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5Z Cod Assessment Framework: Projections and Reference Points

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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.

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ABSTRACT

In 2023, Fisheries and Oceans Canada (DFO) Science initiated the development of a new framework for transboundary 5Z Atlantic Cod (*Gadus morhua*), prompted by the absence of a functioning population model and associated precautionary approach-compliant reference points for the stock since 2018. Following the completion of the Data Inputs and Modeling peer review meetings, the current work summarizes the subsequent development of reference points, advice and assessment schedule for the Eastern Georges Bank stock unit.

INTRODUCTION

During the peer review of candidate population dynamics models for 5Z Atlantic Cod (*Gadus morhua*) for both eastern Georges Bank (EGB) and total Georges Bank (TGB) assessment units, both models were deemed appropriate for the assessment of stock status, with neither model free of uncertainty or limitations (Andrushchenko et al. 2026a; Figure 1). The TGB model was proposed as the best option, as it encompassed the biological unit within the constraints of practical considerations of US fishery data (Andrushchenko et al. 2026a). However, due to limitations in accessing raw (sub trip-level) US fishery data, the EGB model has been selected as the basis for the assessment framework.

Projection methods and candidate reference points are proposed for the EGB model only. If there is a change in the factors inhibiting Fisheries and Oceans Canada (DFO) Science in the domestic implementation of the TGB model, the feasibility of implementing the TGB model domestically can be re-evaluated at the next assessment framework review.

SIMULATION

During the modeling review, unexpected trends in projections of recruitment and process error resulted in the recommendation to explore projections on alternate platforms to the Woods Hole assessment model WHAM (Andrushchenko et al. 2026a). A logical alternative framework is MSEtool; a simulation platform currently used in various other Canadian stock assessments (Andrushchenko et al. 2026c, Barrett et al. 2025, Wang et al. 2022). **MSEtool** is an open source product and compatible with WHAM output structure, which makes it conducive to investigating alternative approaches to projections for 5Z Cod (Hordyk et al. 2024). WHAM assessment models were converted to MSEtool operating models (OMs) and these OMs were used for projections.

OPERATING MODELS

The **WHAM2OM** function in MSEtool creates a custom OM from a WHAM output file (Hordyk et al. 2024). During the peer review of the models, a misspecification of the input natural mortality rate (M) was evident in both candidate models, resulting in large, directional trends in process error on numbers-at-age (NAA; Andrushchenko et al. 2026a). These temporal trends in process error on NAA were considered to principally reflect changes in M and important for projections. A modification to the WHAM2OM function was made to account for the process error on NAA in the projection period.

WHAM2OM generates a set of simulations by sampling from a multivariate normal distribution defined by the WHAM model parameter estimates and their variance-covariance matrix. This results in matrices for stock NAA, fishing mortality-at-age (FAA), and with the modified version of WHAM2OM, the process error on NAA. For each model, 100 simulations were generated to capture model uncertainty in the historical stock dynamics. Matrices for spawning stock biomass weight-at-age (SSB WAA), catch WAA, maturity-at-age, and natural mortality-at-age (MAA), which were used as time-varying data inputs to the corresponding WHAM model, were provided to the modified WHAM2OM function and remained constant across simulations.

The initial year NAA values are model-estimated parameters in the WHAM models. In MSEtool, the initial year NAA values were estimated using a_{max}=9 (i.e., the number of age classes in the model), recruitment deviations prior to the first historical year (1978), and the initial year NAA. The stock dynamics for the OMs with process error $\varepsilon_{a,y}$ follow the equations:

$$N_{a,y} = \begin{cases} N_{0,y-1}\exp(\varepsilon_{0,y}) & a = 0 \\ N_{a-1,y-1}\exp(-F_{a-1,y-1} - M_{a-1,y-1} + \varepsilon_{a,y}) & a \in (1, a_{max}-1) \\ (N_{a-1,y-1}\exp(-F_{a-1,y-1} - M_{a-1,y-1}) + N_{a,y-1}\exp(-F_{a,y-1} - M_{a,y-1}))\exp(\varepsilon_{a,y}) & a = a_{max} \end{cases} \quad \text{(Eqn 1)}$$

Recruitment for a given year was modeled as the previous year's recruitment times the annual recruitment deviation $\exp(\varepsilon_{0,y})$. Following Thorson et al. (2014), the $\varepsilon_{0,y}$ were assumed to follow a stationary AR1 process with variance σ_R^2 and correlation ρ such that

$$\varepsilon_{0,y} = \rho\varepsilon_{0,y-1} + \sqrt{1-\rho^2}\delta_y \quad \text{(Eqn 2)}$$

where,

$$\delta_y \sim \text{Normal}\left(\frac{-\sigma_R^2}{2}\frac{1-\rho}{\sqrt{1-\rho^2}}, \sigma_R^2\right)$$

The MSEtool OM structure uses an age-of-recruitment of zero; therefore, the modified WHAM2OM function defined the OMs by shifting the NAA-1 for year y to NAA-0 in year y – 1 and setting an MAA of 1×10^{-6} (i.e., approximately 0) for age zero.

MSEtool only supports single fleet OMs. Therefore, the multiple fleets from the WHAM models were consolidated into a single fleet for each OM. The catch weight-at-age for a given year was defined as the average across the fleets, weighted by the catch by fleet for that year. The consolidation of FAA for three fleets into a single fleet resulted in a time-varying selectivity-at-age matrix.

Comparisons were conducted between the WHAM models and the median across 100 simulations from the OMs for historical SSB, fully-selected *F*, catch, and recruitment to confirm that the OMs truly capture the WHAM model dynamics (Figure 2). The full NAA matrices from the WHAM models were also compared with the medians across 100 simulations from the OMs (Figure 3).

PROJECTIONS

Projections forecast stock dynamics into the future and can be short- or long-term. Short-term (i.e., 1–3 years) projections are used to provide total allowable catch (TAC) advice in many traditional stock assessments, while long-term projections (e.g., two generations) are used to test various management scenarios, such as multi-year advice, against long-term management objectives. Both short- and long-term projections are used in the final framework for assessing the 5Zjm Cod stock. Uncertainty in model parameter estimates is maintained in the projections by projecting the 100 simulations of the OM.

Predicting the future is accompanied by uncertainty, which compounds with each subsequent future year in the projection. The described methodology focused on propagating uncertainty in recruitment and M, which are considered the most influential and uncertain parameters in both short- and long-term projections.

GENERATION TIME

Generation time is a metric used in estimating the timeline needed for achieving long-term management objectives (DFO 2022). DFO guidelines define generation time as the average age of the SSB that produced the current cohort, which is intended to reflect the turnover rate of

breeding individuals in a population (DFO 2022). For EGB Cod, this value has remained between 4 and 5 years throughout the time series, with the absence of older fish reducing it closer to 4 in recent years (Figure 4).

Generation time is generally used to quantify rebuilding timelines, specifically by evaluating the proximity of the stock in relation to the limit reference point (LRP) within two generation times (DFO 2022). For EGB Cod, this would define an eight to ten year window in evaluating rebuilding progress.

WEIGHT-AT-AGE

The WAA for 5Z Cod has shown signs of an increase in recent years, with fish less than age 6 weighing 26–34% more during 2021–2023 than they did in 2018–2020 (Figure 6, TRAC 2023). Neither the mechanism nor the driver behind this improvement have been identified, so the persistence of this increase in WAA in future years is a source of uncertainty. An initial look at growth from the 2024 surveys and Canadian port sampling indicates some reappearance of slow growing fish for ages 2 through 5 (Figure 5). This is expected to result in lower WAA for those ages compared to 2021–2023, suggesting that the recent increase in growth may be temporary and will not persist in the future. Consequently, the assumed growth in both short- and long-term projections was based on the average WAA from the terminal six years, which is considered more robust to interannual variations and avoids overly optimistic growth expectations on younger fish in recent years (Figure 6). Two sensitivities are also available for review: (1) assuming the most recent increase during 2021–2023 persists in the projections, and (2) assuming the projected WAA reverts back to the slower growth observed during 2018–2020 (Table 1).

RECRUITMENT

The assumptions around future recruitment are very influential for both short- and long-term projections. For the EGB Cod model, recruitment (Age 1) was estimated to be consistently high in earlier years (>10 million fish; pre-1994) and consistently low (<10 million; 1994–2020) in subsequent years (Figure 2). Recently, EGB Cod has had higher recruitment rising to around 10 million in 2021, 2022, and 2023. In all other years since 1994, with the exception of the recruitment for the 2013 year-class, recruitment has remained below 7 million (Figure 2). Both short- and long-term projections require an assumption around whether this recent increase in recruitment is expected to persist or not in the coming years.

Historic recruitment is specified in the assessment model as a deviation from the previous year (random walk), with an AR1 correlation structure imposed on the deviations. In WHAM, recruitment is projected as a random walk with AR1 deviations, resulting in future recruitment decreasing from the terminal year value towards a low value in the long term (Figure 7). In MSEtool, recruitment is projected as a continuation of the random walk, and process error deviations on recruitment were projected following the continuation of the AR1 process without bias correction, such that the recruitment deviation (ε) in a given year (y) was:

$$\varepsilon_y = \rho_{year}\varepsilon_{y-1} \quad \text{(Eqn 3)}$$

This resulted in a gradual progression of recruitment from the terminal year value to a lower value, similar to WHAM (Figure 7). This approach to projecting recruitment is acceptable for short-term projections, but introduces a negative bias into long-term projections.

For long-term projections, projected recruitment was sampled from recruitment in the terminal six years (2018–2023; Figure 4). The terminal three years exhibited surprisingly high recruitments, despite low biomass, but were preceded by several decades of very low

recruitment. The use of the six terminal years is thought to balance the low long-term recruitment tendency with the consistently high recruitment in the terminal three years. Given the significant uncertainty in the assumed recruitment, the following sensitivities were also investigated:

1. Projected recruitment was sampled from historic recruitment in the whole time series (1978–2023; Figure 8).
2. Projected recruitment was sampled from the period of 'low recruitment' since 1994 (1995–2023; Figure 8).
3. Projected recruitment was sampled from the higher recruitment observed since 2020 (2021–2023; Figure 8).

The first sensitivity assumes the stock's recruitment potential remains unchanged throughout the entire period, with all deviations (including low recruitment since 1994 and higher recruitment since 2020) considered temporary, random deviations from the series mean. This sensitivity results in approximately the same projected median recruitment as the candidate long-term projection run, but with higher variability (Figure 8). The second sensitivity assumes a permanent shift in stock productivity occurred in the mid-1990s, resulting in a sustained period of low productivity since then, which is expected to continue into the future. This is considered a sensitivity because the three highest recruitments over that time interval have all occurred in the last three years, creating uncertainty about whether the low recruitment scenario is persisting. The third sensitivity assumes that the higher recruitment estimates from 2021 to 2023 are not random fluctuations, but will persist over the next two generations, becoming the new norm, and lead to more optimistic outlooks for this stock. However, the brief longevity of the recent increase in recruitment (3 years) is insufficient to determine whether this constitutes a transition to a new productivity state for this stock, resulting in this sensitivity.

The candidate assumption put forward for short-term projections projects the random walk for mean recruitment and the AR1 correlation structure for the recruitment process error, resulting in a gradual decrease for 2024–2026 from the terminal year recruitment (2023; Figure 8). For long-term projections, the candidate assumption is to project recruitment sampled from the terminal six years (2018–2023; Figure 8; Table 1).

