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Western Component Pollock Management Strategy Evaluation – Population Modeling, Operating Model Conditioning and Reference Points

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Foreword

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

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ABSTRACT

Pollock (*Pollachius virens*) in Northwest Atlantic Fisheries Organization (NAFO) Divisions 4VWX5 comprise two population components: a slower-growing Eastern Component including NAFO Divisions 4V and 4W, as well as DFO statistical units 4Xm and 4Xn, and a faster-growing Western Component (WC) including 4Xopqrs and Canadian portions of NAFO Division 5. The WC Pollock underwent a management strategy evaluation (MSE) in 2011. A review of the original MSE was initiated in 2022, and combined with a modeling framework review for this stock. This document constitutes the second half of this process, summarizing the science-led components of the MSE (changes to the population model, operating model conditioning, management procedure evaluation metrics and reference points) for WC Pollock.

INTRODUCTION

The Pollock stocks in the Maritimes Region are managed by Fisheries and Oceans Canada (DFO) under a two component structure. The eastern component (EC) currently has no analytical assessment, while the western component (WC) underwent an management strategy evaluation (MSE) process in 2011, resulting in a harvest control rule (HCR) used to provide Managers with annual total allowable catch (TAC) advice since then. The original MSE was intended to have a five year lifespan, with a revision scheduled for 2016. In addition, 2016 was the start of the development of an acoustic index for Pollock through a collaborative agreement with stakeholder groups, with the expectation that the acoustic index would be integrated into the revised MSE. The need to collect at least five years of data for the new acoustic index deferred the revision of the 2011 MSE until 2022.

The MSE process can accommodate multiple operating models (OMs) encompassing a range of uncertainties. As in 2011, if multiple combinations of stock dynamics are considered equally plausible for WC Pollock, the 2022 MSE can include a reference set (RS) of OMs that encompass those scenarios and account for associated uncertainty, against which candidate management procedures can be tested. In addition to the RS, sensitivity OMs that are less plausible than the OMs in the RS but yield useful information about the sensitivity of the OMs to certain parameters can be created. The sensitivity OMs are not used in evaluating the management procedures, and only exist for exploratory purposes.

The MSE undertaken in 2011 used a RS of six OMs with varying specifications related to the stock-recruitment relationship, bias correction, exclusion of the terminal survey point and levels of natural mortality (M); all were based on the existing virtual population analysis (VPA) assessment (DFO 2011a, DFO 2011b, Porter and Docherty 2011). The specifications were all tied to sources of uncertainty identified during the 2011 process, as described in Butterworth and Rademeyer (2011):

- Variability of research vessel surveys
- Changes in M over time
- Changes in partial recruitment/selectivity on older ages
- High variability in recruitment
- The stock-recruitment relationship (SR)

The review of the Pollock MSE has been completed through three CSAS meetings. The meetings conducted in March and May 2022 reviewed and updated the available data inputs and the population model for the MSE, respectively. The third meeting conducted in October 2022 finalized the operating models, reference points, exceptional circumstance triggers and options for providing advice for the eastern component of the management unit.

This document is the product of the May and October peer review meetings and builds upon the accepted population model for the WC Pollock (VPA model, Stephenson 2004), proposes stepwise modifications to the 2011 population model, and discusses various options for moving forward. In addition to the original VPA, this paper outlines parameterization for a statistical catch-at-age model, which is considered a more flexible alternative to the VPA. The comparison of outputs from the two modeling frameworks help identify aspects that are characteristics of the assumptions made in each approach, rather than the population dynamics. The original working paper presented all output figures from each model to allow participants attending the modelling review access to the outputs from each investigated model. Within this document, the list of figures was shortened to only include models E through J, which were discussed during the meeting.

The CSAS model review meeting in May 2022 concluded that the MSE OMs should be conditioned based on models I and K, although investigation of model performance under dome shaped selectivity was also requested. The OMs and management procedure testing was carried out using the openMSE package suite, specifically MSEtool (https://openmse.com/, Carruthers and Hordyk 2018).

POPULATION MODEL INPUTS

COMMERCIAL CATCH-AT-AGE

The commercial fishery catch at age (CAA) was calculated back to 1982, and is limited to ages 2 through 13 (Andrushchenko et al. 2025). This approach is consistent with the 2011 MSE, with no new information indicating that a change is required. Following the CSAS meeting in March 2022 to review data inputs, an error in the process of uploading the commercial fishery ages in recent years was identified. The issue revolved around an age adjustment made to the assigned age to account for a January birthday for fall otoliths with a hyaline. Erroneously, this age adjustment step was omitted for otoliths processed between 2017 and 2020. Once the error was identified, the otoliths were re-aged, the adjustment was applied, the data re-loaded, and the commercial catch at age updated. All subsequent figures and tables (e.g., Figure 1, Table 1) use the corrected ages.

SURVEY INDICES OF ABUNDANCE

The RS of OMs for the 2011 MSE was based on a VPA run that was tuned to age-specific indices of abundance from the DFO Maritimes Region Summer Ecosystem Research Vessel Survey (summer RV survey). These were the area-weighted averaged mean number at age per tow for ages 3 through 8, starting in 1984 and ending in 2009, which have now been expanded to 2020 (Andrushchenko et al. 2025). The availability of the 2021 survey data requires the future calculation of conversion factors due to a change in both vessel and gear in 2021. Given the broader range of ages available in the survey in recent years, the ages included in the index can be expanded to match those in the commercial catch (ages 2–13); a modification agreed to during the review of data inputs in March 2022.

A second modification from the approach taken in 2011 is the inclusion of an acoustic biomass index as a second tuning index. Although this is a relatively short time series (2012, 2016 to present), it is expected to account for the semi-pelagic nature of Pollock by estimating the biomass throughout the whole water column, and not just along the swath of the bottom trawl. The two tuning indices can also be weighted by the coefficient of variation (CV), giving greater weight to the more accurate acoustic index, although estimates of CV are not currently available for the acoustic index.

Finally, the 2011 MSE used a mean number per tow in lieu of total abundance within the WC area since no summer RV survey coverage of Eastern Georges Bank (EGB) existed at that time. This approach was adopted at the 2004 Framework and allowed the assessment to function under the assumption that the Pollock trends in NAFO Division 5Z did not substantially differ from those in NAFO Division 4X; using a total biomass index for only DFO statistical areas 4Xopqrs5Y would underestimate the population by excluding the 5Z strata. Considering stakeholder comments, fishery trends and recent coverage of EGB in the summer RV survey, it was apparent the assumption of homogeneity may be false. Since 2016, the summer RV survey has sampled EGB strata and is expected to continue to do so in the future, making the generation of a relative index of abundance-at-age for all of WC Pollock (4Xopqrs5) possible moving forward. Switching to a relative index of abundance spanning the whole area requires missing EGB strata prior to 2016 to be accounted for, which is currently not possible without assuming that Pollock trends in NAFO Division 5Z have mirrored those in NAFO Division and DFO statistical areas 4Xopqrs5Y. During the CSAS meeting in March 2022, an approach simulating a historic EGB Pollock index based on National Marine Fisheries Service (NMFS) and DFO surveys was presented and approved for further development to address this issue.

Eastern Georges Bank Index

The summer RV survey did not have consistent spatial coverage within EGB over time (Figure 2, Figure 3). To derive a survey index for EGB, Pollock population abundance was modeled by integrating multiple surveys within or close to the region, including the DFO Maritimes Region Winter Ecosystem Research Vessel Survey (winter RV survey) (February and March), the summer RV survey (June to August), and the NMFS spring survey (March to May). Although the timing and spatial coverage of these surveys vary annually, it is assumed they are similar in space and time to provide shared information on the underlying population (Figure 2, Figure 4). The assumption that population signals remain detectable and consistent over that time and space is fundamental to this approach.

Model Description

A generalized linear mixed model (GLMM) was used and catch number per tow, Y, is assumed to follow a zero-inflated negative binomial distribution, where zero-inflation is allowed to vary for each stratum, and dispersion depends on the survey vessel. Prediction for Y, denoted as u, is modeled as

$$\log(u) = year + survey + \varepsilon_1(stratum) + \varepsilon_2(year, stratum, survey) + f,$$

where log is the natural logarithm, year and survey are fixed effects (the survey effect incorporates both seasonal differences in population and vessel differences in catch efficiency as the two are confounding factors), ε_1 is a random stratum effect that includes between-strata correlation, ε_2 is an additional random effect to allow for potential spatiotemporal variations related to the survey effect, and f is an offset term to standardize tows based on swept area (including both tow distance and opening of the trawl). The GLMM was fit to catches from the three surveys during 1983–2020. The study area was restricted to the summer RV survey strata 480–485 and winter RV survey 5Z1, 5Z2, and 5Z9; EGB includes strata 5Z1, 5Z2 and 5Z9, but data in adjacent 4X strata (480–485) were included to optimize overlap in survey coverages (Figure 5, Figure 6). For the US dataset, this spatial approach amounts to tows occurring in Management Area 551–-552 (EGB) and 462–468 (4X, Figure 7).

Diagnostics and output

Residual diagnostics provided by the R DHARMa package (Hartig 2020) indicated a reasonable model fit where DHARMa quantile residuals did not show significant patterns (Figure 8). Mean number per tow for strata 5Z1, 5Z2, and 5Z9 was estimated for a standard summer RV survey tow (with a tow distance of 1.75 nm and a trawl opening of 41 ft). Estimation uncertainty was generally high (Figure 9), but expected considering data sufficiency and quality due to the lack of coverage, and efficacy of the bottom trawl survey at catching Pollock. Population abundance for each stratum was calculated by scaling the estimated mean catch per tow to total trawlable area, and a total abundance index for EGB was subsequently derived (Figure 10).

Generating Indices at Age

In lieu of modeling indices at age, an assumption of accompanying length frequency was made with respect to modeled total abundance. The available empirical length frequencies were examined across seasons and between areas in each year; within each year-season-area combination the length frequencies were standardized to their respective means to remove the effect of magnitude. In the DFO dataset, comparisons could be made across season (EGB winter to EGB summer) and across region (4X summer to EGB summer, Table 2) for the years where full coverage of EGB strata in summer is available (2016, 2017, 2019, and 2020). With the addition of the US survey data, the comparison of length frequency could be made across season (EGB winter to EGB summer), but the unquantifiable difference in the effect of net selectivity on size was expected to have an impact based on expert opinion (pers. comm. D. Clark). To avoid confounding impacts of the catchability by US trawl on the size frequency of the catch, particularly prior to the gear change in 2009, this analysis was limited to DFO data only.

For consistency with regular processing methods of survey data, length frequency distributions were calculated at 3 cm bins. Comparisons were made by first scaling the length frequency distribution of each area and season dataset within a given year by its total number (Scaled Number at $\text{Length}_{y,s,a}$ = Number at $\text{Length}_{y,s,a}$ / Total $\text{Number}_{y,s,a}$), and overlaying the length frequencies for each year, season, and area combination (Figure 11, Figure 12).

A comparison of length frequencies between the EGB and 4X areas during the summer shows that although the length frequencies are similar in 2016 and 2017 (Figure 11), they differ notably in 2019 and 2020, and this difference is not driven by low sample size (Table 3). A comparison of EGB winter and summer seasons indicate length frequencies are similar in all years except 2016 (Figure 12), which had a relatively low number of fish sampled, indicating that the difference may be a consequence of low sample size (33, Table 3). In years with sufficient sampling (>50 fish), winter length frequency data was substituted for missing EGB summer length frequency data. In cases where the EGB winter RV survey data are not available (1984–1986) or the number of fish sampled on EGB in the winter is < 50 (eight years, Table 3), the summer length frequency data from NAFO Division 4X was used. As EGB and 4X length frequency distributions are not always consistent, even when a high number of fish are measured, the substitution of 4X data occurred in the eight years where no viable alternative was available while respecting the area boundaries (Figure 13, Figure 14). This substitution does introduce additional uncertainty into the final indices at age; however, an alternative was not identified.

