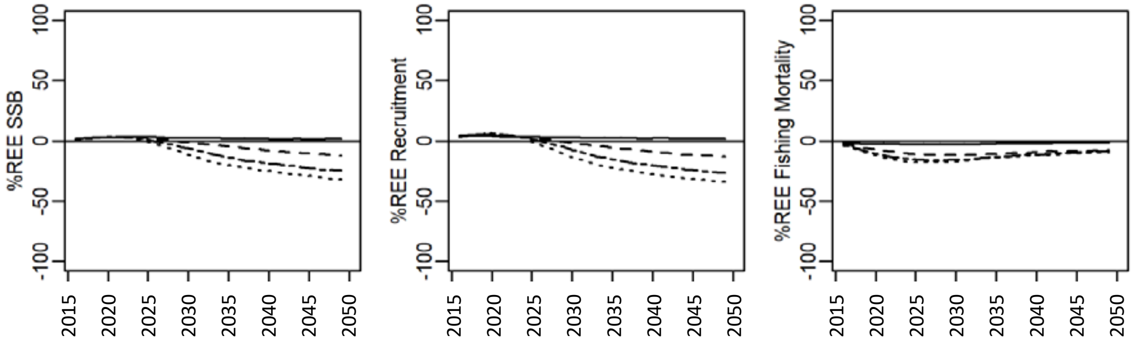


Figure A6. Time series of median percentage relative error estimates (%REE) comparing the average assessment to the operating model spawning stock biomass, recruitment, and fishing mortality across 100 simulations