NATURAL MORTALITY AND PROCESS ERROR

The population dynamics model has a fixed Lorenzen M matrix, with directional trends in process error on NAA inferred to reflect, principally, changes in M (Andrushchenko et al. 2026a). This assumption was accounted for in the projections by propagating the combined impact of the Lorenzen M and the NAA (Ages 2+) process error from a given historical time period (i.e., 2018–2023) into the future. Given that process error can both add and remove fish as the cohort progresses, while M can only remove them, the net effect of combining the two can result in negative values throughout the time series (i.e., ages 1 through 3 in Figure 9), implying that processes other than mis-specification of M are contributing to the process error estimates. When compared to a WHAM model with a time- and age-varying M, the combination of the Lorenzen M and the NAA process error approximates the trends in estimated M relatively consistently for ages 4+ (Figure 9), supporting the inference that directional trends in process error principally reflect changes in M. The inconsistencies for ages 1 through 3 seem to be a function of confounding issues identified in the time-varying M model (Andrushchenko et al. 2026a), as well as large positive process error on these ages in the mid-2000s (Figure 9). The inability to distinguish between true M and other factors contributing to process error is identified as a major source of uncertainty in the current approach to estimating M.

The combined influence of the Lorenzen M and NAA process error on stock dynamics has increased in recent years across all ages, regularly reaching equivalent values of natural mortality (i.e., M – $\varepsilon_{a,y}$) in excess of 1 for fish aged 6+ since 2010 (Figure 9). The only notable decrease on older fish since the 1990s coincides with an influx of fish in the mid-2010s, returning to a high level after the influx had passed (Figure 9). The proposed approach to characterizing the combined impact in both the short- and long-term projections resamples the projected values from the terminal six years (2018–2023; Figure 10). This approach is thought to capture the recent trend in both Lorenzen M and NAA process error, without letting the latter dissipate, while propagating the uncertainty around these parameters. This approach also matches the time period used for resampling projected recruitment, accounting for any interdependence between the two (i.e., higher recruitment is accompanied by higher negative process error on younger fish).

Additional sensitivities examining the impact of the six-year assumptions around the combined Lorenzen M and NAA process error are also available, as needed (i.e., 1978–2023, 1994–2023, 2010–2023, 2020–2023; Table 1).

FISHING MORTALITY

In the absence of an F reference point, projections are provided under two levels of fishing: the mean F of the terminal six years (F=0.03) and a constant catch of 520 mt. A third scenario is included which updates the F=0.03 every two years, demonstrating the impact of multi-year catch advice. These three scenarios are thought to encompass the most pertinent options. Additional values of F deemed relevant to the discussion (e.g., F=0, arbitrarily high F, etc.) and multiple year considerations (e.g., update every three years) are also available as sensitivity scenarios.

CONSIDERATIONS

In summary, the candidate parameterization for short-term (up to three years) projections uses recruitment with projected AR1 correlation structure, with the combined Lorenzen M and NAA process error drawn from an age-specific distribution of both in the terminal six years (2018–2023). The candidate parameterization for long-term projections (two generations; 8–10 years) used both recruitment and natural mortality drawn from an age-specific distribution of the terminal six years for each parameter (2018–2023). All other biological parameters are taken as the average of the last six years, without projecting the associated uncertainty (i.e., maturity-at-age, fishery selectivity).

Uncertainty in model parameter estimates is maintained in the projections by projecting the 100 simulations of the OM. Attempts to propagate uncertainty into the projections were made for recruitment, M, and NAA process error only, as these are considered the projection parameters with the largest uncertainties in this model. Propagation of uncertainty around other parameters (e.g., WAA) is also possible, but was not pursued due to time constraints and the relatively small (assumed) impact on the outcomes. Sensitivities are provided to help quantify the impact of the candidate assumptions on projections, including a sensitivity where no uncertainty is projected for either recruitment, M, or NAA process error (Figure 12).

REFERENCE POINTS

Reference points are used to delineate the three status zones (critical, cautious, and healthy), with the removal reference (RR) for each zone indicating the maximum rate of harvest for a stock within that zone (DFO 2009). The RRs are expected to decrease progressively from healthy to the critical zone, with the RR in the healthy zone never exceeding a maximum

sustainable yield rate (F_{lim}) for the stock (DFO 2009). The final choice of reference point and removal rate is expected to be based on best available science, taking into account any limitations in data and assumptions, and be compliant with DFOs *Precautionary Approach Policy* (PA; DFO 2009).

Default policy guidance for reference points suggests evaluation of various candidate metrics, in order to provide confidence in the selected value and identify existing risks should approaches result in divergent values (DFO 2002, Barrett et al. 2024). In addition, comparison to previously accepted reference points is considered good practice, as drivers of substantial deviations from previously accepted values need to be identified.

TIME PERIOD

In general, existing guidance suggests reference points should be based on as long of a time period as possible, and include both high and low productivity periods (DFO 2013). Using a shorter time period is only acceptable when (DFO 2013):

1. the change in productivity is strongly associated with a wider multi-decadal regime shift,
2. the change is not believed to be reversible, or
3. there has been a change in the capacity of the environment to support the stock.

Although several attempts have been made to identify broad-scale regime shifts on Georges Bank, the definition of what constitutes a regime shift, and consequently its timing, seem to vary greatly (e.g., Collie et al. 2004, Mountain and Kane 2010). In addition, methodology used to detect regime shifts has come under increased scrutiny due to high rates of false positives (Haines et al. 2024), making it more difficult to provide conclusive evidence of an ecosystem-level regime shift on Georges Bank to inform a shorter time period for reference points. The M, recruitment, and growth experienced by the stock have undergone significant changes, mostly in the direction of lower productivity, though periodic improvements in the state of all three cast doubt on these low productivity states being irreversible. Finally, although some directional environmental changes on Georges Bank have taken place since 2010 which may impact the capacity of the environment to support this stock (i.e., temperature anomalies, spring and fall transition dates, north wall of the Gulf Stream Index, dominant zooplankton abundance, fish condition across species, NEFSC 2024), these changes are fairly recent and their persistence remains to be seen.

Given that none of the conditions for considering a shorter time series were met for this stock, the full time series (1978–2023) was used for calculating candidate reference points.

LIMIT REFERENCE POINT

Within the PA policy, a limit reference point (LRP) is defined as the point below which the reproductive capacity of the stock is expected to be impaired to the point of serious harm (DFO 2009). More recent guidance further clarifies serious harm as an undesirable state that may be irreversible or only slowly reversible over the long-term (DFO 2023). Although the PA Policy specifically identifies 40% of biomass at maximum sustainable yield ($0.4B_{MSY}$) as a provisional LRP falling in line with international standards and the associated F_{MSY} as the limit fishing mortality rate, it permits other approaches that are appropriate for the stock and consistent with the intent of the PA (DFO 2009, Annex 1b).

Estimation of traditional equilibrium reference points requires a well-parameterized stock-recruitment relationship. In the case of EGB Cod, the SSB-recruitment scatterplot shows a period with high recruitment at high SSB, and a period of low recruitment at low SSB

(Figure 14). Within each period, recruitment does not appear to be positively correlated with SSB, meaning traditional stock recruitment relationships (SRRs; for example, Beverton-Holt or Ricker models) do not fit well. Given the lack of a SRR, high uncertainty in M, and time-varying productivity observed for this stock, traditional equilibrium reference points based on B_{MSY}, B_0, and spawning potential ratio (SPR) were not proposed.

Estimation of a candidate LRP via surplus production (SP) focused on identifying a biomass (B) below which there is serious harm to the productivity of the stock. Following Forrest et al. (2023), surplus production at time *t* was defined as:

$$SP_t = B_{t+1} - B_t + C_t \quad \text{(Eqn 4)}$$

where B_t is SSB at time *t*, and C_t is catch biomass at time *t*. A phase plot of SP across the range of SSB values revealed a peak near 60 kt, and negative SP at low SBB (Figure 15). A loess smoother (span=0.75) fit to the data resembled the traditional downward concave yield curve, with a tail at low biomass with a mean SP above zero. The SSB below which there is negative surplus production was identified as being consistent with the PA definition of the LRP. Given the variability in the SP-SSB curve, the proposed LRP was the SSB at which the mean is not significantly different from zero (i.e., intersection of the lower 95% confidence interval for the mean and the x-axis NegativeSP95CI, Figure 15). The method for estimating the mean was chosen during the peer review meeting as a GAM model fit to the historical SP versus SSB. This LRP is also consistent with that defined for stocks of Pacific Herring (*Clupea pallasii*) on the west coast of Canada, which represented a threshold for persistent low biomass and low production states (Forrest et al. 2023; Kronlund et al. 2018).

The SP-SSB yield curve revealed other candidate reference points that were reviewed as the basis of LRPs (Figure 15), namely:

1. 0.4 B_{MSY}-proxy, where B_{MSY} is estimated as the SSB at maximum mean SP, and
2. 0.2 B_0-proxy, where B_0 is estimated as the intersection of the right side of the SP-SSB curve and the x-axis

These B_{MSY} and B_0 proxies were based on the entire time series of data and reflect productivity of the stock before it entered the current lower biomass/low productivity state.

The SSB where the mean surplus production is not significantly different from zero (NegativeSP50CI; Figure 16) was adopted as the LRP. This LRP was consistent in magnitude with the 0.4 B_{MSY}-proxy and 0.2 B_0-proxy (Figure 16).

FISHING MORTALITY REFERENCE POINT

A fishing reference in the critical zone should result in the stock moving out of the critical zone within a reasonable time frame (DFO 2009). Given the long-term projection trajectory of biomass and the fact that the LRPs that were considered range from 22–25 kt, it is highly unlikely that the SSB will exceed the LRP with a high probability (>75%) within two generations, even in the absence of fishing (Figure 17). Consequently, an F reference point cannot be provided under current projected stock dynamics.

Estimating an F reference point may become possible if productivity of this stock improves in the future. However, any future candidate fishing reference points have to account for risks of hyperdepletion associated with this model, and would ideally be developed for a model for which the mis-specification of M is resolved.

UPPER STOCK REFERENCE POINTS

Options for an upper stock reference (USR) are difficult for DFO Science to advise on for this stock, as a biological definition of what constitutes a change from a cautious state to a healthy state of the stock is not available. In the Maritimes Region, science advice on a USR has often been limited to recommendations to set the USR as a multiplier of LRP, usually double (DFO 2012). Double the accepted LRP remains an option for consideration as a USR, while other candidate approaches are outlined below.

The stock-recruitment plot for EGB Cod shows fairly compelling evidence of a high period of recruitment prior to 1992, and a low period of recruitment since then (Figure 14). The transition between these two time periods can be used to identify the boundary between healthy and cautious zones (DFO 2004). The most basic estimation of this transition involves calculating the SSB mid-way between the highest SSB in a period of low recruitment and the lowest SSB in a period of high recruitment (Figure 14). An additional approach to estimating this transition point involves using the lowest SSB which produced half of the maximum recruitment calculated by a non-parametric analysis, such as the loess (NP50; DFO 2002, DFO 2004). Both of these approaches are independent of the uncertainty around M and result in USR estimates of 43.7 kt and 51.4 kt, respectively (Figure 18).

