Evaluation of Alternative Harvest Control Rules for New England Groundfish

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1. Executive Summary

Management of New England groundfish fisheries has been challenging due to the multispecies nature of the fishery and the varied status of stocks that ranges from historic low to record high biomasses. Additionally, most groundfish stock assessments exhibit inconsistencies among recent stock assessment estimates (a.k.a. retrospective patterns), which can present challenges for sustainable management of fisheries. Accordingly, the New England Fishery Management Council (NEFMC) initiated a review of groundfish harvest control rules (HCRs) to improve the performance of fisheries management. Management strategy evaluation, a general framework aimed at simulation testing management strategies, was used to evaluate the performance of alternative HCRs for a suite of New England groundfish species. We evaluated their performance in the context of two groundfish stocks: Gulf of Maine cod and Georges Bank haddock because these stocks typified a range of conditions currently experienced by groundfish stocks. Scenarios with different combinations of stock size, recruitment, and natural mortality assumptions as well as stock assessment model specifications were simulated to evaluate the performance of HCRs when a stock was overfished, not overfished, and when a stock assessment model had a misspecification which could result in retrospective patterns. Four different HCRs were evaluated: ramp, P*, F-step and constrained ramp HCRs. The ramp HCR was designed to emulate the basic structure of the current Acceptable Biological Catch control rule and promoted rebuilding and optimal yield by decreasing fishing mortality (F) gradually with spawning stock biomass (SSB) if SSB was below the threshold (50% SSB_{MSY}). The P* HCR also ramps down F as SSB decreases below a threshold but avoids overfishing by accounting for uncertainty with a probabilistic approach. The F-step HCR emulated a step in F between 75% F_{MSY} and 70% F_{MSY} which is the rebuilding F for several New England groundfish stocks. The constrained ramp HCR emulated a ramp HCR that includes a catch variation constraint (i.e., catch advice cannot change more than 20% from the previous year's catch). Stock assessment misspecifications included incorrect natural mortality, recruitment, and survey catchability assumptions.

The performance of HCRs differed between scenarios, metrics, and time periods. HCRs resulted in similar stock status at the end of the management procedure (MP) period, although

the HCRs took different trajectories to achieve this status. When the stock was not overfished, the ramp, P*, and F-step HCRs performed similarly, because SSB was above the overfished threshold, resulting in similar F. However, all HCRs performed differently when the stock was overfished. In this case with no stock assessment misspecifications, all HCRs were able to rebuild the stock above SSB_{MSY} in the long-term, but the F-step HCR achieved this later than the other HCRs. The trajectories under the constrained ramp HCR usually differed the most from all other HCRs, and the constrained ramp HCR did not always provide the highest catch stability. The variation constraint restricted the ability to take full advantage of large recruitment events that resulted in a high catch for the other HCRs.

In general, HCRs performed differently with a misspecification. The frequency of overfished and overfishing stock status depended more on the type of stock assessment misspecification, rather than the HCR. Due to over- and under-estimation of SSB, F, and SSB_{MSY}, the natural mortality misspecification led to overfishing under all HCRs but more so under the F-step HCR. This misspecification also prevented the stock from rebuilding. On the other hand, the survey catchability misspecification led to more conservative catch advice due to lower perceived SSB. The natural mortality misspecification led to retrospective patterns while the survey catchability and recruitment misspecifications did not. In the case of the combined mortality and recruitment misspecification, the stock was still not rebuilt at the end of the MP period under any of the HCRs. Additionally, with the negative impact of temperature on recruitment, SSB and catch declined at the end of the MP period. Under the combined natural mortality and recruitment misspecification, a retrospective pattern adjustment led to more conservative catch advice by decreasing the perceived SSB. Annual stock assessment updates also led to more conservative catch advice in the long-term as catch advice was more responsive. In scenarios that held the first year of projected catch constant, the HCRs performed more conservatively, because the first year of projected catch was usually less than the second year of projected catch.

Each HCR performed well under different conditions and for different performance metrics, highlighting the tradeoffs that each HCR provided. The classification of which HCR performs best across a range of conditions will depend on the definition and prioritization of management objectives for the groundfish fishery which was outside the scope of this study.

2. Background

Twenty groundfish stocks are managed under the Northeast multispecies groundfish federal fishery management plan (FMP) by the New England Fishery Management Council (NEFMC). Management of the groundfish fisheries are challenging because of the multispecies nature of the fisheries and aspects of groundfish population dynamics that are not completely understood (Brodziak et al., 2008). Currently, several New England groundfish stocks are at or near historic low biomass (e.g., Gulf of Maine (GOM) cod, Georges Bank (GB) cod, GB winter flounder, GB yellowtail flounder, Southern New England-Mid Atlantic (SNE/MA) yellowtail flounder, witch flounder, and GOM-GB windowpane flounder), whereas other stocks have increased to record highs (e.g., GB haddock, GOM haddock, and redfish; NEFSC 2019).

The status of twelve of these groundfish stocks are assessed by analytical assessments (e.g., statistical catch-at-age models) and eight by empirical approaches (e.g., survey-based index methods; NEFSC, 2019). The NEFMC’s Scientific and Statistical Committee (SSC) recommends Acceptable Biological Catch (ABC) for each groundfish stock based on the Council's harvest control rule (HCR), also known as the ABC control rule. HCRs define management actions and are oftentimes based on the status of a stock relative to its reference point. The current groundfish HCR was implemented in 2010 through Amendment 16 to the Northeast multispecies FMP. The ABC control rule states that: a) ABC should be determined as the catch associated with 75% of F_{MSY}; b) if fishing at 75% of F_{MSY} does not achieve the mandated rebuilding requirements for overfished stocks, ABC should be determined as the catch associated with the fishing mortality that meets rebuilding requirements ($F_{rebuild}$); c) 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 (i.e., the proportion of the stock caught as bycatch); and d) interim ABCs should be determined for stocks with unknown status according to case-by case recommendations from the SSC. This HCR was designed to account for scientific uncertainty in the overfishing limit. The HCR is part of the overall management procedure (MP), which defines management actions as well as the data and assessment methods used in determining catch advice. The MP implementation also includes retrospective adjustments, which revise stock estimates for stock status determination to account for recent retrospective inconsistency (NEFSC, 2019). Catch advice is determined for stocks with analytical assessments approximately every two years based on projected exploitable biomass and target or limit fishing mortality (F) rates.

The majority of groundfish stocks that have analytical assessments now exhibit a similar 'retrospective pattern' with estimates of stock size revised downward and estimates of fishing mortality revised upwards with the addition of new data (NEFSC, 2019). Retrospective patterns are inconsistencies of recent estimates after adding another year of data to the stock assessment (Mohn, 1999). These patterns are often caused by stock assessment model misspecifications whereby the stock assessment model assumptions are incorrect. Retrospective patterns represent a large source of uncertainty and pose challenges in the classification of Northeast groundfish stock status and determination of catch advice (Brooks & Legault, 2016; Wiedenmann & Jensen, 2018). Retrospective patterns, if left unresolved, can lead to unintentional overfishing that undermines efforts to sustainably manage fisheries (Deroba, 2014). Many factors can contribute to retrospective patterns in stock assessments, making it challenging to pinpoint the cause (Hurtado-Ferro et al. 2017). Some of the candidate causes relevant to Northeast groundfish stocks include: 1) ecosystem change (e.g., impact of ocean warming on population dynamics), 2) changes in fishing behavior and misreporting of catch, or 3) changes in survey or fishery catchability and selectivity.

The performance of the current New England groundfish HCR and possible alternatives have not yet been fully evaluated through simulation testing. There have also been several changes in policy since the development of the HCR (e.g., the Council's risk policy), and recent problems applying the HCR (e.g., some 2019 catch recommendations remanded back from the Council to the SSC), suggesting that reevaluation is needed to determine if the HCR is consistent with meeting the Council's policy. Additionally, in practice, the prescribed F when SSB is below the threshold (i.e., $F_{rebuild}$) has not been consistent. Furthermore, in hindsight it has been recognized that application of the groundfish HCRs did not always prevent overfishing (Brooks & Legault, 2016; Wiedenmann & Jensen, 2018). The accuracy of the stock assessment, retrospective patterns, and the quality of projections are likely key contributors to these issues with management performance. In response to the issues raised regarding the current ABC control rule, the NEFMC initiated a review of groundfish HCRs to improve the performance of fisheries management.

Management strategy evaluation (MSE) is a general framework aimed at simulation testing MPs, which include HCRs. This model framework involves simulating the natural and human aspects of the managed fishery resource system under different circumstances and evaluating performance based on management objectives. A key advantage of the approach is that the operating model (OM) provides a representation of 'true' population dynamics and a baseline for comparison of performance across estimation approaches and alternative HCRs. MSE can identify the performance of an existing HCR and can allow for comparisons across alternative HCRs based on metrics that reflect management objectives. Additionally, trade-offs among management objectives achieved by different HCRs can be evaluated while explicitly accounting for uncertainty (Dichmont et al., 2008). This approach is valuable for identifying HCRs that are robust to natural variation in the system and to uncertainty and error, both in stock assessments (e.g., retrospective patterns) and implementation (ICES, 2020).

The goal of this analysis was to evaluate the performance of alternative HCRs for New England groundfish stocks using a MSE model framework and provide information that can help managers evaluate tradeoffs and identify HCRs that are robust to a range of uncertainties. Specific objectives included: 1) development of OMs that emulate groundfish dynamics and span a range of characteristic stock conditions, 2) misspecification of OMs and stock assessment models to generate retrospective patterns, and 3) simulation testing of a suite of HCRs. Although both analytical and non-analytical assessments are applied to New England groundfish, this study focused on MPs that incorporate analytical assessments.

We structured scenarios to address a series of research questions:

a) How do alternative HCRs perform when a stock is overfished?
b) How do alternative HCRs perform when a stock is not overfished?
c) How do alternative HCRs perform when there is a stock assessment misspecification that may result in retrospective patterns?
d) When retrospective patterns exist, do retrospective adjustments result in better performance than no retrospective adjustments?

2. Methods

This study utilized a previously developed MSE framework for New England groundfish (NOAA COCA # NA17OAR4310272, NOAA SK #NA17NMF4270213, NEFMC Award ID: NA10NMF4410007). Detailed method descriptions can be found in Appendix A. In the MSE framework, (1) the OM represented the true fish population dynamics and was the basis for evaluating performance relative to the 'true' values for the stock and fishery (Fig. 1). Through an observation model (2), simulated trawl survey data and catch data were generated with plausible random error to represent the information available for groundfish assessment and management. The simulated survey and catch data informed a stock assessment model (3) used to estimate stock and fishery metrics. Biological reference points (4; BRPs) were then calculated. The stock assessment output and estimated BRPs were compared to produce estimated stock status. A HCR (5) then determined F based on the estimated stock status. Both the F from the HCR (5) and output from the stock assessment (3) were used in projections (6) to determine catch advice. This catch advice was then applied to simulate harvest in the OM (7). The advised catch was assumed to be caught. Performance of the alternative HCRs were evaluated at each timestep (8; Fig. 1).

This simulated process was designed to be consistent with current New England groundfish management whereby the stock assessment performed in year *t* has a terminal year of *t-1*, and the resulting catch advice is for year *t+1* and greater depending on the stock assessment frequency. Thus, there is a lag in information that informs the catch advice. This simulated fishery resource, management, and harvest feedback loop continued until the end of the MP period (2019 - 2040). The MSE approach used in this study was not a full MSE because management objectives were not identified and prioritized.

We focused OM development on two groundfish stocks: GOM cod and GB haddock to typify a range of conditions currently experienced by groundfish stocks (Table A1). Stock status of GOM cod is overfished and overfishing is occurring, whereas GB haddock is not overfished and not experiencing overfishing (NEFSC, 2019). GB haddock exemplifies a groundfish stock with a recently increasing stock size. GB haddock also exhibit periodic high recruitment events that are not explained by a theoretical stock-recruitment relationship (SRR), but linked to ocean conditions (i.e., autumn bloom; Leaf and Friedland, 2014; Friedland et al., 2015).

The OMs for groundfish stocks in this framework were single species, stochastic, age-structured models designed to emulate population dynamics. Abundance-at-age was calculated using exponential survival (Table A2). Weight-at-age was constant over time for cod but changed over time for haddock during the historical period. During the MP period, haddock weight-at-age was constant over time. In the base case OMs, recruitment was modeled using empirical cumulative distribution functions (Table A2).

Historical Period

The GOM cod and GB haddock historical trajectories were reconstructed by incorporating recruitment and F time series (1982-2018 for cod, 1931-2018 for haddock) from the most recent stock assessments (NEFSC, 2019) and calculating SSB and catch as emergent properties. The purpose of the historical period was to emulate reality, as it was perceived by groundfish stock assessments. The MP period began in 2019.

Management Procedure Period

A variety of simulations with different OMs and stock assessment misspecification scenarios, retrospective adjustment scenarios, stock assessment frequencies, and HCR alternatives were conducted to address the research questions of this study (Table 1).

<u>Operating model and misspecification scenarios</u>

The following scenarios have different population dynamics assumptions in the OM, observation model assumptions, and stock assessment model assumptions. Each scenario was simulated for 1000 iterations.

<u>Stock Status: Overfished</u>

Base Case for a Stock that is Overfished: Stock: Gulf of Maine cod; Recruitment: Moderate; Natural mortality: Constant; Misspecification: None

The aim of this scenario was to evaluate HCR performance for a groundfish stock that was overfished in the absence of any misspecifications in the stock assessment and with the following characteristics: moderate recruitment and constant natural mortality (M=0.2). The stock-recruit relationship (SRR) derived recruitment from an empirical cumulative distribution function when SSB was greater than a threshold, and a linear decline to zero based on the ratio of SSB to the threshold. The empirical cumulative distribution was of historic observed recruitments from 1998 to 2018. This scenario can be considered the GOM cod base case.

Stock Status: Not overfished

Base Case for a Stock that is Not Overfished: Stock: Georges Bank haddock; Recruitment: Random large recruitment events; Natural mortality: Constant; Misspecifications: None

The aim of this scenario was to evaluate HCR performance in the absence of any stock assessment misspecifications for a stock that has the following characteristics: random large recruitment events and in good status (i.e., not overfished). In the SRR, recruitment was modeled using an empirical cumulative distribution function with recruitment values from the last 20 years of the historical period (1998-2018). This scenario was the GB haddock base case.

Stock assessment misspecification scenarios

To evaluate the impact of stock assessment model misspecifications, scenarios with incorrect stock assessment assumptions were also simulated. This study included incorrect stock assessment assumptions of natural mortality, recruitment, and survey catchability. These incorrect assumptions, or stock assessment misspecifications, were induced in the historical period in the case of natural mortality, and in the beginning of the MP period for recruitment and catchability. When a stock assessment model was misspecified, the stock assessment assumptions remained unchanged from the Base Case Scenarios, and the OM parameters changed. In a previous report (Kerr et al. 2020), we focused on simulating stock assessment misspecifications associated with catch misreporting and here we focused on misspecifications due to unaccounted for impacts of a changing ecosystem. In recent decades, the Northeast shelf ecosystem has warmed four times faster than the global average rate and groundfish, such as Atlantic cod, have exhibited sensitivity to changing environmental conditions that has influenced productivity and distribution (Pershing et al. 2015, Hare et al. 2016). In addition, there have been significant shifts in the biomass of key groundfish predators (e.g., seals and spiny dogfish) in recent decades that could impact natural mortality of groundfish (Link et al., 2002).

Natural Mortality Misspecification for a Stock that is Overfished: Stock: Gulf of Maine cod; Recruitment: Moderate; Natural mortality: Increases; Misspecification: Natural mortality

The aim of this scenario was to evaluate HCR performance for a stock that was overfished and undergoing overfishing with a natural mortality misspecification. In this scenario, the OM was conditioned on the assumptions of the M-ramp stock assessment model for GOM cod (NEFSC, 2019) in which natural mortality increased from 0.2 to 0.4 from 1988 to 2003 and remained constant at 0.4 through the MP period. The stock assessment model and projections assumed natural mortality was constant at 0.2.

Recruitment Misspecification for a Stock that is Overfished: Stock: Gulf of Maine cod; Recruitment: Beverton-Holt stock-recruitment model with temperature; Natural mortality: Constant; Misspecification: Recruitment in the management procedure period

The aim of this scenario was to evaluate HCR performance for a groundfish stock that was overfished and undergoing overfishing with a recruitment misspecification (Table A3). The difference between this scenario and the Base Case for a Stock that is Overfished was that recruitment was modeled using a Beverton-Holt stock recruitment model that included the effect of projected temperature increase on recruitment in the MP period. The stock assessment assumed recruitment was not impacted by temperature. In BRP estimation, recruitment was assumed to be the mean of the previous 20 years of recruitment (i.e., assumed stationarity and did not account for the influence of temperature). The projections assumed recruitment was from an empirical cumulative distribution function, so the effect of temperature on recruitment was not considered. In the OM, the SRR was fit with recruitment and SSB output from the most recent stock assessment (M=0.2; NEFSC, 2019) and annual mean sea surface temperature anomalies for the GOM. This relationship showed a negative impact of temperature on cod recruitment. Previous studies have documented evidence of the negative impacts of warming water temperatures on GOM cod recruitment (Fogarty et al., 2008, Pershing et al., 2015).

Natural Mortality and Recruitment Misspecification for a Stock that is Overfished: Stock: Gulf of Maine cod; Recruitment: Beverton-Holt stock-recruitment model with temperature; Natural mortality: Increases; Misspecification: Natural mortality and recruitment in the management procedure period

The aim of this scenario was to evaluate HCR performance for a groundfish stock that was overfished with both a natural mortality and recruitment misspecification (Table A3). This scenario included the misspecifications from the previous two scenarios. However, in this scenario, the SRR was fit with recruitment and SSB output from the most recent stock assessment with increased natural mortality (M=0.4; NEFSC, 2019) and annual mean sea surface temperature anomalies for the GOM.

Catchability Misspecification for a Stock that is Not Overfished: Stock: Georges Bank haddock; Recruitment: Random large recruitment events; Natural mortality: Constant; Misspecification: Survey catchability in the management procedure period

The aim of this scenario was to evaluate HCR performance for a groundfish stock in good status with a survey catchability misspecification. In this scenario, survey catchability decreased over time as temperature increased, but the stock assessment assumed that survey catchability was constant over time. Survey catchability started at 1, but then decreased with temperature to half of the original survey catchability at 0.5 by the end of the MP period. This means that the catchability used to convert ‘true’ stock size into the survey index changed, and the survey data input to the stock assessment reflected this change in catchability. The stock assessment assumed survey catchability was fixed or constant. This scenario differed from the Base Case for a Stock that is Not Overfished in that survey catchability decreased in the observation model and there was a stock assessment misspecification.

Stock assessment scenarios

This study emulated current groundfish stock assessment methods and applied the Age Structured Assessment Program (ASAP; Legault & Restrepo, 1998), which is used for the majority of analytical groundfish stock assessments in the region.

Stock assessments with retrospective pattern adjustments

Retrospective Adjustment Scenario 1: No retrospective pattern adjustment

In these scenarios, no retrospective pattern adjustment, or rho-adjustment, was used to adjust stock estimates for retrospective inconsistencies. In scenarios with no retrospective patterns, this scenario was automatically applied.

Retrospective Adjustment Scenario 2: Retrospective pattern adjustment

This stock assessment scenario option evaluated the impact of a rho-adjustment on HCR performance (Table A6; Mohn, 1999; Deroba, 2014). In this scenario, the terminal estimated SSB was rho-adjusted. SSB rho-adjustments were also applied to the abundance estimate in the 'bridge' year of the projections. Rho-adjustments were only applied if the absolute value of Mohn's Rho for SSB was greater than 0.15. Rho-adjustments were not applied to recruitment in the projections or in calculation of SSB_{MSY}. This is consistent with how rho-adjustments are applied in current groundfish assessments. A rho-adjustment has been applied to most analytical New England groundfish NEFSC stock assessments.

Stock assessment frequency and projections

Catch advice was generated from projected catch with F determined from the HCR for either one or two years. There were 100 iterations for each projection which incorporated uncertainty in recruitment and the initial abundance derived from the last year of the stock assessment. Because the stock assessment assessed up to year *t-1*, a 'bridge' year was projected to estimate abundance at the beginning of the following year (Figure 3). Initial abundance was drawn from a lognormal distribution with a mean of the final abundance estimate and a standard deviation corresponding to the standard deviations of the total abundance estimates from the most recent stock assessment conducted by the NEFSC. This approach was used in this study because the MSE framework does not use a Monte Carlo Markov Chain (MCMC) approach to estimate uncertainty in the stock assessment models due to computational constraints. For NEFSC stock assessments, a MCMC approach provides multiple realizations of numbers at age that can be used in the projections. F from the previous iteration of the HCR, or the F from the previous year's catch advice, was used in the 'bridge year' to calculate total mortality. Projections are currently used in determining catch advice for almost all New England groundfish with analytical assessments. Stock assessment outputs with a terminal year of *t-1* were used in projections at year *t* to estimate catch advice for year *t+1* and year *t+2*.

Frequency Scenario 1: 2-Year

In this scenario, the stock assessment was updated every 2 years, which is the frequency of many of the New England groundfish stock assessments. This scenario had two sub-alternatives: the median of the catches from each of the two projected years (not including the 'bridge' year) were used as the catch advice for the two following years (*Sub-alternative a*) or the median of the catches from the first projected year (not including the 'bridge' year) was used as the catch advice for the two following years (*Sub-alternative b*; Fig. 2).

Frequency Scenario 2: 1-Year

In this scenario, the stock assessment was updated every year. Since the stock assessment was updated every year, projections were run for one year. The median catch from the projected year (not including the ‘bridge’ year) was used as the catch advice for the following year (Fig. 3).

<u>Harvest control rule alternatives</u>

Four different HCRs were evaluated: ramp, P*, F-step and constrained ramp HCRs (Table 1, Fig. 1). All HCR alternatives included a constraint on catch advice so that it would not be higher than the estimated catch that corresponds to the estimated overfishing limit (OFL) from the stock assessment to emulate the current in-season quota monitoring system. However, in misspecified scenarios, the true catch could be larger than the catch that corresponds to the true OFL in the OM when there is biased estimation from the stock assessment. All these alternatives also have a minimum catch limit (i.e., the minimum bycatch of the last ten years in the historical period), which would prevent F from declining to zero.

The F associated with the maximum sustainable yield (F_{MSY}) proxy used in these HCRs was $F_{40\%}$, or the F expected to maintain 40% of the unfished SSB per recruit, which was determined with spawner per recruit (SPR) analysis. The F_{MSY} proxy will hereafter be referred to as F_{MSY}. The SSB_{MSY} proxy was the long-term equilibrium SSB that corresponded to F_{MSY}. For the estimated and true SSB_{MSY} proxies, recruitment used in the equilibrium calculation was the mean of the previous 20 years of estimated or true recruitment values. These recruitment values were dynamic and changed with the addition of years in the simulation. The SSB_{MSY} proxy will hereafter be referred to as SSB_{MSY}. Both true and estimated reference points were estimated with natural mortality at 0.2, even if natural mortality increased to 0.4 in the OM, because the stock is at a lower productivity (Legault and Palmer, 2016). The SSB threshold used in alternative HCRs was 50% SSB_{MSY}.

Alternative 1: Ramp

The intention of this HCR was to promote rebuilding and optimal yield. When stock status was greater than 50% SSB_{MSY} (i.e., the ‘overfished’ threshold), the target F was 75% F_{MSY}. When stock status was perceived to be less than 50% SSB_{MSY}, the target F linearly decreased as SSB decreased (Appendix A: Eqn. 12).

*Alternative 2: P**

The aim of this HCR option was to avoid overfishing by accounting for scientific uncertainty with a probabilistic approach. In this scenario, the P* approach (Prager & Shertzer, 2010) was used to derive target catch. The P* method derives target catch as a low percentile of projected catch at the OFL. The distribution of the catch at the OFL was assumed to follow a lognormal distribution with a CV of 1 (Wiedenmann et al., 2016). The target catch corresponds to a probability of overfishing no higher than 50% (P*<0.5) in accordance with the National Standard 1 guidelines. The level of P* depended on the level of SSB (Appendix A: Eqn. 13). This alternative differed from alternative 1 in that scientific uncertainty was quantified by the P* approach rather than the current 25% buffer. This alternative emulated HCRs used in the Council’s Small Mesh Multispecies FMP.

Alternative 3: F-step

If the SSB decreased below the biomass threshold (50% SSB_{MSY}), this HCR used a target F of 70% F_{MSY} that has recently been applied to some New England groundfish, such as SNE/MA yellowtail flounder and GB winter flounder, as the $F_{rebuild}$. If the SSB never decreased below the biomass threshold or increased to over SSB_{MSY} (rebuilt) after dropping below the biomass threshold, this HCR used a target F of 75% F_{MSY}. National Standard Guidelines were amended in 2016. These revisions reduced the need to identify an incidental bycatch ABC and indicated that $F_{rebuild}$ need not be recalculated after every assessment, making it less likely that $F_{rebuild}$ will be set to zero in response to short-term lags in rebuilding.

Alternative 4: Constrained ramp

The aim of this HCR alternative was to promote rebuilding, optimal yield, and to provide catch stability if stock biomass were to substantially change from year to year. Stable catch was identified as an objective in the Council's risk policy (NEFMC, 2016). This differed from alternative 1 in that there was a constraint on variation in target catch from year to year, meaning that the current year's catch limit will not change more than 20% from the previous year's catch limit. The threshold of 20% change in catch is in the middle of the range of change in catch thresholds used in HCRs in other fisheries (Appendix B). Catch was constrained so that it was not higher than the perceived OFL.

Performance metrics

To evaluate the performance of alternative HCRs, a range of performance metrics were compared, including stock performance, stock assessment performance, and management performance metrics. Stock performance metrics included OM catch stability, and SSB, F, catch, and recruitment trajectories. Stock assessment performance metrics included accuracy (measured as relative error (REE)) and Mohn's Rho trajectories for SSB and F and accuracy of estimated reference points (F_{MSY} and SSB_{MSY}) (Tables A10 and A11). Mohn's Rho values were calculated with a 7-year peel each year in the MP period and plotted over time. REE was the relative error of the terminal estimated assessment values at each year. Management performance metrics included true or OM stock status trajectories, the true frequency of undergoing overfishing, and the true frequency of being overfished. When there was a misspecification, estimated terminal stock status from each year's assessment was also included. Metrics were characterized in the short-term (1-5 years), medium-term (6-10 years), and long-term (11-21 years).

In this report, radar charts are used to summarize results across performance metrics for multiple HCRs. In a radar chart, each axis is a performance metric. Results are plotted relative to each other, such that the inside most line is the minimum of that metric for all HCRs, and the outside line is the maximum of that metric for all HCRs. The more area a HCR takes up on the plot, the better it performed in the context of the performance metrics that are plotted. Performance metrics are weighted equally.

Line, box, and Kobe plots are also used to show HCR performance. For the box plots in this report, the box midline is the median, the upper box limit is the 75% quartile (upper hinge), the lower box limit is the 25% quartile (lower hinge), the lower whisker is the smallest observation greater than or equal to the lower hinge minus 1.5 times the interquartile range (IQR), and the upper whisker is the largest observation less than or equal to the upper hinge plus 1.5 times the IQR. The Kobe plot is a phase plot where F/F_{MSY} is plotted against SSB/SSB_{MSY}.

The quadrants are color coded: green for not overfished and no overfishing, red for overfished and overfishing, and yellow otherwise. Kobe plots are shown for the true stock status from the OM and when there was a misspecification, for the estimated terminal stock status from each year's assessment (what catch advice is based on).

Stakeholder engagement

Throughout this process we solicited feedback from stakeholders in the groundfish fishery, including the Groundfish Plan Development Team, Groundfish Advisory Panel, Groundfish Committee, Science and Statistical Committee, MSE experts at NEFSC, and NEFMC for feedback regarding the plan for HCR testing. This feedback occurred through meetings via conference calls and through solicitation of written feedback.

Results

Performance of Harvest Control Rules for an Overfished Groundfish Stock (Gulf of Maine Cod)

<u>Base Case for a Stock that is Overfished (GOM cod)</u>

Stock performance

In the short-term (1-5 years), SSB of GOM cod increased similarly across HCRs, although at a slightly higher rate under the ramp and P* HCRs (Figs. 4 and 5). Initially, F and catch were highest under the constrained ramp and F-step HCRs with lower F and catch under the P* and ramp HCRs. However, over the short term F and catch decreased under the constrained ramp HCR and remained stable or increased under the other HCRs. Overall, median catch was lowest under the ramp and P* HCRs and highest under the F-step and constrained ramp HCRs (Fig. 6). Recruitment was similar across HCRs in the short-term.

In the medium-term (6-10 years), SSB under the constrained ramp HCR increased at the fastest rate and resulted in the highest SSB (Figs. 4 and 5). Over this period, F increased to the highest level under the ramp and P* HCRs with similar, slightly lower levels under the F-step HCR and the lowest F values under the constrained ramp HCR. In the medium-term, catch increased under all HCRs, however, median catch was considerably lower under the constrained ramp HCR compared to other HCRs (Fig 6). Recruitment was similar across HCRs in the medium-term.

In the long-term (11-21 years), GOM cod SSB increased under the ramp, P*, and F-step HCRs to asymptote at a similar magnitude with the highest SSB realized under the constrained ramp HCR (Figs. 4 and 5). F increased under the constrained ramp HCR to a similar level under the ramp, P*, and F-step HCRs. Median catch was similar across HCRs, with the exception of lower values under the constrained ramp HCR, in the long-term (Fig 6). Recruitment was similar across HCRs in the long-term.

Assessment performance

REE, Mohn's Rho values, and error in reference point estimation were minimal because there was no stock assessment misspecification (Figs. 7, 8, and 9). There was a tendency for SSB to be slightly overestimated and F slightly underestimated.

Management performance

In the short-term, the GOM cod stock remained overfished, but was not undergoing overfishing under any of the HCRs (Figs. 10 and 11). In the medium-term, the stock was not undergoing overfishing and SSB increased above the 'overfished' stock size threshold (i.e., 50%SSB_{MSY}) after six years across HCRs (Figs. 10, 11). The stock did not rebuild to SSB_{MSY} in the medium-term under any of the HCRs. SSB/SSB_{MSY} and its variability increased between the short- and medium- term and was similar across HCRs. F/F_{MSY} was considerably lower under the constrained ramp HCR compared to other HCRs. In the long-term, all HCRs resulted in a stock that was not overfished or undergoing overfishing (Figs. 10 and 11). The stock was rebuilt above SSB_{MSY} after nine years under the ramp, P*, and constrained ramp HCRs and in ten years under the F-step HCR. SSB/SSB_{MSY} and its variability increased and was highest under the constrained ramp HCR. In the long term, F/F_{MSY} was lowest under the constrained ramp HCR.

Synthesis

In the short-term, all HCRs resulted in no overfishing, but the stock remained overfished (Fig. 12). Median SSB was similar among HCRs, but median catch and catch stability were highest under the F-step HCR. The ramp and P* HCRs resulted in the lowest catch and catch stability in the short-term. In the medium-term, all HCRs resulted in a stock that was not overfished and no overfishing. Median SSB was similar under the ramp, P*, and constrained ramp HCRs and slightly lower under the F-step HCR. Catch was lowest, but catch stability was highest under the constrained ramp HCR. In the long-term, all HCRs resulted in no overfishing and a stock that was rebuilt above SSB_{MSY} (Fig. 10). Median SSB was highest under the constrained ramp HCR (Fig. 12). Catch and catch stability were highest under the ramp, P*, and F-step HCRs and lowest under the constrained ramp HCR.

<u>Natural Mortality Misspecification for a Stock that is Overfished (GOM cod)</u>

Stock performance

HCR performance in the Mortality Misspecification Scenario differed from the Base Case Scenario for GOM cod (Figs. 13, 14, and 15). Overall, F was considerably higher in these scenarios and SSB considerably lower compared to the Base Case. In the short-term, the F-step HCR resulted in the highest F and catch and lowest SSB across HCRs. In the medium-term, cyclical patterns in F, catch, and SSB arose under the ramp and P* HCRs. In the long-term, the HCRs resulted in similar SSB and catch with the exception of the constrained ramp HCR which resulted in higher SSB and catch.

Assessment performance

Assessment performance differed from the Base Case when a natural mortality misspecification was introduced in the GOM cod stock assessment. In the short-term, SSB was overestimated under all HCRs, and F was underestimated under all HCRs (Fig. 16). In the medium-term, SSB was overestimated under the ramp, P*, and constrained ramp HCRs but underestimated under the F-step HCR. F was underestimated under all HCRs. In the long-term, error in F was small under the ramp, P*, and F-step HCRs and the magnitude of error decreased over this time period under the constrained ramp HCR. At the end of the long-term, SSB was underestimated under all HCRs. Over the short- to long-term, Mohn's Rho values for SSB became increasingly positive and then decreased, but remained positive in value under all HCRs (Fig. 17). Mohn's Rho values for F became increasingly negative during the short- to medium-term and subsequently decreased, but remained negative in value under all HCRs. The timing of trends in Mohn's rho values lagged under the constrained ramp HCR compared to the other HCRs. SSB_{MSY} was overestimated in the medium-term and underestimated in the long-term (Fig. 18). There was no error in F_{MSY} (Fig. 18).

Management performance

Management performance with a natural mortality misspecification differed from the Base Case scenario (Figs. 19 and 20). Due to over- and under-estimation of SSB, F, and SSB_{MSY} in this scenario, the true and estimated stock status differed resulting in a misperception of stock status (Fig. 19a,b). Comparisons of terminal estimates of F and SSB to estimated biological reference points revealed that the estimated stock status was typically overfished in the short- to medium-term across HCRs with a shift to not overfished status after seven years under the ramp and constrained ramp HCRs, after nine years under the P* HCR, and after eleven years the F-step HCR. The stock was never estimated to be rebuilt under the ramp, P*, and F-step HCRs. The stock was estimated to be rebuilt after eleven years under the constrained ramp HCR, however SSB subsequently decreased below SSB_{MSY} but remained above the overfished threshold. Overfishing was estimated in the later part of the MP period under all HCRs. The true stock status based on the OM was overfished in the short-term with overfishing occurring only under the F-step HCR. The other HCRs did not result in overfishing at first. In the medium-term, all HCRs resulted in a stock that increased above the overfished threshold. The F-step HCR resulted in a not overfished stock a year later than the other HCRs. However, by year six, eight, and 15, the P*, ramp, and constrained ramp HCRs resulted in overfishing. In the long-term, the stock did not rebuild under the ramp, P*, and F-step HCRs. The stock was rebuilt for only two years under the constrained ramp HCR.

Synthesis

In the short-, medium-, and long-term, the increase in natural mortality specified in the GOM cod operating model and misspecification of the stock assessment resulted in differences in HCR performance relative to the Base Case with no misspecification (Fig. 21). In the short-term, the stock remained overfished under all HCRs, but the F-step HCR was the only one to result in overfishing. In the medium term, the stock remained overfished for portions of this period under all HCRs and all HCRs, except for the constrained ramp HCR, resulted in overfishing. The F-step HCR resulted in the highest catch stability in the medium term. In the long-term, all HCRs resulted in some overfishing and the constrained ramp HCR resulted in the highest catch and catch stability.

Recruitment Misspecification for a Stock that is Overfished (GOM cod)

Stock performance

HCR performance was similar to the Base Case Scenario when a recruitment misspecification was simulated for GOM cod (Figs. 22, 23, and 24). In the short-term, there were no notable differences in stock performance when compared to the Base Case Scenario. However, in the medium-term, SSB and catch did not increase to the same magnitude as the Base Case, and in the long-term, SSB and catch declined. These changes in stock performance were a function of the modeled decline in recruitment over the MP period.

Assessment performance

Assessment performance with a recruitment misspecification was similar to the Base Case Scenario with no misspecification in that REE and Mohn's Rho values were small to negligible (Figs. 25, 26, and 27). However, SSB was more overestimated and F was more underestimated than in the Base Case Scenario. Similar to the Base Case Scenario, reference points were well estimated, however, in the long-term, SSB_{MSY} was slightly overestimated in this scenario.

Management performance

Management performance with a recruitment misspecification and different recruitment dynamics was slightly different from the Base Case Scenario (Figs. 28 and 29). The estimated stock status from each year's assessment was similar to the true stock status (Fig. 28). The stock was estimated to be overfished in the short-term, but was not overfished in medium-term, and was rebuilt in the long-term under all HCRs.

True stock status in this scenario was similar to the Base Case Scenario with rebuilding taking one year longer under all HCRs. In the long-term, F/F_{MSY} was slightly higher and SSB/SSB_{MSY} was slightly lower than under the Base Case Scenario. In the long term, the ramp, F-step and P* HCRs did not result in a stock that remained rebuilt due to the gradual decrease in recruitment.

Synthesis

HCR performance with a recruitment misspecification was similar to the Base Case Scenario, but with some key differences (Fig. 30). In the short-term, there was some overfishing under the constrained ramp HCR due to the slight overestimation of SSB. In this scenario, the stock remained overfished for a longer period under the F-step and constrained ramp HCRs. Despite rebuilding of the stock in the short- to medium-term, in the long-term, the gradual decrease in recruitment resulted in a stock that was not rebuilt under the ramp, F-step and P* HCRs.

Natural Mortality and Recruitment Misspecification for a Stock that is Overfished (GOM cod)

Stock performance

HCR performance with natural mortality and recruitment misspecifications differed from that in the Base Case (Figs. 31, 32, and 33). Under all HCRs, SSB and recruitment increased in the short-term, but subsequently declined over the medium- to long-term. With the decline in SSB, the F and catch subsequently declined, with a lag in the timing of this decrease under the constrained ramp relative to other HCRs.The F-step HCR resulted in the highest F and catch in the short-term, whereas the ramp and P* HCRs resulted in highest F and catch in the medium-term. In the long-term, median catch was highest under the constrained ramp HCR, despite being lowest in the short- and medium-term.

Assessment performance

Assessment performance differed from the Base Case Scenario (Figs. 34, 35, and 36). In the short-term, SSB was overestimated and F was underestimated by the stock assessment. In the medium-term, error in SSB switched directions and became negative under the ramp, P*, and F-step HCRs but SSB remained overestimated under the constrained ramp HCR. Error in the estimation of F decreased towards zero under the ramp, P*, and F-step HCRs but F remained underestimated under the constrained ramp HCR. In the long-term, SSB was underestimated under all HCRs and error in F was near zero. In the short- and medium-term, Mohn's Rho values became increasingly positive for SSB and increasingly negative for F. In the long-term, the values of Mohn's Rho decreased towards zero although Mohn's Rho values remained positive for SSB and negative for F. SSB_{MSY} was overestimated in the medium-term and underestimated in the long-term. There was no error in F_{MSY}.

Management performance

Management performance differed from the Base Case Scenario (Figs. 37 and 38). Due to over- and under-estimation of SSB, F, and SSB_{MSY} in this scenario, the true and estimated stock status differed resulting in a misperception of stock status. Estimated stock status indicated that the stock remained overfished in the short-term and increased above the overfished threshold under the ramp and constrained ramp HCRs in seven years, in nine years under the P* HCR, and in eleven years under the F-step HCR. In the medium-term, overfishing was estimated to occur under the F-step HCR and status shifted to overfishing under the P* HCR in seven years and in nine years under the ramp and constrained ramp HCRs .

The true stock status was not rebuilt under any of the HCRs and overfishing occurred for extended periods under each HCR. True stock status remained overfished in the short-term and increased above the overfished threshold in seven years under the ramp, P*, and constrained ramp HCRs and nine years under the F-step HCR. However, the stock never rebuilt under any of the HCRs. The stock hovered around the overfished threshold under all HCRs, although SSB/SSB_{MSY} was slightly larger under the constrained ramp HCR. The stock was always undergoing overfishing under the F-step HCR. The stock was undergoing overfishing after six years under the ramp and P* HCRs and after twelve years under the constrained ramp HCR.

Synthesis

HCR performance differed from that in the Base Case Scenario (Fig. 39). In the short-term, the true stock status was overfished across HCRs and overfishing occurred under the F-step HCR. Catch stability was highest under the constrained ramp HCR. Catch was lowest and similar under the ramp, P*, and constrained ramp HCRs. Under all HCRs, the stock was overfished for part of the medium-term and overfishing occurred under the ramp, P*, and F-step HCRs. The stock remained overfished for the longest period under the F-step HCR. Catch stability was highest under the F-step HCR. Catch was highest under the ramp and P* HCRs. Under all HCRs, the stock was also overfished for part of the long-term but more so under the ramp and P* HCRs. Also, in the long-term, overfishing occurred under all HCRs but less so under the constrained ramp HCR. The constrained ramp HCR resulted in the highest catch and catch stability in the long-term.

Natural Mortality and Recruitment Misspecification with Year One Projections Held Constant for a Stock that is Overfished (GOM cod)

Stock performance

HCR performance with year one projections held constant for catch advice was similar to that with catch advice based on two-year projections with natural mortality and recruitment misspecifications. However, the HCRs performed more conservatively with year one projections held constant. F and catch were slightly lower in the short- and medium-term (Fig. 40, 41, and 42).

Assessment performance

Trends in assessment performance were similar when catch advice was based on the year one projections held constant and when catch advice was based on two-year projections (Figs. 43). However, the magnitude of assessment error was higher with the year one projections held constant. Mohn's Rho values were similar to that with catch advice based on two-year projections (Fig. 44).

Management performance

Management performance was similar when catch advice was based on the year one projections held constant and when catch advice was based on two-year projections (Figs. 46 and 47). However, less overfishing was estimated under the ramp and F-step HCRs. Estimated and true F/F_{MSY} were also slightly lower and estimated and true SSB/SSB_{MSY} were slightly higher with year one projections held constant. Regardless of the projection year that catch advice was based on, at the end of the MP period, true stock status was fluctuating around the overfished threshold under all HCRs. Estimated and true stock status had a similar level of agreement and disagreement as in the scenario with catch advice based on two-year projections.

Synthesis

Relative HCR performance was similar with catch advice based on the year one projections held constant and with catch advice based on two-year projections (Fig. 48). Overall, the stock spent less time overfished (on the order of 1-4 years) and undergoing overfishing (on the order of 0-5 years) with catch advice based on the year one projections.

Natural Mortality and Recruitment Misspecification with Retrospective Adjustments for a Stock that is Overfished (GOM cod)

Stock performance

HCR performance differed between scenarios with and without a rho-adjustment for an overfished stock with stock assessment misspecification (Figs. 49, 50, and 51). In the short-, medium- and long-term, F and catch were lower with a rho-adjustment. In the medium- to long-term, SSB was higher compared to the scenario without a rho-adjustment. In the long-term, SSB was similar under the ramp, P*, and F-step HCRs. This differs from the scenario without a rho-adjustment, where SSB was slightly higher under the F-step HCR in the long-term.

Assessment performance

Compared to the scenario with natural mortality and recruitment misspecifications without a rho-adjustment, assessment performance was similar (Figs. 52, 53, and 54). However, the magnitude of stock assessment error was higher under the constrained ramp HCR.

Management performance

Compared to the scenario with natural mortality and recruitment misspecifications without a rho-adjustment, management performance was different (Figs. 55 and 56). The terminal estimated stock status from each year's assessment differed from the perceived stock status without a rho-adjustment. With a rho-adjustment, the perceived stock was overfished for longer (on the order of two to four years). The F-step HCR was always estimated to result in overfishing. None of the HCRs resulted in a stock that was estimated to be rebuilt and SSB/SSB_{MSY} was lower with a rho-adjustment.

The true stock status differed from the true stock status with no rho-adjustment in that there was less overfishing. Also, SSB/SSB_{MSY} was higher and F/F_{MSY} was lower compared to the scenario without a rho-adjustment.

Synthesis

Overall, the relative performance of HCRs with the natural mortality and recruitment misspecifications was slightly different with a rho-adjustment (Fig. 57). In the medium-term, there was less overfishing with a rho-adjustment. In the long-term, there was less overfishing and a lower frequency of the stock being overfished.

Natural Mortality and Recruitment Misspecification with Annual Updates for a Stock that is Overfished (GOM cod)

Stock performance

HCRs performed slightly different in this scenario with annual updates of the stock assessment compared to scenarios with stock assessment updates every two years (Figs. 58, 59, and 60). In scenarios with annual updates, the changes in stock performance metrics were generally more gradual. Overall, F and catch were lower across HCRs when stock assessment updates occurred annually.

Assessment performance

Assessment performance was similar to assessment performance with natural mortality and recruitment misspecifications and stock assessment updates every two years (Figs. 61, 62, and 63).

Management performance

Annual stock assessment updates resulted in similar management performance to the scenario with natural mortality and recruitment misspecifications with stock assessment updates every two years (Figs. 64 and 65). However, at the end of the MP period, SSB/SSB_{MSY} was estimated to be higher. Also, under the ramp, P*, and constrained ramp HCRs, F was estimated to be just over the overfishing limit at the end of the MP period, while F under the F-step HCR was estimated to be just under the overfishing limit.

True stock status was slightly different from that with assessment updates every two years. Under the ramp and P* HCRs, the stock took one year longer to increase above the overfished threshold, F/F_{MSY} did not get as high, and at the end of the MP period, SSB/SSB_{MSY} was higher than in the scenario with assessment updates every two years. Annual stock assessment updates improved true management performance in the long-term.