for each scenario with Constant and changepoint catch bias under M = 0.2 and M-ramp under a constant harvest control rule. The horizontal black line is to reference zero bias.

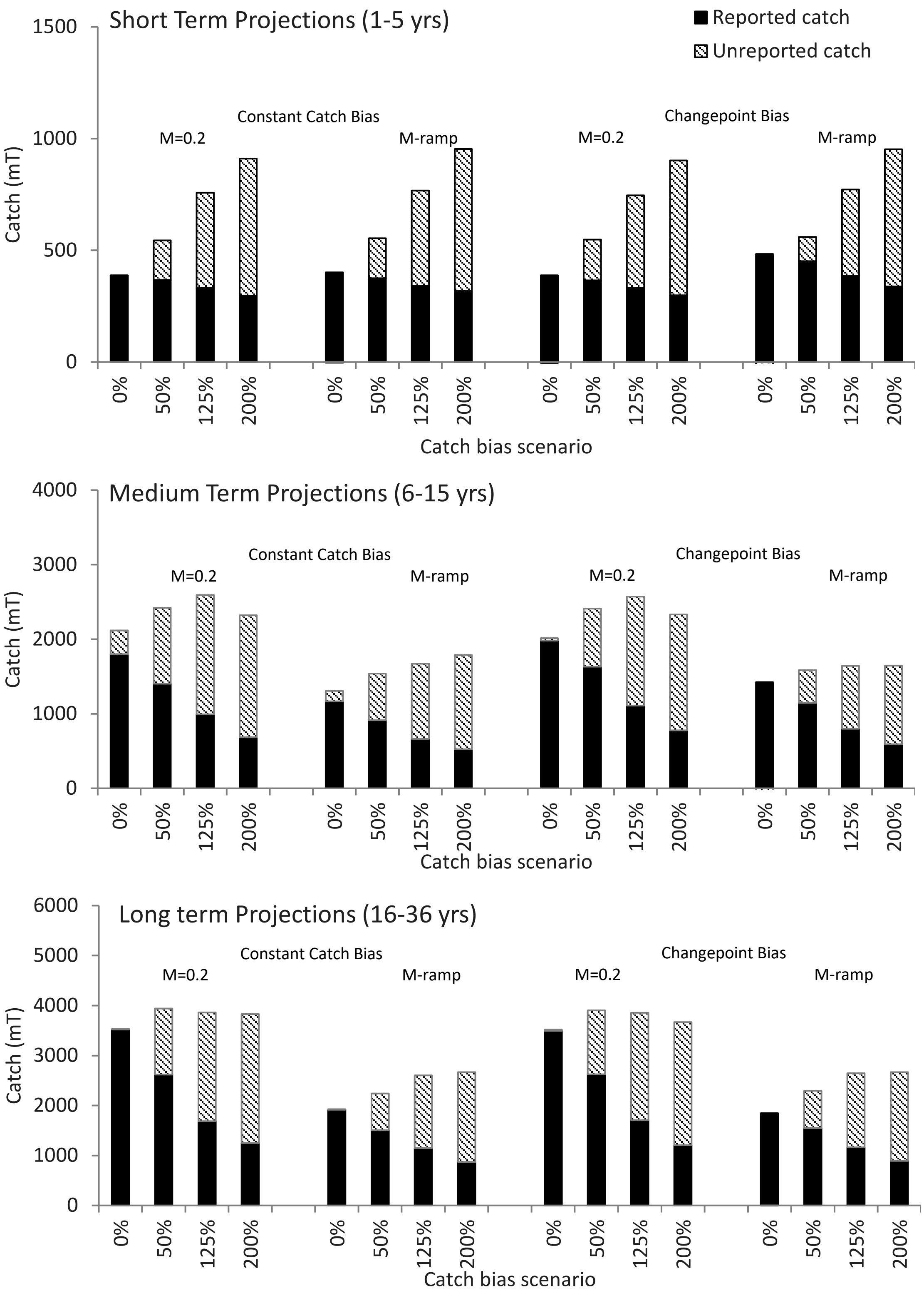
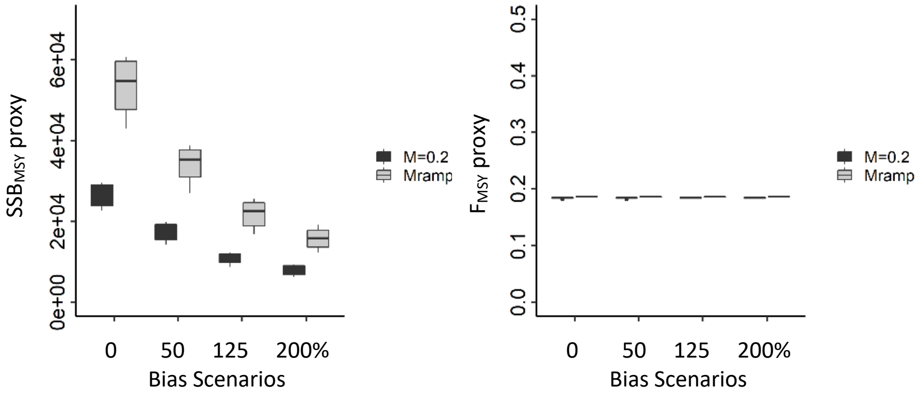