PREVIOUS REFERENCE POINTS

Understanding and communication of the general cause in changes in biomass magnitude or reference points between assessments is suggested to help understand the uncertainty impacting the advice (Barrett et al. 2024). Although there is no change in stock status from previous frameworks for this stock, the historic biomass is generally higher with the new model, compared to the previously accepted Virtual Population Analysis (VPA; Figure 13). Given similar inputs in both models, this difference is likely to be tied to the different modeling assumptions between the two modeling frameworks (VPA vs. statistical catch at age model; error in the catch, process error, etc.).

The previously-accepted Canadian biological reference points were 21,000 mt as the LRP (DFO 2011) and 34,000 mt as the USR (NEFSC 2013); both were based on the VPA M0.8 model (TRAC 2017). When adjusted for magnitude of SSB for a common time period (1978–2013), both the adopted LRP and candidate USR are consistent with the previously accepted values (Figure 19).

APPROACHES TO ADVICE

An F reference cannot be determined under the current stock dynamics as biomass is unlikely to exceed the LRP with a high probability (>75%) within two generations, even in the absence of fishing (F=0). Given the multi-species nature of the Canadian groundfish fishery, it was proposed that TAC advice be provided based on recent F or catch levels, particularly removal levels of Cod resulting from bycatch fishing only. Note that both projections and advice based on F or catch would assume 100% utilization, so accounting for the underutilization of transboundary stocks will have to be done post-hoc.

ASSESSMENT FREQUENCY

Uncertainty and risk related to the provision of advice on a multi-year basis was considered. In this case, multi-year implementation of advice did not result in a noteworthy change in the trajectory of the stock. However, there are some unexpected, but persistent, recent changes in recruitment and growth which indicate the stock is undergoing a transition. Attempts to account

for that uncertainty were made in the projections, but it would be prudent to monitor signals on an annual basis to ensure observed trends remain within the bounds of the projection assumptions. Consequently, the following three options are outlined for possible frequency of assessment of 5Z Cod:

- Model is run annually with current data and single year projections/advice for the subsequent year.
- Model is run with current data and projections/advice for the subsequent two years. Model is rerun again once three-year projections expire or an exceptional circumstance is triggered. Exceptional circumstances are checked annually to see if a model run is triggered the subsequent year.
- Model is run with current data and provides projections/advice for the subsequent three years. Model is run again once projections expire or an exceptional circumstance is triggered. Exceptional circumstances are checked annually to see if a model run is triggered the subsequent year.

If stock advice is multi-year, the following exceptional circumstances would apply and trigger a model run:

- Projected SSB moves outside of the predicted bounds.
- Evidence of major shifts in the fishery logistics.
- Empirical evidence that stock dynamics (growth, recruitment or fecundity/spawning potential) have changed, in either direction.

An assessment framework review may be conducted on a regular cycle, typically five to ten years after development. Alternatively, there are factors that may trigger the need for a framework review sooner than expected. In both the single-year and multi-year advice scenarios, factors that may trigger a framework include:

- Evidence of substantial changes in data inputs, fishery dynamics or understanding of stock dynamics.
- A stable WHAM model capable of estimating M without confounding with process error on recruitment.
- Access to raw US fishery data to enable implementation of the TGB model.

SOURCES OF UNCERTAINTY

The largest source of uncertainty is associated with the misspecification of M in the population model. The candidate model has a fixed Lorenzen M matrix, with directional trends in process error on NAA inferred to principally reflect changes in M (Andrushchenko et al. 2026a). This inference is articulated in the projections by assuming the terminal model year estimates of both Lorenzen M and NAA process error persist in the future. Several of the candidate reference points reviewed which depend on M also assume that the combination of Lorenzen M and process error throughout the time series are the closest representation of the true M. The assumption about the true level of M, especially in the absence of a functioning WHAM run with time- and age-varying M not confounded with recruitment, represents the largest uncertainty. Currently, stock dynamics are projected using the NAA process errors which accounts for the uncertainty in M in estimated projected SSB. However, should a version of WHAM that addresses the confounding between process error on recruitment and deviations on M be made available, estimating a time- and age-varying M within the model should be pursued.

Projections make assumptions about how various aspects of stock dynamics are expected to unfold in the near future. EGB Cod experienced low recruitment/SSB ratios and decreasing WAA over decades, until the most recent years when the recruitment/SSB ratio suddenly increased to an all-time high and all fish started growing faster. The persistence of these changes through multiple consecutive years makes it difficult to attribute this to a year effect. Its occurrence in the terminal years of the model makes it difficult to determine whether it will revert back in the first projected year or continue at its current level. The proposed projection assumptions encompass both scenarios, and inadvertently widen the uncertainty around the projected stock trends.

Attempts to propagate additional uncertainty into stochastic projections were made for recruitment and process error only, as these are considered the most impactful on the projections. Propagation of the uncertainty around other parameters (i.e., weight at age, maturity) was not accounted for at this time.

RESEARCH RECOMMENDATIONS

Should a version of WHAM that addresses the confounding between process error on recruitment and deviations on M be made available, estimating a time- and age-varying M within the model will be pursued.

Propagation of the uncertainty around other relevant parameters (i.e., weight at age, maturity) can be pursued in the future.

Monitoring productivity is important for this stock, even in cases where multi-year advice is requested. Changes in productivity can be detected by individually monitoring various stock parameters, such as recruitment, natural mortality, weight at age, maturity at age. Alternatively, annual estimates of unfished spawning biomass per recruit can provide a single metric for monitoring natural mortality, weight at age, and maturity at age. This metric is subject to uncertainty around the true M, therefore additional exploration and simulation testing of such an approach is recommended.

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TABLES

Table 1. Summary table of various options for recruitment, natural mortality (M) and weight at age assumptions examined. Candidate runs for long and short term are identified in bold. All others are options which can be toggled for sensitivity runs (i.e., Rec1978+ can be combined with any M option, not just M46Sample). Dash indicates not applicable.

Projections	Recruitment	Natural Mortality	Weight at age
Candidate Run - Short Term	**AR1**	**Sampled 2018–2023 (M6Sample)**	**Mean 2018–2023**
Candidate Run - Long Term	**Sampled 2018–2023**	**Sampled 2018–2023 (M6Sample)**	**Mean 2018–2023**
Sensitivity Options	Sampled 1978–2023	Sampled 1978–2023 (M46Sample)	Mean 2021–2023
Sensitivity Options	Sampled 1995–2023	Sampled 1995–2023 (M29Sample)	Mean 2018–2020
Sensitivity Options	Sampled 2021–2023	Sampled 2010–2023 (M13Sample)	–
Sensitivity Options	Sampled 2018–2023_noUnc	Sampled 2021–2023 (M3Sample)	–
Sensitivity Options	–	Sampled 2018–2023 (M6Mean)	–
Sensitivity Options	–	Sampled 2018–2023_noUnc	–

FIGURES

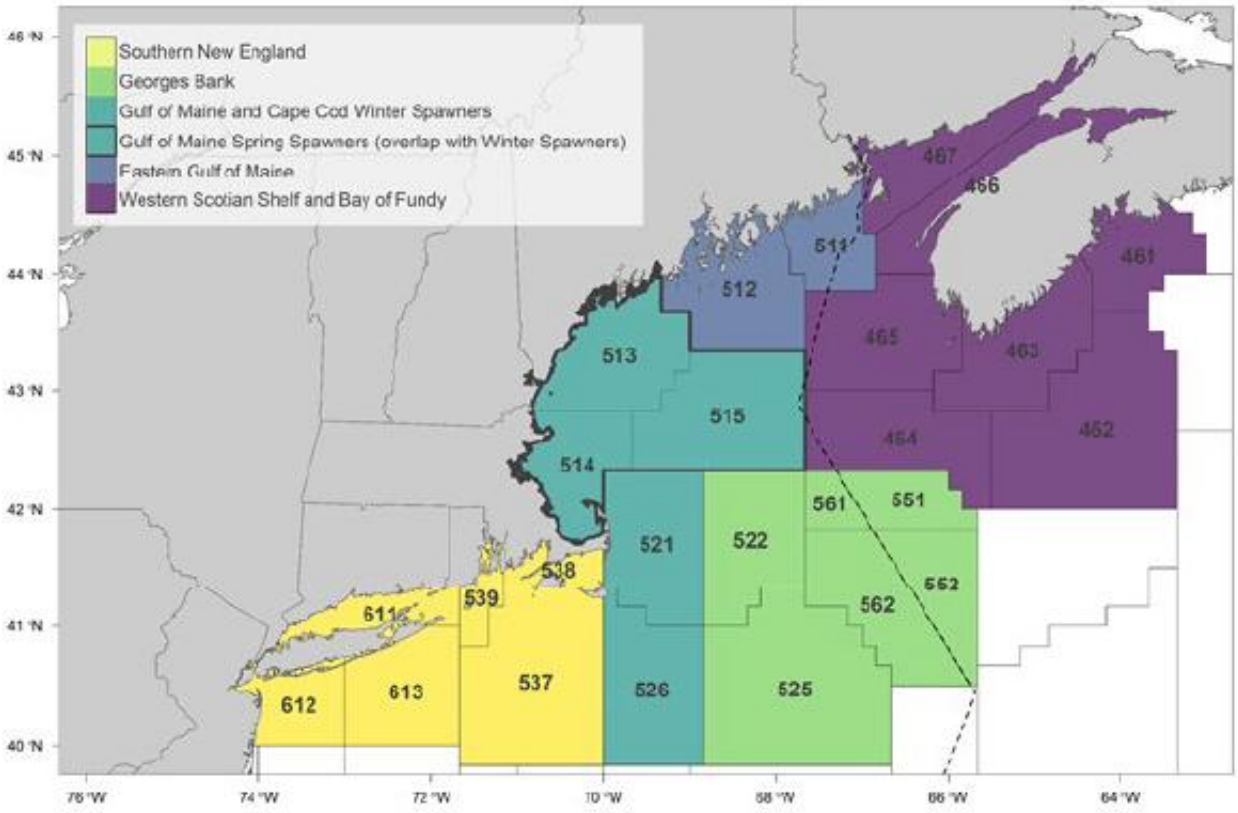


Figure 1. The revised biological stock structure of Atlantic Cod in US waters mapped to statistical units (NAFO Divisions 5 and 6). Numbers identify statistical areas used in US fishery assessments and management. Figure originally from McBride and Smedbol (2022). Dashed/grey line represents the Hague Line. Previous definition of Georges Bank included statistical areas 521, 526, 537, 538, 539.

