Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2025/010

Maritimes Region

Identification of a Limit Reference Point and Proposal of an Upper Stock Reference Point for Canadian Fishery Management of Eastern Georges Bank (5Zjm) Haddock (*Melanogrammus aeglefinus*)

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March 2025

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-75618-9 Cat. No. Fs70-5/2025-010E-PDF

Correct citation for this publication:

Wang, Y., and Carruthers, T. 2025. Identification of a Limit Reference Point and Proposal of an Upper Stock Reference Point for Canadian Fishery Management of Eastern Georges Bank (5Zjm) Haddock (*Melanogrammus aeglefinus*). DFO Can. Sci. Advis. Sec. Res. Doc. 2025/010. iv + 27 p.

Aussi disponible en français :

*Wang, Y. et Carruthers, T. 2025. Détermination d'un point de référence limite et proposition d'un point de référence supérieur du stock pour la gestion des pêches canadiennes de l'aiglefin (*Melanogrammus aeglefinus*) de l'est du banc de Georges (5Zjm) Secr. can. des avis sci. du MPO. Doc. de rech. 2025/010. iv + 27 p.*

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ABSTRACT

Haddock (*Melanogrammus aeglefinus*) on eastern Georges Bank (DFO statistical unit areas 5Zj and 5Zm; EGB) is a Canada/U.S. transboundary species assessed by the Transboundary Resource Assessment Committee (TRAC). A new statistical catch-at-age stock assessment model was developed for EGB Haddock in March 2022. To meet the requirement of Fisheries and Oceans Canada's Precautionary Approach framework, this document addresses the identification of a limit reference point (LRP) and proposal of an upper stock reference (USR) for Canadian fisheries management of EGB Haddock. Examination of the relationship between spawning stock biomass (SSB) and recruitment shows no evidence of a change in recruitment for the same level of SSB at two different time periods (1931–1954, 1969–2020). Similarly, comparison of surplus production in different time periods does not show evidence of productivity regime shifts. Therefore, the longer time series of data (i.e., 1969–2020) is considered the most appropriate for the calculation of reference points. Multiple candidate LRPs were proposed for peer review, with several deemed inappropriate based on the dynamics of the stock. $B_{recover}$, defined as the minimum biomass between 1991 and 1996 that resulted in sustained recovery to historically high levels, was determined to be the most appropriate LRP for EGB Haddock (8,620 mt). EGB Haddock appears to have two distinct groupings in magnitude of recruitment, with large SSB generally resulting in high recruitment and small SSB generally resulting in low recruitment. The proposed USR was calculated using the "Rago--Razor" method based on SSB and recruitment data and is estimated as 26,732 mt. Historical retrospective closed-loop simulation confirmed that the biomass dynamics of EGB Haddock were strongly driven by high recruitment variability over the past two decades. If using LRP and USR as control points in the historical fishery, retrospective closed-loop simulation showed that historical terminal biomass and average yield would be largely invariant to the implementation of alternative harvest control rules and various levels of the specified LRP and USR.

INTRODUCTION

One component of the Fisheries and Oceans Canada (DFO) fishery decision-making framework that incorporates the precautionary approach (PA Policy, DFO 2009) is to define reference points while taking into account uncertainty and risk for key harvested stocks managed by DFO. The limit reference point (LRP) and the upper stock reference (USR) are used as the boundaries delineating the critical, cautious and healthy zones (Figure 1). The amended Fisheries Act (2019) includes new Fish Stocks Provisions that introduce legal obligations to implement measures to maintain prescribed major fish stocks above the LRP (DFO 2021a). For stocks at or below their LRP, there is a requirement to implement measures intended to rebuild fish stocks (DFO 2021b).

Haddock (*Melanogrammus aeglefinus*) on eastern Georges Bank (DFO statistical unit areas 5Zj and 5Zm; EGB) is a Canada/U.S. transboundary species assessed by the Transboundary Resource Assessment Committee (TRAC). The Transboundary Management Guidance Committee (TMGC) develops guidance in the form of harvest strategies, resource sharing and management processes of this stock. In 2003, the TMGC adopted a harvest strategy for EGB Haddock to maintain a low to neutral risk of exceeding the fishing mortality reference. When stock conditions are poor, fishing mortality rates should be further reduced to promote rebuilding (TMGC Guidance Document 2003[1]). Although the TMGC harvest strategy was developed before the establishment of DFO PA framework, the concept of preserving a threshold biomass is consistent. Under this harvest strategy, no explicit biomass reference points that define "poor stock conditions" have been developed by TRAC or requested by TMGC, and stock condition has been inferred based on expert judgement in TRAC assessments. However, in Canadian domestic fishery management, biological reference points are required to evaluate the status of EGB Haddock via the Canadian Environmental Sustainability Indicators program and the Sustainability Survey (DFO 2021a).

The current Canadian LRP was developed in the 2012 DFO Maritimes Region Reference Point Regional Assessment Process with data from the 2011 virtual population analysis (VPA) assessment model run (Wang and Van Eeckhaute 2012). A new statistical catch-at-age model, implemented using the Woods Hole Assessment Model (WHAM; Stock and Miller 2021), was developed for EGB Haddock at the Haddock Research Track peer review assessment meeting held in March 2022 (TRAC 2022). The addition of new data after 2011, together with the new model, could reveal characteristics of stock productivity not previously observed. Accordingly, the 2022 TRAC proposed $F_{40\%spr} = 0.367$, a fishing mortality rate that reduces spawning stock biomass per recruit to 40% of the unfished level, as a candidate fishing reference point for consideration by the TMGC.

This paper is focused on the identification of an LRP and proposal of a USR for Canadian fisheries management of EGB Haddock. Retrospective closed-loop simulations were conducted to quantitatively evaluate the sensitivity of historical fishery yields and spawning stock biomass (SSB) to alternative reference points.

[1] Transboundary Management Guidance Committee Guidance Document 2003/01

DATA

Many stocks show substantial variation in productivity over a long time period. As a general rule, reference points should be established for a stock over the longest possible time period to account for such variation (DFO 2013). EGB Haddock has supported a commercial fishery since the early 1920s (Clark et al. 1982). Catches from EGB Haddock during the 1930s to 1950s were relatively stable and generally ranged between 20,000 mt and 40,000 mt (Figure 2) (Schuck 1951). The highest annual landings of approximately 60,000 mt were reported from EGB during the early 1960s. The age composition of EGB Haddock catches from 1931 to 1955 are only known approximately. Given this limitation, an illustrative VPA under an assumption of constant natural mortality (M) of 0.2 was used to calculate the beginning-of-year biomass, spawning stock biomass (SSB) and recruitment at age 1 (R) for 1931–1955. Considering the uncertainties in fishery age composition and lack of survey abundance indices, data from this early time period was only used for evaluating the possibility of regime shifts.

The time series of biomass, SSB, and R from 1969 to 2021 are generated from the research track model from the 2022 TRAC EGB Haddock assessment (Wang et al. In Prep[2]). Maturity ogives derived from samples in the National Marine Fisheries Service (NMFS) spring survey and weight-at-age observed from samples in DFO winter survey are used to calculate SSB (Wang et al. In Prep[2]). Prior to the mid-1990s, EGB Haddock had been overfished for decades. Improved recruitments in the late 1990s, lower exploitation, and reduced capture of small fish in the fisheries allowed the biomass to increase from near a historical low of 12,000 mt in 1993 to 50,000 mt in 2002. The continued increase of biomass after 2003 was due to the contribution of the exceptionally strong 2003, 2010 and 2013 year classes (Figure 3). Biomass increased to 100,000 mt in 2009 and reached a historical high of 150,000 mt in 2019 (Figure 2). The sharp decrease after 2009 (Figure 2) was largely driven by the slower growth and high estimated natural mortality of 0.516 over 2010–2021.

PRODUCTIVITY REGIME SHIFTS

The specification of reference points strongly depends on both the choice of method and time--series length. DFO guidance suggests that biomass reference points should only be estimated from data during a period of low productivity when there is no expectation that the conditions consistent with higher productivity will ever recur naturally or be achievable through management (DFO 2013, 2023).

The primary biological processes that comprise the production response are growth, maturation, natural mortality, and recruitment. For recent time periods when EGB Haddock biomass was relatively high, a decrease in growth and older maturation have been observed from both survey and fishery samples, and an increase in natural mortality has been estimated. Studies have shown that there is a density-dependent impact on growth and natural mortality for this stock (TRAC 2020, TRAC 2022, Wang et al. 2021, Wang et al. In Prep[2]). Changes caused by density-dependence should not be considered as productivity regime shifts, but be regarded as transient because the stock is expected to return to earlier conditions when biomass returns to

[2] Wang Y., Regnier-McKellar, C. and Kraska, K. In Prep. Assessment of Haddock on Eastern Georges Bank for 2022. TRAC Reference Document.

lower levels. This is reflected by the observed improvements of length- and weight-at-age in fishery and survey samples coinciding with the sharp decrease in biomass in the last few years (TRAC 2022).

Further examination of the relationship between SSB and R shows that recruitment has been highly variable (log standard deviation = 2). There is no evidence of a change in recruitment for the same level of SSB at two different time periods (1931–1954, 1969–2020) (Figure 4). Similarly, comparison of surplus production (Biomass[t+1]-Biomass[t]+Catch[t]) in different time periods does not show compelling evidence of productivity regime shifts (Figure 4). Therefore, the longer time series (1969–2020) of data is considered more appropriate for the calculation of reference points.

LIMIT REFERENCE POINT

The LRP is defined as the stock level below which productivity is sufficiently impaired to cause serious harm to the resource (DFO 2009). "Serious harm" is an undesirable state that can be associated with impaired productivity or reproductive capacity, resulting from changes to biological processes such as recruitment, growth, maturation and survival, and may lead to a loss of resilience, defined as an impaired ability to rebuild, exceed replacement or to recover from perturbation (DFO 2023).

METHOD

Approaches for estimating candidate LRPs normally differ in their assumption of resilience of the stock. No single method of identifying an LRP is suitable for every stock (Myers et al. 1994, Kronlund et al. 2018). Best practice when defining an LRP should evaluate as many diagnostic measures as possible to account for uncertainty. To identify a plausible LRP for EGB Haddock, the following methods that could reflect Haddock reproductive capacity or productivity are evaluated:

1. *B_{MSY} or B_0 based approach (DFO 2023).* In the concept of stock productivity, LRPs are frequently defined as a proportion of B_{MSY} (equilibrium biomass at maximum sustainable yield) or B_0 (mean equilibrium unfished biomass). However, both MSY and B_0 based biomass reference points are defined under the condition of equilibrium. For B_{MSY}, there are assumptions of stationarity in key model productivity parameters such as growth, M, and recruitment. For B_0, there is sensitivity to uncertainty in model assumptions (e.g., M, and reproductive resilience *h* which is the fraction of recruitment when the SSB declines to 20% of its unfished level). For dynamic $B_{0,}$ there is an implicit assumption that temporal changes in biological parameters are independent of fishing and are not density dependent (DFO 2023). However, the population dynamics of EGB Haddock are characterized by large variation in recruitments driven by environment, density-dependent growth and M. These approaches violate the assumption of equilibrium and exclude the use of B_{MSY} or B_0 based approach to define biomass reference points.
2. *Per-recruit reference points* (DFO 2023). In this approach, the long-term equilibrium biomass at a constant proxy F_{MSY} ($F_{X\%SPR}$ or others) is used as a proxy for B_{MSY} (DFO 2023). However, the density-dependent M, growth and subsequent changes in fishery selectivity make it challenging to select an appropriate percentage (X) and $F_{X\%SPR}$ for EGB Haddock. In addition, per-recruit reference points do not account for reductions in the number of recruits

as SSB declines (Sainsbury 2008). Therefore, it does not provide an internal basis for defining a threshold for recruitment overfishing and is not consistent with the objective of setting an LRP to prevent serious harm to the stock. For EGB Haddock, a positive relationship is observed between R and SSB (Figures 5 and 6); therefore, this approach is not feasible to calculate an LRP.