Figure A7. Median reported and unaccounted catch (together equating to "true" catch) across 100 simulations of catch bias scenarios for each scenario under constant and changepoint catch bias for M = 0.2 and M-ramp operating models in the short term (1-5 projected years), medium term (6-15 projected years), and long term (16-36 projected years).

Constant catch bias, constant F harvest control rule



Changepoint catch bias, constant F harvest control rule

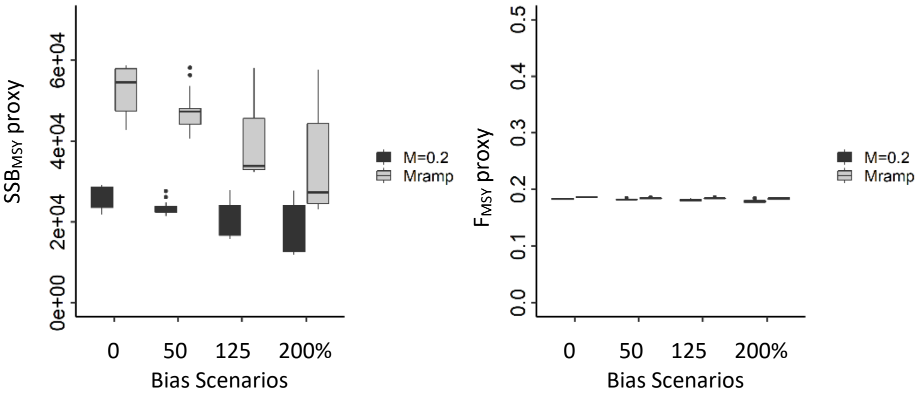
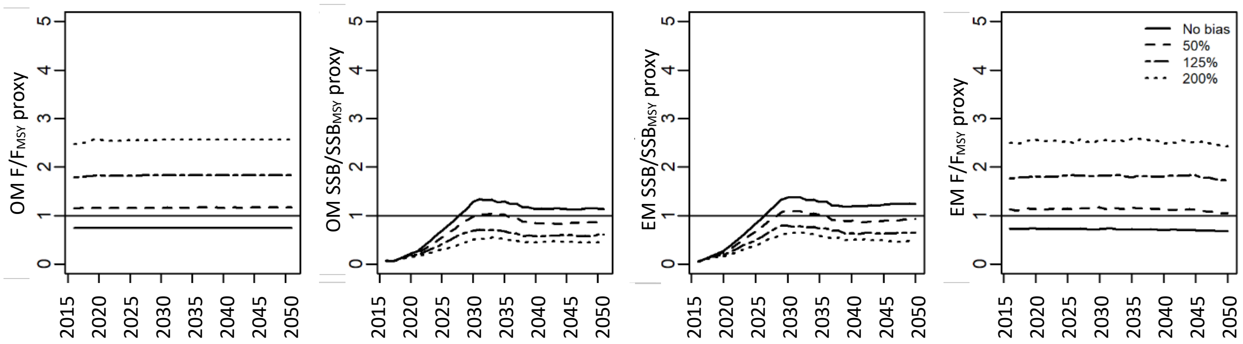
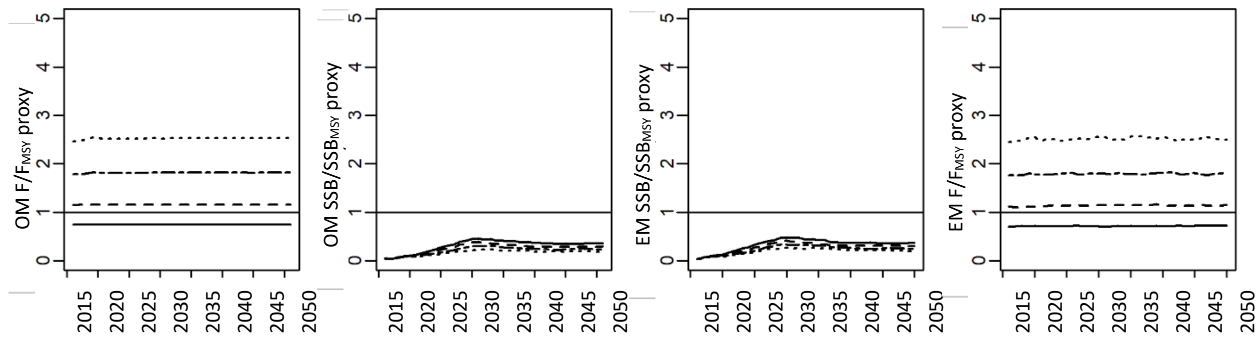


Figure A7: Boxplots of spawning stock biomass ($SSB_{F40\%}$) and fishing mortality ($F_{40\%}$) biological reference point values for M = 0.2 and M-ramp realizations under contant catch bias and changepoint catch bias across catch bias scenarios using a constant fishing mortality harvest control rule. Note that M-ramp biological reference points were calculated assuming M= 0.2.

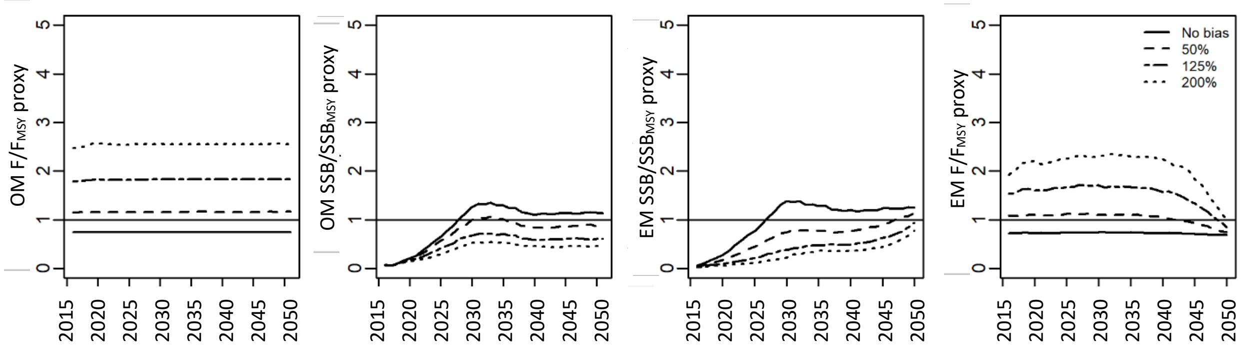
Constant catch bias, M = 0.2, constant F harvest control rule