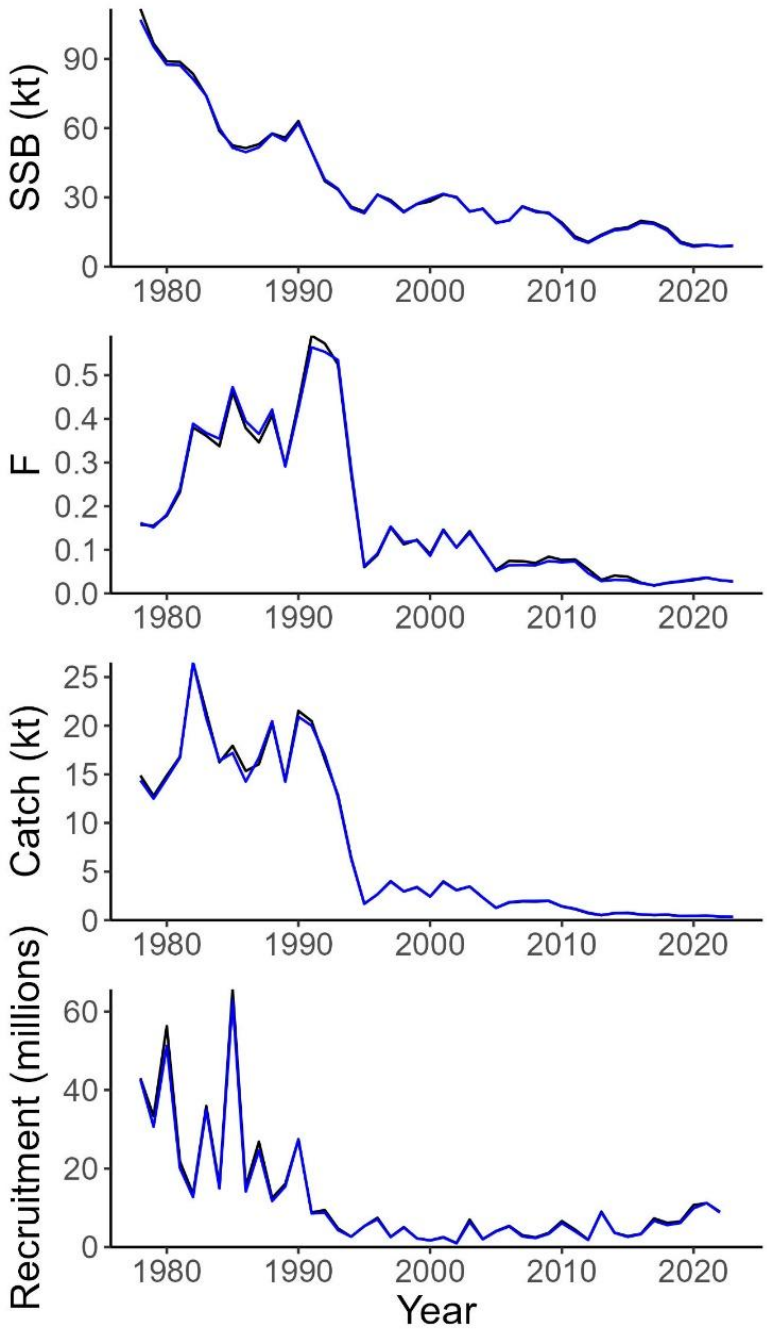


Figure 2. Comparison of historical spawning stock biomass (SSB) (kt), fully-selected fishing mortality (F), catch (kt), and recruitment (Ages 0 – lagged from the operating model (OM) to compare to Age 1 in WHAM) from the Woods Hole assessment model (WHAM) (blue lines) to the median of 100 simulations from the OM (black lines).

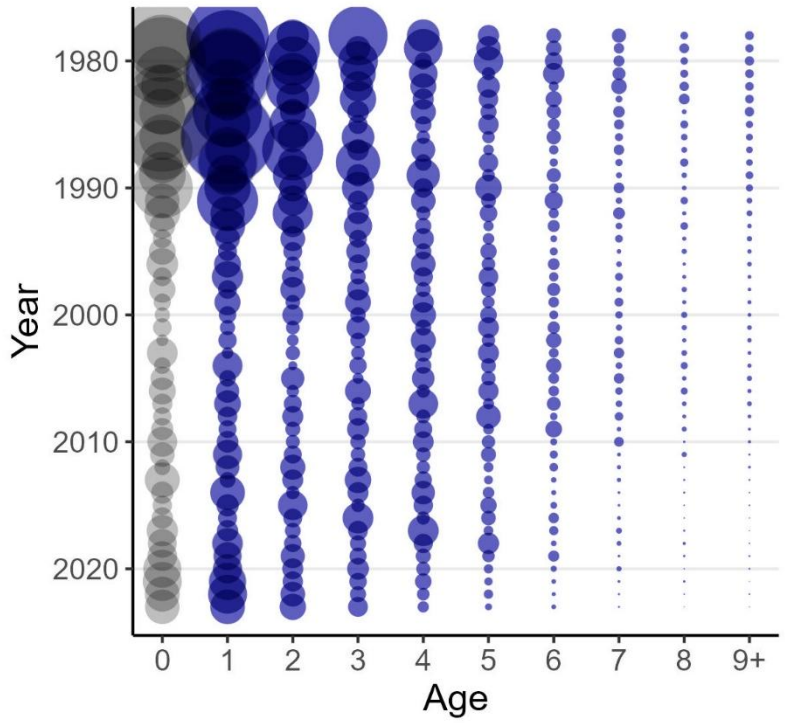


Figure 3. Comparison of the historical EGB Cod stock numbers-at-age-matrix from the Woods Hole assessment model (blue circles) to the median of 100 simulations from the operating models (OM, black circles). Points are plotted with 50% transparency and a natural mortality rate (M) of 1×10-6 is assumed for age 0 in the OMs.

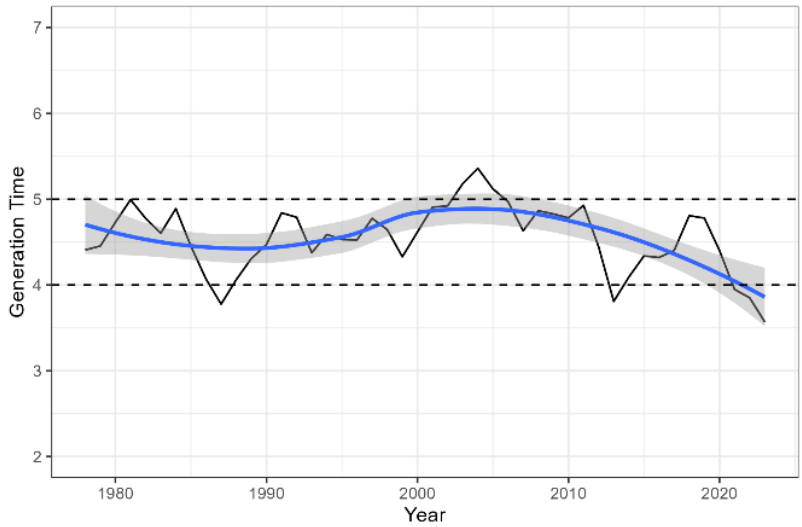


Figure 4. Generation time for eastern Georges Bank Cod. Black line represents the annual data, blue line shows the smoothed trend with standard error (grey shading) and dashed horizontal lines are references for ages 4 and 5.

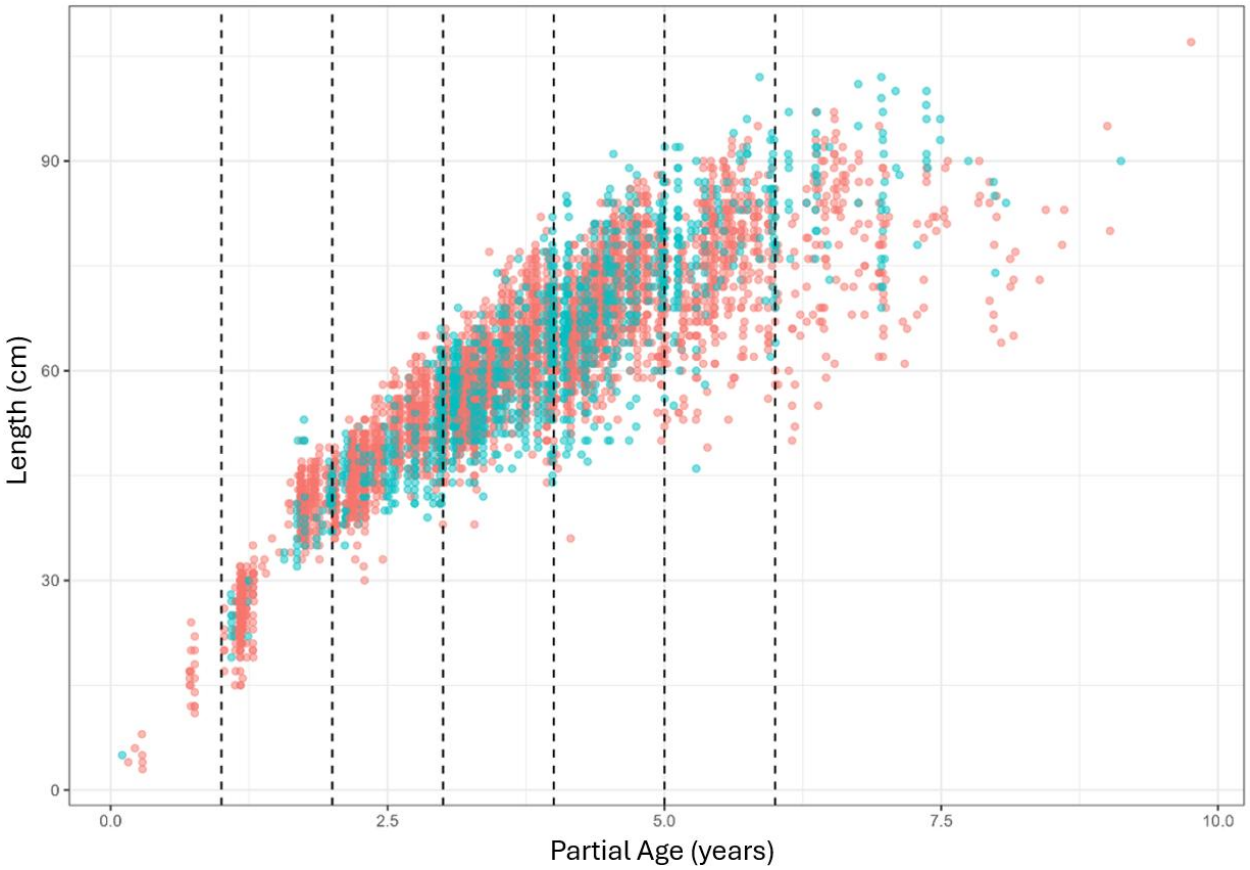


Figure 5. Combined growth (FISHLEN, length at age in cm) data for eastern Georges Bank Cod collected in recent years from the US Spring Survey, US Fall Survey, DFO Winter Survey and Canadian Port Sampling. Partial age was calculated based on the day of the year the otolith was collected. Ages were adjusted for birthdate depending on the lab they were aged at (Saint Andrews Biological Station or Woods Hole). Vertical dashed lines identify integer ages. Colours distinguish otoliths collected from 2021 to 2023 (red) and in 2024 (blue) calendar years.