3. *BH50 or RK50* (DFO 2002, DFO 2023). Following this method, the SSB at which expected average recruitment is one half of the maximum recruitment predicted by assuming an underlying Beverton-Holt (BH) or Ricker (RK) stock-recruit relationship. For EGB Haddock, BH50 and RK50 are not considered due to the unreasonable fit of BH and RK stock-recruit models.

Consequently, candidate LRPs for EGB Haddock are estimated using the following empirical approaches (note that recognizing the uncertainty in estimates of the most recent recruitment due to limited observations, the 2020 year class was excluded in the calculation of the LRP):

1. *Surplus production.* Surplus production is a direct measure of stock productivity (NAFO 2004). Serious harm can be associated with an elevated risk of depensation. That is, negative density dependence, in which the intrinsic rate of increase for a stock decreases, rather than increases, as abundance declines (DFO 2023). Here, using the time series of total biomass estimated from the 2022 TRAC Haddock assessment model and fishery catch, surplus production (SP) was estimated as the annual change in total biomass plus fishery removals (i.e., SP[t] = Biomass[t+1] - Biomass[t] + Catch[t]). The relationship of surplus production rate (i.e., SP[t] / Biomass[t]) versus Biomass (t) is shown in Figure 7. A loess smoothed curve was fitted to check for evidence of depensation, characterized by a lower production rate when biomass falls below a distinct threshold.

2. $B_{recover}$ *(DFO 2002, DFO 2023)*. $B_{recover}$ is defined as the lowest SSB on record that produced the recruitment that allowed the stock to readily recover. It is a proxy for recruitment overfishing, reflecting productivity at low stock sizes under average conditions and is recommended for stocks with occasional large recruitment (DFO 2023). For EGB Haddock, large pulse recruitments and long time series of SR data with a wide range of productivity make $B_{recover}$ an appropriate candidate LRP (Figure 8).

3. *Sb50/90 (DFO 2002).* Sb50/90 is the SSB corresponding to the intersection of the 50th percentile of the recruitment observations and the replacement line for which 10% of the stock-recruitment (SR) points are above the line (Figure 9). It represents the biomass limit below which the population is unlikely to produce average recruitment under good early life history stage survival condition. At the 2002 National Workshop for Reference Points for Gadoids (DFO 2002), this method was shown to be robust to SR model uncertainties and provides a reasonable estimate of an LRP across stocks. Given the challenges of fitting a parametric SR relationship for EGB Haddock, this method is explored here.

4. *International Council for the Exploration of the Sea (ICES) Blim approach.* ICES Technical Guidelines (2021) describe Blim as a deterministic biomass limit below which a stock is considered to have reduced reproductive capacity. Similarly to EGB Haddock, a number of ICES stocks such as Norwegian Spring-Spawning Herring (*Clupea harengus*) and Western Horse Mackerel (*Trachurus trachurus*) have stock dynamics characterized by sporadic, large recruitment events that prevent the identification of a clear, empirically-derived SR function. In such cases, biomass fluctuates due to occasional very strong years classes, complicating

the identification of biomass reference points that are responsive to exploitation levels. For these types of stocks, ICES recommends specifying Blim as the lowest SSB that produced large recruitment (ICES Technical Guidelines, 2021). In Canada, this approach has been applied to identify an LRP for 3Ps Haddock (DFO 2019). Currently, there is a lack of clear definition of "large" recruitment in the ICES Technical Guidelines (2021). Here for EGB Haddock, we simply define a recruitment index anomaly amongst the 90th percentile as a "large" recruitment (Figure 10).

RESULTS

In the surplus production approach, the surplus production rate is mostly positive and increases at lower biomass, as would be expected from simple compensation (Figure 7). Depensation is therefore not detected and may not be a consideration in defining serious harm for this Haddock. Consequently, this approach was not considered appropriate for calculating an LRP for EGB Haddock.

$B_{recover}$ was identified as the SSB in 1993 (8,620 mt) from which the stock recovered steadily (Figure 8).

Sb50/90 was calculated as 5,058 mt (Figure 9).

According to the ICES Blim approach, the 1975 year class is at the 90th percentile of recruitment anomaly of the SR estimates. Based on the definition of "large" recruitment in this study, a SSB of 7,138 mt that produced the strong 1975 year class is the candidate LRP (Figure 10).

A comparison among the candidates estimated from different approaches provides insight into the certainty of advice for EGB Haddock (Figure 11). For the ICES Blim approach, using the 90th percentile here to define "large recruitment" is arbitrary, and the identified Blim value may change in future stock assessments with updated data. It is worthwhile noting that an LRP should reflect levels that are detectable before serious harm occurring. For Sb50/90, 5,058 mt is below the lowest historic SSB observation and a lack of information of population dynamics at this stock level makes it potentially risky to use as the LRP. In contrast, $B_{recover}$ at 8,620 mt occurs within the range of assessment stock biomass levels and is considered more appropriate (Table 1).

- As a proxy for recruitment overfishing, $B_{recover}$ has been deemed an acceptable basis for the LRP for species with sporadic recruitment dynamics (DFO 2022, DFO 2023).
- EGB Haddock has been exposed to full exploitation over an extended time series and experienced secure recovery twice from similarly low stock levels in the mid-1970s and 1990s (Figure 8). $B_{recover}$ reflected the productivity of this stock at low levels and its resilience under different fishing pressure. Given no evidence of regime shift, $B_{recover}$ is appropriate to be used as the LRP.
- The LRP could not be defined as any biomass greater than $B_{recover}$. A median recruitment was produced at this level of SSB under good (75th percentile) early life history stage survival condition in 1993. Additionally, an SSB (7,138 mt) of below $B_{recover}$ in 1975 produced the large (90th percentile) recruitment.

UPPER STOCK REFERENCE

In the DFO PA Policy (DFO 2009), the upper stock reference (USR) is defined as the boundary between the cautious and healthy zones, the threshold below which removals must be progressively reduced in order to avoid reaching the LRP. The USR is not applied in the current TMGC harvest rules of EGB Haddock. Therefore, the USR to be proposed here is only to be used for Canadian domestic fishery management. In addition, PA Policy guidance indicates that the USR is not determined solely by biological considerations, social and economic objectives for the fishery are other considerations, and therefore, the USR is not identified by the DFO Science Sector (DFO 2021a). Accordingly, the proposed USR is based on available biological information for the stock to support Canadian domestic fishery management of EGB Haddock.

Although it is challenging to characterize a well-defined, empirically-derived SR function for EGB Haddock, there appears to be two distinct groupings in magnitude of recruitment, with large SSB generally resulting in high recruitment and small SSB generally resulting in low recruitment (Figure 5). For stocks which show two groupings in the SR relationship, it was suggested the boundary between the two groupings could be used as the USR (DFO 2004). This is the lowest SSB where further increases in SSB did not produce markedly improved recruitment. This method embodies concepts of density-dependent suppression of population production and has some similarities to SSBMSY (Duplisea and Fréchet 2011).

Based on the relationship between SSB and R of EGB Haddock, the SSB breakpoint, delineating two stanzas of recruitment, is estimated by minimizing the sum of mean square error of estimated recruitments points, R, for each year, y, between 1969 and 2021 (does not extend to later years in subsequent assessments), from the mean recruitment in each stanza using the "Rago-Razor" method (NEFSC 2008). The proposed USR of 26,732 mt is calculated as the mean of the highest value in the lower SSB stanza and the lowest value in the highest SSB stanza (Figure 12, see detailed description in Table 2).

While there are other methods that could be used to estimate the USR, the approach established here is relatively simple and straightforward to implement in the face of high recruitment variability. In addition, a large recruitment of 110 million was preliminarily estimated from a SSB of about 26,000 mt in 2020 (Wang et al. In Prep[2]), which would further support the proposed USR.

RETROSPECTIVE TEST OF REFERENCE POINTS

A QUANTITATIVE EVALUATION OF REFERENCE POINTS AS CONTROL POINTS

Stock assessments of EGB Haddock provide estimates of SSB and recruitment that reveal no clear stock-recruitment relationship (Figure 11). Due to the availability of relatively complete and informative data that includes three corroborative independent surveys of age-specific numbers, this lack of stock-recruitment relationship is consistent among a wide range of assessment sensitivity analyses (Wang et al. In Prep[2]). When profiled over steepness, there is little empirical evidence for a specific level of stock resilience (Figure 13). For this reason, the stock was assessed assuming deviations from mean historical recruitment. Assuming alternative steepness levels does not change estimates of historical recruitment and spawning biomass, and simply provides a relatively slight adjustment to the very large annual recruitment deviations. Hence, the pertinent dynamics that make EGB Haddock a challenging subject for establishing absolute biomass reference points are not related to the assumed level of steepness but rather the very high interannual variability in recruitment that has previously allowed the stock to recover from spawning biomass near the lowest historical level to the historical high (Figure 14).

Historically, management of EGB Haddock has established catch advice consistent with a target exploitation rate. If instead, a harvest control rule with the proposed LRP and USR (8,620 mt and 26,732 mt, respectively) had been applied, *qualitatively* it is likely to have reduced historical yields and provided higher spawning biomass, particularly during low recruitment/biomass periods in the 1980s and 1990s. For example, if implemented in any given year between 1982 and 2000, where spawning biomass was estimated to be between the proposed LRP and USR, the removal rate would have been reduced in proportion to the distance from the USR to the LRP, and in some years closed or nearly closed the fishery (1984 to 1995, Figure 11). However, any reduction in yields in a given year would have positively impacted vulnerable biomass in subsequent years and then provided higher yields for the same exploitation rate. It follows that it is not clear *quantitatively*, how impactful alternative reference point systems would have been over the historical period of the fishery given the dynamics estimated by the stock assessment.

To provide a clearer quantitative evaluation of the sensitivity of yield and biomass outcomes to alternative LRPs and USRs, we conducted a retrospective closed-loop evaluation of various harvest control rules with operational control points corresponding to various levels of removal reference (RR), LRP and USR, including those proposed above.