Constant catch bias, M-ramp, constant F harvest control rule



Changepoint catch bias, M = 0.2, constant F harvest control rule



Changepoint catch bias, M-ramp, constant F harvest control rule

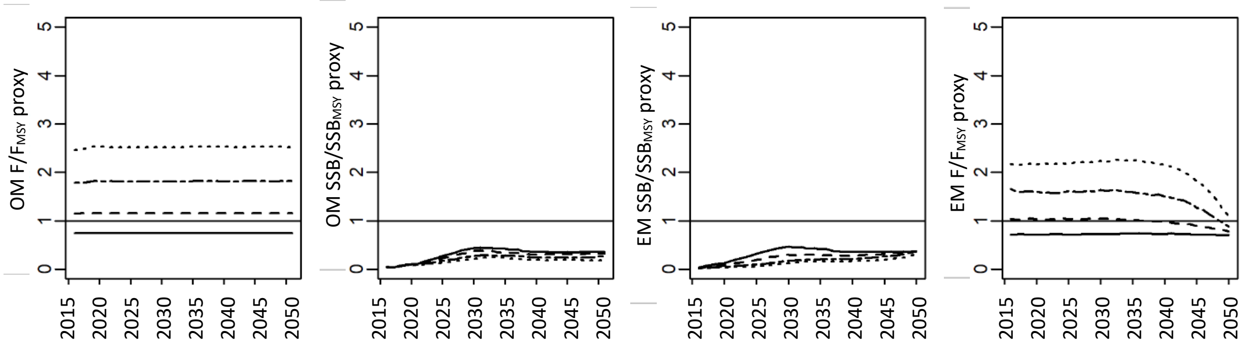


Figure A8. **Left panels:** Operating model (OM) fishing mortality and spawning stock biomass values relative to "true" proxy reference points (Black lines are relative to $F_{40\%}$ and $SSB_{F40\%}$, red line is relative to 0.5 $SSB_{F40\%}$. **Right panels:** Stock assessment estimates (EM) of spawning stock biomass and fishing mortality relative to the estimated biological reference point proxies. Results are from 100 simulations of scenarios.

Background:
Excerpt from Amendment 23 Draft Environment Impact Statement formal submission, March 4, 2020 (pg. 300-303)

Magnitude of potential 2018 missing Gulf of Maine cod discards

A sub-panel of the SSC reviewed PDT analyses showing evidence of an observer effect and concluded that observed trips are not representative of unobserved trips in the groundfish fishery (see Section 6.6.10.5 and Appendix V). However, the magnitude of the missing removals that results from illegal discards across the entire fishery was not quantified at the SSC review (the PDT does provide an estimate of potential magnitude of missing removals for GOM cod on gillnet trips; see Section 6.6.10.5.3 and Appendix V, "Predicting Gulf of Maine (GOM) cod catch on Northeast Multispecies (groundfish) sector trips: implications for observer bias and fishery catch accounting"). The reviewers did suggest that further investigation into quantifying the missing catch should be done.

Overall Approach - The concept behind the following analyses is to calculate potential landings in a target year by multiplying the landings per unit of effort (landings/day absent) from a reference year by the amount of effort (days absent) in the target year. In this analysis, the reference year is chosen as a year where the stock size is similar to the target year, but the ABC is larger. Under the assumption that landing rates (landings/days absent) are influenced by stock size, the landing rates would be expected to be similar for the reference year and target year. Based on analyses in Appendix V, a lower allowable catch would be expected to change fishing behavior. Fisherman could change fishing practices in a number of ways, but one possible response would be to increase discards of legal-sized fish. The landing rate in the reference year (with the higher ABC) could be multiplied by the total effort measure in the target year (with the lower ABC) to estimate a potential landings amount. This could be compared to the actual landings, and the difference can be considered a rough estimate of discards. Since all legal-sized fish are required to be landed in the sector system, this estimate could represent unaccounted for legal-sized discards.