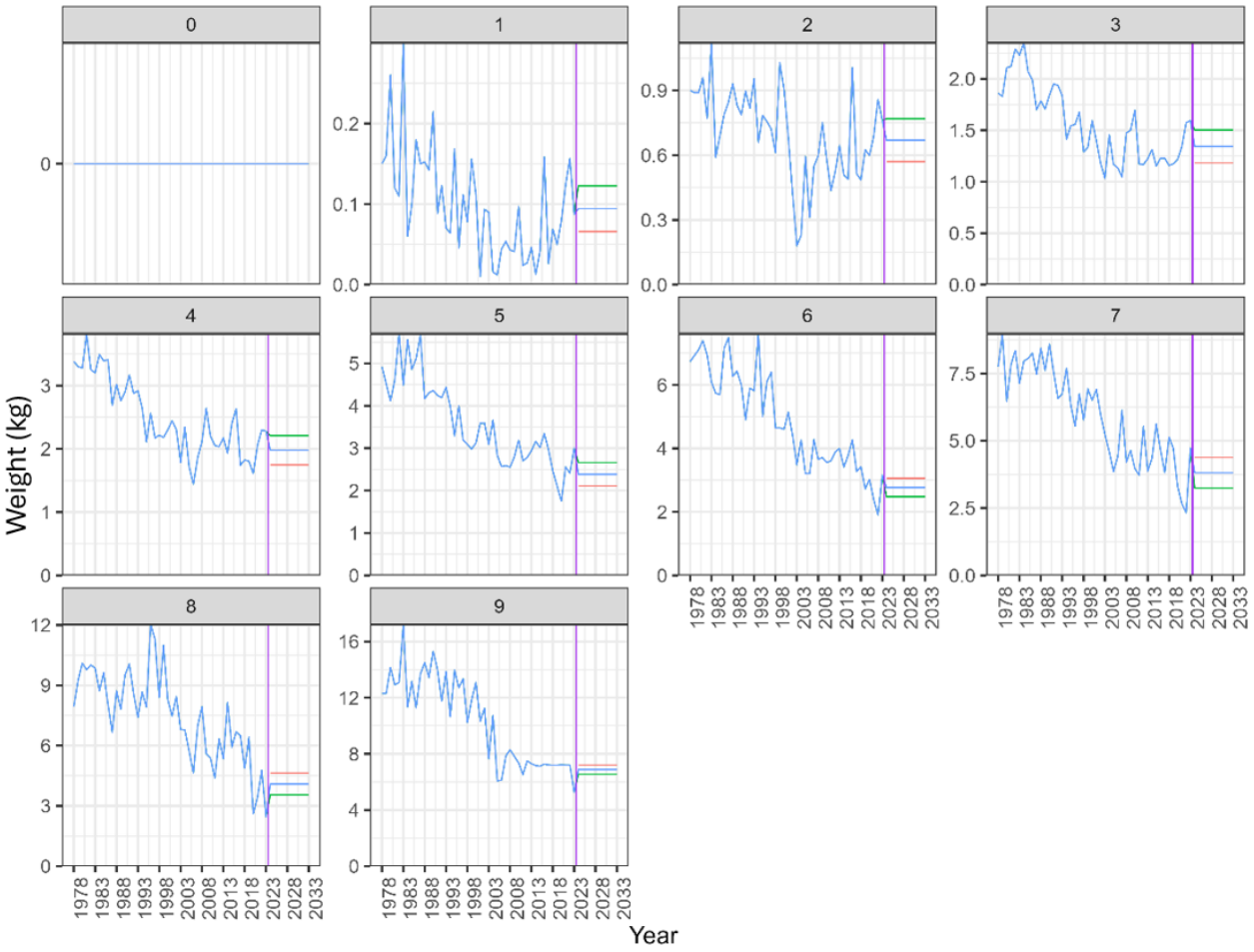


Figure 6. Weight at age matrix for the eastern Georges Bank cod model. Facets are ages 0 to 9, while the colours represent three different growth assumptions used in the projections: the terminal three years of growth (green; 2021–2023), the terminal six years of growth (blue; 2018–2023), and the most recent slow growth period (red; 2018–2020). Vertical solid line indicates transition from historic to projected years.

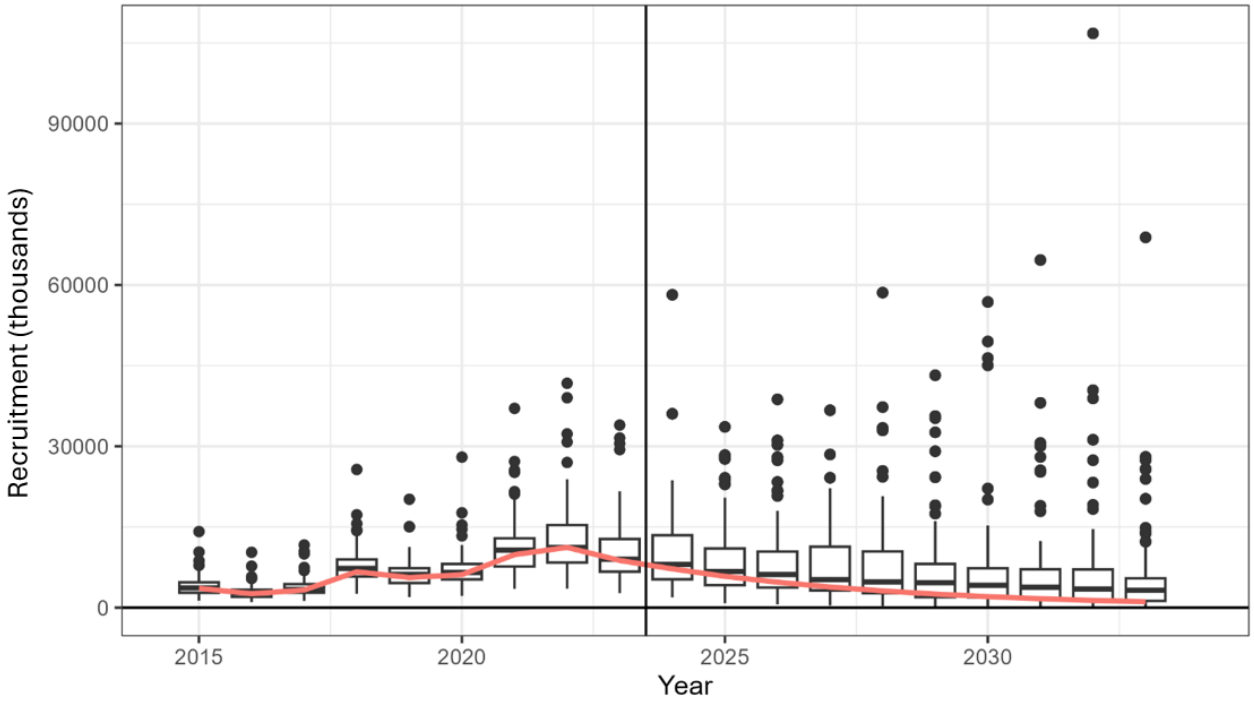


Figure 7. Recent historic (2015–2023) and projected (2024–2033) recruitment from the Woods Hole assessment model (red line) and MSEtool (black boxplots) with AR1 correlation structure.

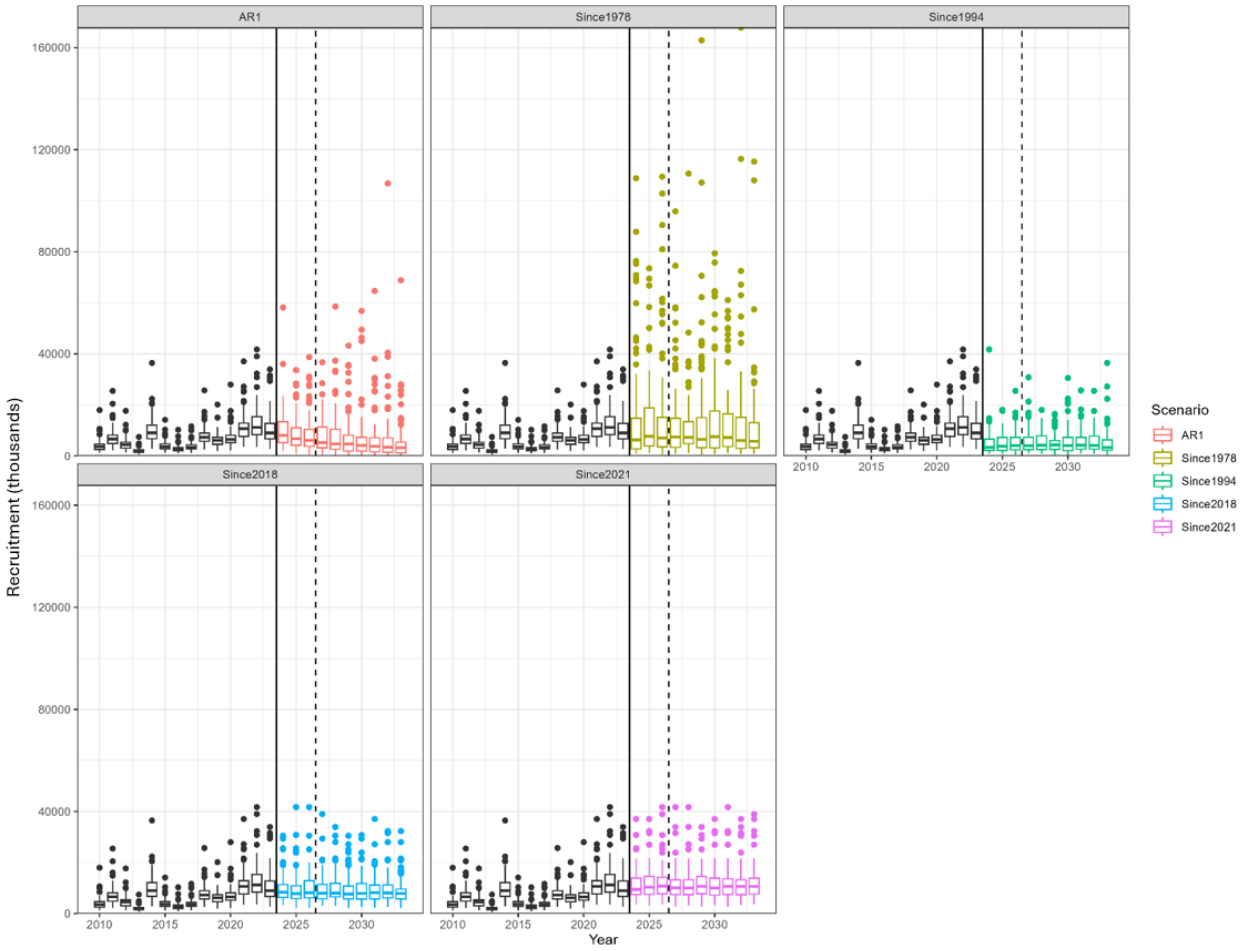


Figure 8. Recruitment (thousands) in the recent historic time period (2010–2023, black boxplots on each facet) and various projected recruitment scenarios (facet/colour combinations). Vertical solid line indicates transition from historic to projected years. Dashed vertical line indicates the terminal year of a 3-year (short term; 2024–2026) projection.