OPERATING MODEL

The fishery and population dynamics of the 2022 stock assessment (Wang et al. In Prep[2]) were exactly reproduced in an age-structured operating model and the last 35 years (1987-2021) were ‘replayed’ as though the management advice provided by the harvest control rules were taken exactly, without implementation error.

Closed-loop simulations were undertaken using the openMSE R package (Hordyk et al. 2023).

HARVEST CONTROL RULES INVESTIGATED

A range of alternative Harvest Control Rules (HCRs) were investigated that were single factor variants of a Base HCR (Table 3).

For the Base HCR, we used the RR that was established in the previous assessment (Wang et al. In Prep[2], $F_{40\%SPR}$ = 0.367). That calculation was conducted using the average data of the last five years (2017–2021). Closed-loop simulation suggested that it would be appropriate to recalculate and apply the RR every three years. An alternative approach (Rrfix) was evaluated where the RR did not change throughout the retrospective time period and was fixed at the RR of the most recent time period (0.367). For all HCRs, the removal reference level was calculated directly from the operating model and assumed to be known perfectly without estimation error.

For the Base HCR, we assume that SSB was observed without bias and with an imprecision equal to the error calculated from a simulation self-test of the Base assessment (CV = 10.8%) (Wang et al. In Prep[2]). Hence, in the Base HCR, TAC advice was provided each year based on imperfect information of biomass at the start of that year (the independent variable of the HCR), using an LRP, USR and RR that were calculated from perfect information of operating model dynamics (the dependent variable of the HCR). Two alternatives were evaluated where SSB was known without error (Err0, CV = 0) and where observation error was double the base level (Err2, CV = 21.6%).

In order to provide a wider test of sensitivity, an alternative HCR was specified (noCP) in which there were essentially no control points and the LRP and USR were both set to zero (fishing at constant RR levels).

The primary focus of this retrospective evaluation is to quantify the sensitivity of yield and SSB outcomes to alternative LRP and USR levels. Four alternative HCRs were specified that were a full-cross of low (3/4) and high (4/3) factors of the Base LRP and USR (Low_Low, Low_High, High_Low, High_High) (Table 3).

RESULTS

In general, over the retrospective time period there was greater similarity in exploitation history among the various HCRs (Table 1) than with the real historical pattern of exploitation (Figures 15–17). Historical fishing mortality rates were more variable and substantially higher than those prescribed by the HCRs (e.g., Figure 15, panels d, j, and p).

Since the Base HCR—as is the case for most of the HCRs—initially throttles exploitation rate relative to historical levels (Figure 15, panel c), biomass subsequently increases relative to historical levels (Figure 15, panel a) and consequently, catches (Figure 14, panel e) are much more comparable with historical levels than are exploitation rates (Figure 15, panel d).

The HCRs tested here would have fished substantially harder than historical levels for a small number of years during the late 1990s where both removal reference and vulnerable biomass were relatively high (catches of Figures 15–17).

Average yield and final (2021) SSB levels were very comparable among HCRs (Figure 18, panels a and b, respectively). Yield differences were more pronounced during the earlier, lower recruitment period from 1987 to 1995 (Figure 18, panel c). During this time period (where the HCRs were throttling RR), among the most extreme cases (RRfix and High_High), the mean yield outcomes were roughly twice as disparate as SSB outcomes (Figure 18, panels c and d). Unsurprisingly, the lower range of SSBs (the 5th percentile, Figure 18, panel e) occurs during this early period and follows the same pattern as mean SSB (Figure 18, panel d). Despite differences in yield and SSB among HCRs during this early period, final spawning biomass was largely unaffected, underlining that given these assessed dynamics, biomass of EGB Haddock is largely environmentally driven.

CONCLUSION

Examination of the relationship between SSB and R shows no evidence of a change in recruitment for the same level of SSB at two different time periods (1931–1954, 1969–2020). Similarly, comparison of surplus production in different time periods does not show evidence of productivity regime shifts (Figure 4). Therefore, the longer time series (1969–2020) of data is considered the most appropriate for the calculation of reference points. If regime shifts were detected in the future, the biomass reference points developed would need to be reviewed. The LRP methods presented here do not explicitly incorporate how changes in ecosystems or environmental conditions (e.g., species interaction, climate and other factors) can affect the productivity of the EGB Haddock stock. Future research is required to fill these gaps and better meet the new requirement of DFO's PA framework under the Fish Stocks Provisions (DFO 2021b). Additionally, the LRP and USR are developed for Canadian domestic fishery management requirements under the DFO PA framework (DFO 2009) and are not required for the evaluation of stock status at TRAC.

Comparison among different methods illustrated that $B_{recover}$ is the most appropriate LRP for EGB Haddock. Considering the possible changes in the estimated SSB of 1993 in future stock assessments, it was recommended that $B_{recover}$ for EGB Haddock was explicitly defined as the minimum biomass between 1991 and 1996 (Figure 8, see detailed description in Table 1). Using this definition, and the current model outputs, the minimum estimate of SSB at 8,620 mt occurring in 1993 is the identified LRP for EGB Haddock (Figure 14). The LRP can be used to calculate either a single estimate of stock status, SSB_{now} / LRP, or a probabilistic representation of stock status, P(SSB_{now} > LRP) (Table 1).

The proposed USR was calculated as 26,732 mt using the "Rago-Razor" method based on data between 1969 and 2020. USR can be used to calculate either a single estimate of status, SSB_{now} / USR; or a probabilistic representation of stock status, P(SSB_{now} > USR) (Table 2).

The conditions for review of the LRP and proposed USR are listed in Table 1 and 2. The uncertainty that exists within the modelling framework is propagated in the value of the reference points. Reducing the sources of uncertainty (e.g., sampling error, model assumptions, input data, etc.) would improve model estimates and the precision of reference points.

Historical retrospective closed-loop simulation confirmed that the biomass dynamics of EGB Haddock were strongly driven by high recruitment variability over the past two decades. If using the LRP and USR as control points in the historical fishery, retrospective closed-loop simulation showed that historical terminal biomass and average yield would be largely invariant to the implementation of alternative HCRs and various levels of the specified LRP and USR. Given the candidate LRP and USR, exploitation rates were substantially lower than historical levels during the 1980s and 1990s, but subsequently provided higher stock sizes and comparable catches. The candidate LRP and proposed USR provided stock rebuilding when applied below USR levels, even during the period of low productivity (i.e., 1987–1995). The candidate LRP and USR also did not lead to stock declines below the USR, even during the period of low productivity (i.e., 1987–1995).

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TABLES

Table 1. The specification of a limit reference point (LRP) for eastern Georges Bank (EGB) Haddock. Based on the assessment result from Wang et al. (In Prep[2]), LRP = 8,620 mt.

Attribute	Specification
Theory	$B_{recover}$ (DFO 2002; DFO 2023). $B_{recover}$ is defined as the lowest spawning stock biomass (SSB) on record that produced the recruitment that allowed the stock to readily recover.
Definition	min([SSB_{1991}, SSB_{1992}, …, SSB_{1996}]), the current stock assessment maximum likelihood estimate of SSB in 1993 (LRP = SSB_{1993}).
Intent	A proxy for recruitment overfishing, reflecting productivity at low stock sizes under average conditions recommended for stocks with occasional large recruitment (DFO 2022, 2023).
Updated	Every three years.
Conditions for review	If: SSB_{1993} != min([SSB_{1991}, SSB_{1992}, …, SSB_{1996}]).
Application	Can be used to calculate either a single estimate of stock status, *SSBnow / LRP* or a probabilistic representation of stock status, P(*SSBnow* > *LRP*).
LRP	8,620 mt

Table 2. The specification of a proposed upper stock reference (USR) for EGB Haddock. Based on the assessment from Wang et al. (In Prep[2]), proposed USR = 26,372 mt.

Attribute	Explanation
Value	26,732 mt (based on the 2022 assessment [Wang et al. In Prep[2]]).
Theory	For stocks that show two groupings of stock-recruitment estimates corresponding to relatively high and relatively low recruitment, the USR can be calculated as the SSB that delineates the two groupings (DFO 2004).
Definition	The SSB breakpoint *BP*, delineating two stanzas of recruitment is estimated by minimizing the sum of mean square error of estimated recruitments points *R*, for each year *y*, between 1969 and 2021 (does not extend to later years in subsequent assessments), from the mean recruitment in each stanza ("Rago-Razor" method, NEFSC 2008): $$\min_{BP} \left(\sum_{y=1969}^{2021} k_y R_y - \left[\sum_{y=1969}^{2021} k_y R_y \Big/ \sum_{y=1969}^{2021} k_y \right] \right)^2 + \left(\sum_{y=1969}^{2021} j_y R_y - \left[\sum_{y=1969}^{2021} j_y R_y \Big/ \sum_{y=1969}^{2021} j_y \right] \right)^2$$ where *SSB* is the estimated spawning stock biomass in a given year *y,* and *k* and *j* are binary values indicating the corresponding stanza. Their value depend on whether SSB_y is above or below the USR: $$k_y = \begin{cases} 0 & SSB_y > BP \\ 1 & SSB_y < BP \end{cases}, \; j_y = \begin{cases} 1 & SSB_y > BP \\ 0 & SSB_y < BP \end{cases}$$ The USR is calculated at the mean of the highest value in the lower SSB stanza and the lowest value in the highest SSB stanza: $$USR = \frac{\max([k_{1969}\, SSB_{1969}, \ldots k_{2021}\, SSB_{2021}]) + \min([j_{1969}\, SSB_{1969}, \ldots j_{2021}\, SSB_{2021}])}{2}$$
Justification	Upper stanza of SSB is a proxy for SSB_{MSY}
Updated	Every three years
Conditions for review	• Lack of positive relationship between ln(SSB) and ln(R) when including all estimated data points (two recruitment stanzas are not apparent). • Mean recruitment in lower SSB stanza is higher than mean recruitment in upper SSB stanza: $\left[\sum_{y=1969}^{2021} k_y R_y / \sum_{y=1969}^{2021} k_y\right] > \left[\sum_{y=1969}^{2021} j_y R_y / \sum_{y=1969}^{2021} j_y\right]$
Application	Can be used to calculate either a single estimate of status, SSB_{now} / *USR*; or a probabilistic representation of stock status, P(SSB_{now} > *USR*)
Proposed USR	26,372 mt

Table 3. The specification of the Base harvest control rule (HCR) and alternatives. CV: coefficient of variation.