The length frequencies were applied to the predicted total abundance or biomass by calculating a scaling factor for each year and measurement unit (number of fish or kgs, Figure 15). This approach could be further improved by propagating the error from the modeled biomass or abundance estimate through to the indices at age, but this was not done at this time due to time constraints.

The above approach generates indices of abundance and biomass at length for EGB; to generate indices at age, an age length key is applied. A change in growth, starting in the 2010 year class was identified during the CSAS meeting in March 2022 (Andrushchenko et al. 2025). Consequently, the age-length key (ALK) can be modeled as two aggregate keys, one spanning the older time period (1983 year to 2009 cohort) and a second one spanning the more recent time period (2010 cohort to current). The use of aggregated time periods would ensure high sample sizes for each ALK; however, it would mask progression of year classes in a given year. The annual empirical length-at-age (LAA) matrix for 4Xopqrs5Y was used to simulate the EGB age-specific indices. The downside to using an annual empirical LAA matrix is the presence of missing values, which accounts for < 1% of the total number of fish measured; in this case, missing ages were supplemented with the aggregated period-specific ALK, as required. In addition, Pollock ages from the winter survey on EGB are currently only available since 2012 and do not show a difference in growth between winter EGB and summer 4X (Figure 16, Figure 17). This application of the ALK assumes no difference in growth between winter EGB and summer 4X Pollock throughout the 1990s and 2000s, for which there is currently no empirical evidence. The resulting abundance indices at age for EGB are presented in Table 4.

Finally, a performance test was administered to the simulated EGB indices at age by comparing them to the actual EGB Pollock indices at age from the four years that the bottom trawl survey covered EGB (2016, 2017, 2019 and 2020). In general, the simulated and the actual EGB indices agreed in both magnitude and inter-annual trend, except for ages 8 and 13 in 2017 (Figure 18). Considering the assumptions involved in generating the simulated EGB index and the subsequent disaggregation into ages, this approach yielded a predicted index with surprising consistency to the observed values.

Since the 2004 Framework, WC Pollock stock assessments have operated under the assumption that Pollock trends in NAFO division 5Z have were identical to those in NAFO division and DFO statistical area 4Xopqrs5Y. The simulation of historic EGB indices indicates this assumption is generally correct, with only the most recent time period showing a consistent divergence between the two areas (Figure 19). The disappearance of older fish from the survey catch throughout the 2000s is less apparent due to the inclusion of the simulated EGB index i; an effect driven by the use of EGB winter length frequencies in simulating the data (Figure 14).

The abundance-at-age indices for WC Pollock used in the models below are reported in Table 5, with the actual EGB indices included in lieu of simulated ones for 2016, 2017, 2019 and 2020.

MATURITY

The 2011 MSE assumed the spawning stock biomass (SSB) constituted ages 4+ Pollock. Additional data since the 2011 MSE indicate age-at-50% maturity may have increased since the 1980s to present; however, > 75% of the fish are still mature at age 4 (Andrushchenko et al. 2024). The maturity dataset is limited and therefore, insufficient information exist to suggest a change in the definition of SSB.

CATCH PER UNIT EFFORT

A catch per unit effort (CPUE) tuning index was incorporated into the Pollock assessment up to and including the 2004 framework, but due to problems with the index, it was not updated in subsequent years. For unclear reasons the index was used in the 2011 VPA, spanning ages 3 through 8 and years 1982 through 2004. The useability of this index has been questioned over the years, and it was concluded at the Data Inputs meeting in March 2022 that it be excluded from future model runs for WC Pollock.

NATURAL MORTALITY

During the 2011 MSE, M was assumed to be stationary across the time series, with five of six reference OMs using 0.2 for all years and ages (Rademeyer and Butterworth 2011). One OM had a higher M on ages 5+ starting in 1996, making it the most pessimistic of the OMs (Rademeyer and Butterworth 2011). Data reviewed in Andrushchenko et al. (2024) suggest that models be parameterized to allow a change in M over time since the assumption of a stationary M is difficult to support empirically.

Total mortality (Z) information is highly variable; however, the catch-curve analysis and Sinclair Z suggests a change in the level of Z throughout the 2000s for Pollock aged 5–7

(Andrushchenko et al. 2024). The disappearance of older fish in both the survey and fishery catch-at-age throughout the 1980s and 1990s, followed by their re-appearance throughout the 2000s supports a change in Z between the two time periods for fish aged 8+; this argument was also employed when justifying the 2011 OM with higher M (Rademeyer and Butterworth 2011). Since 2010, the catch-curve analysis suggests a return to a relatively high level of Z on ages 5–7, which Sinclair Z does not support.

The trend in relative fishing mortality (F) is highly variable over time, but it generally indicates a high level of F before 1995, and a relatively low level of F since then, which in combination with the trends for total mortality, suggests that M be estimated by the model in three time periods (pre-2000, 2001–2010 and 2011+), for three age groups (Ages 1–4, Ages 5–7 and ages 8+).Given the high level of relative F in the early time period, the assumption of a fixed M of 0.2 across all ages before the 1994 is also plausible. Variability in relative fishing and total mortality trends across methods allows for ambiguity around the exact ‘break-year’ between time periods (i.e., 1996 for relative F, 2002 for Z).

Departure from an assumption of stationary M over time and age would signify a substantial change from the 2011 approach.

FISHING MORTALITY

During the 2011 MSE, the VPA assumptions focused on the F on the oldest ages within a given year. In general, F on age 12 was assumed to be a number-weighted average of Fs on 9–11. For years when there were no fish at younger ages (i.e., 2009), the F was assumed to be the number-weighted average of the previous two available ages. This assumption is retained for the updated VPA runs.

WEIGHT-AT-AGE

Given the shifts in both LAA and weight-at-age (WAA) over time (Andrushchenko et al. 2024), their use in the MSE warrants discussion. For the population model, the WAA inputs are used to convert total abundance to total biomass. The conversion of total abundance to biomass during the historic years (1982-2010) was not detailed in the 2011 MSE; however, it is assumed that an annual WAA matrix based on available empirical data was used. Missing values within the WAA matrix can occur for older fish, and these gaps were addressed by averaging the weight for that age from the preceding and subsequent available year. This approach captures shifts in WAA over time and the treatment of WAA data in MSE projections are discussed below.

The WAA from the summer RV survey is considered a mid-year value. Since the modeled abundance-at-age values are considered beginning-of-year estimates, the mid-year WAA values were back-calculated to a beginning-of-year WAA following the method outlined in Rivard (1982).

MATURITY

In the 2011 MSE, the maturity-at-age was assumed to be zero for Pollock aged 1 to 3, and increased to 1 for ages 4+ (Rademeyer and Butterworth 2011). Although there is a slight shift in age-at-50% maturity from 3.22 to 3.37 years (Andrushchenko et al. 2024), the increase is not drastic enough to move the assumption of 100% maturity to an age older than 4. Data scarcity further complicates this, as the current dataset only represents samples of maturity from the 1980s and the 2010s (Andrushchenko et al. 2024).

VIRTUAL POPULATION ANALYSIS

The 2011 OMs were conditioned on a base formulation of a VPA that used the ADAPT software (Porter and Docherty 2011). The VPA uses the size and age composition of the commercial catch and is calibrated with trends in abundance-at-age from the summer RV survey and a CPUE index (Mohn and Cook 1992, VPA/ADAPT Reference Manual, Porter and Docherty 2011). Computational formulae used in ADAPT are described in Rivard and Gavaris (2003).

This work is a revision of the 2011 MSE, and starts the model examinations by replicating the final 2011 VPA formulation with data sources updated to the most recent available year. In subsequent steps, the modifications that received consensus at the data inputs meeting in March 2022 (Andrushchenko et al. in press) are gradually introduced. The performance of each model formulation was assessed by examining the major outputs (recruitment, F, SSB), the visual examination of residuals, the sum of the residuals across time and age, the standardized deviation of the normalized residuals (SDNR, Francis 2011), and mean residual sum of squares metrics (MRSS). A five and seven year retrospective analyses was also completed on the final candidate models.

The SDNR statistic is calculated by dividing the standardized deviation of normalized residuals by the sampling standard deviation (Francis 2011, Porch 2018). Simulation studies have shown it can detect model misspecification related to selectivity (Carvalho et al. 2017), which was identified as a source of uncertainty in the 2011 MSE and discussed during the data inputs meeting (Andrushchenko et al. 2025).

The MRSS consists of calculating the standardized residual sum of squares (RSS) for each index and dividing it by the sample size (n) derived from the number of years and ages within each index. This is an additional metric that measures the size of the residual deviation, while the SDNR and the sum of residuals' show the overall tendency. The ADAPT framework provides a mean square residual metric, which is reported here, although the calculations are not clearly explained in Rivard and Gavaris (2003). The visual examination of residuals remains the most reliable method of identifying blocks or patterns, as various tests for randomness in a time series have been found to be unreliable (Carvalho et al. 2017).

Based on various simulation studies, this list of diagnostics is expected to detect model misspecifications related to the observation model, as well as time-varying biological parameters (Legault 2009, Carvalho et al. 2017). Additional performance metrics focusing on misspecifications of system dynamics (i.e., ASPM), were not performed due to time constraints.

The original working paper presented during the May 2022 meeting included the detailed outputs of each model run.. Following the meeting, the final research document was reduced and only contains information relevant to key discussion points.

MODEL A – NO MODIFICATIONS FROM 2011

Parameterization

The formulation of the 2011 VPA was followed, as detailed in Appendix 4A of Porter and Docherty (2011). The 2011VPA Base Model formulation accepted for the 2006 and 2008 assessments, and updated during the 2010 run, used the following datasets:

> $C_{a,t}$ = commercial fishery CAA for ages a = 2 to 13, and time t = 1982–2010, where t represents the year during which the catch was taken.

$I_{1,a,t}$ = survey indices for ages a = 3 to 8, and time t = 1984.5, 1987.5… 2009.5 2010.5,where the index is assumed proportional to the population with the following relationship:

$$I_{a',t} = q_{a'} P_{a',t}$$

where a' represents age, t represents year, $I_{a',t}$ represents is the index for age a' at time t, and $P_{a',t}$ is the population for age a' at time t.

$I_{2,a,t}$ = CPUE indices for ages a = 3 to 8, and time t = 1982.5, 1983.5… 2004.5. where the index and the population are assumed to have a power relationship, implying hyperstability conditions (Rivard and Gavaris 2003):

$$I_{a't} = q_{a'} P^{\alpha}{}_{a',t}$$

The 2011 VPA run calculated the population to the fall of 2010 (2010.67), with both the survey the CPUE indices designated as occurring mid-way through the year (i.e., 2010.5). The truncated CPUE series excluded 2005–2010, years that had more restrictive quota and fewer Pollock-directed trips, and were considered to be unrepresentative of abundance trends.

During the 2004 framework assessment, it was concluded that the catch rate series was useful as a tuning index to dampen the year effects apparent in the RV series (Stephenson 2004). After 2004, the CPUE series had very little influence on the model results and tuning was based on the RV indices. To remain consistent with the 2011 approach, the 2022 VPA uses the truncated CPUE time series (1982–2004), while the CAA and RV indices were updated to 2020. Although the commercial fishery CAA could be updated to 2021, the absence of a useable 2021 summer RV survey index resulted in 2020 being the terminal year in the model. Model A inputs are summarized as:

$C_{a,t}$ = commercial fishery CAA for ages a = 2 to 13, and time t = 1982–2020, where t represents the year during which the catch was taken.

$I_{1,a,t}$ = survey indices for ages a = 3 to 8, and time t = 1984.5, 1987.5… 2019.5 2020.5, with the proportional assumption on the relationship between the index and the population.

$I_{2,a,t}$ = CPUE indices for ages a = 3 to 8, and time t = 1982.5, 1983.5… 2004.5, with a power relationship assumed between the index and the population.