Synthesis

In general, HCR performance was similar with natural mortality and recruitment misspecifications and annual stock assessment updates to that with two year updates (Fig. 66). However, in the short-term, there was more overfishing under the ramp and P* HCRs with annual updates. In the medium-term, the constrained ramp HCR resulted in the lowest catch stability. In the long-term, no HCRs resulted in an overfished stock, and there was less overfishing than with two year stock assessment updates.

Performance of Harvest Control Rules for a Groundfish Stock that is Not Overfished (Georges Bank haddock)

<u>Base Case for a Stock that is Not Overfished (GB haddock)</u>

Stock performance

In the short-, medium-, and long-term, the ramp, P*, and F-step HCRs resulted in similar stock trajectories for GB haddock (Figs. 67, 68, and 69). The constrained ramp HCR stood out as performing differently, with the lowest levels of F and catch in the short- and medium-term and highest levels of SSB. In the long-term, F under the constrained ramp HCR increased to levels similar under other HCRs (Figs. 67, 68, and 69). Median catch was similar among HCRs in the long-term. However, the trajectories of catch differed for the constrained ramp HCR, which increased catch over that of the other HCRs by the end of the MP period. Although variability was high, in the short-, medium-, and long-term, median recruitment was steady and similar among HCRs (Figs. 67 and 68). Large recruitment events occurred, but they are not apparent in the plotted medians (Fig. 67) or 95% confidence intervals of the medians (Fig. 68).

Assessment performance

REE and Mohn's Rho values were negligible since there was no stock assessment misspecification (Figs. 70 and 71). In the short-, medium-, and long-term, there was negligible error in SSB_{MSY} and no error in F_{MSY} (Fig. 72).

Management performance

Stock status determination was equivalent between the true OM and stock assessment perception in the Base Case due to the accuracy of the assessment under this scenario. Under all HCRs, the GB haddock stock was maintained above the rebuilding target (SSB_{MSY}) in the short-, medium-, and long-term (Figs. 73 and 74). However, there were some iterations where SSB was below $SSB_{MSY.}$ In the short-term, median F/F_{MSY} was below the overfishing threshold. However, in the beginning of the MP period there was some overfishing under the ramp, P* and F-step HCRs due to slight underestimation of F. In the medium-term, median SSB/SSB_{MSY} was highest under the constrained ramp HCR. Under the constrained ramp HCR, F/F_{MSY} increased. Median F/F_{MSY} was below the overfishing threshold under all HCRs. In the short-, medium-, and long-term, median F/F_{MSY} was lower under the constrained ramp HCR.

Synthesis

Throughout the MP period, the constrained ramp HCR resulted in the highest median SSB (Fig. 75). However, in the short-term, the constrained ramp HCR resulted in the lowest median catch but highest catch stability. All HCRs resulted in a stock size above the overfished threshold in the short-, medium-, and long-term. However, overfishing occurred in the short-term under the ramp, P*, and F-step HCRs. All HCRs resulted in no overfishing in the medium- to long-term. The ramp, P*, and F-step HCRs resulted in the highest median catch and catch stability in the medium-term. In the long-term, all HCRs resulted in a similar median catch, although median catch was slightly higher under the constrained ramp HCR.

<u>Survey Catchability Misspecification for a Stock that is Not Overfished (GB haddock)</u>

Stock performance

HCR performance with a catchability misspecification was similar to the Base Case scenario (Figs. 76, 77, and 78). However, in the medium- and long-term, SSB increased under the ramp, P*, and F-step HCRs and did not decline as much under the constrained ramp HCR as in the Base Case. In addition, F gradually decreased under the ramp, P*, and F-step HCRs and did not increase as much under the constrained ramp HCR. Catch was slightly lower under the ramp, P*, and F-step HCRs and did not increase as much under the constrained ramp HCR.

Assessment performance

The introduction of a survey catchability misspecification resulted in assessment performance that differed from the Base Case (Figs. 79, 80, and 81). SSB was increasingly underestimated and F increasingly overestimated over time and then leveled off at the end of the MP period. In the medium- and long-term, the magnitude of error was greater under the constrained ramp HCR. Retrospective patterns were minimal. SSB_{MSY} was slightly underestimated in the short-, medium-, and long-term.

Management performance

Management performance with a survey catchability misspecification was similar to that in the Base Case (Figs. 82 and 83). However, there were some slight differences. The stock was usually perceived to always be rebuilt. Although near the end of the MP period, the estimated stock status hovered around the rebuilding target under the ramp, P*, and F-step HCRs. Also, in year five and six, overfishing was estimated under the ramp, P*, and F-step HCRs. At the end of the MP period, estimated stock status was similar under all HCRs: rebuilt and not overfishing. True stock status was similar to the estimated stock status from each year's assessment and also similar to the true stock status with a correctly specified assessment. However, true SSB/SSB_{MSY} was slightly higher and true F/F_{MSY} was slightly lower than in the Base Case Scenario.

Synthesis

With a survey catchability misspecification, relative HCR performance was similar to that without a misspecification for a not overfished stock (Fig. 84).

Discussion

This analysis provides information on the performance of alternative HCRs across a range of conditions currently experienced by New England groundfish stocks. Scenarios with different combinations of stock size, recruitment, natural mortality, and survey catchability assumptions as well as stock assessment model specifications were simulated to evaluate the performance of HCRs when a stock was overfished, not overfished, and when a stock assessment model had a misspecification that could result in retrospective patterns. Overall, the ramp, P*, and F-step HCRs resulted in different catch advice when a stock was overfished, but performed relatively similarly when not overfished. There were trade-offs in the performance of HCRs in the short- , medium- and long-term relative to key metrics (e.g., SSB, catch, catch stability, and frequency of overfished and overfishing status). For an overfished stock, the choice of HCRs was most influential in the short- and medium-term, as there were more significant differences in HCR performance during this period. In the long-term, the ramp, P*, and F-step HCRs typically performed similarly because stock size increased over the SSB overfished threshold and thus catch advice was similar among HCRs.

Comparing correctly specified scenarios to those with stock assessment misspecifications allowed us to understand how stock assessment bias and unaccounted changes in population dynamics can impact HCR performance. We found that stock assessment misspecifications played a larger role in long-term stock status than the choice of HCRs. For example, the frequency of overfished and overfishing stock status depended more on the type of stock assessment misspecification, rather than the type of HCR. In scenarios that incorporated a natural mortality misspecification, retrospective patterns appeared. Retrospective patterns are a sign that there is a stock assessment misspecification that has greatly impacted our perception of reality. The scenario with the combined natural mortality and recruitment misspecification simulated retrospective patterns similar in scale to what are seen in several groundfish assessments and also captured the expected negative impact of temperature on recruitment for cod. The intent of this analysis was to provide insight on the performance of alternative HCRs for New England groundfish stocks across a range of conditions. The classification of which HCR performs best across a range of conditions will depend on the definition and prioritization of management objectives for the groundfish fishery which was outside the scope of this study.

How do alternative HCRs perform when a stock is overfished and the assessments are well specified (Base Case for a Stock that is Overfished)?

All HCRs were able to rebuild the stock above SSB_{MSY} in the long-term, although the unique features of HCRs resulted in different pathways to achieve this stock status. With no bias and nearly perfect information provided to the stock assessment, all HCRs were able to produce sustainable catch advice. The ramp and P* HCRs performed similarly and resulted in reduced catch and catch stability in the short-term. The F-step HCR tended to provide the highest catch and also the highest catch stability in the beginning of the MP period, because F did not change much with changes in SSB.

The trajectories under the constrained ramp HCR differed the most from all other HCRs. This HCR resulted in the lowest F and catch in the medium-term and resulted in the highest SSB in the long-term. However, the constrained ramp HCR did not always result in the highest catch stability. This variability constraint prevented the catch from increasing as fast as under the other HCRs in the short- to medium-term. However, in the long-term, this HCR resulted in more variable catch as a 20% difference in catch became larger as catch increased at the end of the MP period. None of the HCRs allowed GOM cod catch to increase to the level of the 1980s and 1990s, because F was not allowed to get as high as it had in the past. HCRs performed differently for an overfished stock because the prescribed F across HCRs differed in response to the SSB being below the overfished threshold at the start of the MP period. However, in these scenarios, there were negligible REE and retrospective patterns, which is not what is experienced in most groundfish stocks.

How do alternative HCRs perform when a stock is not overfished (Base Case for a Stock that is Not Overfished)?

Overall, the ramp, P*, and F-step HCRs performed similarly for a stock that was not overfished because the prescribed F was often the same since SSB was above the overfished threshold throughout the MP period. Conditioning these simulations on haddock provided a contrast to those conditioned on GOM cod and captured unique features of haddock population dynamics (i.e. influence of large recruitment events). The ramp, P*, and F-step HCRs allowed the fishery to take advantage of large recruitment events resulting in high catch in the short- to medium-term. In contrast, the constrained ramp HCR did not enable taking full advantage of the large recruitment events; however, this HCR provided high catch stability in the short-term and ultimately resulted in the highest SSB and catch in the long-term. A large recruitment event occurred near the end of the historical period for all haddock scenarios and the high catch at the beginning of the MP period depended on that recruitment event. Similar to the correctly specified cod scenarios, these scenarios had negligible errors and no retrospective patterns, which is not what is experienced in most groundfish stocks.

How do alternative HCRs perform when stock assessments are misspecified?

In scenarios that incorporate stock assessment misspecifications, stock assessment assumptions were not an accurate reflection of the 'reality' in the OM. With the misspecifications, fisheries management is informed by imperfect knowledge. As a result, the HCRs did not always perform as well as with no misspecifications. These scenarios are especially important since retrospective patterns, indicative of stock assessment misspecifications, are apparent in groundfish stock assessments (NEFSC, 2019). The misspecifications simulated in this study were related to climate change impacts. In the GOM and GB, water temperatures are continuing to warm past historical highs. The four stock assessment misspecifications simulated in this study had different effects on population trajectories and performance of HCRs. All misspecified scenarios resulted in assessment error, either under or overestimation of outputs in the stock assessment, and some resulted in retrospective inconsistencies. The natural mortality misspecification led to retrospective patterns on the scale observed in current groundfish stock assessments while the survey catchability and recruitment misspecifications did not. Kritzer et al. (2019) found that a HCR that changes F with biomass performed better in the face of adverse effects of climate change and retrospective patterns than a HCR with a fixed F.

In the scenario with a natural mortality misspecification, natural mortality was higher in the OM than assumed in the assessment model or the base case OM. This contributed to more time spent overfished, more overfishing, lower catch and lower SSB in these misspecified scenarios. In the stock assessment, natural mortality was assumed to be lower, and this caused retrospective patterns and over- and under-estimation of SSB and F, respectively. With a natural mortality misspecification, the stock was not rebuilt at the end of the MP period under any of the HCRs.

In scenarios with a recruitment misspecification, recruitment was a function of SSB and temperature, whereas the assessment (and the base case OM) assumed recruitment was not negatively impacted by temperature. In this scenario, the ramp and P* HCRs increased SSB at the fastest rate and decreased the frequency of being overfished. However, catch was lower under these HCRs in the short-term. Also, there was overfishing in the long-term due to error in the estimated SSB.

In the previous scenarios, only one parameter was misspecified at a time, but in reality, multiple parameters can be misspecified (Cao et al., 2016). In scenarios with a natural mortality and recruitment misspecification, retrospective patterns and stock assessment error were comparable to those in the natural mortality misspecified scenario. The negative impact of temperature and higher natural mortality combined with the stock assessment misspecifications contributed to lower catch and SSB and more time spent overfished and overfishing (Fig. 87). These changes in population dynamics and error in the assessment caused the stock to not rebuild. Although the F-step HCR resulted in overfishing in the beginning of the MP period, the error under this HCR was smaller, which resulted in in higher SSB, catch, catch stability, and less overfishing and time overfished in the long-term than the ramp and P* HCRs. The misspecification led to cyclical patterns in stock dynamics in the ramp and P* HCRs, which change F with changes in SSB. Although catch was high under the ramp and P* HCRs in the medium-term, this catch was not sustainable, as it resulted in low SSB and catch in the long-term. When catch advice was determined holding the first year of the projections constant, the HCRs performed more conservatively than when catch advice was based on two-year projections (Fig. 88). This is because catch from the first year of the projection was often smaller than that of the second year of the projection with an overfished stock. In these scenarios, SSB increased faster, stocks rebuilt faster, and F and catch did not increase as fast. With annual updates, the HCRs performed similarly but were more reactive and conservative in the long-term, as catch advice was updated annually (Fig. 88). This caused higher catch stability, higher SSB, less time overfished, and less overfishing in the long-term.

In scenarios with a survey catchability misspecification, the population dynamics were not directly altered from the correctly specified scenario, rather survey data from the observation model were altered. In the stock assessment, survey catchability was assumed to be constant, and this caused an underestimation of SSB and overestimation of F. This misspecification caused the HCRs to be more conservative since the estimated SSB was smaller than the true SSB (Fig. 89).

Mohn's Rho values were negligible under all misspecifications except for the natural mortality and combined natural mortality and recruitment misspecifications. With these misspecifications, Mohn's Rho values got as large as in some of the current groundfish assessments (NEFSC, 2019). The degree of bias in the stock assessment performance and retrospective inconsistencies varied among HCRs and did not always coincide in their direction. This is similar to other findings that the direction and magnitude of retrospective patterns are not related to true bias (Huratdo-Ferro et al., 2015). Additionally, Kerr et al. (2020) found that biases in SSB were sometimes in the opposite direction of the retrospective patterns. Trends in Mohn's Rho did not always reflect trends in stock assessment error and sometimes both varied among HCRs. Indeed, a lack of retrospective patterns does not mean that there is not data or model inconsistency (Legault, 2009). In the natural mortality and combined natural mortality and recruitment misspecified scenarios, assessment error and retrospective patterns were sometimes in opposition. At the end of the MP period, SSB was underestimated but Mohn's Rho for SSB was positive in these scenarios.

When retrospective patterns exist, do retrospective adjustments result in better performance than no retrospective adjustments?

When retrospective patterns existed, the rho-adjustment impacted the performance of HCRs (Fig. 90). A rho-adjustment created more conservative catch advice and caused less overfishing and a lower frequency of overfished stock status. With a rho-adjustment, SSB/SSB_{MSY} was higher and F/F_{MSY} was lower. F and catch were lower, which resulted in a higher SSB. A previous study found that the effect of a rho-adjustment depends on the HCR form (Deroba, 2014). The decision of whether to apply a rho-adjustment should depend on the direction of the retrospective pattern and short and long-term management objectives (Deroba, 2014). ICES guidelines for biased assessments suggest that if SSB is consistently overestimated and F is consistently underestimated, a rho-adjustment should be applied to catch advice (ICES, 2020).

Caveats and Limitations

It is important to recognize the caveats and limitations of this analysis. The results of this analysis are conditional upon the underlying assumptions of modeled scenarios and the HCRs evaluated. There are additional HCR forms and adjustments to the features of the HCRs evaluated in this study that could be worthwhile exploring in the future based on the desired outcomes of groundfish management (i.e., management objective setting process). For example, a constant F HCR was not explored in this analysis. Kerr et al. 2020 did simulate a constant F HCR in context of catch misreporting scenarios which could be informative for decision making regarding this HCRs performance. Additionally, the threshold at which F begins to change in the HCRs was 50% of SSB_{MSY} in this study; however, alternative SSB thresholds could be explored (e.g. SSB_{MSY}). One of the limitations of this analysis was that technical interactions were not simulated. For some stocks, the groundfish fishery harvests considerably less than the annual catch limit (ACL) due to technical interactions of the mixed-stock fishery (i.e., choke species issues; Cadrin, 2016). These issues influence the realized catch and can alter the anticipated outcomes of a harvest strategy. Without technical interactions, these scenarios are a departure from reality. However, if technical interactions were included in the haddock scenarios, HCR performance would be difficult to evaluate if the catch was a small percentage of the ACL. HCR performance is also dependent upon the reference point calculation. Reference points were calculated to be consistent with the current groundfish stock assessments (NEFSC, 2019). Future work can use the MSE approach to evaluate the performance of alternative reference points. Also, only the terminal estimated SSB was rho-adjusted and not SSB_{MSY}. Unadjusted estimates of SSB_{MSY} can introduce biased estimates of stock status. However, there is not clear guidance on how to rho-adjust biomass reference points.

In addition, the OMs are flexible and can be further tuned to represent additional complexity and variability in groundfish dynamics and operation of groundfish fisheries. For example, declining weight-at-age and density-dependent growth are evident for GB haddock (NEFSC, 2019; Wang et al., 2021), but this was not included during the MP period for haddock scenarios. Additionally, index age composition may change with changes in survey catchability, but this was not incorporated in the survey catchability misspecification scenario. The OMs did not consider spatial complexity which can affect HCR performance. Additionally, unbiased implementation of HCRs was assumed (i.e., no bias in catch observations but some random error), however there is some evidence of an observer effect in catch reporting in the groundfish fishery that could introduce bias (Demarest, 2019; McNamee et al., 2019; Nitschke, 2019). HCR performance may also vary with autocorrelated errors. Additionally, waters in the GOM are continuing to warm (NOAA Fisheries, 2021) with impacts on aspects of groundfish population dynamics. We simulated the impact of warming on recruitment, but impacts on other aspects of dynamics could be incorporated as well (e.g., growth). Future analyses can incorporate additional complexities and variabilities.

Another limitation was the characterization of uncertainty in this MSE approach. In many cases, the ramp and P* HCRs performed nearly identical due to the manner which the P* approach was simulated. In this study, the P* approach used a constant CV of 1 to determine the distribution of catch at the OFL. In reality, CVs used in P* approaches are often not estimated. However, future studies could explore alternative simulations of the P* approach that more fully capture uncertainty in the stock assessment. The better uncertainty is represented in an MSE, the more informative MSE is for fisheries management (Punt et al., 2016). However, despite these caveats and limitations, these simulations provide valuable information on HCR performance and capture sufficient complexity to address the research questions.

Conclusions

The performance of HCRs differed between scenarios, metrics, and time periods. HCRs resulted in similar stock status at the end of the MP period, although the HCRs took different trajectories to achieve this status. When the stock was not overfished, the ramp, P*, and F-step HCRs performed similarly, because SSB was above the overfished threshold, resulting in similar F. However, these HCRs performed differently when the stock was overfished. In this case, all HCRs were able to rebuild the stock above SSB_{MSY} in the long-term, but the F-step HCR achieved this later than the other HCRs. The trajectories under the constrained ramp HCR typically differed the most from the other HCRs, and the constrained ramp HCR did not always provide high catch stability. The variation constraint restricted the ability to take full advantage of large recruitment events that resulted in a high catch for the other HCRs.

In general, HCRs performed differently with a misspecification. The frequency of overfished and overfishing stock status depended more on the type of stock assessment misspecification than the HCR. The natural mortality misspecification led to retrospective patterns while the survey catchability and recruitment misspecifications did not. Due to changes in population dynamics and over- and under-estimation of SSB, F, and SSB_{MSY}, the natural mortality misspecification led to overfishing under all HCRs. This misspecification also prevented the stock from rebuilding. Additionally, with the negative impact of temperature on recruitment in the combined natural mortality and recruitment misspecification scenario, SSB and catch declined at the end of the MP period. On the other hand, the survey catchability misspecification led to more conservative catch advice due to perceived lower SSB.

With the natural mortality misspecification and resulting retrospective patterns, the rho-adjustment led to more conservative catch advice by decreasing the perceived SSB. Annual stock assessment updates also led to more conservative catch advice as catch advice was more responsive. In scenarios that held the first year of projected catch constant, the HCRs performed more conservatively, because the first year of projected catch was usually less than the second year of projected catch for an overfished stock. The performance of HCRs under misspecifications is especially important because it is likely that New England groundfish stock assessments that exhibit retrospective patterns have one or more misspecifications. Furthermore, understanding the performance of HCRs in the context of changing ocean conditions (e.g., negative impact of temperature on recruitment for an overfished stock) is also important because groundfish stocks, such as GOM cod, will continue to be impacted by warming waters.

Each HCR performed well under different conditions and for different performance metrics, highlighting the tradeoffs that each HCR provided. The classification of which HCR performs best across a range of conditions will depend on the definition and prioritization of management objectives for the groundfish fishery which was outside the scope of this study.

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Appendix A

Operating models

We developed operating models (OMs) designed to emulate Gulf of Maine (GOM) cod and Georges Bank (GB) haddock stock dynamics to typify a range of conditions currently experienced by groundfish stocks (Table A1). The OMs were age-structured, stochastic models. Abundance of fish at age over time was calculated based on exponential survival (Eqn. 1, Table A2). For both cod and haddock, there were nine age bins (1-9+). Spawning stock biomass (SSB) was a function of abundance-at-age, weight-at-age, and maturity-at-age of fish (Eqn. 2, Table A2). Unless otherwise specified, recruitment was modeled using an empirical cumulative distribution function (Eqn. 3, Table A2). Catch by the fishery was calculated as a function of the Baranov catch equation (Eqn. 4, Table A2) and informed by annual F rates derived from the HCR and projections.

Table A1. Conditions of New England groundfish stocks with analytical assessments. M= natural mortality; GOM= Gulf of Maine; GB= Georges Bank; SNE= Southern New England.

Stock	Catch bias	High M uncertainty	Productivity decrease	Productivity increase	Overfishing	Overfished
GOM Cod	X	X	X		X	X
GB Haddock				X		
GOM Haddock	X			X		
GB Winter flounder			X			X
White hake			X			X
Pollock				X		
American plaice						
Cape Cod/GOM yellowtail flounder		X	X			
SNE/Mid-Atlantic yellowtail flounder		X	X			X
Redfish						

Table A2. Description of equations and symbols used in simulating the population dynamics in an age-structured operating model.

Eqn. 1

$$N_{a,t} = \begin{cases} N_{1,t} & if\ a = 1 \\ N_{a-1,t-1}e^{-[M_{t-1}+F_{t-1}(s_{a-1}^F)]} & if\ 1 < a < x \\ N_{a-1,t-1}e^{-[M_{t-1}+F_{t-1}(s_{a-1}^F)]} + N_{a,t-1}e^{-[M_{t-1}+F_{t-1}(s_{a}^F)]} & if\ a = x \end{cases}$$

Eqn. 2

$$SSB_t = \sum_{a=1}^{a=x} N_{a,t}W_aP_a$$

Eqn. 3

Gulf of Maine cod:

$$N_{1,t} \begin{cases} ecdf(R_{obs}) & if\ SSB_{t-1} \geq SSB_* \\ \frac{SSB_{t-1}}{SSB_*}\left(ecdf(R_{obs})\right) & if\ SSB_{t-1} < SSB_* \end{cases}$$

Georges Bank haddock:

$$N_{1,t} = ecdf(R_{obs})$$

Eqn. 4

$$C_{a,t}^N = N_{a,t}\frac{s_a^F F_t}{s_a^F F_t + M_t}(1 - e^{-s_a^F F_t - M_t})$$

Symbols used in equation		
	$N_{a,t}$	abundance of fish at age *a* at time *t*
	M_t	natural mortality at time *t*
	F_t	fishing mortality at time *t*
	s_a^F	selectivity to the fishery at age *a*
	x	plus group
	SSB_t	spawning stock biomass at time *t*
	W_a	average weight-at-age, *a* of fish
	P_a	fraction of fish of age, *a* that are mature
	SSB_*	spawning stock biomass hinge value
	$ecdf(R_{obs})$	sample from empirical cumulative distribution of historic observed recruitments (R_{obs})
	$C_{a,t}^N$	catch of age, *a* fish in time *t* in numbers

The models were parameterized based on the most recent stock assessment update and benchmark assessment for GOM cod (NEFSC 2013, NEFSC 2019, Tables A3 and A4) and GB haddock (Brooks et al. 2008, NEFSC 2019, Tables A5 and A6). For cod, growth was modeled using a time invariant weight-at-age vector and maturity-at-age followed a logistic pattern. Values for cod were consistent with the specification of growth and maturity used in stock assessment projections (Table A4, NEFSC 2019). For haddock, growth was modeled using a time varying weight-at-age vector during the historical period and maturity-at-age followed a logistic pattern. Haddock weight-at-age was consistent throughout the management procedure (MP) period. Values for haddock during the MP period were based on the average of the last five years of the stock assessment (Table A6, NEFSC 2019).

We modified the stock-recruit relationship (SRR) that was used in stock assessment projections of GOM cod (NEFSC 2013) to utilize the last 20 years of observed recruitment

(1998-2018) in the cumulative distribution function. The original fitting of the SRR used all historically observed recruitments, including extreme high values from the 1980s. In OM simulations, this resulted in periodic extreme high recruitment in future projections which were not consistent with the moderate to low values of recruitment observed in recent decades. For GB haddock, the last 20 years of observed recruitment (1998-2018) were used in the cumulative distribution function, to capture the periodic high recruitment values that were more frequent in recent years of the historical period. For the Beverton-Holt stock-recruitment scenarios, parameters were estimated outside of the model with the most recent stock assessment output (Tables A3). The stock-recruitment parameters differed when natural mortality was constant and when natural mortality increased overtime. Annual sea surface temperature anomalies for the GOM were incorporated into the SRR. We also incorporated a small amount of stochasticity (i.e., random process error, Tables A3 and A5).

We modeled the harvest by the fishery as a single fleet (i.e., recreational and commercial combined) consistent with the current stock assessments. Fishery selectivity-at-age was informed by the selectivity-at-age in the most recent stock assessments for the most recent selectivity blocks (Tables A4 and A6). The selectivity curve represented the combined recreational and commercial catch. Fishing mortality (F) was not permitted to go over 2. In the survey catchability misspecification, survey catchability decreased as temperature anomalies increased:

$$qI = 1 - (0.125T) \qquad \text{(Eqn. 5)}$$

, where qI is survey catchability, and T is the temperature anomaly. Survey catchability was not permitted to decrease below 0.5, which was half of the initial catchability.

Table A3. Associated parameter names, symbols and input values used in the Gulf of Maine cod operating models.

Parameter	Symbol	Value	Source (model)
Natural mortality (M = 0.2 scenarios)	M_t	0.2	NEFSC 2019 (ASAP)
Natural mortality (M-ramp scenarios)	M_t	0.2-0.4	NEFSC 2019 (ASAP)
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		0.5	NEFSC 2019 (ASAP)
Recruitment process error		0.5	Assumed
Beverton-Holt productivity parameter (M=0.2)	α	5.17	Estimated
Beverton-Holt density-dependence parameter (M=0.2)	β	0.000289	Estimated

Beverton-Holt temperature effect parameter (M=0.2)	Υ	-1.42	Estimated
Beverton-Holt productivity parameter (M-ramp)	α	5.15	Estimated
Beverton-Holt density-dependence parameter (M-ramp)	β	0.000255	Estimated
Beverton-Holt temperature effect parameter (M-ramp)	Υ	-0.90	Estimated

Table A4. Gulf of Maine cod operating models 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 ($N_{1,t}$)	15000	17000	6000	3500	2000	200	300	150	100	NEFSC 2019 (ASAP)
Weight-at-age (W_a)	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 (P_a)	0.087	0.318	0.697	0.919	0.982	0.996	0.999	1	1	NEFSC 2019 (AGEPRO)
Fishery selectivity-at-age, M = 0.2 (s_a^F)	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 (s_a^F)	0.009	0.051	0.241	0.651	0.917	0.985	0.997	1	1	NEFSC 2019 (AGEPRO)
Survey selectivity-at-age (s_a^I)	0.038	0.134	0.289	0.531	0.778	1	1	1	1	NEFSC 2019 (ASAP)

Table A5. Associated parameter names, symbols and input values used in the Georges Bank haddock operating models.

Parameter	**Symbol**	**Value**	**Source (model)**
Natural mortality	M_t	0.2	NEFSC 2019 (VPA)
Fishery catchability	q^F	1	Assumed
Constant survey catchability	q^I	1	Assumed
Time-varying survey catchability	q^I	Eqn. 5	Assumed
Survey timing	st	0.5	Assumed
Catch weight observation error		0.05	Assumed

Index observation error	0.2	NEFSC 2019 (VPA)
Recruitment process error	1	Assumed

Table A6. Georges Bank haddock operating models 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 ($N_{1,t}$)	39938	80387	14081	17665	17144	10197	5491	3086	961	NEFSC 2019 (VPA)
Weight-at-age (W_a)	0.1774	0.4291	0.6939	0.8887	1.089	1.247	1.396	1.577	1.784	NEFSC 2019 (VPA)
Maturity-at-age (P_a)	0.0338	0.2592	0.7464	0.9532	0.9928	0.9988	1	1	1	NEFSC 2019 (VPA)
Fishery selectivity-at-age (s_a^F)	0.0114	0.0296	0.1014	0.3002	0.3976	0.6324	0.9574	0.6626	0.6626	NEFSC 2019 (VPA)
Survey selectivity-at-age (s_a^I)	0.444	0.697	0.755	0.759	0.779	0.712	0.807	0.772	0.772	NEFSC 2019 (VPA)

Historic estimates of F and recruitment from the most recent stock assessments (NEFSC, 2019) were used to condition the models and emulate estimated stock trajectories. The historic period of the OMs spanned 1982-2018 for cod and from 1931-2018 for haddock and served to initialize forward projections. The models were projected forward 21 years, from 2019 to the year 2040, under alternative harvest control rules (HCRs).

Management Procedures

We aimed to emulate the current groundfish fishery MP. The MP included: 1) data collection, 2) fitting a stock assessment, 3) estimating biological reference points (BRPs), and 4) determining catch advice from a HCR. The MP was applied starting in 2019.

Observation models

Observation models were designed to simulate collection of fishery dependent and fishery independent data with the characteristics and quality (i.e., uncertainty) that typically inform the GOM cod and GB haddock stock assessments. 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 OM), catchability of the survey, survey selectivity-at-age, and observation error (Eqn. 6 and 7, Table A7). Observation error was informed by the current stock assessments (NEFSC, 2019; Tables A3 and A5). We assumed lognormal error for the index of abundance and multinomial error for the index of abundance-at-age (Tables A3 and A5). Survey selectivity-at-age followed a logistic pattern based on stock assessment fit values for the NEFSC spring bottom trawl (Tables A4 and A6).

Table A7. Description of equations and symbols in the observation model to generate simulated catch and index data.

Eqn. 6		$I_{a,t}^{N} = q^{I} N_{a,t} e^{(-s_{a}^{I} F_{t} - M_{t}) st}$
Eqn. 7		$I_{t}^{N} = \sum_{a=1}^{a=x} I_{a,t}^{N}$
Eqn. 8		$C_{a,t}^{W} = C_{a,t}^{N} W_{a}$
Eqn. 9		$C_{t}^{W} = \sum_{a=1}^{a=x} C_{a,t}^{W}$
Symbols used in equations	$I_{a,t}^{N}$	survey catch in numbers for age *a* in time *t*
	q^{I}	survey catchability coefficient
	s_{a}^{I}	survey selectivity at age, *a*
	st	survey timing, given as proportion of the year that has elapsed
	$C_{a,t}^{W}$	catch weight at age *a* at time *t*
	C_{t}^{W}	total catch weight at time *t*

We modeled the fishery catch in number as described previously (Eqn. 4, Table A2) and calculated catch and catch-at-age in weight as described in Eqn. 7 and 8 (Table A7). We assumed lognormal observation error on total catch and multinomial errors on catch-at-age (Tables A3 and A5). We assumed an observation error for the combined commercial-recreational catch based on values used in the GOM cod assessment (i.e., CV = 5%) and assumed an equivalent error for GB haddock.

Stock Assessment Model

We integrated the current stock assessment model used in the majority of groundfish analytical assessments, the Age-Structured Assessment Program (ASAP; Legault & Restrepo, 1998) into the simulation framework. Model parameters in the estimation model were consistent to those specified in the OM, such that the assessment model was not misspecified, except in the misspecified scenarios. In the base case 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 OM and estimation model. Fishery selectivity and survey selectivity-at-age were estimated in the assessment. Recruitment process errors were set to 0.5 for cod and 1.0 for haddock and the CV on catch and the survey index was consistent between the operating and estimation models (Tables A3 and A5). The assessment accumulated an additional year of data each year the simulation loop was run such that the first assessment included 33 years of data and the final assessment included 54 years of data. Further details on specifications of ASAP are provided as dat files for cod and haddock models (Supplementary Materials).

Biological Reference Points

BRPs are the criteria by which we determine stock status and inform triggers for management actions in the context of HCRs. A F_{MSY} proxy was calculated using a spawning potential ratio approach (Eqn. 10 and 11, Table A8). Spawning potential ratio was calculated at 40% and the value of F^* that results in the given ratio was used as the F_{MSY} proxy reference point (i.e., $F_{40\%}$, the F expected to conserve 40% of the maximum spawning potential; Eqn. 10 and 11, Table A8). The associated biomass proxy was calculated through projection of the stock to an equilibrium SSB, with recruitment as an average of the estimated recruitment from the last 20 years. Reference points were recalculated every time there was an assessment. We calculated both the "true" F_{MSY} and SSB_{MSY} proxy reference points and estimated reference points based on the OMs and the stock assessments, respectively. Estimated reference points were used to determine perceived stock status, which catch advice was based on.

Table A8. Description of equations and symbols used to calculate biological reference points from the stock assessment in the management procedure.

Eqn. 10		$\frac{SSB}{R}_{F^*} = \sum_{a=1}^{a=x} e^{-s_a^F F^* - M} P_a W_a$
Eqn. 11		$SPR_{F^*} = \frac{[\frac{SSB}{R}_{F=F^*}]}{[\frac{SSB}{R}_{F=0}]}$
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	average weight at age *a* of fish
	P_a	fraction of fish of age *a* that are mature
	SPR_{F^*}	spawning potential ratio (F^* = 0.4)
	$\frac{SSB}{R}_{F=0}$	estimated spawning stock biomass per recruit when $F = 0$ for an average individual

Harvest Control Rule

Four HCRs were tested: 1) the ramp HCR, 2) the P* HCR, 3) the F-step HCR, and 4) a constrained ramp HCR. In the ramp HCR, F-based advice decreased linearly when stock biomass was estimated to be less than the overfished threshold (i.e., 50% SSB_{MSY}; Eqn. 12, Table A9). In the P* HCR, P* depended on the estimated biomass (Eqn. 13, Table A9). The catch advice was the P* percentile of the catch at the overfishing limit (OFL). The OFL catch distribution was lognormal with a mean of the log of the median of the catch projected 100 times with F at

F_{MSY} with a CV of 1 (Wiedenmann et al., 2016). In the F-step HCR, if the SSB decreased below 50% SSB_{MSY}, this HCR used a target F of 70% F_{MSY}. If the SSB never decreased below 50% SSB_{MSY} or increased to over SSB_{MSY} after dropping below 50% SSB_{MSY}, this HCR used a target F of 75% F_{MSY}. In the constrained ramp HCR, the ramp HCR was applied, but the catch limit could not change more than 20% from the previous year's catch limit. However, catch was constrained so that the projected catch was not higher than the estimated OFL. The prescribed target catch or ABC was estimated by projecting the catch with F determined from the F-based HCRs. In simulating these HCRs, we assumed the annual catch limit was set to equal to the acceptable biological catch.

Table A9. Description of equations and symbols used in harvest control rules.

Eqn. 12	$F_t = \frac{75\% F_{MSY}^{t-1} SSB_{est}^{t-1}}{50\% SSB_{MSY}^{t-1}}$ if $SSB_{est}^{t-1} \leq 50\% SSB_{MSY}^{t-1}$ $F_{t+1} = 75\% F_{MSY}^{t-1}$ if $SSB_{est}^{t-1} \geq 50\% SSB_{MSY}^{t-1}$
Eqn. 13	$P_{t+1}^{*} = 0.4$ if $SSB_{est}^{t-1} \geq 50\% SSB_{MSY}^{t-1}$ $P_{t+1}^{*} = 0.4 \frac{SSB_{est}^{t-1}}{50\% SSB_{MSY}^{t-1}}$ if $5\% SSB_{MSY}^{t-1} < SSB_{est}^{t-1} < 50\% SSB_{MSY}^{t-1}$ $P_{t+1}^{*} = 0$ if $SSB_{est}^{t-1} < 5\% SSB_{MSY}^{t-1}$
Symbols used in equations	F_{t+1} fishing mortality at time *t+1* determined from the harvest control rule F_{MSY}^{t-1} estimated fishing mortality maximum sustainable yield proxy (F40%) at time *t-1* SSB_{est}^{t-1} estimated spawning stock biomass from the stock assessment at time *t-1* SSB_{MSY}^{t-1} estimated spawning stock biomass maximum sustainable yield proxy at time *t-1* P_{t+1}^{*} the percentile of the OFL catch distribution used in the harvest control rule at time *t+1*

Projections

Initial abundance in the projections was drawn from a lognormal distribution with a mean of the last estimate of abundance from the stock assessment and a CV that corresponds to the CV of the terminal abundance values from the GOM cod and GB haddock NEFSC stock assessments (NEFSC, 2019). Initial abundance proportions-at-age were randomly drawn from a multinomial distribution with a probability vector of the last estimate of proportions of abundance-at-age from the stock assessment.

Because the stock assessment assessed up to year *t-1*, a 'bridge year' was used in the projections. With the exponential survival equation, abundance at the beginning of year *t* was calculated using terminal estimated abundance, terminal estimated F, and natural mortality assumed in the stock assessment. Recruitment in the 'bridge year' was the geometric mean of the last five years of estimated recruitment from the stock assessment. F in the bridge year was F from the previous iteration of the HCR, or F from the most recent catch advice. Exponential survival with F determined from the HCR was then used for following years. Recruitment in the following years was drawn from the empirical cumulative distribution functions with recruitment values estimated from the stock assessment. Catch was determined with the Baranov catch equation with F determined from the HCR. Projections were performed 100 times, and the medians of the catches from the first projection year (Frequency Scenario 2) or each of the two years (Frequency Scenario 1) were calculated.

Rho-adjustments

Rho-adjustments were applied to correct for recent retrospective inconsistencies. Mohn's Rho values ($\hat{p}_T$) provide measures of the retrospective inconsistencies (Eqn. 14, Table A10). In a rho-adjustment, the final year SSB estimate is divided by $\hat{p}_T + 1$(Deroba, 2014). Seven year peels, or seven assessments with different terminal years, were used to calculate Mohn's Rho.

Table A10. Description of equations and symbols used to calculate Mohn's Rho.

Eqn. 14	$\hat{p}_T = \frac{\sum_{n=1}^{x} \frac{SSB_{est=T-n,T-n} - SSB_{est=T-n,T}}{SSB_{est=T-n,T}}}{x}$ (SSB as an example)	
Symbols used in equations	$\hat{p}_T$	Mohn's Rho at year *T*
	x	desired number of assessments with different terminal years to be used in estimating Mohn's Rho (i.e. the number of "peels")
	$SSB_{est_{y1,y2}}$	estimated spawning stock biomass from the stock assessment at year *y1* and estimated at year *y2*

Performance metrics

Performance metrics included stock performance metrics, stock assessment performance metrics, and management performance metrics. Stock performance metrics included SSB, F, catch, recruits, and catch stability, which was measured by the interannual variation in catch (IAV; A'Mar et al., 2009; Eqn. 15, Table A11). SSB was calculated as in Equation 2 (Table A2). Stock assessment performance metrics included relative error (REE; Eqn. 16, Table A11) and Mohn's Rho for both SSB and F and the accuracy of reference point estimations. The REE reflected the error of terminal year estimates at each year in the MP. Management performance metrics included the frequency of being overfished, the frequency of undergoing overfishing, and stock status trajectories. When there was a misspecification, estimated terminal stock status from each year's assessment was also included. A stock was overfished if SSB was less than 0.5 SSB_{MSY}. A stock was undergoing overfishing if F was greater than F_{MSY}.

Table A11. Description of equations and symbols used to calculate performance metrics.

Eqn. 15	$$IAV = \frac{\sqrt{\frac{1}{n-1}\sum_{t=1}^{n-1} (C_{t+1}^{W} - C_t^{W})^2}}{\frac{1}{n}\sum_{t=1}^{n} C_t^{W}}$$	
Eqn. 16	$$REE = \frac{SSB_{est} - SSB_{true}}{SSB_{true}} * 100$$ (SSB as an example)	
Symbols used in equations	IAV	interannual variation in catch
	n	number of years
	C_t^W	total catch weight at time *t*
	REE	relative error
	SSB_{est}	estimated terminal spawning stock biomass from the stock assessment
	SSB_{true}	true or simulated spawning stock biomass corresponding to the terminal year of the stock assessment

Appendix B

Harvest control rule review

Harvest control rules (HCRs) from around the world were reviewed, with a focus on HCRs used for groundfish. This review consisted mostly of HCRs that were described in peer-reviewed papers but also included some HCRs described in technical reports. This review does not include all HCRs used for groundfish fisheries.

Harvest control rule forms

1. Constant catch (Annala, 1993; Caddy and Mahon, 1995 ; Mace, 2001; Punt, 2010; Berkson et al., 2011; Fig. A1)

A 'constant catch' harvest control rule (HCR) harvests the same number of fish regardless of stock status. Thus, as stock biomass declines, the fishing mortality (F) increases, because the fishery is removing a larger proportion of the stock. Conversely, as the stock increases, F decreases. The catch can be based on different percentiles of the annual catch series, recent average catch, or precautionary buffers (e.g., 75% of long-term median catch; Berkson et al., 2011). This HCR can provide catch stability, however, simulation testing of this rule in a stochastic environment revealed that constant catch can lead to depletion (Mace, 2001; Punt, 2010). Constant catch has been applied in the management of some developed fisheries in New Zealand in the 1990s (Annala, 1993).

Status in New England groundfish management: This option has been implemented in the short-term for catch advice of some data-limited stocks.

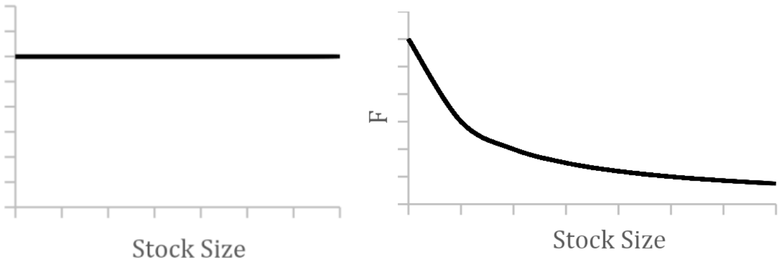

Figure B1. Constant catch harvest control rule.

2. Constant escapement (Caddy and Mahon, 1995; Hancock et al., 1997; Deroba and Bence, 2008; Cleary et al., 2010; Punt, 2010; FAO, 2020; Fig. A2)

A 'constant escapement' HCR conserves a target stock biomass and harvests the difference between the current biomass and target biomass. This HCR aims to keep the population at a constant target biomass reference point, so it has relatively low risk of stock depletion. This HCR can also maximize long-term catch if there is perfect information (Deroba and Bence, 2008). Constant escapement HCRs have been applied in the management of Pacific salmon (Hancock et al., 1997) and South Atlantic squid (FAO, 2020).

Status in New England groundfish management: This option has not been implemented.

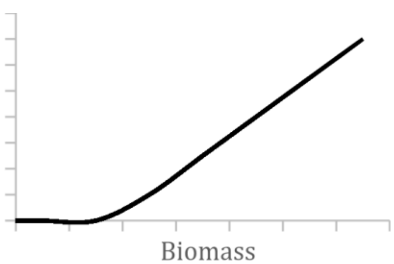

Figure B2. Constant escapement harvest control rule.

3. Constant fishing mortality (Caddy and Mahon, 1995 ; Restrepo et al., 1998; Mace, 2001; Goodman et al., 2002; Punt, 2010; Doonan et al., 2014 ; Dichmont et al., 2016 ; Fig. A3)

A 'constant fishing mortality' HCR harvests the same fraction of the stock regardless of biomass, and consequently catch increases linearly with abundance (e.g., 75% F_{MSY}; Restrepo et al., 1998; Goodman et al., 2002). The catch is set equal to a fixed proportion of the estimate of the population size. This option provides a balance between constant catch and constant escapement HCRs, as this option responds to stock size (Punt, 2010). Variants of this HCR could be based on different precautionary buffers (Restrepo et al., 1998). Constant F HCRs have been applied in the management of the U.S. west coast groundfish fishery (Dichmont et al., 2016) and the New Zealand orange roughy fisheries (Doonan et al., 2014).

Status in New England groundfish management: This option (75% F_{MSY}) is the Acceptable Biological Catch (ABC) control rule for many stocks that had not rebuilt on the expected schedule.

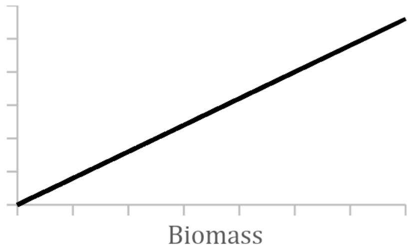

Figure B3. Constant fishing mortality harvest control rule.

4. Threshold (Butterworth and Best, 1994; Caddy and Mahon, 1995; Smith et al., 2008; Punt, 2010; Deroba et al., 2019; Feeney et al., 2019; Fig. A4)

A ‘threshold’ HCR harvest changes target F as a simple step function of stock biomass, with F set to zero at a level of abundance (e.g., 50%$SSB_{MSY;}$ Punt, 2010). Variants of this HCR could be based on different biomass thresholds (Deroba et al., 2019; Feeney et al., 2019). Threshold HCRs have been applied in management of whales by the International Whaling Commission (Butterworth and Best, 1994).

