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### **5Z Cod Assessment Framework: Review of Modelling Approaches**

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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 a Data Inputs peer review, the current work summarizes the subsequent model development. Population models were developed for both the larger total Georges Bank assessment unit, currently used in domestic assessments in the United States of America (US), and the smaller eastern Georges Bank assessment unit, currently used by Canada and the US to provide stock assessment advice to the Transboundary Management Guidance Committee to support the management of transboundary stocks.

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## INTRODUCTION

Eastern Georges Bank (EGB) Atlantic Cod (*Gadus morhua*) is a transboundary resource co-managed by Canada and the United States through the Transboundary Management Guidance Committee (TMGC). The population model developed by the Transboundary Resource Assessment Committee (TRAC) was rejected in 2018 without replacement, leaving the transboundary Cod stock without reference points or stock status. In 2023 DFO Science initiated a framework review process to develop a new modeling and assessment framework that is compliant with the precautionary approach for the transboundary Cod stock (DFO 2009). This work represents the peer review of candidate models for the framework, with the subsequent peer review of reference points and projections expected to complete the framework in the fall of 2024.

A mismatch between the boundaries for the biological stock, the aggregate units used for catch reporting in the US and the unit used for management of the stock necessitated particular consideration of the spatial coverage for this framework, as detailed in Andrushchenko et al. (2026). The most recent efforts to review Cod biological stock structure in NAFO Subareas 5 and 6 discussed evidence of a boundary between eastern (EGB) and western (WGB) Georges Bank around the 68<sup>th</sup> meridian west line, which bisects US statistical areas 522 and 525 (McBride and Smedbol 2022; Figure 1). Splitting those statistical areas introduces uncertainty into the US catches, outweighing the evidence for this division, and resulted in the revised stock structure including US statistical areas 522 and 525 in their entirety (McBride and Smedbol 2022; Figure 1). As this revised stock definition results in a mismatch between the assessment and management unit, the current framework examines two spatial configurations of the assessment unit:

1. US statistical areas 551, 552, 561, and 562, spanning DFO statistical unit areas 5Zejm (Figure 1, Figure 2); henceforth referred to as eastern Georges Bank (EGB). This area is consistent with the eastern Georges Bank assessment and management units currently accepted by the TMGC (TRAC 2002).
2. US statistical areas 551, 552, 561, 562, 522, and 525, spanning DFO statistical unit areas 5Zejmhn (Figure 1, Figure 2); henceforth referred to as total Georges Bank (TGB). This area is consistent with the domestic Georges Bank assessment unit currently applied in the US (NEFSC 2023a).

The examination of candidate models spanning both areas should allow for pragmatic comparisons of model performance and outputs, under a common modelling framework involving common model structure and assumptions. Examination of differences in performance and outputs between the two is expected to help quantify the trade-offs associated with using either assessment unit given that the transboundary management unit persists as EGB.

The majority of the population model inputs used here were peer reviewed and accepted at the Canadian Science Advisory Secretariat (CSAS) peer review meeting on the Assessment Framework Review for Atlantic Cod in NAFO Subdivision 5Z: Part 1 Review of Data Inputs, which took place on November 14–16, 2023, with technical details of pertinent data and analyses documented in Andrushchenko et al. (2026). Detailed descriptions of the data inputs are not repeated here, but there has been some additional work on inputs since the last CSAS review and is presented herein for review (see New Data Inputs and Considerations section).

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## NEW DATA INPUTS AND CONSIDERATIONS

In both the eastern (EGB) and total (TGB) Georges Bank candidate models the US and Canadian fisheries are treated as separate fleets, which helps account for the nuances of each country's fleet (i.e., differences and uncertainty in the reliability of fishery and catch monitoring, and relevant fishery changes over time). This approach is implemented because each fleet is subject to its own fishery management and monitoring framework, and because basic fishery practices may differ between harvesters in each country. Furthermore, this approach is particularly useful in recent years, when the US fishery catch-at-age or weight-at-age cannot be calculated due to low sampling and can therefore be treated as a missing value. A model with a single combined fleet would have required either imputing the missing US fishery catch-at-age data by assuming values similar to recent ones in that fishery, or that the US fishery has the same selectivity as the Canadian fishery.

The US fishery data products represent the component of the model inputs which differs the most between the EGB and TGB candidate models and therefore underlie the differences between the EGB and TGB model outputs. The Canadian fishery data inputs are identical between the EGB and TGB models, while the US fishery contributions to the overall removals are understandably greater for the TGB model (Table 1). Historically, the Canadian catches constituted 50–80% of all removals from EGB but have jumped to approximately 90% in recent years (Figure 3). In comparison, the Canadian contribution to removals of Cod from the TGB area have varied between 25% and 55% in the past, increasing to approximately 70% in recent years (Figure 3). The increase in recent years is driven by a notable decrease in US removals from Georges Bank starting around 2017, rather than increases in Canadian landings (Figure 4).

There have been longstanding concerns with the reliability of some of the data from US fisheries used as inputs to EGB Cod assessments. The characterization of misreporting in the US fishery has been discussed at length during TRAC, though the absence of viable estimates of misreported catch has made incorporation into past models difficult (O'Brien and Worcester 2010, Wang and O'Brien 2013, Clark and Trinko-Lake 2019). In the context of evidence for an increase in natural mortality for the stock, this uncertainty has consistently cast doubt on how much of the estimated natural mortality actually constitutes misreported or misattributed US catch. Consequently, additional work was carried out since the data inputs peer review meeting (Andrushchenko et al. 2026) to quantify the magnitude of suspected misattribution of EGB Cod in the US fishery, as well as considerations of uncertainty in both the US and Canadian fleets.

## CATCH MISCHARACTERIZATION AND UNCERTAINTY

### US Fishery

There are two known types of mischaracterizations in the US commercial fishery on Georges Bank: misattribution and misreporting (Hayes and Demarest 2023<sup>1</sup>, NMFS 2018). Misattribution of catch between areas stems from the requirement for fishermen to report the area where haul-back of gear occurs (Hayes and Demarest 2023<sup>1</sup>). As such, all fishing activity crossing a boundary between two adjacent areas ('straddle sets', Figure 1) must report the entirety of that catch as being caught in the area where haul back of gear occurred, even if most of the set was

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<sup>1</sup> Hayes, C., and C. Demarest. 2023. Comparing groundfish landings estimates aggregated at the broad stock area level based on vessel trip reports and vessel monitoring system data. Working Paper presented during the 2023 Cod Research Track.

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fished in an adjacent area. In contrast to misattribution, misreporting of Cod refers to intentionally reporting either a different fishing area where the tow was hauled back, an inaccurate amount of the species caught, or deliberate misidentification of one species as another (NMFS 2018). In a multispecies fishery, all three misreporting tactics buffer the impact of a choke species (a species caught incidentally while targeting other species and, that if caught in excess of its quota limits, can trigger a halt to fishing on the target species) in a given area, allowing the fishery to continue operating without exceeding the allowable catch of a species that would lead to fishery closure.

The incentive to misattribute, misreport, or discard catch can be tied to quota imbalances between areas or species, financial considerations, as well as periods of steep changes in allowable removals of a species (Holland et al. 2019, Palmer 2017). In the case of Cod on EGB, the imbalance of US quotas between EGB and TGB between the 2004 and 2015 fishing years created strong incentive to misattribute EGB Cod as being caught in the west, where quota was much higher during that time (Figure 5). However, misattribution of Cod between EGB and WGB only became legal starting in 2006, when vessels were first permitted to fish in multiple areas on the same trip (Table 2b in Wang et al. 2009). The disparity in total allowable catches (TAC) is expected to incentivize legally misattributing EGB removals of Cod as WGB, and resulted in an increase in the mean proportion of TGB Cod catch reported along the east-west boundary from 3% to 10% per year (Figure 6, Figure 7). Given the lag between implementation of management measures in a fishing year (May–April) and the aggregation of catch data available here (calendar year; January–December), the calendar years 2005 and 2016 are considered ‘transitory’ and are therefore excluded from the subsequent calculations.

Assuming the increased catches of Cod along the eastern boundary of US statistical area 522 between 2006 and 2015 were from straddle sets, an estimate of misallocated EGB Cod during incentivized years can be calculated as follows:

$$C_y = Si_y - Sn_\mu$$

where  $C_y$  is the misattributed catch in incentivized year  $y$ ,  $Si_y$  is the straddle catch in incentivized year  $y$ , and  $Sn_\mu$  is the mean straddle catch in all non-incentivized years (Figure 7). Based on straddle set catches in non-incentivized years, mean values for the annual catch were estimated as 3.1% with an associated standard deviation of 1.8% (Figure 7). Applying this approach results in mean annual estimates of misattributed EGB Cod ranging from 65 mt to 232 mt, which represents an increase of 30–163% over the current reported US fishery catches for EGB Cod in incentivized years (Figure 8). The uncertainty around the base level of activity along the boundary in incentivized years can be propagated as uncertainty in the misattributed amount, by assuming the base level of activity in incentivized years follows a normal distribution with a mean of 3.1 and a standard deviation of 1.8. Resampling  $Sn_\mu$  from that assumed distribution 1000 times results in a coefficient of variation (CV) of 0.57 around the misattributed catch estimates (Figure 9).

This method makes several assumptions that could be improved upon with increased knowledge of the fishery and access to the raw data. Currently, the estimated catch attributed to straddle sets is dependent, in part, on the coarseness of the spatial grid in the US fishery plots. A finer spatial aggregation of the fishery data or Vessel Monitoring System (VMS)-based analysis may help separate true straddle sets across the boundary from those occurring entirely along the border of statistical area 522. Assuming all catch along the eastern boundary during these years is misattributed, the amount of misattributed EGB Cod increases to 150–350 mt, and would entail a 48–281% increase in reported annual US catches for EGB Cod. Although unlikely, this provides an upper limit for the maximum amount of Cod misattributed via straddle sets during those years. In addition, this method focuses on quantifying misattributed EGB Cod

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from straddle sets across the EGB-WGB boundary only; it does not attempt to quantify the magnitude of any misreporting during those years or misattribution across other boundaries.

A different method of quantifying all removals (including misattributed, misreported and discarded) of EGB Cod using VMS data was originally described by Palmer (2017) and expanded on by Hayes and Demarest (2023<sup>1</sup>). This method applied an assumed average catch rate of Cod on EGB to the time groundfish vessels spent fishing on EGB between 2009 and 2022. The resulting estimates are generally higher (2011–2013) or equivalent (2014–2016) to those produced here (Figure 8). Interestingly, in 2009 and 2010, the VMS method produces EGB catch estimates which are equivalent to the reported catch for that year, implying that mischaracterization was not occurring. This is at odds with the straddle method presented here, which indicates that misattribution was incentivized to continue in those years. Both approaches indicate a decrease in misattribution of EGB Cod after 2016, lending further credibility to the assumption that mischaracterization is, at least in part, driven by quota imbalances.

Quantifying the magnitude of other types of mischaracterizations of both EGB and TGB Cod is extremely difficult and requires a very thorough understanding of US fisheries and monitoring systems. As such, the current framework relies on previously calculated values of any misreporting besides those sets straddling the EGB-WGB boundary. Misreporting estimates of both EGB and TGB Cod as another species between 2012 and 2017 was compiled by NMFS (2018) and amounted to 1.7–2.3 mt for EGB and 4.4–25 mt of TGB in the 2014 and 2015 fishing years (1.5–2% of reported EGB catches and 1–3% of reported TGB catches in those years). Although likely an under-estimate, these are the only known quantitative estimates of species-level misreporting on Georges Bank. Furthermore, species-misreporting is thought to have occurred prior to 2012 as well, but no estimates exist.

Uncertainty around the US removals of EGB Cod was incorporated into the models by treating the misattributed catches as a separate fleet from the reported US catch. This approach allowed for separation of the estimated bias (directional misattribution) from the uncertainty (CV, no directionality) around the reported US catches on EGB. Since these estimates were only available for 2005–2016 and the current modeling framework software cannot accept zeroes in the total catch of a fleet, this fleet was assigned a catch of 1 mt in all other years; an assumption which can be easily modified if more refined, non-zero estimates of misattribution become available for other years. The selectivity for the misattributed fleet was assumed to be the same as that of the US reported fleet, given the absence of age composition data specific to the misattributed catch. There is no reason to expect a difference in selectivity between these two fleets.

Since the calculated misattribution estimates dealt with straddle catch between EGB and WGB only, the TGB model already accounted for this misattribution internally and did not require a third fleet.

## **Canadian Fishery**

Currently, misreporting associated with the Canadian fleets fishing on Georges Bank is thought to be relatively minor, with monitoring systems and high observer coverage acting as a deterrent to misreporting of Cod between areas or as a different species. Any substantial misreporting is thought to be limited to the 1970s and early 1980s, when fishermen were reluctant to provide information in case it was used for enforcement purposes (Haché 1989). The disparity in TACs between EGB and the adjacent stock area (NAFO 4X5Y) has never been large enough to incentivize misreporting of Cod between the two areas given the high risk of detection (Figure 10). As quantifiable estimates of historic misreporting in the Canadian fishery are not currently

available, they are captured as part of the uncertainty (coefficient of variation, CV) around the total removals.

## MODEL STRUCTURE

Two proposed candidate population models for transboundary Cod are presented, with one spanning EGB (DFO unit areas 5Zejm; US statistical areas 551, 552, 561, 562) and the other spanning TGB (DFO unit areas 5Zejmhn; US statistical areas 551, 552, 561, 562, 525, 522; Figure 1). Both models were developed using the Woods Hole Assessment Model framework (WHAM), a state-space age-structured modeling framework (Stock and Miller 2021).

Furthermore, process error on population numbers at age can be parameterized as a random effect, estimated as independent identically distributed (IID) variates or as correlated values across years, ages, or both. In this case, the random effects estimated on numbers at age are expected to encompass process error on recruitment, natural mortality, movement in and out of the area as well as fishing mortality resulting from factors such as variation in fishery selectivity and uncertainty in fishery catch at age.

For the purposes of this review, relevant population and observation equations for WHAM are summarized in brief below, with detailed explanations available in Stock and Miller (2021), Miller and Hyun (2018), and Miller et al. (2016).

## PROCESS MODEL

The WHAM framework separates the population dynamics (process model) from the fishery and surveys used to observe the population (observation model). For a model that includes an age class that aggregates abundance at older ages, commonly called a plus group, the cohort dynamics model structure within WHAM is as follows:

$$\log N_{a,y} = \begin{cases} \log(N_{1,y-1}) + \varepsilon_{1,y}, & \text{if } a = 1 \\ \log(N_{a-1,y-1}) - Z_{a-1,y-1} + \varepsilon_{a,y}, & \text{if } 1 < a < A \\ \log(N_{A-1,y-1} e^{-Z_{A-1,y-1}} + N_{A,y-1} e^{-Z_{A,y-1}}) + \varepsilon_{A,y} & \text{if } a = A \end{cases}$$

where  $N_{a,y}$  is the numbers at age  $a$  and year  $y$  ( $A$  being the plus group),  $\varepsilon_{a,y}$  is the process error associated with the numbers at age for age  $a$  and year  $y$  and  $Z_{a,y}$  is the total mortality experienced at age  $a$  and year  $y$  (Stock and Miller 2021). The model is structured according to ages 1 through 9+, with age 1 considered recruitment and age 9 including older ages. Assuming a plus group for ages 9+ balances the model's ability to deal with nil catches in surveys or the fishery at older ages in certain years, while retaining relevant information on cohort dynamics over several adult age classes. Recruitment in a given year is estimated as the previous year's recruitment plus process error  $\varepsilon$  that is assumed to follow a stationary AR(1) process with variance  $\sigma^2_R$  and correlation  $\rho$ :

$$\varepsilon_{1,y+1} \sim \mathcal{N}(\rho_{year}\varepsilon_{1,y} - \frac{\sigma_R^2}{2(1-\rho_{year}^2)}, \sigma_R^2)$$

The correlation parameter incorporated in the recruitment process error results in a correlation in recruitment across years.

The alternative option in WHAM estimates a mean recruitment across the time period, with process error accounting for annual deviations as:

$$\log(N_{1,y}) = \log(R_0) + \varepsilon_{1,y}$$

where  $R_0$  is the recruitment series mean and  $\varepsilon_{1,y}$  is the process error with the AR(1) covariance structure across years. Both of the candidate models use the random walk approach, but sensitivities were carried out with the alternate option as well.

Separately from recruitment, process error is also implemented on ages 2+ but assumed to follow a two-dimensional AR1 correlation structure by both year and age. Natural mortality (M) is parameterized as an input matrix of fixed values varying by age and by year, estimated external to WHAM using the empirical relationship between body weight and M from Lorenzen (1996, Figure 11).

Random effects on natural mortality (M) can be implemented in WHAM with random effects correlated by age and year [2DAR(1), Stock and Miller 2021]. However, the current correlation structure must encompass all ages (1–9+) and cannot be separated into random effects on recruitment (age 1) and random effects on older ages (2+). Consequently, correlated random effects on natural mortality are heavily confounded with recruitment process error, so estimating M within the model was not considered a viable route at this time. In both models, M was calculated empirically as a function of weight at age (Lorenzen 1996) and set as a fixed effect in both models. This approach allowed M to vary by age but also reflect the temporal trends in weight at age over time (Figure 11). Unfortunately, this approach does not account for extrinsic drivers of natural mortality, such as predation or competition (Lorenzen 2022).

## OBSERVATION MODEL

The observation component of WHAM considers the expected aggregate survey indices as relative indices of the true population, defined as:

$$\hat{I}_{y,i} = \sum_a q_i S_{a,i} N_{a,y} W_{a,y,i} e^{-Z_{a,y} f_{y,i}}$$

where  $q_i$  is the time invariant catchability for survey  $i$ ,  $S_{a,i}$  is the time-invariant selectivity at age  $a$  for survey  $i$ ,  $W_{a,y,i}$  is the weight at age  $a$ , year  $y$  and survey  $i$ , and  $f_{y,i}$  is the fraction of year associated with survey timing.  $W_{a,y,i}$  and  $f_{y,i}$  are model inputs. For both EGB and TGB Cod, the selectivity for the NMFS spring surveys is estimated as a logistic ('flat-top'), while the selectivity for the NMFS fall surveys is assumed to follow a dome shape. The dome shape is informed by the absence of older fish in the fall catch (i.e., 7+ throughout the 2000s, 5+ since 2021), while the NMFS spring surveys continue to catch older fish. Dome shaped selectivity in WHAM is estimated as age-specific estimates of selectivity, in the present case with selectivity on ages 2 and 3 fixed at 0.8 and 1, respectively. Initially, dome-shaped selectivity estimation was attempted by assuming an underlying double logistic selectivity curve, but both models encountered issues with selectivity parameter bounds and did not converge. Estimating selectivity at age required fixing at least one age, with empirical analyses suggesting full selectivity at ages 2–3. Fixing full selectivity at only age 3 resulted in intermittent bound issue for the age 2 estimate, while fixing full selectivity at age 2 resulted in a non-invertible hessian matrix. Based on previous treatment of the NMFS fall survey in transboundary Cod assessments, full selectivity was set at age 3, with age 2 selectivity fixed at 0.8, which stabilized the model.

The log aggregate survey index observation is assumed to follow a normal distribution with a bias correction term ( $-\frac{\sigma_{I_{y,i}}^2}{2}$ ) and the standard deviation ( $\sigma_{I_{y,i}}^2$ ) a function of a user-specified CV (Figure 12):

$$\log(I_{y,i}) \sim \mathcal{N} \left( \log(\hat{I}_{y,i}) - \frac{\sigma_{I_{y,i}}^2}{2}, \sigma_{I_{y,i}}^2 \right)$$

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The considerations going into informing the fishery CV are outlined below (section Fishery Coefficient of Variation). The expected aggregate fishery catch is defined as:

$$\hat{C}_{y,i} = \sum_a N_{a,y} (1 - e^{-Z_{a,y}}) \frac{F_{y,i} S_{a,b,i}}{Z_{a,y}} W_{a,y,i}$$

where  $F_{y,i}$  is the fishing mortality of fleet  $i$ ,  $S_{a,b,i}$  is the selectivity for fleet  $i$  in block  $b$  and age  $a$ , and  $W_{a,y,i}$  is the fleet-specific weight at age matrix. Fishery selectivity is estimated as a logistic function, as no evidence exists of a decrease in fishery selectivity on older fish. There appears to be a tendency for the Canadian fleet to catch a slightly higher proportion of older fish compared to the US, suggesting that estimating selectivity separately for each fleet is appropriate (Figure 13).

Decisions regarding changes in fishery selectivity were informed by several factors. Initially, examination of fishery management measures identified the early to mid 1990s as having some changes to minimum mesh sizes, with Canada implementing a 130 mm square minimum mesh size in 1990 and adding a 145 mm diamond minimum in 1991; the US implemented an increase from 5.5 to 6 inches starting in 1994 (Table 2). In addition, the Canadian fishery shifted from directing for Cod to directing for Haddock at this time (Andrushchenko et al. 2026). Finally, a notable decrease in length at age occurred in the mid 1990s for Cod caught in all three surveys across both spatial units, and since selectivity is likely to be size-based, this change is expected to affect changes in age-specific selectivity (Figure 14). These three factors all culminated in an expected change in the fishery selectivity for both the Canadian and US fleets, shifting the peak of empirically calculated selectivity from ages 2–4 prior to the mid 1990s to ages 3–5 afterwards (Figure 15a, Figure 15b). Consequently, selectivity was estimated in two blocks ( $b$ ) for each of the reported fleets (1978-1993, 1994+), with the exact year for the break representing a balance between changes in growth, species directing, and mesh size. For the EGB models, the selectivity for the misattribution fleet was assumed to be the same as the US reported fleet.

Similar to the aggregate survey indices, the log aggregate catch is assumed to have a normal distribution with a standard deviation informed by a user-specified coefficient of variation for each fleet  $i$ :

$$\log(C_{y,i}) \sim \mathcal{N}(\log(\hat{C}_{y,i}) - \frac{\sigma_{C_{y,i}}^2}{2}, \sigma_{C_{y,i}}^2)$$

The negative log-likelihood component for age compositions for both the fishery and the surveys catch at age data were assumed to follow a Dirichlet distribution, with observations of nil catch pooled with adjacent classes (Stock and Miller 2021). The Dirichlet was chosen because it is self-weighting and does not require a user-specified estimate of effective sample size (ESS) for each fishing fleet and survey age composition dataset ( $i$ ). The age composition likelihood equation is:

$$-\log \mathcal{L}(\hat{p}, \phi | p^*) = \Gamma(\phi) - \sum_a [\Gamma(\phi \hat{p}_{a,y,i}) + (\phi \hat{p}_{a,y,i} - 1) \log p_{a,y,i}^*] \quad \phi > 0$$

where  $\phi$  is an estimated parameter,  $p_{a,y,i}^*$  is the observed proportion at age vector for dataset  $i$ , year  $y$  and age  $a$ , while the predicted proportion vector ( $\hat{p}_{a,y,i}$ ) for each age  $a$ , year  $y$  and dataset  $i$  is defined as:

$$\hat{p}_{a,y,i} = \frac{\hat{C}_{a,y,i}}{\sum_{a=1}^A \hat{C}_{a,y,i}}$$

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With  $\hat{C}_{a,y,i}$  being the predicted catch at age for each fleet ( $i$ ) and is replaced by  $\hat{I}_{a,y,i}$  when applied to the survey datasets.

### **Fishery Coefficient of Variation**

The CV associated with each fleet is intended to reflect the uncertainty around total removals. In the case of the US misattributed fleet, the CVs can be calculated from the uncertainty around the estimated removals (Figure 9), resulting in a CV of 0.57. However, such a high level of uncertainty can result in unrealistic interannual fluctuations in the catch for that fleet (e.g., 4,000 mt per year, Figure 16). To avoid this issue, the CV on the misattributed fleet has been set at 0.2. The CVs for the reported fleets (US and Canada) are difficult to estimate quantitatively and are therefore partly based on expert opinion.

For the Canadian fleet, the high CV leading up to 1990, is thought to reflect the higher uncertainty due to the mistrust of the fishermen in the scientific use of the data at the time (Figure 17, Andrushchenko et al. 2026). Through the 1990s, trust increased but the drastic interannual changes in the TAC likely maintained a level of uncertainty in the reported catches. Finally, as TAC stabilized and VMS became well established in the late 1990s, the CV on the Canadian removals decreased further. The implementation of the Maritimes fisheries (MARFIS) database in 2003 eliminated the uncertainty associated with querying the databases, effectively reducing the uncertainty to only encompass that associated with the estimation of Cod discards from the groundfish and Scallop fisheries (Figure 17).

For the US reported fleet, the CV was also highest up until the mid-1990s, when information about the area fished was collected using dockside interviews rather than trip reports (Figure 17). Following the implementation of mandatory vessel trip reports, the CV on the US fleet catches decreased but remained higher than the Canadian fleet due to uncertainty associated with using two sets of monitoring systems in the US. The implementation of Amendment 16 in 2010 led to the adoption of various accountability measures which increased data quality, but the existence of two monitoring systems persisted (NEFMC 2010). The introduction of the Catch Accounting and Monitoring System (CAMS) in 2021 resolved this issue for the US, further decreasing the CV. The most recent level of CV specified for the US reported removals encompasses uncertainty with respect to discard estimation and some outstanding issues with respect to monitoring and catch accounting in the fishery (SSC 2019).

The trend in reported fleet CVs over time is informed by a progressive increase in data quality, improvement in monitoring systems and reporting consistency for each country. The absolute value of the CVs, however, is based on a mixture of expert opinion and the unrealistic deviations estimated by WHAM when CV exceeds 0.2 (Figure 16). In this case, expert opinion was obtained by asking the fishermen how much the true catch ranged from the reported values in the 1980s (Figure 18) and now (Figure 19).