The ADAPT framework is described in detail in Rivard and Gavaris (2003); however, relevant highlights are summarized here. The ADAPT framework assumes that observation errors for the catch-at-age data are negligible. Observation errors for the abundance indices at age are assumed to be independent and identically-distributed after taking natural logarithms of the values. Zero observations for abundance indices were treated as missing data, as the logarithm of zero is not defined.

The ADAPT framework minimizes the objective function, as described in Rivard and Gavaris (2003):

$$\sum_{s,a,t} \left(lnI_{s,a,t} - \left(\hat{\kappa}_{s,a} + v_{a,t} \right) \right)^2$$

where s refers to the survey or the CPUE, at age a during year t and the estimated parameters are:

$v_{a,t} = ln(N_{a,t})$ for survivors being estimated at age a and year t

$\kappa_{s,a} = ln(q_{s,a})$ for each age specific index, s

The outputs are provided as start of year estimates (2020.0 = Jan 1, 2020), but tuning indices and catch are assumed to occur mid-year (2020.5 = Jun 1, 2020). The difference throughout the year (Δt) is accounted for by the following:

$$N_{a+\Delta t,t+\Delta t} = N_{a,t} e^{-\left(F_{a,t}+M_{a,t}\right)\Delta t}$$

The Pollock-specific formulation of Model A closely followed the VPA set-up from 2011 (Appendix 4A of Porter and Docherty 2011). In the earlier part of the time series (1982–1993), terminal year F was calculated based on the number-weighted average of the preceding three ages (F12 = F9_10_11). The abundance at age 13 was assigned a small value (1) for years 1995–2010, which was thought to be appropriate with the disappearance of older fish from the population during that time. Since 2010, the age range of both the survey and commercial catch-at-age have expanded (Figure 1, Figure 20). To avoid artificially deflating the population by setting abundance at age 13 low, the recent time period was parameterized by making an assumption on F for the oldest age being equal the number-weighted average of the previous two years, similar to the 1982–1993 time period.

Finally, in the terminal year for the 2011 VPA, abundance was estimated for ages 3–8 but set as 1 for ages 10–12. Setting the abundance at older ages to a low number was deemed appropriate in 2010 as older fish were absent from the survey and fishery catch, but applying the same approach to the 2020 VPA terminal year is problematic as the older fish have appeared in both the survey and fishery catch in recent years. To avoid artificially deflating the population and forcing the model to be inconsistent with the survey tuning index in recent years, the abundance-at-age was estimated for ages 3–9 in the terminal year and set as the average of the previous three years for ages 10–12 (2020.67). Abundance at age 2 in the terminal year was set as the average of the preceding three years, though this number does not have a big impact on the population model.

Outputs

The fit of Model A to the summer RV survey and CPUE tuning indices is shown in Figure 21 and Figure 22. Compared to the summer RV survey, the model tends to over-estimate most ages at the beginning of the time series (1984–1987) and again from 1997–2002, followed by a block of positive residuals across most ages from 2006–2009 (Figure 21, Figure 23, Table 6). The over-estimation of abundance at age early in the time series is also evident when examining the CPUE residuals (Figure 22, Figure 24, Table 6), implying that this trend was likely driven by the commercial catch at age. The residual patterns seen in Model A (Figure 23) are consistent with those in both the 2010 model run (Porter and Docherty 2010, Appendix 4a, Figure 25) and an earlier 2006 model run (Stone et al. 2006, Figure 23), indicating that these were considered acceptable for this model in the past.

The summary residual statistics for this model are reported in Table 7**,** with separate values reported for each tuning index**.** A good model fit is characterized by an SDNR close to 1, a residual sum close to 0 and a low MSSR. In the case of Model A, both the SDNR and sum of residuals are above 3 for the RV survey and just below 0 for the CPUE index.

The main recruitment (Rec2), F, and SSB outputs of this model are shown in Figure 26. The SSB is calculated by multiplying the model-estimated start of year abundance-at-age by the empirical start of year weight-at-age, and summed across ages 4+. In general, Model A shows a decrease in biomass from a peak in the late 1980s throughout the 1990s, with the biomass oscillating at around 10,000 mt since 2007 (Figure 26). Note that the recent decrease in empirical weights-at-age observed in both the survey and the fisheries catch is reflected by a slight decrease in biomass in recent years, despite the presence of a relatively strong year class in the population (Figure 27). In addition, the abundance-at-age for the resulting population shows very strong 1979 and 1980 year classes (Figure 27) that primarily drive the increase in population SSB in the late 1980s (Figure 26). Discussions with fishermen active during this time confirmed the presence of very large year classes in the late 1970s.

The F-at-age outputs from Model A show an unexpectedly high F across the older ages in 2012, 2013 and 2018, caused by the presence of age 13 fish in the fishery CAA in those years (Figure 27). The model-based survey selectivity in Model A continues to show that fish are fully selected to the survey at age 8, which is similar to the outcome of the 2011 run and continues to be inconsistent with the model-independent selectivity curve estimates for the survey (Figure 25).

The parameters estimated by Model A refer to the catchability (q) for the summer RV survey index assuming a proportional relationship (Table 8) and q and α for the CPUE index, which assumes a power relationship (Table 9). Although the parameters estimated in Model A for the summer RV survey index show an acceptable level of relative error and bias, those attributed to the CPUE index show a high level of relative error (> 50% for all ages) and relative bias (> 0.5 for all except Age 8). It is unclear whether this poor performance was discussed at the 2004 Framework or at the 2011 MSE, but given the similar performance of Model A across all other indicators to the model run for both of those processes, these issues were likely present in the 2011 run and are not a function of the data update.

MODEL B – EXCLUSION OF CPUE

Parameterization

The parametrization of Model B is a step-wise progression from Model A, but excludes the CPUE index. The CPUE index was included in the 2000 and 2004 frameworks as it was expected to dampen the year effects of the summer RV survey (Stephenson 2004). In subsequent assessments, however, the CPUE index was not updated past 2004 based on stakequolder comments about significant changes in the fishery, particularly the restrictive quota during that time period (Stone et al. 2006).. The inputs for Model B are:

> $C_{a,t}$ = commercial fishery CAA for ages a = 2 to 13, and time t = 1982–2020, where t represents the year during which the catch was taken.
>
> $I_{1,a,t}$ = survey indices for ages a = 3 to 8, and time t = 1984.5, 1987.5… 2019.5 2020.5.

The specifics of the formulation with respect to M and assumptions on oldest age abundance and oldest age F mirror that of Model A.

MODEL C – EXPANSION OF THE SURVEY INDICES TO AGES 2–13

Parameterization

The parametrization of Model C is a step-wise progression from Model B, but expands the range of ages in the summer RV survey index from ages 3–8 to ages 2–13. The initial decision to restrict the age range was in response to uncertainty about the survey selectivity on older ages (Stephenson 2004), as the older fish disappeared from the survey CAA throughout the late 1990s and early 2000s (Figure 20). In recent years, however, the age structure of the survey indices has expanded, indicating that the disappearance of fish may not be tied to survey selectivity, but is a reflection of trends in the population. Consequently, the inputs for Model C are:

$C_{a,t}$ = commercial fishery CAA for ages a = 2 to 13, and time t = 1982–2020, where t represents the year during which the catch was taken.

$I_{1,a,t}$ = survey indices for ages a = 2 to 13, and time t=1984.5, 1987.5… 2019.5 2020.5.

With the inclusion of the additional ages, the relationship of survey selectivity between the various additional ages (i.e., 2 and 9–13) needs to be identified. In previous approaches, the selectivity on each age between 3 and 8 was considered independent of adjacent ages. In the ADAPT framework, it is possible to link multiple ages together, forcing a common selectivity between them and a flat-top selectivity for a tuning index (Rivard and Gavaris 2003).

Catchability is determined by the presence of fish in the trawl path and the ability of the survey gear to capture them. A flat top selectivity curve assumes that larger fish are available to the survey gear and are retained by it once they are of a certain size, while a dome shaped selectivity assumes that larger fish are either unavailable to the survey gear (e.g., they move higher in the water column) or the survey gear is less effective at retaining them as compared to smaller fish (e.g., larger fish outswim the net). The absence of a tuning index for ages 9–13 in the 2011 VPA conceptually sets a very sharp dome-shaped selectivity for ages 9+ (Figure 28), with the population dynamics for the older ages being driven by commercial catch and system dynamics as estimated for ages 3–8. The reappearance of older fish in the survey catch in recent years gives more credence to a flat top selectivity on the survey, and the inclusion of survey indices for ages 9–13 allows some testing of this assumption in Model C.

The selectivity parameterization for Model C includes a selectivity of 1 for ages 8–13, forcing a flat top in the base run of Model C. The selectivity on ages 2-7 was estimated for each age. An additional sensitivity run which allowed the selectivity for ages 8–13 to vary independently for each age was done for exploratory purposes (Model C – Sensitivity). The inclusion of older ages in the tuning indices introduces many zeroes into the tuning index, particularly in the late 1990s and early 2000s. The ADAPT framework treats zeroes in observations for abundance indices as missing values, as the logarithm of zero is not defined.

All other specifics of the model formulation with respect to mortality and abundance assumptions on the oldest age mirror that of Model B.

MODEL D – INCLUSION OF THE ACOUSTIC INDEX

Parameterization

Model D is a step-wise progression from Model C, introducing the acoustic index as a second tuning index into the population model. Currently, the acoustic index only has full coverage of the WC area in 2012 and 2016 through 2020, so its impact is expected to be limited to the latter part of the time series. The acoustic index follows the bottom trawl index in most years, with only 2020 showing a divergence (Figure 29).

In order to incorporate the acoustic index, the total biomass was disaggregated into a biomass index-at-age by applying the appropriate length frequency from each tow (Table 10). As survey acoustic methodology evolves and the ability to differentiate schools by size improves, a more precise method may be applied (A. Debertin, pers. comm.). The inputs for Model D are:

$C_{a,t}$ = commercial fishery CAA for ages a=2 to 13, and time t=1982–2020, where t represents the year during which the catch was taken.

$I_{1,a,t}$ = survey trawl indices of abundance for ages a=2 to 13, and time t=1984.5, 1987.5… 2019.5 2020.5.

$I_{2,a,t}$ = survey acoustic indices of biomass for ages *a*=2 to 13, and time *t*=2012.5, 2016.5… 2019.5 2020.5.

$W_{a,t}$ = survey WAA for ages *a*=2 to 13, and time *t*=2012.5, 2016.5… 2019.5 2020.5 to accompany the biomass index $I_{2,a,t}$.

Initially, the selectivity on the acoustic index (I_2) was allowed to vary between ages and was estimated to have > 95% selectivity at age 5. This is substantially younger than the estimated selectivity from the survey RV trawl index, which reaches > 95% selectivity at age 8. The estimates of q for the acoustic index are based on six years of data, which is reflected in the high relative error for the estimates (Table 8). The precision and accuracy of these estimates should improve with additional years of data. Assuming the trend in selectivity-at-age is not solely a function of the low sample size, full selectivity at younger ages is appropriate for an acoustic index, as it has no net to hinder the catchability of fish across sizes, nor is the availability of the fish to the acoustic sensors impacted by the fishes' placement in the water column. The low selectivity of acoustic gear on young fish (i.e., ages 2 and 3) is also plausible, as young fish may stay in shallower waters closer to shore, where the summer RV survey does not sample. Given the high level of uncertainty and low sample size of the acoustic survey indices, the selectivity was fixed for ages 5–13.

All other specifics of the model formulation with respect to mortality and abundance assumptions on the oldest age mirror that of Model C.

MODEL E – INCLUSION OF EGB

Parameterization

All previous models with a survey tuning index relied on a mean number per tow at age derived from strata in DFO statistical unit and NAFO divisions 4Xopqrs5Y. Model E uses a relative abundance at age for all of WC and includes the simulated abundance indices on EGB (see Model Inputs/Survey Indices of Abundance/Eastern Georges Bank Index section). The inputs for Model E are:

$C_{a,t}$ = commercial fishery CAA for ages *a*=2 to 13, and time *t*=1982–2020, where *t* represents the year during which the catch was taken.