Status in New England groundfish management: This option has not been implemented.

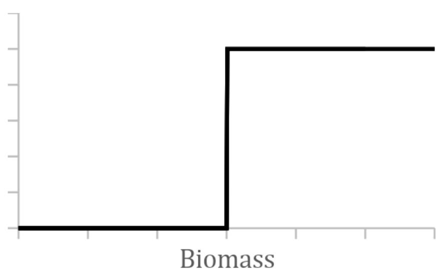

Figure A4. Threshold harvest control rule.

5. Ramp (Duplisea et al., 2012 ; Eikeset et al., 2013; Wetzel and Punt, 2015; Dichmont et al., 2016; FAO, 2016; Kvamsdal et al., 2016; PEW, 2016; Forrest et al., 2018 ; Deroba et al., 2019; Feeney et al., 2019; Fig. A5)

A ‘ramp’ HCR changes catch as a more complex function of stock biomass, typically with F increasing as biomass increases to some maximum rate. F is set at a constant level when the biomass is above the target biomass reference point and decreases when biomass is less than target level (e.g. 0.5Bmsy). The change in F can differ in steepness, and F does not need to be zero at a certain biomass. Variants of this HCR could be based on different ramp steepness and biomass thresholds (Deroba et al., 2019; Feeney et al., 2019). Ramp HCRs have been applied in management of Alaska crab fisheries, the Norwegian spring spawning herring fishery, the North sea cod fishery (Kvamsdal et al. 2016), the Northeast Arctic cod fishery (Eikeset et al. 2013), groundfish fisheries managed by the Pacific Fishery Management Council (Wetzel and Punt 2015), tuna fisheries managed by regional fisheries management organizations (FAO, 2016; PEW, 2016), and the Atlantic Canadian redfish fishery (Duplisea et al., 2012).

Status in New England groundfish management: This option has not been implemented but has been recommended to incorporate rebuilding plans into ABC control rules.

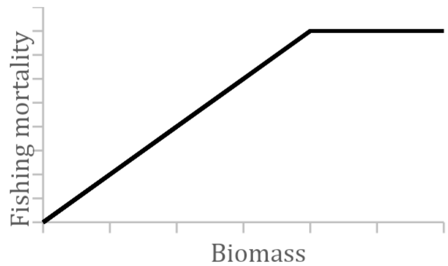

Figure B5. Ramp harvest control rule.

6. P* approach (Prager and Shertzer, 2010)

The P* approach avoids overfishing by accounting for scientific uncertainty with a probabilistic approach (Prager and Shertzer, 2010). The P* method derives target catch as a low percentile of projected catch at the overfishing limit. The level of P* can depend on the level of stock biomass.

Status in New England groundfish management: The P* approach is currently used in the Council's Small Mesh Multispecies FMP.

7. Data-limited (Stobutzki et al., 2001; King and McFarlane, 2003; Jennings, 2005; Little et al., 2011; Geromont and Butterworth, 2015; Jardim et al., 2015)

Data-limited HCRs' harvest typically increases with abundance indices (e.g. CPUE). Catch length composition and survey biomass indices are available for many data-limited stocks. These HCRs are valuable when monitoring and assessment is expensive and when data are scarce (Little et al., 2011). Assessment for data-limited stocks can be based on state indicators (Jennings, 2005), qualitative risk assessments (Stobutzki et al., 2001), and life history characteristics (King and McFarlane, 2003).

Status in New England groundfish management: A wide range of data-limited HCRs are applied for catch advice.

7.1 Based on short-term changes in the abundance index (Jardim et al., 2015)

In the first option, catch is determined from short-term changes in the abundance index. The HCR takes the form: $C_y = C_{y-1} * \alpha$, where *C* is catch in weight and *y* is year. In this option, $\alpha = \frac{\sum_{i=y-2}^{y-1} I_i/2}{\sum_{i=y-5}^{y-3} I_i/3}$, where *I* refers to the abundance index. Jardim et al. (2015) found that this HCR performed poorly, and biomass was at low levels. A similar approach is applied to Georges Bank cod ('Plan B Smooth'; NEFSC, 2019).

7.2 Based on confidence intervals of abundance index (Jardim et al., 2015)

In the second option, catch is determined from confidence intervals of the abundance index. Again, the HCR takes the form: $C_y = C_{y-1} * \alpha$, where *C* is catch in weight and *y* is year. In this option,

$$\alpha = \{\alpha_l \; if \; I_{y-1} < \mu_l + z_{low}\frac{\sigma_l}{\sqrt{n_l}} \; 1 \; if \; \mu_l + z_{low}\frac{\sigma_l}{\sqrt{n_l}} \le I_{y-1} \le \mu_l + z_{upp}\frac{\sigma_l}{\sqrt{n_l}} \; \alpha_u \; if \; I_{y-1} > \mu_l + z_{upp}\frac{\sigma_l}{\sqrt{n_l}}$$

,where μ_l is the mean abundance index, σ_l is the standard deviation of the abundance index, n_l is the length of the time series, z_{low} and z_{upp} are the confidence interval limits (-1.96 and 1.96), and α_l and α_u are catch multipliers (0.75 and 1.25). Jardim et al. (2015) found that his HCR allowed stocks to reach MSY and had low to moderate biological risk.

7.3 Based on historical abundance index (Little et al., 2011)

In the third option, catch is based on averages of catches and abundance indices from a historical period of relative stability. The target abundance reference point is set to the average abundance index during a period of relative stability. The limit abundance reference point is a fraction of the target abundance reference point. The value for the target catch reference point is set to the average catch over the same period. Such historical proxies have been applied to several data-limited groundfish stocks (Applegate et al., 1998).

Harvest control rule reference points

Reference points are the benchmarks that trigger change in management action in the context of a HCR. Below we have outlined a range of different approaches to defining reference points for HCRs.

1. MSY (Restrepo et al., 1998; Mace, 2001 ; Brodziak et al., 2008; Punt, 2010; Hill et al., 2011; PFMC, 2014; Kvamsdal et al., 2016)

Maximum Sustainable Yield (MSY) reference points are based on F that provides the highest long-term yield. Fmsy (the fishing mortality that produces MSY) and Bmsy (the long-term stock size expected from fishing at Fmsy) are the most common target reference points, although they may not be the most economically beneficial option (Punt, 2010). Reliable estimation of these reference points requires either an informative time series of catch and relative stock size indices (Hilborn and Walters, 1992) or information about the stock-recruitment relationship (Punt, 2010). MSY reference points can incorporate environmental effects if an environmental variable, such as sea surface temperature, is included in the stock-recruitment relationship (Hill et al., 2011). In MSY-based HCRs, the target biomass reference point is typically Bmsy and the limit biomass reference point is typically (1-M)Bmsy or 50%Bmsy. The limit fishing mortality reference point is typically Fmsy, and the target fishing morality reference point is typically 0.75Fmsy (Restrepo et al., 1998; NPFMC, 2015). If there is only a target fishing mortality reference point and no limit reference point, then the target fishing mortality reference point is typically Fmsy. MSY-based HCRs have been applied in the management of the Pacific sardine fishery (Hill et al., 2011) and United States west coast groundfish fisheries by the North Pacific Fishery Management Council (PFMC, 2014).

Status in New England groundfish management: MSY-based reference points are used for Georges Bank winter flounder (NEFSC, 2019).

2. SPR (Punt, 2010; PFMC, 2014; Kvamsdal et al., 2016)

Spawning Potential Ratio (SPR) reference points are based on the expected spawning-biomass-per-recruit, given a certain F, fishery selectivity, and other population dynamics parameters (Punt, 2010). In the United States, proxies for Fmsy based on a percentage of unfished spawning-biomass-per-recruit are suggested. Fx% is the long-term F that would result in the spawning-biomass-per-recruit to be x% of unfished spawning-biomass-per-recruit. SPR-based HCRs have been applied in the management of United States west coast groundfish fisheries by the North Pacific Fishery Management Council (F40% or F50% and B40%; Punt, 2010; PFMC, 2014; Kvamsdal et al., 2016).

Status in New England groundfish management: Most groundfish stocks are managed using F40%SPR as a proxy for Fmsy (NEFSC, 2019).

3. B0 (Smith et al., 2008; Punt, 2010; Wetzel and Punt, 2015; Dichmont et al., 2016; Forrest et al., 2018)

B0 reference points are based on unfished spawning biomass. In B0-based HCRs, the target biomass reference point has been 0.4B0 (for rockfish) or 0.25B0 (for flatfish), and the limit biomass reference point has been 0.05B0 (for flatfish), 0.1B0 (for rockfish), or 0.2B0 (Smith et al., 2008; Dichmont et al., 2016; Forrest et al., 2018). B0-based HCRs have been applied in the management of Australia's Southern and Eastern Scalefish and Shark Fishery and the U.S. west coast groundfish fisheries by the Pacific Fishery Management Council (Wetzel and Punt, 2015).

Status in New England groundfish management: These reference points are currently not used.

4. Historical (Forrest et al., 2018)

Historical reference points are based on averages from a particular time period. For example, the target biomass reference point can be the average biomass from the historical period, the limit biomass reference point can be the minimum biomass from which the biomass recovered to an above-average biomass level, and the limit fishing mortality reference point can be the average fishing mortality from the historical period. Such historical proxies have been applied to several data-limited groundfish stocks (Applegate et al., 1998).

Status in New England groundfish management: These reference points are currently not used.

5. Length-based (Cope and Punt, 2009; Geromont and Butterworth, 2015)

In a data-limited fishery, reference points can also be based on catch length compositions.

Status in New England groundfish management: These reference points are currently not used.

6. Ecosystem responsive (Anon., 1998; Basson, 1999; A'mar et al., 2009; Hurtado-Ferro et al., 2010; Punt et al., 2014)

Ecosystem responsive reference points are based on ecosystem needs and thresholds. Temperature is often used as an ecosystem indicator. Reference points can be a function of an environmental variable, such as temperature (Punt et al., 2014). For example, B0 can be derived as a dynamic reference point rather than one based on long-term equilibrium (A'mar et al., 2009). A temperature threshold can also be used as a proxy for regime shifts to switch between alternative HCRs. Ecosystem responsive based HCRs can provide risk-averse management. However, sometimes ecosystem responsive based HCRs do not outperform HCRs that do not account for environmental change (Basson, 1999; A'mar et al., 2009). Ecosystem-responsive-based HCRs have been applied in the management of the Pacific sardine fishery (Anon., 1998).

Status in New England groundfish management: These reference points are currently not used.

Harvest control rule additions

1. Target and limit stock size (Restrepo et al., 1998; Kell et al., 1999; Fig. 6)

Harvest of HCRs with both 'target and limit' stock size changes in response to two different biomass reference points, typically with F at zero below the biomass limit reference point. Target reference points reflect desired states, and limit reference points reflect resource protection (Botsford et al., 2004). Target reference points are often based on risk of exceeding limit reference points (Kell et al., 1999).

Status in New England groundfish management: This option has not been implemented.

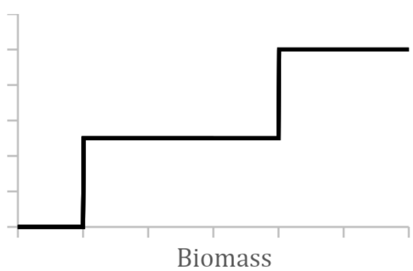

Figure 6. Harvest control rule with target and limit reference points.

2. Target and limit fishing mortality (Restrepo et al., 1998; Kell et al., 1999 ; Goodman et al., 2002; Kvamsdal et al., 2016; Punt et al., 2016 ; Fig. 7)

A target F can be added to any HCR so that F has a low risk of exceeding the limit F (Kell et al., 1999) and can consider social and economic objectives as well (Punt et al., 2016). For example, target F's are used to derive the ABC for US fisheries based on uncertainty in the estimate of Fmsy (Shertzer et al., 2008). Target and limit HCRs have been applied in the management of Alaska groundfish fisheries (Kvamsdal et al., 2016).

Status in New England groundfish management: This option defines the Overfishing Limit (OFL; catch at F_{MSY}) and ABC (catch at 75% F_{MSY}) for most stocks.

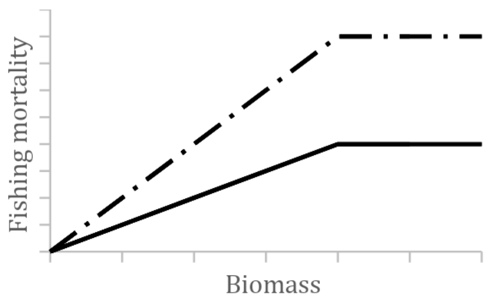

Figure 7. Harvest control rule with target (solid line) and limit (dashed line) fishing mortality reference points

3. Less than 20% variation in catch from year to year (Apostolaki and Hillary, 2009; FAO, 2016; Kvamsdal et al., 2016)

In this addition, the change in catch from year to year is limited to no more than a 20% change. However, the percent change does not always have to be 20%. This addition is useful when reducing catches is difficult, which is often the case in many fisheries. This addition has been applied in the management of the Northeast Arctic cod fishery (10%; Dankel et al., 2016), the Northeast Arctic haddock fishery (25%; Apostolaki and Hillary, 2009), and the skipjack tuna fishery by the Indian Ocean Tuna Commission (30%; FAO, 2016). The New England Fishery Management Councils' risk policy involves catch stability, but such constraints are not included in groundfish HCRs.

Status in New England groundfish management: This option is not currently implemented.

4. Upper limit on catch (PFMC, 2014)

In this addition, the catch that results from the HCR can never be higher than a specified limit. This addition has been applied in the management of the Pacific sardine fishery (PFMC, 2014).

Status in New England groundfish management: This option is not currently implemented.

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Evaluation of Alternative Harvest Control Rules for New England Groundfish

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Tables and Figures

Table 1. Summary of operating model and stock assessment misspecification scenarios, retrospective adjustment scenarios, stock assessment frequencies, and harvest control rule alternatives simulated in this study.

Category	Scenarios	Purpose
Operating model and stock assessment misspecification scenarios	Base Case for a Stock that is Overfished	To emulate a groundfish stock in poor status
	Base Case for a Stock that is Not Overfished	To emulate a groundfish stock in good status with large recruitment events
	Natural Mortality Misspecification for a Stock that is Overfished	To emulate a groundfish stock in poor status with a natural mortality stock assessment misspecification
	Recruitment Misspecification for a Stock that is Overfished	To emulate a groundfish stock in poor status with a recruitment stock assessment misspecification
	Survey Catchability Misspecification for a Stock that is Not Overfished	To emulate a groundfish stock in good status with a survey catchability stock assessment misspecification
Retrospective adjustment scenarios	Retrospective Adjustment Scenario 1	To not apply retrospective adjustments
	Retrospective Adjustment 2	To apply retrospective adjustments
Frequency scenarios	Frequency Scenario 1	To apply 2-year projections which are currently used for New England groundfish
	Frequency Scenario 2	To apply 1-year projections
Harvest control rule alternatives	Ramp	To emulate a ramped harvest control rule, which promotes rebuilding and optimal yield
	P*	To emulate the P* method, which avoids overfishing by accounting for uncertainty with a probabilistic approach
	F-step	To emulate a step in fishing mortality (between 75% F_{MSY} and 70% F_{MSY}) harvest control rule, which has recently been applied to some New England groundfish
	Constrained ramp	To emulate a ramped harvest control rule that includes a catch variation constraint

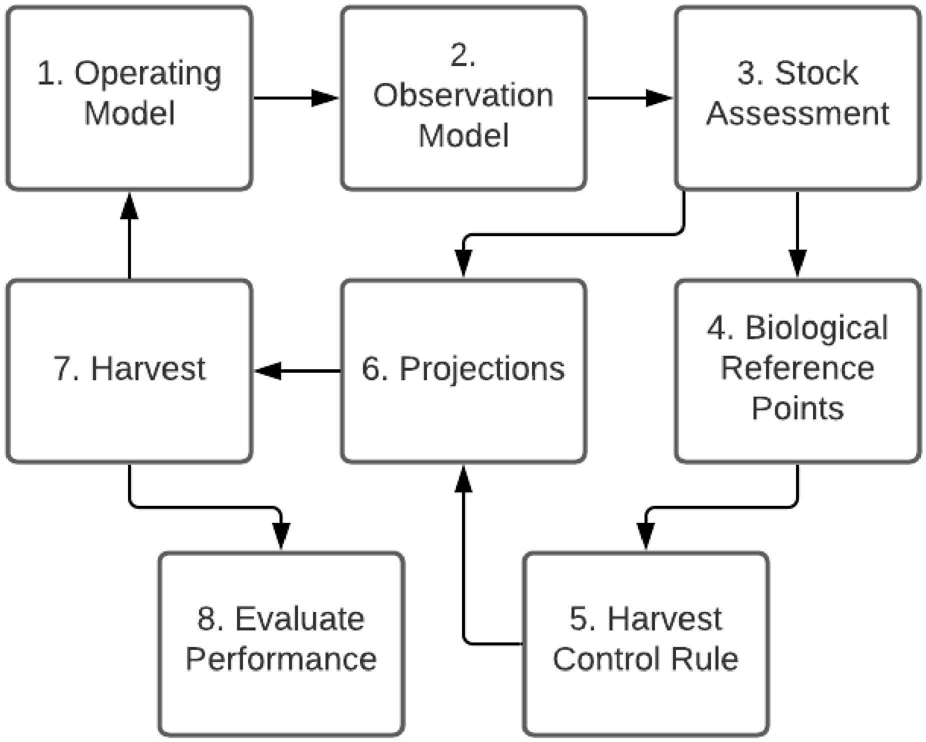


Figure 1. The management strategy evaluation framework used in this project.

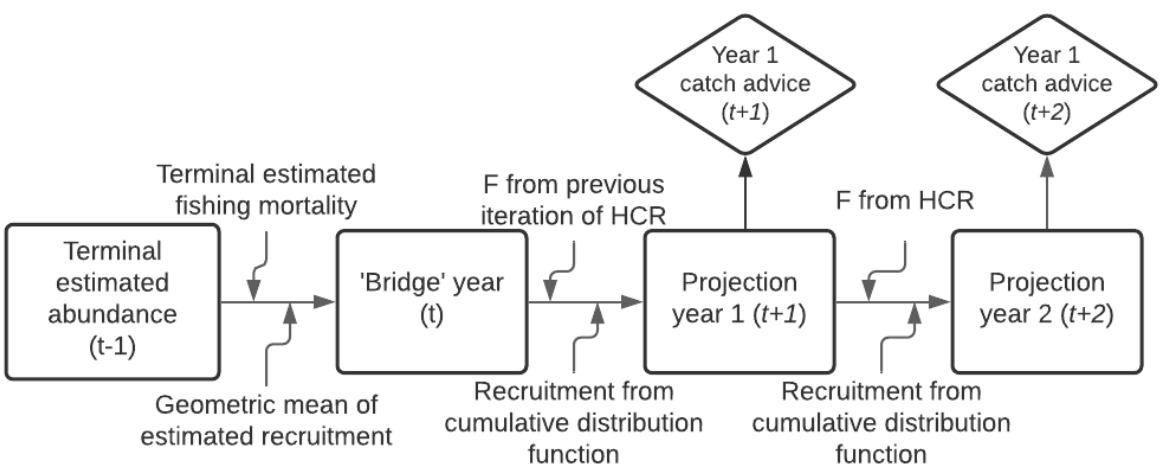


Figure 2. Projection process with a two-year stock assessment update frequency. *t-1* = terminal year of assessment, *t* = current year, *t+1* = next year, *t+2* = year after next year.

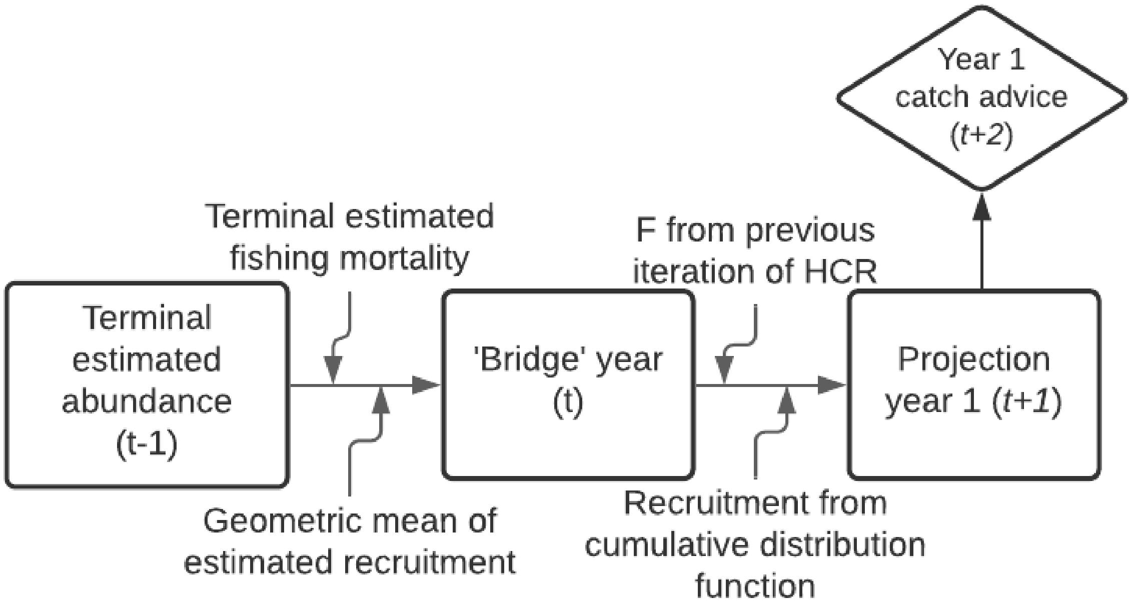


Figure 3. Projection process with a one-year stock assessment update frequency. *t-1* = terminal year of assessment, *t* = current year, *t+1* = next year.

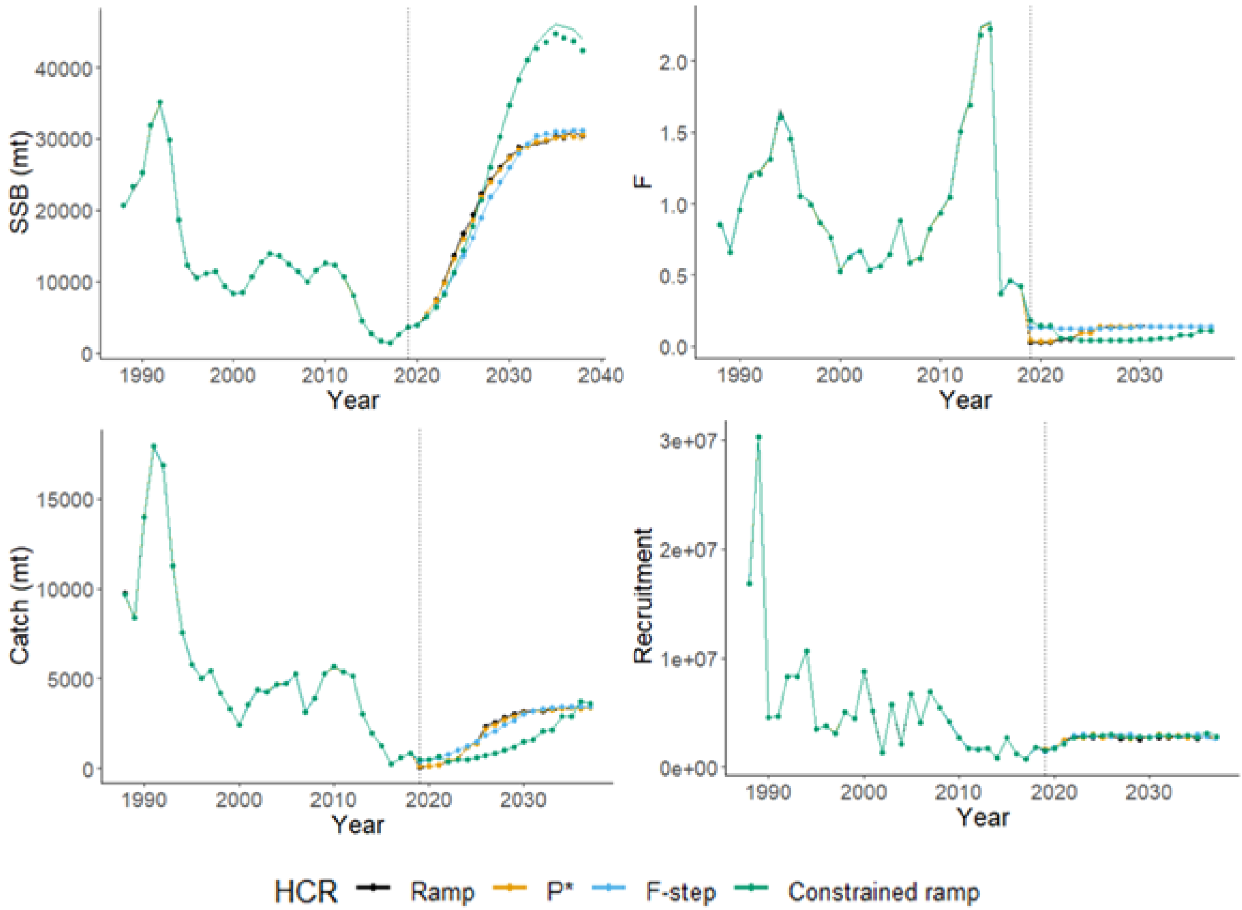


Figure 4. True operating model (closed circles) and estimated stock assessment values from the terminal assessment (stock assessment completed in 2039 with a terminal year of 2038; lines) of spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits for Gulf of Maine cod with no stock assessment model misspecification (Base Case for a Stock that is Overfished) from 1982 to 2038 for SSB and to 2037 for other metrics. The dashed line represents the beginning of the management procedure period (2019).

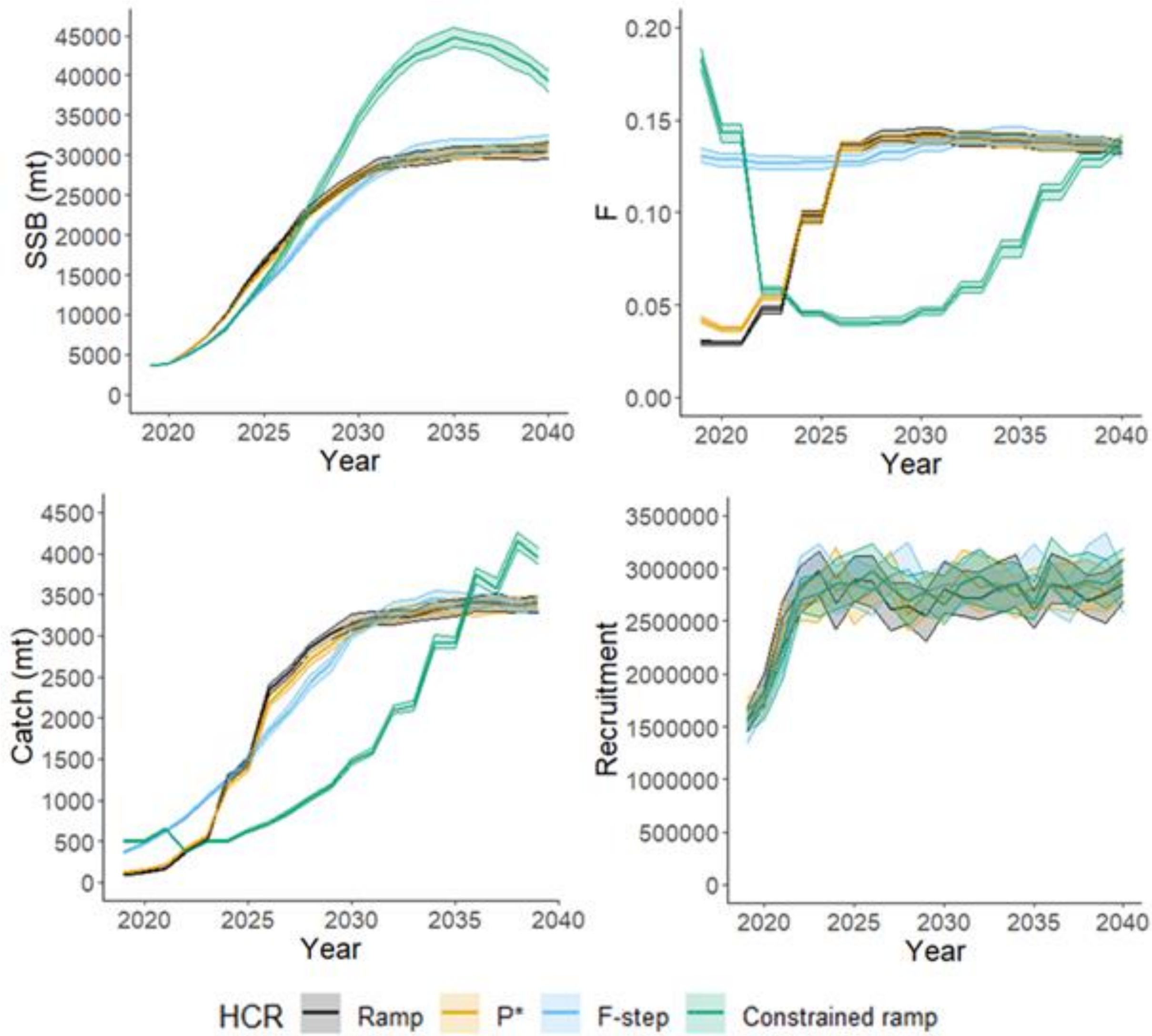


Figure 5. True operating model median spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits with 95% confidence intervals for Gulf of Maine cod with no stock assessment model misspecification (Base Case for a Stock that is Overfished) from 2019 to 2040.

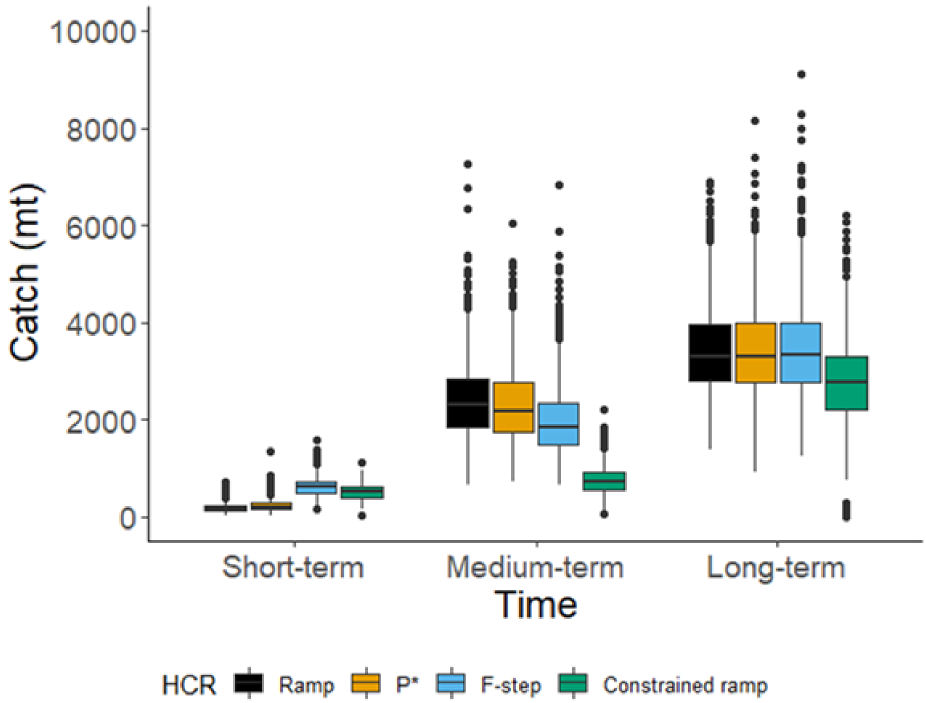


Figure 6. True median catch for Gulf of Maine cod with no stock assessment model misspecification (Base Case for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

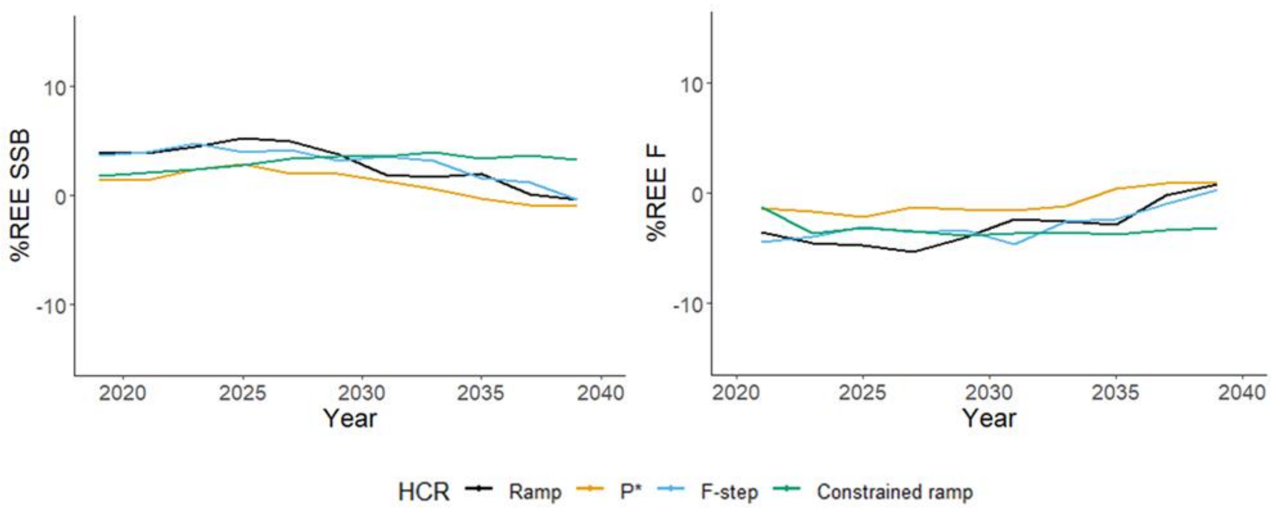


Figure 7. Percent relative error (REE) in terminal estimated spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with no stock assessment model misspecification (Base Case for a Stock that is Overfished).

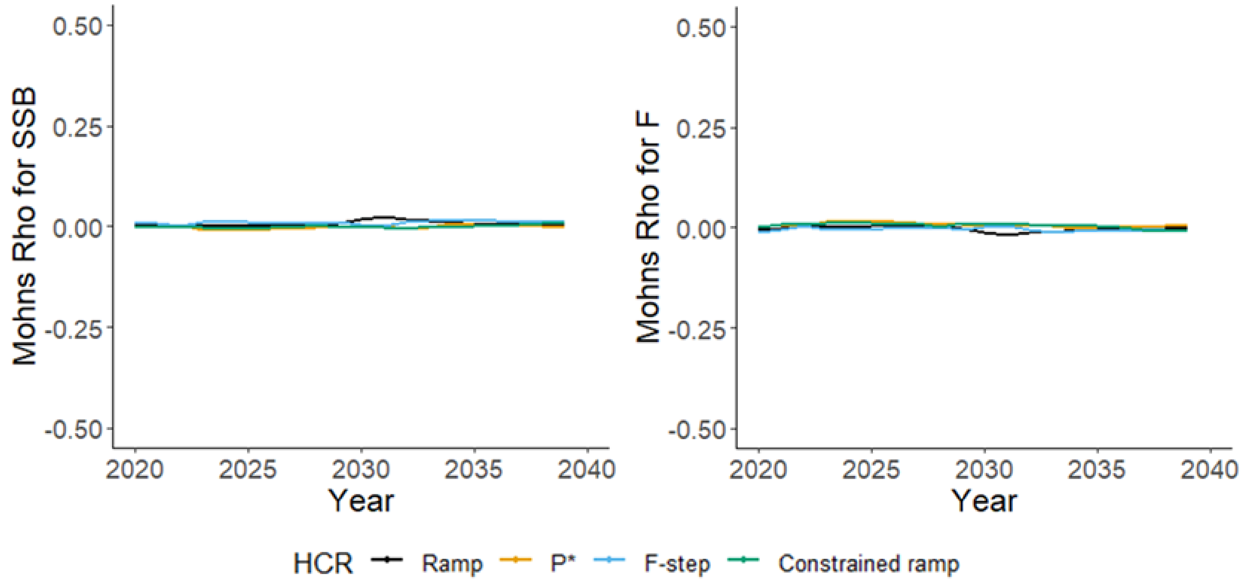


Figure 8. Mohn's Rho values for spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with no stock assessment model misspecification (Base Case for a Stock that is Overfished).

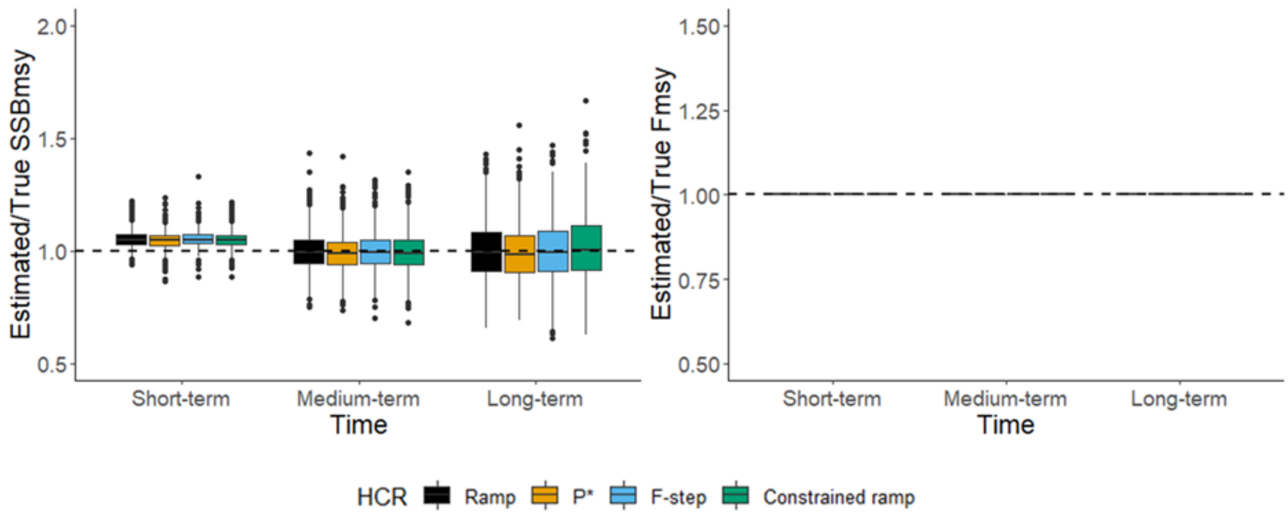


Figure 9. Median ratios of estimated to true stock biomass reference point (SSB_{MSY}) and fishing mortality biomass reference point (F_{MSY}) for Gulf of Maine cod with no stock assessment model misspecification (Base Case for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

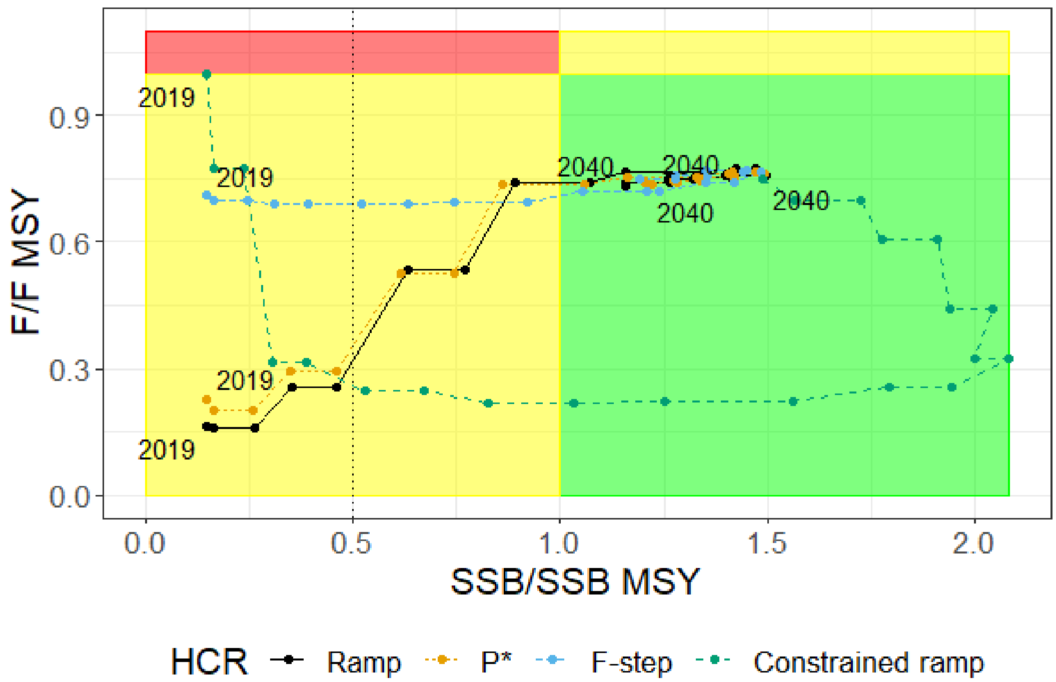


Figure 10. True stock status trajectories (ratio of fishing mortality to the fishing mortality reference point (F/F$_{MSY}$) versus ratio of spawning stock biomass to the spawning stock biomass reference point (SSB/SSB$_{MSY}$)) for Gulf of Maine cod with no stock assessment model misspecification (Base Case for a Stock that is Overfished). The dashed line represents the overfished threshold.

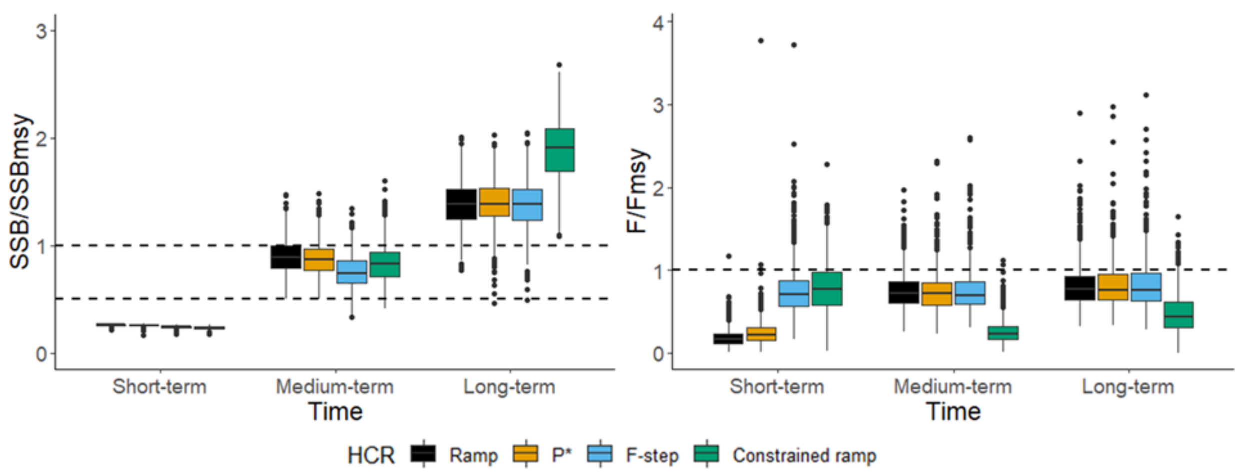


Figure 11. True median ratios of spawning stock biomass to the spawning stock biomass reference point (SSB/SSB$_{MSY}$) and fishing mortality to the fishing mortality biomass reference point (F/F$_{MSY}$) for Gulf of Maine cod with no stock assessment model misspecification (Base Case for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

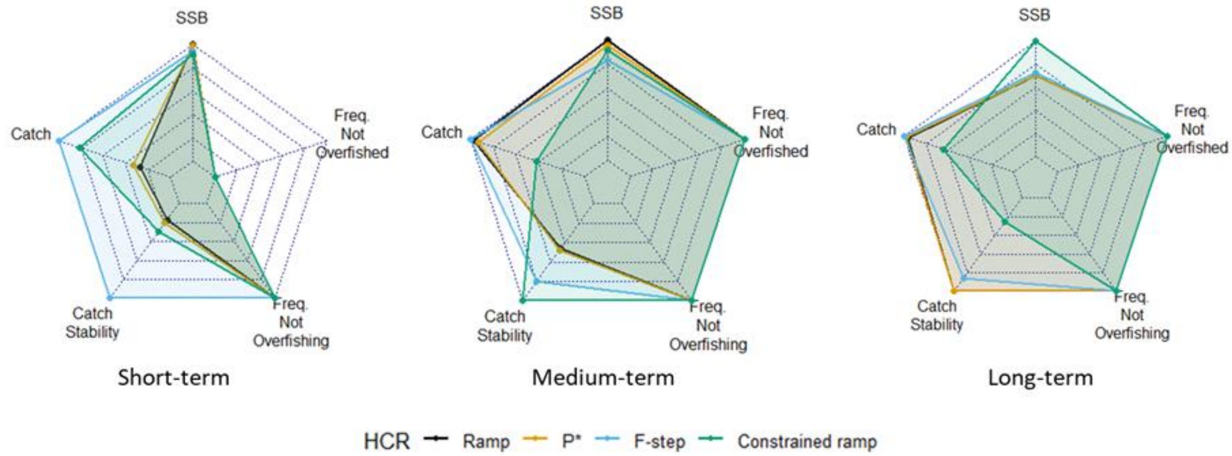


Figure 12. Harvest control rule (HCR) performance for Gulf of Maine cod with no stock assessment model misspecification (Base Case for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years). Metrics are standardized to the maximum value for each metric attained by the different HCRs and equally weighted. Spawning stock biomass (SSB) and catch are median SSB and catch for the time period.