### **CANDIDATE MODELS**

The final candidate models for both TGB and EGB are identically structured, except for the presence of a third 'misallocated' fleet in the EGB model only. Otherwise, both models have separate, country-specific fleets, with fleet selectivity estimated as a logistic curve in two blocks of time (1978–1993; 1994–2023) for each fleet. The fishery CV is a fleet-specific, time-varying input based on expert opinion. Survey selectivity in both candidate models is estimated as a time-invariant logistic flat top selectivity for the DFO winter and NMFS spring surveys, with the NMFS fall survey selectivity estimated at age to allow for doming at older ages. Fishery and survey aggregate index inputs differ accordingly between the two models, as do the age

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compositions for all fleets and surveys. The US fishery age compositions for the US fleet are missing for years 2020–2023 in the EGB model and 2021–2023 for the TGB model.

The recruitment in both candidate models was specified as a random walk with process error on recruitment correlated across years. Process error on numbers at age (2+) was decoupled from recruitment process error with a 2DAR(1) correlation structure imposed on the deviations. Natural mortality was treated as a fixed effect in both candidate models inputted as a matrix of time and age varying Lorenzen M values.

## MODEL OUTPUTS AND DISCUSSION

The population trends from the two models are very similar, with high spawning stock biomass (SSB) throughout the 1980s, stabilizing at a lower level following the early 1990s, and subsequently decreasing to a lower level since then (Figure 21). Despite similar trends, the magnitude of the SSB is lower for the TGB model and is accompanied by greater fishing pressure (Figure 21). The lower SSB in the TGB model is also associated with considerably higher catchability estimates for all three surveys, with the upper bound of uncertainty around the DFO estimate of  $q$  exceeding 1. Interestingly, the lower SSB in the TGB model is associated with the implementation of the correlated process error on numbers at age, as the model where process errors were assumed IID does not exhibit lower SSB; the underlying mechanism for this impact is presently unclear (see Process Error structure section below).

Results from both models also show improvements in recruitment since 2020, which is consistent with signals from the NMFS fall survey. However, the recent increase in recruitment is accompanied by a progressively smaller number of fish above age 5 in the population for both models (Figure 22a–d).

In terms of overall retrospective performance, both models have comparable Mohn's rho values for SSB and fully recruited F (Table 4), showing similar tendencies in individual years within the seven-year peels. The difference in Mohn's rho on recruitment between the two models is driven by a single year.

Estimated survey and fishery selectivity curves are similar between the two models, and no notable differences are evident in the residuals associated with aggregate fishery catch or aggregate survey indices. Age composition residuals show similar patterns for the Canadian fleet and the three surveys, while those for the US fleet show some divergent but notable patterns since 2010 in both models (Figure 23). In the case of EGB, two particularly large residuals on ages 3 and 4 in 2016 align with a year when US fishery sampling intensity was particularly low for EGB (number ( $n$ ) of lengths=715,  $n$  ages=149), which likely contributed to uncertainty in catch characterization in those years. Similarly, the most recent years in the TGB catch have consistently negative residuals on age 3 and consistently positive residuals on age 4.

The model structure of the two candidate models is consistent across both areas, while the survey and fishery inputs differ accordingly. Comparison of identically structured models is intended to showcase the impact of different inputs across the two spatial areas, while influential assumptions remain consistent between the two. These include recruitment estimation, fishery uncertainty, process error, and natural mortality; their respective impact on the outputs of both models is summarized below.

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## Recruitment

Recruitment in both candidate models was assumed to follow a random walk, with the alternative option of estimating a series mean run as a sensitivity (see Process Model section). Note that both approaches rely on process error AR(1) across years to estimate recruitment.

The population estimates resulting from these two approaches are comparable for both EGB and TGB models (Figure 24), while recruitment process error differs accordingly (Figure 25). The process errors on the random walk recruitment oscillate at high frequency around zero throughout the time series, while the process error around the mean recruitment shows a consistently positive tendency early in the time series, changing to a consistently negative tendency starting in the early 1990s (Figure 25). Retrospective analysis shows a substantially lower Mohn's rho (seven-year peel) value for recruitment in the model implementing the random walk, with better retrospective performance on fishing mortality and spawning stock biomass as well (e.g., Runs 1 vs 2 for EGB, Runs 6 vs 7 for TGB in Table 3). Although the population estimates are comparable between the two approaches, better retrospective performance supports the use of the random walk in the final candidate models for both areas.

It should be noted that projections in WHAM are stochastic, with projecting based on the correlation structure estimated for recruitment into the future, as future recruitment moves towards a stationary value. The approach in estimating recruitment in the historic years therefore determines the stationary value for projected recruitment, with the series mean being the long-term value for one, and terminal year recruitment being the long-term value for the random walk (Figure 26). In addition, implementing bias adjustment on numbers at age process error in WHAM appears to have an unintended consequence of reducing the target recruitment for the random walk projection to zero as opposed to terminal recruitment which is the consequence when the bias adjustment is turned off (Thorston and Kristensen 2016, Figure 26). Given the notable impact of the recruitment assumption on projections in WHAM, development of projections will likely be carried out concurrently in MSEtool (Carruthers and Hordyk 2018).

## Fishery Coefficient of Variation

The uncertainty around total fishery removals was assumed to decrease over time in both candidate models, except for the misattributed fleet on EGB where CV was fixed as a time-invariant 0.2. This approach represents a change from all previous benchmarks which assumed a time invariant fishery CV (i.e., 0.05; TRAC 2013). However, assuming a time-varying fishery CV for these fleets is thought to reflect the actual decrease in the uncertainty around aggregate catches over time. In terms of model performance, the time-varying CV understandably results in more deviation from the aggregate fishery catch early in the time series and less deviation in the more recent time period when compared to an invariant CV of 0.05 (Figure 27, Figure 28). Although the magnitude of the deviation differs between the two assumptions, the pattern in residuals for the aggregate fleet catch remains the same (Figure 27, Figure 28). The empirically informed time-varying uncertainty results in almost no discernible difference in stock trends and retrospective values are only marginally different (Figure 29, Table 3).

Given no real change in model output or performance, the time-varying CV assumption was retained for the candidate models as it is considered a more realistic representation of temporal changes in catch uncertainty.

## Misattribution Fleet

The use of a misattribution fleet in the EGB model is intended as an initial step to addressing the known, but officially unquantified, amount of EGB fish reported as being caught on WGB. The estimate of misattributed fish provided here is associated with large uncertainty, but its

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impact on the model output is minimal with a comparable Mohn's rho value and only a marginally higher estimate of F during the incentivized time period in the model with the misattributed catches included (Table 3, Figure 30). Given the minimal impact on model performance and outputs, the misattributed fleet is included in the candidate EGB model as an avenue for incorporating missing catch in the future if improved estimates become available.

### **Process Error Structure**

The process error on numbers at age was implemented for both candidate models assuming a two-dimensional correlation structure, with values correlated by both year and age [2DAR(1)]. The overall trend in correlated process error is generally consistent between the two candidate models, with similar patterns across all ages prior to the early 1990s, and a strong divergence in both magnitude and direction of process errors on younger (age 2–4) and older (age 5+) fish thereafter (Figure 31). A sensitivity analysis run assuming uncorrelated process error (IID) showed a similar temporal divergence in process error for both models (Figure 31). A direct comparison of trends in correlated process error between the candidate models shows that despite similar overall trends, the TGB model has larger, mostly positive process errors throughout the first part of the time series compared to the EGB (Figure 32). This difference between EGB and TGB process error in the first part of the time series is less pronounced with an IID structure (Figure 33).

The implementation of the 2DAR(1) correlation structure impacted the magnitude of the population estimate compared to a model assuming IID process errors for the TGB model, but not the EGB model (Figure 34). The mechanism behind this different impact on EGB and TGB models is currently unclear, but appears tied to the more pronounced difference in process error early in the time series when 2DAR(1) is assumed (Figure 32, Figure 33). The difference in process error correlation structure was also associated with a notable difference in estimated survey q for the TGB model; the winter and spring survey q were 35% greater with the 2DAR(1) error structure (Table 4). In comparison, the q estimated by the EGB model differed by 4% for the winter and spring surveys with the implementation of the 2DAR(1) correlation structure (Table 4).

Other consequences of the 2DAR(1) assumption include smaller retrospective effects, which impacted both models equally, with seven-year peel Mohn's rho values smaller by half in both cases (Table 5). Annual peels show that the change in overall Mohn's rho is driven by both a decrease in the magnitude of the annual, retrospective values and a change in the directionality of peel six (Figure 35).

Finally, the choice between 2DAR(1) and IID correlation structure is also expected to impact projections in WHAM. Given that the process error has a clear temporal trend in both formulations, this indicates that an important time-varying process is not accounted for in the underlying process model. Under the IID assumption, there is no correlation structure associated with the process error on numbers at age, so process error deviations revert to a mean zero process in the first projection. With the 2DAR(1) correlation imposed on future process error, the projections gradually move towards a mean zero process over time, reducing the likely bias in the estimates in short-term projections.

### **Natural Mortality**

The process errors in both candidate models have clear directional patterns, with consistently positive values on ages 2–4 since the early 1990s and consistently negative values on ages 5+ (Figure 31). Such a persistent temporal trend in process error indicates that the underlying

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process model is not accounting for a time-varying gain or loss of fish from the population, such as migration in and out of the unit or misspecification in the survivorship of the fish.

The current assessment considers this stock to have a negligible level of mixing with adjacent populations, as the underlying process equation in WHAM does not have an explicit mixing component. Although the Atlantic Cod Stock Structure working group (ACSSWG) noted some connectivity between EGB Cod and adjacent stocks (primarily NAFO Divisions 4X5Y Cod stock, and to a lesser degree the western Gulf of Maine Cod stock), logistic considerations and uncertainty about the degree of mixing resulted in the continuation of stand-alone assessments for all three (McBride and Smebdol 2022). The peer review of data inputs for this 5Z Cod assessment framework review identified evidence of a temporary introgression of fish into the 5Z unit, characterized by a sudden increase in survey numbers across numerous ages for a couple of years before dropping back down. This effect was also evident in model-independent mortality estimates that suddenly dropped between 2015 and 2017, before returning to higher levels in 2018 and later (Andrushchenko et al 2026). This same event is evident in the process error estimates for both candidate models, in the form of a temporary reprieve from an otherwise continuous downward trend for ages 4+ in the mid to late 2010s (Figure 31).

Although some evidence exists of a periodic influx of fish into the unit (e.g., 2015–2017), a level of emigration equivalent to the magnitude of the process error in both TGB and EGB models in years other than 2015–2017 requires a multi-year, unidirectional flow of adult fish out of the Georges Bank unit and into an adjacent stock. In terms of relative stock size, the terminal year biomass estimates of the 4X5Y Cod stock are comparable to those of the EGB Cod model, but spread over an area five times larger (DFO 2023a). Similarly, the terminal year estimates from the western Gulf of Maine Cod represent a portion of the current estimates for both EGB and TGB (NEFSC 2024). Given the relatively lower densities of both adjacent units compared to Georges Bank, a substantial influx of Georges Bank fish would be detectable in surveys and assessments in both units.

The most recent assessment of the 4X5Y Cod stock confirms that the stock decreased below its limit reference point (LRP) in the late 2000s. It continues to be subjected to high natural mortality, some of which may alias unaccounted for fishing mortality, with the projected population unlikely to increase even in the absence of fishing (DFO 2023a, Rossi et al. 2024). Similarly, the western Gulf of Maine stock, which includes the winter spawning western Gulf of Maine component identified by the ACSSWG, exhibited a notable decrease in biomass throughout the early 2010s and has remained low since then (NEFSC 2024). Continued low productivity of Cod in both of the adjacent stocks, particularly since 2010, indicates that the persistent negative process error in both the TGB and EGB models in recent years is unlikely to be attributable to migration of fish into these adjacent units.

Without evidence of mass emigration from the unit, the large process errors in both models indicate misspecification in one or both aspects of survivorship: missing catch and natural mortality. If attributed entirely to misreporting, there would need to be 1,000–3,500 mt of Cod misreported annually since 2018 to account for the level of process error estimated in the models. Given the regulatory measures in place for the Canadian fishery (e.g., high observer coverage, vessel monitoring systems, mandatory dockside monitoring, etc.), such a high level of misreporting of Georges Bank catch by the Canadian fleet is not plausible. The US fishery has experienced high profile cases of misreporting in the past decade, but subsequent management measures implemented have also made such a persistently high level of misreporting unlikely.

In the absence of large-scale migration and rampant misreporting of Georges Bank Cod, the large negative process errors appear to indicate a misspecification in the  $M$  assumption for both models. If attributed entirely to  $M$ ,  $M$  would be  $>1$  for ages 6+ since 2010, which is substantially

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higher than the Lorenzen M estimate of 0.25–0.3 currently specified for those ages (Figure 36, Figure 11). Since the Lorenzen M does not take into account the external drivers of M (e.g., predation), it is likely that the current approach underestimates the actual level of M experienced by Georges Bank Cod.

Inferences that the increase in mortality is associated with M (ecological and biological sources) and not unaccounted F, are strengthened when there are also notable changes in known drivers of that mortality. A literature review completed during the Cod RT identified temperature and predation as the two most frequently cited contributors to natural mortality for Cod stocks in the Northwest Atlantic (NEFSC 2023a). Stakeholder engagement sessions held during the research track resulted in similar feedback from US fishermen, with discussion focused on prevalence of seals in US waters and the impact of temperature on Cod movement, particularly since 2010 (NEFSC 2023a). Data for both drivers indicate that they have undergone substantial changes in recent years, with bottom temperature anomalies registering record highs on Georges Bank and the abundance of seals in the adjacent 4X5Y management unit beginning to reach a plateau after a decade of record growth (NEFSCa 2023, NEFSCb 2023, DFO 2022). As such, an increase in M on Georges Bank Cod is not only conceivable but appears to be the most likely contributor to the large process error exhibited by both models. Although high, this level of mortality would be consistent with several other Cod stocks in the Northwest Atlantic, where high rates of M are attributed to various drivers, such as predation by seals, decrease in condition and unaccounted for interaction with fisheries (Swain et al. 2019, DFO 2021, DFO 2023a, DFO 2023b, DFO 2024).

A misspecification of input M seems evident in both candidate models, but addressing this misspecification is not simple. Ideally, implementing a M matrix that accurately reflects all intrinsic and extrinsic drivers of M in the transboundary stock would result in process errors with low variance and no strong directional patterns over time. Realistically, a scientifically defensible empirical derivation of a M matrix that accounts for all stock-specific drivers of M experienced by Cod on Georges Bank is not currently possible. For example, derivation of tangible, stock-specific estimates of predation mortality ideally require multi-species or ecosystem models which are beyond the scope of a single species framework (Curti et al. 2013). As such, both candidate models are proposed with a fixed Lorenzen M matrix and directional trends in process error on numbers at age are inferred to reflect principally changes in M. A notable exception is the process errors for the 2015–2017 period, which appear as a classic ‘year effect’ (albeit over three years) in which abundance suddenly changes coherently across all ages, and which is interpreted as an introgression event of fish into and then out of the area.

The consideration of unaccounted for mortality as M, as opposed to a process error, is expected to have a substantial impact on projections and reference point calculations. This impact and associated mitigations will be explored in subsequent work on reference points.

## **Other Considerations**

The quantity and representativeness of the data used to characterize the US fishery catch has decreased in recent years. Insufficient sampling of US catch from EGB has necessitated the intermittent use of WGB age-length keys to characterize EGB catch since 2012 (Table A2 in TRAC 2023), while sampling of the fishery on TGB has been too low to reliably characterize the US commercial catch since 2021 (NEFSC 2023a). Consequently, both the EGB and TGB models are missing the US fishery age compositions since 2020 and 2021, respectively. It is currently unclear how quickly the US fishery sampling will return to levels sufficient to characterize TGB catch, while targeted sampling of US EGB catch is not expected to resume in the future. In addition, differences in timing and frequency of assessments between countries may preclude timely availability of terminal year US fishery data products in future Canadian

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assessments. Consequently, if the data products are not available in time, application of the TGB model would continue treating the US fishery catch at age as missing until sampling reaches sufficient levels, as well as treating the terminal year of the US fishery catch as missing. Application of the EGB model will require the same conditions, as well as relying on assumptions regarding the age composition of US catch each year.

## CONCLUSION

The western biological boundary of the Georges Bank Cod stock is thought to occur along the 68<sup>th</sup> west line. However, the smallest available aggregate unit of the US fishery information (i.e., statistical area) limits the ability for the Georges Bank management unit to follow this boundary, as the 68<sup>th</sup> west parallel bisects US statistical areas 522 and 525 in half (Figure 1). Consequently, this process considered both a smaller EGB assessment unit which excludes the portion of the biological stock area falling within US statistical areas 522 and 525, and a larger TGB assessment unit which includes US statistical areas 522 and 525, encompassing the entirety of the true biological unit, as well as a portion of an adjacent stock.

In terms of data inputs, the EGB model has additional uncertainty due to the acknowledged level of misattribution of EGB Cod as WGB Cod in the US fishery; an uncertainty that is minimized in the TGB model by including the entirety of the US Georges Bank fleet. Both models are equally impacted by any level of misreporting of Cod as another species in the US fishery. The TGB model has some additional uncertainty due to the use of non-post-stratified survey data and exclusion of some deeper strata in US statistical area 522, where the US fishery appears to be active in recent years. In addition, the DFO index for the TGB model required filling of western strata during recent years when coverage did not extend into western Georges Bank. The impact was shown to be minimal given the concentration of fish on the northeastern peak of Georges Bank during the DFO Winter RV Survey. Finally, uncertainty about the availability of US fishery age compositions and timing of data processing constitute logistic concerns for the application of both models.

With respect to model performance, neither model notably outperformed the other in the various metrics considered here. The unexplained impact of the 2DAR(1) correlation structure on model outputs for the TGB model raises some concerns, as it is unclear what is driving the change; the EGB model does not exhibit the same effect, though the cause of this disparity is also unclear. Although the population trends are similar between them, the absolute magnitude differs, along with their estimates of survey catchability. Table 5 provides a summary of these considerations to facilitate discussions about which candidate model is best suited to assess transboundary Cod domestically.

The candidate EGB and TGB models were peer reviewed, and their respective uncertainties and limitations are outlined in Table 5. Reviewers and meeting participants acknowledged that both models are appropriate for assessment of stock status, but neither model is free of uncertainty or limitations. From a biological standpoint, the TGB model was put forward as the best option to assess transboundary Cod, as it encompasses the biological unit within the constraints of practical considerations (McBride and Smedbol 2022).

As per DFO 2023c, a stock can be defined based on the management unit, assessment unit, and/or biological unit. Scale mismatch occurs when there is misalignment in time or space among these units, management or assessment activities, or biological processes. Consequences of scale mismatch can include over- or under-estimation of stock biomass and exploitation rates, as well as impacts to reference points, stock status metrics, and the risk of serial depletion of subunits (DFO 2023c). However, Cod over the past decade have been concentrated on EGB and the current risk of hyperdepletion is low and is expected to remain so.

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Reliable, consistent and timely implementation of a TGB model domestically in Canada is dependent on DFO scientists receiving timely access to raw US fishery data, as removals by the US fishery comprise a large portion of the TGB removals. Access to US fishery data is key to implementing a TGB model domestically and ensuring that the model accurately reflects the dynamics of the US fishery. At the time of the peer review, a data sharing agreement had not yet been established. An agreement is needed to prepare for the next stock assessment to provide advice for the 2026 fishing year. In its absence, the assessment would revert to using the EGB model on an ongoing basis.

## **DEVELOPMENT OF INTERIM ADVICE FOR 2025 FISHING YEAR**

The current framework peer review process will extend into 2025 in order to provide products in full compliance with the PA framework and quantify the risks associated with moving to a multi-year advice schedule. Given the shift in timelines and the absence of a joint transboundary science process in 2024, DFO Resource Management requested that interim advice for the EGB Cod management unit for the 2025 fishing year be provided prior to the completion of this framework.

Interim advice for EGB cannot be provided based on reference fishing mortalities or biomass reference points as these have not yet been developed. The existing TMGC harvest strategy ( $F=0.18$ ) is not appropriate for use, as it was based on an old model. Finally, stochastic projections in WHAM appear to have some unresolved idiosyncrasies that may bias the projections, particularly if projected long term.

Options for interim advice for 2025 fishing year include:

- Project terminal year  $F$  (average of the terminal 3 years) two years to 2025 fishing year.
- Project terminal year catch two years to 2025 fishing year and report on  $F$ .
- Project terminal year TAC two years to 2025 fishing year and report on  $F$ .

For interim advice, short term projections will be conducted for years 2024, 2025, and 2026, with the current fishing year (2024) assumed to have the same catch as was reported in the 2023 fishing year. The impact of various levels of fishing (including 0 catch) in the 2025 fishing year will be presented along with their relative impact on the stock biomass at the beginning of 2026. Biological assumptions such as natural mortality, maturity, and growth are assumed to remain at the average level of the terminal three years.

Note that projections in WHAM have an unexplained downward bias in recruitment, which results in uncertainty about whether the projected decrease of SSB, even in the absence of fishing, is real. To help tease out the impact of various fishery catch levels, three-year projections are provided for the following scenarios:

1.  $F_{\text{term}}$ =The average  $F$  across the three terminal years (2021–2023) is projected for 2025.
2.  $TAC_{\text{term}}$ =The TAC of the terminal year (2023) is projected for 2025. This scenario is done to help understand the risk of implementing a higher TAC with the understanding that realized  $F$  will be lower. This scenario is difficult for TGB.
3.  $F_0$ =Fishing mortality in 2025 is set to 0.0001. This is a run intended to show the projected biomass even in the absence of fishing, highlighting the uncertainty associated with the projected bias adjustment on process error. It is also meant as a base run to help ground the impact of the other  $F>0$  scenarios, excluding the impact of the bias correction.

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## **ALLOCATION OF TGB MODEL ADVICE TO THE EGB MANAGEMENT AREA**

Two candidate models were presented for review: an EGB model and a TGB model. As noted above, the peer review concluded that the TGB model was the preferred option, as it encompasses the biological unit of the stock. However, if access to US fishery data for the TGB area is not possible, as previously discussed, application of the EGB model would be appropriate for assessment of the stock. If the EGB model is applied in the Canadian assessment of transboundary Cod, the resulting advice from the EGB model can be provided directly to Canadian resource managers, since the assessment unit aligns with the current management unit. If the TGB model is applied, the resulting advice would need to be spatially partitioned to align with the EGB Cod management unit. Partitioning the interim advice should take into account the non-uniform distribution of Cod across the TGB area in order to avoid overfishing.

The bottom trawl surveys provide a reasonable estimate of the distribution of Cod biomass across the area, but the use of the survey indices requires several important caveats. For example, the DFO Winter RV survey has not always had complete coverage of WGB strata, so those years should be excluded from the biomass distribution calculations (Figure 37). The inclusion of the NMFS fall and spring surveys should, in principle, capture distribution throughout the year and avoid any season-specific bias in distribution. However, the NMFS Fall Survey has also demonstrated dome shaped selectivity, missing older fish that the DFO Winter RV and NMFS Spring surveys catch. Averaging of spring and fall distribution tempers any seasonal effects but emphasizes distribution of small fish in the fall survey. Averaging all three surveys dampens the impact of the dome shaped selectivity on the NMFS Fall Survey, as distribution of large fish in the fall is difficult to surmise. Averaging just the DFO Winter RV and NMFS Spring surveys avoids issues around domed selectivity in the fall but also ignores the seasonal redistribution of the fish. In this case, accounting for the seasonality of the distribution is important, so only averaging the DFO Winter RV and NMFS Spring surveys is not recommended. The impact of averaging spring and fall seasons, versus averaging all three surveys is relatively small (Figure 38).

The high interannual variability in proportion of biomass on EGB required a smoothing function to stabilize interannual observations in the final allocation. In this case, a loess smoother was applied spanning a 33-year window with a smoothing parameter of 30% (Cleveland 1979). This smoothing approach has been applied to these specific bottom trawl surveys in other applications and is considered to balance responsiveness and stability (Andrushchenko et al. 2023). The terminal year estimate of the smoother (i.e., 2023) will be considered the most appropriate proportional division of biomass between WGB and EGB, given its proximity to the fishing year in which it is applied (i.e., 2025). In order to capture any shifts in biomass between EGB and WGB, this allocation will be applied to a running 33-year window, ending with the terminal year of data (i.e., 2025 advice partitioned based on survey data series spanning 1991–2023). If proportions of biomass in EGB and WGB cannot be calculated for a given survey in a given year, the average would be based on the two remaining surveys.

The proposed approach results in 92–93% of the TGB Cod advice being allocated to EGB, depending on the averaging method.

## **FUTURE RECOMMENDATIONS**

- Explore linkage between Cod in NAFO Divisions 4X (Bay of Fundy/Browns Bank) and 5Z.
- Separate the dynamics of the fixed and mobile fleets of the Canadian groundfish fishery.
- Explore the effect of time varying fishery selectivity in WHAM.

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- Explore the causes of the apparent increase in M on Georges Bank.
  - Work towards improving alignment between survey, fishery, and assessment areas. For example, exploration of the disconnect between the magnitude of removals on WGB compared to the survey catches in WGB strata could help reconcile the differences between the two models.
  - Further exploration of the seasonal movement of Georges Bank Cod.
  - Bottom temperature anomalies are registering record highs on Georges Bank and the grey seal population has increased considerably over the past several decades. Substantial changes in both of these factors are expected to have an impact on the productivity of the stock and their incorporation into the assessment warrant further exploration.