$I_{1,a,t}$ = survey trawl indices of abundance for ages *a*=2 to 13, and time *t*=1984.5, 1987.5… 2019.5 2020.5.

$I_{2,a,t}$ = survey acoustic indices of biomass for ages *a*=2 to 13, and time *t*=2012.5, 2016.5… 2019.5 2020.5.

$W_{a,t}$ = survey WAA for ages *a*=2 to 13, and time *t*=2012.5, 2016.5… 2019.5 2020.5 to accompany the biomass index $I_{2,a,t}$.

To help in the interpretation of the residual fit for Model E, a second version of Model D was run which used a total abundance instead of the mean number per tow. The change in units had a minimal impact on the overall fit of the model, as the residuals used in the calculation are standardized (Table 7).

All other model specifications remain the same as Model D.

MODEL F – TIME-VARIANT NATURAL MORTALITY

Parameterization

The parametrization of Model F is a step-wise progression from Model E, but moves away from the assumption of stationary in M that was established during the 2004 Framework (Stephenson 2004). A review of model-independent estimates of Z on WC Pollock indicated that that one method showed a decrease in Z on ages 5–7 throughout the 2000s and a return to higher levels throughout the 2010s (Figure 30). The fishery removals of WC Pollock were relatively constant within each decade, leading to a generally flat trend in relative F (Figure 31), which implies a possible change in M for this age group around 2000 and again around 2010.

Total mortality on older ages (8–13) is difficult to calculate empirically due to the intermittent presence of older ages in the survey CAA, particularly throughout the 2000s (Figure 20, Figure 30). The presence of older fish in the earlier time period, their disappearance throughout the late 1990s and 2000s, and their re-appearance in the most recent decade implies similar changes to the Z impacting that age group. This reasoning is confounded with the addition of the simulated EGB index into the survey catch, which shows that older fish were more persistently found in the survey catch on EGB throughout that time period (Figure 14). The simulated nature of the index, however, introduces a level of uncertainty into the stationarity of Z over time. Since an MSE framework can operate with multiple alternate, equally plausible scenarios of stock dynamics, both hypotheses are examined under Model F parameterization.

Survey-based Z estimates for younger fish (ages 2–4) show high variance and no obvious trend over time, providing no evidence of a change in M over time (Figure 30); however, low selectivity in the fishery and survey for these fish may prevent the detection of a trend.. Sensitivity runs, where Z was estimated as one (1994–2020), two (1994–2010, 2011–2020), or three (1994–2000, 2001–2010, 2011–2020) blocks on ages 2–4, indicated large relative error values on these estimates (> 50%, Table 11), and should not be estimated separately.

Although ADAPT is capable of estimating M in blocks of ages and years, it is not possible to estimate a full array of time varying M for all ages and years, since at least one block of ages needs to be fixed (Rivard and Stratis 2003). In addition, the block of fixed M has to include the cohorts with incomplete information at the beginning of the time series (i.e., 1967–1979 cohorts), otherwise the VPA does not converge (Rivard and Stratis 2003).

The M=0.2 assumption is wide-spread across stocks and species in the northwest Atlantic and is often seen as a fallback value for M in the absence of information (Thorson et al. 2017). It is not clear what biological basis exists for this assumption specifically for WC Pollock besides historic application. As a test, a model run was set up where M was estimated as a block from the 1980 cohort up until the 1994 year, when wide-spread changes in the local ecosystem precipitated from the collapse of cod stocks in the area. This sensitivity run estimated an M of 0.276 across all ages prior to 1994, with a relative error of 0.337 and a negligible bias (< 0.01), implying an acceptable level of precision for this estimate and support for the 0.2 assumption prior to 1994.

Given the uncertainty around the stationarity of M since 1994, several parameterizations were set up. The first assumed a stationarity in M since 1994 and estimated M as a single block across all ages years since 1994 (Mstat). Since trends in relative F and Z implied non-stationarity, M was also estimated in three, four, or six blocks (Figure 32). The three block model estimated M across all ages (2–13) for three time periods (1994–2000, 2001–2010, 2011–2020), the four block did the same for ages 5+ but set M as 0.2 on ages 2–4 since 1994, and the six block model estimated M for ages 2–7 together and 8–13 together across the same three time periods (Figure 32). Given the high observation error and year effects in the Pollock summer RV survey data, a random walk M was examined but not pursued as a viable alternative.

All other inputs, parameterizations, and assumption for Model F (i.e., assumption on terminal age abundance and oldest F) remained consistent with Model E.

Outputs

The overall performance of all four versions of Model F is summarized in Table 7. In general, the addition of flexibility in the M parameter substantially improves the standardized deviation of normalized residuals (SDNR) and the sum of raw residuals (SumResid) metrics, but leaves mean sum of square residuals (MSSR) metrics relatively unchanged. Allowing a change in M over time leads to a balance of positive and negative residuals for the summer RV survey; however, the overall magnitude of the predicted deviation from the observed remains the same. Although allowing a change in M moves the SDNR metric closer to the generally acceptable value of 1, the two large blocks of residuals across most ages between 1997 and 2010 persists even in the most flexible parameterization of M (Figure 33).

Differentiating between the various M scenarios is difficult. Models that are more flexible demonstrate a better fit with the data when considering standardized residuals; however, as the number of M blocks increases the precision of the M estimate decreases. (Table 12).

All four versions of Model F show that M increased after 1994, most notably on the oldest ages (Ages 8–13, Table 12). Between 2000 and 2010, the estimates of M seem to generally remain stationary for younger fish (Ages 2–7) but decreased for older fish (Ages 8+), though the simulated older fish from EGB are likely contributing to the decline in M. In the most recent decade, M has decreased further across the ages, with the decline likely driven by a decrease in M on older ages, as old fish reappear in the fishery and summer RV survey catch in recent years (Table 5, Figure 1, Figure 20). Despite a variety of M formulations that provide different estimates of M, the above trends are evident across all four formulations, making the final model choice a trade-off between model flexibility with respect to tracking changes in M, and model stability that avoids mistaking observation error for a change in population dynamics. A decrease of M after 2010 is not consistent with the catch-curve based analysis that showed Z increasing while relative F remained unchanged. Inconsistency between catch-curve analysis and Sinclair Z could suggest an issue with one of those methods or the increasing contribution of EGB catches to the population index in recent years, which is not accounted for in the Z estimation.

Both the selectivity curves (Figure 34) and the major population outputs from all parameterizations of Model F are comparable (Figure 35, Figure 36), with the choice of M parameterization expected to primarily impact the reference points and the rebound potential of the stock due to the assumption that terminal level M is expected to persist into the future.

STATISTICAL CATCH AT AGE

The exploration of stock dynamics was carried out in the ADAPT Framework. Despite several changes to the inputs and parameterization, a number of characteristics persisted through all of the VPA runs that resulted from the models back-calculating approach and the assumption of no error on the catch (e.g., high F on age 9 in the terminal year). Given the behaviour characteristic of backward calculating models, a forward-calculating statistical catch-at-age (SCAA) model was applied to WC Pollock. Initially, the Woods Hole Assessment Model (WHAM, Stock and Miller 2021) was considered for WC Pollock; however, the observation error in the Pollock index from the summer RV survey was considered to high for WHAM (Stock and Miller 2021). In addition, technical difficulties with WHAM prevented timely exploration of its use for the population modeling review.

This work could not take advantage of the main benefits of WHAM's ability to incorporate environmental covariates for this model review; however, a comparison run between the VPA and a forward-calculating SCAA model that permits some catch error was still considered beneficial, and the population was modeled in a stock assessment program (ASAP, Miller and Legault 2015). Given the different objective functions of the two frameworks, an attempt was made to generate matching diagnostics based on the output of a SCAA, but not all parameters could be compared directly to the VPA.

The technical details of ASAP are outlined in Miller and Legault (2015). For brevity, the major differences between ASAP and the VPA stem from the forward and backward calculations integral to each approach. The VPA assumes commercial CAA is known without error, requires an assumption on either fishing mortality or abundance at the terminal age in each year, and functions independently of any stock recruitment relationship (SRR). The ASAP can handle errors in the commercial catch, uses the commercial CAA as a tuning index in addition to the surveys, and requires no knowledge about the terminal age mortality or abundance, but relies heavily on the knowledge about the stock recruit relationship and M for the population. The trade-off between the assumptions, requirements and strengths of these two approaches become evident when working in tandem on the same stock.

MODEL I – ASAP VERSION OF MODEL E

Parameterization

Model I is parameterized to recreate the same concepts applied in Model E, but replicated in the ASAP framework to showcase the differences in methodology. The inputs for Model I are:

> $C_{a,t}$ = commercial fishery CAA for ages *a* = 2 to 13, and time *t* = 1982–2020, where *t* represents the year during which the catch was taken.
>
> $I_{1,a,t}$ = survey trawl indices of abundance for ages *a* = 2 to 13, and time *t* = 1984, 1987… 2019, 2020.
>
> $I_{2,a,t}$ = survey acoustic indices of biomass for ages *a* = 2 to 13, and time *t* = 2012, 2016… 2019, 2020.
>
> $W_{a,t}$ = survey WAA for ages *a* = 2 to 13, and time *t* = 1982, 1983… 2019, 2020.
>
> $W2_{a,t}$ = beginning of year WAA for ages *a* = 2 to 13, and time *t* = 1982, 1983… 2019, 2020.
>
> $M_{a,t}$ = natural mortality matrix for ages *a* =1 to 13, and time *t* = 1982, 1983… 2019, 2020.
>
> $Mat_{a,t}$ = maturity matrix for ages *a* = 1 to 13, and time *t* = 1982, 1983… 2019, 2020.
>
> $Catch_t$ = total commercial catch at time *t* = 1982, 1983… 2019, 2020.

In addition to the above matrices, ASAP requires a coefficient of variation (CV) for the catch series (0.2), a CV on the survey (0.4), the shape of the selectivity curve for both fishery and survey (flat top), and steepness for the SRR (0.65).

For this application, the ASAP framework minimizes the following objective function, as described in Miller and Legault (2015):

$$\text{Obj Fun} = \lambda_1 * \text{Fit}_{index1} + \lambda_2 * \text{Fit}_{index2} + \text{Fit}_{CAA}$$

where:

λ_i is a weighting or emphasis factor for each index, set as 1 for the survey trawl, survey acoustic and the commercial CAA indices.

Fit is calculated assuming a lognormal error distribution:

$$-\ln(L) = 0.5\ln(2\pi) + \sum \ln(obs_i) + \ln(\sigma) + 0.5\sum \frac{(\ln(obs_i) - \ln(pred_i))^2}{\sigma^2}$$

Output

Given the differences in objective function between the ASAP and the VPA, direct comparisons between the ADAPT_MSSR and the ASAP_ObjFun metrics in Table 7 are not appropriate. However, the calculations of the SDNR, SumResid and MSSR metrics between the two frameworks can be compared directly, while remaining cognizant of the additional tuning to the commercial CAA performed in ASAP.

Model I was parameterized most similarly to Model E and has similar performance with respect to the SDNR, SumResid, and MSSR metrics on the survey (Table 7). However, looking at the fit of the survey index (Figure 37) some obvious differences emerge between the two similarly parameterized models, which are an artefact of their respective frameworks. For example, the smoothness of the predicted Age 2 index in Model E is a function of ASAP's dependence on a SRR, while the VPA is not constrained by this relationship and has a better fit to the observed index for age 2 (Table 13). This limitation is quite apparent across the younger ages for all ASAP models, regardless of parameterization (Table 13). Temporally, the fits of Models E and I are similar, with Model I also struggling with a block of positive, followed by a block of negative residuals throughout the 2000s (Figure 38), indicating this is not a function of the framework used. Finally, Model I fits the acoustic index better than model E, (Table 7), primarily due to its better fit to the terminal 2020 point, which Model E struggled with (Figure 39).