<table>
<tr><th>Variable</th><th>Base HCR Specification</th><th colspan="3">Alternative HCRs</th></tr>
<tr><td>Removal Reference (RR)</td><td>$F_{40\%SPR}$ averaged over the previous five years and updated every three years</td><td colspan="3">RRfix: as Base, but fixed at the level calculated in 2021</td></tr>
<tr><td>Operational control points</td><td>Operational control points at LRP and USR</td><td colspan="3">noCP: as Base, but no operational control points, fishing at RR (LRP=USR=0)</td></tr>
<tr><td>Spawning Stock Biomass (SSB) estimation</td><td>Sim-Sam derived imprecision in observed SSB</td><td colspan="3">Err0: as Base, but no observation error in SSB

Err2: as Base but double observation error in SSB (CV of 21.6%)</td></tr>
<tr><td rowspan="5">Limit reference point (LRP) and upper stock reference (USR)</td><td rowspan="5">LRP = 8,620 mt

USR = 26,222 mt</td><td>HCRs</td><td>LRP</td><td>USR</td></tr>
<tr><td>Low_Low</td><td>3/4 Base</td><td>3/4 Base</td></tr>
<tr><td>Low_High</td><td>3/4 Base</td><td>4/3 Base</td></tr>
<tr><td>High_Low</td><td>4/3 Base</td><td>3/4 Base</td></tr>
<tr><td>High_High</td><td>4/3 Base</td><td>4/3 Base</td></tr>
</table>

FIGURES

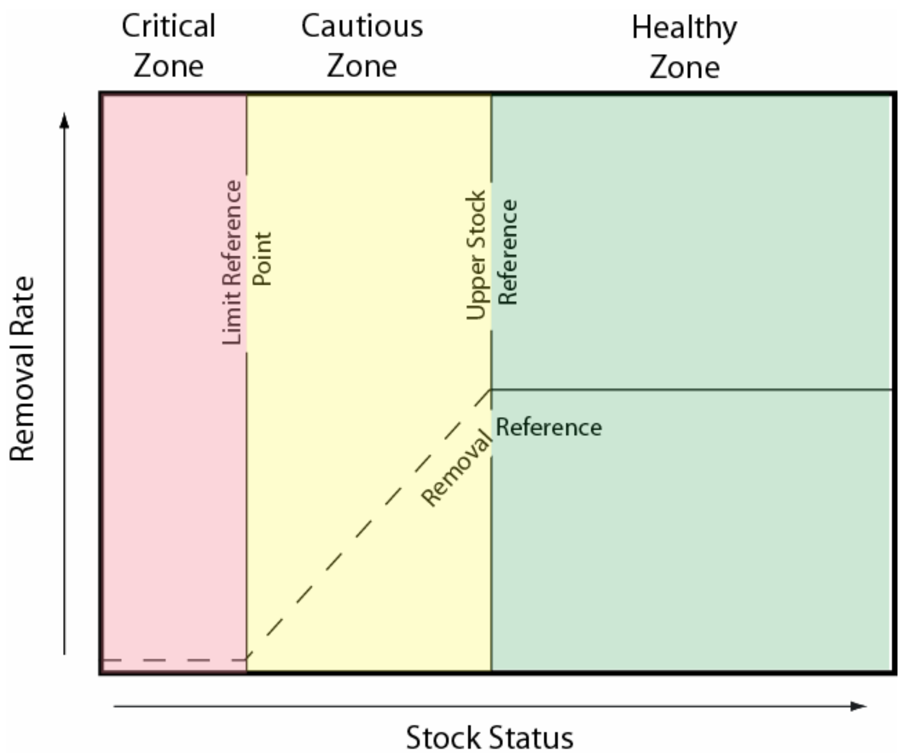


Figure 1. Illustration of the Canadian reference point system, indicating the position of the limit reference point and upper stock reference (Source: DFO 2006).

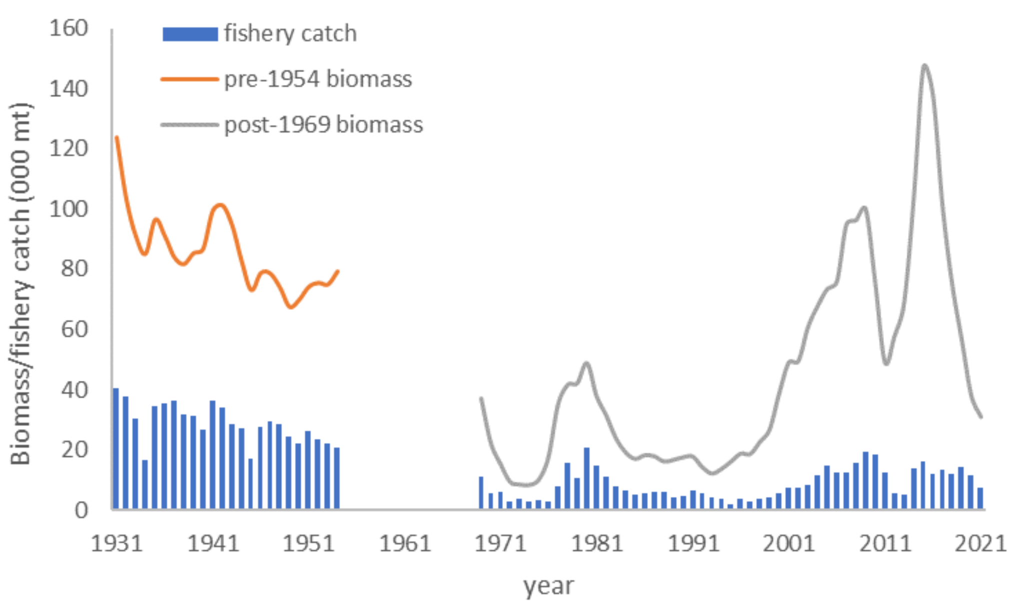


Figure 2. Annual fishery catch of eastern Georges Bank Haddock illustrated as blue bars. Estimated biomass from 1931–1954 (orange lines) derived from an illustrative virtual population analysis. Estimated biomass from 1969–2021 (grey line) derived from the 2022 assessment.

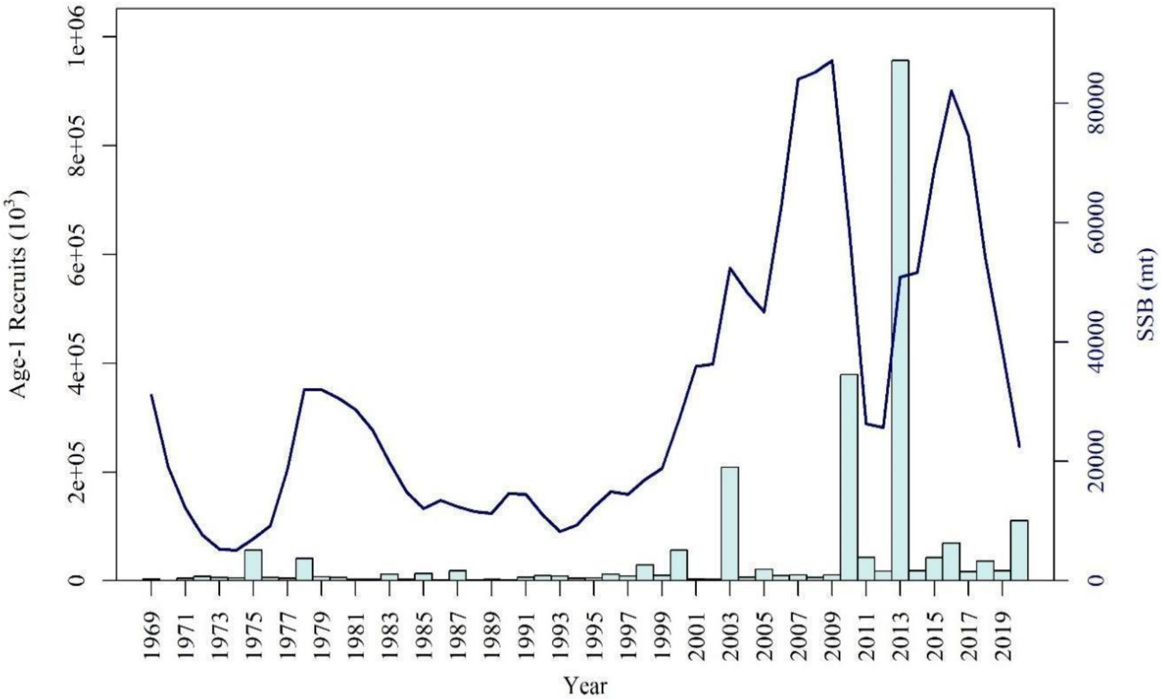
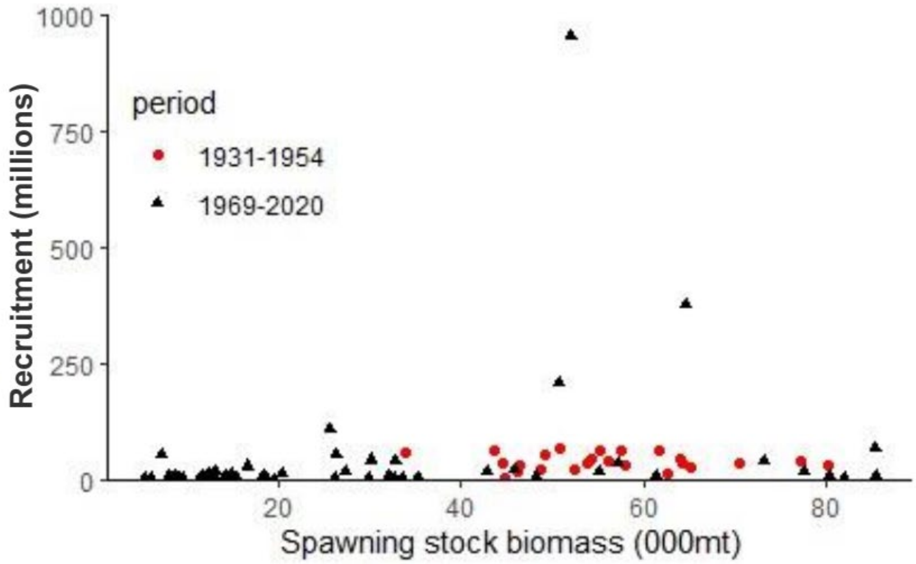


Figure 3. Estimated spawning stock biomass (SSB, dark blue line) and recruitment at age 1 (light blue bars) from 1969–2021 in the 2022 eastern Georges Bank Haddock assessment (Wang et al In Prep[2]).



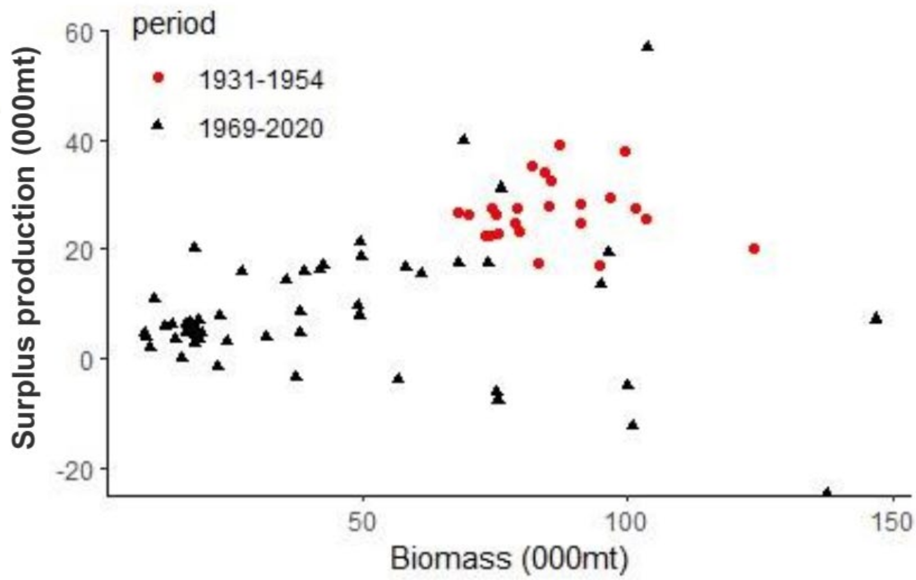


Figure 4. Relationship between spawning stock biomass (SSB) and recruitment (R) (top panel), and biomass and surplus production (bottom panel) for eastern Georges Bank Haddock in the two time periods: 1931–1954 and 1969–2020.