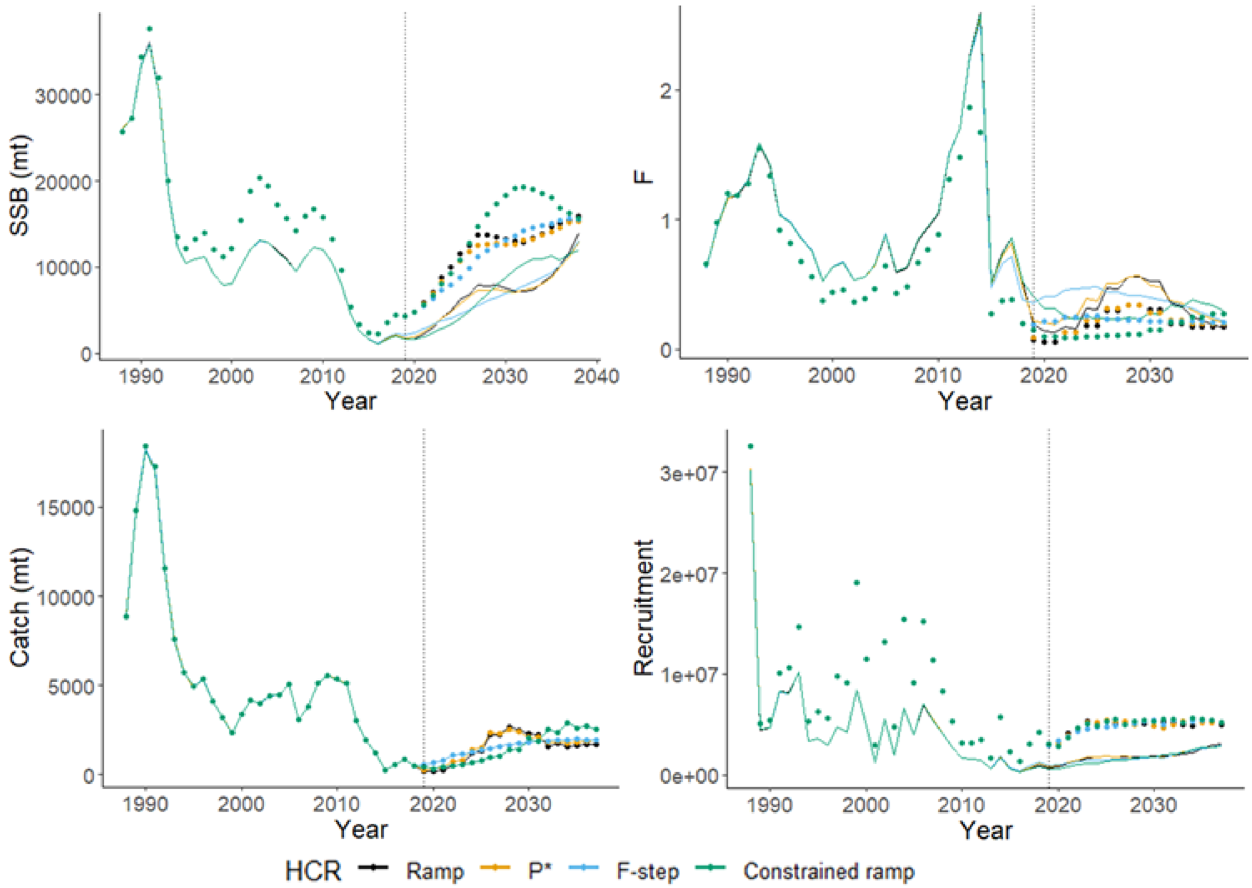


Figure 13. True operating model (closed circles) and estimated stock assessment values from the terminal assessment (stock assessment completed in 2039 with a terminal year of 2038; lines) of spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits for Gulf of Maine cod with a natural mortality stock assessment model misspecification (Natural Mortality Misspecification for a Stock that is Overfished) from 1982 to 2038 for SSB and 2037 for other metrics. The dashed line represents the beginning of the management procedure period (2019).

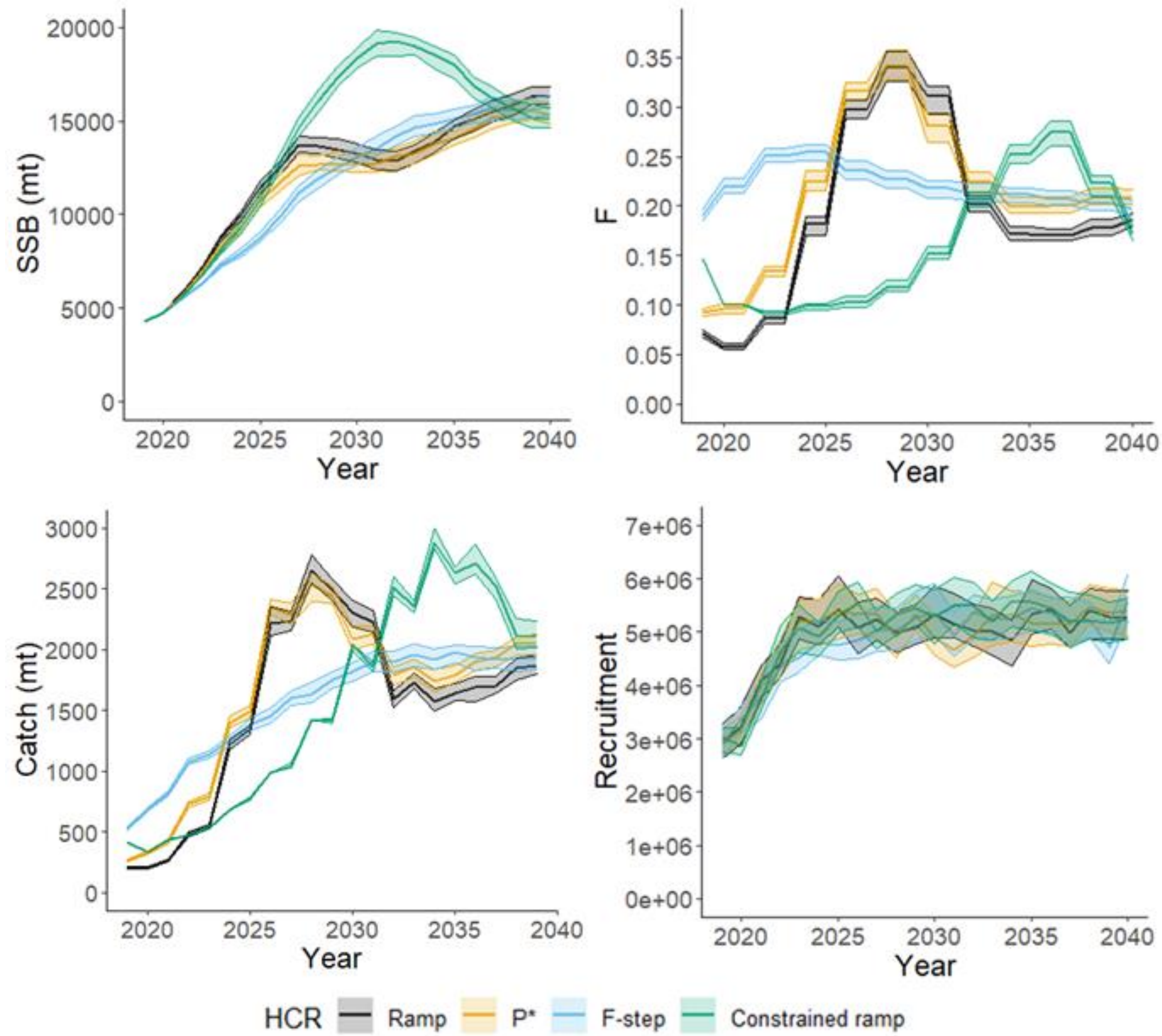


Figure 14. True operating model median spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits with 95% confidence intervals for Gulf of Maine cod with a natural mortality stock assessment model misspecification (Natural Mortality Misspecification for a Stock that is Overfished) from 2019 to 2040.

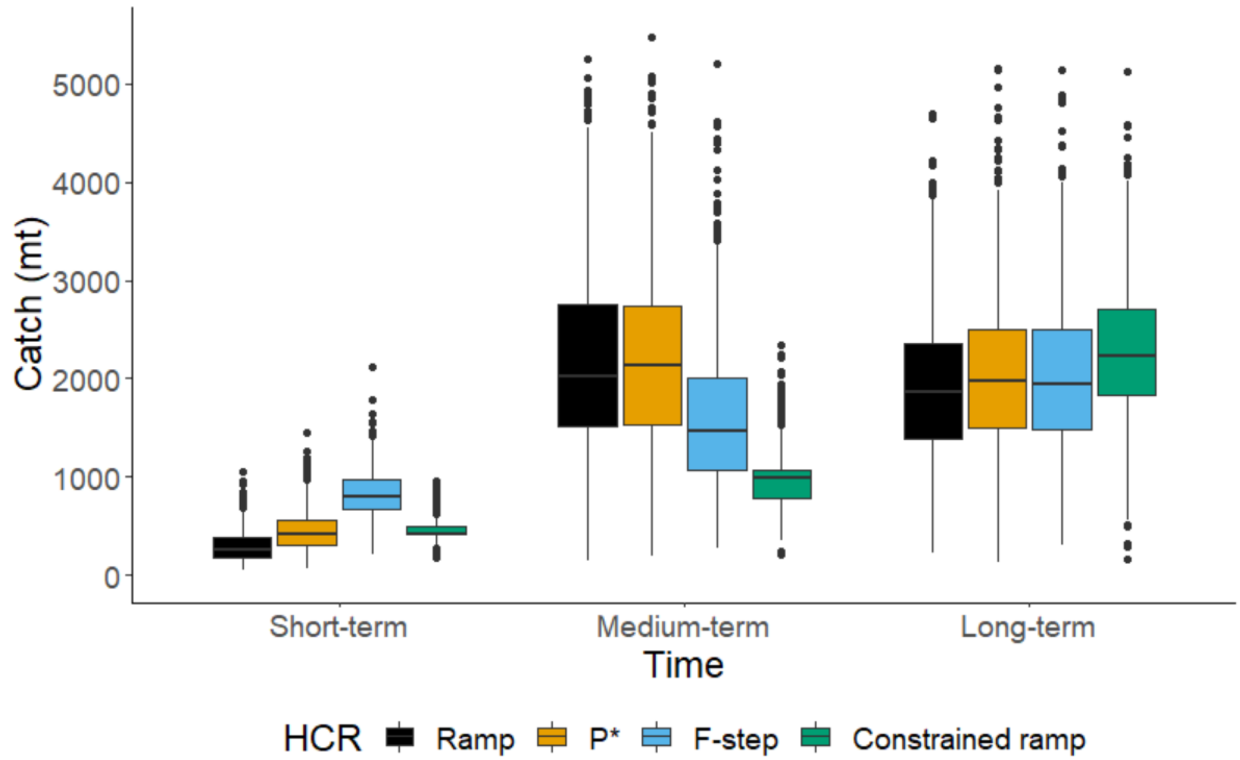


Figure 15. True median catch for Gulf of Maine cod with a natural mortality stock assessment model misspecification (Natural Mortality Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

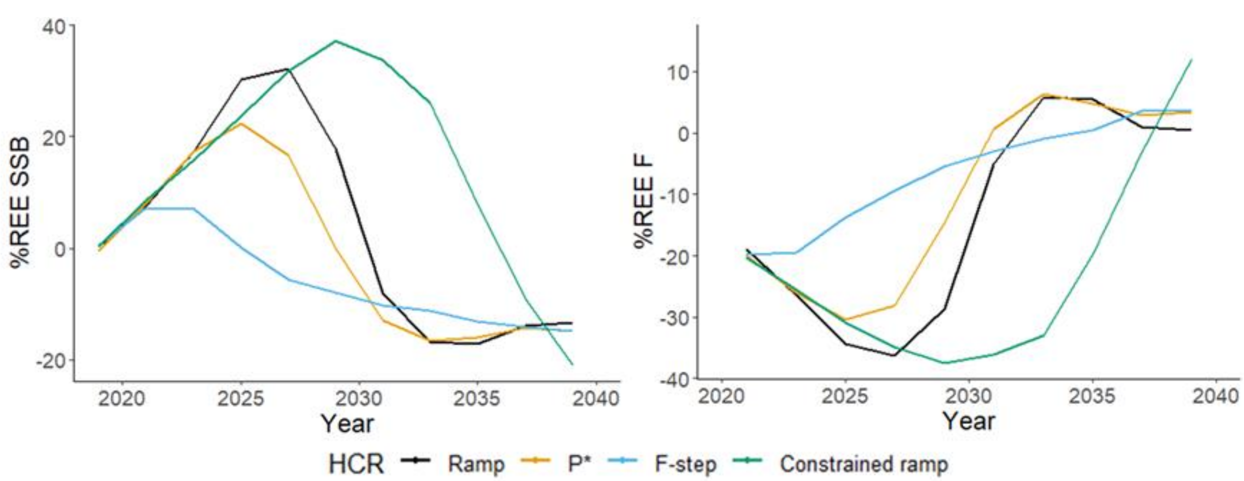


Figure 16. Percent relative error (REE) in terminal estimated spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a natural mortality stock assessment model misspecification (Natural Mortality Misspecification for a Stock that is Overfished).

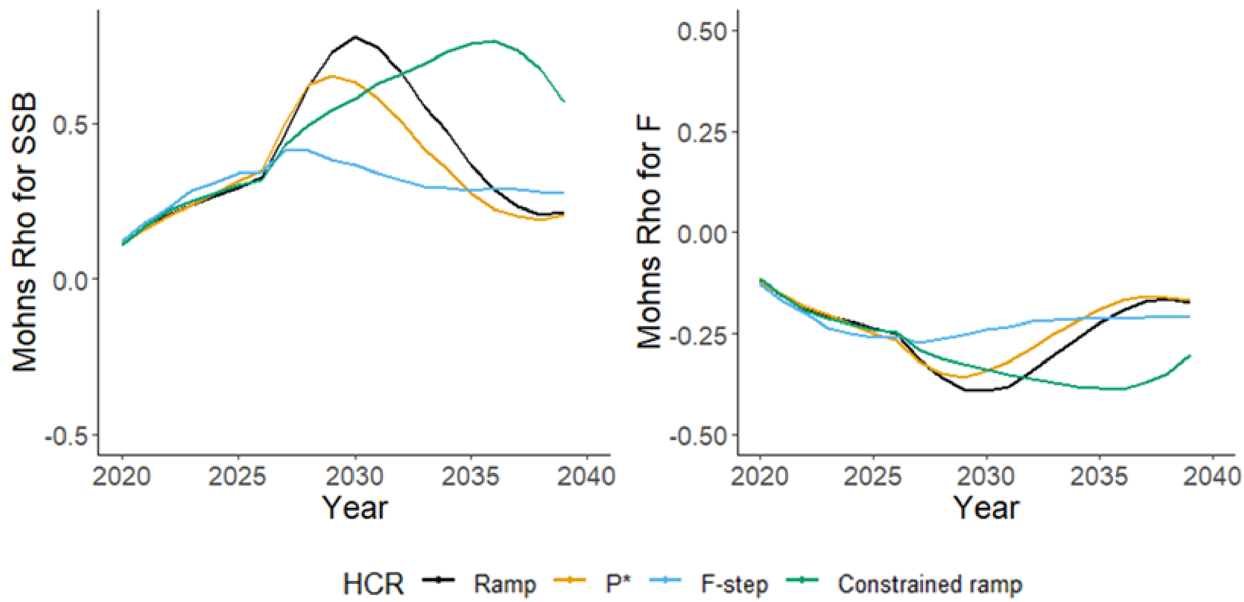


Figure 17. Mohn's Rho values for spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a natural mortality stock assessment model misspecification (Natural Mortality Misspecification for a Stock that is Overfished).

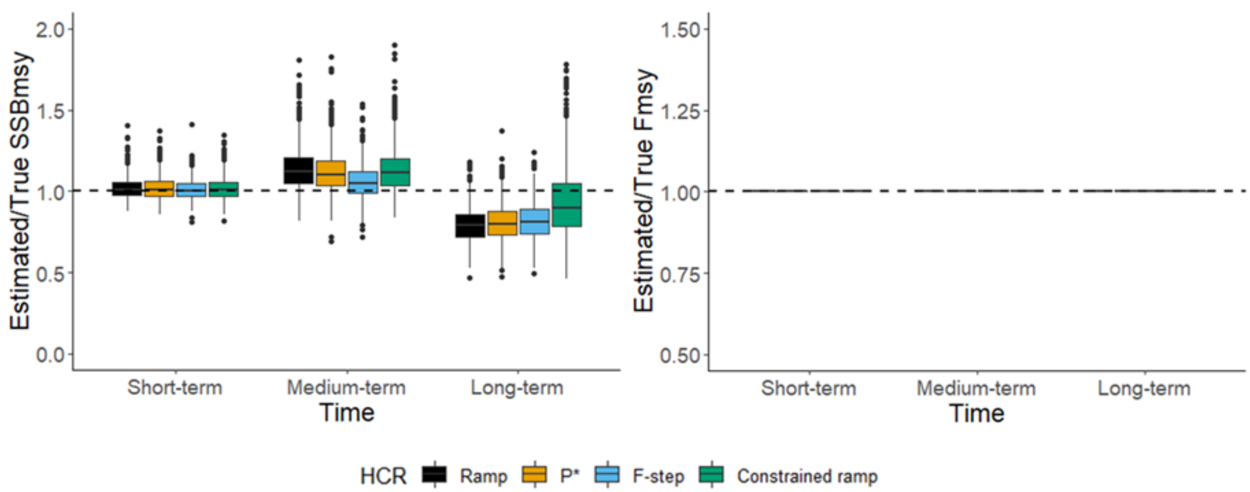
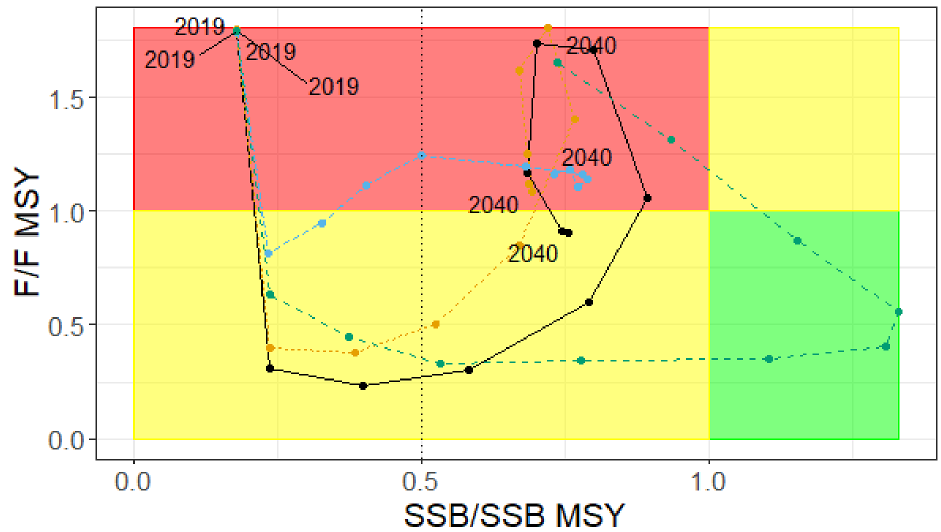


Figure 18. Median ratios of estimated to true stock biomass reference point (SSB_{MSY}) and fishing mortality biomass reference point (F_{MSY}) for Gulf of Maine cod with a natural mortality stock assessment model misspecification (Natural Mortality Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

a



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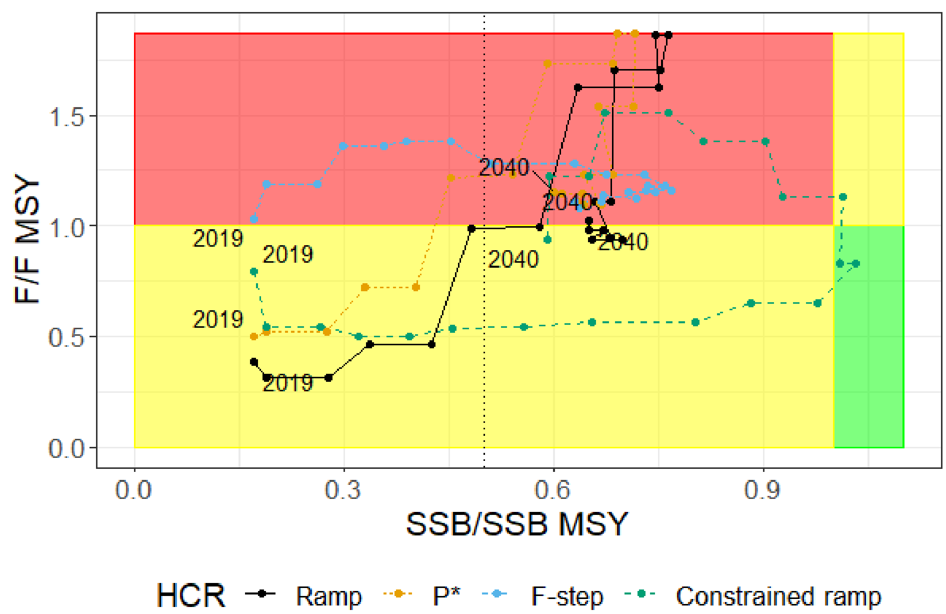


Figure 19. a) Estimated terminal stock status of each year's stock assessment relative to M=0.2 reference points (F/F_{MSY} and SSB/SSB_{MSY}), b) True stock status relative to M=0.2 reference points for Gulf of Maine cod with a natural mortality stock assessment model misspecification (Natural Mortality Misspecification for a Stock that is Overfished). The dashed line represents the overfished threshold. Estimated terminal stock status is lagged behind a year (the last year of data is from the previous year).

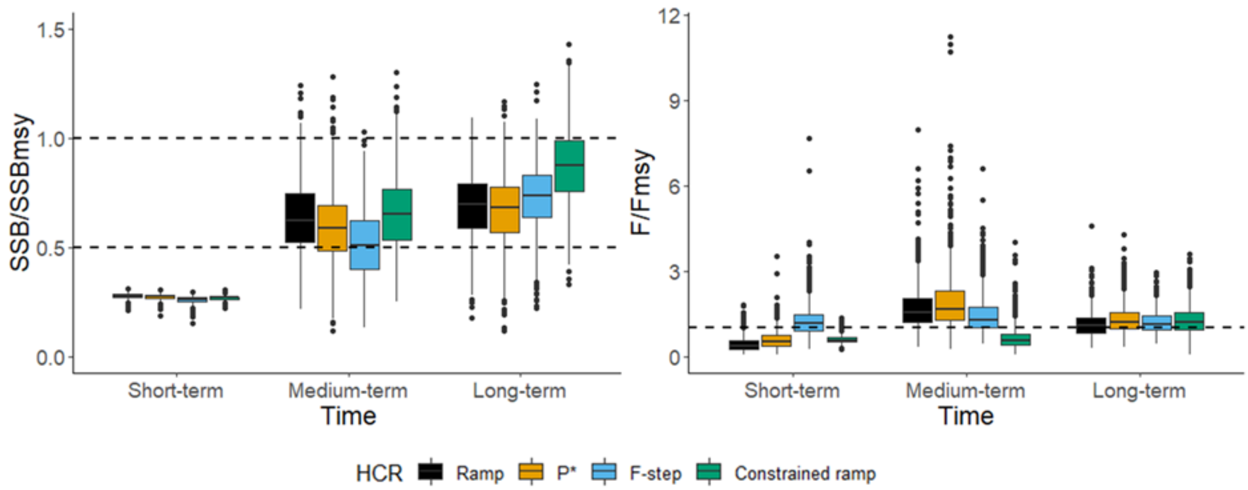


Figure 20. True median ratios of spawning stock biomass to the spawning stock biomass reference point (SSB/SSB$_{MSY}$) and fishing mortality to the fishing mortality biomass reference point (F/F$_{MSY}$) for Gulf of Maine cod with a natural mortality stock assessment model misspecification (Natural Mortality Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (5-10 years), and long-term (10-20 years).

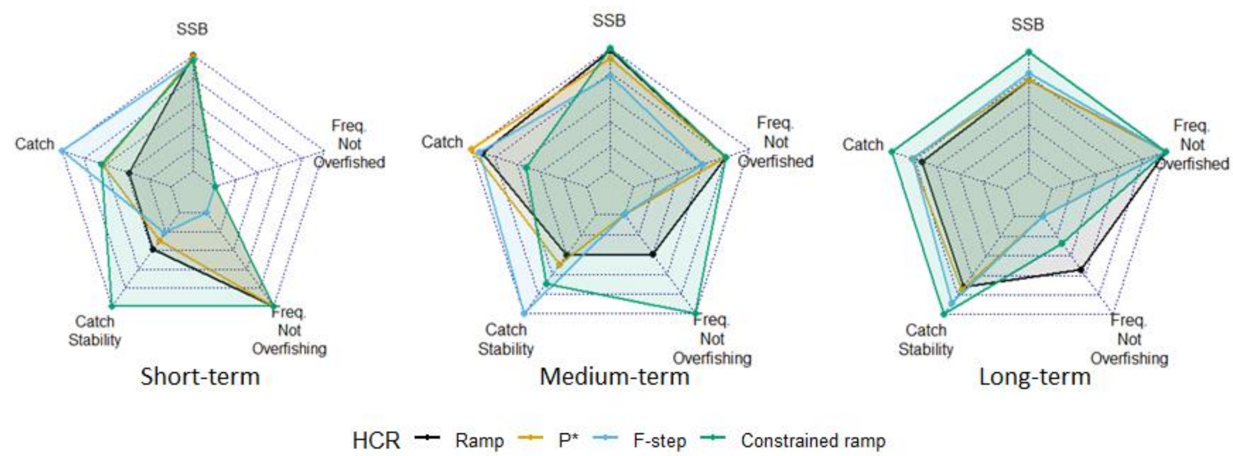


Figure 21. Harvest control rule (HCR) performance for Gulf of Maine cod with a natural mortality stock assessment model misspecification (Natural Mortality Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-20 years). Metrics are standardized to the maximum value for each metric attained by the different HCRs and equally weighted. Spawning stock biomass (SSB) and catch are median SSB and catch for the time period.

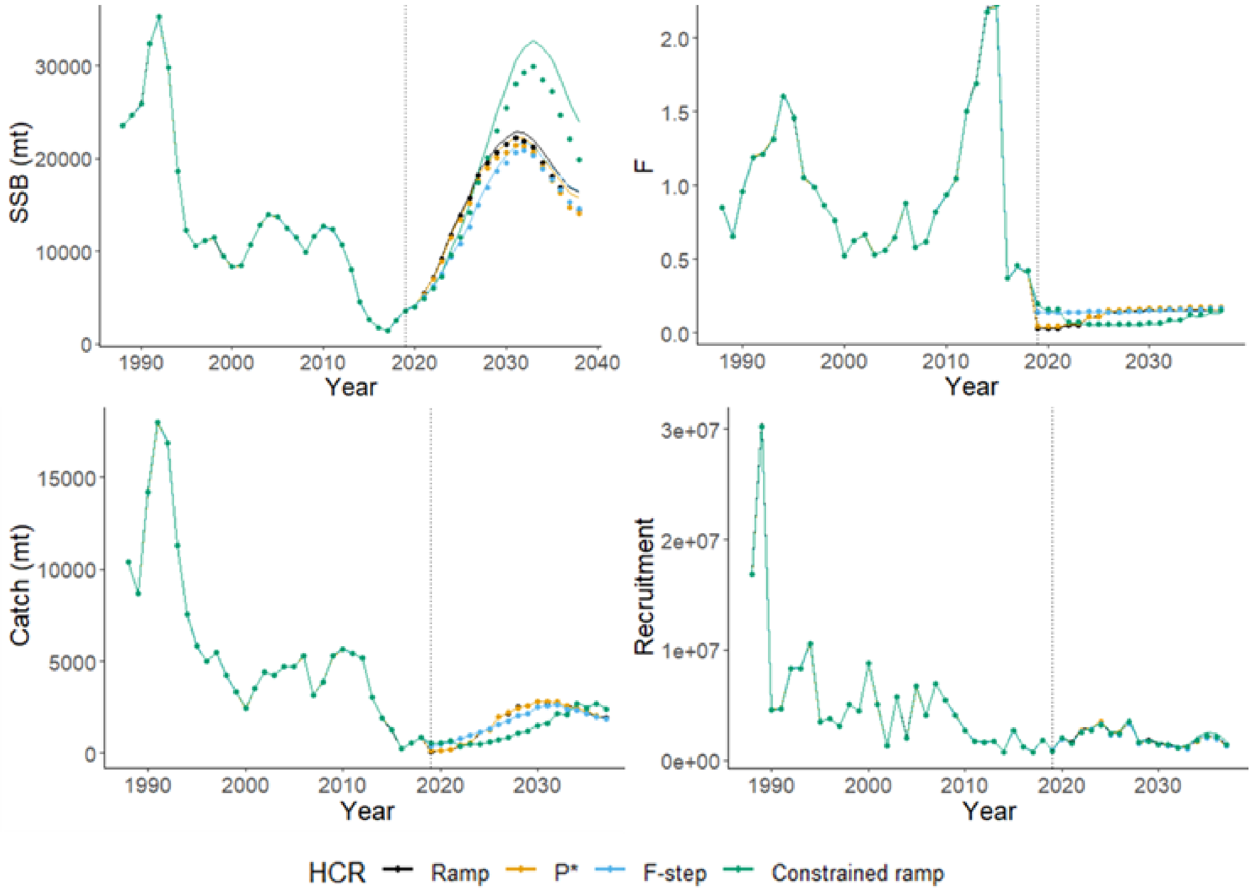


Figure 22. True operating model (closed circles) and estimated stock assessment values from the terminal assessment (stock assessment completed in 2039 with a terminal year of 2038; lines) of spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits for Gulf of Maine cod with a recruitment stock assessment model misspecification (Recruitment Misspecification for a Stock that is Overfished) from 1982 to 2038 for SSB and 2037 for other metrics. The dashed line represents the beginning of the management procedure period (2019).

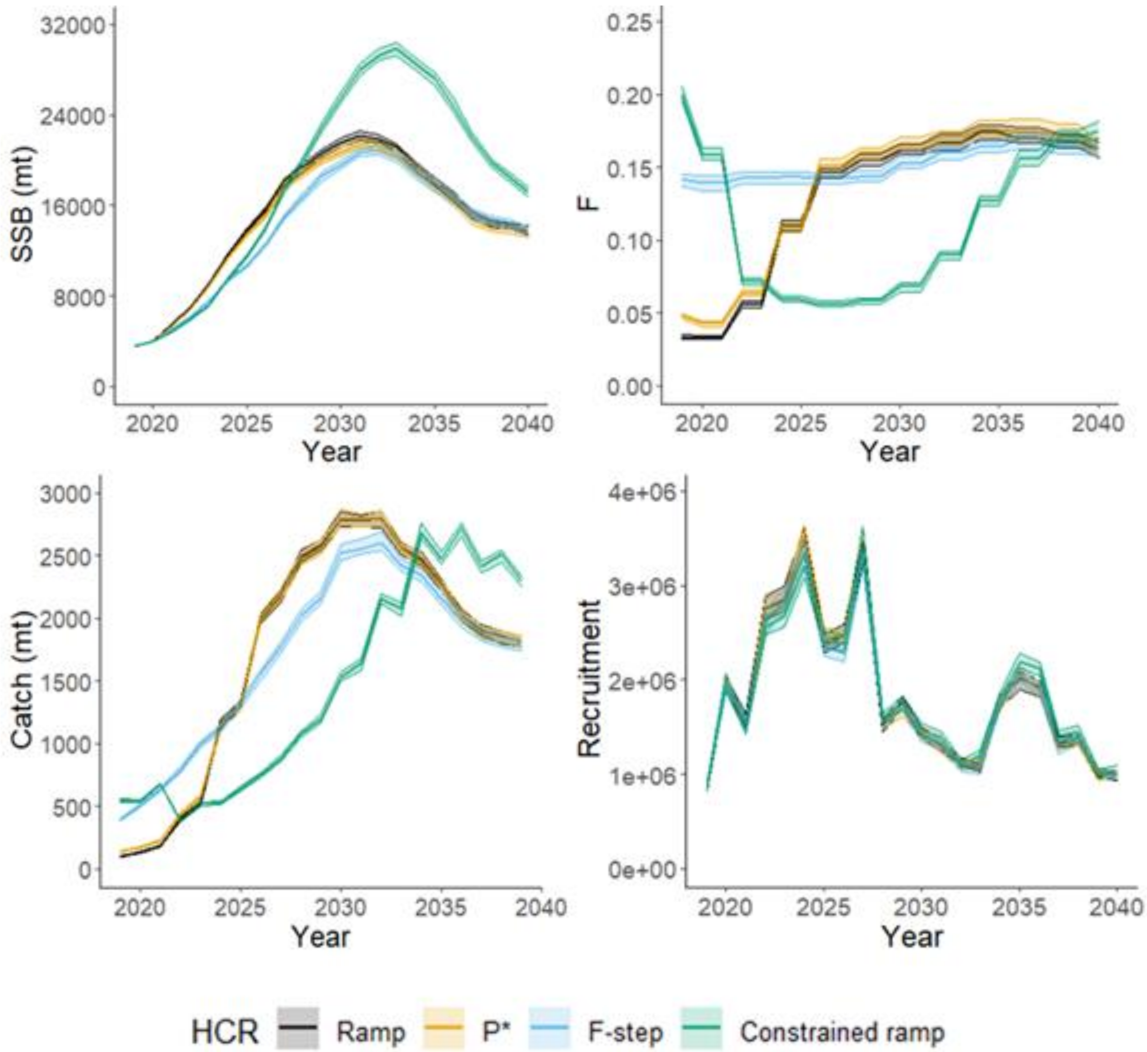


Figure 23. True operating model median spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits with 95% confidence intervals for Gulf of Maine cod with a recruitment stock assessment model misspecification (Recruitment Misspecification for a Stock that is Overfished) from 2019 to 2040.

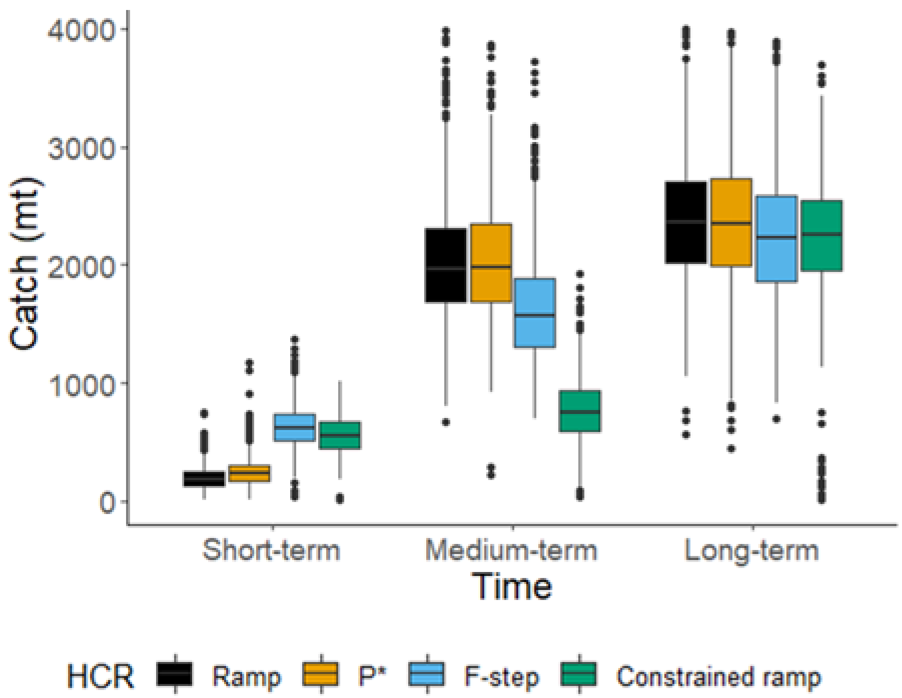


Figure 24. True median catch for Gulf of Maine cod with a recruitment stock assessment model misspecification (Recruitment Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (5-10 years), and long-term (10-20 years).

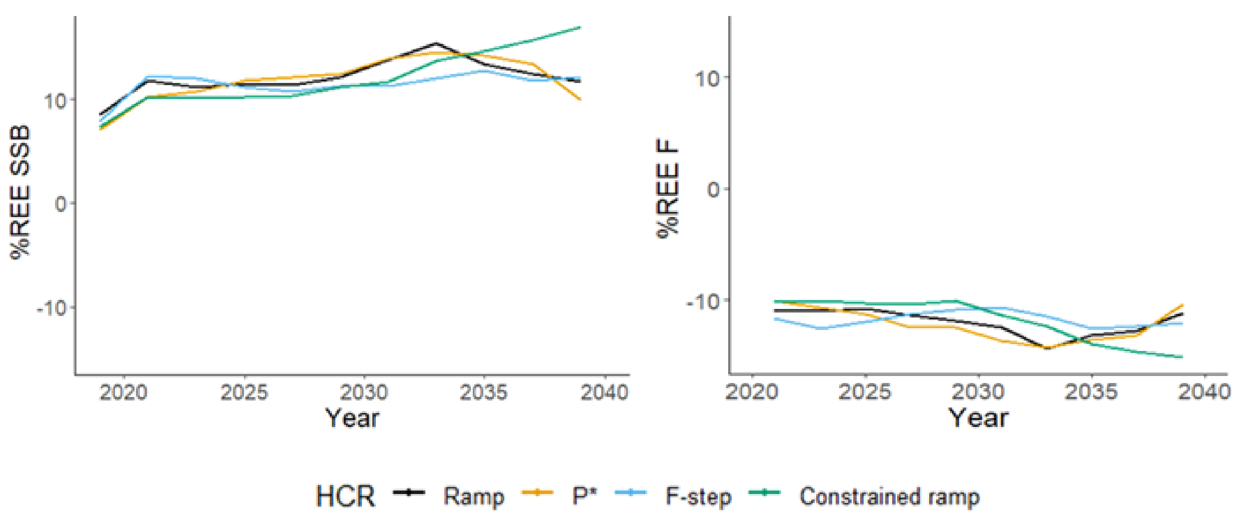


Figure 25. Percent relative error (REE) in terminal estimated spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a recruitment stock assessment model misspecification (Recruitment Misspecification for a Stock that is Overfished).

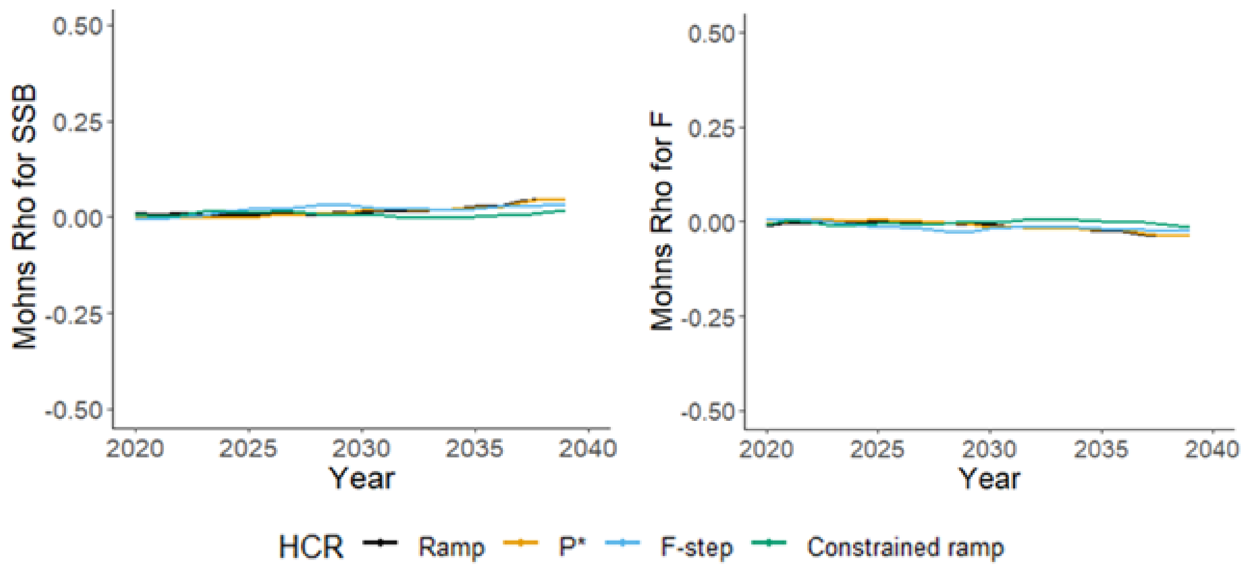


Figure 26. Mohn's Rho values for spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a recruitment stock assessment model misspecification (Recruitment Misspecification for a Stock that is Overfished).

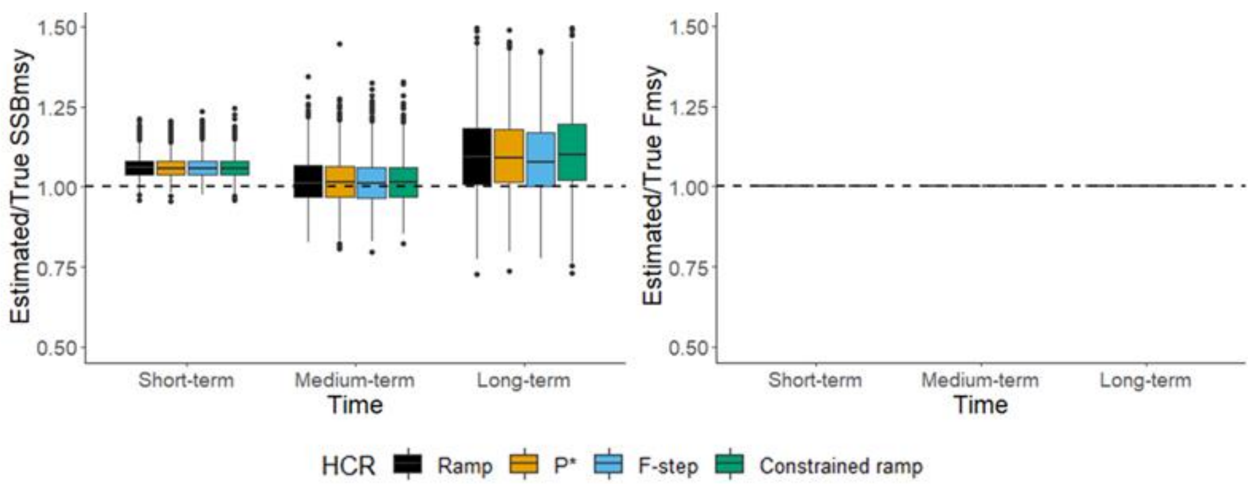


Figure 27. Median ratios of estimated to true ratios of the stock biomass reference point (SSB_{MSY}) and fishing mortality biomass reference point (F_{MSY}) for a stock originally undergoing overfishing and overfished (Gulf of Maine cod) with a recruitment stock assessment model misspecification (Recruitment Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (5-10 years), and long-term (10-20 years).

a

b

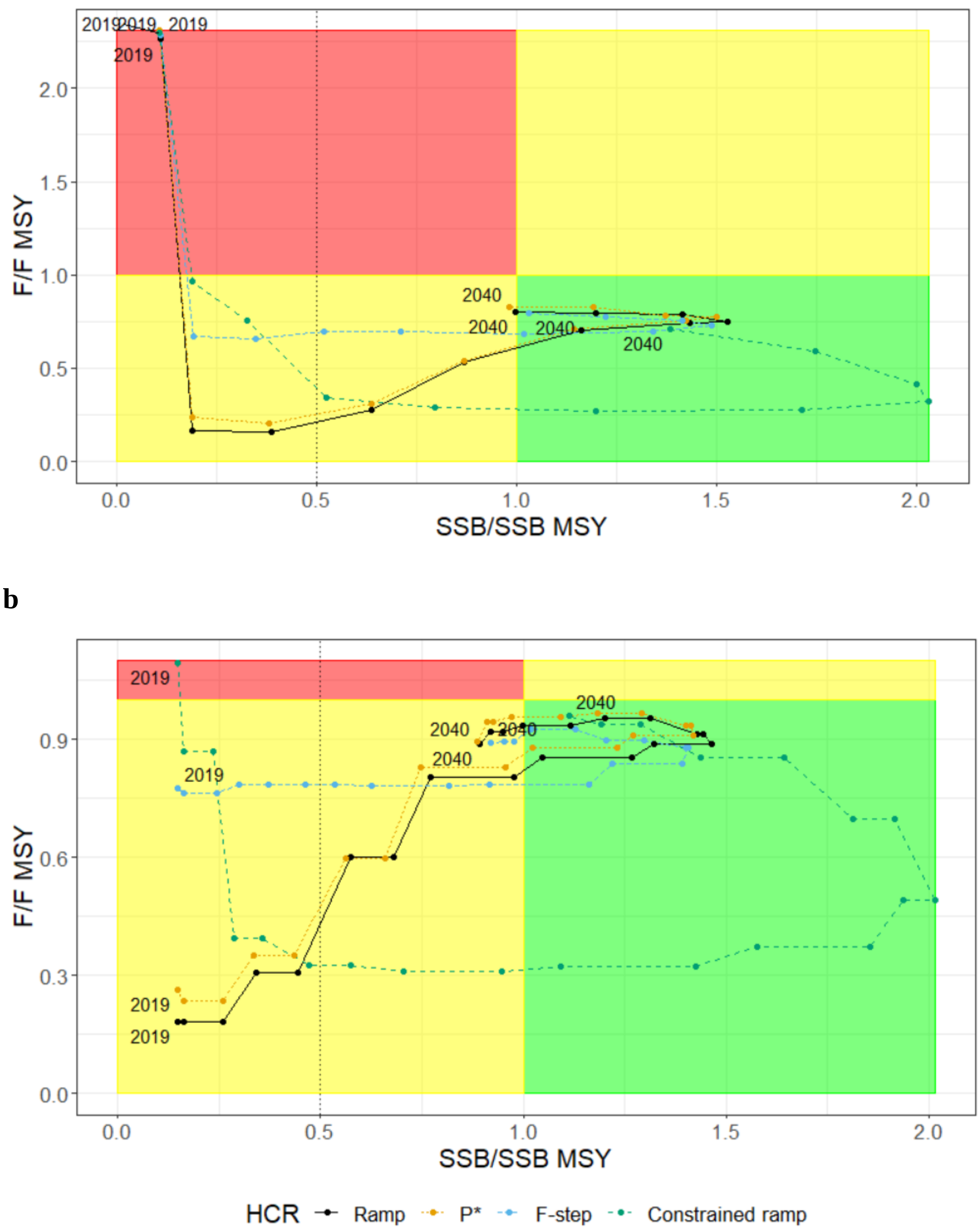


Figure 28. a) Estimated terminal stock status of each year's stock assessment relative to M=0.2 reference points (F/F_{MSY} and SSB/SSB_{MSY}), b) True stock status relative to M=0.2 reference points for Gulf of Maine cod with a recruitment stock assessment model misspecification (Recruitment Misspecification for a Stock that is Overfished). The dashed line represents the overfished threshold. Estimated terminal stock status is lagged behind a year (the last year of data is from the previous year).