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## TABLES

*Table 1. Total fleet catches (metric tonnes, mt) for Canada and US fisheries used in the candidate models (EGB=eastern Georges Bank; TGB=total Georges Bank).*

<b>Year</b>	<b>Canada reported landings</b>	<b>US_Reported EGB landings</b>	<b>US_Misattributed EGB landings</b>	<b>US_Reported TGB landings</b>
1978	8875	5502	1	10327
1979	6082	6408	1	12637
1980	8149	6418	1	15591
1981	8606	8092	1	15541
1982	17898	8565	1	15234
1983	12196	8572	1	15984
1984	5829	10558	1	16906
1985	10545	6641	1	11726
1986	8555	5696	1	8395
1987	11920	4793	1	9123
1988	12824	7645	1	13433
1989	7971	6266	1	10855
1990	14434	6483	1	11693
1991	13532	6465	1	11743
1992	11738	5257	1	8781
1993	8589	4076	1	7884
1994	5340	1003	1	4257
1995	1140	543	1	2258
1996	1980	677	1	2602
1997	3405	555	1	2905
1998	2272	686	1	2694
1999	2156	1204	1	2952
2000	1641	788	1	2517
2001	2286	1634	1	3786
2002	1372	1697	1	4141
2003	1517	1936	1	3714
2004	1257	1063	1	1845
2005	858	370	45	1614
2006	1445	225	186	1365
2007	1222	513	233	2168
2008	1529	244	204	1543
2009	1209	580	211	2042
2010	840	454	134	1596
2011	744	287	148	1393
2012	468	148	156	1095
2013	424	40	65	552
2014	458	116	147	852

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Year	Canada reported landings	US_Reported EGB landings	US_Misattributed EGB landings	US_Reported TGB landings
2015	492	116	167	805
2016	440	97	55	645
2017	488	38	1	205
2018	517	49	1	228
2019	396	31	1	239
2020	377	67	1	225
2021	431	41	1	184
2022	326	37	1	108
2023	329	31	1	96

*Table 2. Summary of known changes to minimum mesh size restrictions on groundfish bottom trawls on Georges Bank. Information collected from the Fisheries and Oceans Canada integrated fisheries management plan for groundfish and Wang et al. 2009. Dash indicates no change.*

Year	US	Canada
1978	5.13 inches (130 mm) minimum	—
1985	5.5 inches (140 mm) minimum	—
1990	—	130 mm square minimum
1991	—	130 mm sq or 145 mm diamond minimum
1994	6 inches (152 mm) minimum	—
1995	—	—
1999	6.5 inches (165 mm) square, 6 inch (152 mm) diamond	—
2015	—	125 mm sq or 145 mm diamond

Table 3. Summary of retrospective values (Mohn's rho; 7-year peel) for various candidate and sensitivity runs. The candidate population models proposed for each area are identified in bold. Model run values in brackets reference sequential model runs and only presented during the peer review (CV=coefficient of variation; EGB=eastern Georges Bank, TGB=total Georges Bank, NAA RE= Numbers at age random effects, SSB=spawning stock biomass, Fbar=mean fishing mortality. NA=not applicable.

Area	Model Run	Recruitment	Fishery CV	Misattributed Fleet	NAA RE Structure	Recruitment Rho	SSB Rho	Fbar Rho
<b>EGB</b>	<b>Run 1</b>	<b>Random Walk</b>	<b>Decreasing</b>	<b>Included</b>	<b>2DAR(1)</b>	<b>0.1134</b>	<b>0.2045</b>	<b>-0.1205</b>
EGB	Run 2	Mean	Decreasing	Included	2DAR(1)	0.3271	0.2591	-0.1513
EGB	Run 3	Random Walk	Time-inv 0.05	Included	2DAR(1)	0.1368	0.2282	-0.1411
EGB	Run 4	Random Walk	Decreasing	Excluded	2DAR(1)	0.1044	0.1979	-0.1176
EGB	Run 5	Random Walk	Decreasing	Included	IID	0.2213	0.4143	-0.2514
<b>TGB</b>	<b>Run 6</b>	<b>Random Walk</b>	<b>Decreasing</b>	<b>NA</b>	<b>2DAR(1)</b>	<b>0.065</b>	<b>0.2139</b>	<b>-0.1251</b>
TGB	Run 7	Mean	Decreasing	NA	2DAR(1)	0.1495	0.2721	-0.1425
TGB	Run 8	Random Walk	Time-inv 0.05	NA	2DAR(1)	-0.0254	0.2379	-0.1296
TGB	Run 9	Random Walk	Decreasing	NA	IID	0.212	0.418	-0.2485

Table 4. Comparison of survey catchability ( $q$ ) and retrospective ( $\rho$ ) for total Georges Bank (TGB) and eastern Georges Bank (EGB) models with correlated (2DAR(1)) and uncorrelated numbers at age random effects (NAA RE). SSB=spawning stock biomass,  $F_{bar}$ =mean fishing mortality, NA indicates not applicable.

Model	Model Run	NAA RE Structure	DFO survey $q$	NMFS spring survey $q$	NMFS fall survey $q$	$\rho_R$	$\rho_{SSB}$	$\rho_{Fbar}$
<b>EGB</b>	<b>Run 1 (84)</b>	<b>2DAR(1)</b>	<b>0.434</b>	<b>0.223</b>	<b>0.109</b>	<b>0.1134</b>	<b>0.2045</b>	<b>-0.1205</b>
EGB	Run 5 (89)	IID	0.415	0.214	0.081	0.2213	0.4143	-0.2514
<b>TGB</b>	<b>Run 6 (115)</b>	<b>2DAR(1)</b>	<b>0.811</b>	<b>0.419</b>	<b>0.159</b>	<b>0.065</b>	<b>0.2139</b>	<b>-0.1251</b>
TGB	Run 9 (117)	IID	0.607	0.309	0.083	0.212	0.418	-0.2485

Table 5. Summary of considerations for eastern (EGB) and total Georges Bank (TGB) models.

Consideration	Eastern Georges Bank	Total Georges Bank
Uncertainty in US fishery data	US fishery age compositions missing since 2020 and will not be available in the future. Requires assumption of missing age comps or equal selectivity in US TGB and EGB catches.	US fishery age compositions missing since 2021, but will be available once sufficient sampling resumes. Requires assumption of missing age comps in affected years.
Uncertainty in US fishery data availability	US fishery data may not be available in the terminal year (or two) of a new model run. Requires imputation of terminal year US fishery catches.	US fishery data may not be available in the terminal year (or two) of a new model run. Requires imputation of terminal year US fishery catches.
Uncertainty in US fishery	Magnitude of misreporting as different species or underreporting in US fishery is unclear. No fix exists at this time.	Magnitude of misreporting as different species or underreporting in US fishery is unclear. No fix exists at this time.
Coverage by DFO survey	DFO consistently surveys assessment area, and no concerns exist about achieving full coverage in the future. No fix necessary. Consider incorporating 5Z9 into future index... somehow.	DFO targets full coverage of the assessment area, but strata on western Georges Bank are the first to be skipped in case of vessel or weather issues. Requires extrapolation or imputation if strata missing; low impact in the past, but still additional resources. Consider incorporating 5Z9 into future index... somehow.
Coverage by NMFS surveys	NMFS survey data post-stratified to fit EGB assessment unit (i.e. only sets within the EGB unit contribute to the index; only portion of stratum within EGB unit is used to calculate the aggregate biomass index). No fix required.	NMFS survey data not currently post-stratified to fit TGB assessment unit (all sets within a stratum contribute to the TGB survey data product; some strata are excluded entirely), so a mismatch exists between assessment unit and survey coverage. Requires post-stratification of US survey data.
Mismatch between survey coverage and US fishery footprint?	No mismatch evident between survey and fishery on EGB. No fix required.	Apparent mismatch between NMFS survey coverage and US fishery footprint (?), but extent of mismatch is unclear, without access to US fishery data. Requires post-stratification of US survey data.
Uncertainty about model performance and scaling	Implementation of 2DAR(1) correlation structure on NAA process error has no notable impact on model output or diagnostics. No fix required.	Implementation of 2DAR(1) correlation structure on NAA process error notable increases survey q and other related quantities or parameters such as fishing mortality and SSB. Requires investigation.
Survey selectivity estimates	Estimates of q and associated bounds are below 1. No fix required.	Estimates of q are below 1, but upper bound on DFO selectivity exceeds 1. No fix proposed at this time.
Post-hoc allocation of advice to Management Unit	Assessment and Management units match, so no spatial allocation of advice necessary. No fix required.	Mismatch between Assessment and Management units. Requires post-hoc allocation of advice to fit the EGB Management Unit. Additional resources.
Biological Stock Alignment	Does not encompass the entirety of the biological transboundary stock. Increases risk of not hyperdepletion if stock expands.	Encompasses the biological stock in its entirety, may encompass a portion of another. Risk unclear.
Ignores mixing	Ignores mixing	Ignores mixing
Implementation Issues	No implementation issues for Canadian assessment (status quo).	Requires additional resources or reallocation of files from DFO Science.

## FIGURES

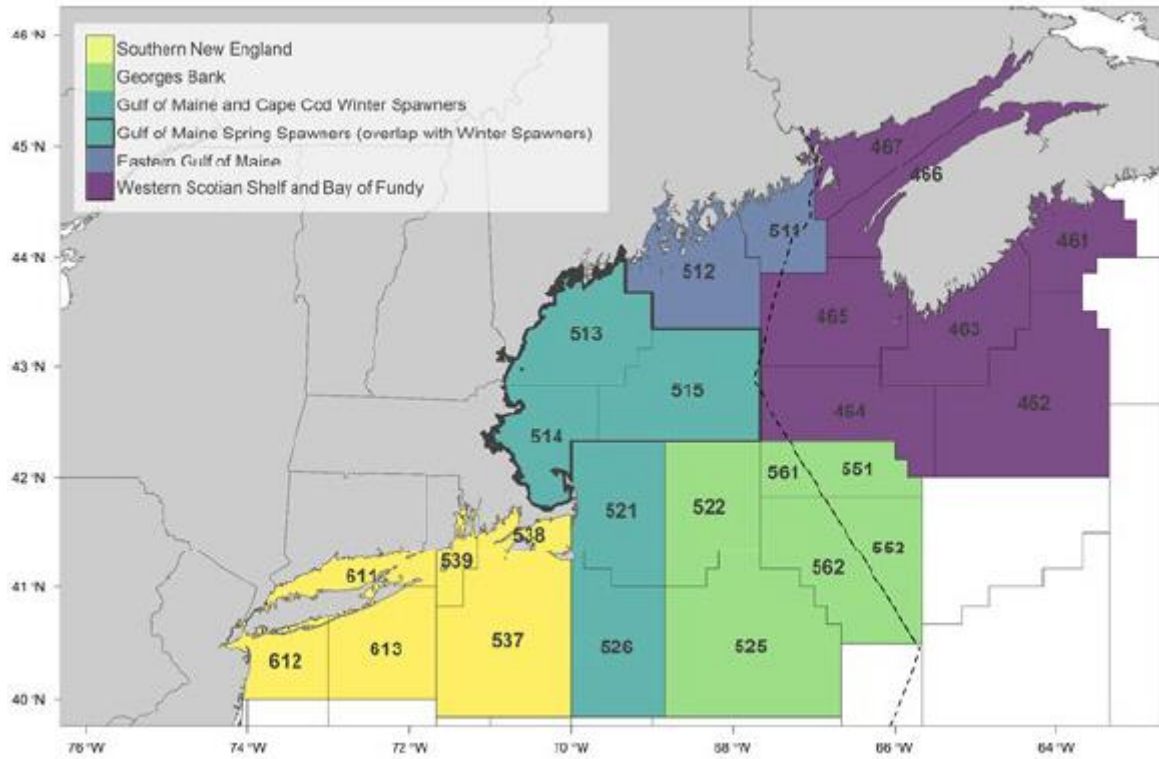


Figure 1. The revised biological stock structure of Atlantic Cod in US waters mapped to US statistical units (Northwest Atlantic Fisheries Organization Subareas 5 and 6). Numbers identify statistical areas used in US fishery assessments and management. Figure originally from McBride and Smedbol 2022. Dashed/grey line represents the Hague Line.

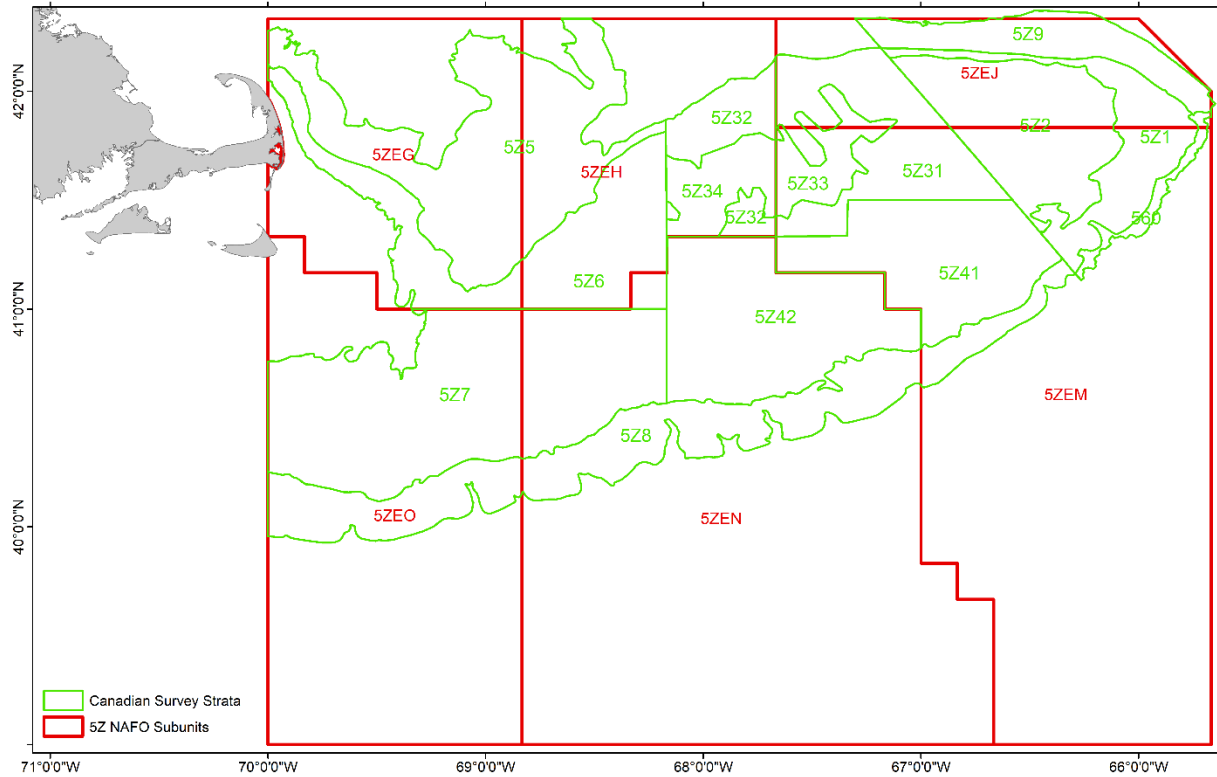


Figure 2. Fisheries and Oceans Canada (DFO) winter ecosystem research vessel survey strata in 5Z (green). No sets are conducted in the shoals of Georges Bank (5Z33, 5Z34). Red lines represent DFO management unit areas and generally align with US statistical areas as follows: 5ZEJ=551+561, 5ZEM=552+562, 5ZEH=522, 5ZEN=525, 5ZEG=521, 5ZEO=526.

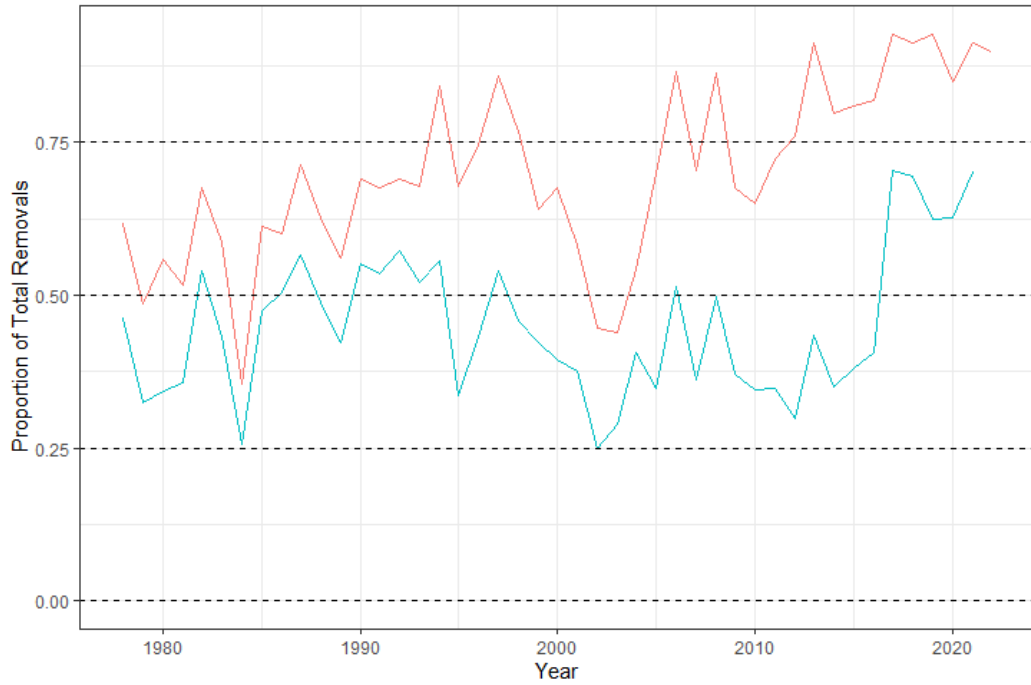


Figure 3. Canadian fleet removals from eastern Georges Bank (red line) and total Georges Bank (blue line) as a proportion of total removals reported for each area.

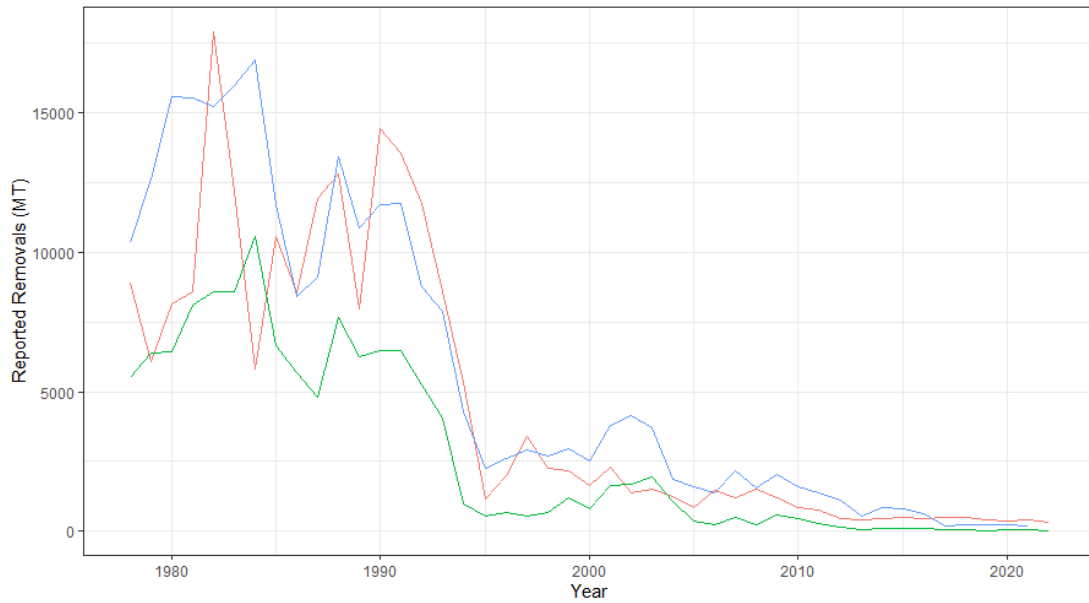


Figure 4. Total annual reported removals (mt, includes discards) by the US fleet on eastern Georges Bank (green lines), Canadian fleet on eastern Georges Bank (red lines) and the US fleet on total Georges Bank.

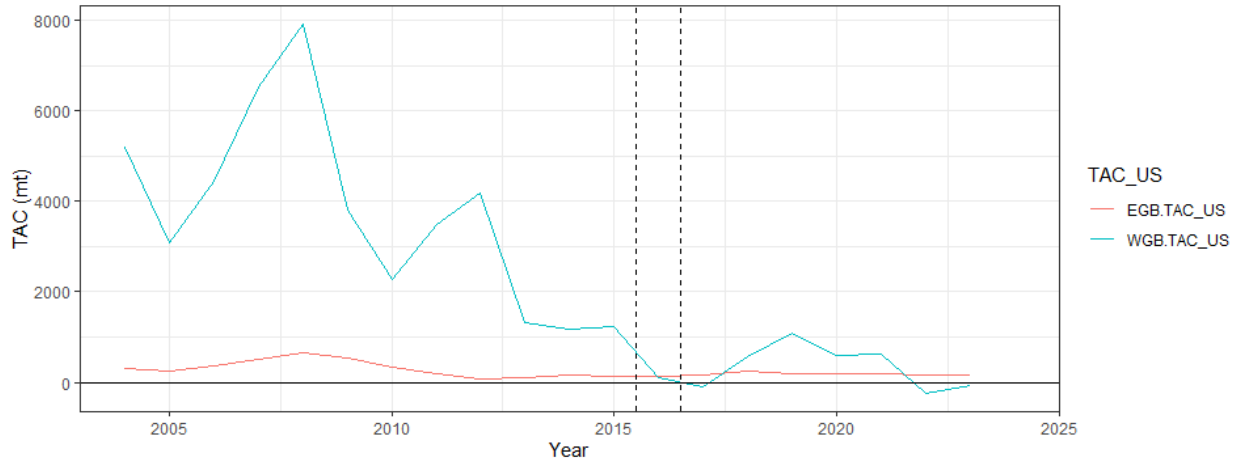


Figure 5. US Groundfish fishery cod quota (TAC) for eastern (EGB, red line) and western Georges Bank (WGB, blue line). The values do not include sector carryover or overages in any given year. Dashed line marks when incentive for misallocation of eastern Georges Bank Cod as western Georges Bank Cod due to quota imbalance between areas disappears.

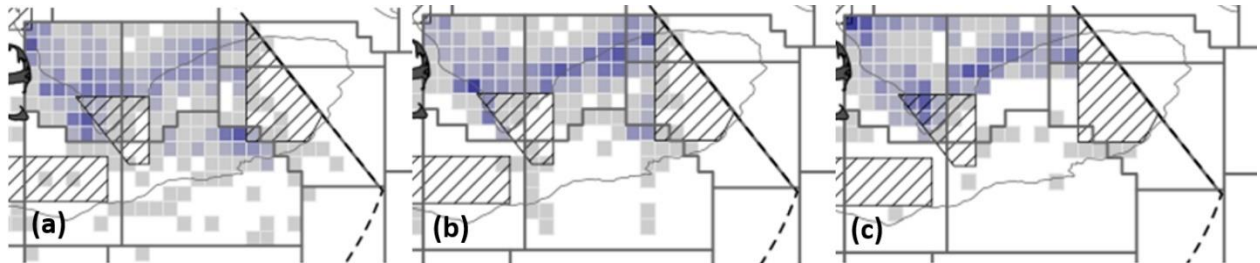


Figure 6. Example distribution of US fishery catch from a year (a) prior to 2004, (b) between 2006 and 2015, and (c) post 2016. Exact years cannot be identified due to confidentiality restrictions.

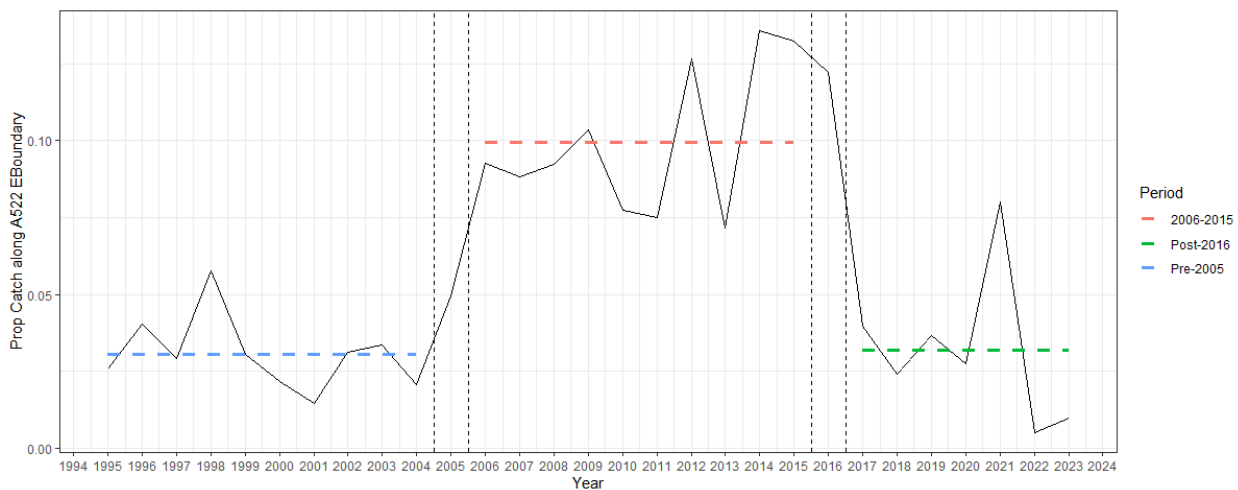


Figure 7. Proportion of annual US fishery catch of cod in the total Georges Bank Unit (old definition) along the eastern boundary of statistical area 522 for each calendar year (Jan–Dec). Vertical dashed lines identify the transitory years in the data, when management measures implemented in fishing years 2006 and 2016 impact the fishing behaviour and catch patterns in calendar years 2005 and 2016. Horizontal coloured lines show series mean for each time period.