The outputs of Model I showcase the dependence of ASAP on the SRR assumption, although the overall biomass trend is similar between Model E and I in both magnitude and trend (Figure 40). The F trend differs between the two models (Figure 40) due to the assumed error on the commercial catch in ASAP, eliminating the high F on age 9 in the terminal year characteristic of all VPA models shown to date (Figure 41) and demonstrating that it is not a population signal that persists across platforms. The estimated ASAP selectivity curves on the acoustic and summer RV survey trawl indices are closer to the model-independent estimate, identifying another VPA-platform specific signal (Figure 42). Preliminary sensitivity runs on the steepness of the SRR (or the selectivity curves?) indicate the majority of the ASAP models had a lower objective function when steepness was set to approximately 0.65(Table 14). Although the differing steepness assumptions (0.2-0.99) had little influence on the overall fit of the model, it is expected to effect Fmsy and any reference points derived from it. This is further explored in the Reference Points section below.

MODEL J – ASAP VERSION OF MODEL F

Parameterization

Model J is considered an ASAP equivalent to Model F. Since ASAP cannot freely estimate M, the input matrices for M were identical to the outputs of the estimated M from Model F, structured along the same blocks of time and age (Figure 32). Consequently, Model J has the same four versions as Model F with a single (J_MStat), three (J_M3B), four (J_M4B) and six (J_M6B) block models. Besides the M matrixes, all other inputs into the various Model J formulations are identical to Model I.

Output

The overall metrics for all versions of Model J are summarized in Table 7. Unlike the VPA versions of the increasingly flexible estimation of M (Model F, Table 7), Model J does not show a progressive increase in model fit to the summer RV survey index with increased flexibility around M (Model J, Table 7). This stems from the inclusion of signals from the commercial fishery CAA in the objective function of ASAP, which continues to contribute to the population signal but is not captured in the residual metrics reported in Table 7; for the VPA, the increasing flexibility on M allows for the estimated population to follow the signal in the main tuning index (survey), progressively improving the fit with additional flexibility in M. The only metric in Table 7 that encompasses the fit to the commercial fishery CAA signals in Model J is the objective function, which shows that the three-block (J_M3B) and the six-block (J_M6B) models are fit marginally worse than the stationary M since 1994 (J_MStat) and the four block (J_M4B) models.

All versions of Model J show a block of positive survey residuals on the older ages; this pattern was not evident for model F (i.e., Figure 43 vs. Figure 44), Furthermore, despite having equal weighting in the objective function, all versions of Model J perform better in fitting the terminal year in the acoustic index compared to their equivalents in Model F, suggesting agreement between the acoustic index and the commercial fishery CAA.

The outputs from all versions of Model J are relatively similar (e.g., Figure 45, Figure 46, Figure 47), with the various versions of M blocks expected to impact reference points as the terminal level of M changes the expected resilience of the stock in the future. The full residual plots are only provided for Model J_M4B, which is the final model selected (Figure 48, Figure 49, Figure 50).

RETROSPECTIVE ANALYSIS

Extensive retrospective analyses were carried out for Models I and J, as ASAP has a very intuitive and user-friendly approach to successive retrospective peels. The resulting data were used to calculate annual Mohn’s rho metrics, comparing the value of F and SSB generated in each peel to the final 2020 run. Mohn’s rho is a common tool used in both ICES and NMFS assessment to account for retrospective patterns in the provision of science advice. In the current framework, Mohn’s rho is used as a stress test to investigate the performance of the model, rather than a fix for a retrospective problem.

The commonly accepted window for the number of peels to include in the calculation of a Mohn’s rho ranges from five (ICES) to seven (NMFS) years, although simulation work by Miller and Legault (2017) acknowledged that the average Mohn’s rho metric stabilizes after five years. A non-zero value of Mohn’s rho can occur for a variety of reasons, though larger values tend to be associated with model misspecification (Hurtado-Ferro et al. 2017). Hurtado-Ferro et al. (2017) also postulated that a biomass-based five-peel Mohn’s rho values falling outside of -0.15 and 0.2 signals a cause for concern for long-lived species. Finally, the directionality of the Mohn’s rho also impacts interpretation, as positive Mohn’s rho for SSB and negative Mohn’s rho for F pose a higher risk with respect to overfishing.

Both the five and the seven year peel for Models I and J are reported in Table 15. Only models I, J_M3B and J_M4B have an acceptable level of Mohn’s rho for SSB for both five and seven year peels. The model performance for F is worse, with only the J_M4B model remaining within the prescribed range for F in both five and seven year peels. Although Mohn’s rho for F from Model I exceeds the prescribed value (0.2), its directionality shows that it will not pose a conservation risk (Table 15).

Given the overall Mohn's rho is a mean across a range of years, these annual values of Mohn's rho can be examined to better understand why some models pass or fail. A visualization of the seven annual Mohn's rho values for each model shows that Models J_MStat and J_M6B likely failed due to extreme values on peel 5 (Figure 51). Although Model I also exhibits this issue on Peel 5, the Mohn's rho values of the adjacent peels balance it out in the overall average, particularly for SSB. Model J_M4B outperforms the others in the five and seven year averages (Table 15), and does this through consistently acceptable values, rather than large extremes balancing each other out (Figure 51).

MODEL SELECTION

Model J_M4B was the accepted candidate population model deemed appropriate for WC Pollock, with Model I suggested as a sensitivity to the assumption of varied M. In addition, sensitivity runs examining the impact of a dome-shape on survey selectivity were also requested.

The VPA-based models discussed (Models A through F) all showed unrealistically high magnitudes of F, often exceeding 1, as well as survey selectivity curves that were not supported by model-independent observations (Figure 52). Both of these seemed characteristic of the VPA platform rather than the parameterization, as comparable SCAA models did not show either of these effects. In addition, the tuning of the SCAA to both the fishery independent indices as well as fishery catch was seen as a desirable characteristic for a stock with a relatively high level of uncertainty associated with the main fishery-independent tuning index. Consequently, Models A through F were not considered viable candidates.

The choice between the various SCAA models was made based on data fit, model performance, and consistency with model-independent observations.

1. Objective Function: Model J_M4B had a substantially lower objective function compared to the other four, which included the fits to both the surveys and the commercial catch; the objective function for Model I was the next lowest.
2. Retrospective: Model J_M4B outperformed all other models with respect to both the multi-year and annual analysis for Mohn's rho, being the only model which showed acceptable levels of Mohn's rho for both SSB and F. Model I showed an acceptable level of Mohn's rho for SSB only, and was outperformed by one other model in the multi-year analysis. However, the notable retrospective pattern on F present for Model I did not pose a conservation risk based on its directionality.
3. Model-independent observations: Model J_M4B represented a scenario where M changed, which was consistent with model-independent observations. Model I provided a sensitivity scenario with an invariable M, which was consistent with the bulk of the OMs during the 2011 MSE. Both models also showed equally good agreement to the model-independent trends in relative F, though model I had a higher correlation in the recent time period (R^2 of 0.737 for 1994–2020 versus R^2 = 0.479 for 1994–2020, Figure 53); this represents the only notable shortcoming of Model J_M4B.

During discussions of model performance, it was suggested that the ITQ survey could be used to ground truth the recruitment signals coming from the selected models. The ITQ survey can provide a model-independent index of recruitment, as it was designed to survey inshore areas missed by the summer RV survey and small Pollock are known to aggregate closer to shore. Given that the fish from the ITQ survey were not aged, a length-based cut-off was applied (30 and 44 cm), though this inadvertently results in smearing of adjacent ages into the proxy Age 2 index. Since the ITQ survey occurred in the summer months (June–July) and the model-based

Age 2 indices represent start of year fish (January), this length range was chosen to account for six months of growth on Age 2 fish (Figure 54). After standardizing the three indices to their respective means during the overlapping time period, there is general agreement in recruitment trend between the two chosen models and a model-independent ITQ survey index (Figure 55). The Inshore Lobster Trawl Survey (ILTS) covers a similar spatial area in more recent years (1995–current), but additional time and resources would be needed to generate a similar index of recruitment (pers. comms, A. Cook, DFO Science).

OPERATING MODEL AND PROJECTION INPUTS

NATURAL MORTALITY

In 2011, the M in the terminal year of the model (i.e., 2010) was assumed to continue into the future. There is no reason to deviate from that assumption for the current MSE, with M in the current terminal year expected to continue into the future.

FISHERY SELECTIVITY/PARTIAL RECRUITMENT

Fishery selectivity, also referred to as partial recruitment (PR), is assumed to be flat-topped as there is no empirical evidence of older fish existing but being unavailable to the fishery. This approach is consistent with the reference set of models used in the 2011 MSE, when several sensitivity runs using domed-shaped selectivity came to the same conclusion (Porter and Docherty 2011).

The treatment of selectivity in the projections of the current MSE differs from the 2011 MSE. Based on the available formulation of the 2011 MSE reference OMs, fishery selectivity in the projected years was applied by randomly sampling a set of annual fishery selectivity vectors from 2000 through 2009 (Porter and Docherty 2011). In the case of SCAA, the model produces a single selectivity curve across all historic years, which will be applied in the projected time period.

SURVEY SELECTIVITY

The 2011 MSE calculated projected survey selectivity based on the q outputs of the VPA, while also assuming a selectivity of 0 on ages 9+ (Rademeyer and Butterworth 2011). This method of using a model-generated q to derive selectivity is generally defensible, but the assumption of a dome shape seemed driven exclusively by the use of ages 3–8 for the survey indices of abundance, and not the perceived unavailability of older fish to the bottom trawl survey. In addition, the survey selectivity from the 2011 VPA substantially differed from the empirical estimate (Figure 28); an issue that was resolved in the SCAA models. As such, the projected period will use the same survey selectivity as the historic years.

Based on EGB (5Z) survey index work, older fish are present on EGB in the spring, although they are absent from 4X5Y in the summer. This suggests that dome-shaped selectivity might be appropriate for a summer RV survey index based on only 4X5Y strata. In generating the historic summer EGB index, the use of EGB spring length frequency introduced the older fish into the summer RV survey index (Figure 14), negating the need for a dome-shaped selectivity in the historic time series. If the summer RV survey continues to sample all of the EGB strata, the assumption of flat-top selectivity for the survey in the projections remains appropriate; however, if the summer RV survey coverage is limited to only 4X5Y strata, the selectivity should be domed on older fish.

SURVEY PROPORTIONALITY

During the 2011 MSE, the relationship between the survey and the population abundance was considered proportional along with some observation error present in any given year (Porter and Docherty 2011). This assumption is still considered appropriate and will be applied again in the 2022 MSE.

MATURITY

As discussed above, no evidence of a change in maturity has been noted in the historic time series (1982–2020), nor is it expected to change in the projections. This is consistent with the assumption of maturity (4+) made during the 2011 MSE (Rademeyer and Butterworth 2011).

GROWTH AND WEIGHT AT AGE

Given the historic shifts in both LAA and WAA over time (Andrushchenko et al. 2025), consideration needs to be given to its use in the projections of the current MSE. The data presented in Andrushchenko et al. (2025) suggests three historic growth scenarios: high growth for cohorts prior to the 1982 cohort, medium growth for cohorts between 1982 and 2010, and the slowest growth exhibited by cohorts since 2011 until present (Figure 56). Given the slower growth observed since the 2010 cohort and the lack of definite cause, incoming cohorts are expected to continue to exhibit the same slow growth in the future. Any projections using the medium or fast growth scenarios would be considered a sensitivity, at least until empirical evidence of growth increase is seen for WC Pollock.

The 2011 MSE used the previous ten years of annual WAA vectors (2000–2009) to guide future stock projections. Unfortunately, the latest shift in growth began with the 2011 cohort, so the 2011 MSE projections overestimated the population biomass in most projected years, explaining some of the divergence between projected and realized stock trends. The historical years of the OM will use an empirical matrix of LAA between 1982 and 2020, with missing data predicted by a VonBertallanfy growth curve based on either the pre or the post 2011 cohort (cpars$Len_age). For the current projections, the growth curve will be fit to represent the slower growth exhibited by the cohorts since 2011, with slight variation introduced to account for year effects (cpars$LenCV=0.1). Although the current population model incorporates data up until 2020, additional data on growth has been collected since then through commercial catch sampling (port sampling), observer and survey programs and suggests the slow growth experienced since the 2011 cohort continues (Figure 57).