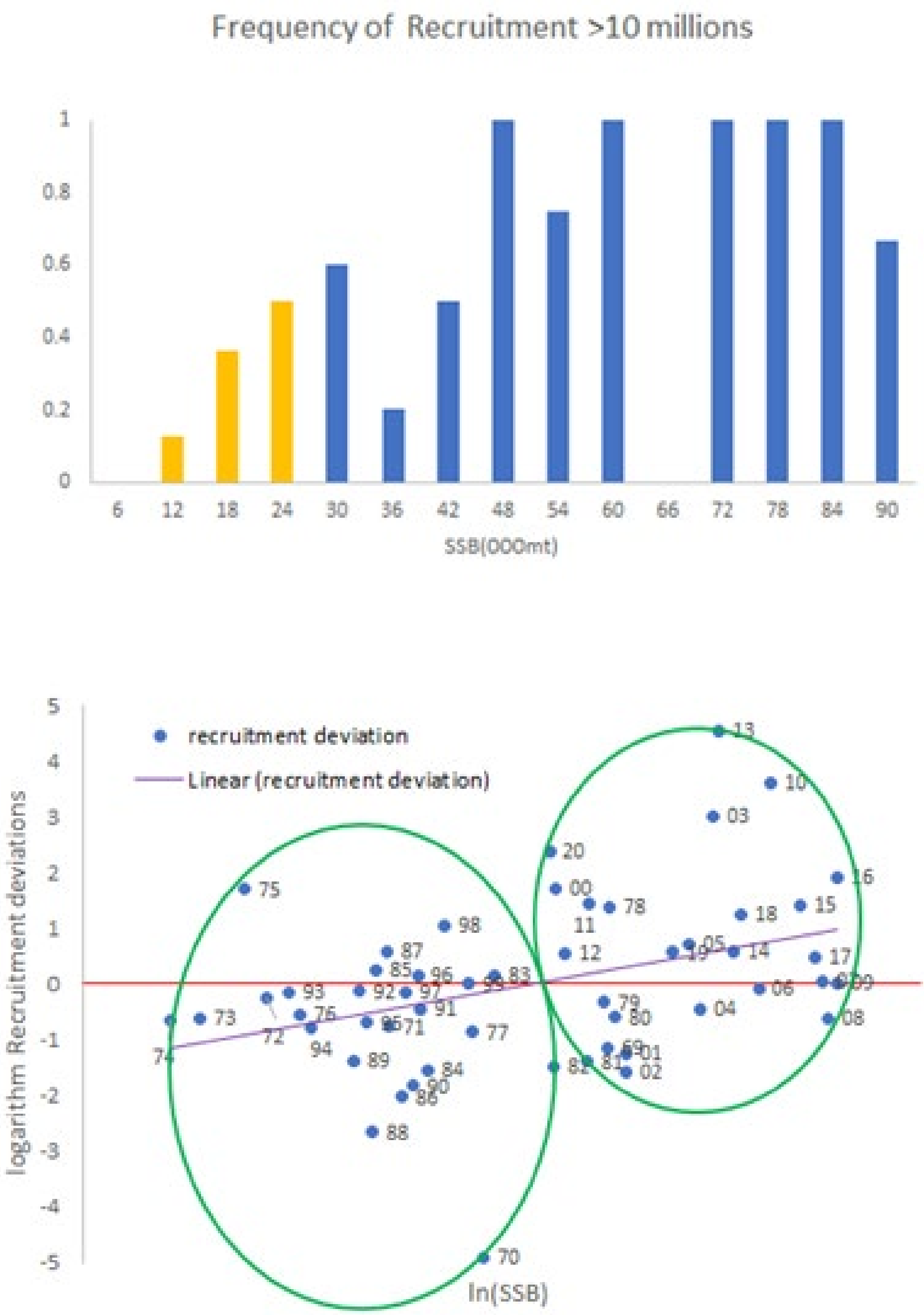


Figure 5. Positive relationship between spawning stock biomass (SSB) and recruitment of eastern Georges Bank Haddock. The frequency of observed recruitment greater than 10 million (top panel) and the logarithm recruitment deviations from mean with a fitted linear line (purple, bottom panel) at different SSB levels. In top panel the yellow bars show the frequency when SSB<30,000 mt, blue bars are for when SSB>= 30,000 mt. The green circles in the bottom panel show the two groupings of stock-recruitment points labeled by the cohort year, for example, "75" labels the 1975 cohort and "20" represents the 2020 cohort.

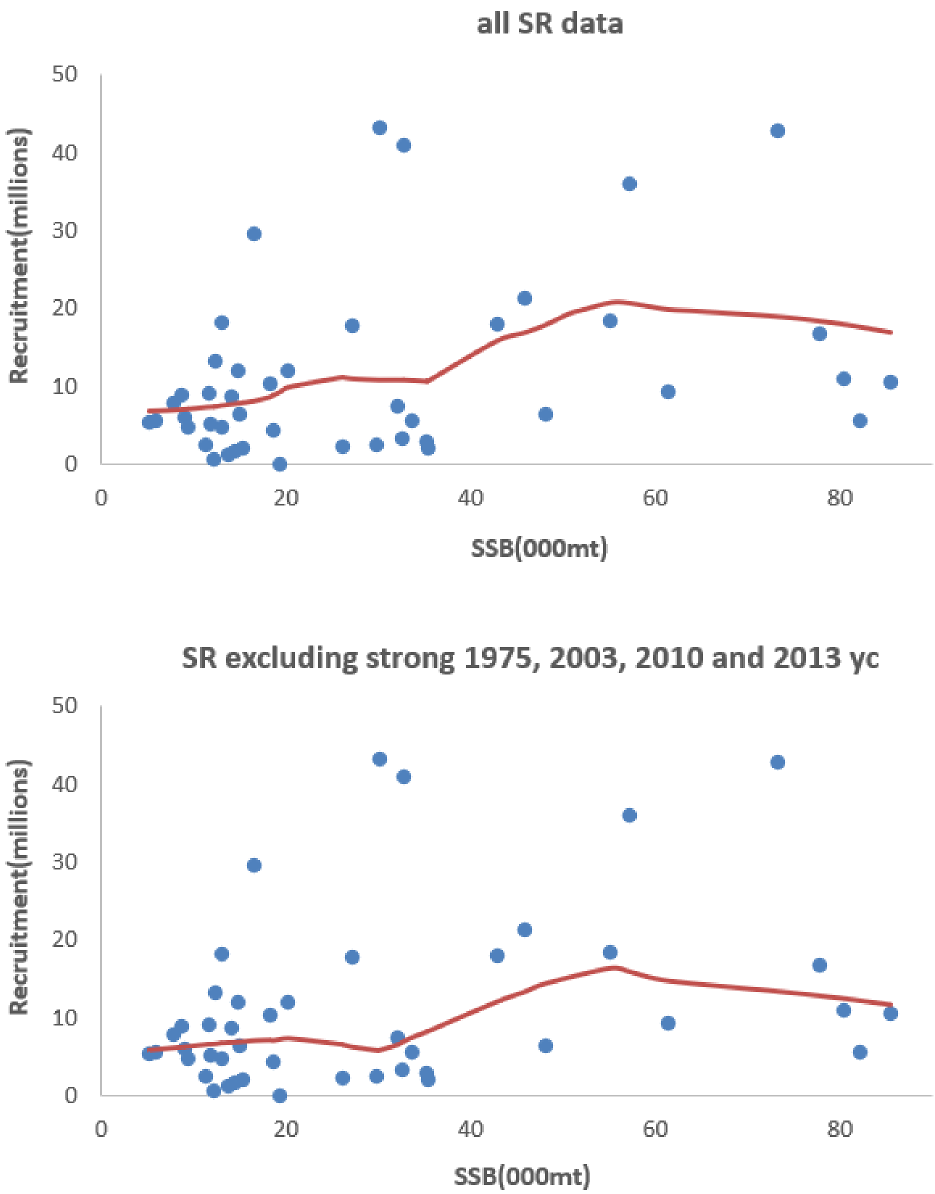


Figure 6. Relationship between spawning stock biomass (SSB) and recruitment of eastern Georges Bank Haddock with fitted smooth curve using the robust locally weighted regression (Loess) method with a span = 0.5 (top panel). Recruitment in the y-axis is truncated in both panels so that the majority of observations are visible; therefore, the 1975 year class (56 million), 2003 year class (209 million), 2010 year class (379 million) and the 2013 year class (956 million) are not shown. The bottom panel is the sensitivity run with the strong year classes of 1975, 2003, 2010 and 2013 excluded to examine their impact on the fitted stock-recruitment curve.

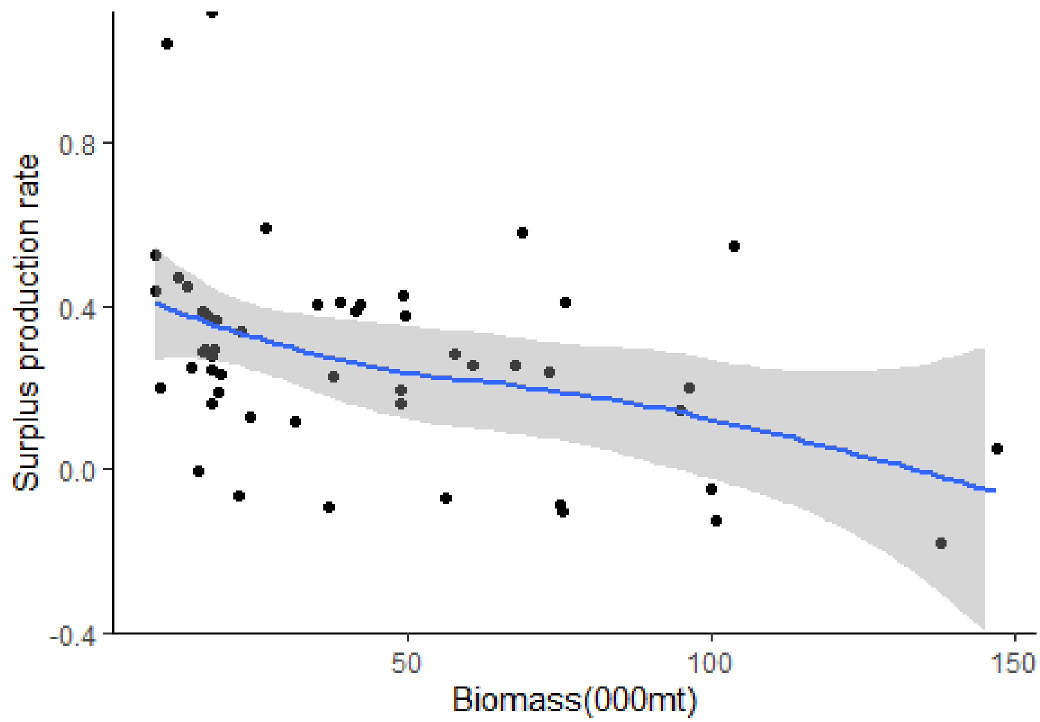


Figure 7. Relationship between the surplus production rate and biomass of eastern Georges Bank Haddock with the fitted smooth line using the Loess method with a span = 0.9.