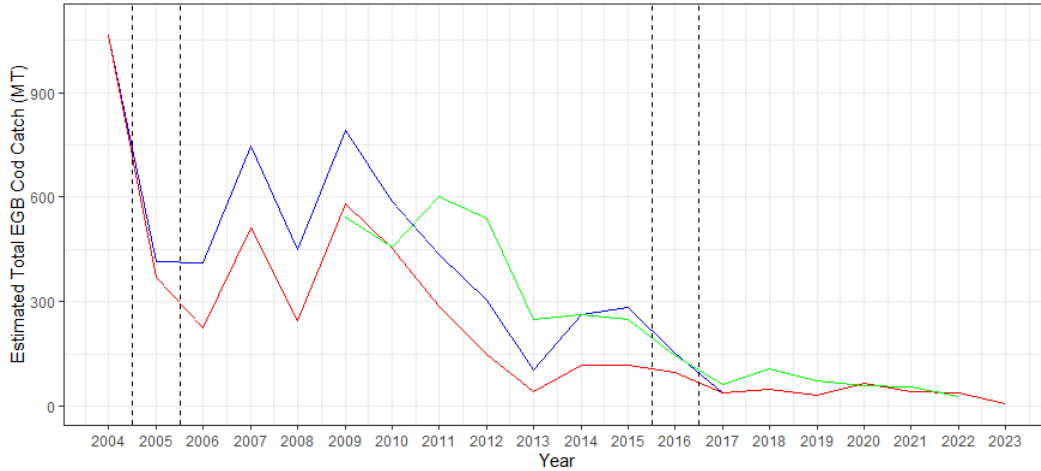


Figure 8. Various estimates of annual catches for eastern Georges Bank (EGB) Cod. Colours represent reported catch (red line), reported catch including estimated misreported catch from straddle sets (blue line) and estimated catch in EGB based on Vessel Monitoring System (VMS) data (green line; Hayes and Demarest 2023). All three are by calendar year and include reported discards for the year.

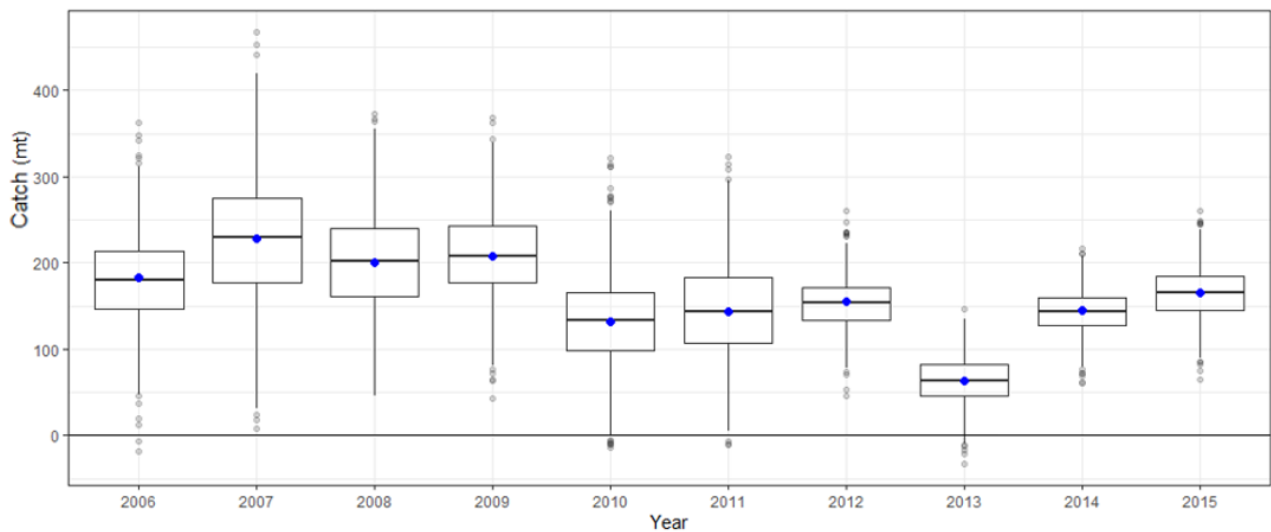


Figure 9. Estimate of eastern Georges Bank (EGB) Cod catches (metric tonnes) by the Groundfish Fleet caught on 'straddle' sets along the US statistical area 522 boundary and reported as western Georges Bank Cod. Boxplots represent the variability introduced by the assumed 'base' level of catches occurring at the boundary in non-incentivized years. Variability is estimated assuming a normal distribution with a mean and standard deviation based on the non-incentivized years, with 1000 replicates drawn from that distribution.

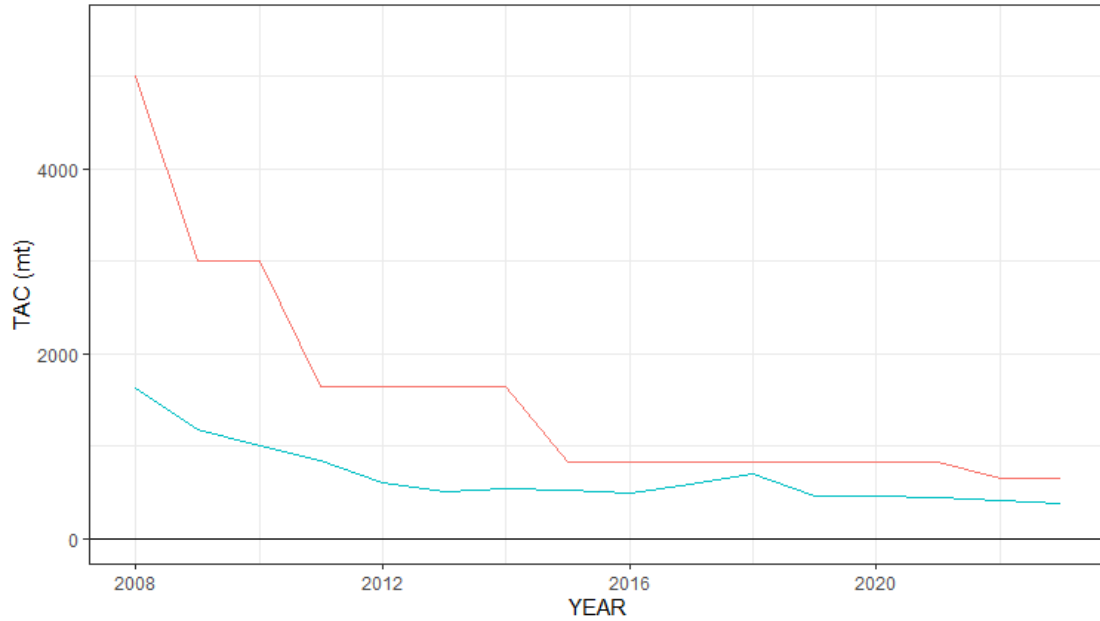


Figure 10. Canadian groundfish fishery cod total allowable catch (TAC) for eastern Georges Bank (5Z, blue line) and the adjacent 4X5Y unit (red line).

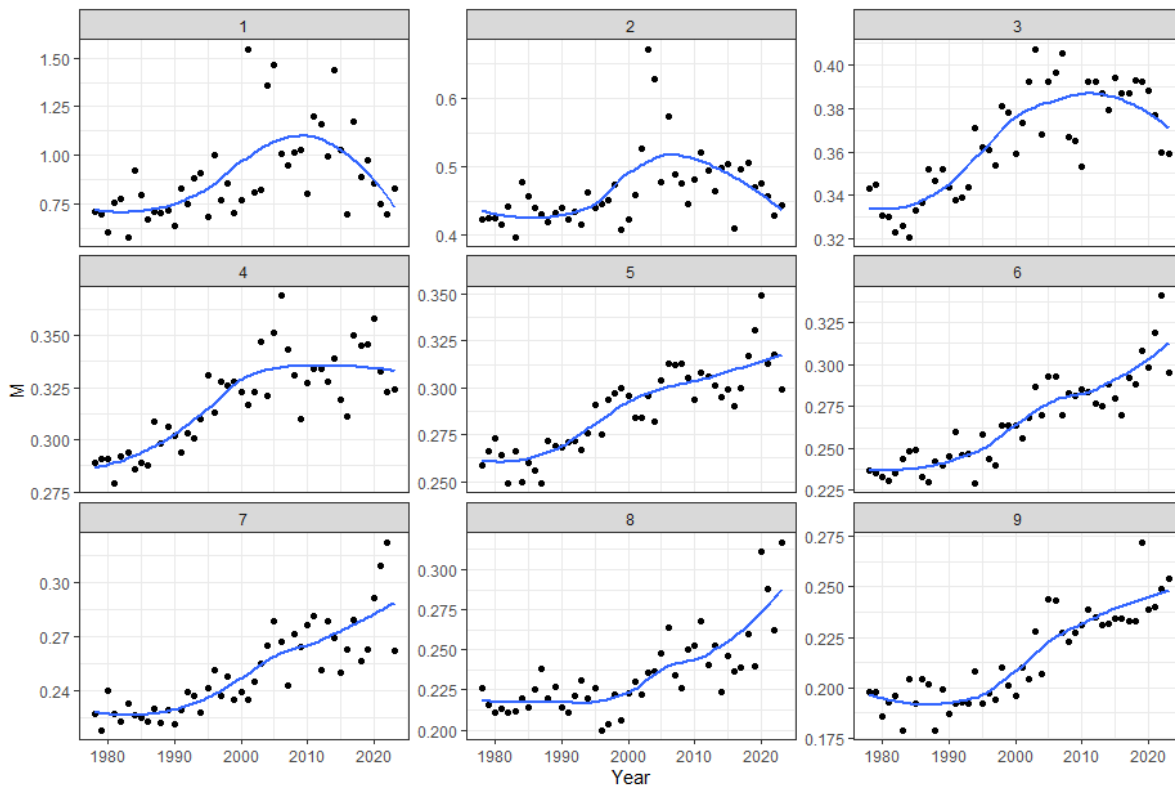


Figure 11. Empirical estimates of natural mortality ( $M$ , y axis) at age (facets) across years (x axis) derived from weight at age using the equation presented in Lorenzen (1996). Black points represent the annual values, and blue line represents a smoother through those points.

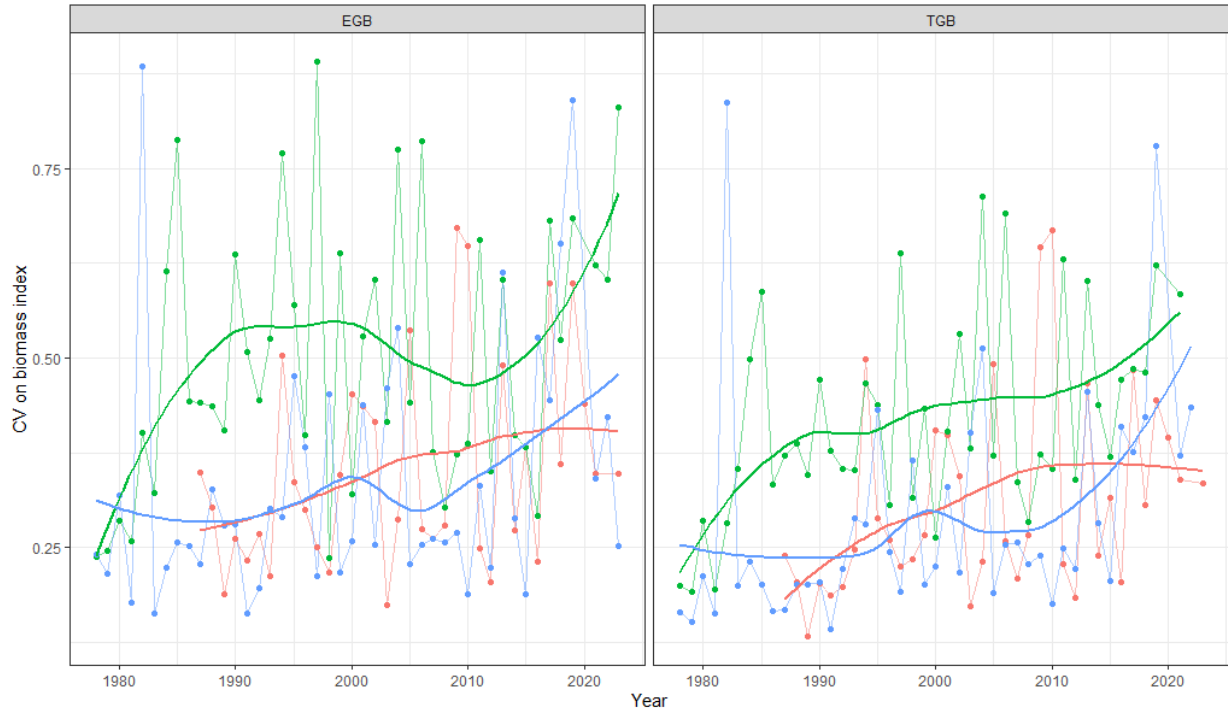


Figure 12. Survey coefficient of variation (CV) estimates for all three surveys (colours; red=Fisheries and Oceans Winter Survey, green=National Marine Fisheries Service (NMFS) Fall Survey, blue=NMFS Spring Survey) for eastern Georges Bank (left panel) and total Georges Bank (TGB) (right panel). A loess smoother has been applied to help interpret the trend in the estimates.

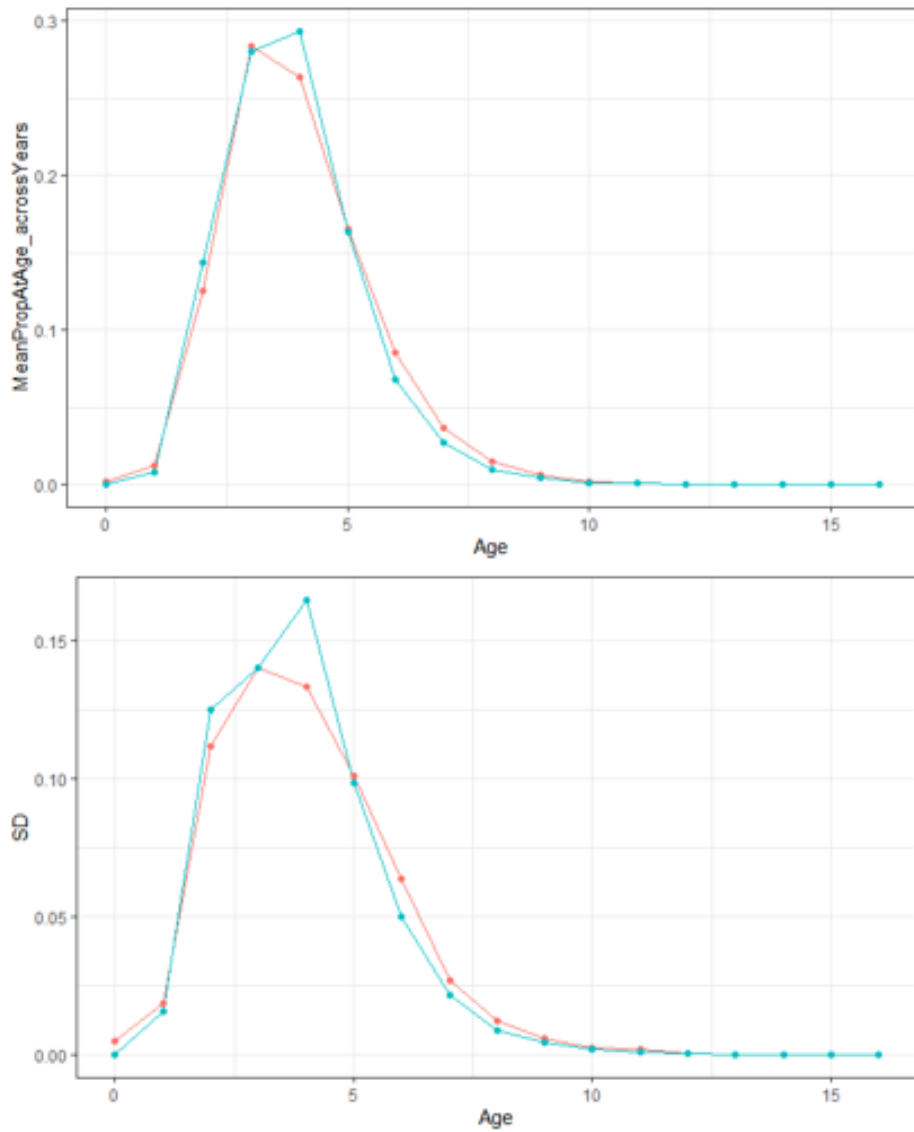


Figure 13. Mean (top panel) and standard deviation (SD) (lower panel) of annual proportions at age for the Canadian (red lines) and US fishery (blue lines) on eastern Georges Bank.

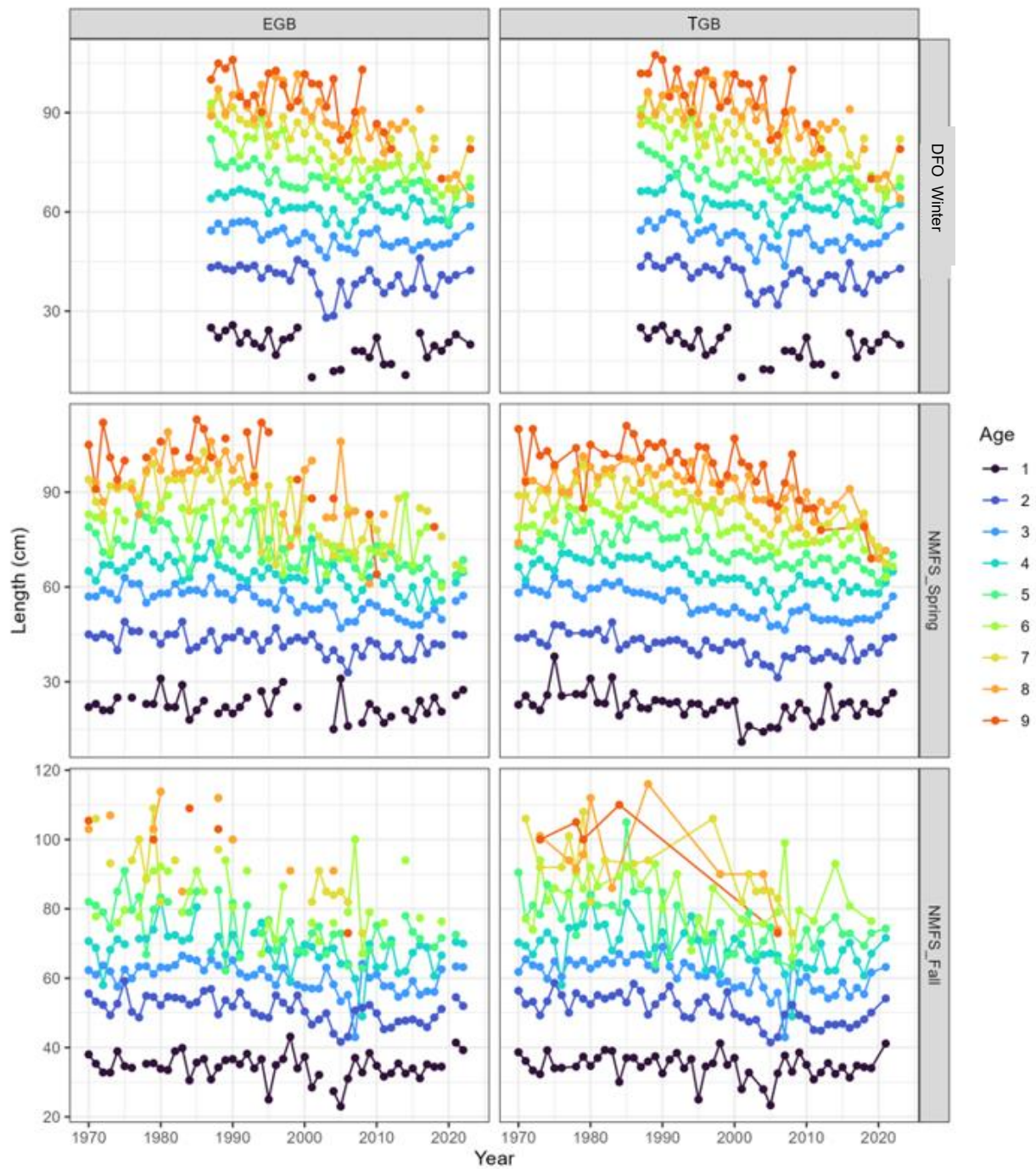


Figure 14. Length at age for the National Marine Fisheries Service (NMFS) spring, NMFS fall, and Fisheries and Oceans Canada (DFO) winter surveys on eastern Georges Bank (EGB) and total Georges Bank (TGB). Figure from Andrushchenko et al. (2026).

CanTota	s0	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12	s13	s14	s15	s16
1978	0.0007	0.0083	0.0582	1	0.239	0.0814	0.0443	0.0337	0.0034	0.0091	0.0026	0.0016	0.0018	0.0003	0.0002	0.0005	0.0003
1979	0.0024	0.0195	0.8001	1	0.314	0.481	0.1481	0.0729	0.033	0.0204	0.0077	0.0017	0.002	0.0005	0.0011	0	0
1980	0.0026	0.0074	0.7811	1	0.2018	0.5952	0.1881	0.0427	0.0068	0.0327	0.0194	0.0016	0.0001	7E-05	5E-05	0	0
1981	0.0059	0.0442	0.3229	0.9856	1	0.275	0.5177	0.1882	0.1176	0.0553	0.0195	0.0019	0.0019	0	0	0.0004	0
1982	8E-06	0.0107	1	0.3261	0.6188	0.4358	0.1091	0.1782	0.0674	0.024	0.0115	0.0171	0.0012	6E-05	0.0018	0.0005	0
1983	0.0078	0.0207	0.2646	1	0.6431	0.2699	0.1551	0.0609	0.0718	0.0359	0.0031	0.0104	0.0015	0.0001	0.0005	0.0002	6E-05
1984	0.0005	0.0361	0.3146	0.4687	0.8565	0.8322	1	0.5131	0.0844	0.1205	0.0505	0.0431	0.004	0.0005	0.0003	0.001	0.0002
1985	0.0222	0.0059	1	0.399	0.2696	0.3773	0.1482	0.0484	0.0337	0.0093	0.0081	0.0049	0.0012	0.0005	0.0002	0	4E-05
1986	0.001	0.0849	0.2865	1	0.2584	0.1233	0.1684	0.0323	0.0169	0.0098	0.0029	0.0015	0.0008	0	3E-05	0	2E-05
1987	0.0011	0.0117	1	0.2447	0.3963	0.0505	0.0414	0.0535	0.0118	0.0087	0.0023	0.0014	7E-05	2E-05	0	0	0
1988	0.0004	0.0107	0.1123	1	0.1639	0.2058	0.0277	0.03	0.0613	0.0129	0.0084	0.0068	0.0034	0.001	0	0.0001	0
1989	0.0016	0.0052	0.2153	0.2539	1	0.1473	0.2038	0.0366	0.0299	0.0441	0.0109	0.007	0.0037	0.0001	0.0004	0	0
1990	0.0006	0.005	0.2262	1	0.3626	0.4468	0.0516	0.0431	0.0032	0.0058	0.0101	0.0015	0.0017	0.0003	0	0.0004	1E-06
1991	0.0004	0.0282	0.4263	0.4735	1	0.4676	0.3937	0.0581	0.0427	0.0126	0.0088	0.0064	0.003	0.002	0.0002	0.0005	0
1992	0	0.0244	1	0.6304	0.2412	0.5025	0.1966	0.1774	0.0257	0.0213	0.0024	0.004	0.0005	0.0008	0.0001	0	0
1993	0	0.0064	0.1846	1	0.5925	0.2055	0.2597	0.1047	0.0782	0.0232	0.014	0.0021	3E-05	0.0004	0	0	0
1994	0.0013	0.0064	0.2035	0.4675	1	0.3867	0.0664	0.087	0.041	0.0286	0.0024	0.001	5E-05	5E-07	7E-05	2E-05	0
1995	0.0299	0.0054	0.2235	1	0.5939	0.6247	0.1308	0.0496	0.0347	0.0263	0.0007	0.0004	8E-05	0	0	0	0
1996	0.0004	0.0165	0.0758	0.5035	1	0.2448	0.1858	0.0453	0.0118	0.0098	0.0008	0.0009	0	0	1E-05	0	0
1997	0.0034	0.0191	0.3175	0.4656	0.9979	1	0.2769	0.1232	0.0396	0.015	0.0033	0.0013	2E-05	0	0	0	0
1998	0.0004	0.0127	0.3185	1	0.4861	0.4933	0.382	0.0672	0.0434	0.0135	0.003	0.0021	0.002	0.0004	0.0002	0	0
1999	0.0005	0.0088	0.12	1	0.7101	0.2181	0.1251	0.0966	0.0332	0.0082	0.0012	0.0007	0.002	4E-05	0	0	0
2000	0.005	0.0084	0.1483	0.2995	1	0.3778	0.1188	0.0808	0.0399	0.0064	0.0016	0.0014	0	0	0.0006	0	0
2001	0.0048	0.0145	0.0528	0.8786	0.4984	1	0.3013	0.1027	0.0554	0.0166	0.0012	0.0005	3E-05	0	0.0005	0	0
2002	0.0041	0.0025	0.036	0.2458	1	0.2774	0.4372	0.1079	0.0307	0.0135	0.0058	0.0011	0.0014	0	0.0005	0	0
2003	0.0872	0.0005	0.0561	0.4791	0.5913	1	0.2023	0.3088	0.0725	0.0184	0.0074	0.0028	0.0001	0	3E-05	0	0
2004	0	0.2311	0.0808	1	0.898	0.7373	0.9513	0.2208	0.2576	0.0633	0.0135	0.0056	0.0024	0	0	0	0
2005	0	0.0269	0.1425	0.216	1	0.2542	0.1839	0.2076	0.0878	0.0346	0.0109	4E-05	0.0005	0.0013	0	0	0
2006	0	0.0103	0.098	1	0.3839	0.9549	0.2363	0.1003	0.1077	0.0103	0.008	0.0017	7E-05	0	0	0	0
2007	2E-05	0.0006	0.1123	0.23	1	0.0857	0.2263	0.0469	0.0287	0.0276	0.0014	0.0005	3E-06	0	0	0	0
2008	0	0.0037	0.1478	0.4611	0.2442	1	0.0749	0.1423	0.0211	0.0106	0.0034	0.0004	4E-05	0	0	0	0
2009	0.0073	0.0042	0.1746	0.9678	0.7202	0.242	1	0.0862	0.0809	0.0094	0.0044	0.0006	0	0	0	0	0
2010	0.0001	0.0125	0.1224	0.4003	1	0.4161	0.0376	0.2565	0.0306	0.0192	0.0041	0.0006	0	0	0	0	0
2011	0	0.0803	0.3372	0.6782	0.7147	1	0.1997	0.1348	0.0751	0.0035	0.0043	0.0005	0	0	0	0	0
2012	0	0.0293	0.5628	1	0.4513	0.3183	0.344	0.088	0.0138	0.013	0.0005	0	0	0	0	0	0
2013	0.0054	0.0063	0.2197	1	0.5119	0.1254	0.0939	0.0244	0.006	0.0003	0.0012	0	0	0	0	0	0
2014	0	0.0429	0.123	0.8294	1	0.2525	0.0277	0.003	0.0008	0.0002	2E-06	2E-05	0	0	0	0	0
2015	0	0.0043	0.882	0.4726	1	0.8026	0.1085	0.1003	0.0012	0.0014	0.0082	0	0	0	0	0	0
2016	0	0.0478	0.1545	1	0.1129	0.3235	0.2403	0.0393	0.0004	0.0001	6E-05	4E-05	0	0	0	0	0
2017	0.0005	0.0053	0.1248	0.4596	1	0.1133	0.2175	0.072	0.0097	5E-05	0	1E-05	0	0	0	0	0
2018	0	0.037	0.1514	0.3429	0.6373	1	0.0885	0.0977	0.0518	0.0017	0.0003	6E-05	0	0	0	0	0
2019	0	0.0913	0.8635	0.9896	1	0.6158	0.7589	0.0506	0.03	0.029	5E-05	0	0	0	0	0	0
2020	0	0.1231	0.4335	1	0.4197	0.2733	0.0978	0.0809	0.0061	0.0016	0	0	0	0	0	0	0
2021	0	0.1735	0.3816	0.8909	1	0.2679	0.0791	0.007	0.0064	8E-06	0	0	0	0	0	0	0
2022	0	0.3188	0.6388	0.3115	1	0.5548	0.0964	0.0562	0.0044	0.0011	0	0	0	0	0	0	0

Figure 15a. Annual empirical estimates of Canadian fleet relative selectivity for eastern Georges Bank (EGB) Cod derived from commercial catch at age (abundance). Empirical estimates are calculated by dividing the catch in each year and age by the largest catch at age within that year. Colours help interpret magnitude, with green close to 1 and red close to 0.