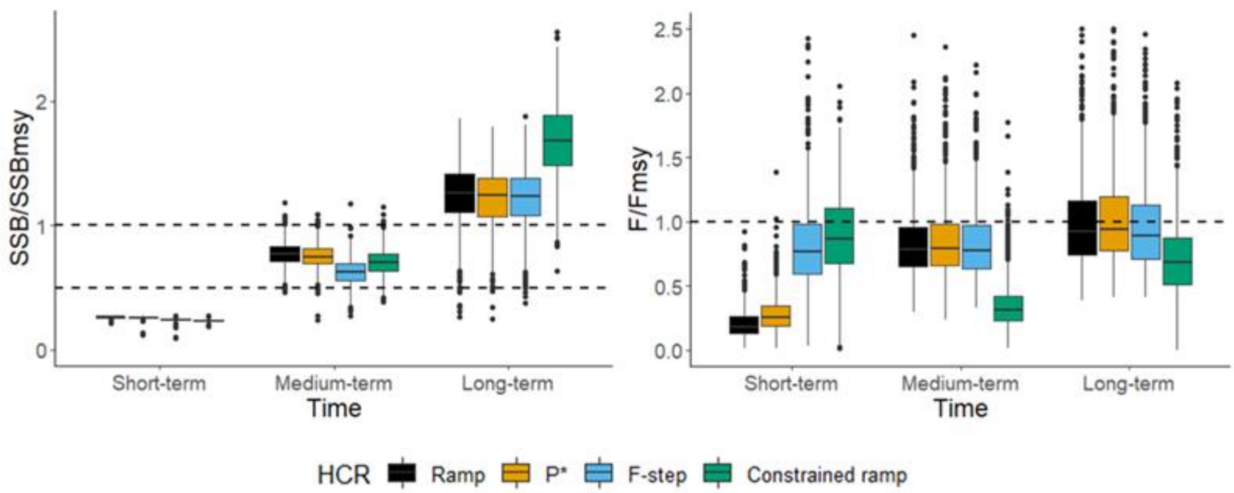


Figure 29. True median ratios of spawning stock biomass to the spawning stock biomass reference point (SSB/SSB_{MSY}) and fishing mortality to the fishing mortality biomass reference point (F/F_{MSY}) for Gulf of Maine cod with a recruitment stock assessment model misspecification (Recruitment Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (5-10 years), and long-term (10-20 years).

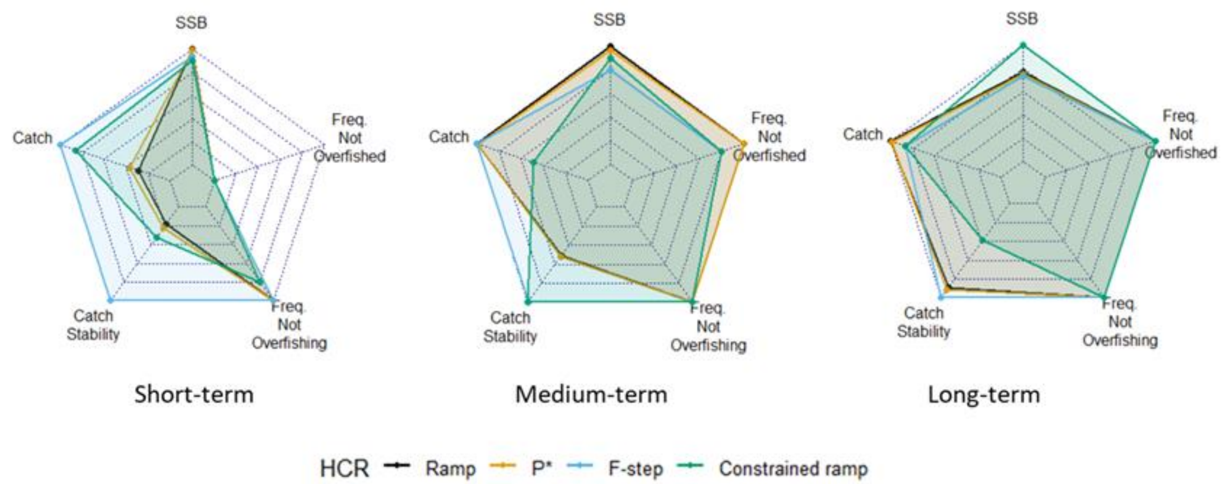


Figure 30. Harvest control rule (HCR) performance for Gulf of Maine cod with a recruitment stock assessment model misspecification (Recruitment Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (10-20 years). Metrics are standardized to the maximum value for each metric attained by the different HCRs and equally weighted. Spawning stock biomass (SSB) and catch are median SSB and catch for the time period.

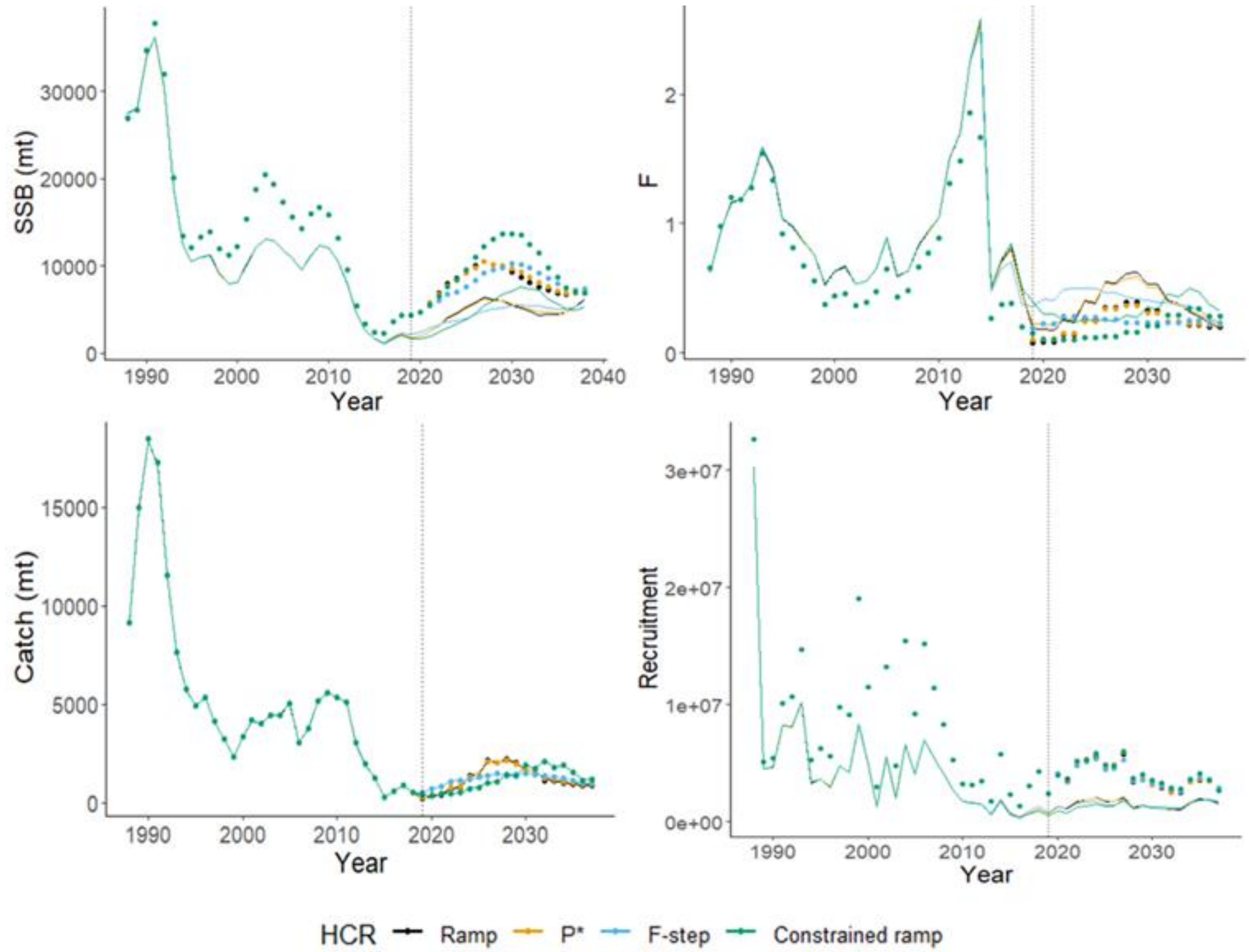


Figure 31. True operating model (closed circles) and estimated stock assessment values from the terminal assessment (stock assessment completed in 2039 with a terminal year of 2038; lines) of spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification (Natural Mortality and Recruitment Misspecification for a Stock that is Overfished) from 1982 to 2038 for SSB and 2037 for other metrics. The dashed line represents the beginning of the management procedure period (2019).

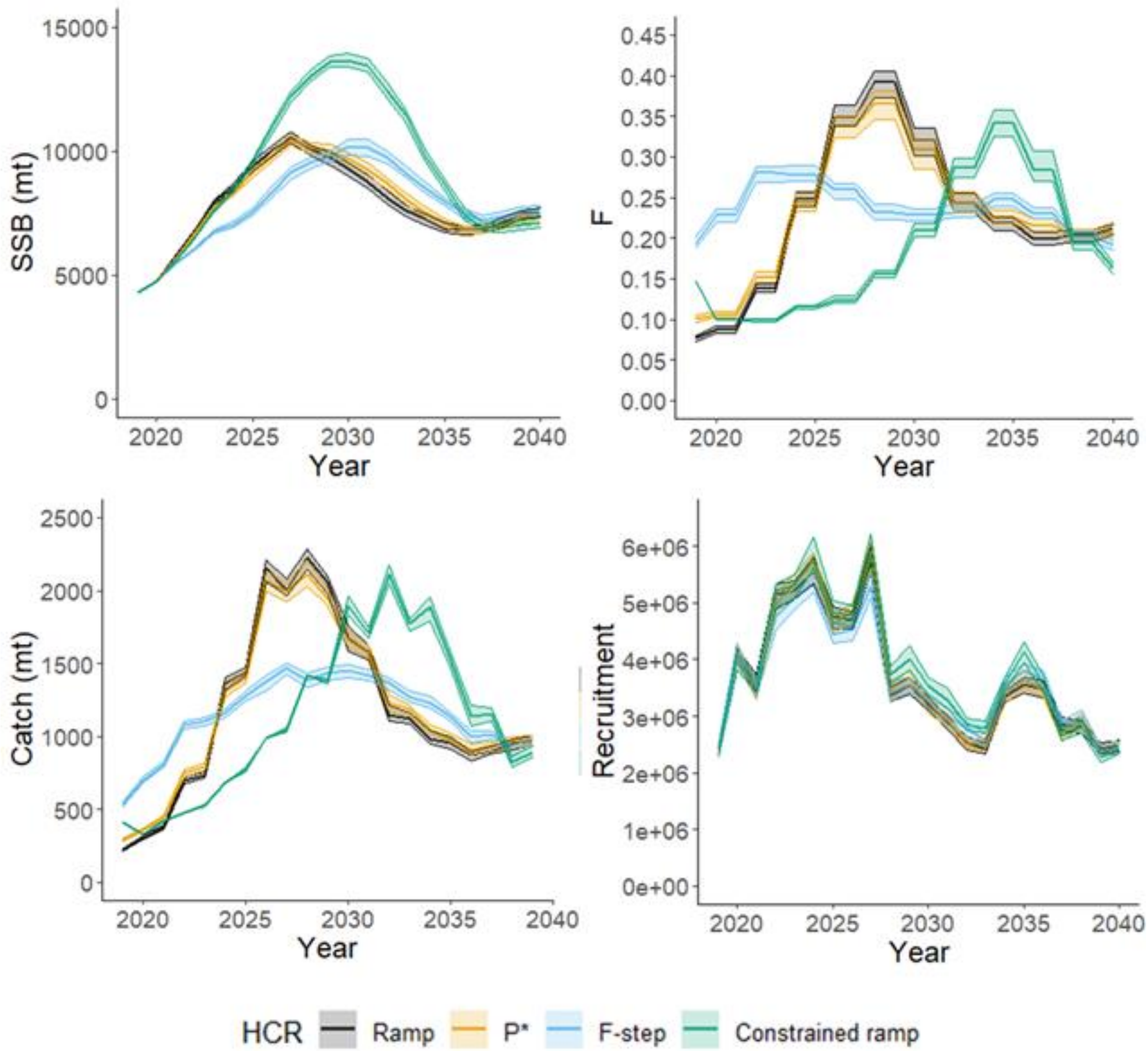


Figure 32. True operating model median spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits with 95% confidence intervals for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification (Natural Mortality and Recruitment Misspecification for a Stock that is Overfished) from 2019 to 2040.

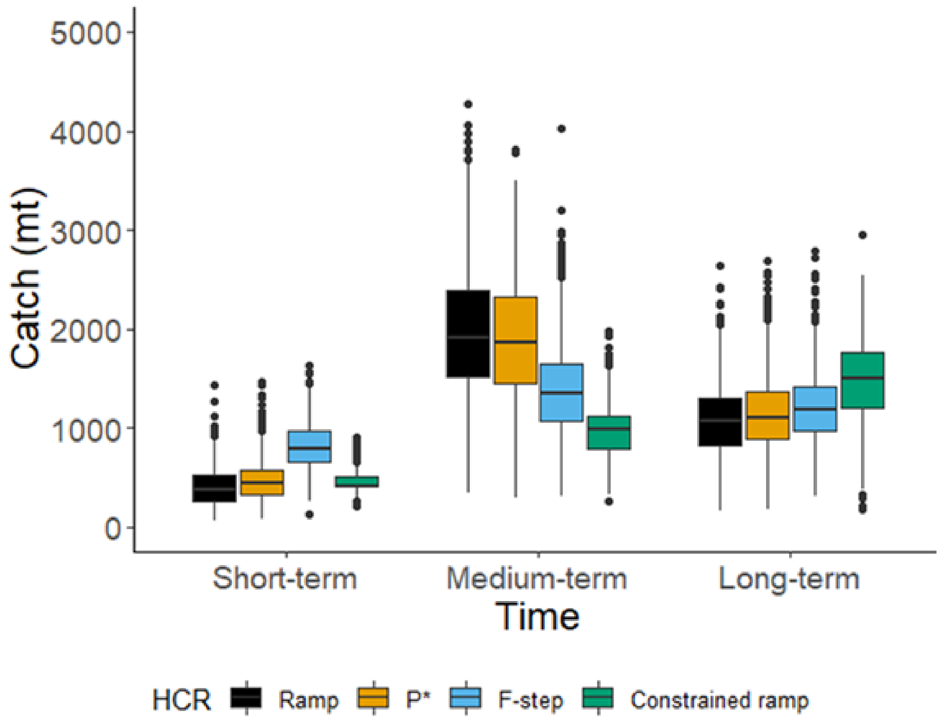


Figure 33. True median catch for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification (Natural Mortality and Recruitment Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

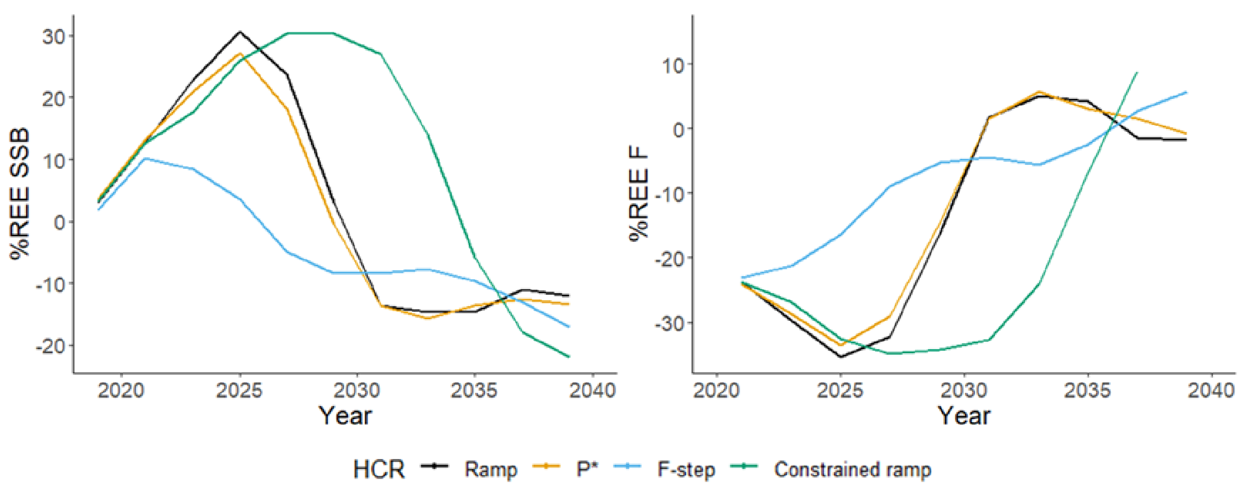


Figure 34. Percent relative error (REE) in terminal estimated spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification (Natural Mortality and Recruitment Misspecification for a Stock that is Overfished).

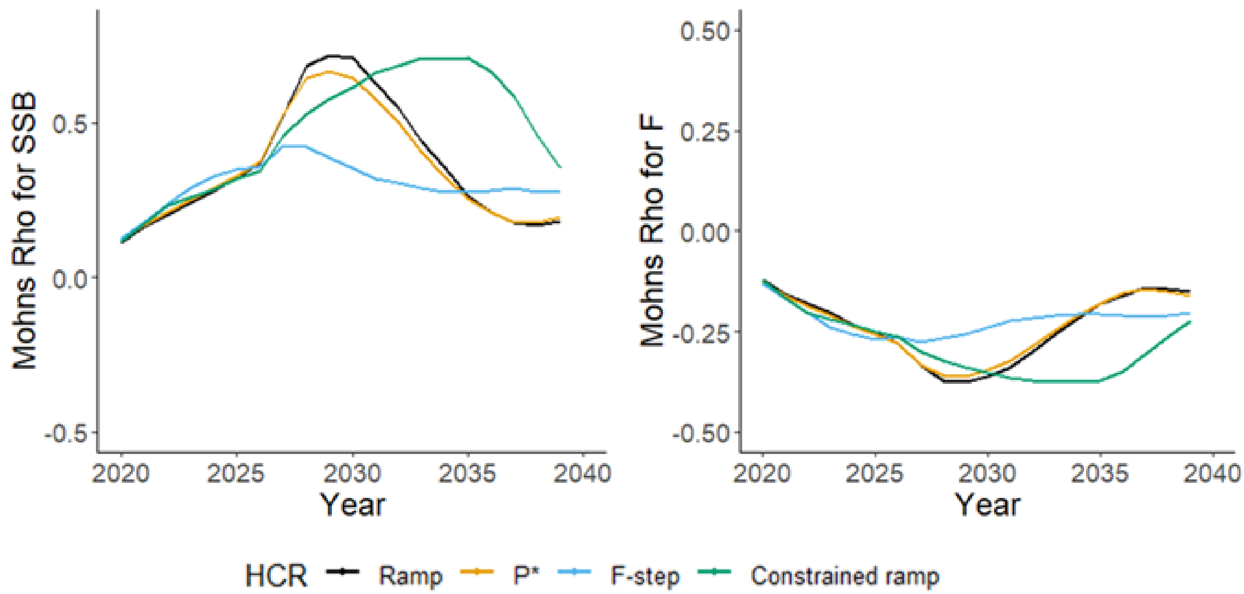


Figure 35. Mohn's Rho values for spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification (Natural Mortality and Recruitment Misspecification for a Stock that is Overfished).

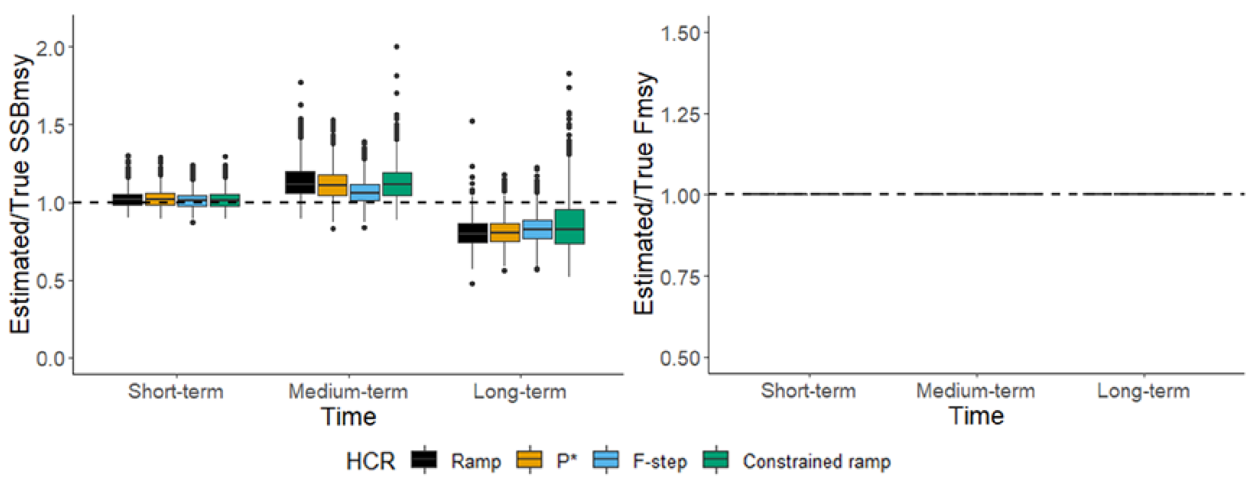
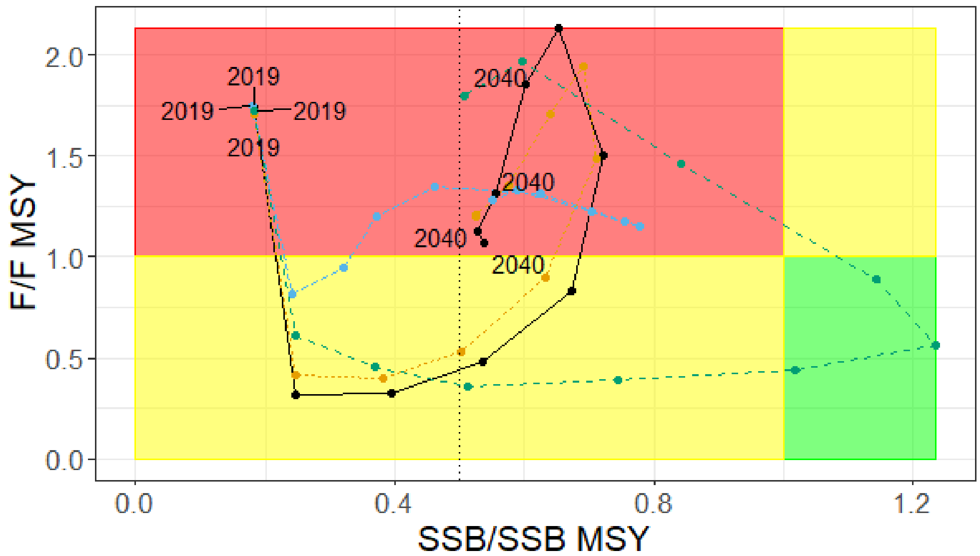


Figure 36. Median ratios of estimated to true stock biomass reference point (SSB_{MSY}) and fishing mortality biomass reference point (F_{MSY}) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification (Natural Mortality and Recruitment Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

a



b

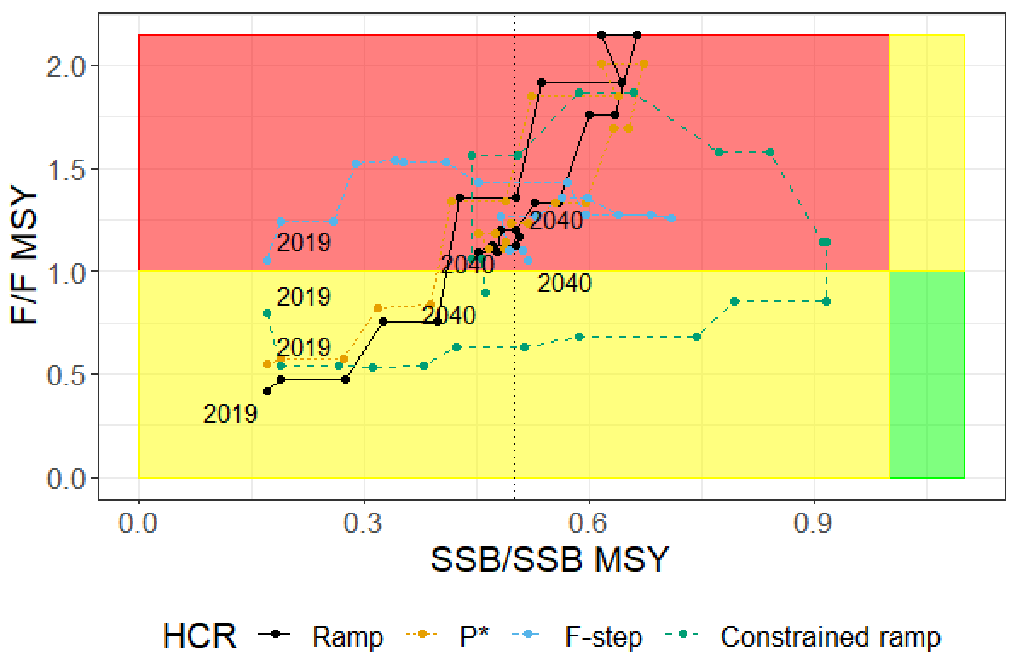


Figure 37. a) Estimated terminal stock status of each year's stock assessment relative to M=0.2 reference points (F/F$_{MSY}$ and SSB/SSB$_{MSY}$), b) True stock status relative to M=0.2 reference points for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification (Natural Mortality and Recruitment Misspecification for a Stock that is Overfished). The dashed line represents the overfished threshold. Estimated terminal stock status is lagged behind a year (the last year of data is from the previous year).

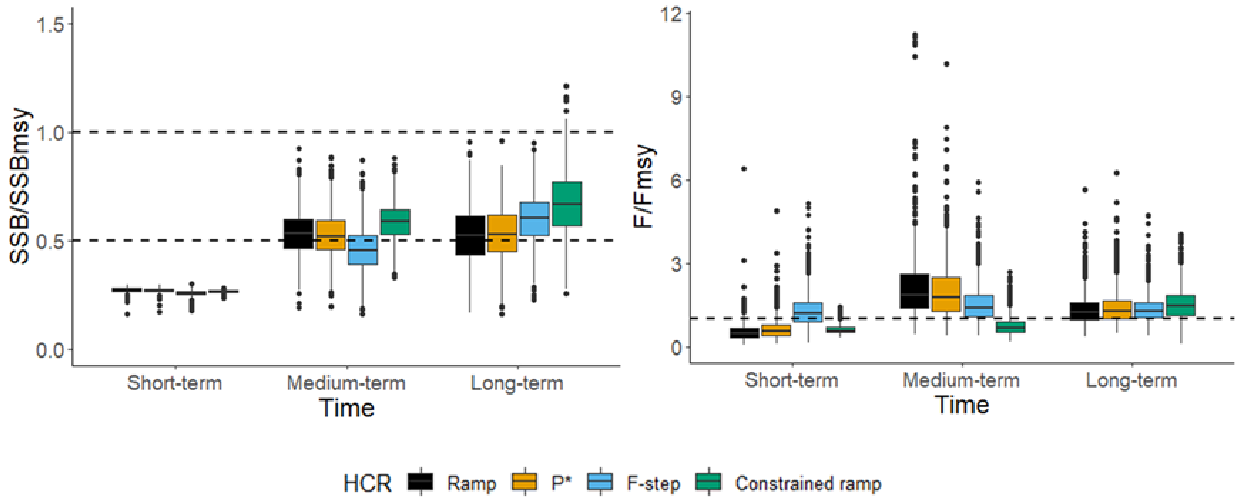


Figure 38. True median ratios of spawning stock biomass to the spawning stock biomass reference point (SSB/SSB$_{MSY}$) and fishing mortality to the fishing mortality biomass reference point (F/F$_{MSY}$) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification (Natural Mortality and Recruitment Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

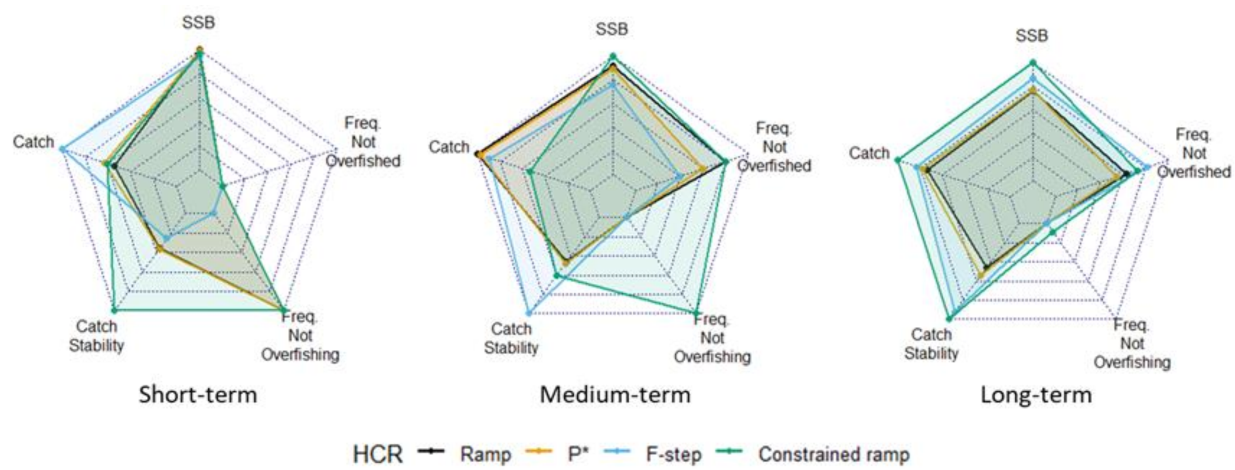


Figure 39. Harvest control rule (HCR) performance for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification (Natural Mortality and Recruitment Misspecification for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years). Metrics are standardized to the maximum value for each metric attained by the different HCRs and equally weighted. Spawning stock biomass (SSB) and catch are median SSB and catch for the time period.

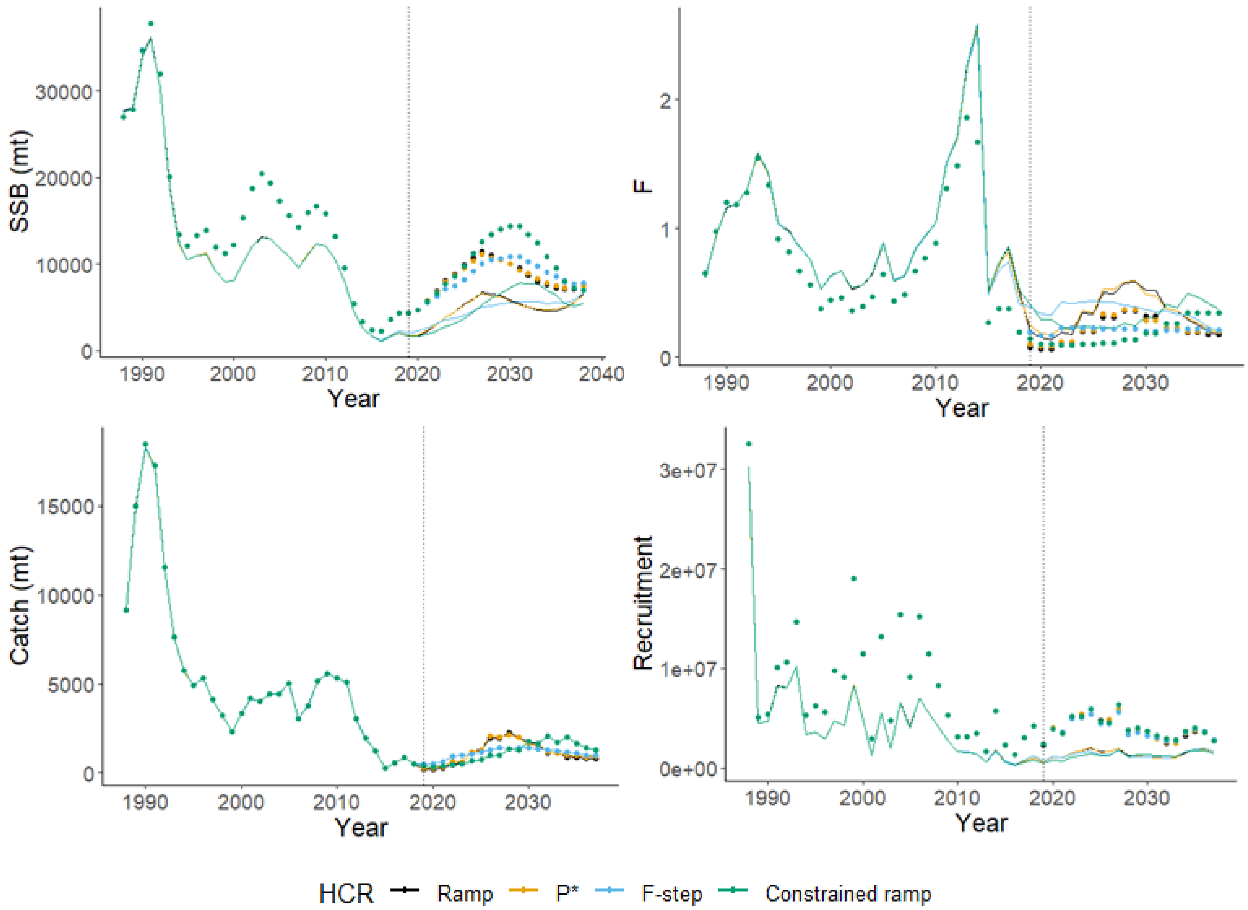


Figure 40. True operating model (closed circles) and estimated stock assessment values from the terminal assessment (stock assessment completed in 2039 with a terminal year of 2038; lines) of spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits for Gulf of Maine cod with a natural mortality and recruitment stock assessment misspecification and year one projections held constant (Natural Mortality and Recruitment Misspecification with Year One Projections Held Constant for a Stock that is Overfished) from 1982 to 2038 for SSB and 2037 for other metrics. The dashed line represents the beginning of the management procedure period (2019).

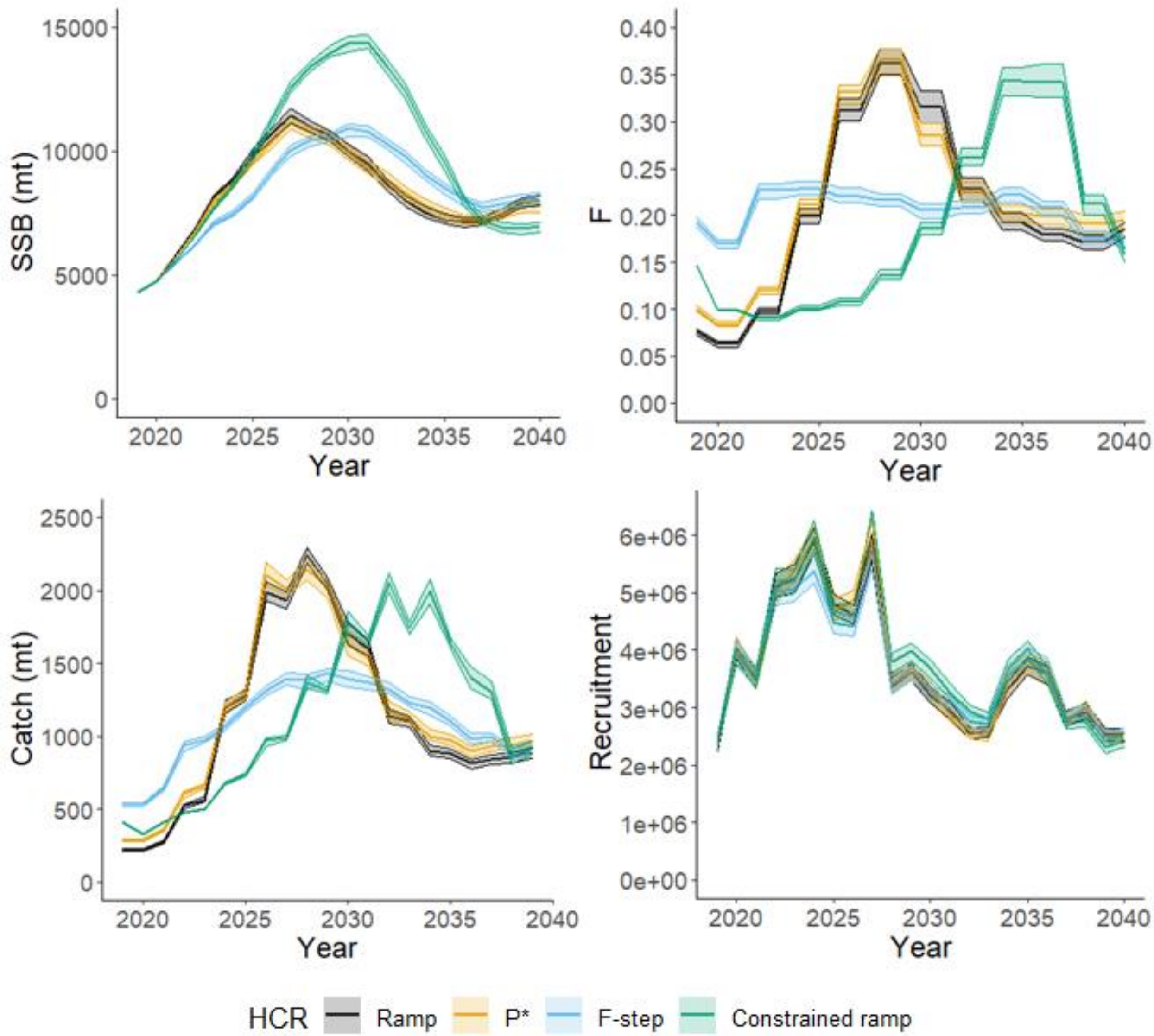


Figure 41. True operating model median spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits with 95% confidence intervals for Gulf of Maine cod with a natural mortality and recruitment stock assessment misspecification and year one projections held constant (Natural Mortality and Recruitment Misspecification with Year One Projections Held Constant for a Stock that is Overfished) from 2019 to 2040.

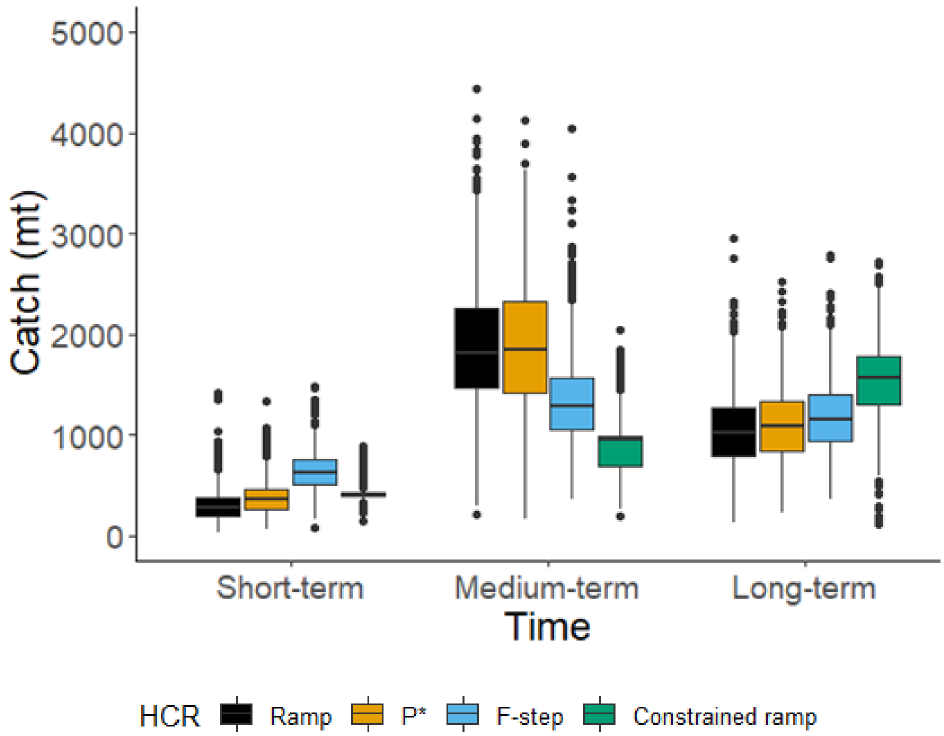


Figure 42. True median catch for Gulf of Maine cod with a natural mortality and recruitment stock assessment misspecification with year one projections held constant (Natural Mortality and Recruitment Misspecification with Year One Projections Held Constant for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

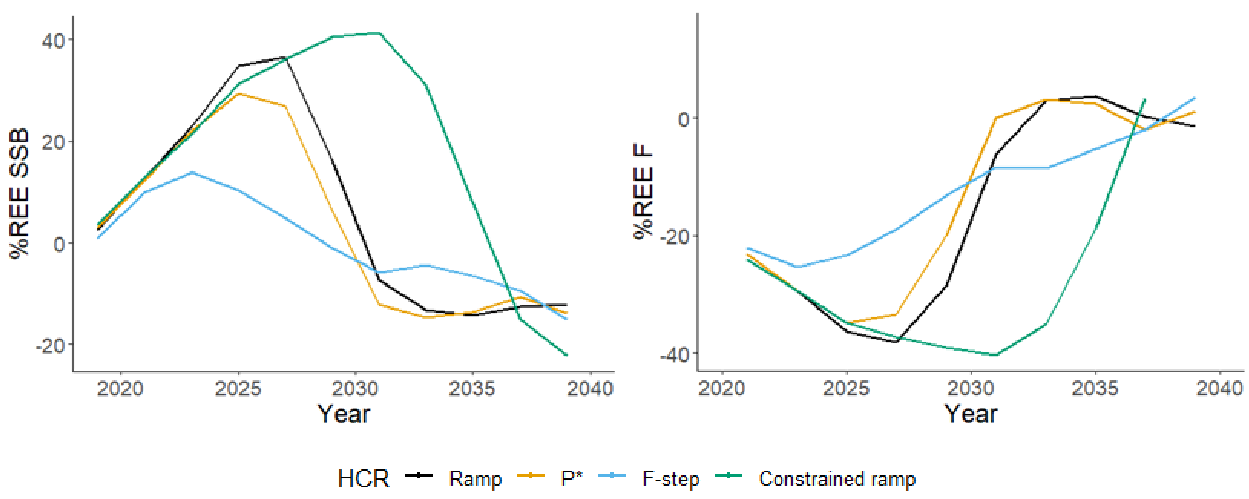


Figure 43. Percent relative error (REE) in terminal estimated spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a natural mortality and recruitment stock assessment misspecification and year one projections held constant (Natural Mortality and Recruitment Misspecification with Year One Projections Held Constant for a Stock that is Overfished).