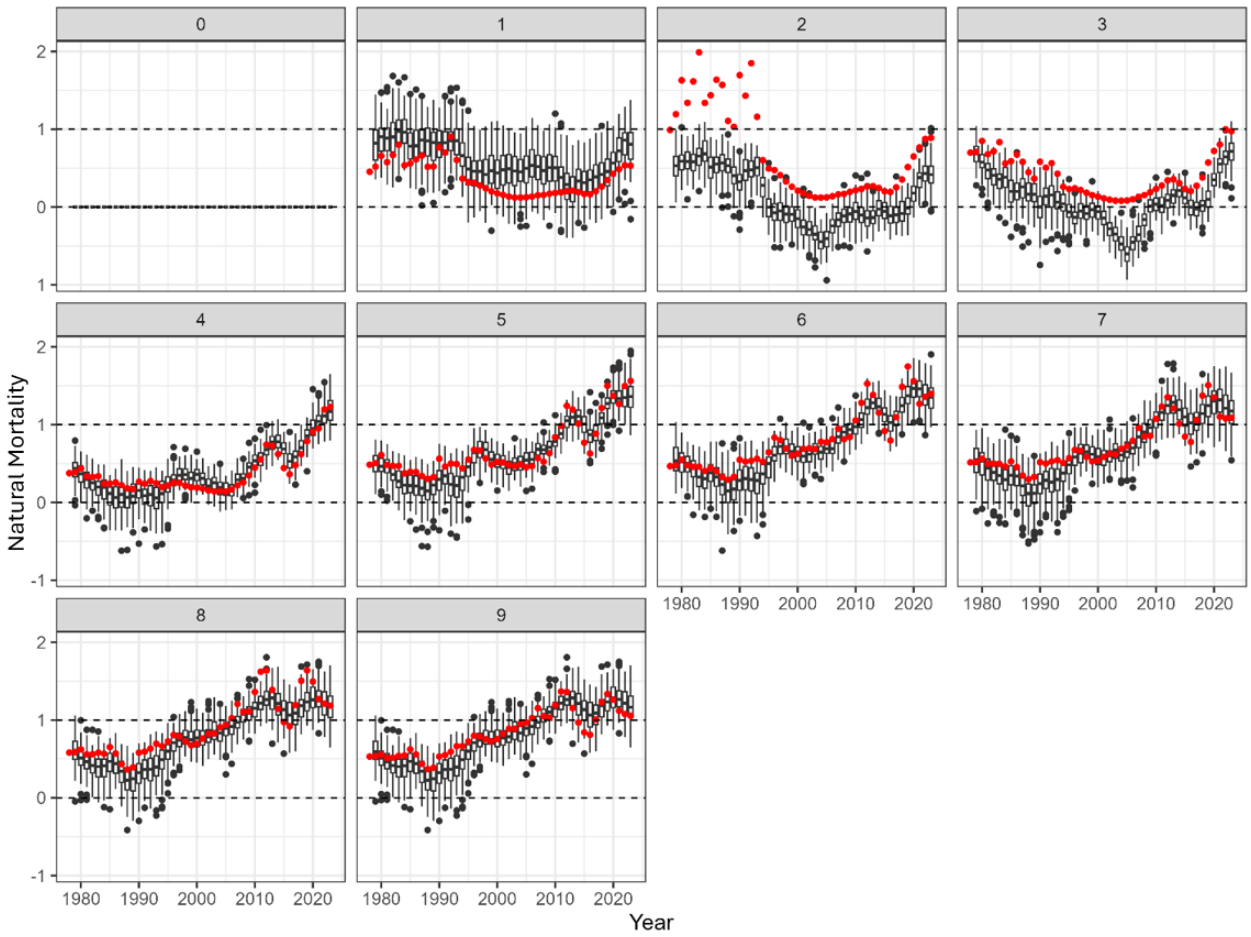


Figure 9. Natural mortality (M_ageArray) trend at age (facets) across the historic years (x axis). Boxplots show the Inferred M from MSEtool. Red points identify the M estimated from the Woods Hole Assessment model WHAM, when M is allowed to vary by time and age with a 2DARI correlation structure.

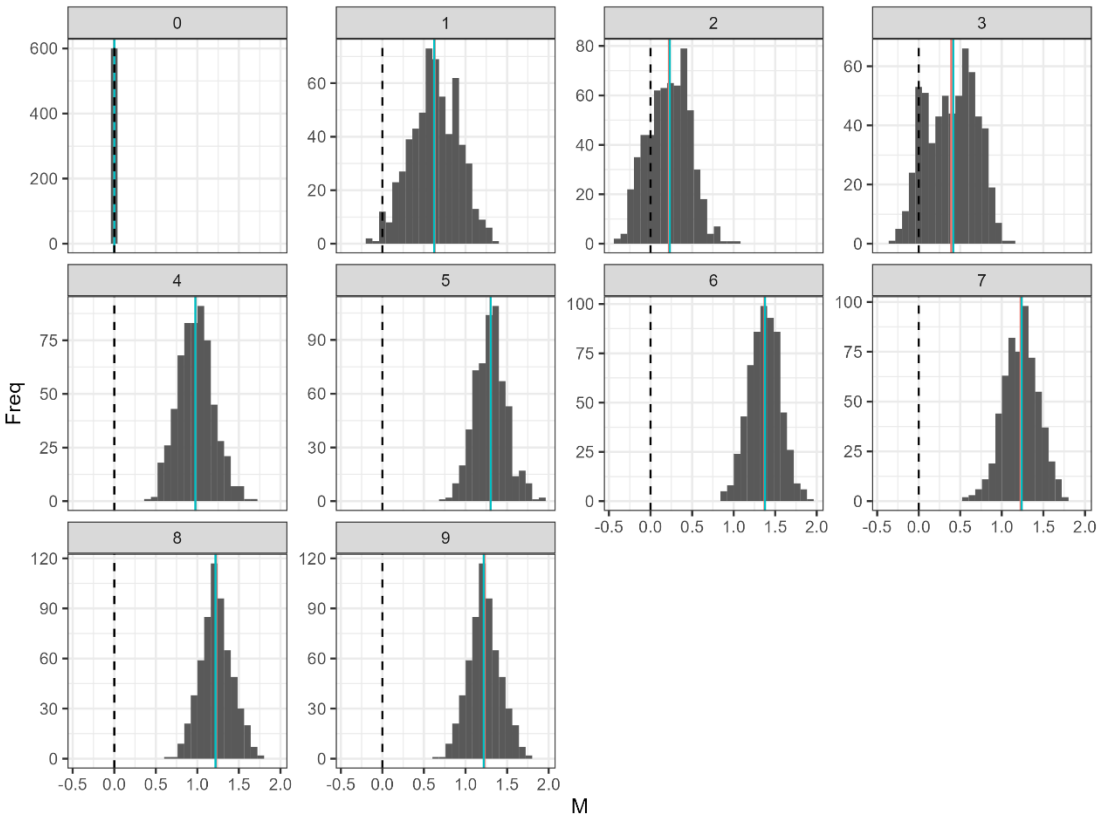


Figure 10. Frequency distribution of natural mortality (M) at age values from 2018–2023. Facets are ages 0 to 9. Dashed vertical line indicates 0. Red vertical lines indicate mean and blue vertical lines indicate median.

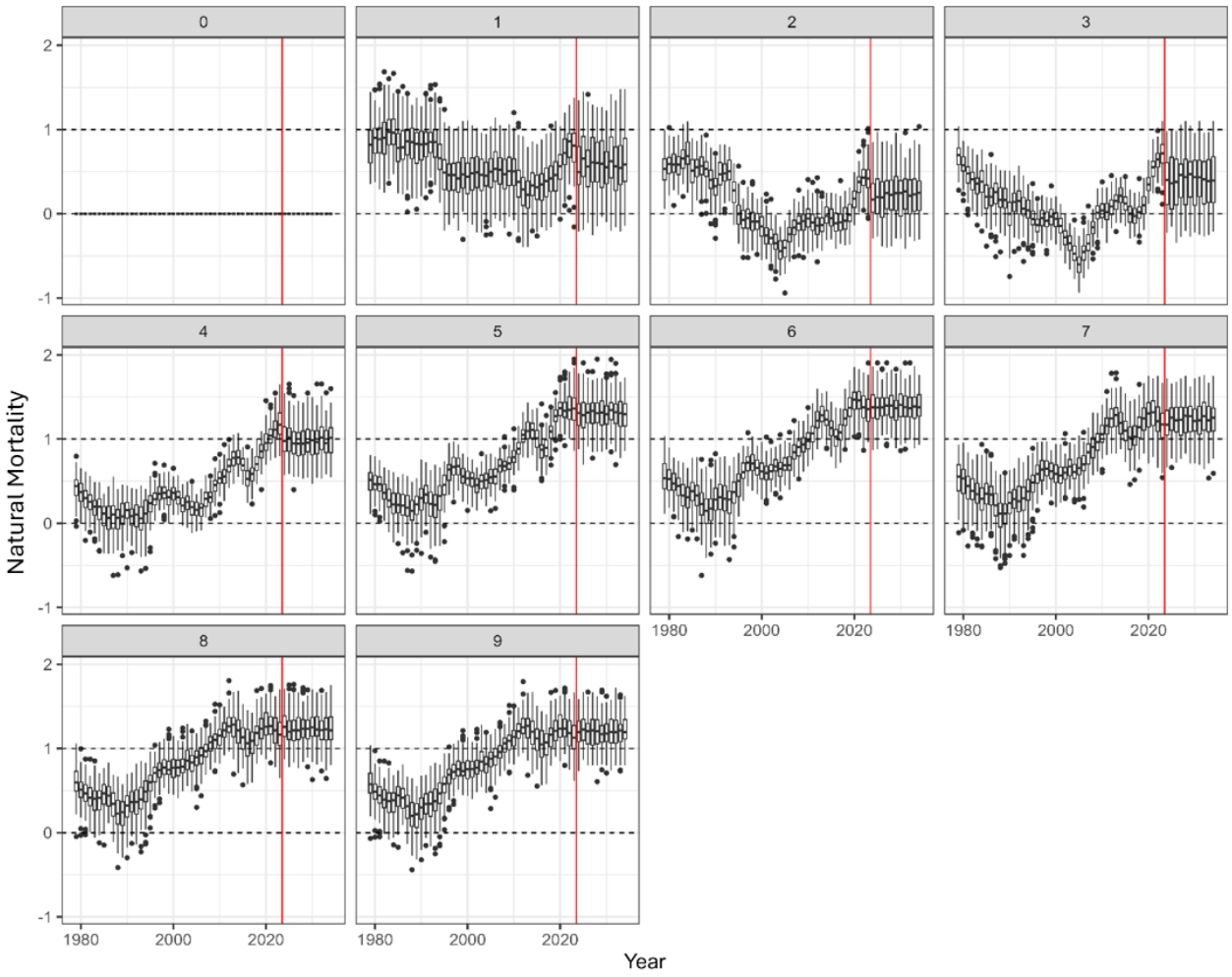


Figure 11. Historic and projected natural mortality (M) distribution for the candidate run (M6Sample). The red lines indicate the switch from historic (2023) to projected (2024).Panels indicate ages 0 to 9.