USATot	a0	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12	a13	a14	a15	a16
1978	0	3E-05	0.0286	1	0.3464	0.1365	0.0671	0.0533	0.008	0.0094	0.0019	0.0005	0.0002	0	4E-05	0.0001	0
1979	0	0.0029	0.4533	0.2822	1	0.382	0.1738	0.0815	0.0673	0.0123	0.0026	0.0013	0.0007	0	0.0005	0	0
1980	0	0	0.4612	1	0.1781	0.8244	0.3871	0.1165	0.0208	0.0357	0.006	0.0013	0	0	0	0	0
1981	0	0.01	0.5371	1	0.7202	0.0981	0.2018	0.0305	0.0555	0.0321	0.0118	0.002	0.001	0	0	0	0
1982	0	0	1	0.3921	0.2796	0.3034	0.0319	0.126	0.0386	0.0147	0.0048	0.0037	0.0024	0.0019	0.0003	0	0
1983	0	0.0047	0.3419	1	0.4051	0.2538	0.1673	0.0261	0.0515	0.0305	0.0128	0.0151	0.0034	0.0013	0.0033	0.0006	0
1984	0	0.0078	0.2114	0.6898	1	0.2979	0.2266	0.1896	0.0212	0.0561	0.024	0.0103	0.0043	0.0022	0.0009	0	0.0004
1985	0	0.0015	1	0.6631	0.3813	0.6436	0.1713	0.0357	0.0893	0.012	0.0264	0.0036	0.0043	0.0012	0.0007	0	0
1986	0	0.0025	0.2243	1	0.213	0.2056	0.2384	0.0334	0.0285	0.0184	0.0017	0.0067	0.0013	0	0	0	0
1987	0	0	1	0.2282	0.365	0.0618	0.0478	0.0556	0.0148	0.0078	0.0039	0.0006	0.0004	0	0	0	0
1988	0	0	0.0397	1	0.231	0.3058	0.0465	0.0309	0.0363	0.0063	0.0041	0.002	0.0004	6E-05	0	8E-05	0
1989	0	0.0128	0.265	0.4478	1	0.087	0.164	0.0201	0.0127	0.0162	0.0023	0.0008	0.0001	0	0	0	0
1990	0	0.0054	0.2962	1	0.336	0.5399	0.0571	0.0597	0.0051	0.0028	0.0037	4E-05	0.0003	0	0	0	0
1991	0	0.027	0.4781	0.5576	1	0.5121	0.4241	0.0605	0.032	0.0086	0.0031	0.0005	0.0013	0	0	0.0005	0
1992	0	0.0243	1	0.559	0.2036	0.4132	0.1329	0.1199	0.0081	0.0079	0.0007	0.001	0	0	0	0	0
1993	0	0.0028	0.3119	1	0.3903	0.1458	0.1529	0.0482	0.032	0.008	0.0028	0.0006	0	0	0	0	0
1994	0	0.0082	0.1864	0.8441	1	0.2806	0.0431	0.0706	0.0323	0.023	0.0019	0.0023	0	0.001	0	0	0
1995	0	3E-05	0.2133	1	0.4349	0.6943	0.0909	0.0309	0.0213	0.0233	0.001	0.001	0	0	0	0	0
1996	0.000135	0.0048	0.0978	0.5407	1	0.2076	0.1994	0.0229	0.0097	0.0116	0.0016	2E-05	0	0	0	0	0
1997	0	0.0438	0.2132	0.3194	0.5117	1	0.2051	0.1191	0.0372	0.0078	0.0045	0.0038	0.0004	0	0	0	0
1998	0	0.052	0.3625	0.3731	0.8254	1	0.3801	0.1249	0.0766	0.0231	0.0036	0.0005	0.001	0	0	0	0
1999	0	0.0158	0.1557	1	0.8239	0.3351	0.1853	0.1876	0.0401	0.0074	0.0014	0	0	0	0	0	0
2000	0	0.0068	0.1829	0.3471	1	0.3896	0.0977	0.0589	0.0304	0.0048	0	0.0002	0	0	0	0	0
2001	0	0	0.309	1	0.3083	0.5788	0.1332	0.0412	0.0256	0.0114	0.0012	0.0005	0.0002	0	0	0	0
2002	0	0.002	0.015	0.2977	1	0.2239	0.2664	0.0529	0.0135	0.0117	0.004	0.0013	0.0006	0	0	0	0
2003	0	0	0.1026	0.2914	0.6033	1	0.2052	0.1883	0.0371	0.0073	0.0021	0.0004	0	0	0	0	0
2004	0	0.0418	0.0636	0.6692	0.8806	1	0.7007	0.2	0.1208	0.0274	0.0031	0.002	0.0004	0	0	0	0
2005	0	0.0028	0.7864	0.272	1	0.268	0.1623	0.1512	0.0174	0.0151	0.003	0.0002	0	0	0	0	0
2006	0	0.0445	0.0544	1	0.3364	0.8432	0.2175	0.059	0.053	0.0117	0.0044	0.0016	0.0012	0	0	0	0
2007	0	0.0139	0.1572	0.1385	1	0.0785	0.1773	0.0091	0.0066	0.0033	0.0008	0.0003	0	0	0	0	0
2008	0	0.0204	0.4609	1	0.2374	0.8436	0.0073	0.0516	0.0008	0.0011	0.0003	0	0	0	0	0	0
2009	0	0.0785	0.2626	1	0.6973	0.239	0.3605	0.009	0.0113	0.001	0	0	0	0	0	0	0
2010	0	0.0219	0.4858	0.6178	1	0.3724	0.0478	0.2126	0.0044	0.0028	0	0	0	0	0	0	0
2011	0	0.0617	0.3659	0.5472	1	0.9394	0.2753	0.0622	0.048	0	0	0	0	0	0	0	0
2012	0	0.0027	0.8781	1	0.5148	0.2096	0.0644	0.0222	7E-05	0	0	0	0	0	0	0	0
2013	0	0.0364	0.5019	1	0.4521	0.0374	0.0087	0.0015	0.0014	0	0	0	0	0	0	0	0
2014	0	0.0283	0.0607	0.5732	1	0.3031	0.0531	0.0005	0.0011	0	0	0	0	0	0	0	0
2015	0	0.0301	0.5571	0.57	1	0.3895	0.0271	0.0007	1E-04	0.0003	0	0.0001	0	0	0	0	0
2016	0	0.0006	0.0471	0.3614	1	0.1691	0.0283	0.0013	0	0	0	0	0	0	0	0	0
2017	0	0.0075	0.0189	0.2036	1	0.125	0.0594	0.0091	0.0002	0	0	0	0	0	0	0	0
2018	0	0.1938	0.0897	0.0862	1	0.5702	0.0137	0.0137	0.0009	0	0	0	0	0	0	0	0
2019	0	0.0088	0.6634	0.3418	1	0.4574	0.3294	0.0031	0	0	0	0	0	0	0	0	0
2020																	
2021																	
2022																	

Figure 15b. Annual empirical estimates of US fleet relative selectivity for eastern Georges Bank (EGB) Cod derived from commercial catch at age (abundance). Empirical estimates are calculated by dividing the catch in each year and age by the largest catch at age within that year. Colours help interpret magnitude, with green close to 1 and red close to 0.

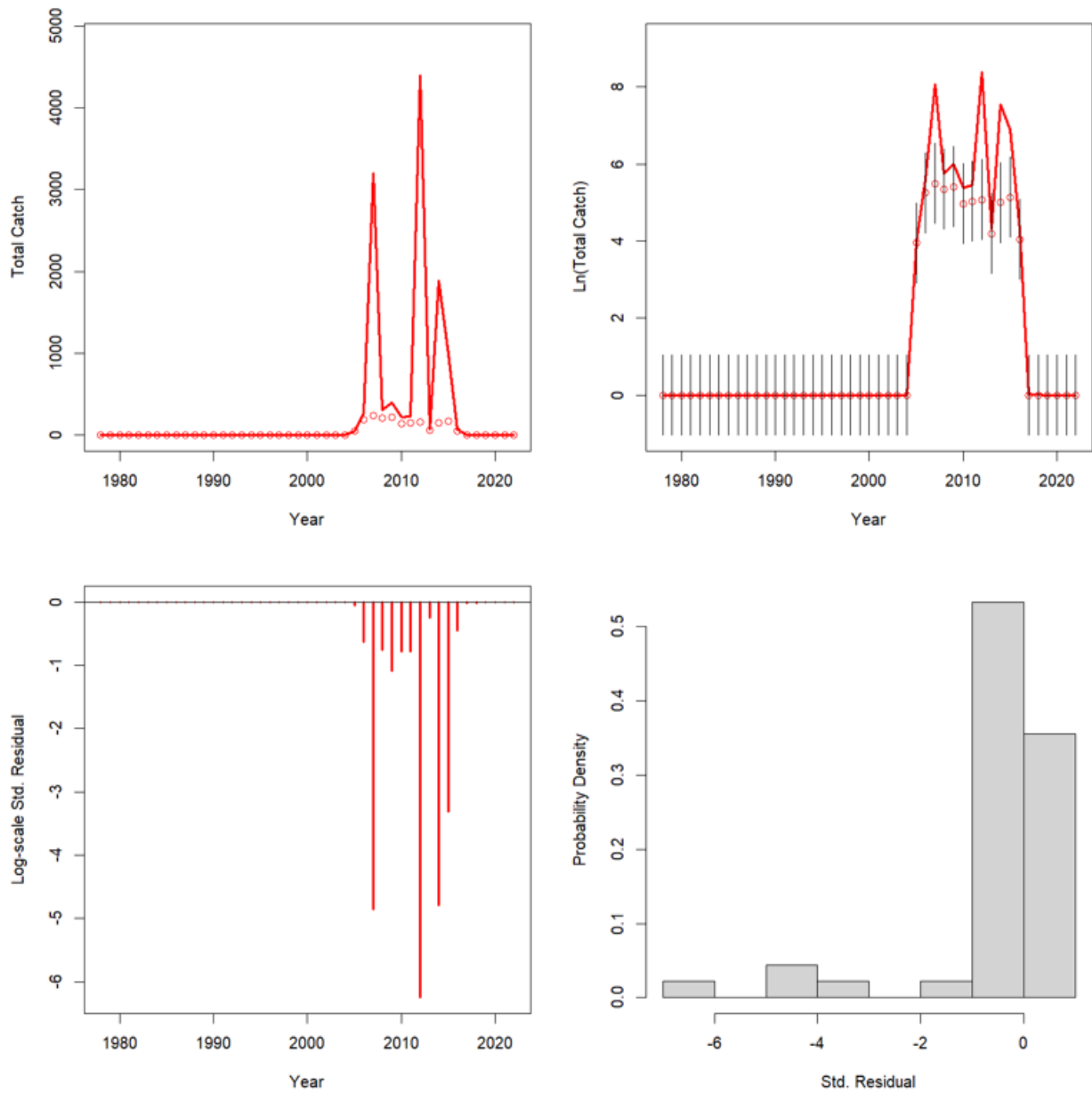


Figure 16. Example diagnostics for total catch by the misallocated when the coefficient of variation (CV) is set to 0.57. Top left panel is actual (point) versus estimated (line) values. Top right panel is the log of the catch with the user specified CV around the actual. Bottom left are the log-transformed residuals between actual and estimated. Bottom right is the probability distribution of the log-transformed residuals.

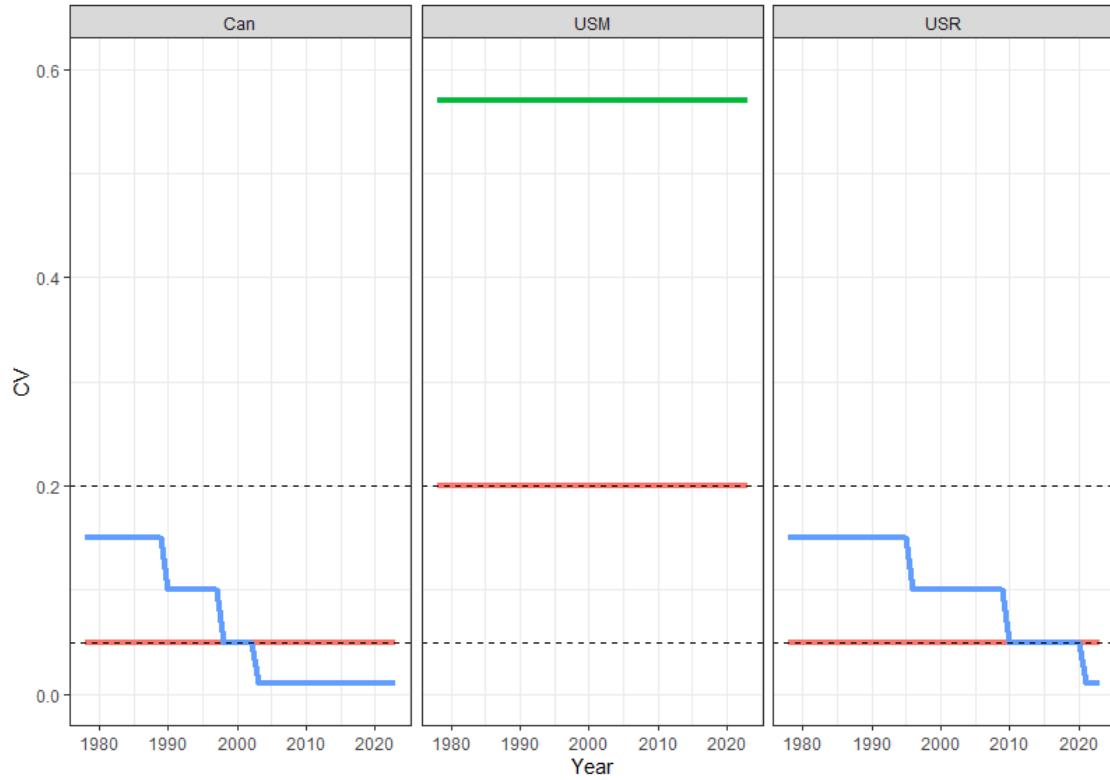


Figure 17. Coefficient of variation (CV) assumptions on Canadian (Can; left panel), US misreported (USM; middle panel) and US reported fleet catches (USR; right panel). Red lines show an uninformed base assumption of fleet CVs; blue lines show CV assumptions based on expert opinion; green line is the calculated CV on the misattributed fleet. Dashed lines are there for reference and indicate a CV of 0.05 and 0.2.

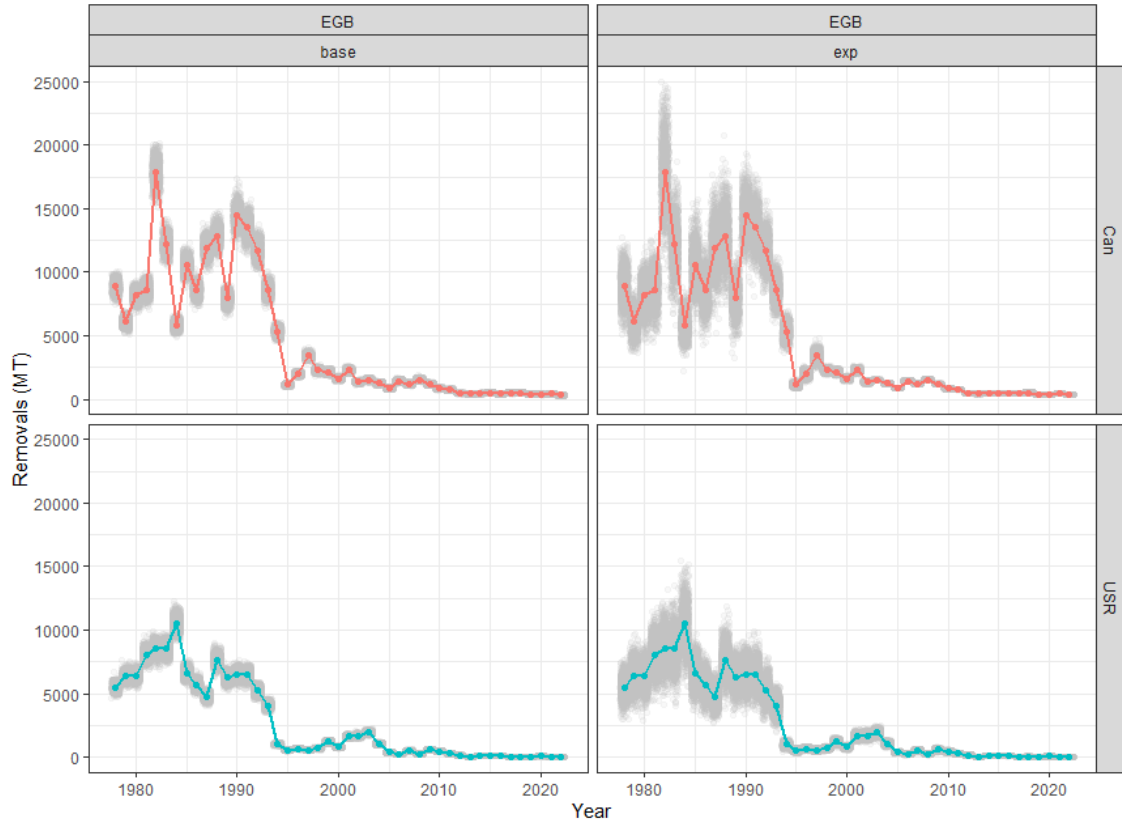


Figure 18. Reported removals for the Canadian (Can, red lines) and US (USR, blue lines) fleets on eastern Georges Bank (EGB), with grey shading showing the expected distribution of true catches given an invariable coefficient of variation (CV) of 0.05 (left; base) and the time varying CV in Figure 18 (right; expert opinion).

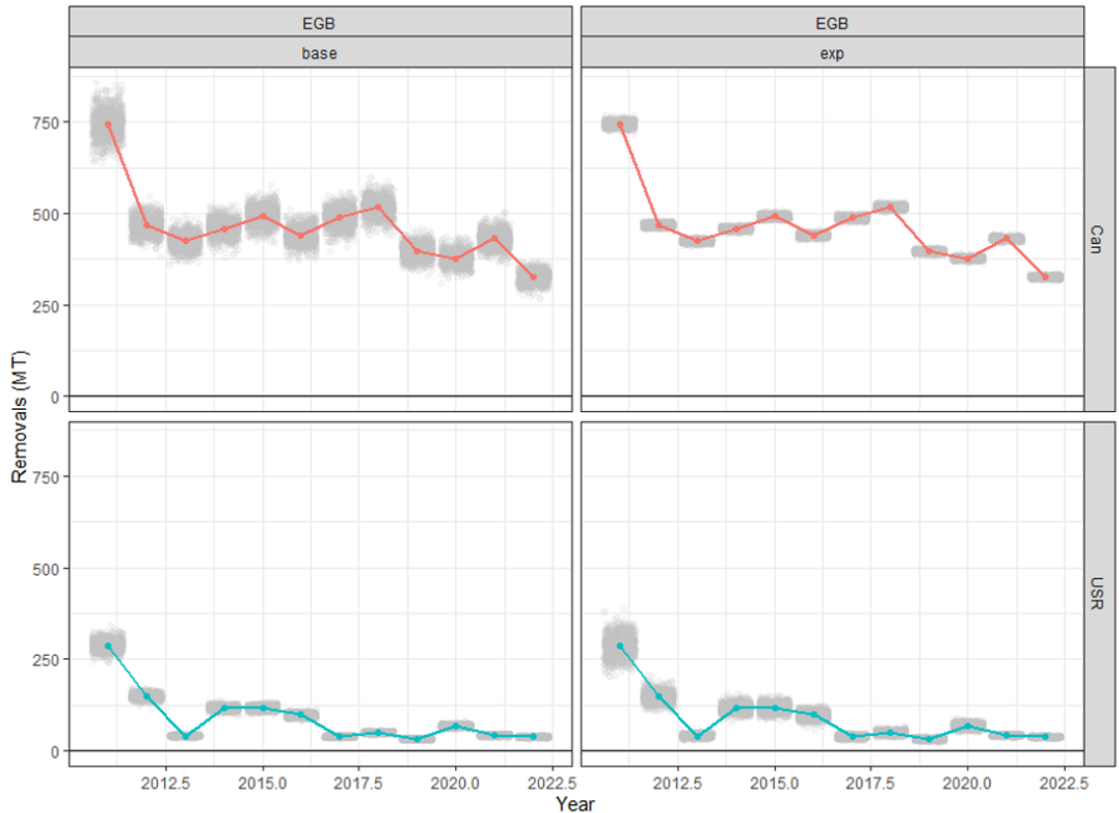


Figure 19. Reported removals (coloured lines) for the Canadian (Can, red lines) and US (US, blue lines) fleets on eastern Georges Bank (EGB) in recent years, with grey shading showing distribution of true catches given an invariable coefficient of variation (CV) of 0.05 (left; 'base') and the time varying CV in Figure 18 (right; expert opinion).

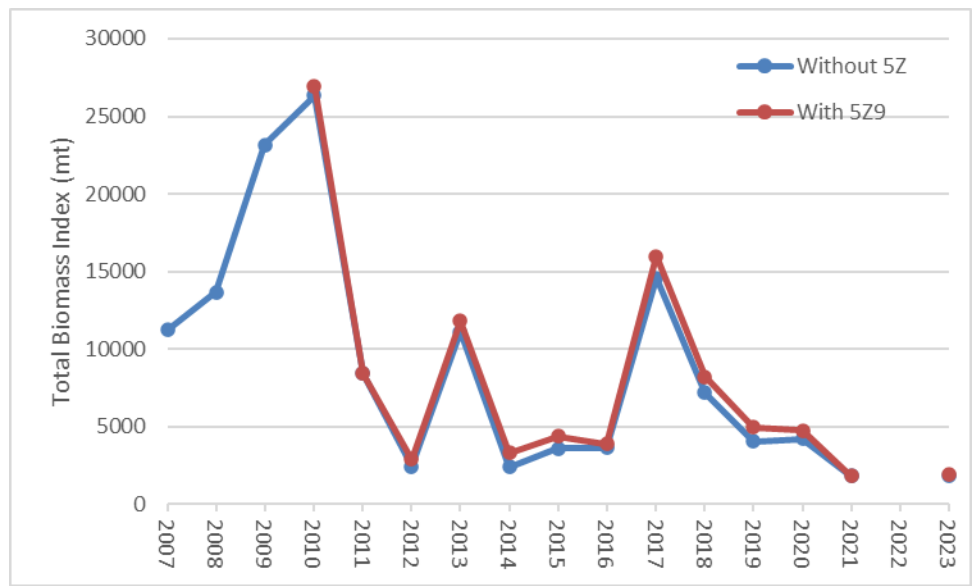


Figure 20. Fisheries and Oceans Canada (DFO) winter survey aggregate biomass index for eastern Georges Bank (Strata 5Z1-5Z4, DFO unit areas 5Zjm). The red line shows the biomass index generated including survey stratum 5Z9 (5Z1-5Z4+5Z9, Management Area 5Zjm).