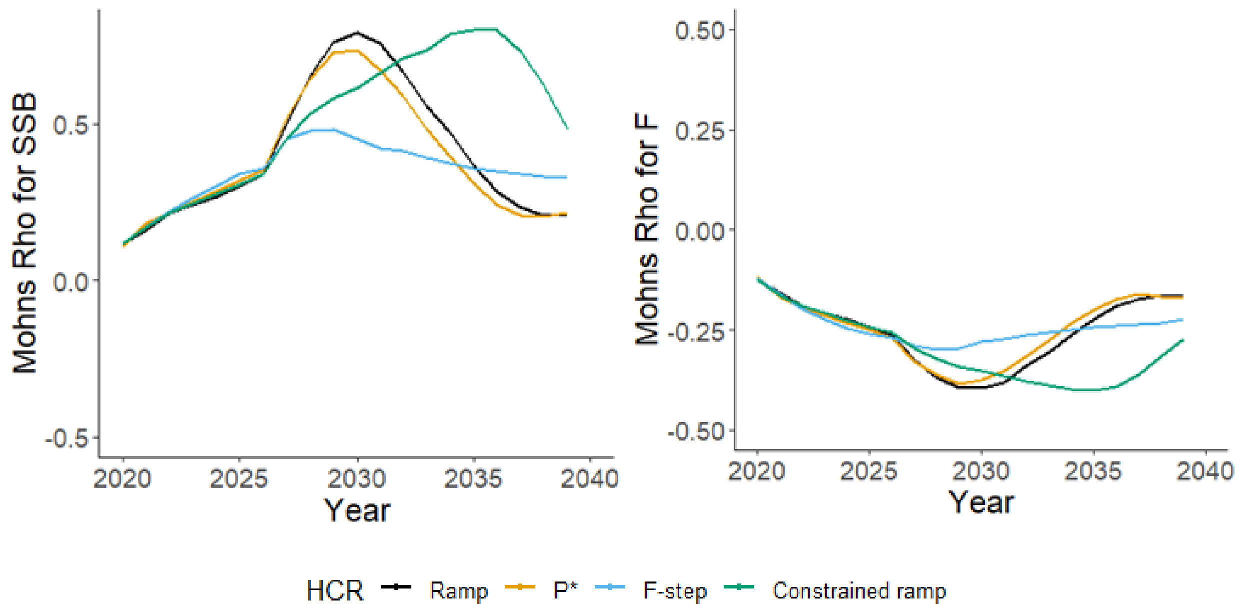


Figure 44. Mohn's Rho values for spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a natural mortality and recruitment stock assessment misspecification and year one projections held constant (Natural Mortality and Recruitment Misspecification with Year One Projections Held Constant for a Stock that is Overfished).

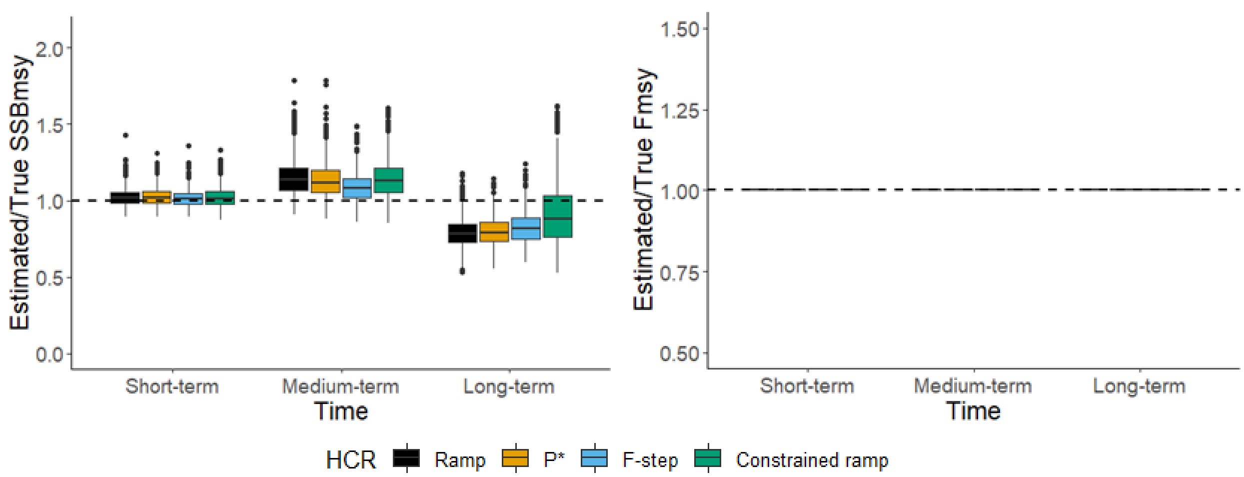
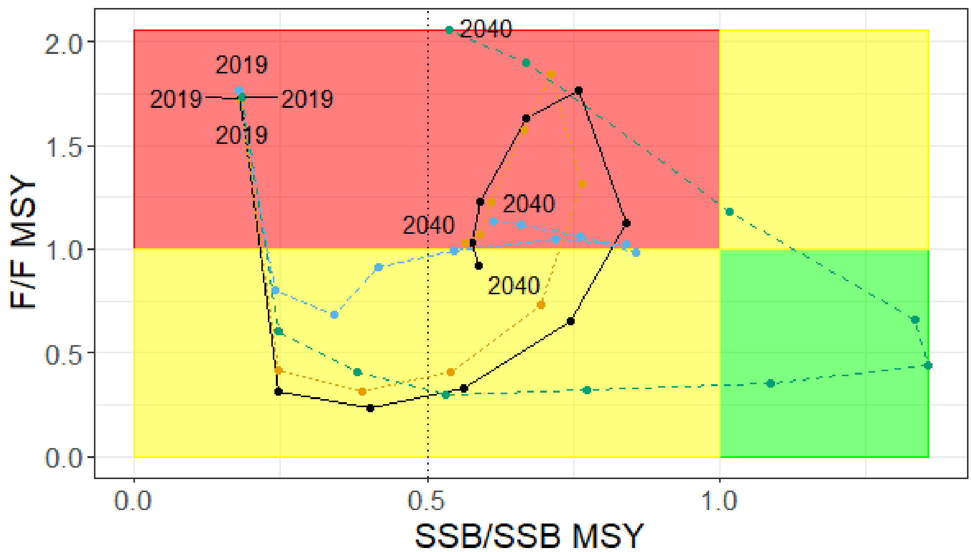


Figure 45. Median ratios of estimated to true stock biomass reference point (SSB_{MSY}) and fishing mortality biomass reference point (F_{MSY}) for Gulf of Maine cod with a natural mortality and recruitment stock assessment misspecification and year one projections held constant (Natural Mortality and Recruitment Misspecification with Year One Projections Held Constant for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

a



b

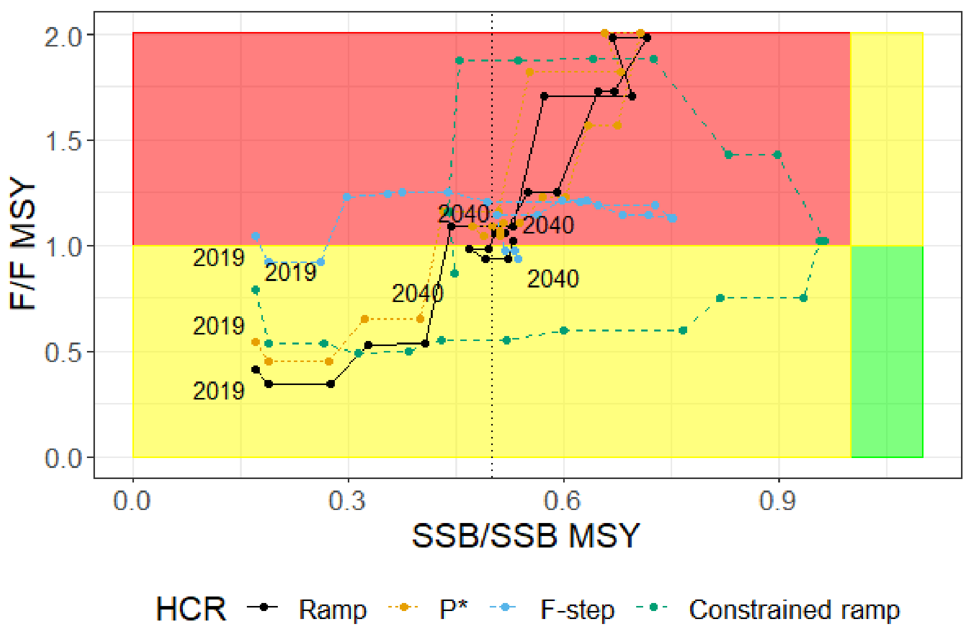


Figure 46. a) Estimated terminal stock status of each year's stock assessment relative to M=0.2 reference points (F/F$_{MSY}$ and SSB/SSB$_{MSY}$), b) True stock status relative to M=0.2 reference points for Gulf of Maine cod with a natural mortality and recruitment stock assessment misspecification with year one projections held constant (Natural Mortality and Recruitment Misspecification with Year One Projections Held Constant for a Stock that is Overfished). The dashed line represents the overfished threshold. Estimated terminal stock status is lagged behind a year (the last year of data is from the previous year).

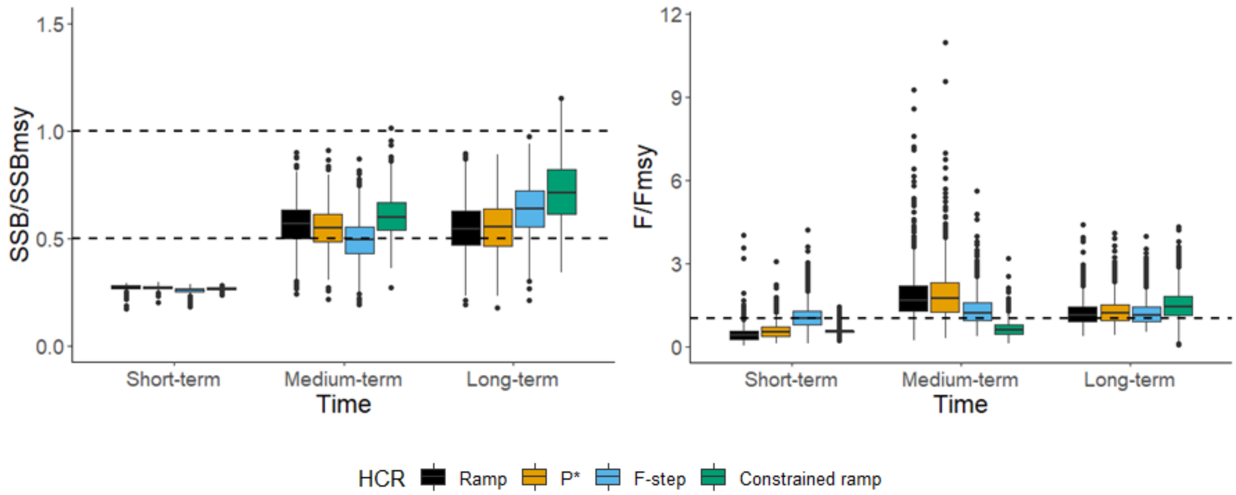


Figure 47. True median ratios of spawning stock biomass to the spawning stock biomass reference point (SSB/SSB$_{MSY}$) and fishing mortality to the fishing mortality biomass reference point (F/F$_{MSY}$) for Gulf of Maine cod with a natural mortality and recruitment stock assessment misspecification and year one projections held constant (Natural Mortality and Recruitment Misspecification with Year One Projections Held Constant for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

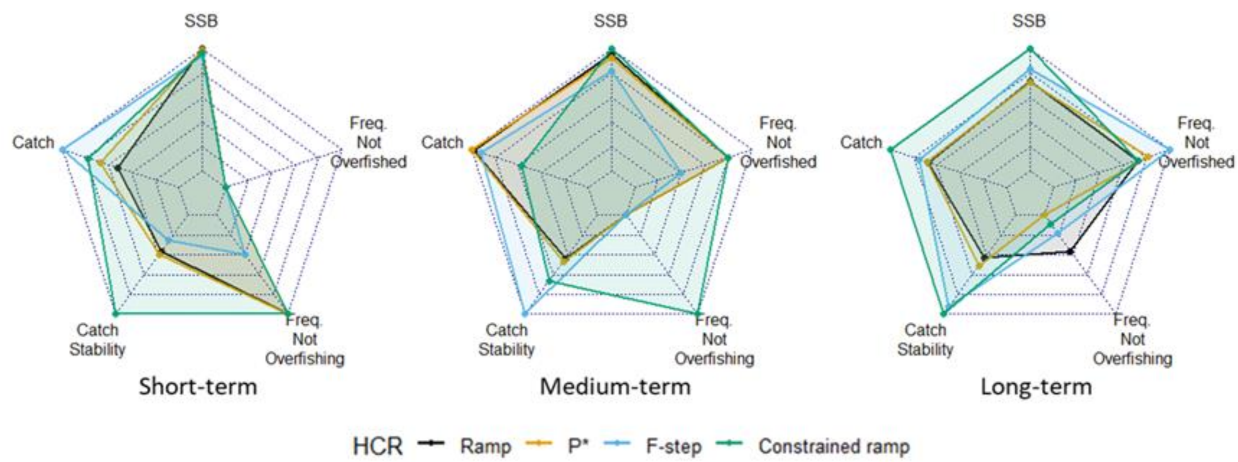


Figure 48. Harvest control rule (HCR) performance for Gulf of Maine cod with a natural mortality and recruitment stock assessment misspecification and year one projections held constant (Natural Mortality and Recruitment Misspecification with Year One Projections Held Constant for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years). Metrics are standardized to the maximum value for each metric attained by the different HCRs and equally weighted. Spawning stock biomass (SSB) and catch are median SSB and catch for the time period.

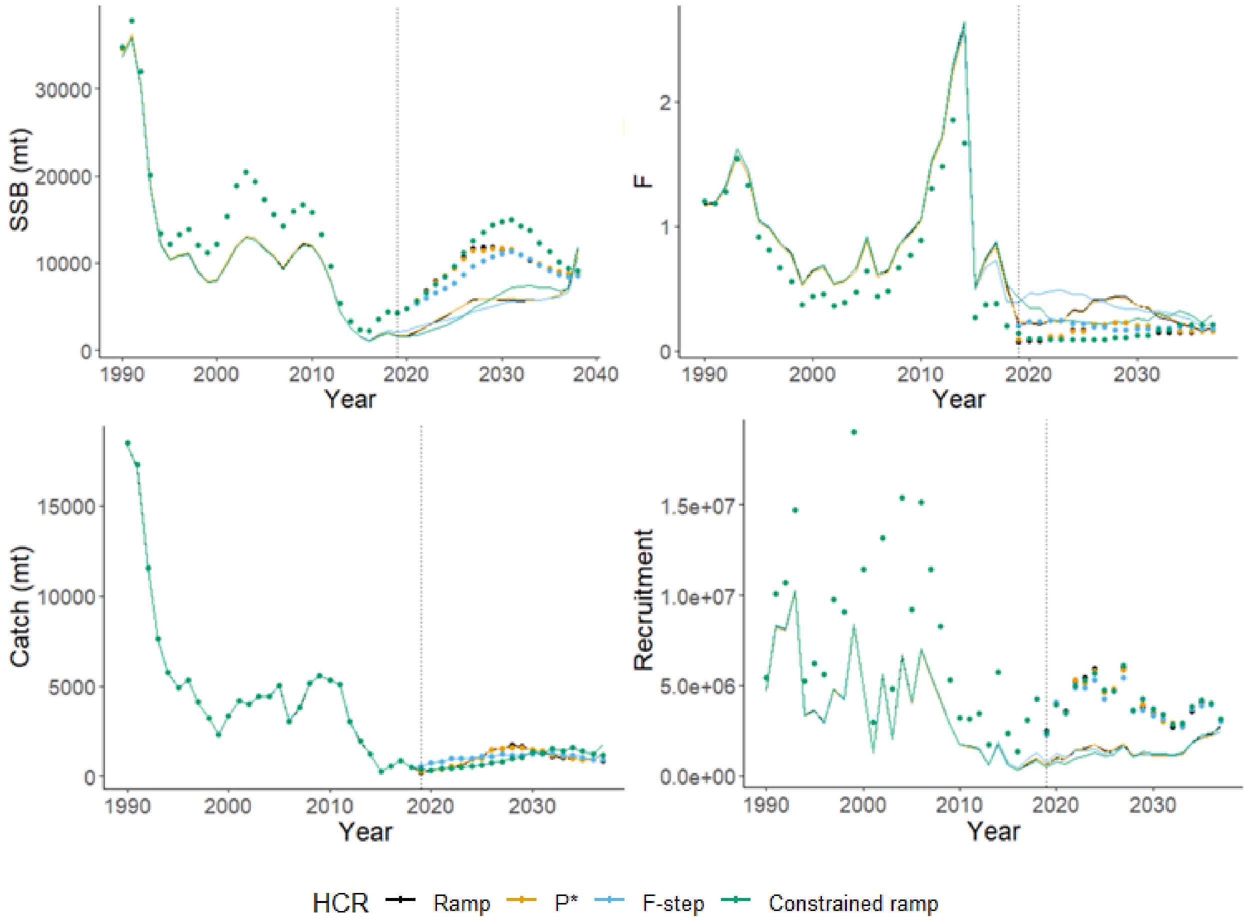


Figure 49. True operating model (closed circles) and estimated stock assessment values from the terminal assessment (stock assessment completed in 2039 with a terminal year of 2038; lines) of spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits for Gulf of Maine cod with natural mortality and recruitment stock assessment model misspecifications and retrospective adjustments (Natural Mortality and Recruitment Misspecification with Retrospective Adjustments for a Stock that is Overfished) from 1982 to 2038 for SSB and 2037 for other metrics. The dashed line represents the beginning of the management procedure period (2019).

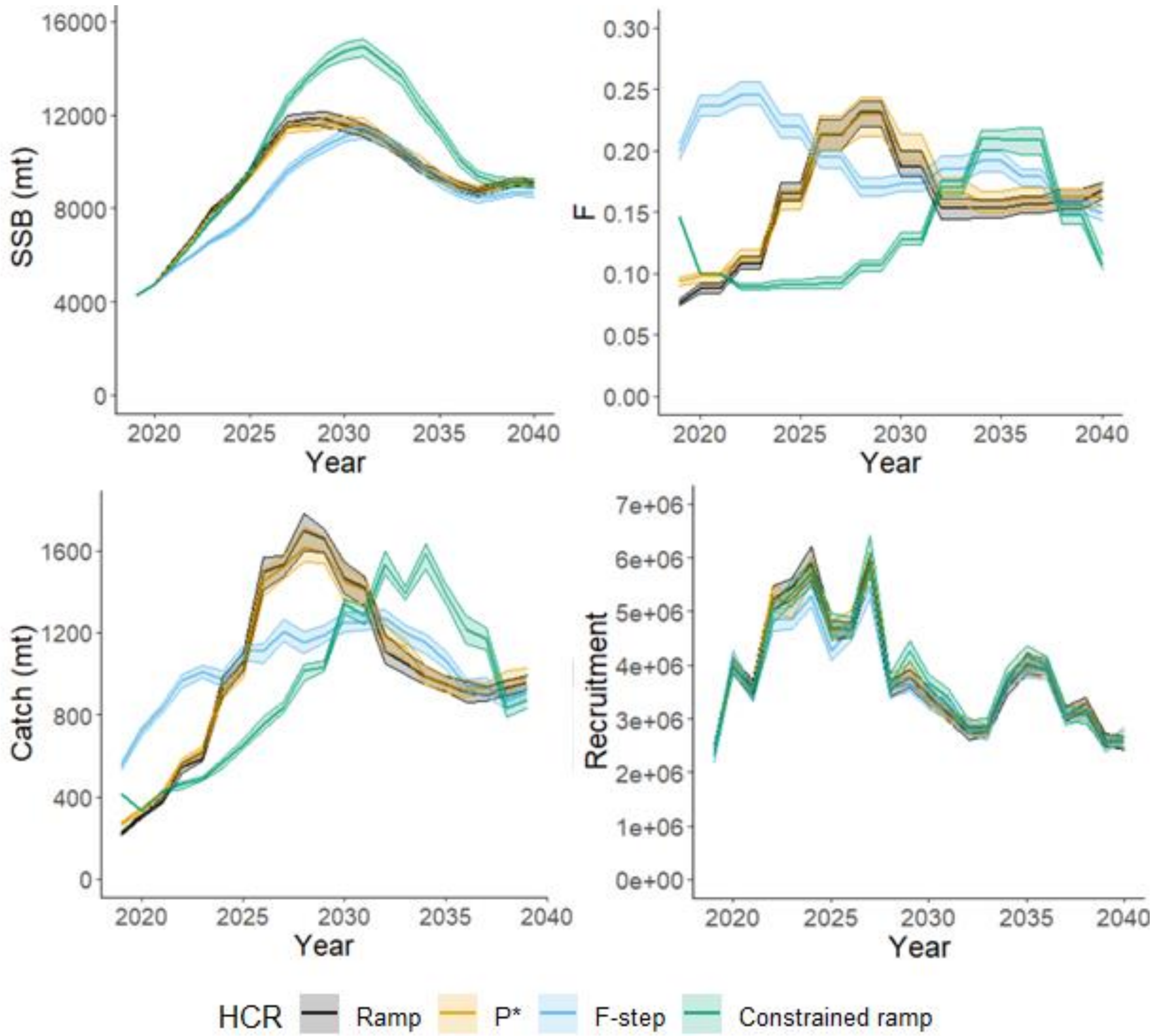


Figure 50. True operating model median spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits with 95% confidence intervals for Gulf of Maine cod with natural mortality and recruitment stock assessment model misspecification and retrospective adjustments (Natural Mortality and Recruitment Misspecification with Retrospective Adjustments for a Stock that is Overfished) from 2019 to 2040.

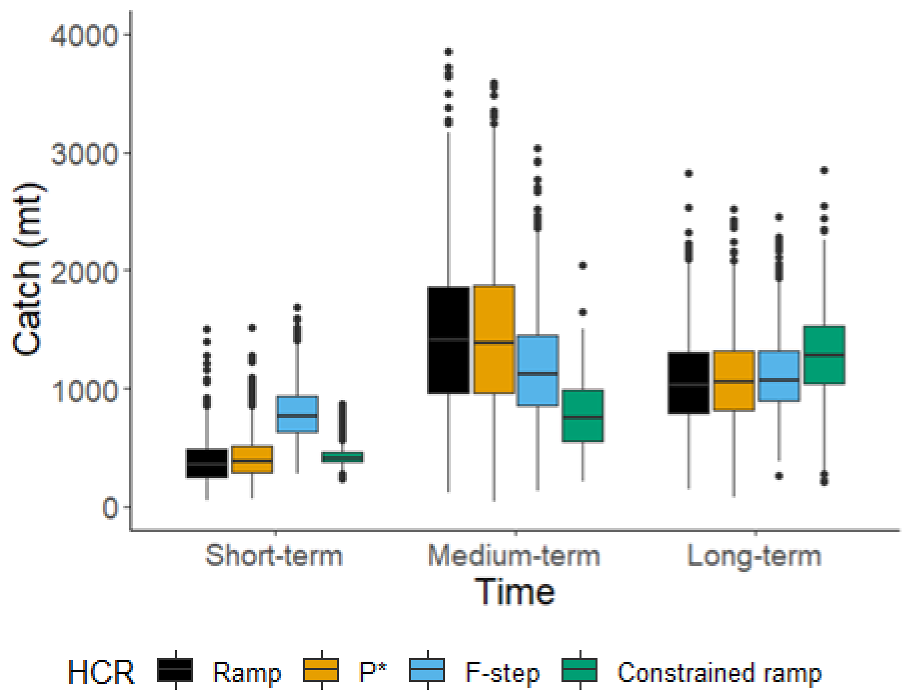


Figure 51. True median catch for Gulf of Maine cod with natural mortality and recruitment stock assessment model misspecifications and retrospective adjustments (Natural Mortality and Recruitment Misspecification with Retrospective Adjustments for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

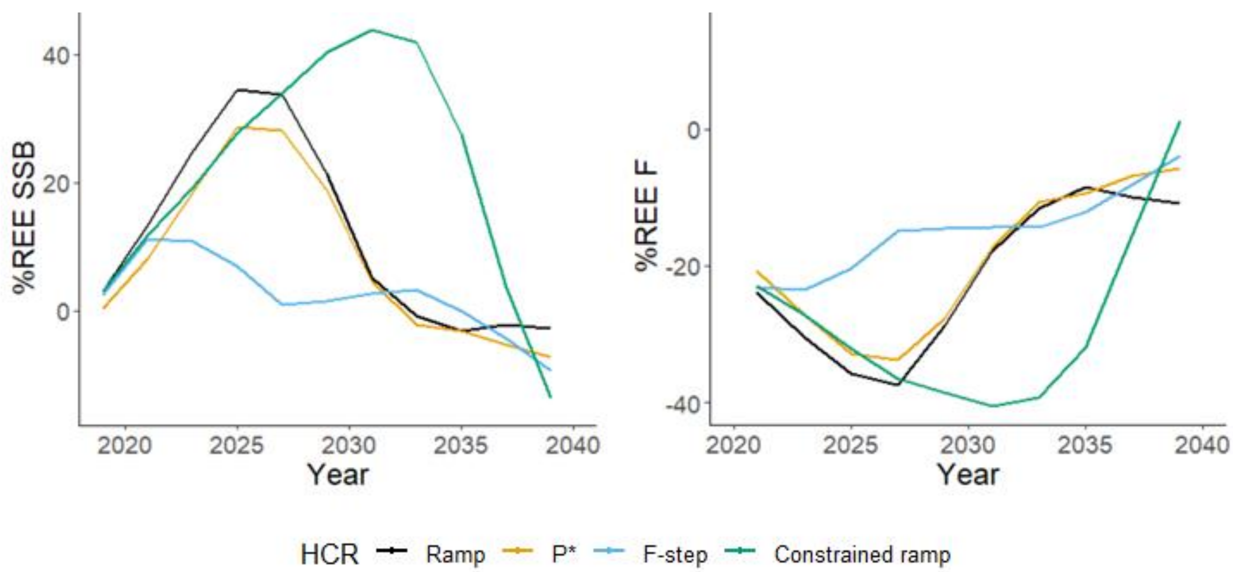


Figure 52. Percent relative error (REE) in terminal estimated spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and retrospective adjustments (Natural Mortality and Recruitment Misspecification with Retrospective Adjustments for a Stock that is Overfished).

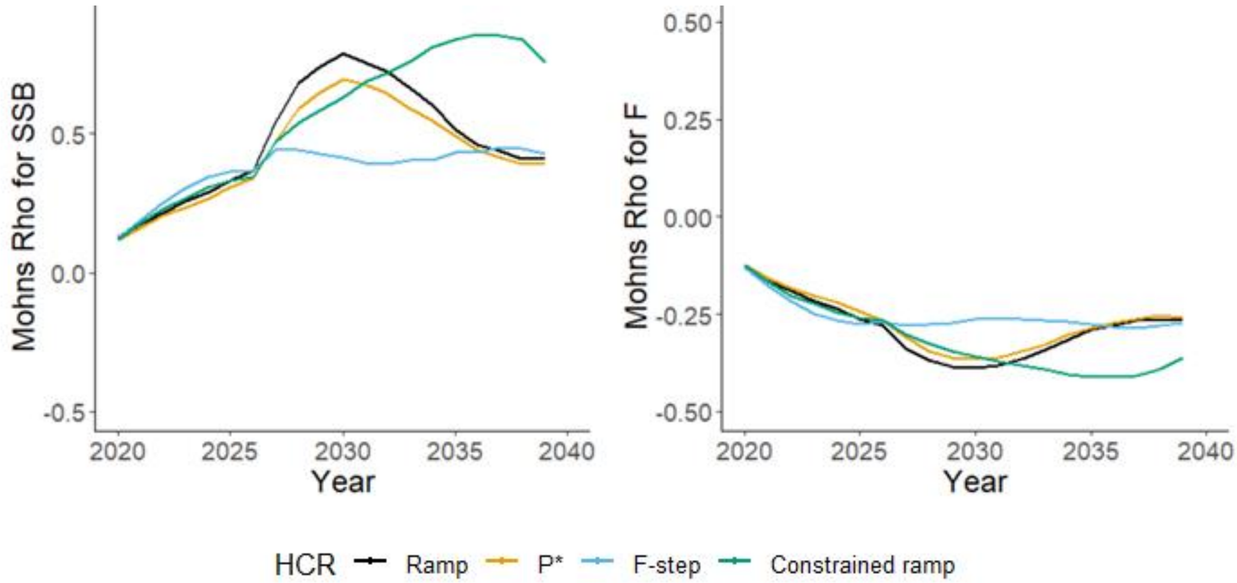


Figure 53. Mohn's Rho values for spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and retrospective adjustments (Natural Mortality and Recruitment Misspecification with Retrospective Adjustments for a Stock that is Overfished).

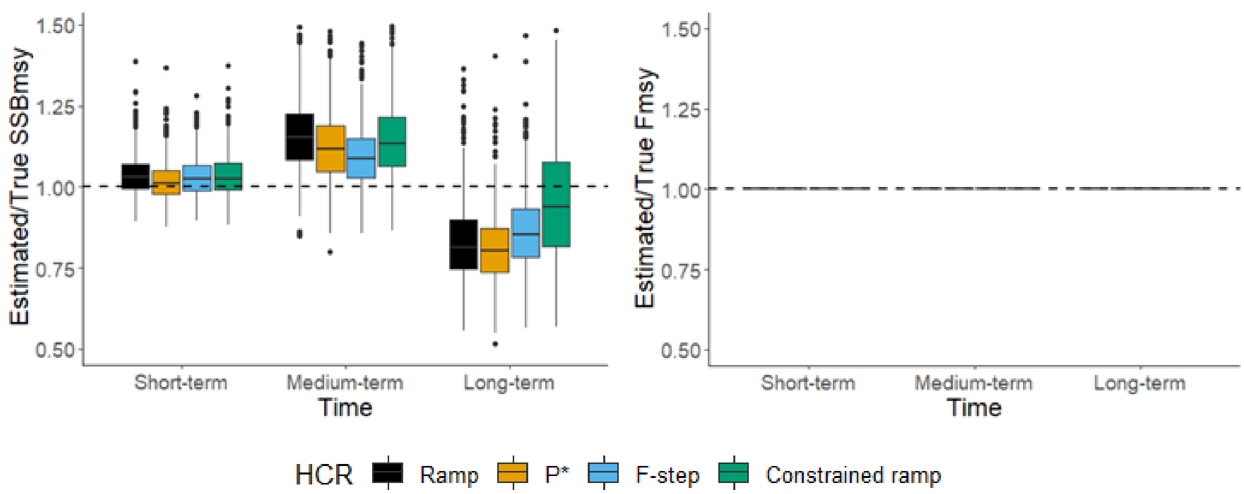
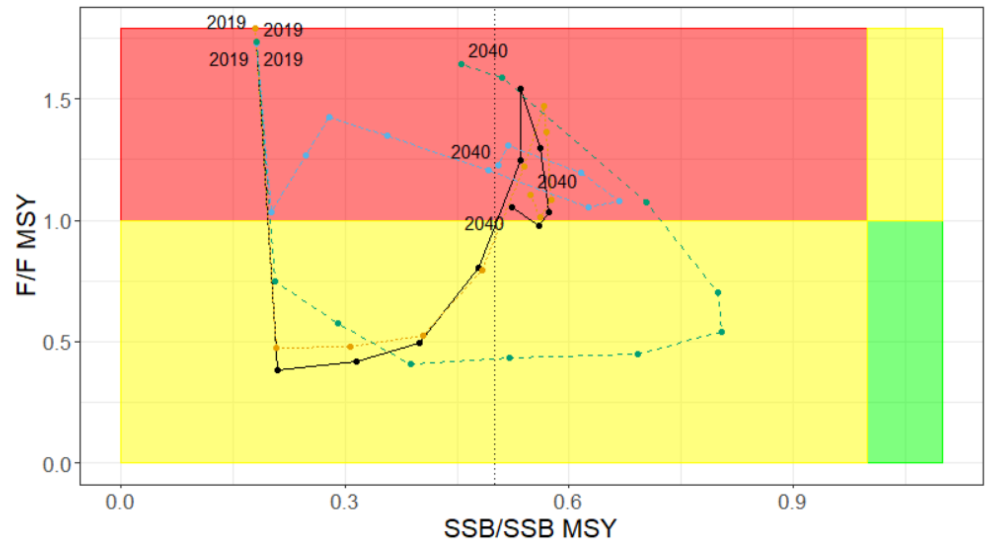


Figure 54. Median ratios of estimated to true stock biomass reference point (SSB_{MSY}) and fishing mortality biomass reference point (F_{MSY}) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and retrospective adjustments (Natural Mortality and Recruitment Misspecification with Retrospective Adjustments for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

a



b

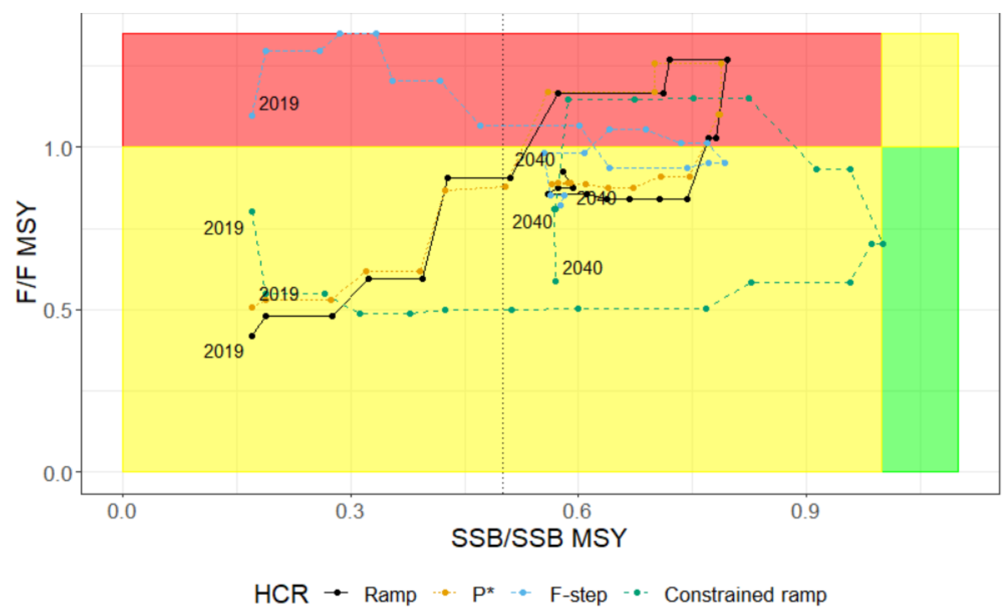


Figure 55. a) Estimated terminal stock status of each year's stock assessment relative to M=0.2 reference points (F/F$_{MSY}$ and SSB/SSB$_{MSY}$), b) True stock status relative to M=0.2 reference points for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and retrospective adjustments (Natural Mortality and Recruitment Misspecification with Retrospective Adjustments for a Stock that is Overfished). The dashed line represents the overfished threshold. Estimated terminal stock status is lagged behind a year (the last year of data is from the previous year).

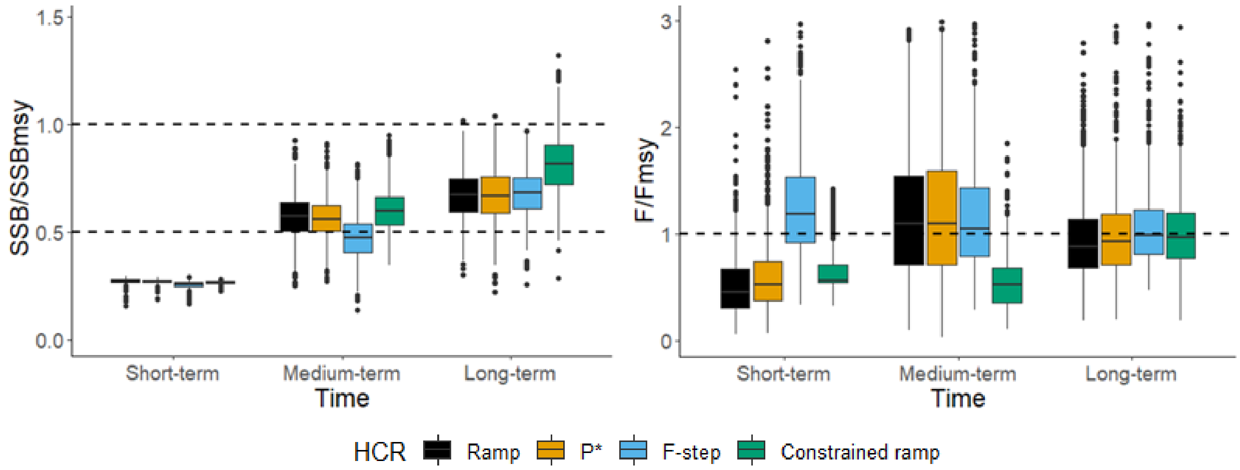


Figure 56. True median ratios of spawning stock biomass to the spawning stock biomass reference point (SSB/SSB_{MSY}) and fishing mortality to the fishing mortality biomass reference point (F/F_{MSY}) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and retrospective adjustments (Natural Mortality and Recruitment Misspecification with Retrospective Adjustments for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

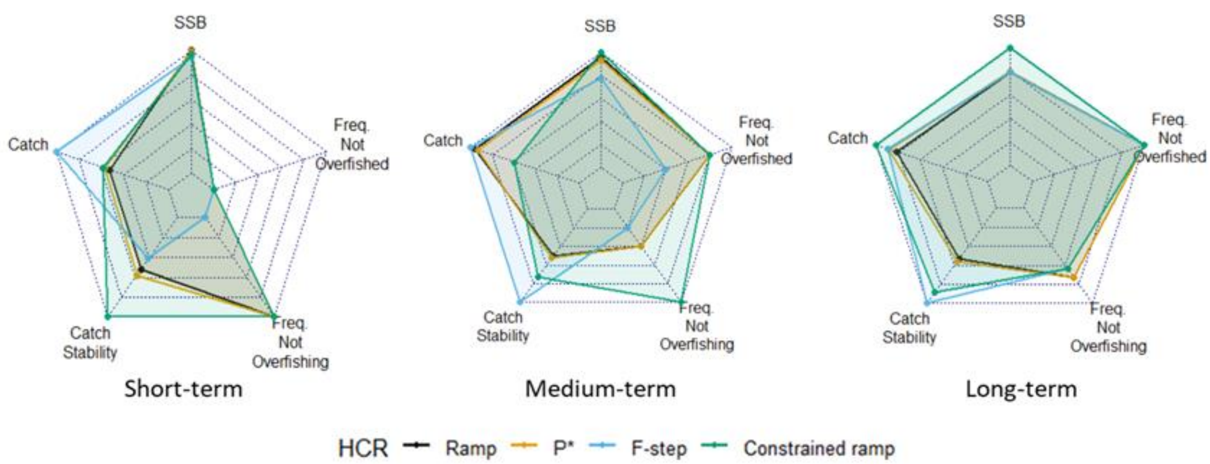


Figure 57. Harvest control rule (HCR) performance for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and retrospective adjustments (Natural Mortality and Recruitment Misspecification with Retrospective Adjustments for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years). Spawning stock biomass (SSB) and catch are median SSB and catch for the time period.

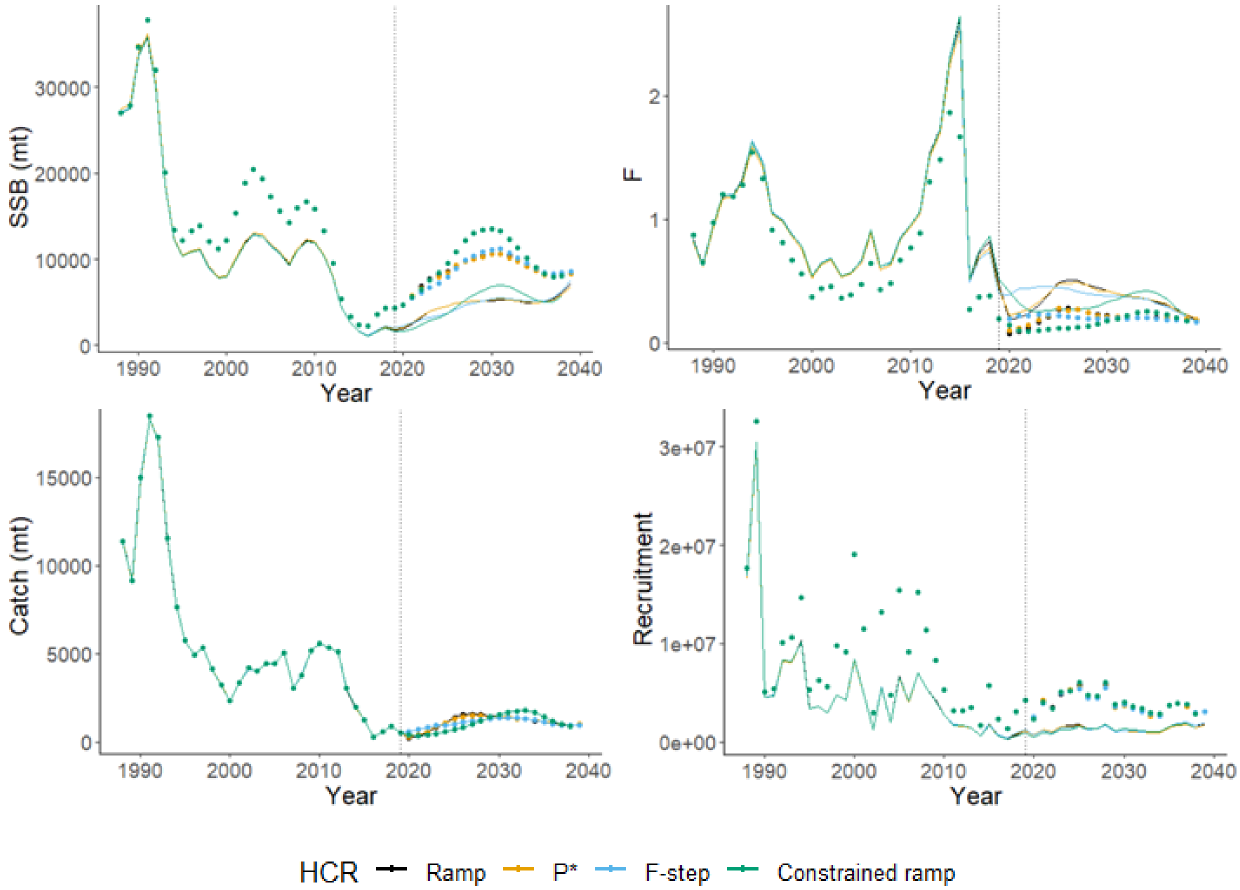


Figure 58. True operating model (closed circles) and estimated stock assessment values from the terminal assessment (stock assessment completed in 2039 with a terminal year of 2038; lines) of spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and annual stock assessment updates (Natural Mortality and Recruitment Misspecification with Annual Updates for a Stock that is Overfished) from 1982 to 2038 for SSB and 2037 for other metrics. The dashed line represents the beginning of the management procedure period (2019).