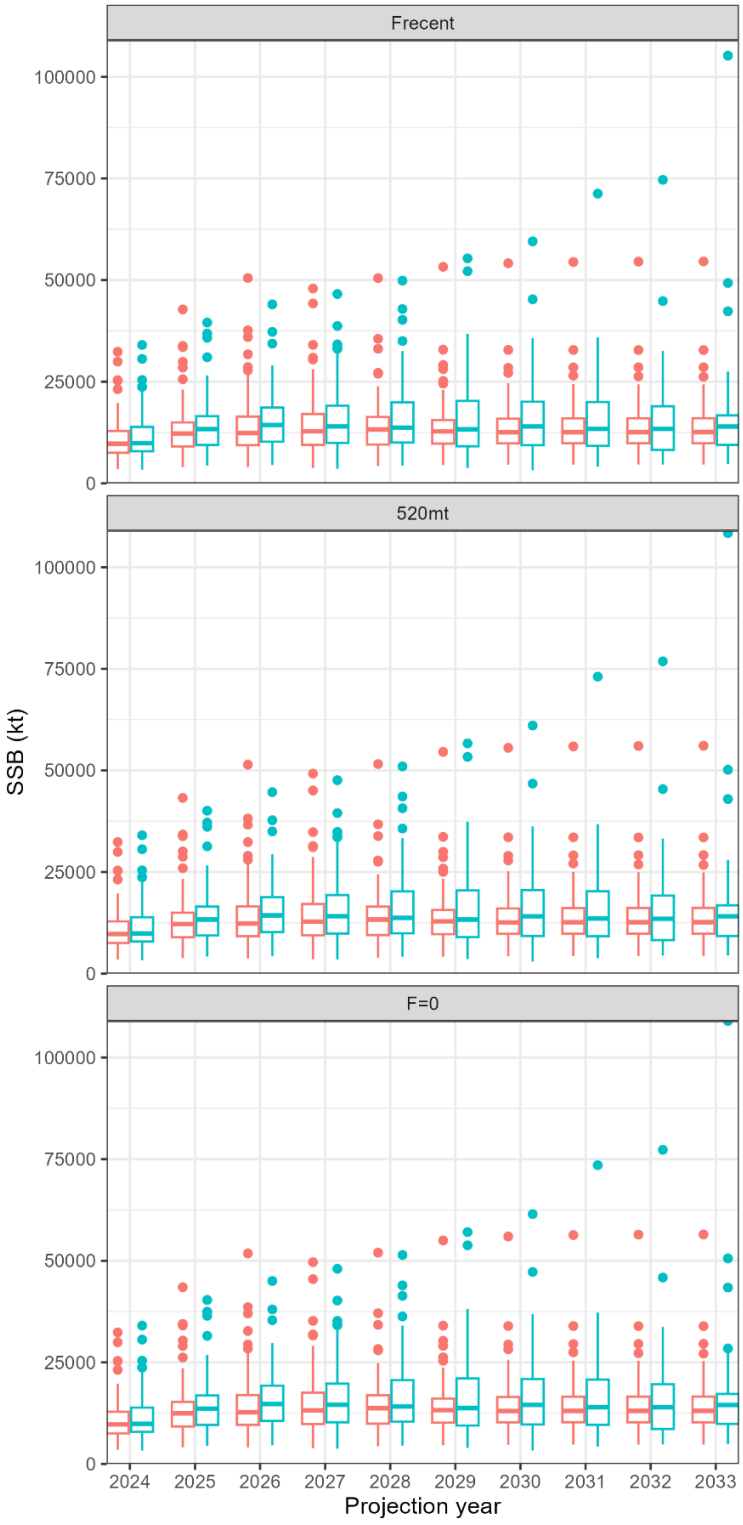


Figure 12. Comparison of projected spawning stock biomass (SSB) (kt) for the candidate long term projection operating model OM (blue lines and points include uncertainty around Recruitment and Natural Mortality) and a sensitivity operating model without uncertainty around Recruitment and Natural Mortality (indicated in red) under various fishing scenarios (F). Upper panel : recent F; middle panel: F=520 mt, bottom panel: F=0).

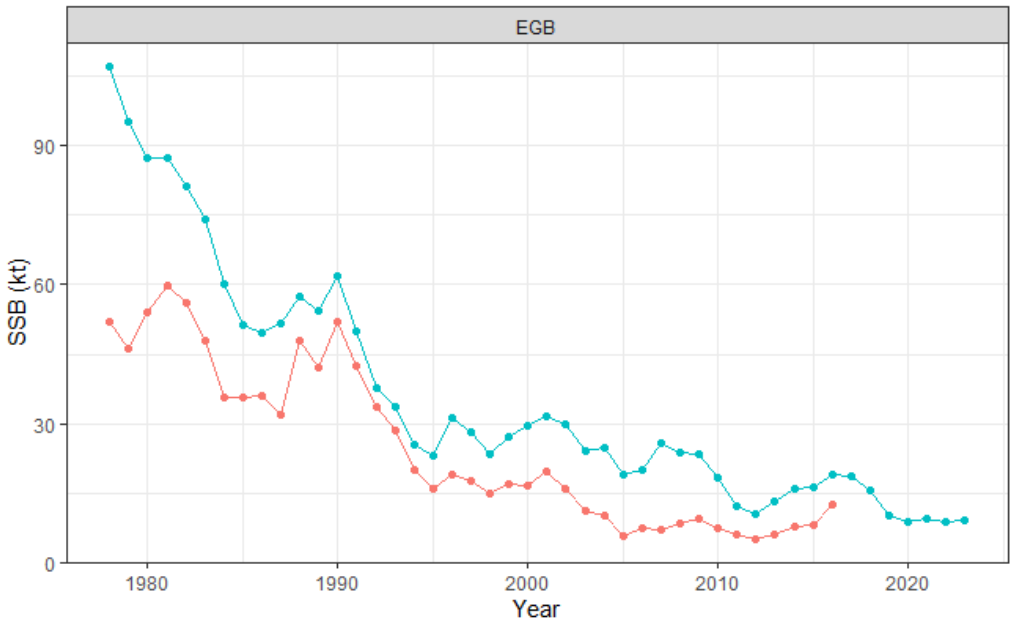


Figure 13. Comparison of the eastern Georges Bank (EGB) Cod spawning stock biomass SSB estimated by the current model (blue lines) compared to the estimates from the most recent accepted assessment model red lines) (TRAC 2018).

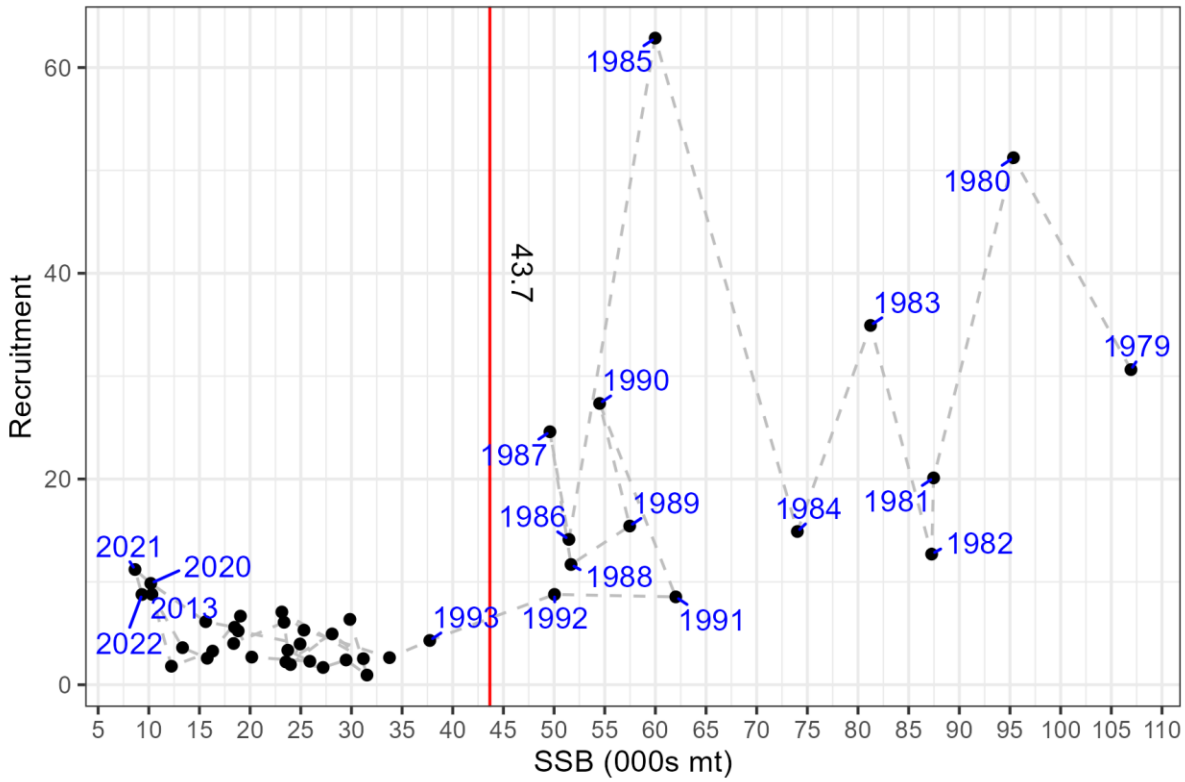


Figure 14. Relationship between spawning stock biomass (SSB) (thousands mt) and recruitment for the eastern Georges Bank Cod model by year. Recruitment (Age 1) was lagged by a year. The red vertical line at 43.7 kt is midway between the lowest SSB on the right and the highest SSB on the left.

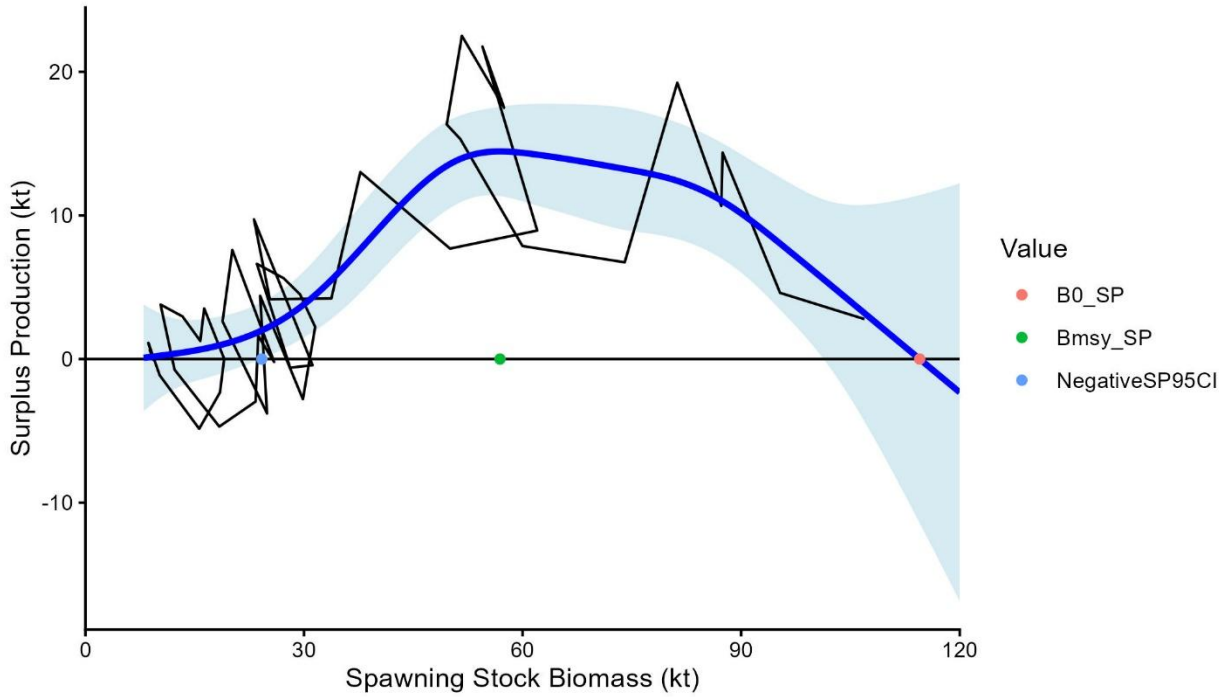


Figure 15. Surplus production versus spawning stock biomass, with a GAM fit with 95% confidence interval (blue) Colours for points identify the method behind the derivation noted in the legend (see text in Limit Reference Point section for full descriptions).