Assumptions - There are several assumptions and limitations to this method:

- Landings per day absent is proportional to stock size and is constant during different years with similar stock sizes.
- Fishing practices are similar in the years that are compared (other than possible discarding). This assumption ignores changes in behavior that reduce the landings per unit of effort in the target year. As a result, the calculation can be viewed as a potential upper bound on the magnitude of uncounted legal-size discards.
- Landings are assumed to be known without error. Other sources of errors in landings amounts, such as stock area misreporting or dealer misreporting, are not estimated and assumed to be insignificant in this analysis.

GOM Cod Example - Using GOM cod as the focal stock, analyses investigated the potential magnitude for missing legal-sized discards in 2018. GOM cod was used as an example for two reasons:

- First, as a result of low ABCs, this stock was highly constraining from 2015 to 2018 which produces economic incentives for sector fishermen to discard legal-size fish (see Section 6.6.10.5.1 and Appendix V, "Modeling Discard Incentives for Northeast Multispecies (Groundfish) Stocks"). In 2012 the GOM cod ABC was 6,700 mt and in 2013 was lowered to 1,550 mt. The ABC became much more constraining after 2014 and was set at 703 mt in 2018.
- Second, the GOM cod spawning stock biomass (SSB) estimate, when the quota was less constraining in 2012 and 2013, was somewhat similar to the 2018 estimate (more so for 2012) when the quota should have been constraining. There is uncertainty in the SSB estimate from the

assessment due to within model retrospective issues and due to the assessment being based on two different model configurations (M=0.2 and M-ramp). The relative change in stock size over this time period (2012-2018) can be seen in Table 72, which shows the estimates of SSB from the 2019 GOM cod stock assessment.

This analysis makes assumptions in stock size over the period examined (2012-2018 or 2013-2018) occurred as described in the assessment and on levels of avoidance behavior of GOM cod by the fishery. There is considerable uncertainty surrounding a potential estimate of the magnitude of unreported legal-sized GOM cod discards.

Table 1 - SSB estimates for GOM cod from the M=0.2 and M-ramp model from the 2019 operational groundfish stock assessment. The rho adjusted SSB estimates are also shown for the terminal year of the assessment. The relative change in the SSB from 2012 and 2013 to the terminal year (2018) are shown on the right. An average of the estimated SSB changes is also given as an approximation for a stock size adjustment.

		SSB				SSB Relative Change				
year	ABC	m=0.2	rho adj	mramp	rho adj	m=0.2	rho adj	mramp	rho adj	Average
2011	9,012	6,723		8,009						
2012	6,700	3,524		4,221		1.06	0.70	0.91	0.71	0.84
2013	1,550	1,874		2,361		2.00	1.32	1.63	1.26	1.55
2014	1,550	1,263		1,809						
2015	386	1,439		2,164						
2016	500	2,258		3,023						
2017	500	3,051		3,593						
2018	703	3,752	2468	3,838	2976					

Data and Analysis - An overview of the data and analysis is summarized in this section.

- Data includes fishing year 2012, 2013, and 2018 large-mesh trawl gear sector groundfish trips or sub-trips that only occurred in the Gulf of Maine stock area. Therefore, trips with and without cod landings are included. Common pool trips are not included. Sub-trips outside of the Gulf of Maine stock area are also excluded. Data was pooled by fishing year.
- For fishing years 2012 and 2013, the ratio was calculated as the sum of all cod landings divided by the sum of all days absent in two ways:
  - First, the ratio calculated across all statistical reporting areas (SRA) and,
  - Second, the ratio calculated by each SRA with an expansion by SRA. Most Gulf of Maine stock area trips (~90%) are reported as single statistical area trips. For trips that reported effort in multiple statistical areas, the catch and effort was apportioned equally between each area, since time spent in each SRA is unknown (not reported).
- *Potential landings estimate*- The resulting ratio for each fishing year (2012 and 2013) was multiplied by the sum of all days absent in fishing year 2018 (∑days absent) to estimate the potential magnitude of discarding of legal-size GOM cod. This estimate only accounts for potential legal-size discards of GOM cod which should have been landed. Therefore, sublegal discards are not part of this calculation and hence referred as a “potential landings estimate”.
  - 2018 Potential Landings Estimate = {∑ 2012 GOM cod landings/∑ 2012 Days Absent (DA) }* Total 2018 Days Absent

    or
  - 2018 Potential Landings Estimate = {∑ 2013 GOM cod landings/∑ 2013 Days Absent (DA) }* Total 2018 Days Absent.