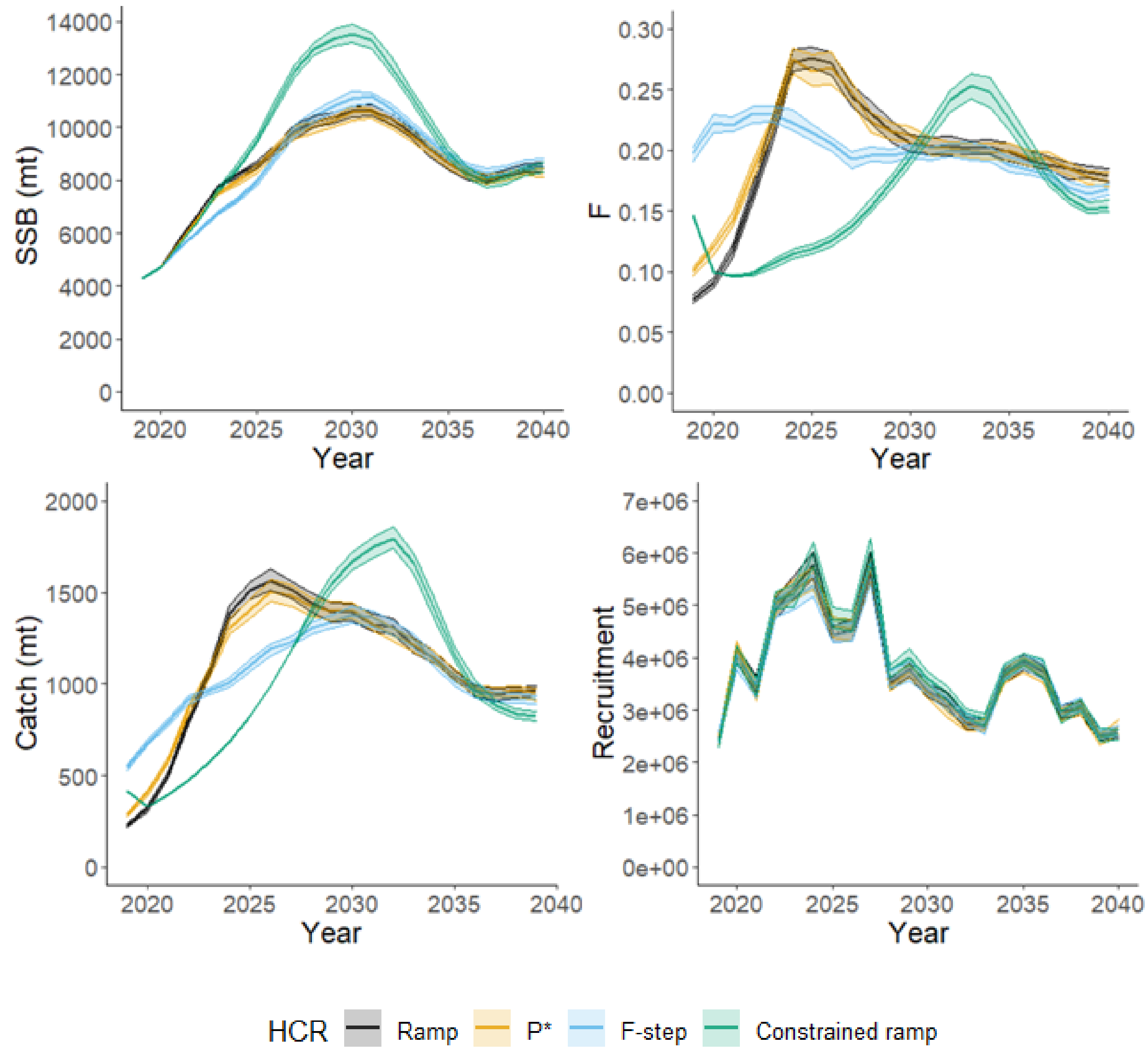


Figure 59. True operating model median spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits with 95% confidence intervals for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and annual stock assessment updates (Natural Mortality and Recruitment Misspecification with Annual Updates for a Stock that is Overfished) from 2019 to 2040.

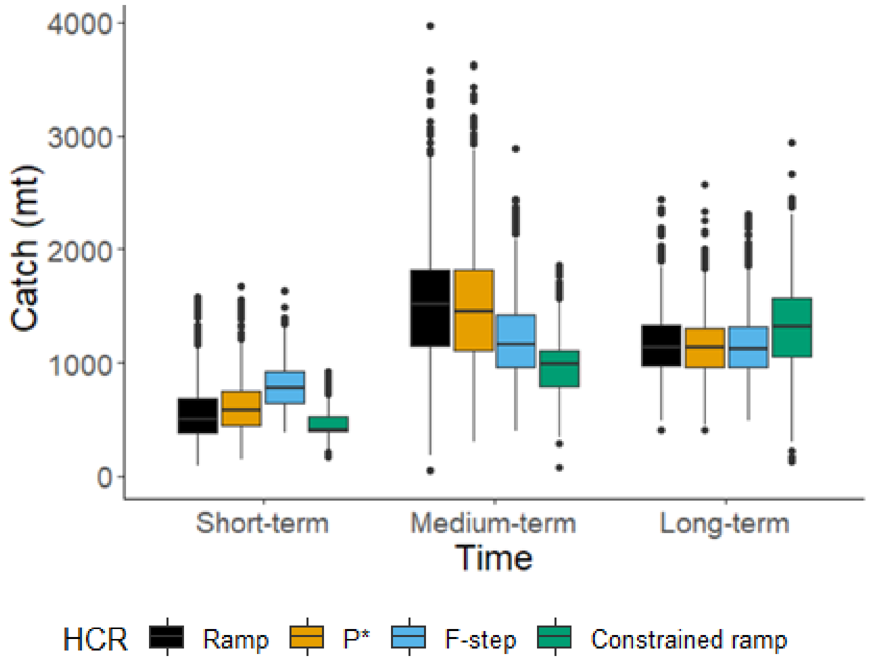


Figure 60. True median catch for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and annual stock assessment updates (Natural Mortality and Recruitment Misspecification with Annual Updates for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

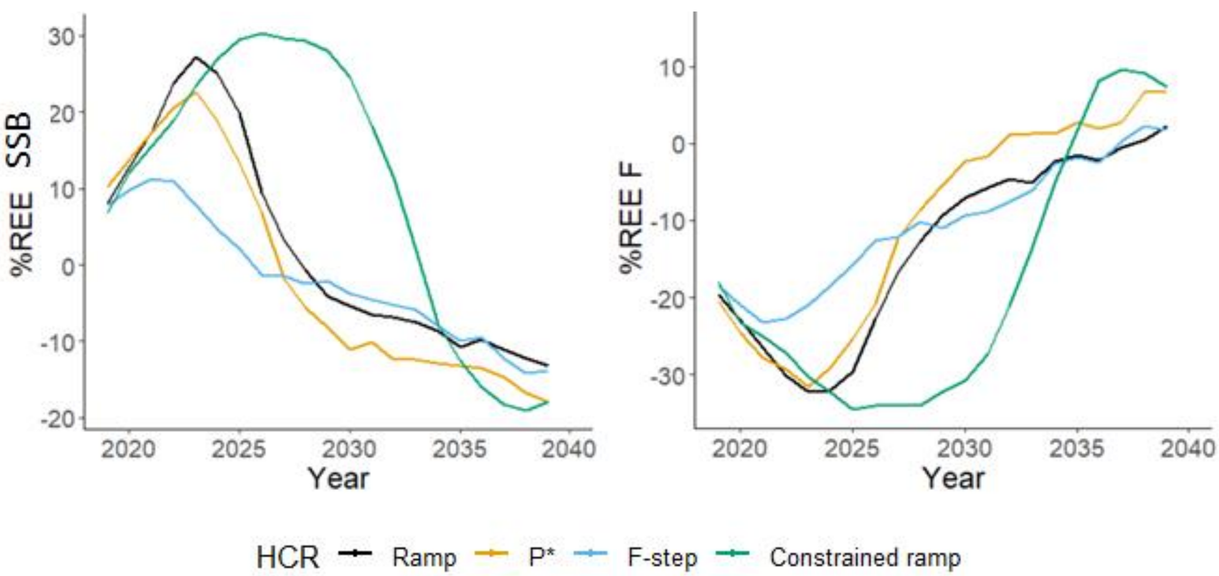


Figure 61. Percent relative error (REE) in terminal estimated spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and annual stock assessment updates (Natural Mortality and Recruitment Misspecification with Annual Updates for a Stock that is Overfished).

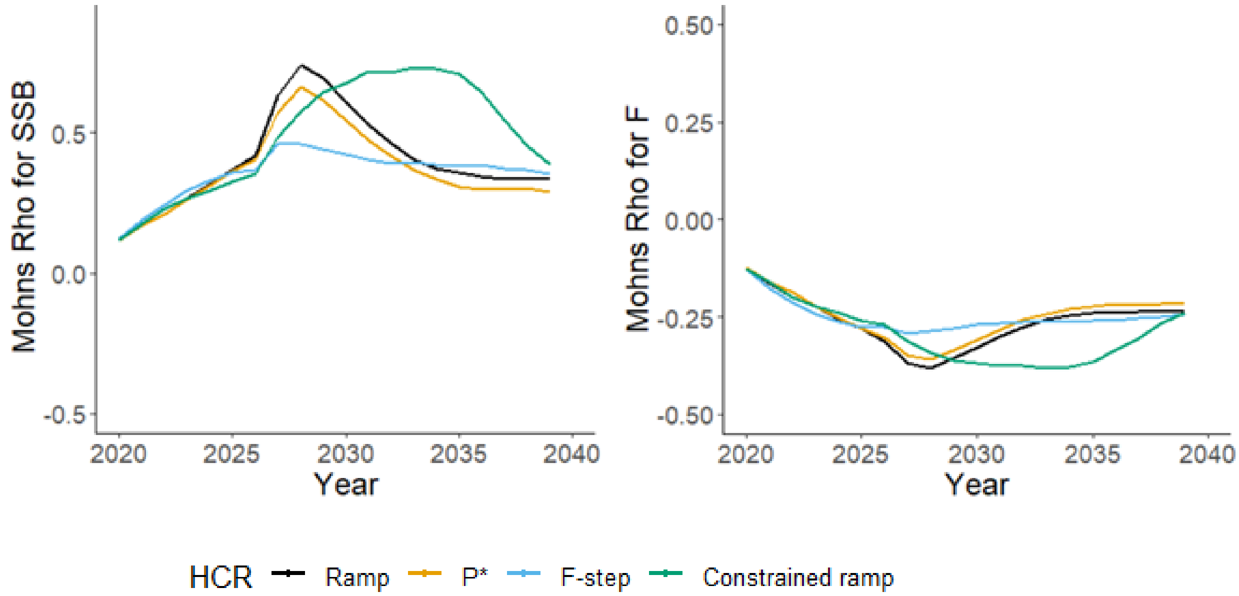


Figure 62. Mohn's Rho values for spawning stock biomass (SSB) and fishing mortality (F) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and annual stock assessment updates (Natural Mortality and Recruitment Misspecification with Annual Updates for a Stock that is Overfished).

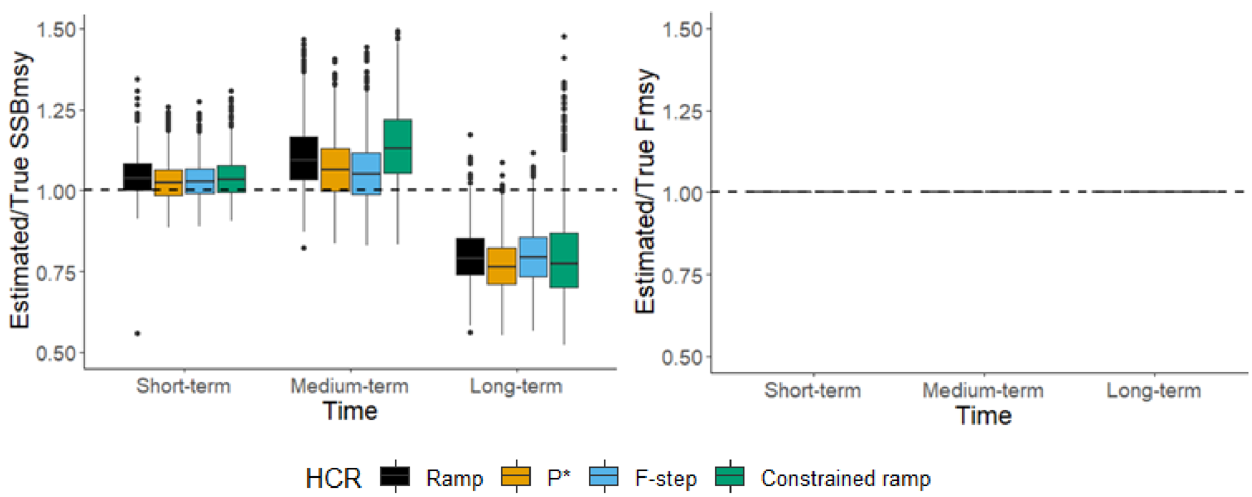
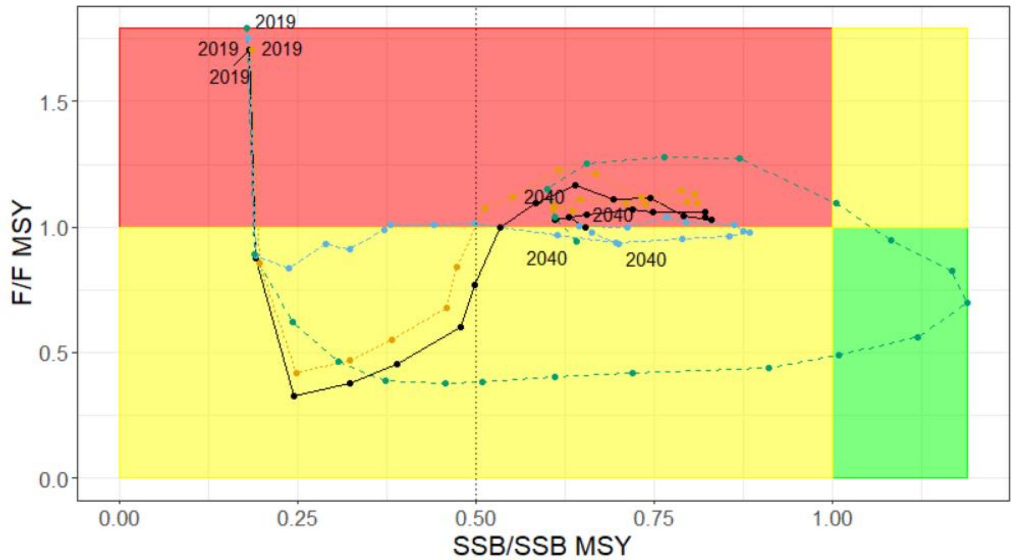


Figure 63. Median ratios of estimated to true stock biomass reference point (SSB_{MSY}) and fishing mortality biomass reference point (F_{MSY}) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and annual stock assessment updates (Natural Mortality and Recruitment Misspecification with Annual Updates for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

a



b

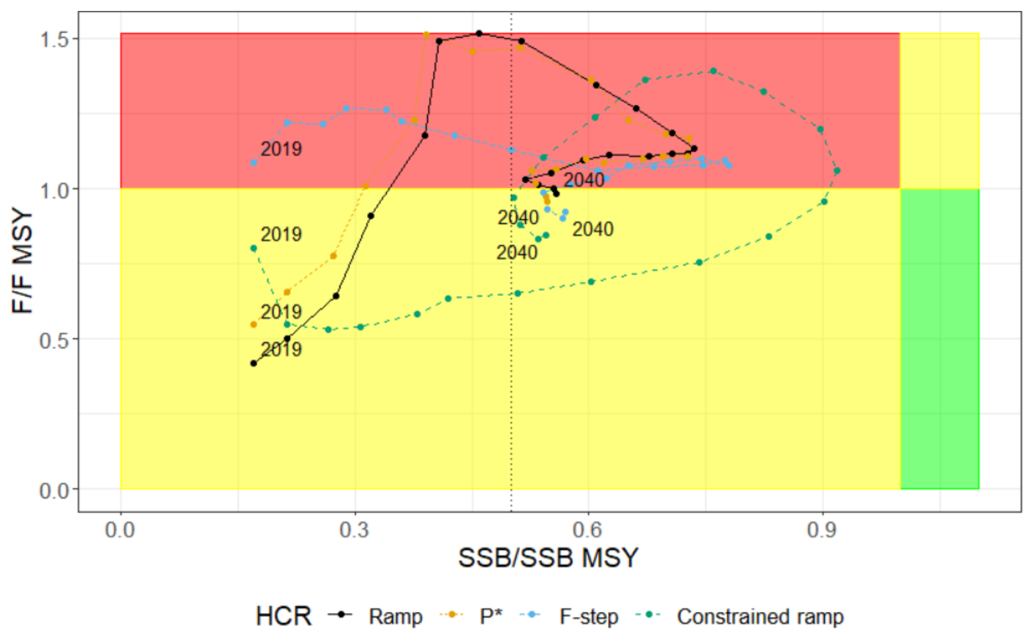


Figure 64. a) Estimated terminal stock status of each year's stock assessment relative to M=0.2 reference points (F/F_{MSY} and SSB/SSB_{MSY}), b) True stock status relative to M=0.2 reference points for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and annual stock assessment updates (Natural Mortality and Recruitment Misspecification with Annual Updates for a Stock that is Overfished). The dashed line represents the overfished threshold. Estimated terminal stock status is lagged behind a year (the last year of data is from the previous year).

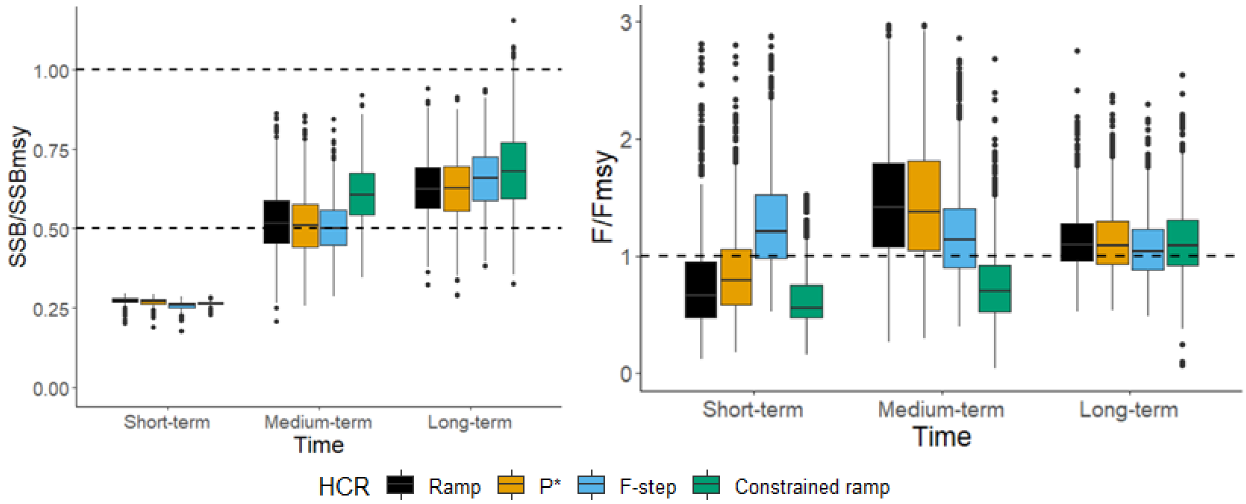


Figure 65. True median ratios of spawning stock biomass to the spawning stock biomass reference point (SSB/SSB$_{MSY}$) and fishing mortality to the fishing mortality biomass reference point (F/F$_{MSY}$) for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and annual stock assessment updates (Natural Mortality and Recruitment Misspecification with Annual Updates for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

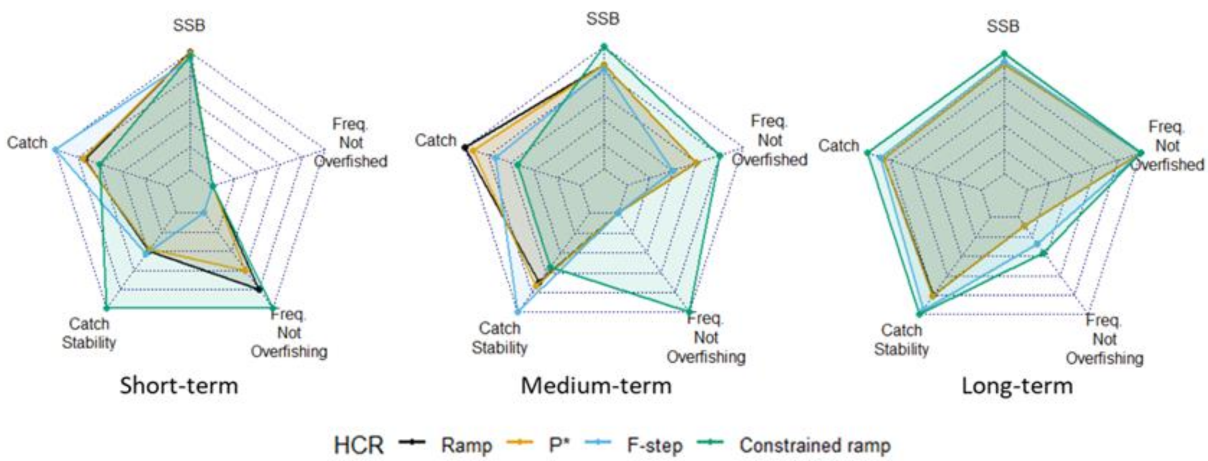


Figure 66. Harvest control rule (HCR) performance for Gulf of Maine cod with a natural mortality and recruitment stock assessment model misspecification and annual stock assessment updates (Natural Mortality and Recruitment Misspecification with Annual Updates for a Stock that is Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-20 years). Metrics are standardized to the maximum value for each metric attained by the different HCRs and equally weighted. Spawning stock biomass (SSB) and catch are median SSB and catch for the time period.

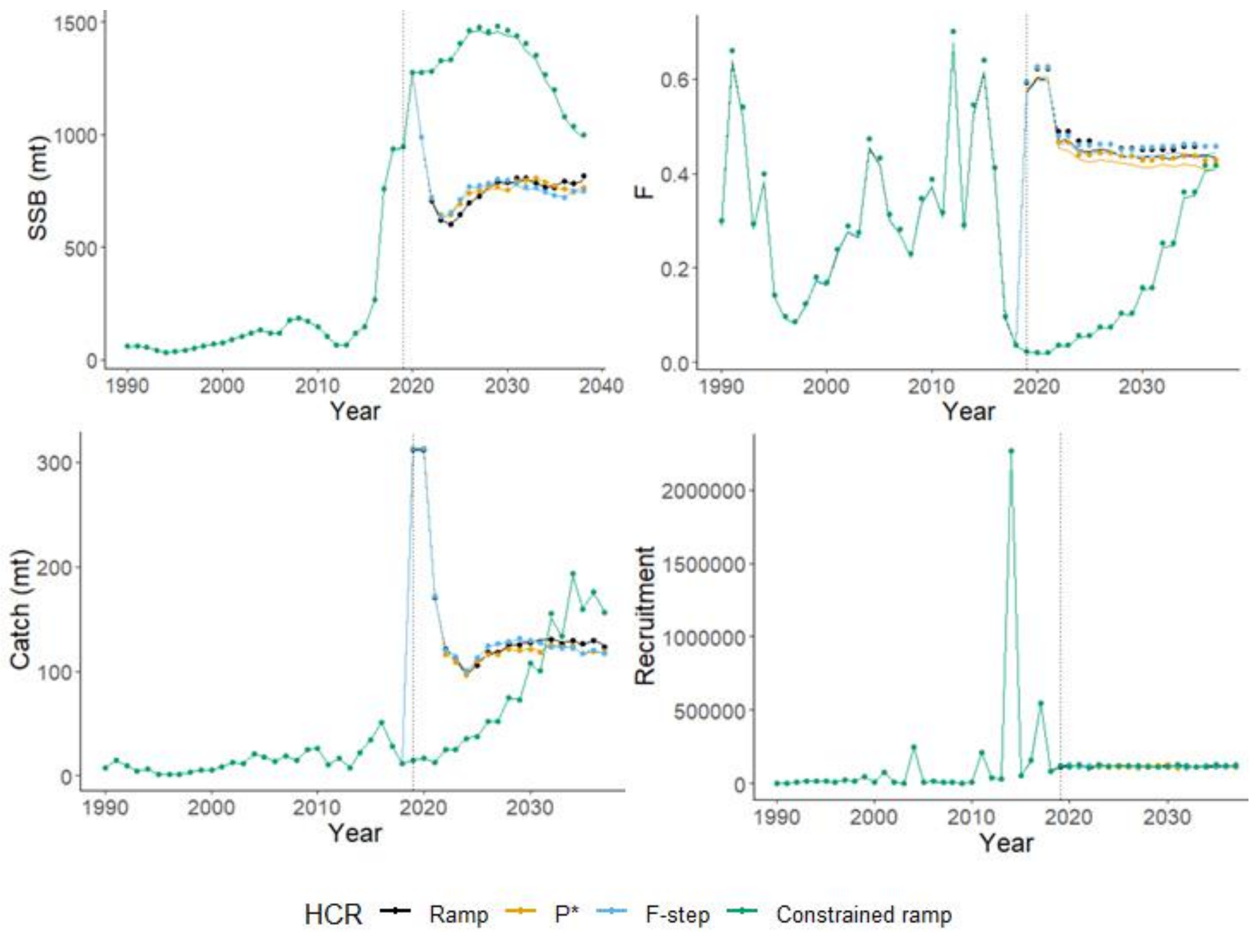


Figure 67. True operating model (closed circles) and estimated stock assessment values from the terminal assessment (stock assessment completed in 2039 with a terminal year of 2038; lines) of spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits for Georges Bank haddock with no stock assessment model misspecification (Base Case for a Stock that is Not Overfished) from 1982 to 2038 for SSB and 2037 for other metrics. The dashed line represents the beginning of the management procedure period (2019).

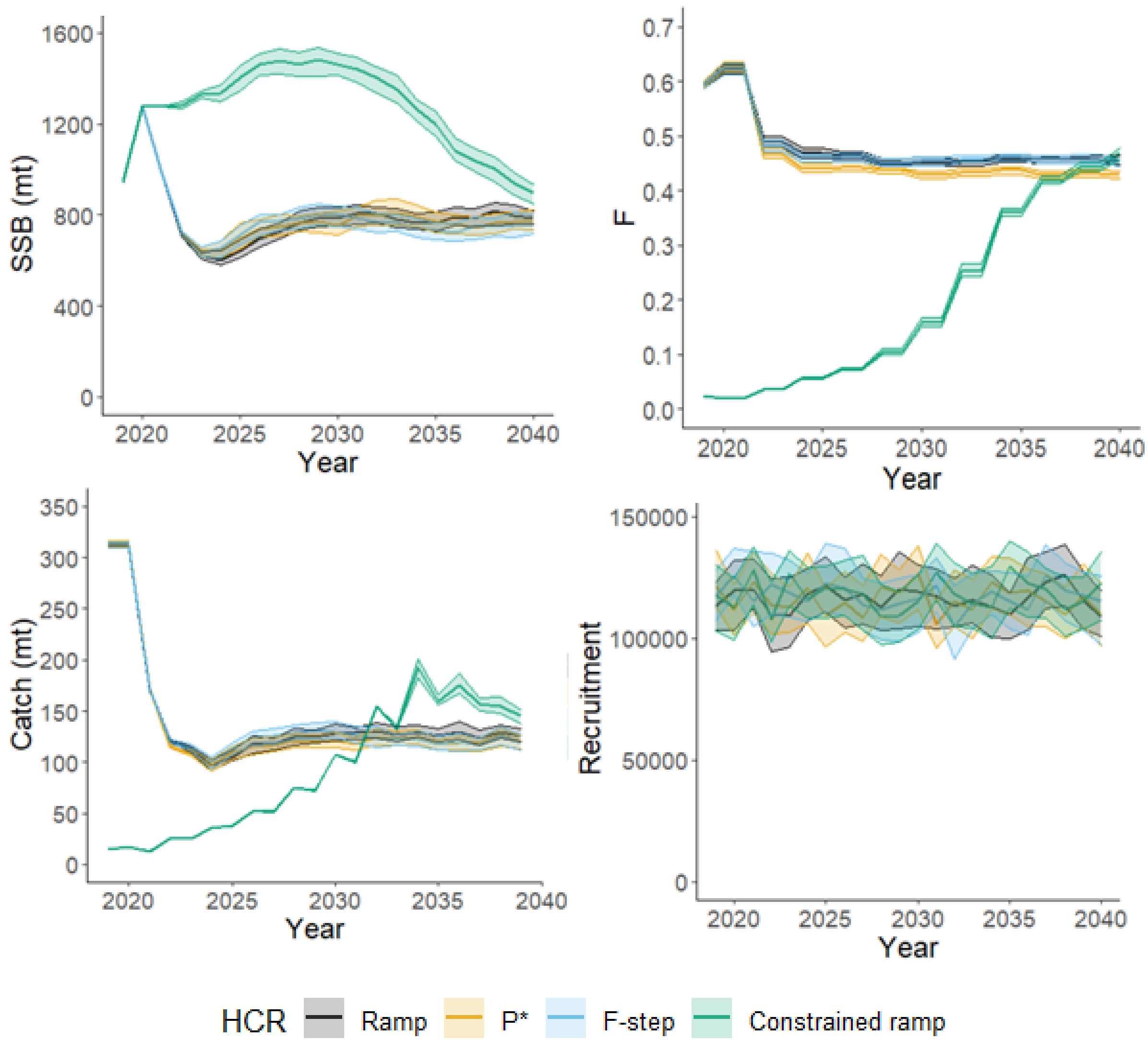


Figure 68. True operating model median spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits with 95% confidence intervals for Georges Bank haddock with no stock assessment model misspecification (Base Case for a Stock that is Not Overfished) from 2019 to 2040.

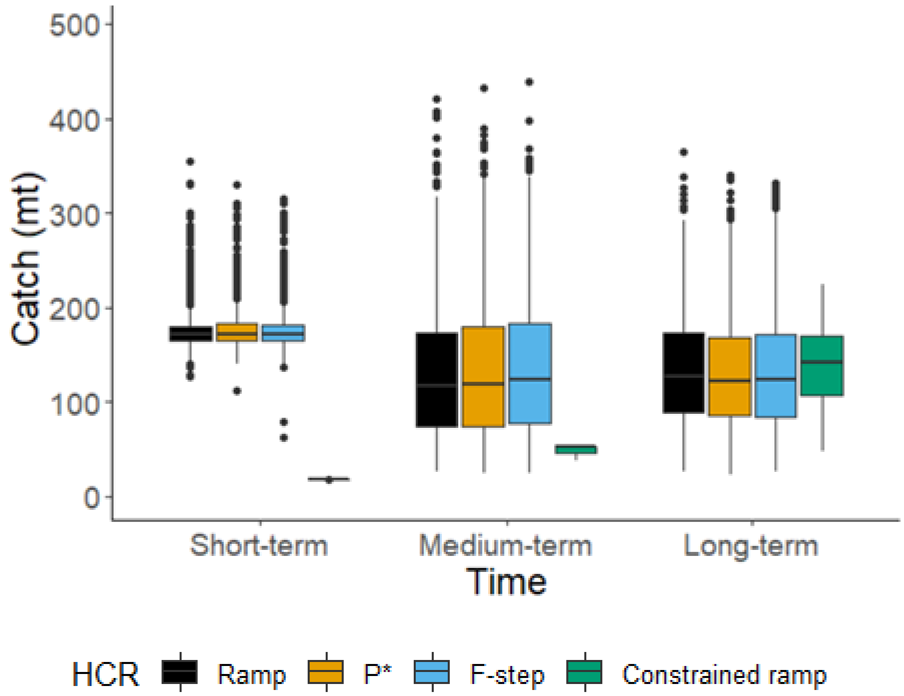


Figure 69. True median catch for Georges Bank haddock with no stock assessment model misspecification (Base Case for a Stock that is Not Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

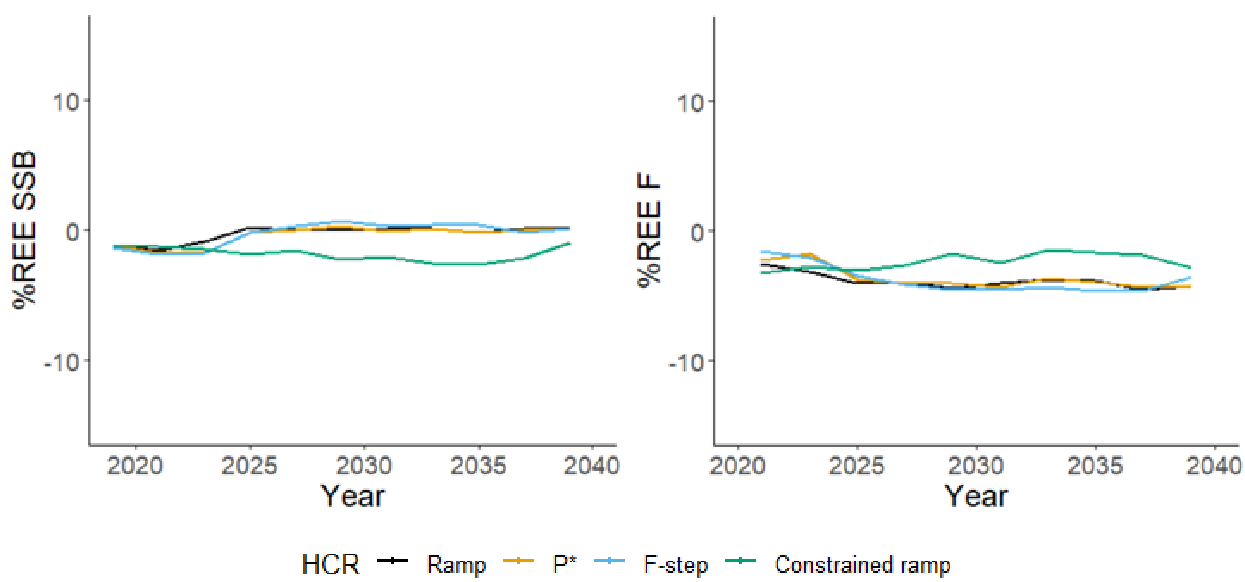


Figure 70. Percent relative error (REE) in terminal estimated spawning stock biomass (SSB) and fishing mortality (F) for Georges Bank haddock with no stock assessment model misspecification (Base Case for a Stock that is Not Overfished).

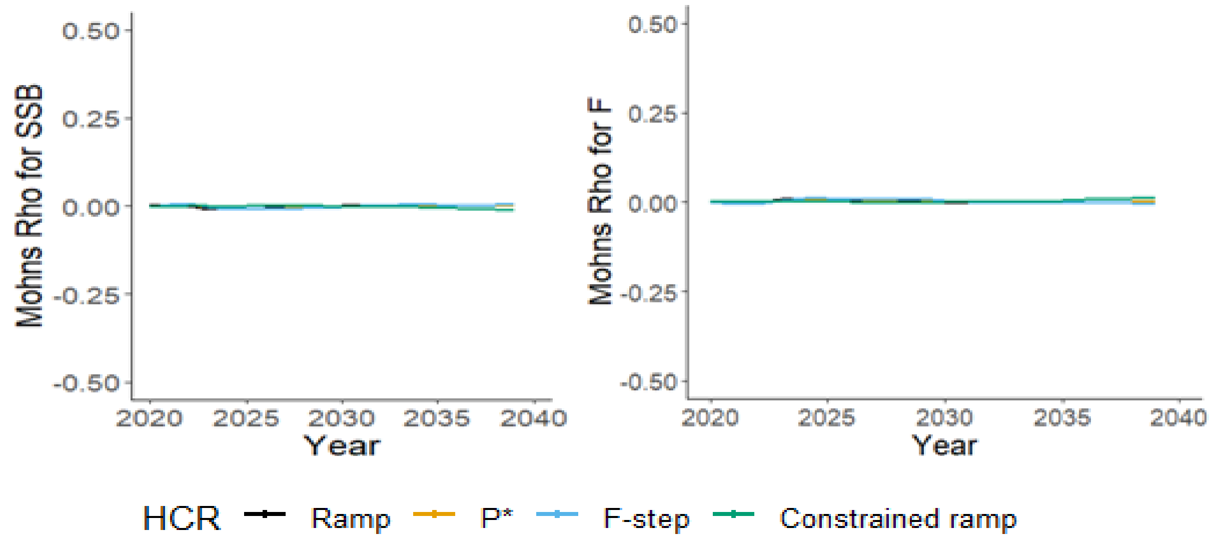


Figure 71. Mohn's Rho values for spawning stock biomass (SSB) and fishing mortality (F) for Georges Bank haddock with no stock assessment model misspecification (Base Case for a Stock that is Not Overfished).

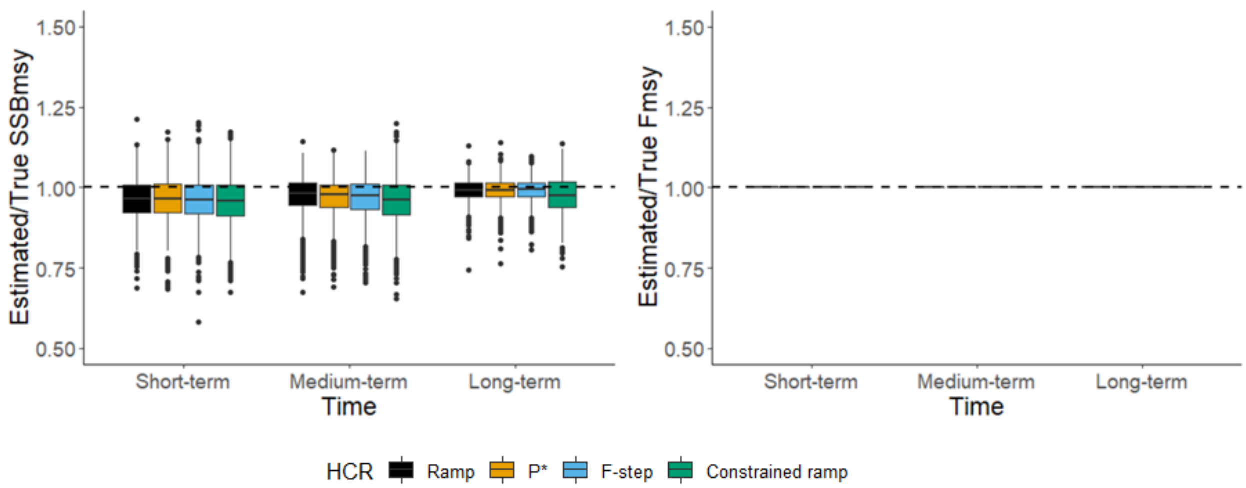


Figure 72. Median ratios of estimated to true ratios of the stock biomass reference point (SSB_{MSY}) and fishing mortality biomass reference point (F_{MSY}) for Georges Bank haddock with no stock assessment model misspecification (Base Case for a Stock that is Not Overfished) in the short- (1-5 years), medium- (5-10 years), and long-term (10-20 years).

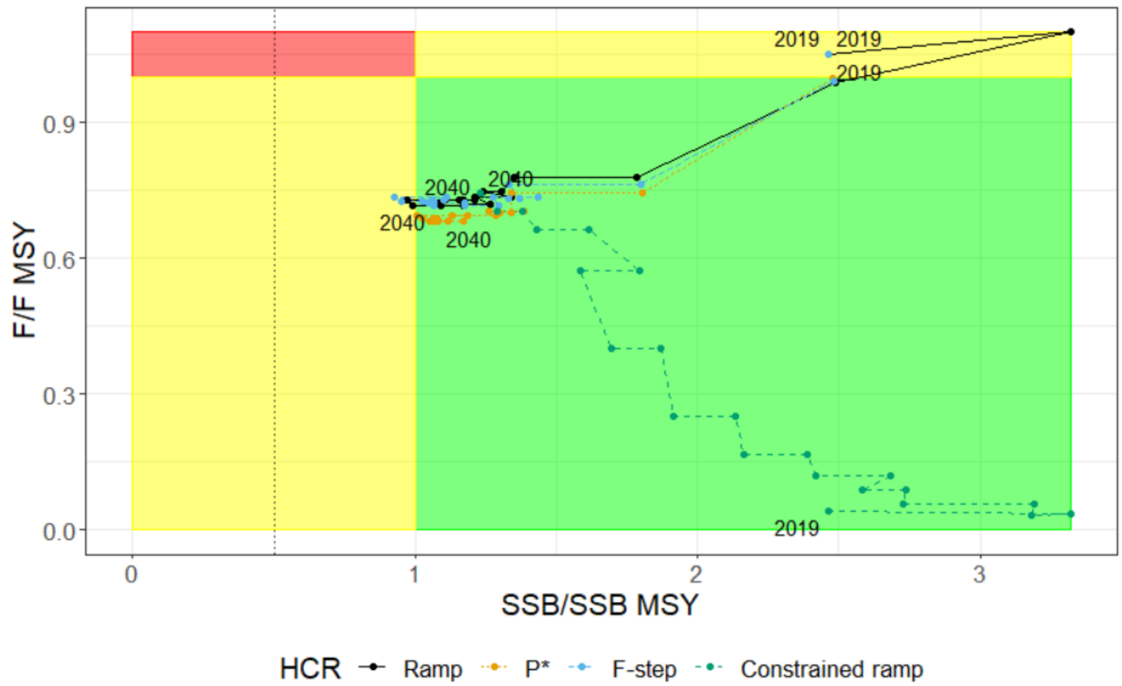


Figure 73. True stock status trajectories (ratio of fishing mortality over fishing mortality reference point (F/F$_{MSY}$) versus ratio of spawning stock biomass over spawning stock biomass reference point (SSB/SSB$_{MSY}$) for Georges Bank haddock with no stock assessment model misspecification (Base Case for a Stock that is Not Overfished). The dashed line represents the overfished threshold.

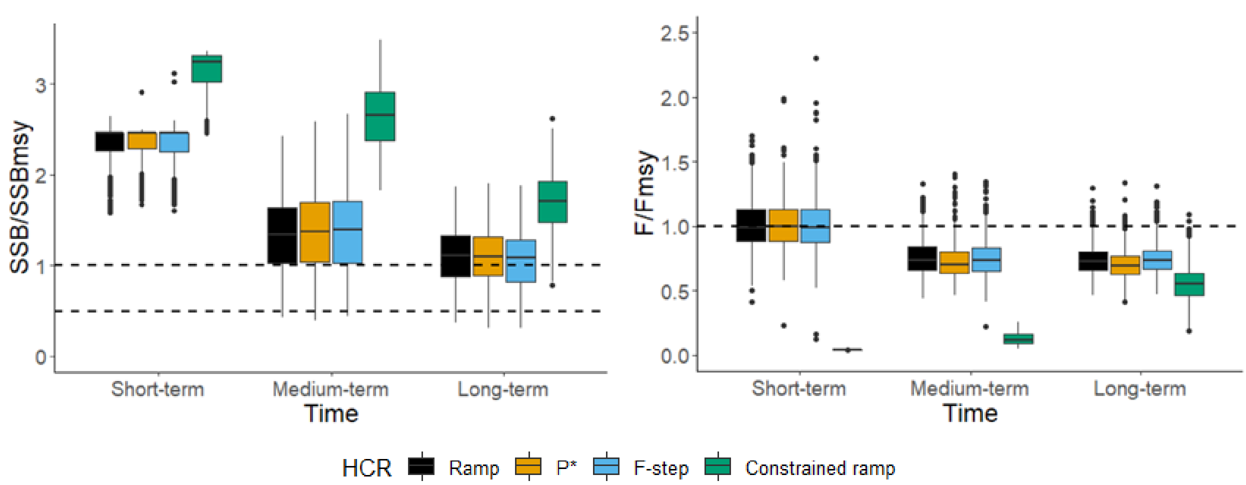


Figure 74. True median ratios of spawning stock biomass to the spawning stock biomass reference point (SSB/SSB$_{MSY}$) and fishing mortality to the fishing mortality biomass reference point (F/F$_{MSY}$) for Georges Bank haddock with no stock assessment model misspecification (Base Case for a Stock that is Not Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

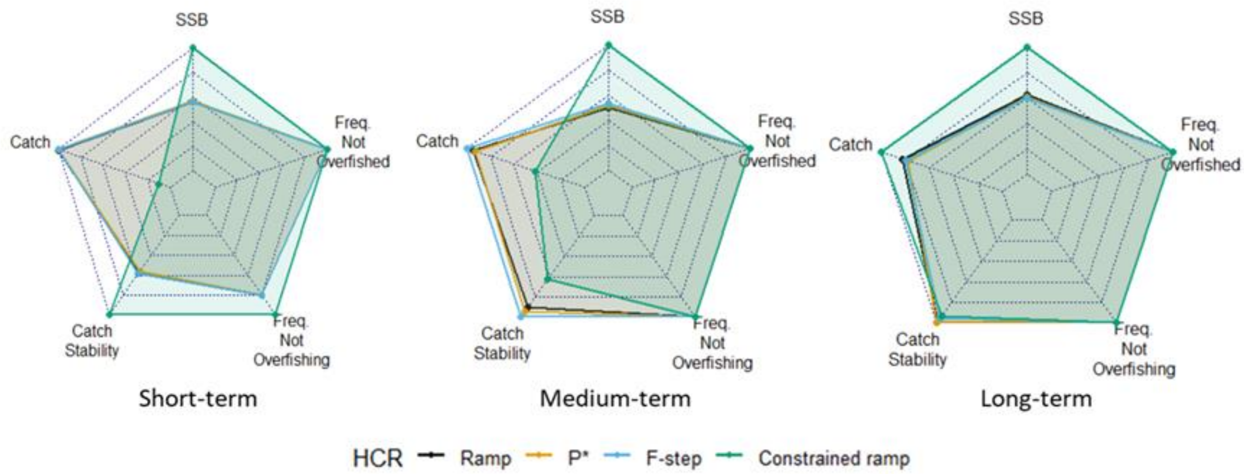


Figure 75. Harvest control rule (HCR) performance for Georges Bank haddock with no stock assessment model misspecification (Base Case for a Stock that is Not Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (10-20 years). Metrics are standardized to the maximum value for each metric attained by the different HCRs and equally weighted. Spawning stock biomass (SSB) and catch are median SSB and catch for the time period.