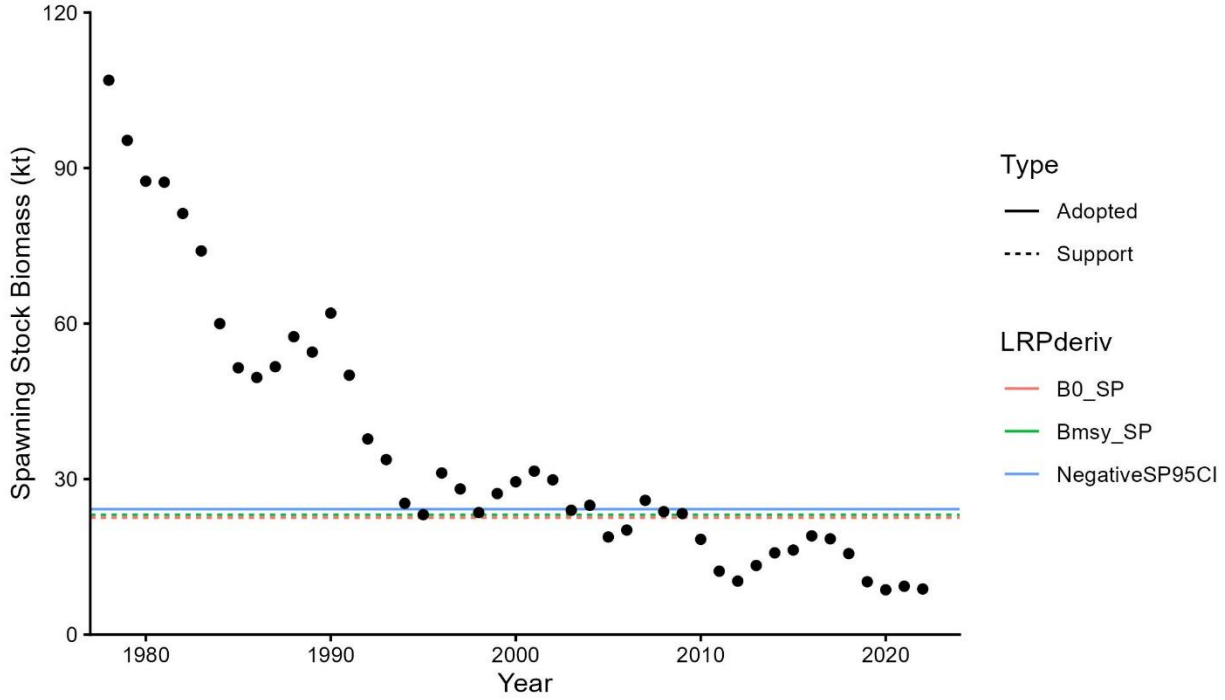


Figure 16. Adopted (solid line) and supporting limit reference points (dashed lines) and median historic stock spawning stock biomass (SSB) trajectory (black points). Colours for horizontal lines match and identify the method behind the derivation noted in the legend (see text in Limit Reference Point section for full descriptions).

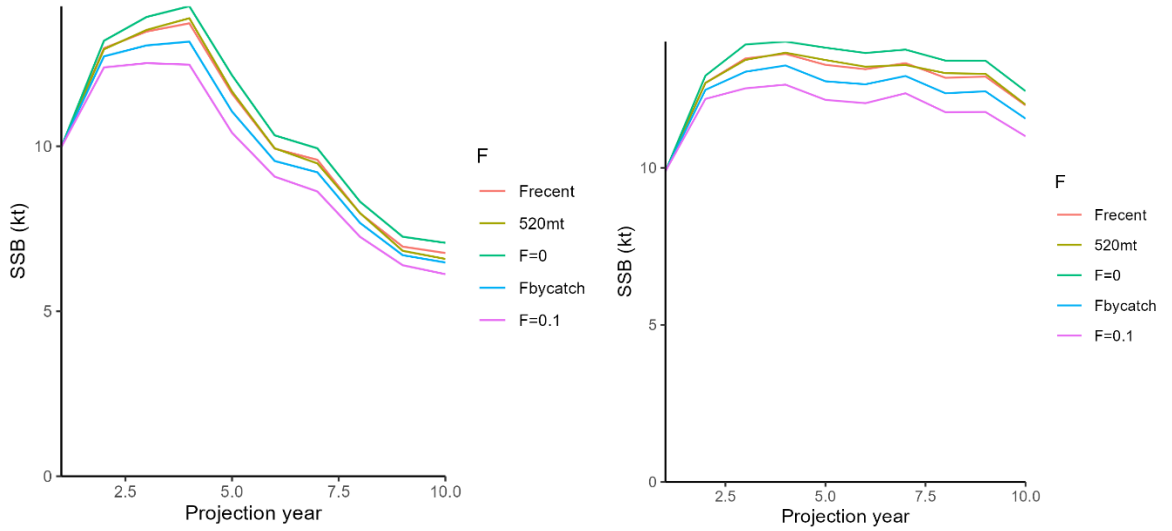


Figure 17. Projected spawning stock biomass (SSB) (kt) for the candidate short-term (left panel) and long-term (right panel) model projections using several fishing mortality (F) scenarios. Red lines: recent F;yellow lines: 520 mt; green lines: no fishing; blue lines: bycatch only; red lines: F0.1)

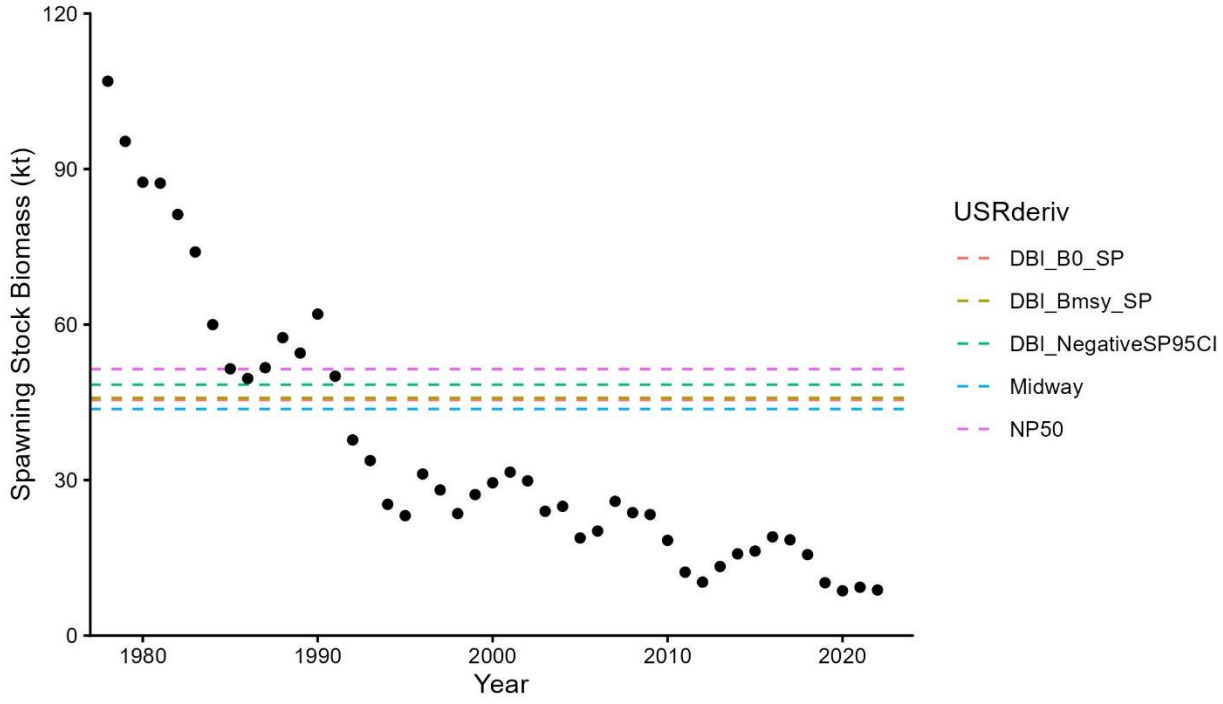


Figure 18. Candidate upper stock reference points (horizontal lines) and median historic stock spawning stock biomass (SSB) trajectory (points). Colours for horizontal lines identify the method behind the derivation noted in the legend (see text in Upper Stock Reference Points Section for full descriptions).

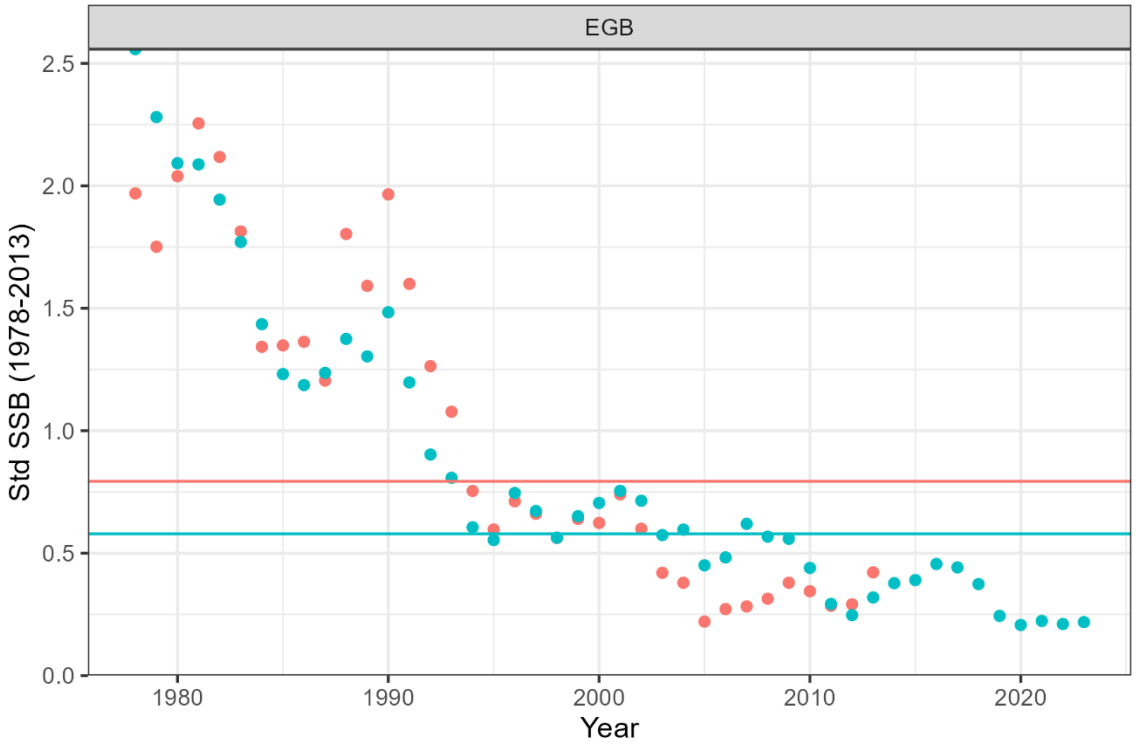


Figure 19. Spawning stock biomass (Std SSB; 1978-2013) estimates from the 2013 virtual population (red points) and 2023 Woods Hole Assessment Models (blue points) for eastern Georges Bank Cod, standardized to the mean SSB across the common time period (1978-2023). Horizontal lines depict the current candidate and previous accepted limit reference points LRPs (solid) and upper stock reference points USRs (dashed), based on the respective models and standardized in the same way.