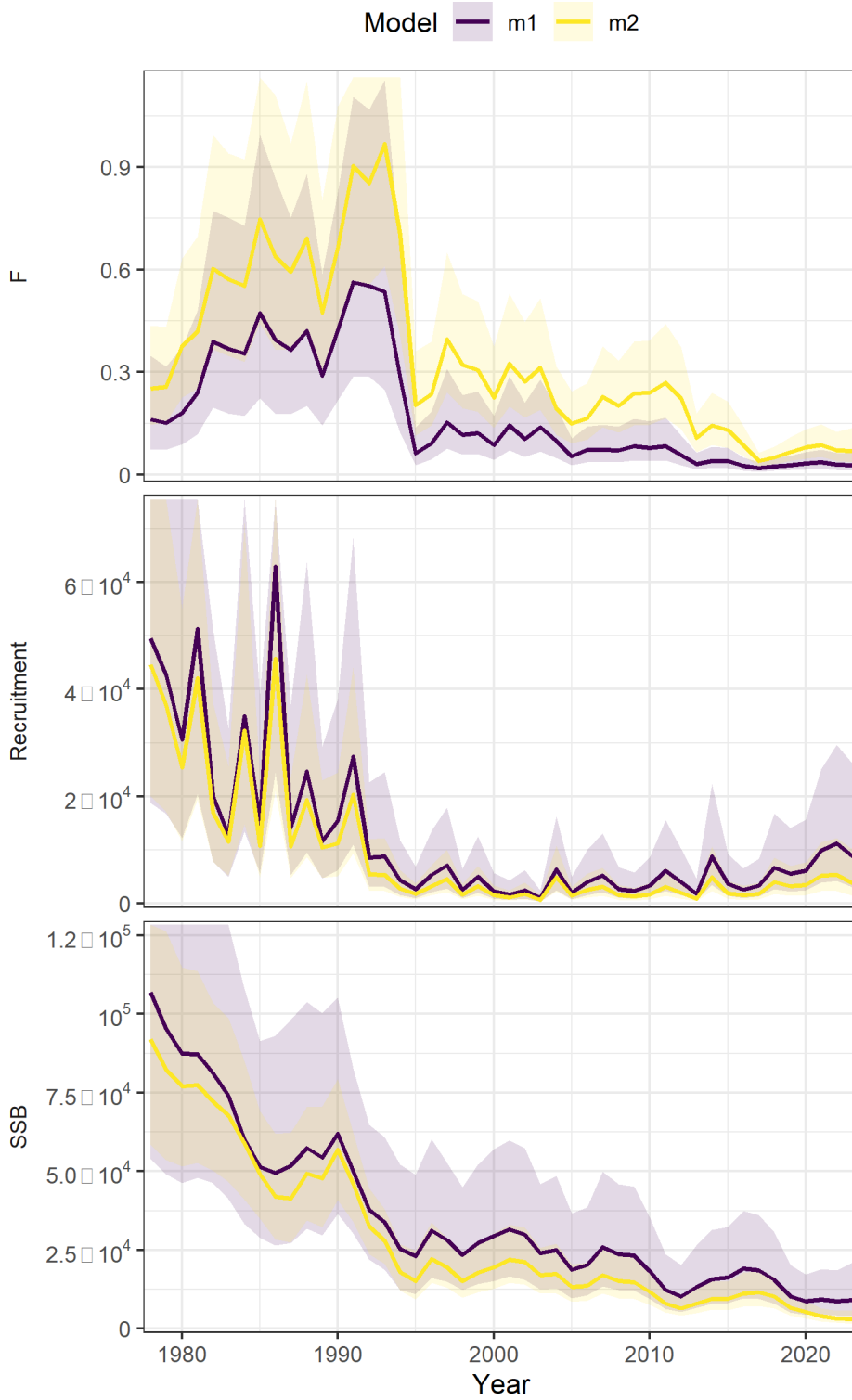


Figure 21. Fishing mortality (F), recruitment and spawning stock biomass (SSB) estimates from the two candidate models (m1 = Run 1 (EGB) (eastern Georges Bank; M2 = Run 6 (TGB) total Georges Bank in Table 3).

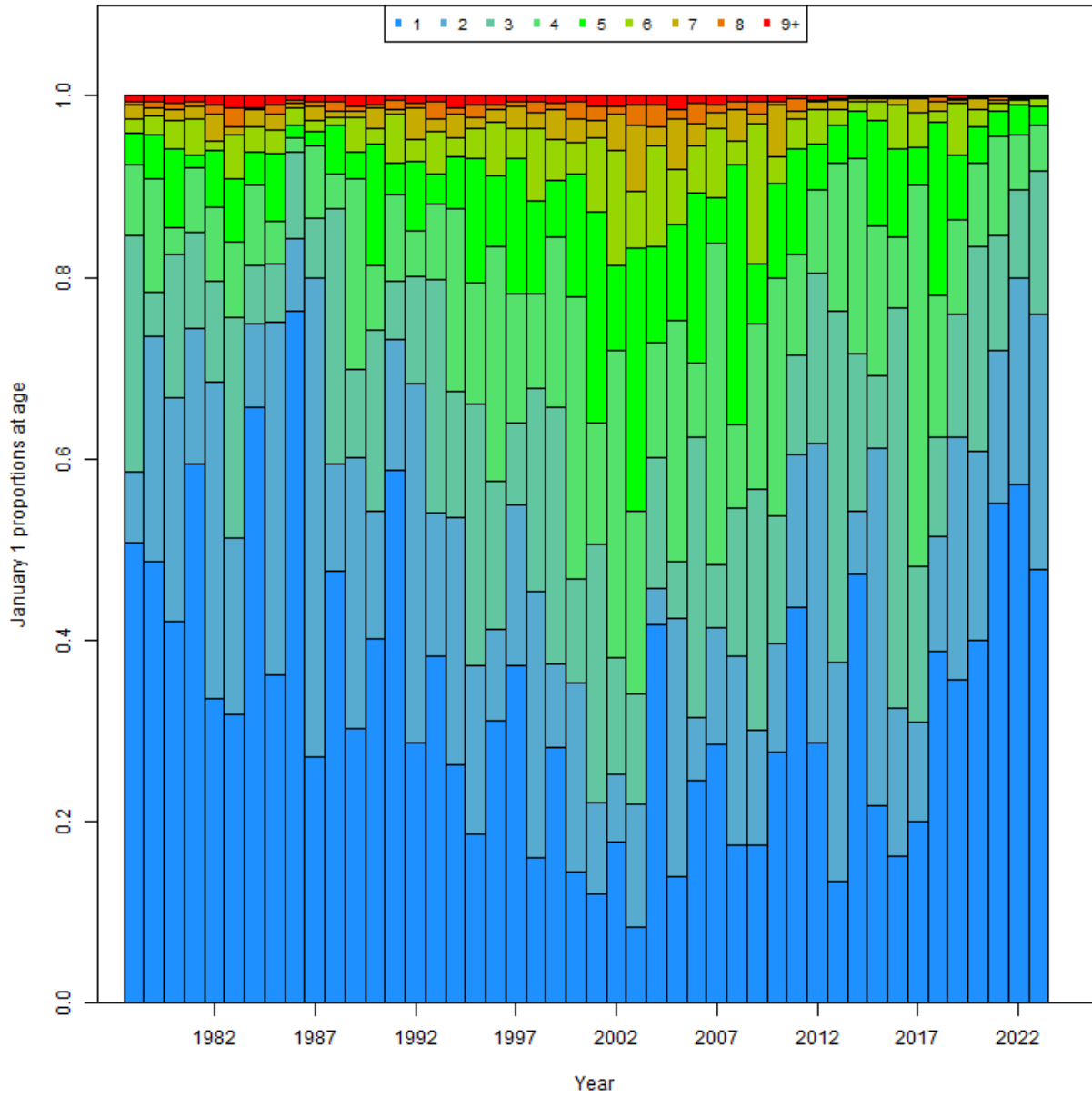


Figure 22a. Proportional population abundance at age for the eastern Georges Bank (EGB) (top; Run 1 in Table 3) candidate model.

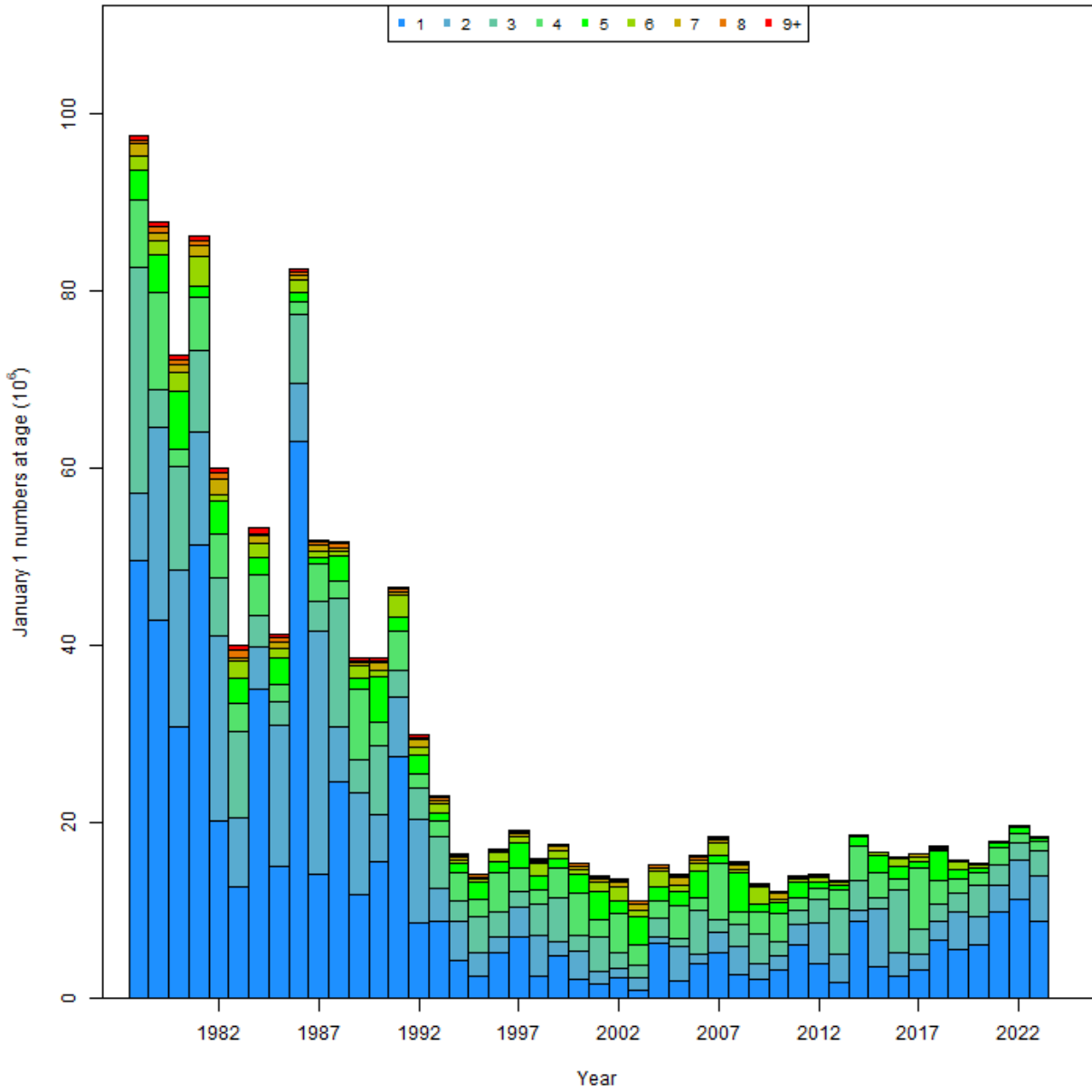


Figure 22b. Actual population abundance at age for the eastern Georges Bank (EGB) (Run 1 in Table 3) candidate model.

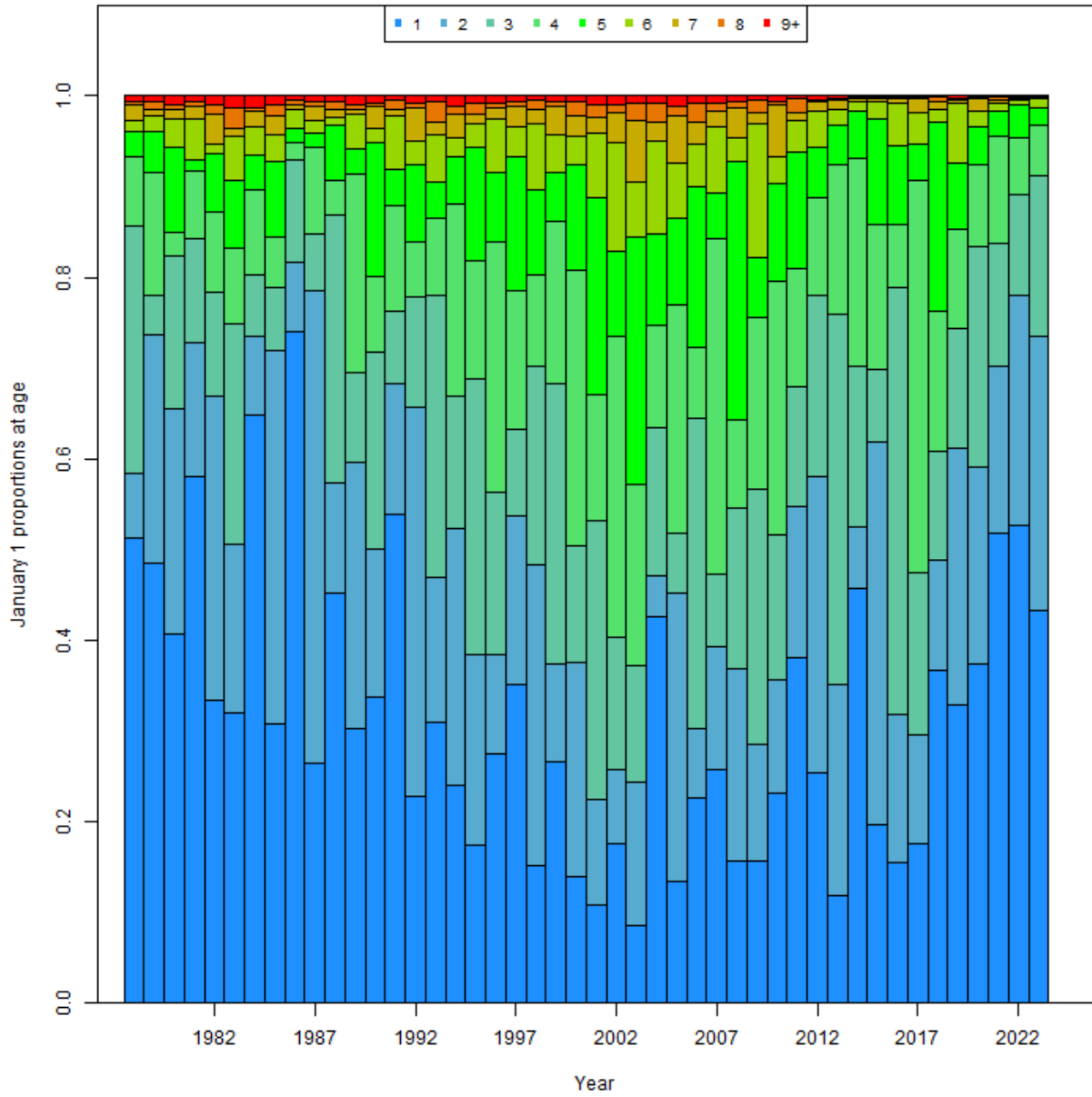


Figure 22c. Proportional population abundance at age for the total Georges Bank (Run 6 in Table 3) candidate model.

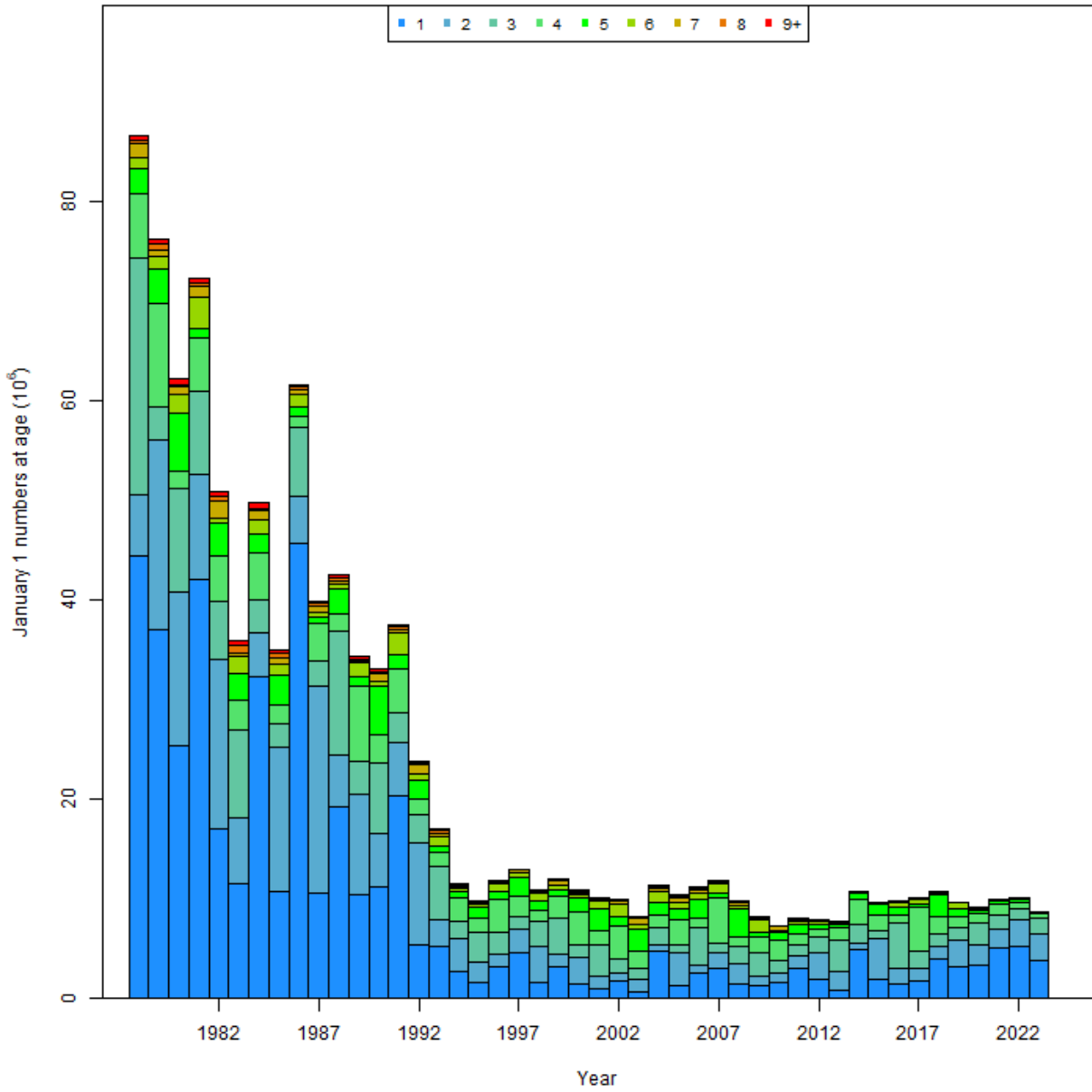


Figure 22d. Actual population abundance at age for the total Georges Bank (Run 6 in Table 3) candidate model.

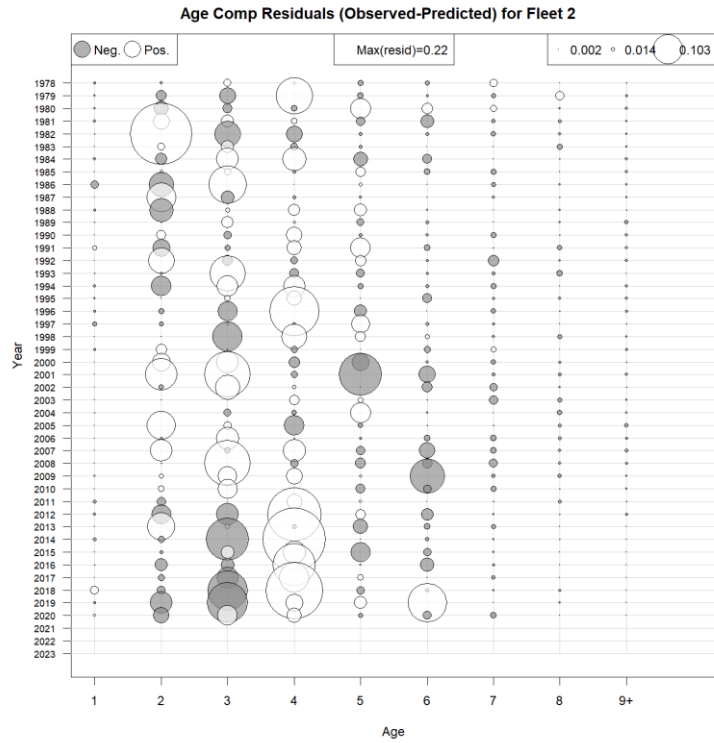
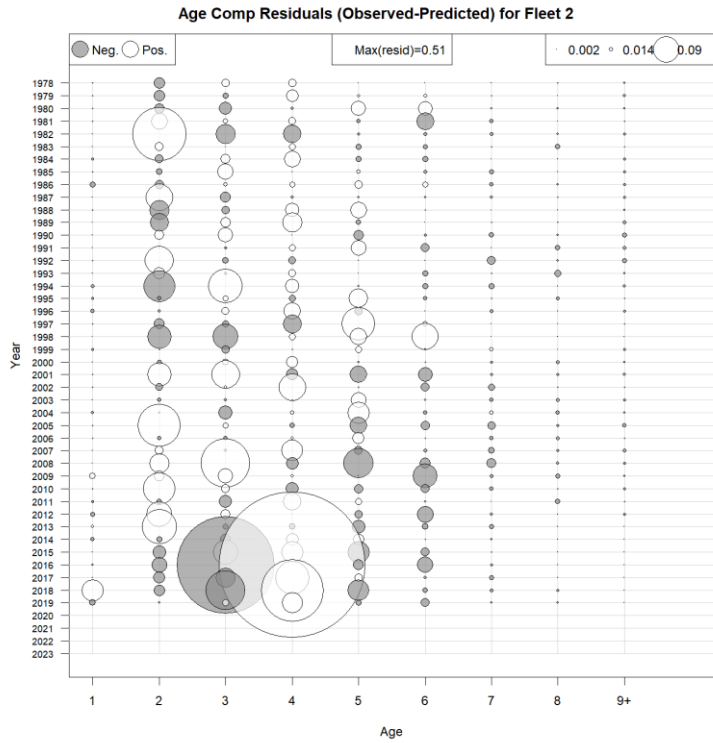


Figure 23. Age composition raw residuals for the US fishing fleet from the candidate eastern Georges Bank EGB (left; Run 1 in Table 3) and total Georges Bank (TGB) (right, Run 6 in Table 3) models.

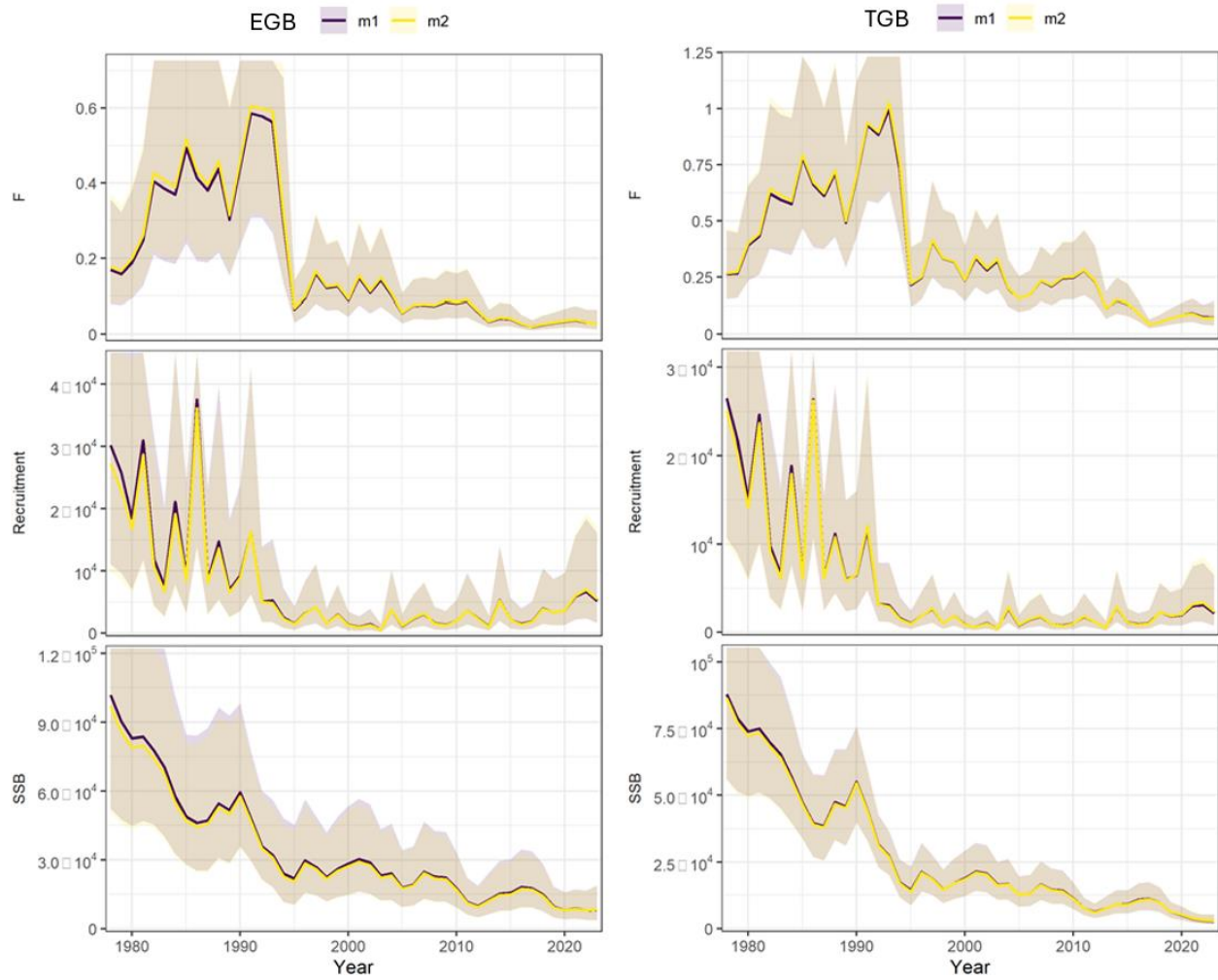


Figure 24. Outputs of the candidate eastern Georges Bank (EGB) (left) and total Georges Bank (TGB) (right column) models, with the recruitment assumed as a random walk (m1) or mean across years (m2). Model nomenclature index shown in Table 3: In the left column m1 = Run 1, m2 = Run 2; in the right column m1 = Run 6, m2 = Run 7. (SSB – spawning stock biomass, F – fishing mortality).