The WAA has undergone a similar shift to growth and will be treated in the same manner as the length at age. The WAA matrix for both beginning of year and mid-year WAA will be customized to reflect the empirical WAA throughout the historic years (1982–2020), and the projected years will use a mean WAA since the 2011 cohort reflecting the assumption that the current growth conditions will continue into the near future. The final customized matrix is specified in each OM using the custom parameters slots (cpars$Wt_age for beginning of year and cpars$Wt_age_C for fishery).

FISHING MORTALITY

The OpenMSE platform requires an input of the fully selected F trend over the non-projected years (i.e., 1982–2020, specified via cpars$Find slot). This trend can be a direct output of F levels for the population model, which MSEtool treats as a relative indicator, with the resulting absolute level of F determined by the optimization routine (Carruthers and Hordyk 2018).

Fishing mortality in the projections is set depending on a given management procedure. In 2011, a limit of 0.95 was imposed on the projected F with catch recalculated to a level of F=0.95 if the limit is exceeded (Rademeyer and Butterworth 2011). MSEtool has an equivalent parameter (Fmax) which was employed with a maximum of 1.

STOCK-RECRUITMENT RELATIONSHIP

Future recruitment can be determined using the model-based SRR, or it can be set as a constant value with inter-annual variation. The 2011 MSE used a hockey-stick relationship for five of its six reference OMs and a Beverton-Holt SRR for the remaining OMs (Rademeyer and Butterworth 2011). The hockey-stick relationship was derived based on data from the last ten years (1999–2008, four reference OMs), or data from all twenty-five years (1982–2008, one reference OM), while the Beverton-Holt relationship was capped at the average value of historic SSBs exceeding 20,000 t (Rademeyer and Butterworth 2011). In the current MSE, the uncertainty around the projected recruitment persists, but while the 2011 MSE focused on the shape of the SRR, the current uncertainty focuses on the deviations from the SRR.

The MSEtool is hardwired to accept a Ricker or Beverton Holt SRR, but the custom parameterization of recruitment calculations (cpars) also allows additional flexibility in recruitment deviations and recruitment process error (Carruthers and Hordyk 2018). If the fit of the SRR from the accepted population model is particularly poor, there is an option to randomly resample projected recruitment from a distribution with a mean and standard deviation derived from any given range of historic years. These assumptions impact both the assumed productivity of the stock and the projected recruitment, and require careful consideration.

Variability in recruitment of a stock can be tied to the size of the adult biomass and the survival of the fish at early life stages (i.e., egg, larval). The first component relies on the theory that a higher number of adult fish is able to generate a larger number of recruits, and is the fundamental concept behind a SRR (Ricker 1954, Beverton and Holt 1957). The second component that can impact the strength of an incoming year class is the survivability of those potential recruits through both egg and larval stages, which is independent of the size of the spawning stock and has been linked to variables such as temperature, prey and predator availability (e.g., Koslow et al. 1985, Bailey and Houde 1989, Houde 2008, Nissling 2004). Teasing apart the impact of these two components on variability in recruitment has been attempted before, with various levels of success (e.g., MacKenzie et al. 2008, Megrey et al. 2005).

There is a relationship between SSB and recruitment for WC Pollock in the accepted population model, with higher recruitment associated with larger biomass, and lower recruitment associated with lower biomass (Figure 58). Large increases in recruitment associated with either no change or very little change in the SSB (i.e., 1986–1988, 2009–2011, Figure 58) indicate that some drivers contributing to the variability in recruitment are independent of SSB. Finally, groups of consecutive years remaining above or below the perceived relationship may suggest that inter-annual connectivity in the environmental factors influencing recruitment, smearing of periodic single large recruitment events into adjacent year classes, or a combination of the two. All of these trends have been confirmed in the sensitivity Model I and the rejected VPA-based formulation (Model E) despite differences in the assumed stationarity of M (Figure 59), implying that they are derived from signals in the data rather than a consequence of the model formulation.

The biomass decrease in recent years is partially caused by a reduction in growth, rather than a decrease in the number of spawning individuals. This is evident when SSB is replaced by Spawning Stock Abundance (SSA, Figure 60), with the most recent years being comparable to those in 2007–2008 levels when using abundance, as opposed to the lower levels in 2009 when using biomass (Figure 58). It is unclear whether the observed decrease in growth is accompanied by a decrease in the relative fecundity of the stock; an important uncertainty as both metrics of spawning stock are a proxy for the reproductive potential of the stock in the SRR.

In 2011, the SRR was fit to the outputs of the VPA in a post-hoc manner (Butterworth and Rademeyer 2010). In the current application, the SRR is an output of the SCAA, with an assumed Beverton Holt shape (Figure 61). The standardized residuals indicates a cyclic oscillation to the deviations from the predicted recruitment (Figure 62), implying that a density-independent covariate regularly oscillates recruitment between periods of high and low productivity at various intervals. The same patterns in recruitment residuals are evident when looking at the outputs of the sensitivity Model I (Figure 63), Model E (Figure 64) and the 2011 VPA (Figure 65).

Several papers examining the appearance of productivity 'loops' in the SRR of Pacific coast species identify environmental indicators as the drivers of these loops, based on a matching period frequency exhibited between the two (Sakuramoto 2018, Tanaka et al. 2021). Various abiotic Scotian Shelf and Gulf of Maine indicators summarized in Casault et al. (2021) and Hebert et al. (2021) were examined visually to check if any followed a similar cycle matching the recruitment. All abiotic factors exhibited either a substantially longer oscillation period (e.g., North Atlantic Oscillation index, Copepod anomaly scorecard), or no observable oscillatory tendencies, indicating that this cannot be linked to a single abiotic index.

Such oscillatory behaviour can also be characteristic of predator-prey cycles (i.e., Krebs et al. 2001); however, no single indicator of total prey or predator biomass correlated significantly ($p < 0.05$) with this trend, even when the RV survey biomass indices were combined for multiple predators (Figure 66). Pollock may have cannibalistic tendencies (Collette and Klein-MacPhee 2002), a view supported by size-based aggregation of the species, but direct evidence of excessive cannibalism on young Pollock was not found during the stomach content analysis data revision (Andrushchenko et al. 2025).

Finally, recruitment deviations were also generated for other groundfish stocks in the area, based on either readily available model outputs (Silver Hake, 4X5Y Cod) or survey CAA in the absence of a model (4X5Y Haddock). Although some periodic consistency could be seen in t blocks of good or bad recruitment between Pollock and Haddock (Figure 67), all correlations were not significant ($p < 0.05$). Additional species could be added into this analysis, as data become more readily available.

Given the oscillatory nature of the SRR deviations, the following two approaches to projecting recruitment were used and included in the reference set:

1. OM_SRNoise – Projected Recruitment is determined by the assumed SRR. Deviations from recruitment curve are drawn from a distribution determined by the mean and standard deviation of all recruitment deviations for the historic time series. This OM ignores the oscillatory nature of the recruitment deviations observed, and is recommended as a sensitivity OM. The only major advantage to this OM is as a bridge from the 2011 MSE, as this approach is consistent with what was done in 2011.
2. OM_SRAutoCorrelated - Projected Recruitment is determined by the assumed SRR. Autocorrelation is introduced into the projected deviations, informed by the correlation coefficient calculated on the historic deviations (rho=0.628). This OM is projects the oscillatory nature of recruitment observed in the past, and does not require an assumption of an oscillation period.

GENERATION TIME

The guidelines for implementing fish stocks provisions (DFO 2022) define generation time as the average age of parents of the current cohort, and are intended to reflect the turnover rate of breeding individuals in a population. The mean generation time of WC Pollock was calculated as 5.8 years, is consistent between both Models I and J_M4B, and shows no directional trend over time (Figure 68). The generation time is a metric required to provide a timeline for the achievement of management objectives.

Currently the population model for WC Pollock is current to 2020, with 2021 being the first projected year. Since the survey index for 2020 and the acoustic index for 2021 and 2022 are not currently available, the model cannot be updated to the current year. As such, the projection will be completed 14 years ahead (from 2020) to evaluate the management objectives within two generations (12 years from 2022).

MANAGEMENT PROCEDURES

A list of candidate Management Procedures (MPs) was not available in time for the review of the operating models . To help visualize the MP performance against the approved management objectives, two sample MP were applied in this document:

1. CC_MP: a MP which keeps catch constant, at terminal level of catch for years between 2016 and 2020.
2. Islope_MP: a MP which changes TAC based on the slope of the recent survey index.

These MPs are used for example purposes only, and are not approved candidate MP for this MSE.

MANAGEMENT OBJECTIVES

Management objectives are used to evaluate the performance of each candidate MP against the uncertainties encompassed by the OM. This application of the MSE uses the following approved management objectives, as provided by DFO Resource Management:

1. Maintain the stock above the limit reference point (LRP) and avoid fishery induced declines to below the LRP.
2. Adjust level of precaution depending on stock status.
3. Provide stable inter-annual TACs.
4. Maintain TAC above a certain level

These management objectives are based on the management objectives outlined in 2011 (Porter and Docherty 2011), but have been modified to align with the precautionary approach (DFO 2009). The candidate MPs will be evaluated against each management objective based on the metrics, probability, and timelines described in Table 16 and will be summarized in a scorecard to be presented at the final CSAS peer review meeting for the Pollock MSE in February 2023. The information contained in this scorecard will be used by resource managers to select a final MP for WC Pollock and so must accurately and concisely communicate the performance of each MP against the management objectives. Although the candidate set of MPs has not been agreed upon, this document presents an example of a scorecard to ensure all of the information required for decision making is contained within. This scorecard is shown for demonstration and formatting purposes only, and does not reflect the final outputs.

Scorecard

The projected SSB and simulation envelopes for each OM under a given MP are shown in Figure 69. These are presented to help interpret the subsequent scorecard figures and do not reflect actual results.

The performance of a MP against the first objective will be summarized with a table showing the proportion of simulations falling below the LRP in the terminal year (2034), after two generations (Table 17). In addition, the proportion of simulations in each of the projected years which fall below the LRP, containing a horizontal line at both 5% and 25% percent, as in Figure 70, will be presented. For conciseness, a single plot will contain multiple lines for each OM (differentiated by colour), but refer to a single MP. There will be a single plot for each MP considered to help evaluate its performance.

The performance of a MP against the second objective will be summarized with a similar table to Objective 1, with the proportion of simulations above USR in terminal year (2034, Table 17) presented. In addition, a plot showing the proportion of simulations in each of the 14 projected years that fall above the USR, with a horizontal line at 50% and 75%, as in Figure 71. For conciseness, a single plot will contain multiple lines for each OM (differentiated by colour), but refer to only a single MP. There will be a single plot for each MP considered to help evaluate its performance.

The performance of an MP against the third objective will be shown as the proportion of years within each time period that a given MP resulted in a change in TAC exceeding the specified limit (i.e., 15%), averaged across all simulations for each OM. This value will be reported for each OM and MP combination for a short, medium, and long-term time period as in Table 18. Similarly, the performance of a MP against the fourth objective will be shown as the mean number of years (with standard deviation), across all simulations for each OM that a given MP resulted in a TAC in excess of 3,000 mt. This value will be reported for each OM and MP combination, with a column for each of the three timelines as in Table 18.

REFERENCE POINTS

Reference points were estimated across a spectrum of assumptions, from production-based approaches (i.e., equilibrium biomass at maximum sustainable yield, B_{MSY} and equilibrium unfished biomass, B_0) to empirical-based approaches (i.e., $B_{recover}$). The reference points are used to delineate three status zones (critical, cautious and healthy), with the removal reference (RR) for each zone indicating the maximum rate of harvest within that zone (DFO 2009). The RRs are expected to decrease progressively from the healthy to the critical zone, with the RR in the healthy zone never exceeding a maximum sustainable yield rate (F_{lim}) for the stock (DFO 2009). The final choice of reference point and RR is expected to be based on best available science, take into account any limitations in data and assumptions, and be compliant with DFOs Precautionary Approach (PA) Policy (DFO 2009).