Results and Discussion - The magnitude of the missing landings (unreported discards of legal-sized cod) was summarized as a multiplier relative to the 2018 fishing year. The estimated multipliers calculated from 2012 or 2013 landings per days absent (LPUE) and applied to the total effort in 2018 (∑days absent) are shown in Table 73 (results at 100% for "Total" and "By Stat Area"). This estimate of an upper bound of the potential magnitude for missing legal-sized discards of GOM cod. The landings multipliers are relative to the total commercial landings for sector trawl trips in 2018. The sector trawl landings were 218 mt (480 thousand pounds) in 2018. Therefore, the potential landings estimate under a multiplier of 1.71 would be 373 mt.

Estimation of the multiplier by SRA was also done since there was spatial shift in fishing effort - inshore to offshore (for example NEFSC 2017) over this time period when cod became more constraining. This did result in the slight reduction in overall estimated multipliers, as expected (Table 73).

It's possible that the reduced ABC in 2018 led fishermen to reduce cod catches by fishing differently. The impact of such changes was evaluated with a sensitivity analysis that removed a proportion of the 2012 and 2013 trawl trips that had the greatest landings of GOM cod (Table 73). Lower percentages (25% and 50%) signify the 2012 and 2013 trips used to estimate the multipliers. For example, 25% of the highest cod landings trips were eliminated in estimation of the multiplier.

The multiplier estimate is sensitive to the unknown targeting and avoidance behavior in the overall fishery. The ability of the fishery to preferentially target certain stocks is a difficult factor to account for in estimating the bound of missing catch. The fleet's true ability to avoid constraining stocks on groundfish trips is not known. Likewise, true fishery avoidance behavior is unknown for constraining stocks when a trip is unobserved because of the potential targeting of non-constraining stocks in areas of high catch per unit effort (CPUE) that may also overlap areas where cod are caught. To help bound this issue, all of the trips (no targeting behavior change) were used in the estimator and also some of the highest cod landing trips (approximate a change in targeting behavior) were eliminated from the estimate. Not surprisingly, the estimate of potential missing cod is sensitive to the elimination of the trips that caught the highest amount of cod. For example, eliminating the top 50% of the total GOM cod landings trips from the estimator (landings per unit effort) in 2013 results in predicted landings below the actual reported landings. This estimate is not realistic since one would not expect actual landings to be below the reported landings. Using all trips in the estimator may also not be realistic but this may give a sense of a bound for the missing catch given all of the other assumptions.

Table 2 - Estimated multipliers calculated for all trips and for trips by statistical area. Sensitivity of the estimate to elimination of the top 25% and 50% of GOM cod trips is also shown.

	Total			By Stat Area		
year	100%	75%	50%	100%	75%	50%
2012	3.84	2.99	2.15	3.03	2.42	1.82
2013	1.71	1.32	0.92	1.67	1.32	0.95

For further refinement, the multipliers on missing GOM cod landings were adjusted by the relative average SSB change from the stock assessment (2012 SSB estimate/2018 SSB estimate = 0.84 and 2013 SSB estimate/2018 SSB estimate = 1.55). Adjusting for the change in SSB estimated by the assessment would bring the 2012 and 2013 estimates slightly closer together between years which can be seen in Table 74.

Table 3 - Estimated multipliers calculated for all trips and for trips by statistical area which were also adjusted for the relative average SSB change from the stock assessment (2012 = 0.84 and 2013 = 1.55).

	Total			By Stat Area						
year	100%	75%	50%	100%	75%	50%	Max	min	average	median
2012	3.24	2.53	1.82	2.56	2.04	1.54	3.24	1.54	2.31	2.29
2013	2.65	2.05		2.59	2.05					

In conclusion, the results of the analysis indicate a possible upper bound multiplier of 2.3 times GOM cod landings, roughly 1,100 thousand pounds (~498mt) of missing landings (or missing legal-sized discards), with an uncertainty range of 1.5 to 2.5, or about 700 thousand pounds to 1,200 thousand pounds (~317mt to 544mt). This estimate is perhaps a more realistic bound on the potential missing catch for GOM cod relative to multipliers that are much higher since total fishing effort will limit the potential for missing discards.