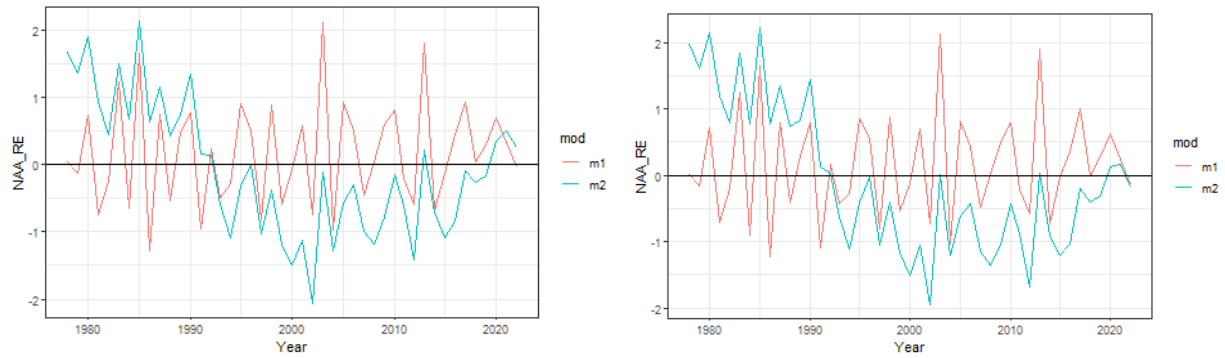


Figure 25. Process error on recruitment (NAA RE) for the candidate eastern Georges Bank (EGB) (left panel) and total Georges Bank (TGB) (right panel) models, with the recruitment assumed as a random walk (m1) or mean across years (m2). Nomenclature index to Table 3: In the left plot m1 = Run 1, m2 = Run 2; in the right plot m1 = Run 6, m2 = Run 7.

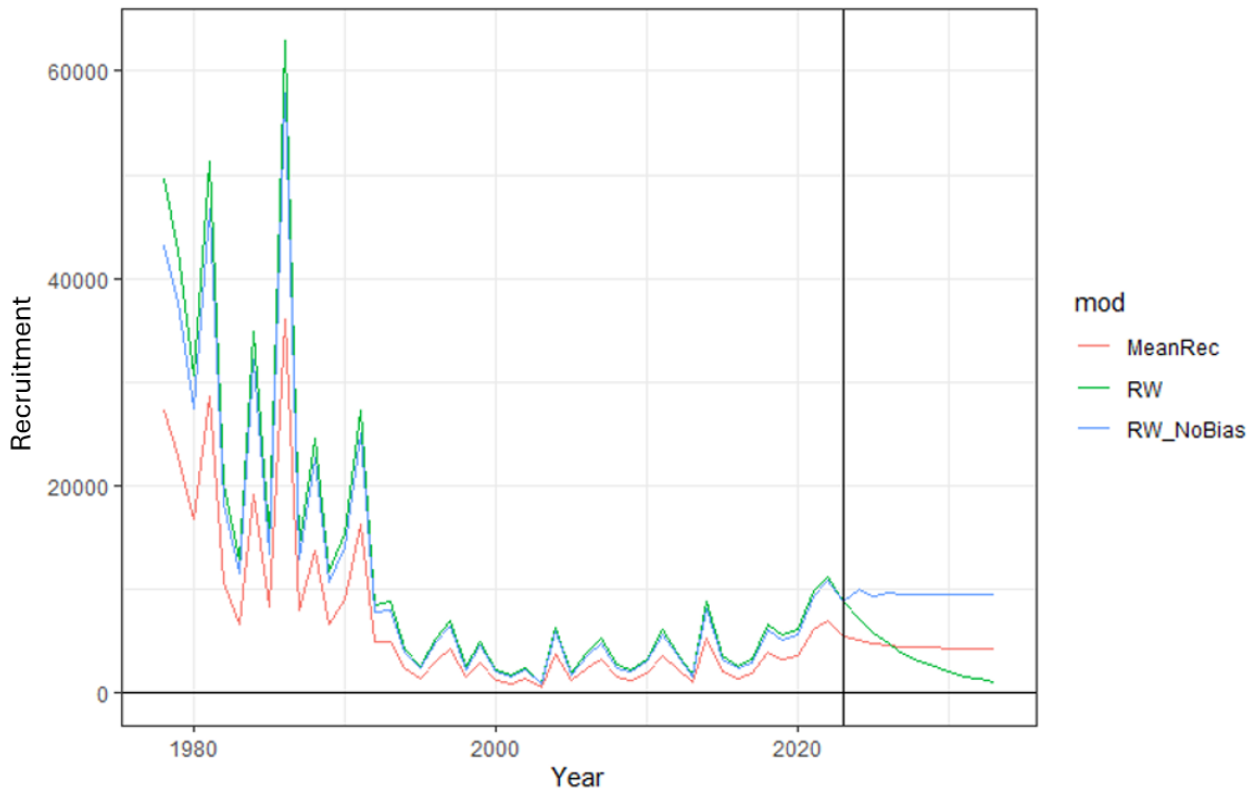


Figure 26. Historical and projected (10 yr) recruitment for the eastern Georges Bank (EGB) model when recruitment (REC) is estimated as a series mean with random process error (MeanRec; Run 2 in Table 3), a random walk (RW; Run 1 in Table 3) with default Woods Hole Assessment Model (WHAM) settings for bias adjustment and a random walk with the bias adjustment on population process error turned off (RW\_NoBias; modified version of Run 1 in Table 3). Vertical line identifies the terminal historic year for recruitment.

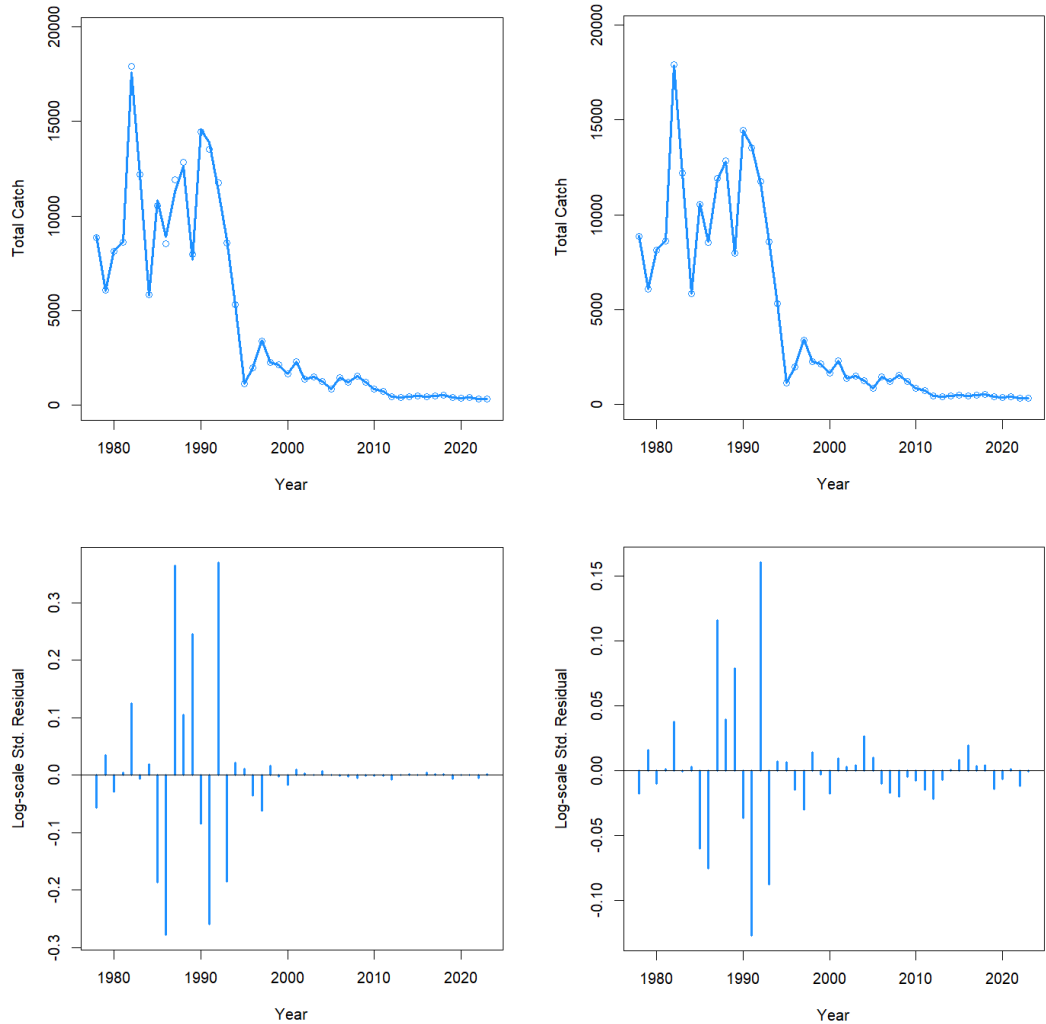


Figure 27. Predicted versus actual (top row) aggregate catches by the Canadian fleet from the candidate eastern Georges Bank (EGB) model with a time-varying (left column; Run 1 in Table 3) and time invariant (right column; Run 3 in Table 3) fishery coefficient of variation (CV). Bottom row shows log transformed residuals.

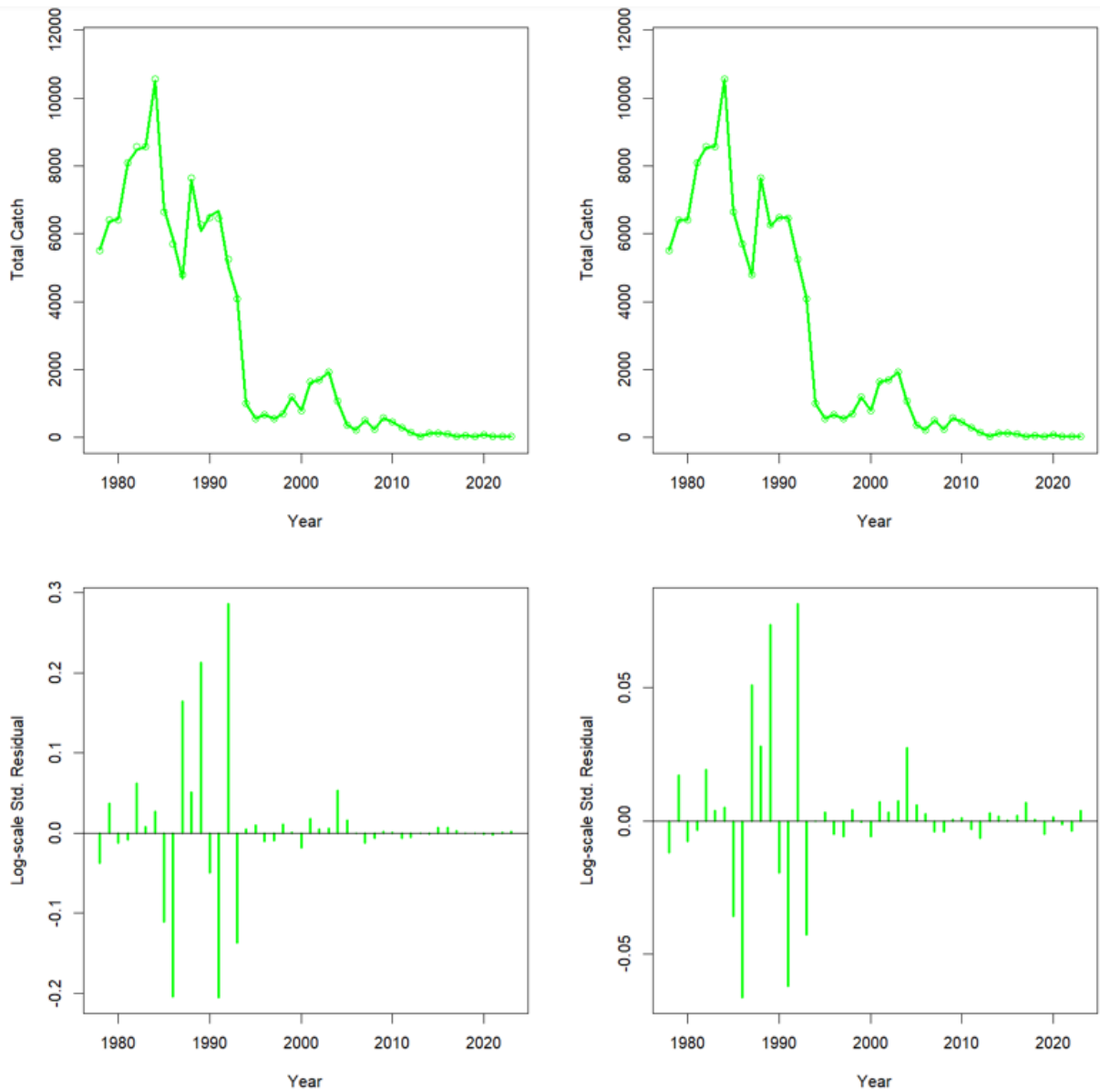


Figure 28. Residuals on aggregate catches by the US fleet from the candidate eastern Georges Bank (EGB) model with a time-varying (left column; Run 1 in Table 3) and time invariant (right column; Run 3 in Table 3) fishery coefficient of variation (CV).

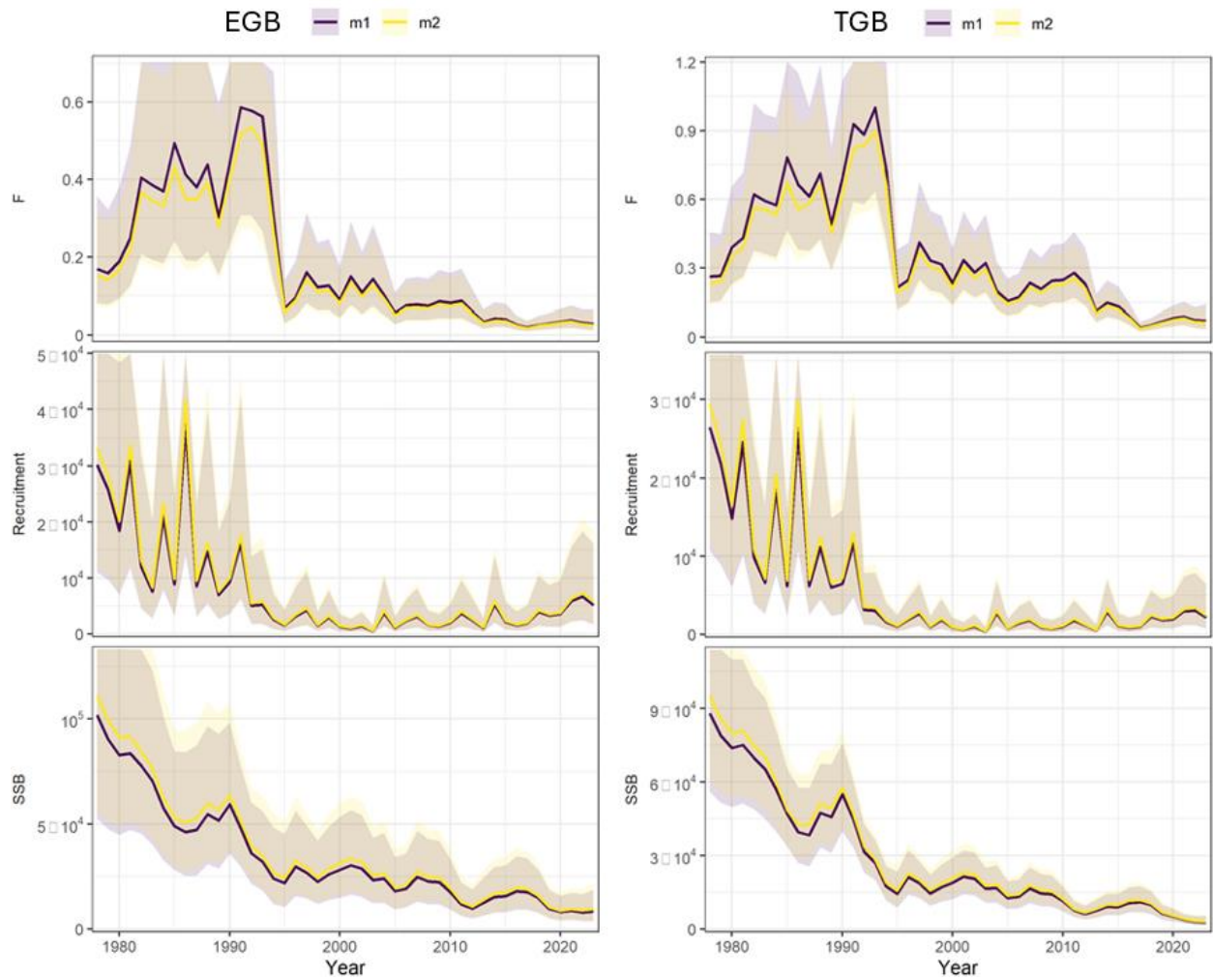


Figure 29. Outputs of the candidate eastern Georges Bank (EGB) (left column) and total Georges Bank (TGB) (right column) models, with the decreasing fishery coefficient of variation (CV) (m1 = Run 1 in Table 3) or time-invariant fishery CV of 0.05 (m2 = Run 3 in Table 3). (SSB – spawning stock biomass, F– fishing mortality)

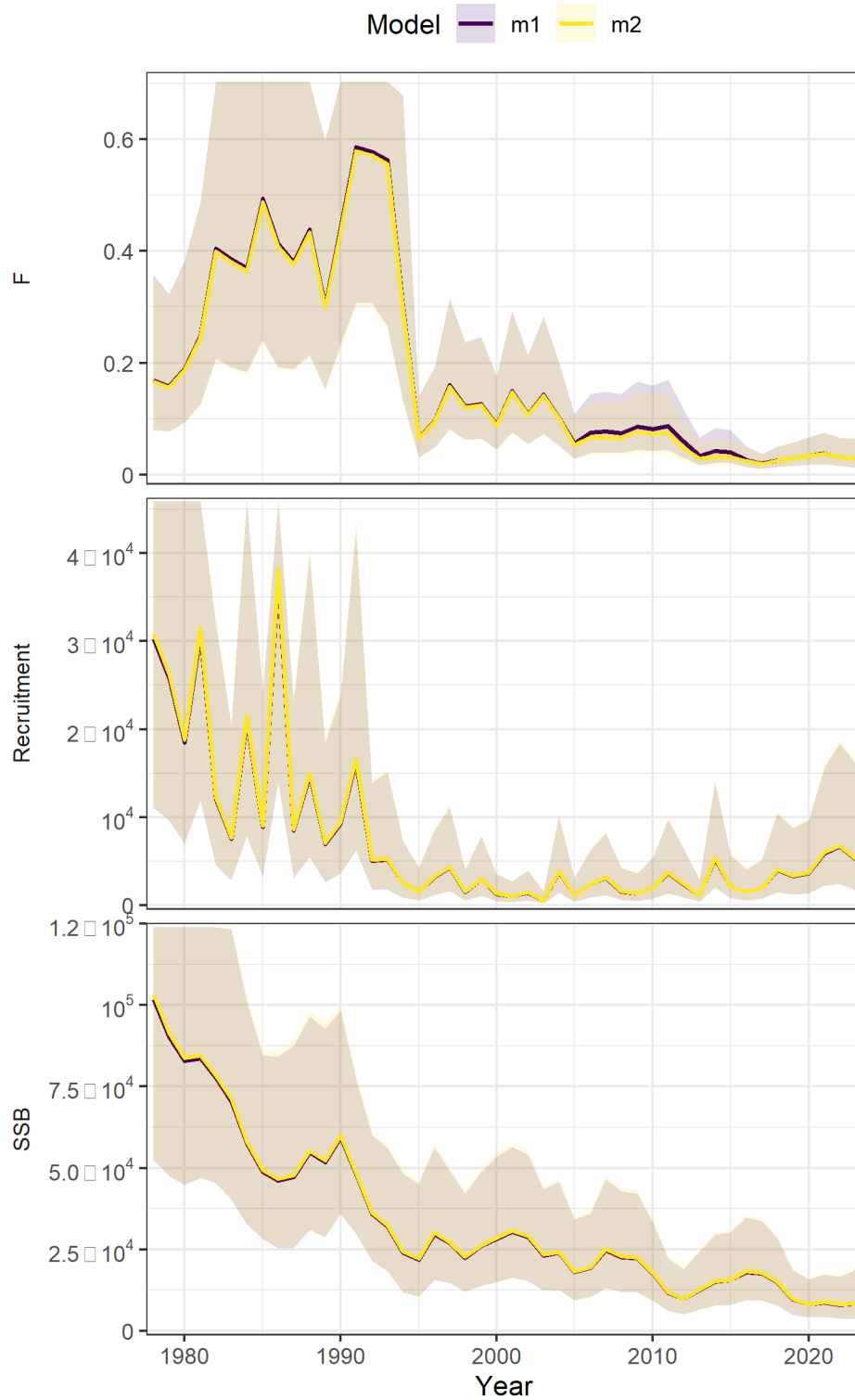


Figure 30. Comparison of model outputs for the EGB candidate model, including (m1 = Run 1 in Table 3) and excluding (m2=Run 4 in Table 3) the misallocated fleet. (SSB=spawning stock biomass, F=fishing mortality).

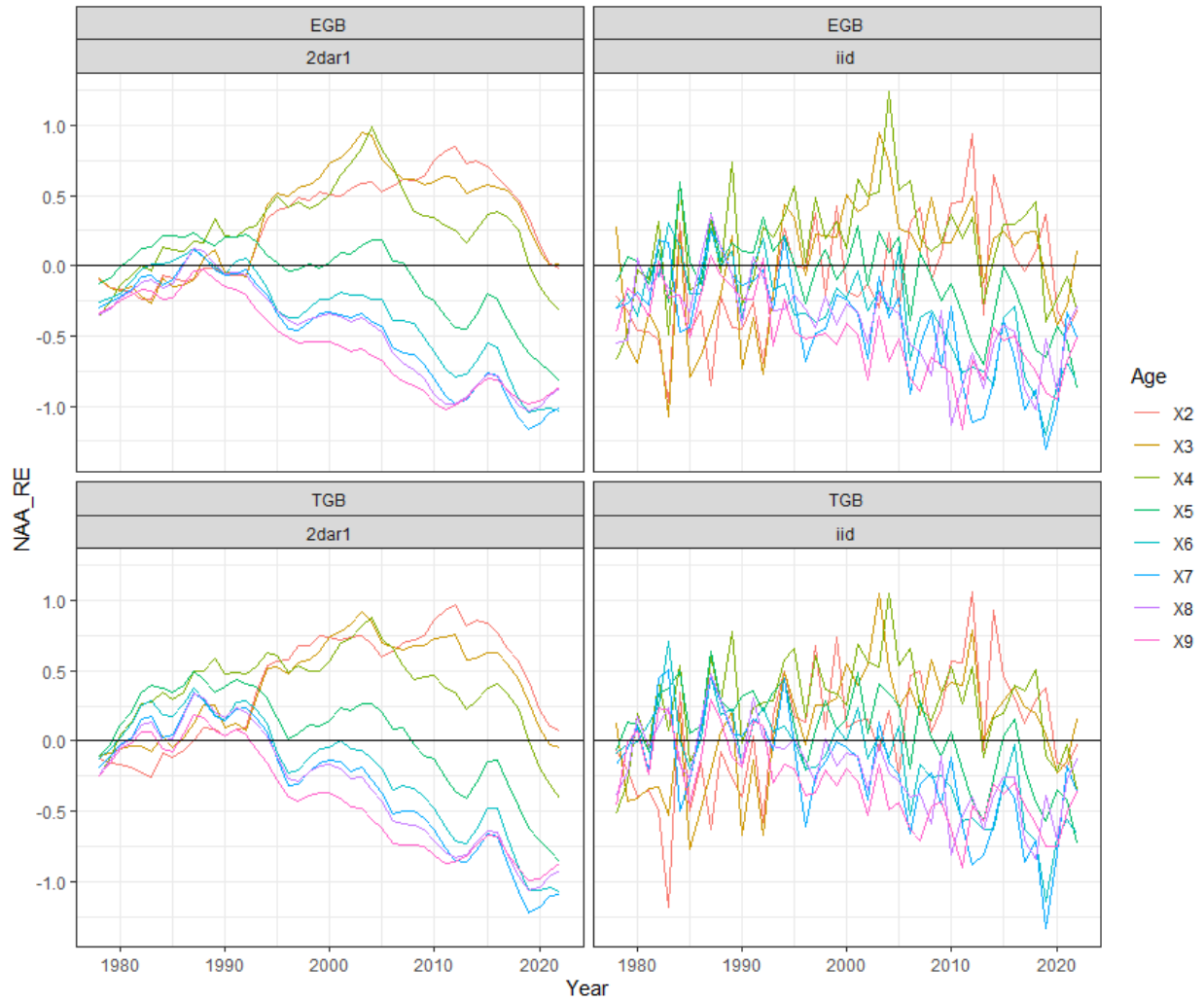


Figure 31. Process error on numbers at age (NAA\_RE) (colours) with a 2DAR(1) (left) and independent identically distributed (IID) (right) correlation structures imposed for the candidate eastern Georges Bank EGB (top row) and total Georges Bank (TGB) (bottom row) models. Model nomenclature shown in Table 3: EGB-2DAR(1) = Run 1, EGB-IID = Run 5, TGB-2DAR(1)= Run 6, TGB-IID = Run 9.