This work outlines options for setting an LRP, an upper stock reference point (USR) and a F_{lim}, which the RR in the healthy zone cannot exceed. The candidate production-based and empirical reference points are summarized in Table 19, Figure 72, and Figure 73, while their respective derivations are detailed below. In accordance with the PA Policy, the USR is selected by fishery managers based on advice from DFO Science and extensive consultation processes with relevant Advisory Committees (DFO 2009). Options for a USR are more difficult for DFO Science to outline, as a biological definition of what constitutes a change from a cautious state to a healthy state of the stock is not defined, but some candidate USRs are outlined below.

LIMIT REFERENCE POINT AND REMOVAL REFERENCE

Within the PA Policy an LRP is defined as the point below which the reproductive capacity of the stock is expected to be impaired to the point of serious harm (DFO 2009). The PA Policy notes the association of the LRP with respect to serious harm, but allows some flexibility in defining serious harm. Although the PA Policy specifically identifies $0.4B_{MSY}$ as a provisional LRP falling in line with international standards and the associated F_{MSY} as the limit fishing mortality rate, it permits other approaches that are appropriate for the stock and consistent with the intent of the Precautionary Approach (DFO 2009, Annex 1b).

Productivity-based reference points are intended to reflect the productivity potential of the stock, which is directly impacted by both the growth and the M experienced by the fish. For WC Pollock, fish growth has changed beginning with the 2011 cohort, with no mechanistic relationship identified for the change and no empirical evidence that the change is reversible. As such, productivity-based reference points are calculated based on the slow growth only; however, if evidence of further changes in growth emerges, the productivity-based reference points will need to be recalculated. This stock also appears to be experiencing a change in M. Unlike growth, the M of the stock has experienced both increases (mid 1990s) and decreases (2000s and 2010s) over the time series, adding uncertainty about whether the current level of M represents a permanent new state for the stock, or is a temporary deviation from a long-term average M experienced by the stock. Candidate reference points were initially calculated based on both M scenarios.

The estimation of $0.4B_{MSY}$ for Model J, using the most recent estimate of M (0.340) results in a value of 9,738 mt and an accompanying F_{MSY} of 0.175 (Table 19). The F_{MSY} was estimated as the long-term F that maximizes yield under equilibrium assumptions, while B_{MSY} was estimated as the long-term equilibrium biomass from fishing at F_{MSY}. The estimate of B_{MSY} is equivalent to the intersection of the SRR and a straight line through the origin whose slope is the inverse of spawning biomass per recruit at F_{MSY}. As such, the assumed steepness of the SRR has a significant impact on the value of B_{MSY}. For WC Pollock, the steepness (h=0.65) was fixed in the population model based on the level of h that tended to yield the lowest objective function across the various ASAP model formulations. Given the sensitivity of B_{MSY} to the assumption of steepness, alternative candidate LRPs were explored.

In addition to B_{MSY}, reference points can be based on a theoretical level at which biomass and recruitment stabilize under equilibrium conditions with no fishing (B_0, Gabriel et al. 1989). A value equivalent to 20% of B_0 (i.e., $0.2B_0$) has been used as a LRP, as it is expected to avoid recruitment overfishing in a stock (Myers et al. 1994, Sainsbury 2008). Assuming the most recent levels of stock dynamics persist (i.e., slow growth and M of 0.340), the $0.2B_0$ value for WC Pollock is estimated as 14,350 mt (Table 19). Alternatively, assuming slow growth persists and the M for the stock is oscillating around a mean value of 0.415, the $0.2B_0$ value is estimated as 10,749 mt (Table 19). Although B_0 also depends on the SRR, it is derived as the intersect of the SRR and a line through the origin with a slope equivalent to the inverse of spawning biomass per recruit when F=0. Since this intersect occurs further along the x axis than B_{MSY}, it is less influenced by the uncertainty in the steepness parameter of the SRR.

Production-based reference points can also be calculated based on Spawning Potential Ratio (SPR), avoiding the assumption of a SRR for WC Pollock. The F that results in 40% of the spawning biomass per recruit in an unfished state (i.e., $F_{40\%SPR}$) can be considered a proxy for F_{MSY} and yields values of 0.187 under the current M (0.340) and 0.220 under the series mean M (0.415, Table 19).

Given uncertainty around production-based reference points, various stocks in the Maritimes region rely on empirical reference points (DFO 2012). The most prominent of these is $B_{recover}$, conceptualized as the lowest historic level from which the stock has recovered (DFO 2012). Despite being operational for various stocks in the region, what constitutes recovery is subjective. In the case of the biomass trend for WC Pollock, the lowest point which is followed by a multi-year increase in biomass occurs in 2013, at 16,701 mt (Figure 72). The recent change in growth of WC Pollock prevents a selection of a $B_{recover}$ in years prior to 2010, as the impact of changes in growth on the reproductive potential of a fish has not been quantified.

, An LRP of $0.2B_0$ (14,350 mt) was selected for WC Pollock. The use of B_{MSY} based reference points was not recommended due to its sensitivity to the assumed steepness of the SRR, while the SPR-based reference points were not selected due to the impact of the assumption of the equilibrium recruitment that would be used to calculate the equilibrium biomass from fishing at $F_{40\%SPR}$; a B_0-based reference point was thought to be buffered against both of these uncertainties. The uncertainty around the level of M was addressed by using the most current level (0.340) with an exceptional circumstance incorporated into the assessment cycle that monitors for a change in M, triggering a review of reference points.

Unlike the candidate LRPs, the options for the maximum F (F_{lim}) were based on F_{MSY} or $F_{40\%SPR}$. The $F_{40\%SPR}$ did not require an assumption of SRR, while the F_{MSY} option was still sensitive to the assumption of steepness. As such, $F_{40\%SPR}$ under the most recent levels of M (0.34) was selected as the best candidate, setting 0.187 as the maximum removal rate (F_{lim}) for a stock in the healthy zone.

UPPER STOCK REFERENCE POINT

In Maritimes Region, science advice on an USR has been limited to setting the USR as a multiplier of LRP, often double the LRP (DFO 2012). Given this precedent, double the LRP remains an option for a USR, but additional work was carried out to evaluate the performance of this and other candidate USRs under various projected scenarios.

Testing candidate USRs under a constant F of 0.187 (limit on F in the healthy zone) is not informative, as this situation is not realistic given the application of the PA Policy in Canadian fisheries. A relatively generic HCR where F is low when the stock biomass is below the LRP, F is at 0.187 when the stock biomass is above the USR, and F is gradually decreased between them when the stock is in the cautious zone was considered consistent with the PA Policy and more useful in evaluating the performance of the candidate USRs (Figure 74).

Pollock is subject to a large amount of observation error in its surveys (CV=0.6–0.7). Testing a USR without accounting for this error gives a false sense of certainty. Applying the HCR without accounting for this error could result in the stock being below the USR but the survey erroneously showing it as being above, and vice versa, leading to poorly informed decisions. To address this, stock status was determined by the generic HCR based on the survey index derived from the projected biomass, with the high observation error incorporated into the derivation of that survey index. Given the high variability of the Pollock survey, the simulated survey index was smoothed by taking a three-year running mean of the terminal three years, with the stock status determined by the smoothed value. This approach is consistent with the real-life application of the HCR from the 2011 MSE to deal with the high variability in the summer RV survey index for Pollock.

Although the example HCR derived from the PA Policy implies a reduction of F in the critical zone to a low level (i.e., 0.00001*RR), the reality of multi-species fisheries makes this a difficult level of F to achieve. Although directed fishing may be eliminated when the stock is in the critical zone, bycatch removals can still result in significant levels of F. Ideally, the HCR for a stock in the multi-species fishery would consider Fs which amount to the lowest feasible level of bycatch, but this realized level of bycatch is difficult to estimate.

A range of USRs spanning from the LRP to double the LRP was broken down into 10 segments, and projected out 60 years over 1000 simulations. The resulting simulations were summarized across the short term (two generations) and over the long term (terminal 40 out of 60 projected years, where the stock levels out), to find the lowest USR that resulted in a < 5% probability of entering the critical zone over each time period. This test was run under both reference OMs to ensure that the final USR is robust to the uncertainty under both projected recruitment scenarios.

For OM1, values of 21,525 mt and 18,655 mt were the lowest USR to result in a < 5% chance of going below the LRP in the long term and over the next two generations (14 years, including two years projected into 2022, Table 20a,b), respectively. OM2 has lower variability in the projections than OM1, resulting in a lower proportion of simulations going below the LRP (Table 20a,b). Consequently, the USRs that result in approximately 5% of simulations dropping below the LRP are lower than the LRP itself in both the short and long term.

In cases with multiple USRs across various OMs and time frames, the highest would ensure that all of the scenarios have a < 5% chance of going below the LRP. Among those tested, 21,525 mt is the most precautionary of the tested options and constitute a value which is equivalent to $0.3B_0$ and $0.68B_{MSY}$ proxy. Given the unrealistic expectation that F will be reduced to 0.00001*RR when the biomass falls below the LRP, a second test was also run to examine how robust this value is to the level of F below the LRP by setting the F below the LRP to 0.06. This resulted in the new candidate USR of 22,960 mt, both in the long and short term for OM1, which is equivalent to $0.32B_0$ and $0.73B_{MSY}$ proxy (Table 20a,b); OM2 continued to show unreasonably low USRs.

Based on this analysis, DFO Science recommends that the final USR remain above 21,525 mt to ensure a low probability of entering the critical zone in the long and short term across all plausible scenarios. Since the testing was performed under conditions where F was reduced to low levels when biomass decreased below the LRP, a lower limit of 22,960 mt for the USR may be more robust to this uncertainty, but it is acknowledged that the assumption of an F = 0.06 in the critical zone is not well informed.

This information is considered guidance for setting a threshold to avoid when selecting a USR and does not preclude the choice of a higher USR (i.e., double the LRP). A higher USR is beneficial conservation-wise, but results in a trade-off with yield. However, along with foregoing yield, a higher USR also provides more stability to the fishery, as it allows for more time to transition between the high and low levels of F. The advised USRs are appropriate for HCRs with F equivalent to or below those prescribed by the generic HCR tested here (Figure 74); HCRs where F may exceed the levels tested would require a higher USR to remain precautionary. In general, it is recommended that the candidate USRs be tested with realistic HCRs, as less precautionary HCRs would require a higher USR. The generic HCR did not impose a limit on interannual changes of TAC beyond the smoothing of the survey; a characteristic that could not be incorporated at this time and is not expected to substantially change the final recommendations. The full tables were provided to facilitate discussion and allow resource managers to consider thresholds other than the 5%.

Simulation testing of various USRs as control points in a HCR was also carried out, resulting in the selection of 0.32 Bo (22,960 mt) as the Upper Stock Reference Point during a meeting of Scotia Fundy Groundfish Advisory Committee members, led by Fisheries and Oceans Canada (DFO) Resource Management in November 2022.

EASTERN COMPONENT – NAFO 4XMN

The management and assessment units differ for the WC Pollock (Figure 75). Resource managers have requested that DFO Science provide advice for the WC management unit as a whole, which includes a portion of the Eastern Component (EC) Pollock assessment unit encompassed by DFO statistical area 4Xmn. For Science, EC Pollock is considered a secondary stock, meaning that no regular assessment is carried out. Data on the EC stock is available from the commercial fishery (NAFO 4Xmn), the summer RV survey (NAFO 4XmnVW), and two Sentinel Surveys (NAFO 4VsW and 4Vn). Since 2011, the 4Xmn portion of the WC management unit was assigned a TAC of 700 mt, which could be caught anywhere in the 4X5 management unit. With the slow growth recently observed in EC Pollock, an invariable TAC for EC fish in statistical area 4Xmn may not be appropriate. In addition, given that allowing the EC TAC to be caught anywhere in the WC management unit could result in exceeding the advised F in NAFO 4Xopqrs5, it is recommended that the removal of any EC TAC be limited to the areas occupied by EC fish.