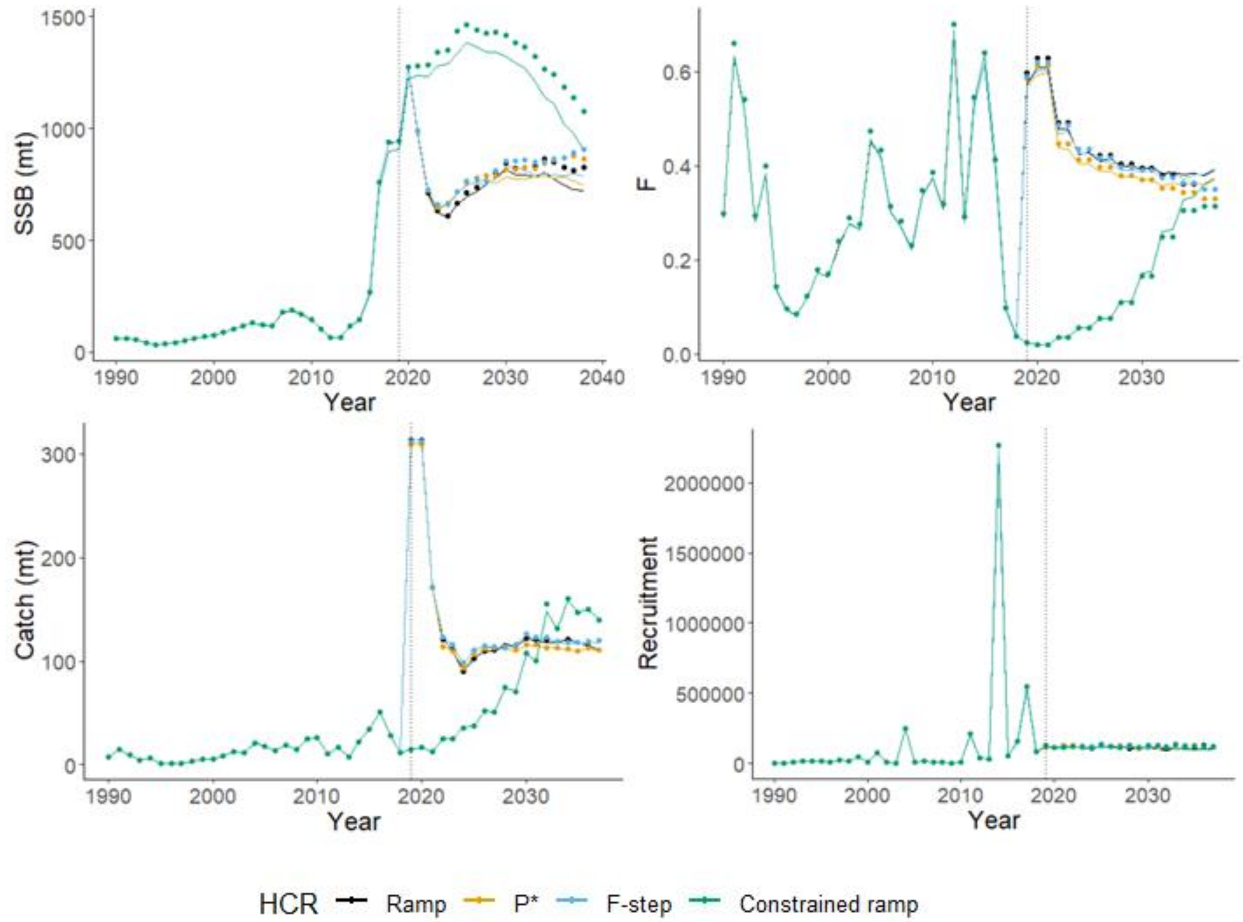


Figure 76. True operating model (closed circles) and estimated stock assessment values from the terminal assessment (stock assessment completed in 2039 with a terminal year of 2038; lines) of spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits for Georges Bank haddock with a survey catchability stock assessment model misspecification (Survey Catchability Misspecification for a Stock that is Not Overfished) from 1982 to 2038 for SSB and 2037 for other metrics. The dashed line represents the beginning of the management procedure period (2019).

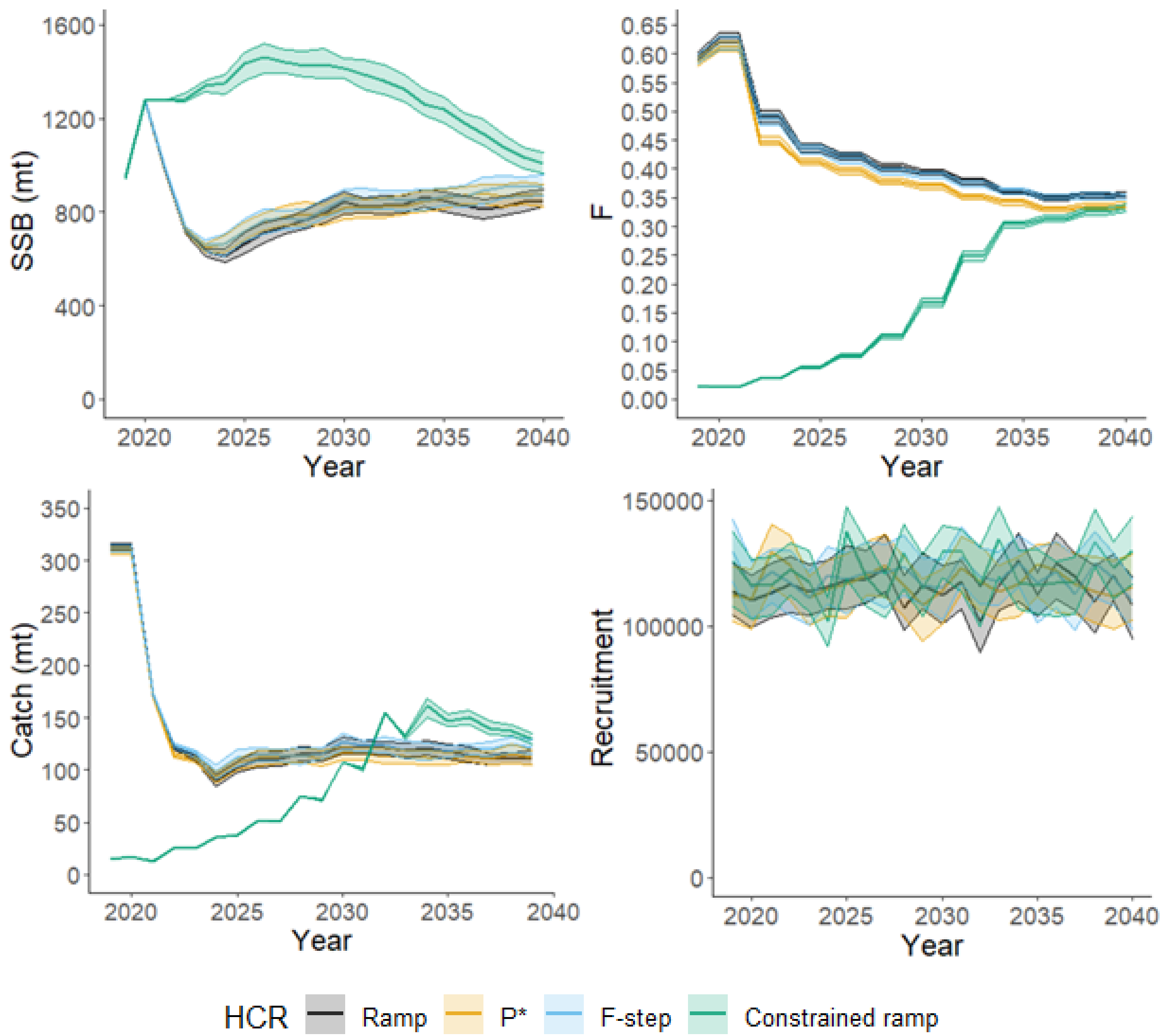


Figure 77. True operating model median spawning stock biomass (SSB), fishing mortality (F), catch (mt), and recruits with 95% confidence intervals for Georges Bank haddock with a survey catchability stock assessment model misspecification (Survey Catchability Misspecification for a Stock that is Not Overfished) from 2019 to 2040.

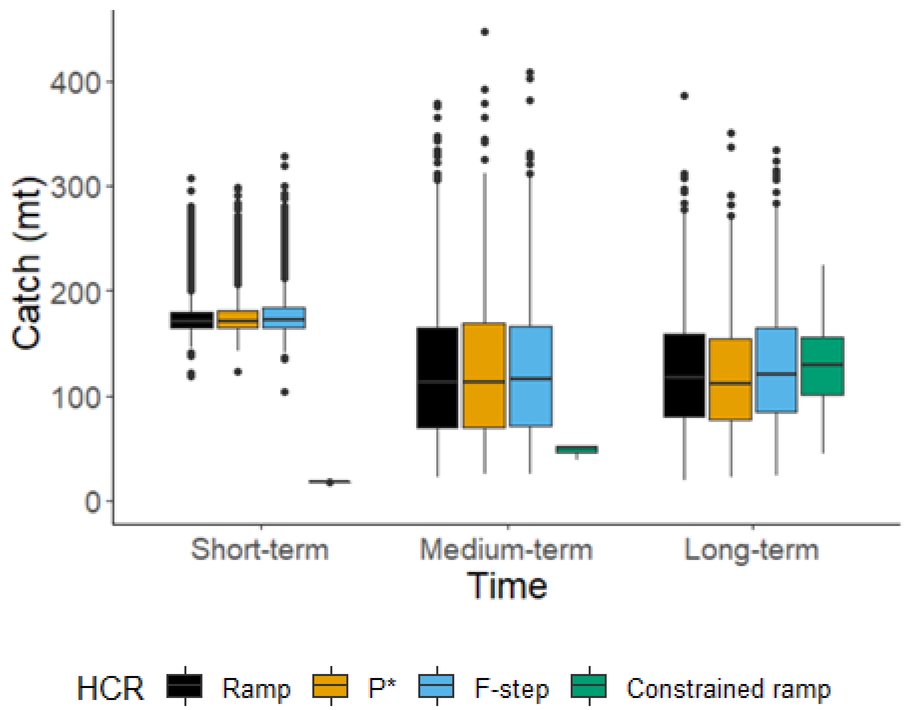


Figure 78. True median catch for Georges Bank haddock with a survey catchability stock assessment model misspecification (Survey Catchability Misspecification for a Stock that is Not Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

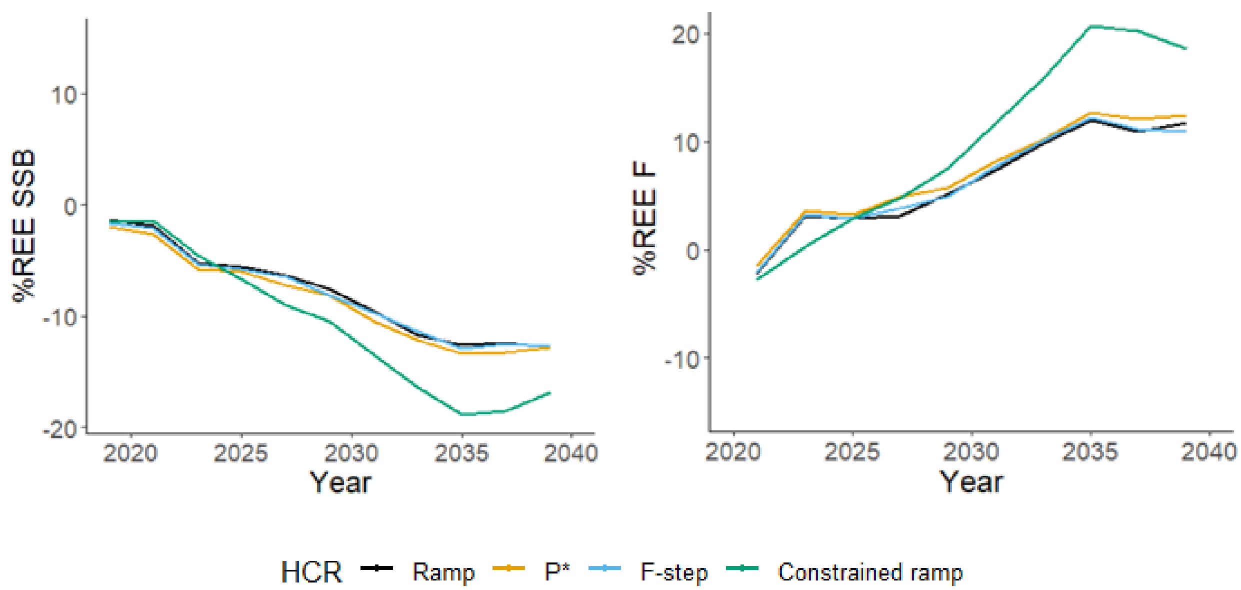


Figure 79. Percent relative error (REE) in terminal estimated spawning stock biomass (SSB) and fishing mortality (F) for Georges Bank haddock with a survey catchability stock assessment model misspecification (Survey Catchability Misspecification for a Stock that is Not Overfished).

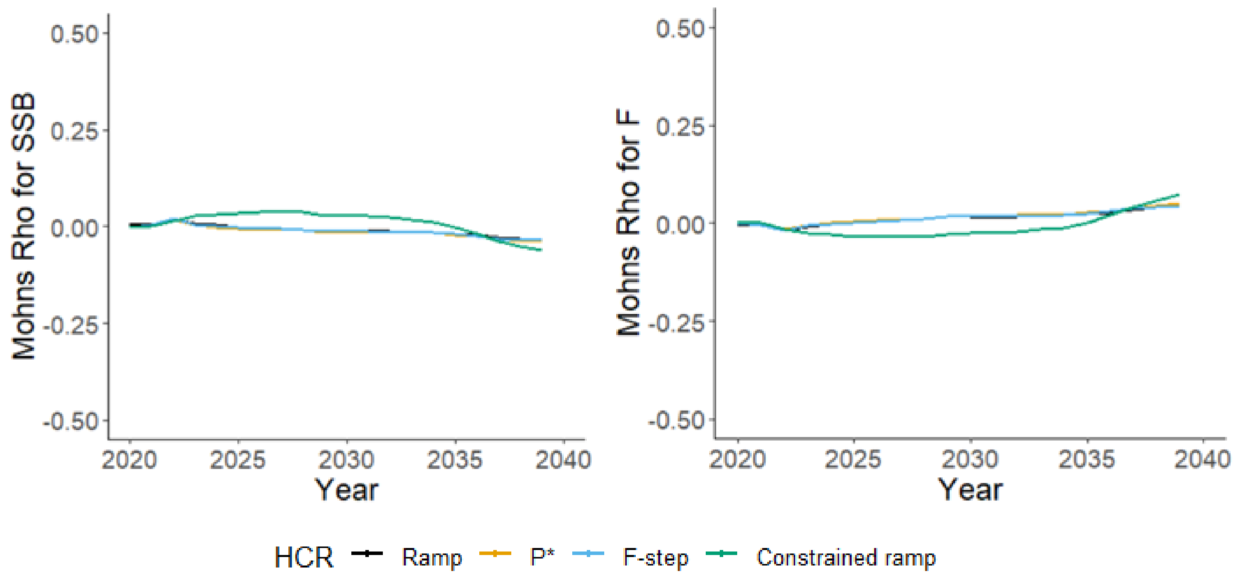


Figure 80. Mohn's Rho values for spawning stock biomass (SSB) and fishing mortality (F) for Georges Bank haddock with a survey catchability stock assessment model misspecification (Survey Catchability Misspecification for a Stock that is Not Overfished).

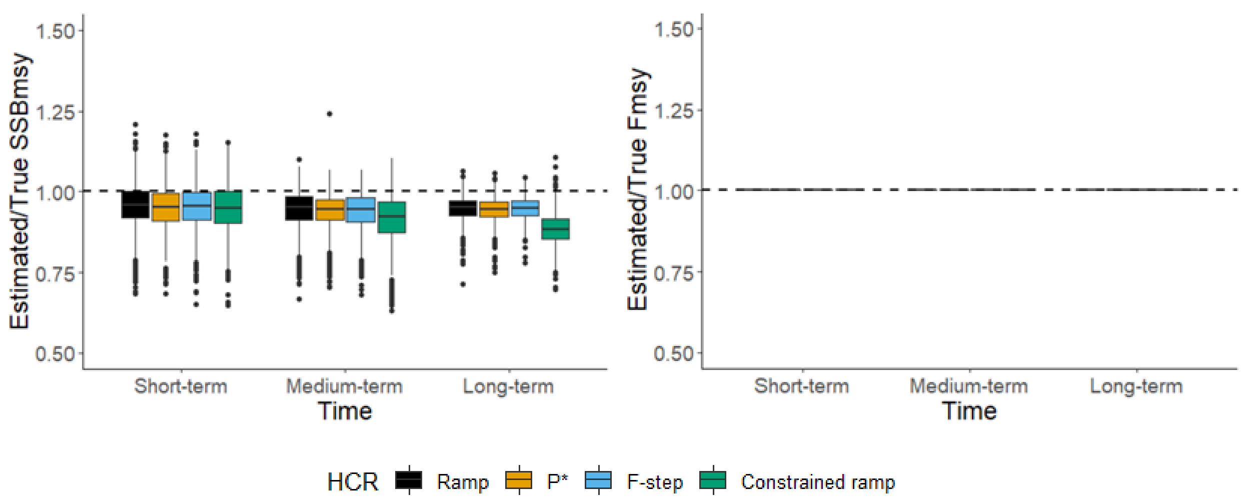
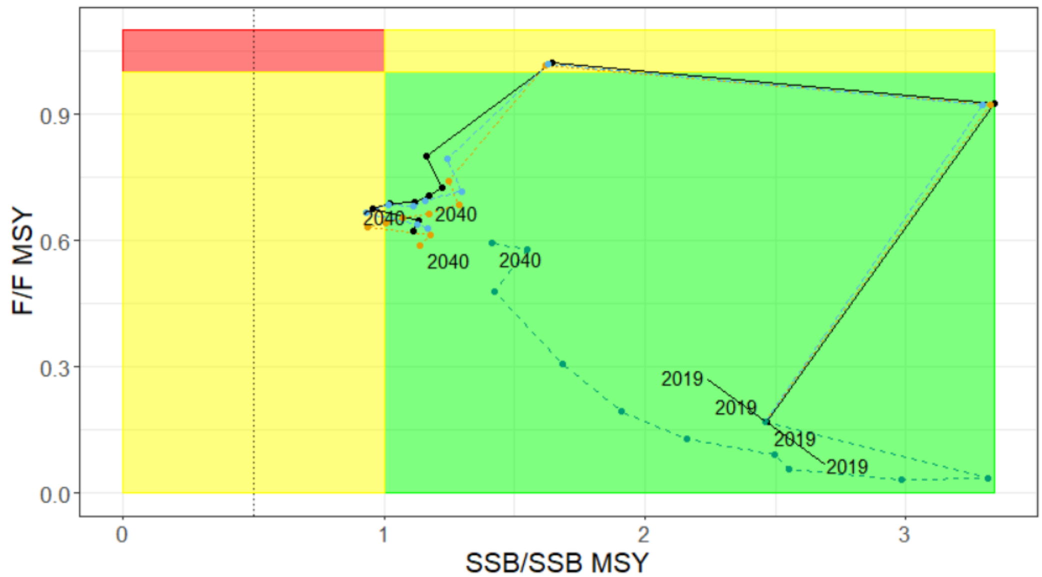


Figure 81. Median ratios of estimated to true ratios of the stock biomass reference point (SSB_{MSY}) and fishing mortality biomass reference point (F_{MSY}) for Georges Bank haddock with a survey catchability stock assessment model misspecification (Survey Catchability Misspecification for a Stock that is Not Overfished) in the short- (1-5 years), medium- (5-10 years), and long-term (10-20 years).

a



b

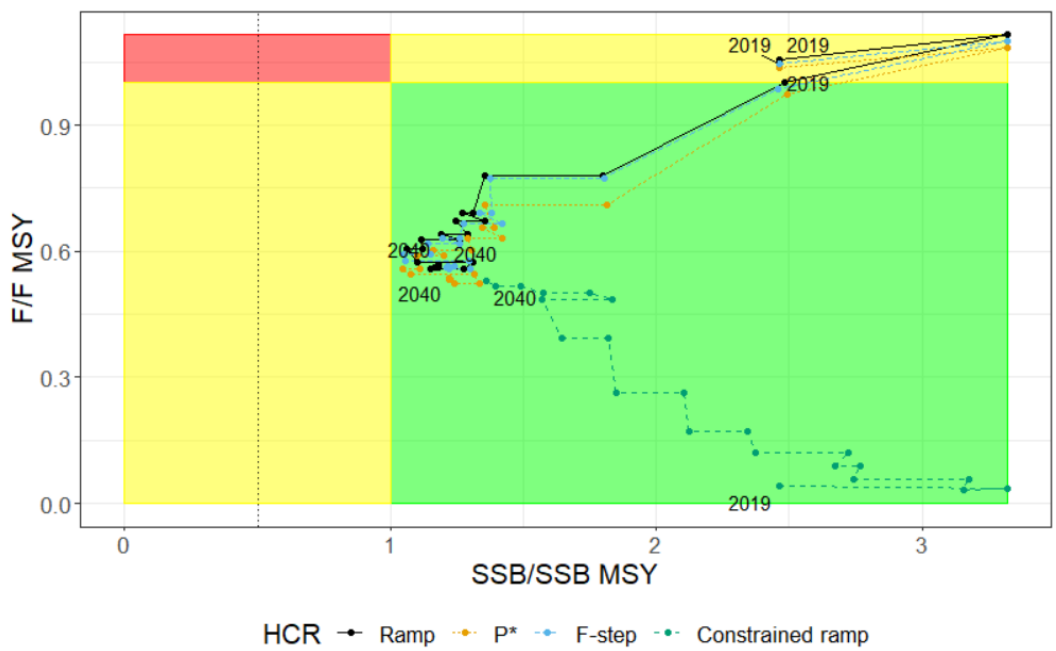


Figure 82. a) Estimated terminal stock status of each year's stock assessment relative to M=0.2 reference points (F/F_{MSY} and SSB/SSB_{MSY}), b) True stock status relative to M=0.2 reference points for Georges Bank haddock with a survey catchability stock assessment model misspecification (Survey Catchability Misspecification for a Stock that is Not Overfished). The dashed line represents the overfished threshold. Estimated terminal stock status is lagged behind a year (the last year of data is from the previous year).

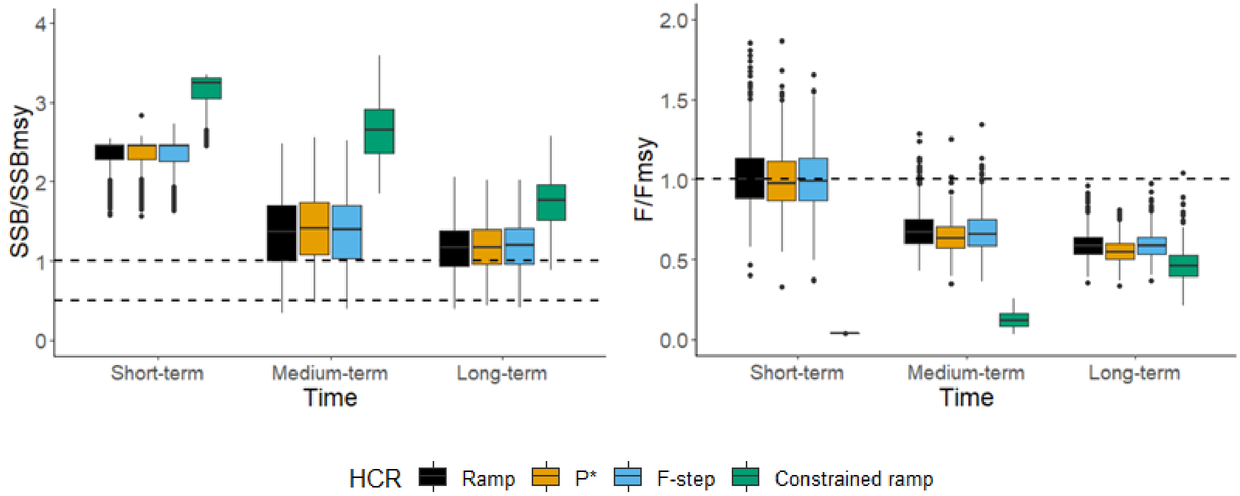


Figure 83. True median ratios of spawning stock biomass to the spawning stock biomass reference point (SSB/SSB_{MSY}) and fishing mortality to the fishing mortality biomass reference point (F/F_{MSY}) for Georges Bank haddock with a survey catchability stock assessment model misspecification (Survey Catchability Misspecification for a Stock that is Not Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-21 years).

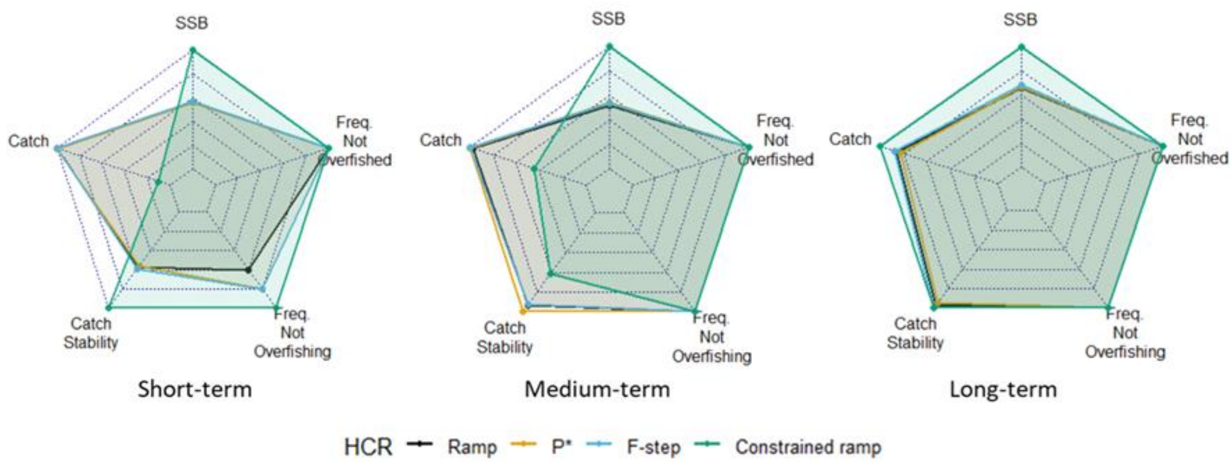


Figure 84. Harvest control rule (HCR) performance for Georges Bank haddock with a survey catchability stock assessment model misspecification (Survey Catchability Misspecification for a Stock that is Not Overfished) in the short- (1-5 years), medium- (6-10 years), and long-term (11-20 years). Metrics are standardized to the maximum value for each metric attained by the different HCRs and equally weighted. Spawning stock biomass (SSB) and catch are median SSB and catch for the time period.

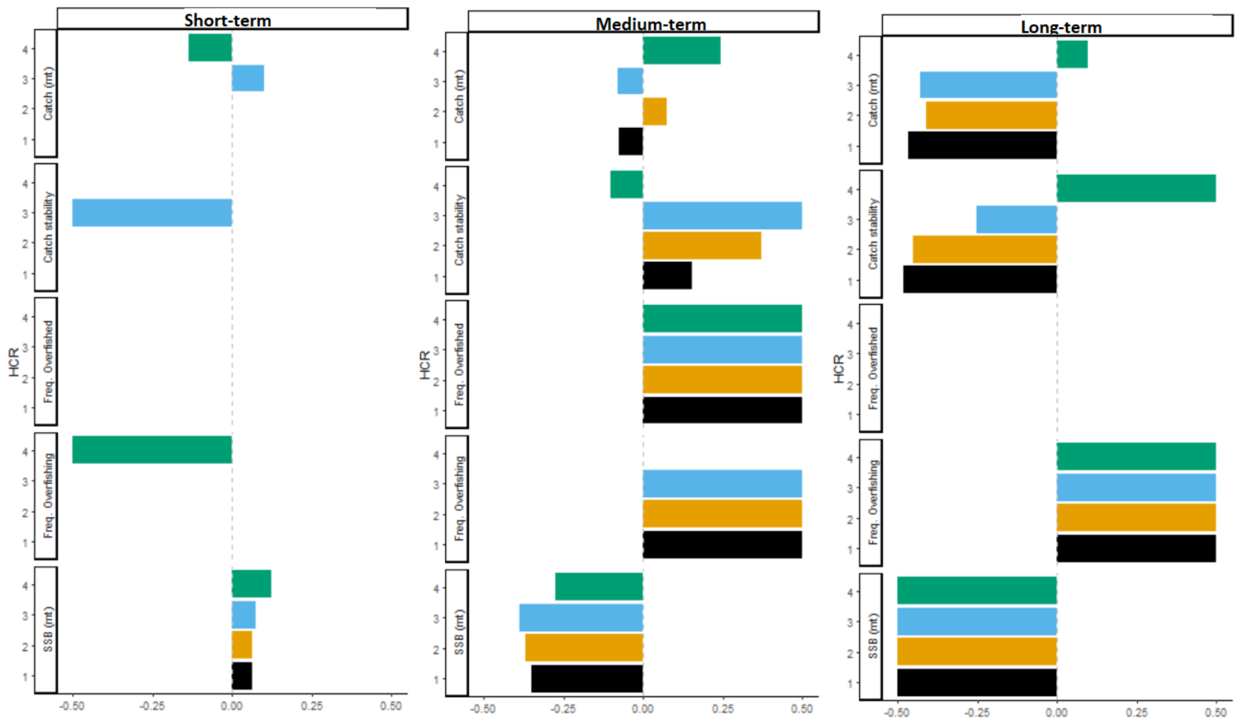


Figure 85. Short- (1-5 years), medium- (6-10 years), and long-term (11-21 years) relative difference in harvest control rule performance between the Base Case for a Stock that is Overfished and the Natural Mortality Misspecification for a Stock that is Overfished Scenarios. 1= ramp HCR; 2= P* HCR; 3= F-step HCR; 4= constrained ramp HCR.

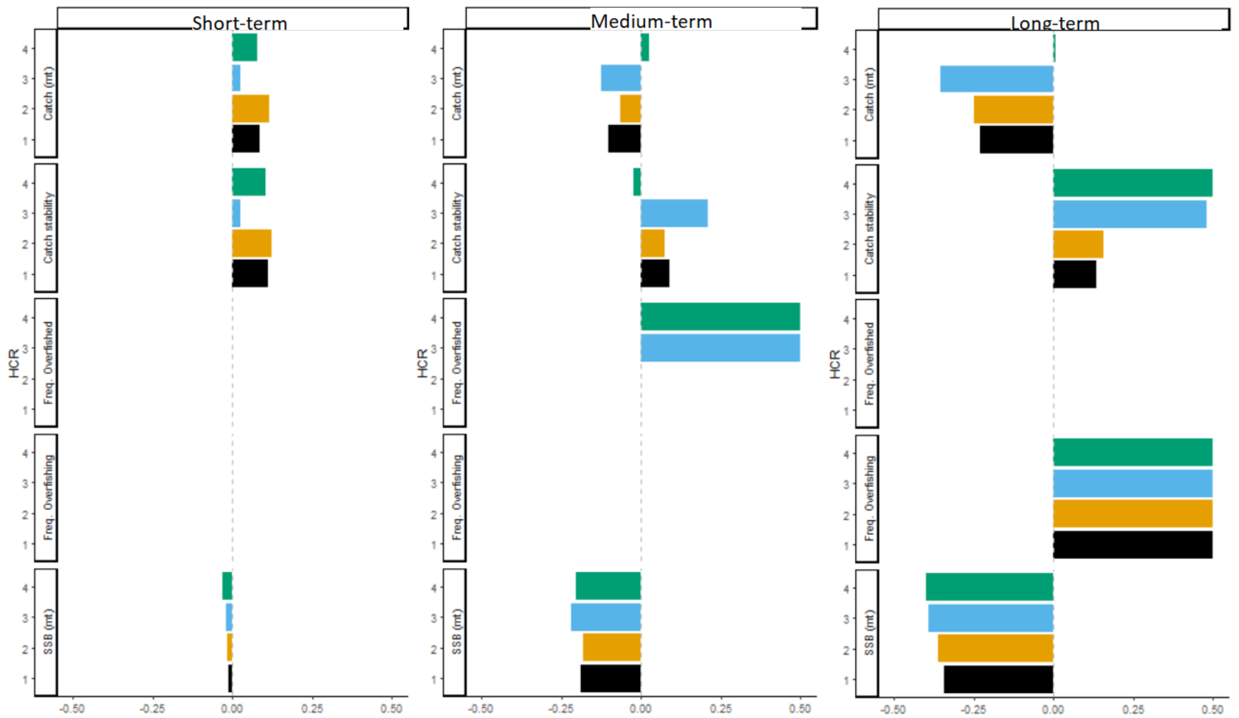


Figure 86. Short- (1-5 years), medium- (6-10 years), and long-term (11-21 years) relative difference in harvest control rule performance between the Base Case for a Stock that is Overfished and the Recruitment Misspecification for a Stock that is Overfished Scenarios. 1= ramp HCR; 2= P* HCR; 3= F-step HCR; 4= constrained ramp HCR.

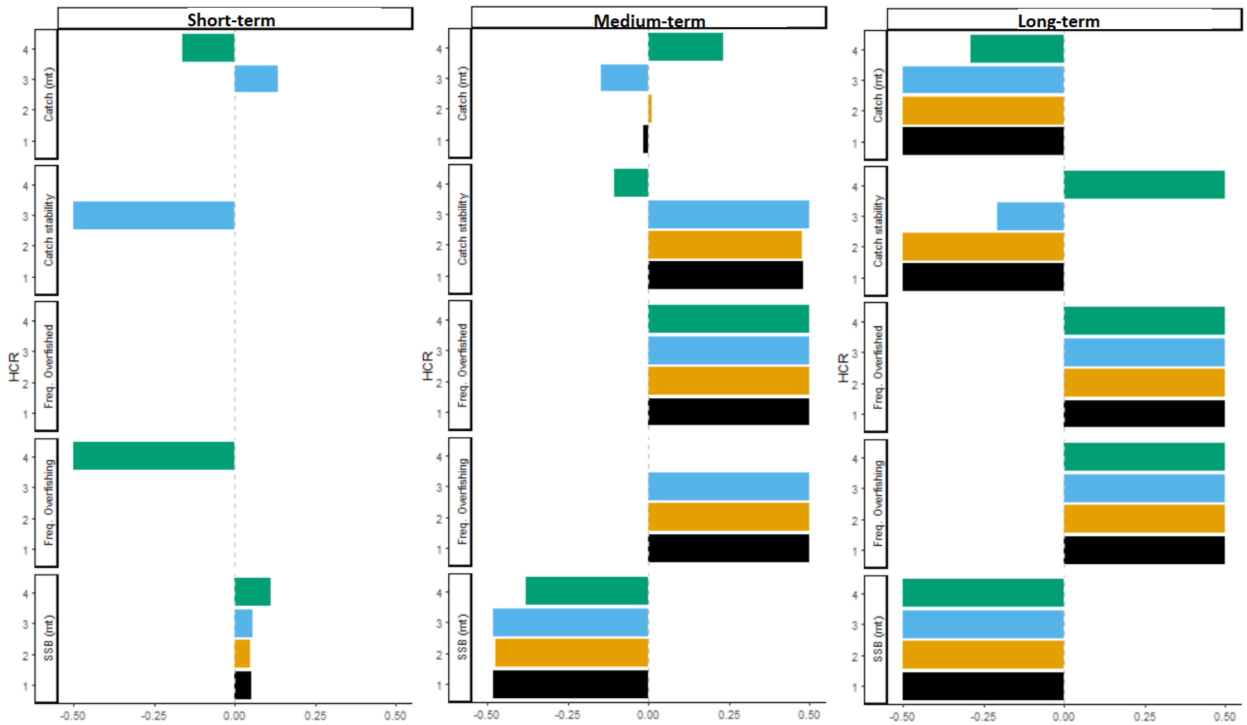


Figure 87. Short- (1-5 years), medium- (6-10 years), and long-term (11-21 years) relative difference in harvest control rule performance between the Base Case for a Stock that is Overfished and the Natural Mortality and Recruitment Misspecification for a Stock that is Overfished Scenarios. 1= ramp HCR; 2= P* HCR; 3= F-step HCR; 4= constrained ramp HCR.

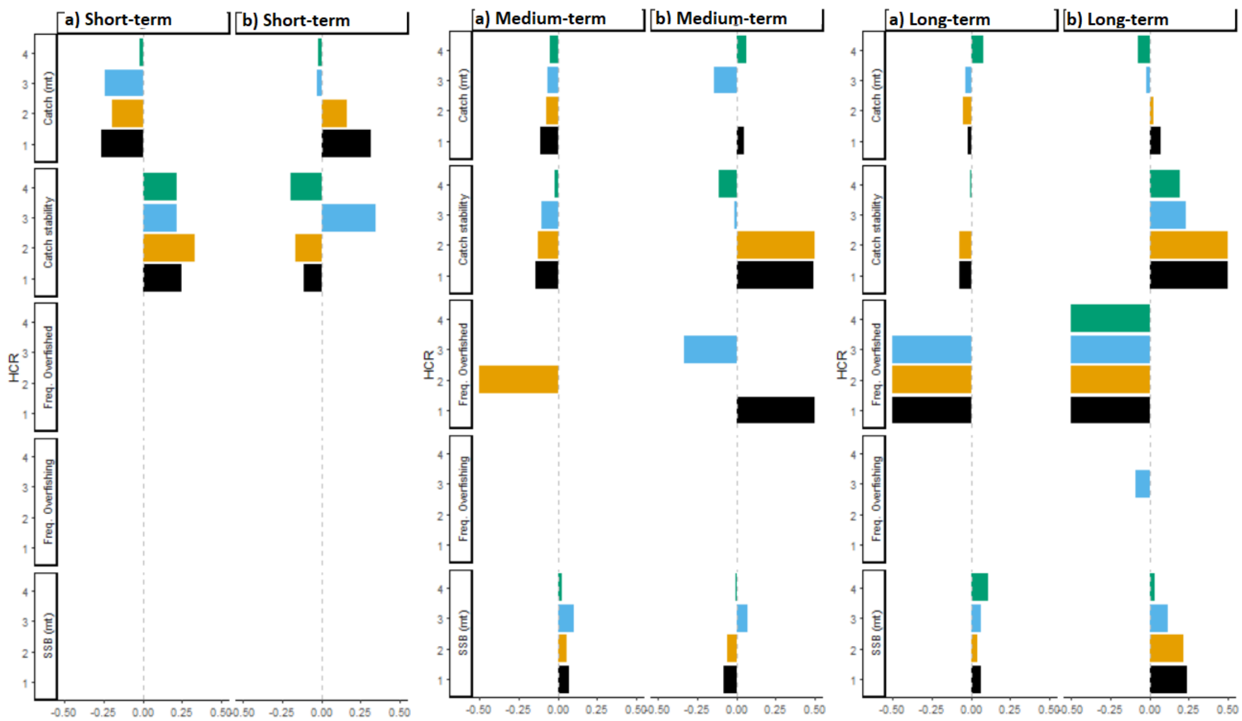


Figure 88. Short- (1-5 years), medium- (6-10 years), and long-term (11-21 years) relative difference in harvest control rule performance for the Natural Mortality and Recruitment Misspecification for a Stock that is Overfished Scenarios with catch advice based on two-year projections and a) catch advice based on year one projections held constant and b) annual stock assessment updates. 1= ramp HCR; 2= P* HCR; 3= F-step HCR; 4= constrained ramp HCR.

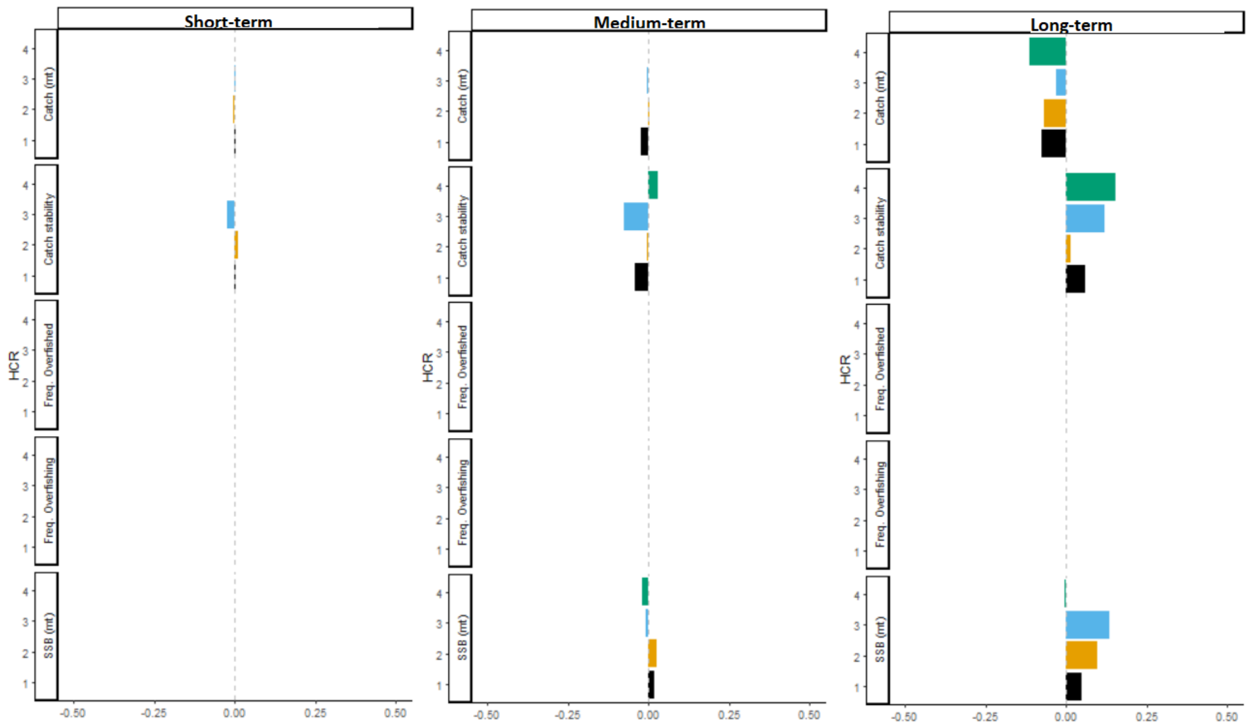


Figure 89. Short- (1-5 years), medium- (6-10 years), and long-term (11-21 years) relative difference in harvest control rule performance between the Base Case for a Stock that is Not Overfished and the Survey Catchability Misspecification for a Stock that is Not Overfished Scenarios. 1= ramp HCR; 2= P* HCR; 3= F-step HCR; 4= constrained ramp HCR.

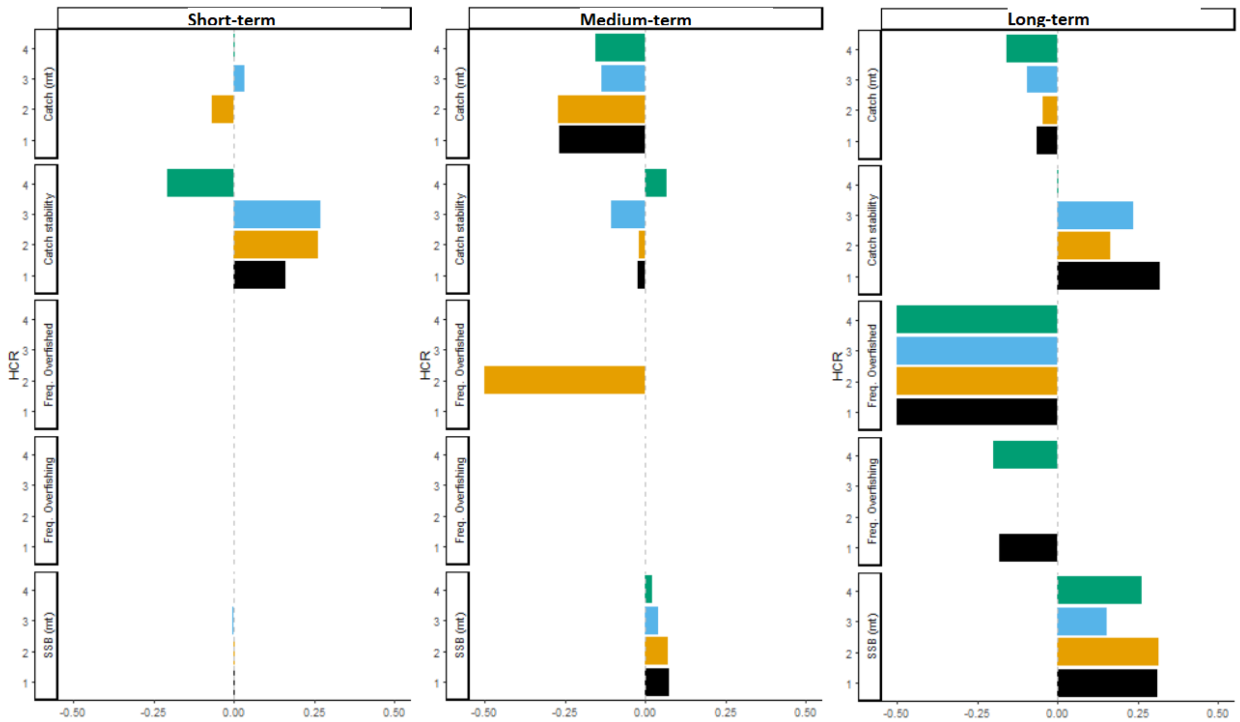


Figure 90. Short- (1-5 years), medium- (6-10 years), and long-term (11-21 years) relative difference in harvest control rule performance with the Natural Mortality and Recruitment Misspecification for a Stock that is Overfished Scenario without and with rho-adjustments. 1= ramp HCR; 2= P* HCR; 3= F-step HCR; 4= constrained ramp HCR.