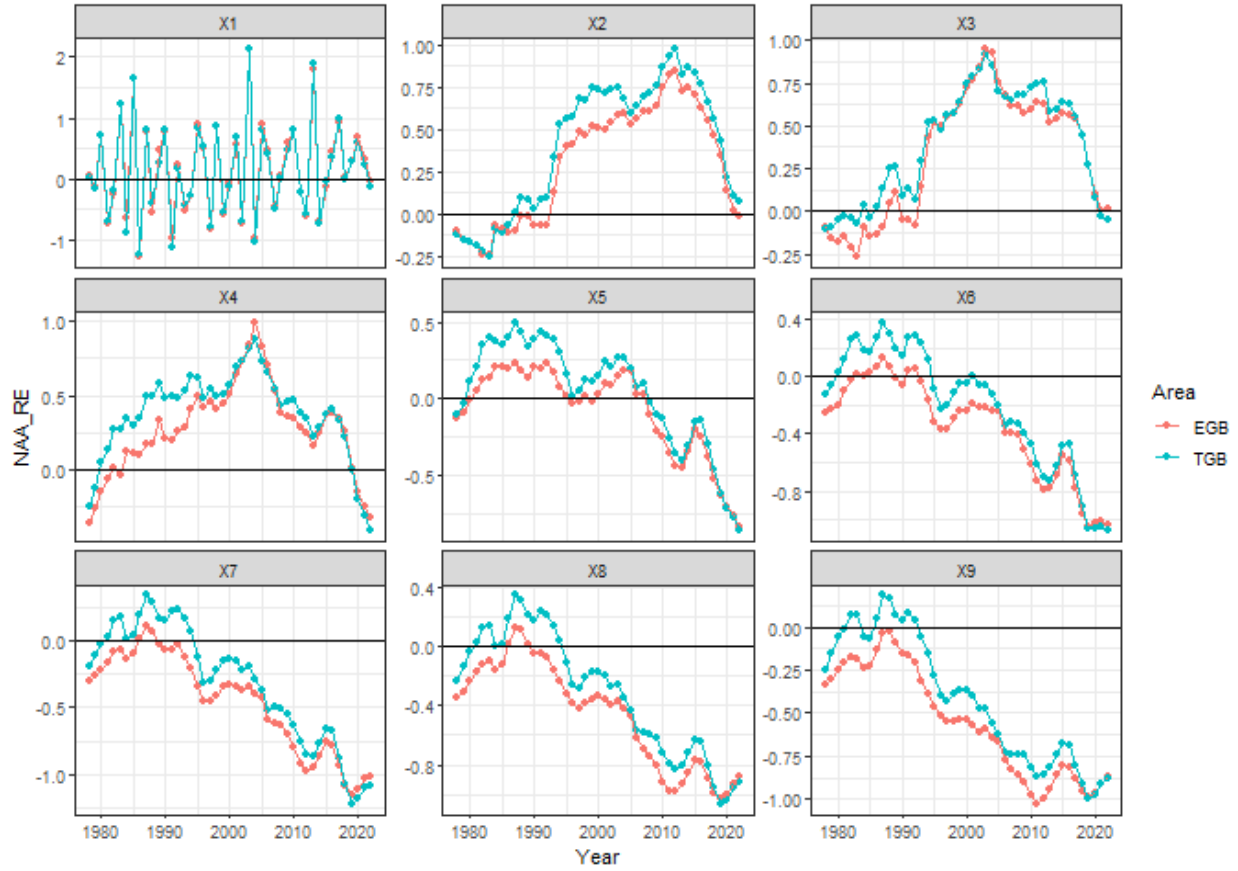


Figure 32. Process error on numbers at age (NAA\_RE) between the candidate eastern Georges Bank (EGB) (Run 1 in Table 3) and total Georges Bank (TGB) (Run 6 in Table 3) models with 2DAR(1) correlation structure. Facets indicate age.

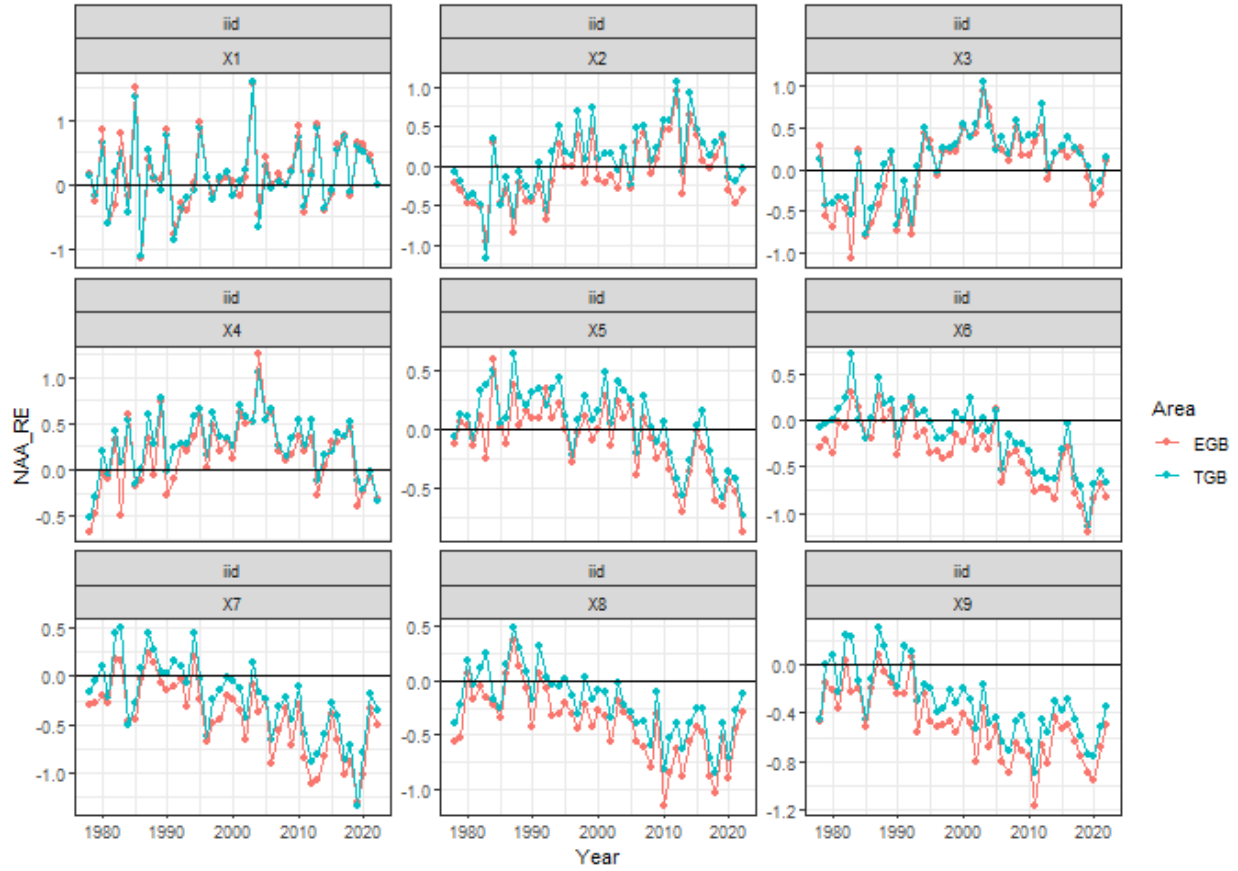


Figure 33. Process error on numbers at age (NAA\_RE) between the eastern Georges Bank (EGB) (Run 5 in Table 3) and total Georges Bank (TGB) (Run 9 in Table 3) models with independent identically distributed (IID) correlation structure. Facets indicate age.

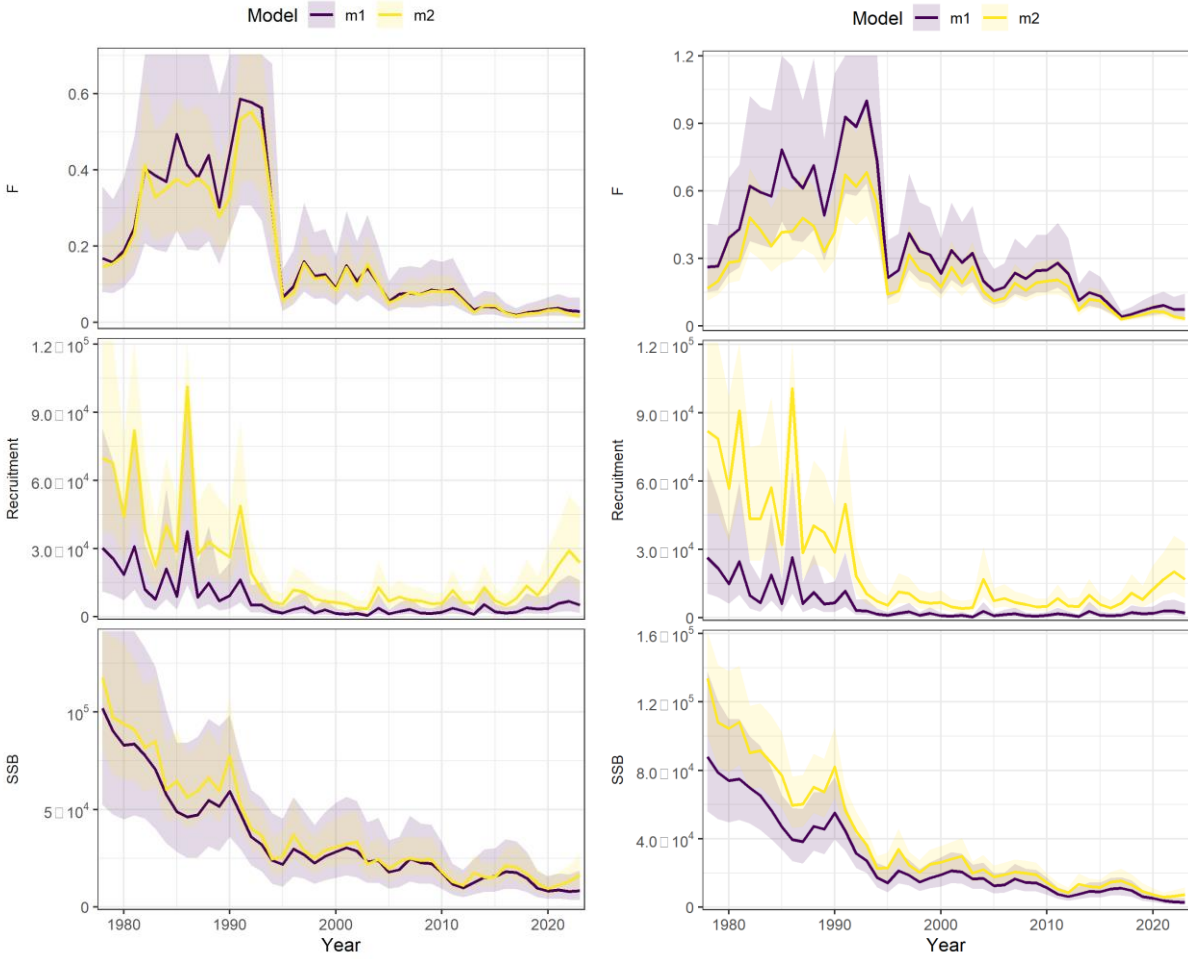


Figure 34. Population outputs from the eastern Georges Bank (EGB) (left column) and total Georges Bank (TGB) (right column) models using 2DAR(1) (m1) and independent identically distributed (IID) (m2) correlation structure on Numbers at Age Random Effects (NAA RE). Nomenclature link to Table 3: Left column m1 = Run 1 and m2 = Run 5; Right column m1 = Run 6 and m2= Run 9 (SSB – spawning stock biomass,  $F$  – fishing mortality).

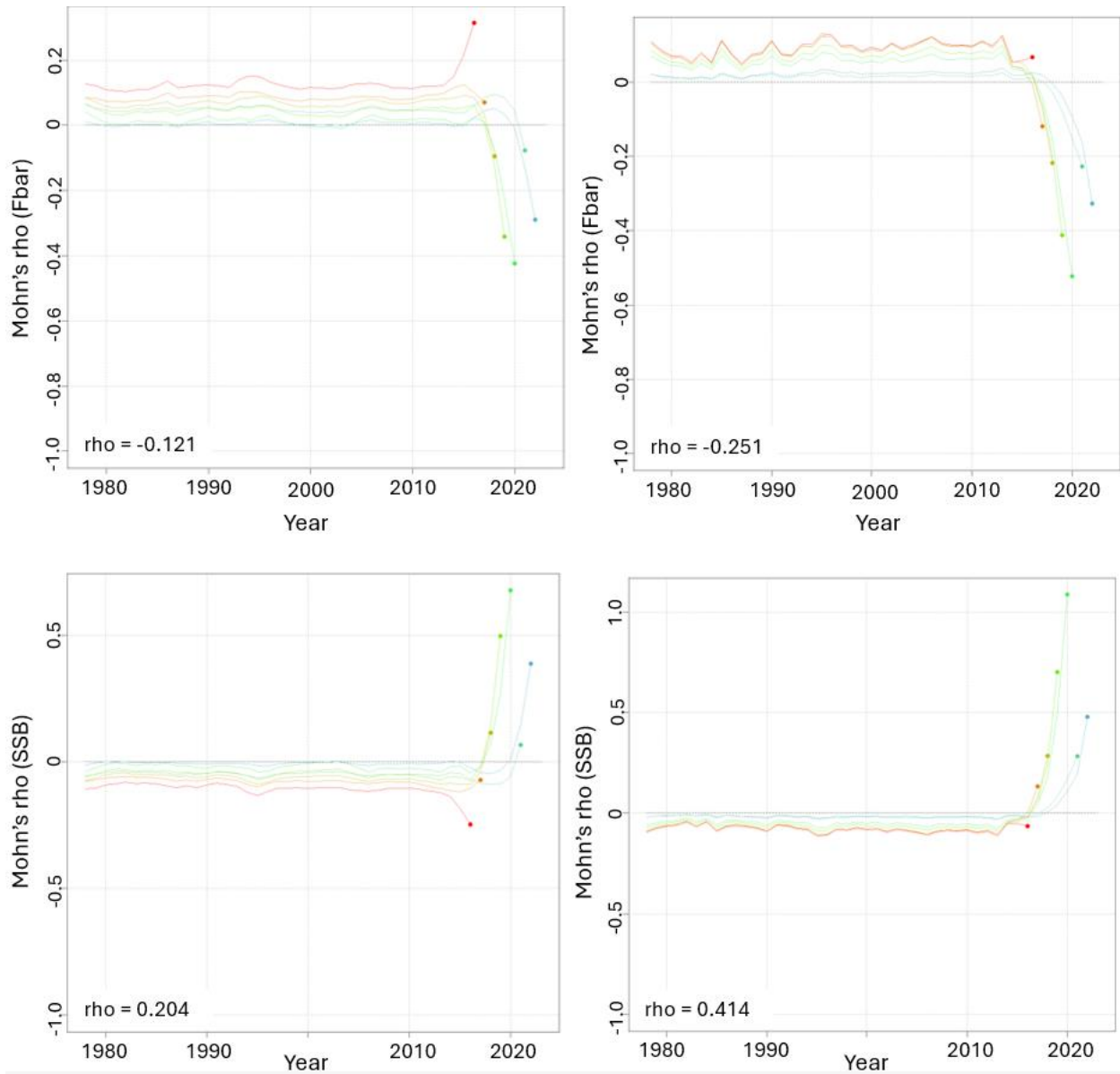


Figure 35. Annual Mohn's rho values (seven-year peel) on fully selected mean fishing mortality ( $F_{bar}$ ) (top row) and spawning stock biomass (SSB) (bottom row) for the eastern Georges Bank (EGB) model with 2DAR(1) (left column) and independent identically distributed (IID) (right column) correlation structure on process error. Nomenclature link to Table 3: Left column = Run 1; Right column = Run 5.

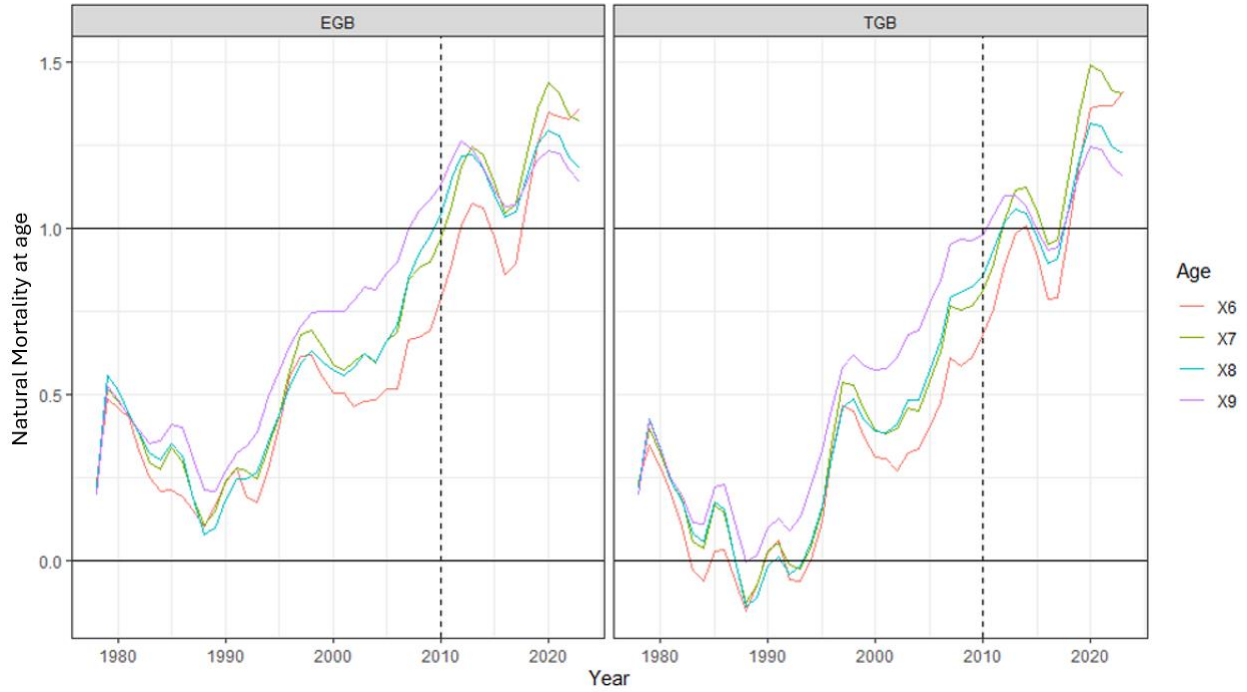


Figure 36. Estimate of natural mortality for ages 6+ (X6–X9) from eastern Georges Bank (EGB) (left; Run 1 in Table 3) and total Georges bank (TGB) (right; Run 6 in Table 3) candidate models if the NAA process errors were converted entirely to natural mortality.

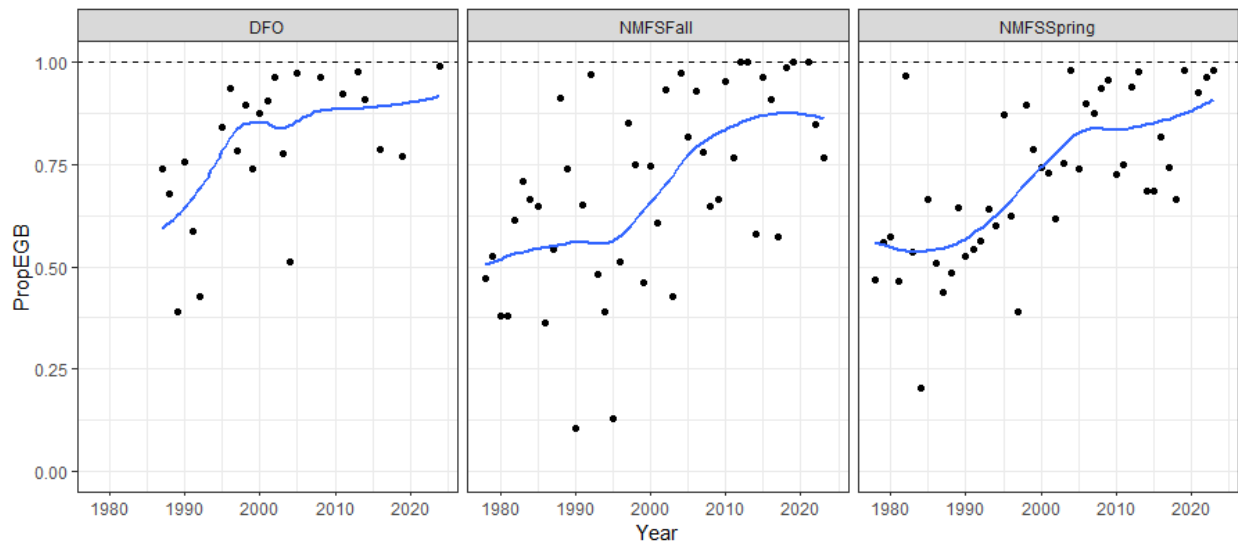
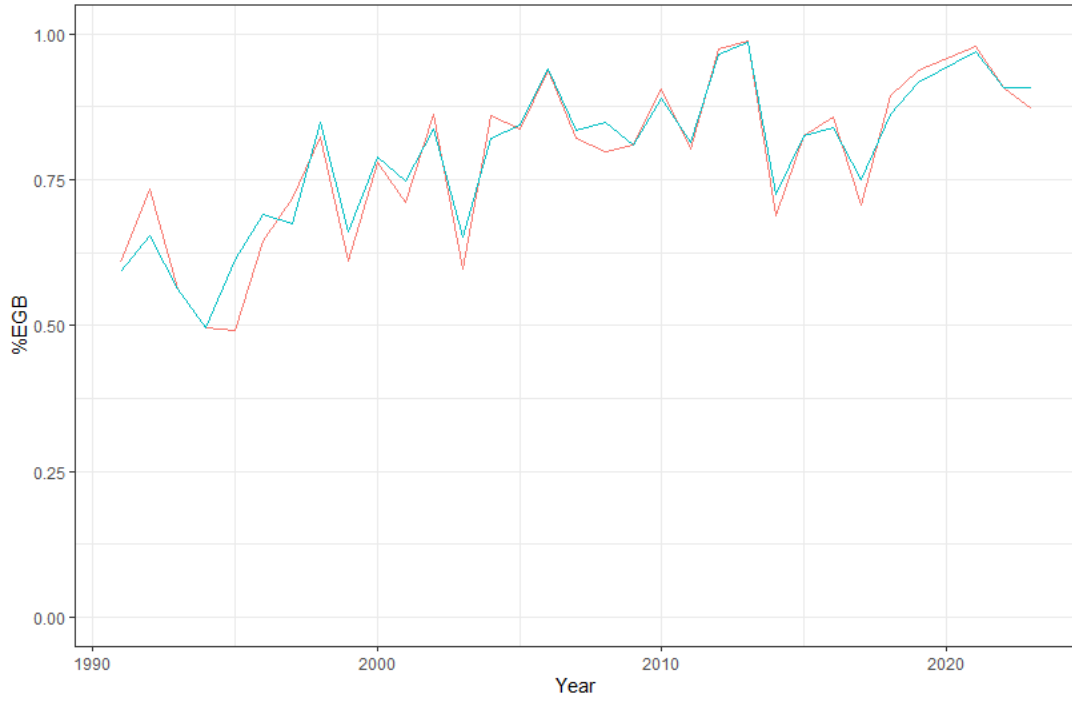


Figure 37. Annual proportion of total Georges Bank survey biomass on eastern Georges Bank EGB (PropEGB; black points). Blue line is a loess smoother applied to help show the trend. In the actual EGB/WGB allocation procedure, the loess is only applied once the surveys are averaged together. Black dashed line at top of panels represents 100%. DFO – Fisheries and Oceans Canada (DFO); NMFS – National Marine Fisheries Service



*Figure 38. Resulting average proportion of Cod survey biomass on eastern Georges Bank (%EGB) obtained by averaging the spring and fall seasons (red line) and averaging all three surveys (blue line).*