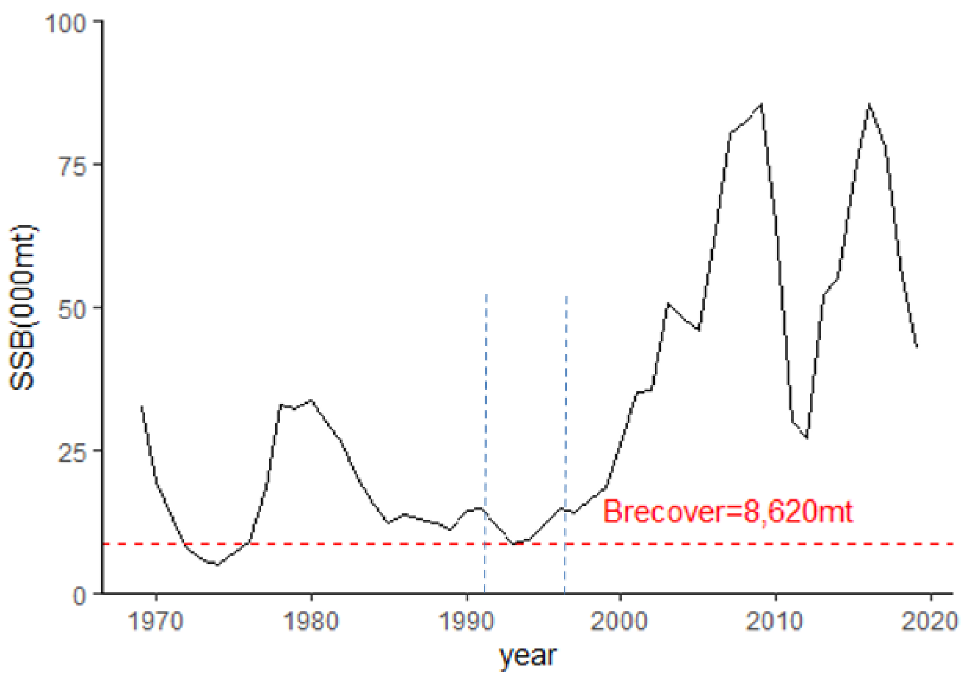


Figure 8. Time series of the spawning stock biomass (SSB) of eastern Georges Bank Haddock. $B_{recover}$ is shown in horizontal dashed red line which is the lowest biomass between 1991 and 1996 (vertical blue dashed lines).

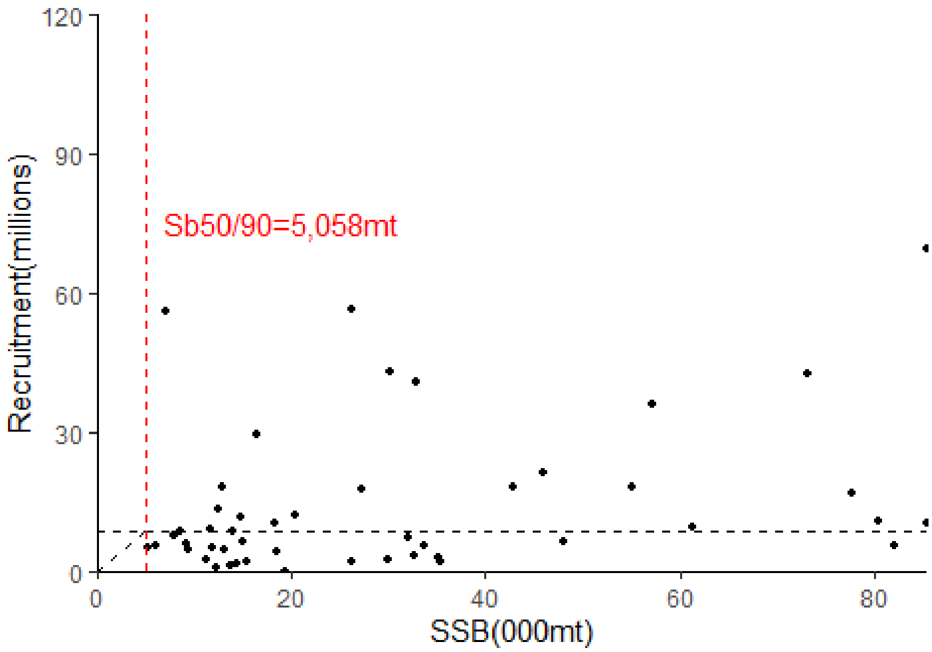


Figure 9. Sb50/90 of eastern Georges Bank Haddock shown with the vertical dashed line. The two black dashed lines are the median recruitment and 90th percentile of recruitment rate of recruitments from 1969–2019. The recruitment in the y-axis is truncated so that the majority of observations are visible. The 2003 year class (209 million), 2010 year class (379 million) and the 2013 year class (956 million) are not shown.

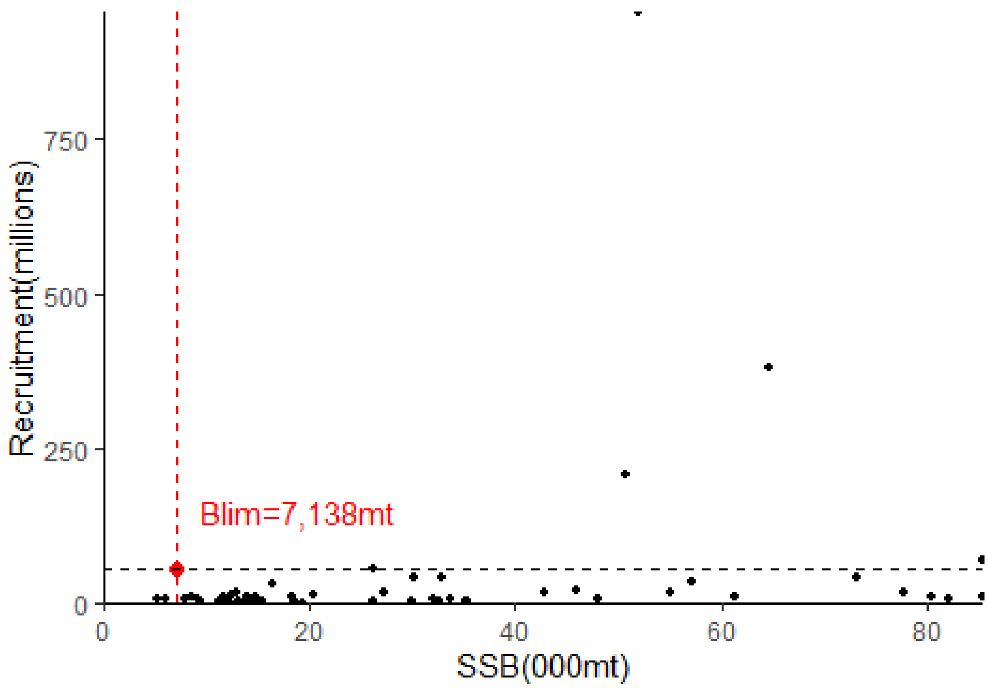


Figure 10. Candidate limit reference point (red dashed line) of eastern Georges Bay Haddock based on ICES Blim approach. The black dashed line represents the 90th percentile of recruitments from 1969–2019.

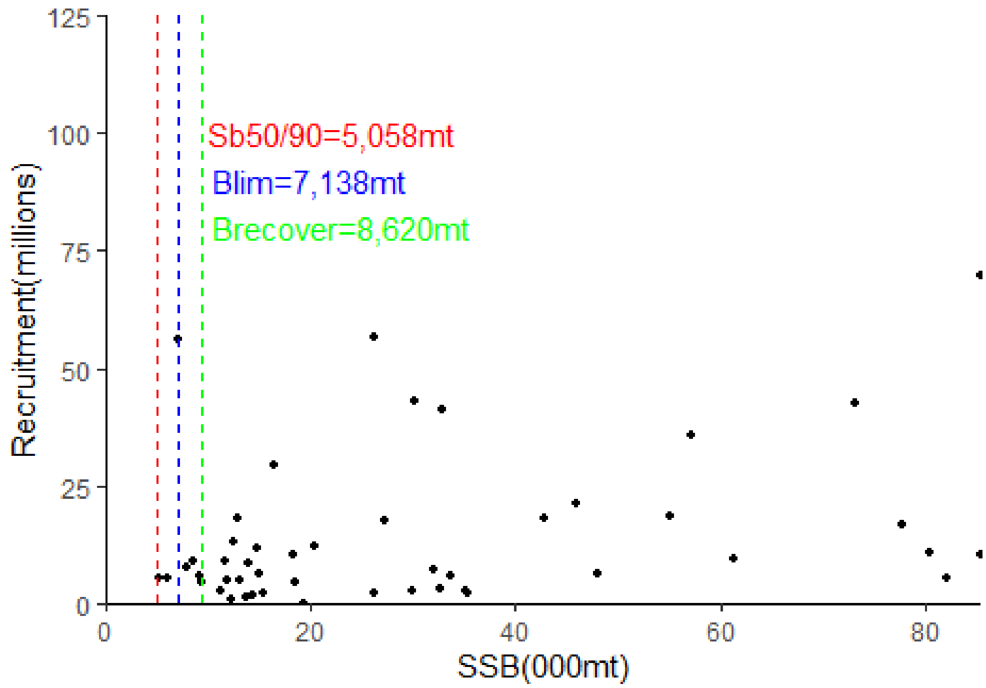


Figure 11. Comparison of candidate limit reference points of eastern Georges Bank Haddock derived from three different methods, the data labels show the year classes. The recruitment in the y-axis is truncated so that the majority of observations are visible. The 2003 year class (209 million), 2010 year class (379 million) and the 2013 year class (956 million) are not shown.

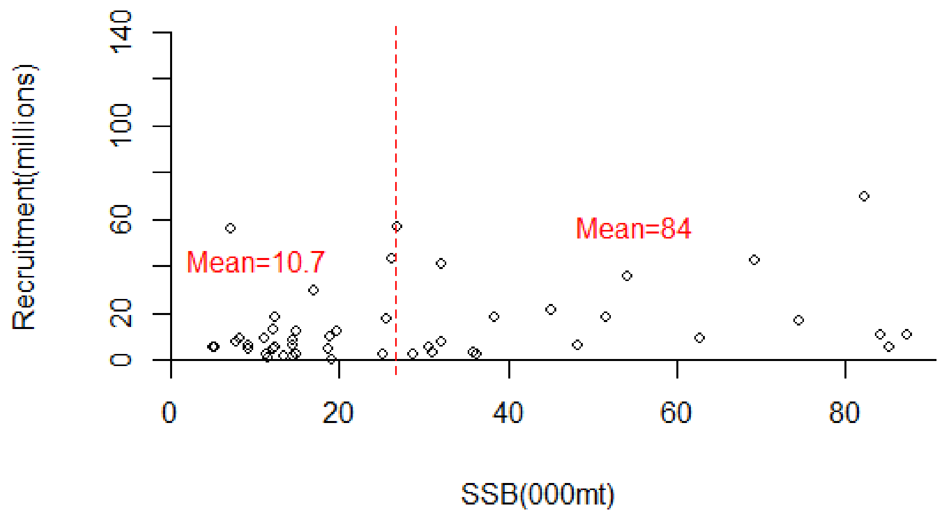


Figure 12. The spawning stock biomass breakpoint (SSB=26,222 mt; indicated by red dashed line) for eastern Georges Bank Haddock estimated using the "Rago-Razor" method. The recruitment in the y-axis is truncated so that the majority of observations are visible. The 2003 year class (209 million), 2010 year class (379 million) and the 2013 year class (956 million) are not shown.

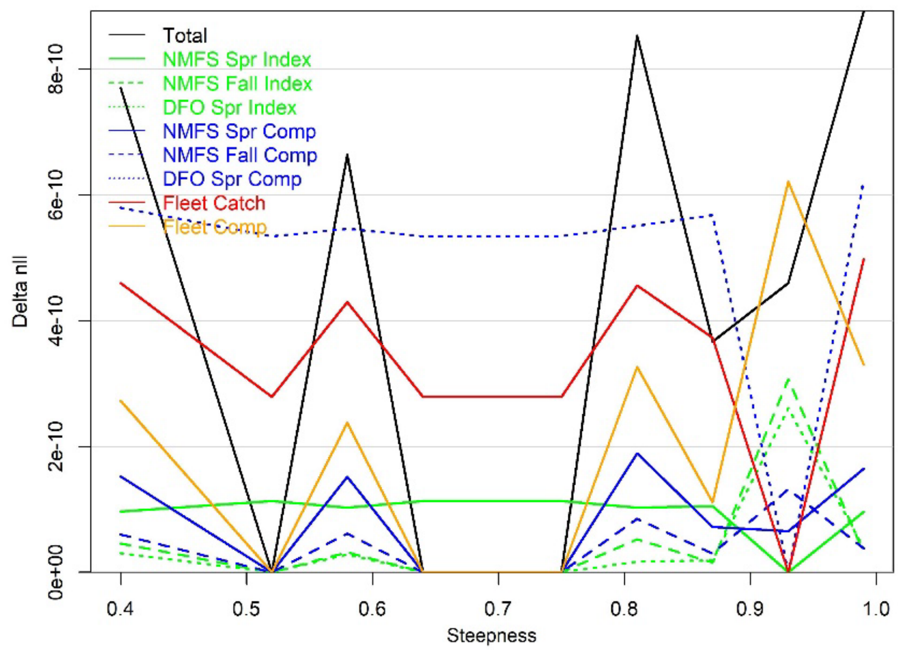


Figure 13. Objective function likelihood profile across alternative steepness values. The global objective function (Total) and its components associated with the indices and age composition (Comp) data are all essentially identical (within the tolerance for numerical converge) across alternative specified values of steepness. Note that when steepness is specified, the Woods Hole Assessment Model treats recruitment deviations as random effects and hence the likelihood penalty for recruitment deviations is not reported in the global likelihood function (Total). NMFS: National Marine Fisheries Service, Spr: spring, DFO: Fisheries and Oceans Canada.

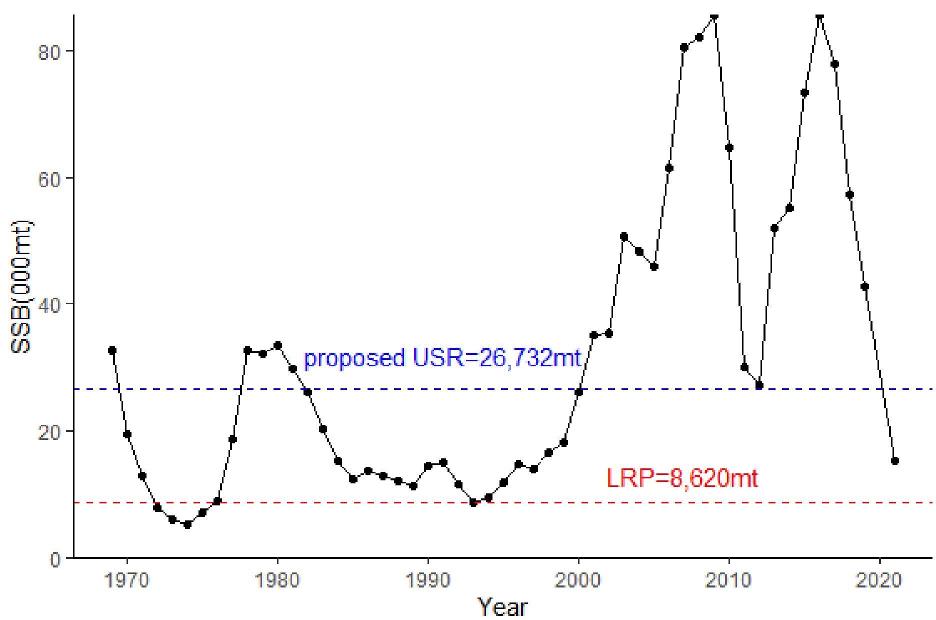


Figure 14. Time series of spawning stock biomass (SSB) of eastern Georges Bank Haddock estimated from the 2022 stock assessment with the identified limit reference point (LRP, red dashed line) and proposed upper stock reference (USR, blue dashed line).

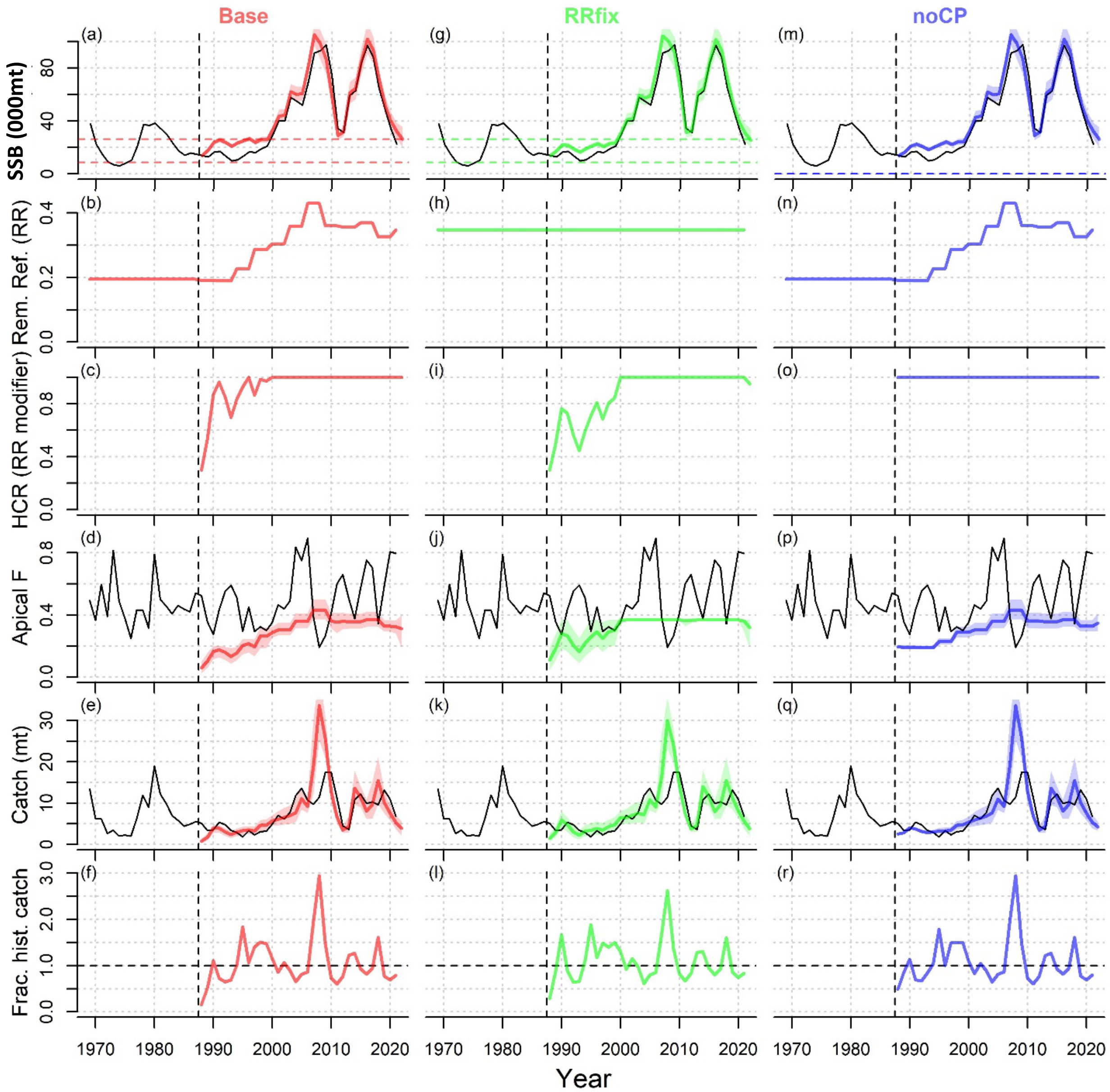


Figure 15. Retrospective simulation results (1987–2021) for the (Base) base harvest control rule using a moving mean of $F_{40\%SPR}$ as the removal reference, (RRfix) the HCR with fixed removal reference (RR = 0.365, mean $F40\%_{SPR\ 2017—2021}$) and (noCP) an identical HCR as Base that has no operational control points (LRP = USR = 0). The solid black lines represent the mean values of the reconstruction with historical catch levels. Solid colored lines indicate the mean simulated values for each HCR (n = 2000). Shaded regions represent the 95% interquantile ranges and are included here for the SSB, apical F and catch panels. The vertical dashed lines mark the start of the retrospective closed-loop simulation. The colored horizontal dashed lines correspond with the operation control points of each HCR.

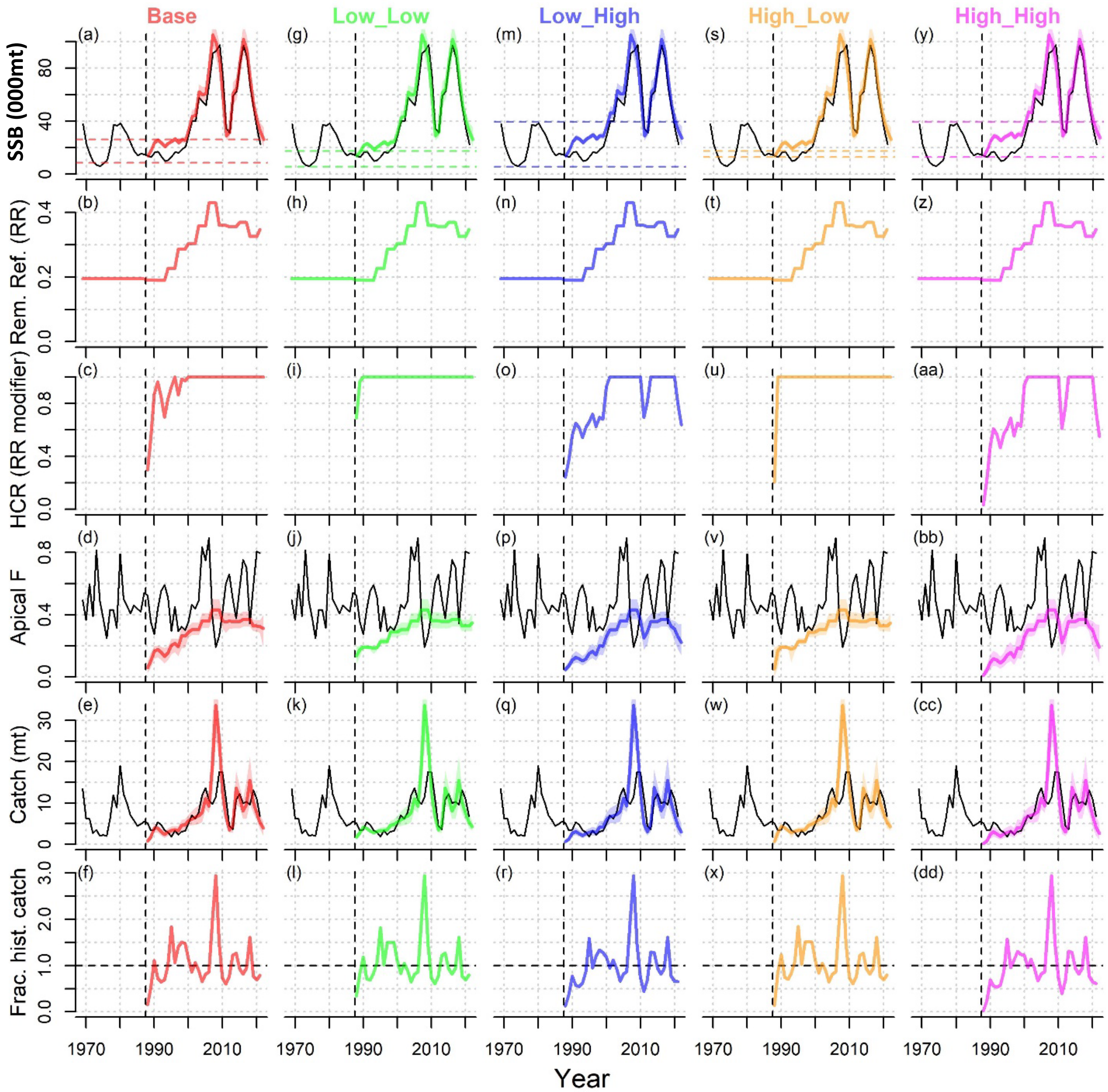


Figure 16. As Figure 15, but for four alternative Harvest Control Rules (HCRs) that have combinations of low (3/4) and high (4/3) levels of the Base limit reference point and upper stock reference (Table 1).

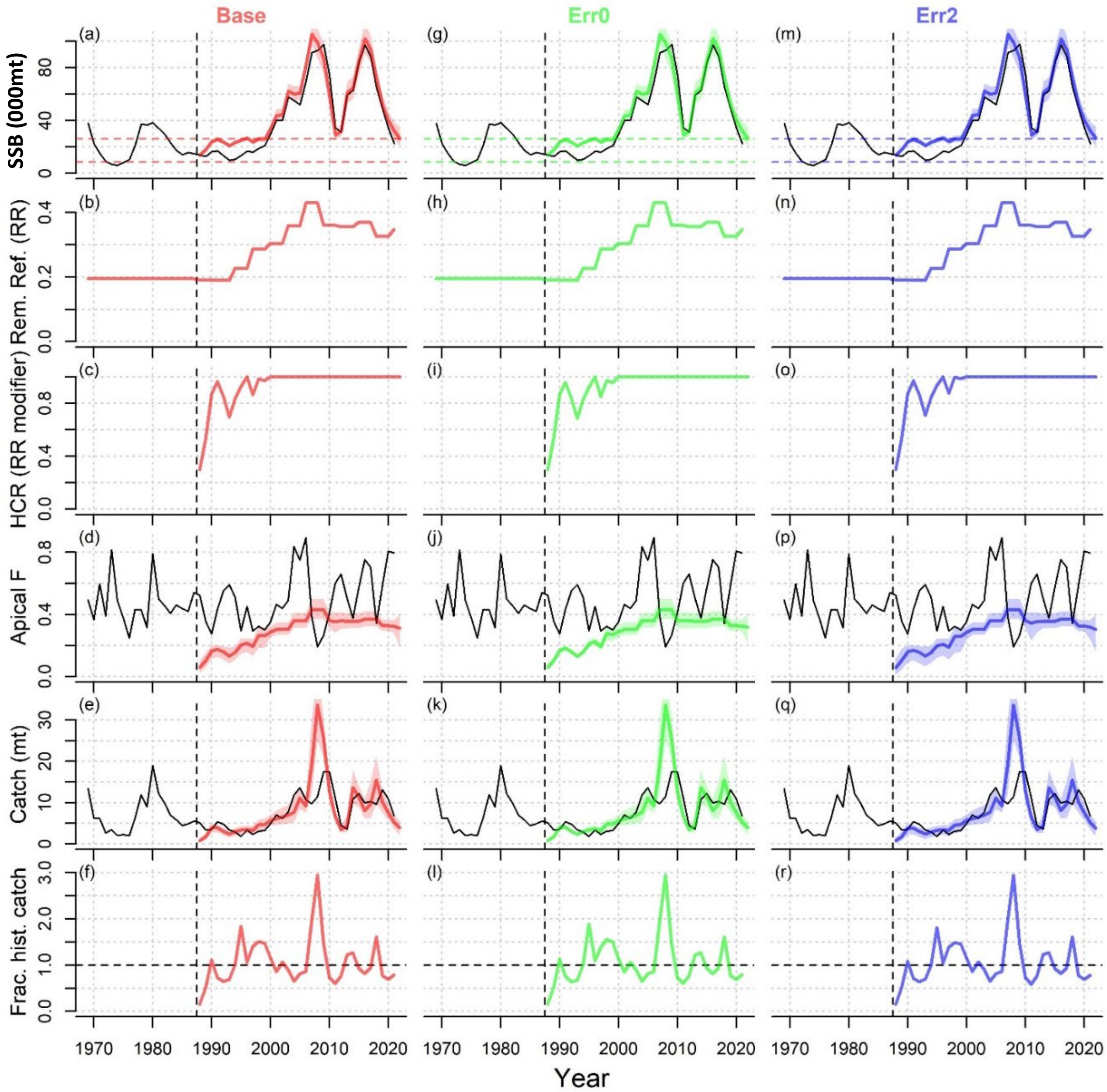


Figure 17. As Figure 15 but for Harvest Control Rules (HCRs) that have no observation error in spawning biomass (Err0) and those that have double the observation error in spawning biomass (Err2).

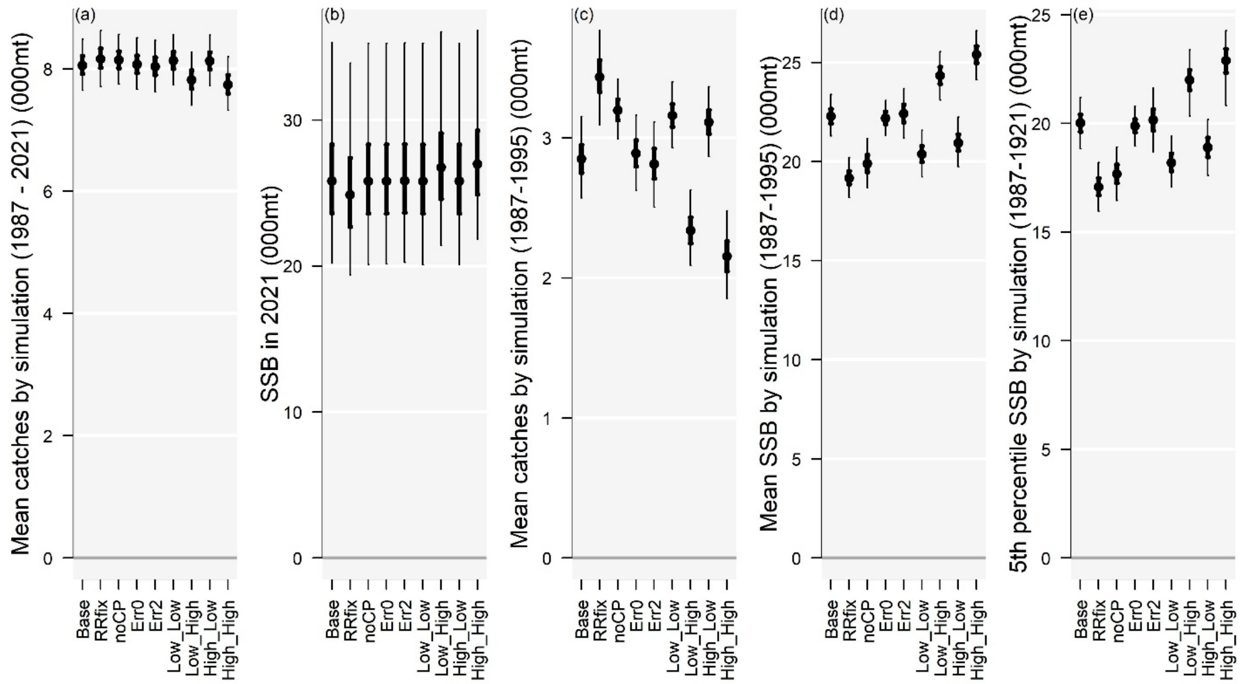


Figure 18. Mean catch over the full retrospective time period (1987–2021, panel a), Spawning Stock Biomass (SSB) at the end of the retrospective time period (2021, panel b), mean catch and SSB performance during the historical low recruitment period from 1987–1995 (panels c and d). Also plotted are the lowest 1st percentile of SSB by simulation over the full time period (panel e). Points represent the median estimates among all simulations (n = 2000), thick lines are the interquartile range, and the thin wider bars represent the 95% interquantile range.