ASSESSMENT CYCLE AND EXCEPTIONAL CIRCUMSTANCES

The objective of the MSE assessment cycle is to achieve a balance between workload and retaining confidence in the appropriateness of advice. Given the complexity of the MSE process, five levels of review have been identified for this assessment framework. :

- (Level 1) Annual provision of advice: HCR update with new survey and generate new TAC advice.
- (Level 2) The model remains appropriate, but projections have very wide uncertainty after several years. This review updates accepted model with the most recent data and generates new projections (two generations). The HCR is evaluated to ensure it continues to perform well.
- (Level 3) Something has changed in the fishery dynamics which may require a modified HCR; understanding of stock dynamics has not changed. The accepted population model is updated with additional data, projected forward two generations, and both old and new HCRs are tested to see if modification is appropriate.
- (Level 4) Something has changed in stock dynamics or understanding of the stock, namely the recruitment cycle is not consistent If recruitment cycle not consistent with predicted AC/Cycle, update model with additional data, modify appropriate projection of recruitment, re-test MPs.
- (Level 5) Something has changed in stock dynamics or understanding of the stock, namely a change in growth, mortality or fecundity is evident, requires a full revision of MSE and reference points. This is also triggered if the stock dynamics move outside of predicted bounds.

The proposed timeline for these are an annual Level 1, with a check of exceptional circumstance to see if levels 3 through 5 are triggered the following year. After five years (2027), a Level 2 review is undertaken automatically. After ten years (2032), a Level 5 review is undertaken automatically. Aside from these scheduled reviews, levels 3 through 5 can be triggered in the interim if one of the following exceptional circumstance is met:

- \- Evidence of major shifts in the fishery logistics (Level 3)
- \- Evidence of a change in recruitment cycle for the stock (Level 4)

- - Empirical evidence that growth has changed, in either direction (Level 5)
- - Empirical evidence that the fecundity or spawning potential of the stock has changed. Examples of empirical evidence are shift in spawning timing, a change in age at maturity, etc. (Level 5)
- - Evidence of a change in the M experienced by the stock (Level 5)
- - Stock signals move outside of the predicted bounds (Level 5)

Additional exceptional circumstances may be added during the first application of the this assessment framework.

CONCLUSION

This document summarizes the outcomes of the modelling framework review, simulation conditions and reference point development of the Pollock 2011 MSE revision. The 2011 MSE process did not thoroughly review the population model and leaned heavily on the VPA population model accepted at the 2004 Framework (Stephenson 2004) to condition the OMs (Porter and Doherty 2011). Consequently, it has been 18 years since the population dynamics of WC Pollock have been examined, so modeling framework review was done in concurrence with the MSE revision to ensure that the population model(s) used to condition the OMs in 2022 reflected the current stock dynamics.

Major deviations from the 2011 MSE include the use of a statistical catch-at-age model (ASAP), the exclusion of the commercial CPUE as a tuning index, accounting for expansion in the survey coverage for the stock, and the inclusion of a new acoustic tuning index.

The current MSE was conditioned on a single accepted population model (J_M4B), with a reference set of Operating Models (2) examining uncertainty around projected recruitment, and a sensitivity set (3) examining impacts of an invariant M and a manually specified oscillation in recruitment. A change in the population model necessitated a new set of reference points for WC Pollock. An LRP of 14,350 mt and a RR of 0.18 were accepted, while additional analyses around candidate USRs resulted in DFO Resource Management accepting a value of 22,960 mt as the USR for WC Pollock. Exceptional circumstance and an assessment cycle for the next 10 years were outlined for WC pollock, and recommendations were made with respect to the EC pollock in 4Xmn portion of the WC management unit. The candidate management procedures will be simulation tested and the scorecard provided to DFO Resource Management for final decision making. Once the final management procedure is chosen, its application to provide advice will be outlined in a science advisory report.

SOURCES OF UNCERTAINTY

Throughout the review of the Pollock MSE, a number of uncertainties have been identified. They are summarized here both to frame the results of the MSE and to provide guidance for future research related to WC Pollock.

- The cause of the slower growth experienced by WC Pollock since the 2011 cohort remains unclear. Given that it appears to be tied to a cohort rather than a year, the cause is likely ecosystem-based, but no clear link could be established throughout the MSE process. Identification of a cause would help monitor the change and may help determine whether the change is permanent or reversible.
- The impact of slower growth on productivity of the stock remains unclear.

- Recruitment of WC Pollock appears to exhibit a multi-year oscillatory tendency, which is caused by something other than the SSB which produced it. Identifying a mechanistic relationship for SSB-independent impacts on recruitment would help improve the predictive capacity of the models.

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TABLES

Table 1. Pollock commercial fishery catch-at-age, updated with correct ages for 2017–2020. Units are in thousands of fish.

Year	2	3	4	5	6	7	8	9	10	11	12	13
1982	95	1,618	1,352	371	1,031	838	425	145	45	33	13	0
1983	45	1,283	3,966	854	179	314	291	138	59	17	19	0
1984	4	370	1,832	2,751	465	85	148	114	41	19	2	0
1985	5	195	621	1,806	2,142	328	38	100	99	62	30	0
1986	1	162	1,410	1,136	1,329	876	88	37	37	41	15	0
1987	5	104	628	1,622	883	786	490	68	17	15	28	0
1988	19	425	990	1,126	1,281	519	424	242	22	14	20	0
1989	93	386	1,533	1,129	576	463	147	129	65	6	7	0
1990	47	776	1,102	1,621	873	429	174	138	49	23	10	0
1991	58	1,013	1,900	1,506	1,395	347	157	56	49	25	10	0
1992	46	1,250	2,678	1,651	675	314	124	96	61	14	12	0
1993	4	551	1,989	2,125	1,143	318	92	27	10	7	6	0
1994	51	259	675	1,327	1,151	494	166	59	14	8	2	0
1995	24	263	537	949	676	294	63	17	4	1	1	0
1996	14	202	949	710	473	256	55	15	0	0	1	0
1997	6	151	900	1,654	780	217	54	4	0	1	0	0
1998	7	228	829	1,368	1,262	307	47	16	2	1	0	0
1999	13	89	496	621	426	173	22	4	1	2	0	0
2000	86	581	404	592	319	139	27	6	1	0	0	0
2001	15	335	814	571	314	91	14	5	2	1	1	0
2002	7	191	787	1,073	416	127	20	6	1	0	0	0
2003	2	111	1,302	1,331	513	120	18	5	1	1	0	0
2004	2	173	542	1,876	696	118	13	4	2	1	0	0
2005	0	37	842	759	1,160	170	13	5	1	0	0	0
2006	1	30	154	534	353	218	18	3	0	0	0	0
2007	5	69	370	453	619	223	28	3	1	0	0	0
2008	20	97	175	390	429	260	52	11	1	0	0	0
2009	25	336	296	291	357	157	51	7	2	0	0	0
2010	16	157	360	355	243	234	69	32	9	1	0	0
2011	63	307	698	430	186	93	25	15	3	0	0	0
2012	32	282	476	790	292	108	52	21	13	7	5	1
2013	29	189	341	436	362	122	40	11	3	3	2	1
2014	19	375	402	261	208	98	14	2	0	0	0	0
2015	11	171	908	452	213	125	19	2	0	0	0	0
2016	3	102	344	658	292	96	26	7	2	0	0	0
2017	6	28	253	307	431	167	37	10	6	1	0	0
2018	3	42	201	627	330	341	105	20	6	3	2	1
2019	1	94	194	242	448	216	134	50	14	5	2	0
2020	18	94	315	297	229	256	102	96	16	2	0	0

Table 2. *Number of DFO RV survey sets available within each year, season and area since 1984 (WC – western component, EGB – Eastern Georges Bank, GB -Georges Bank).*

YEAR	Winter Survey 4X_WC	Winter Survey EGB(Can)	Winter Survey GB(US)	Summer Survey 4X_WC	Summer Survey EGB(Can)	Summer Survey GB(US)
1984	37	0	40	36	0	0
1985	21	0	0	35	0	0
1986	0	0	77	37	0	0
1987	2	16	52	47	0	0
1988	0	52	80	52	0	1
1989	0	43	73	49	14	0
1990	0	45	78	46	10	0
1991	0	48	84	48	0	0
1992	0	43	48	49	0	1
1993	0	46	19	49	0	0
1994	0	30	15	43	0	0
1995	0	41	44	47	0	0
1996	0	42	44	46	0	0
1997	0	41	49	49	0	0
1998	0	47	49	48	0	0
1999	0	39	43	47	0	0
2000	0	45	55	47	0	0
2001	0	42	34	50	0	0
2002	0	44	45	50	0	0
2003	0	48	50	62	0	0
2004	0	45	40	40	0	0
2005	0	62	69	49	0	0
2006	0	51	41	58	0	0
2007	0	45	43	44	0	0
2008	24	34	36	52	0	0
2009	0	25	43	60	0	0
2010	0	35	31	52	0	1
2011	0	47	52	65	12	0
2012	30	50	32	56	9	1
2013	1	43	45	60	10	0
2014	33	34	37	52	2	0
2015	0	33	18	54	3	0
2016	45	38	49	62	20	0
2017	3	34	28	63	20	1
2018	0	39	21	50	2	0
2019	44	48	51	63	19	1
2020	35	39	26	53	16	0

Table 3. Number of Pollock measured during the summer RV survey on the Canadian portion of Eastern Georges Bank (EGB) or NAFO areas 4X during winter or summer surveys. Dashes (–) indicate no fish measured. Bold numbers indicate years where length-frequency comparisons across area and season were made.

Year	Winter_EGB	Summer_4X	Summer_EGB
1984	–	142	–
1985	–	137	–
1986	–	317	–
1987	41	245	–
1988	214	238	–
1989	172	174	27
1990	143	488	8
1991	215	304	–
1992	110	184	–
1993	21	301	–
1994	51	189	–
1995	31	203	–
1996	72	175	–
1997	81	154	–
1998	85	79	–
1999	14	142	–
2000	85	230	–
2001	42	261	–
2002	218	145	–
2003	257	236	–
2004	93	195	–
2005	192	166	–
2006	139	315	–
2007	64	152	–
2008	72	144	–
2009	8	178	–
2010	10	65	–
2011	160	184	143
2012	129	148	20
2013	53	322	47
2014	227	237	10
2015	321	125	15
2016	**33**	**644**	**579**
2017	**388**	**323**	**94**
2018	222	214	16
2019	**89**	**174**	**165**
2020	**86**	**262**	**115**

Table 4. Modeled Pollock abundance (number of fish) at age for Eastern Georges Bank in the summer survey.

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
1984	0	74,881	36,346	59,122	175,699	70,106	5,912	20,832	69,448	31,529	788	0	12,612
1985	13,292	0	53,169	161,410	541,371	658,892	166,948	0	66,462	26,585	48,739	53,169	17,723
1986	85,370	452,166	301,937	466,452	541,060	1,064,225	754,750	40,943	17,422	57,494	44,159	24,391	15,680
1987	0	165,241	285,170	474,288	1,066,176	413,047	784,933	465,114	39,537	75,295	27,676	48,840	76,516
1988	0	13,186	450,435	529,598	874,965	565,741	473,501	191,478	197,602	26,372	0	15,823	31,646
1989	0	124,454	123,836	376,899	158,315	133,477	73,620	13,423	13,748	8,694	0	0	12,112
1990	0	37,878	217,353	314,660	653,301	174,836	55,719	48,536	23,624	12,411	11,032	17,138	11,032
1991	4,778	385,535	1,142,094	925,074	997,326	777,169	232,875	162,665	45,159	3,982	1,858	1,593	0
1992	62,248	494,402	1,202,648	1,139,660	713,512	255,813	26,678	8,893	8,893	0	0	0	0
1993	0	216,995	692,147	716,491	744,604	488,877	187,934	10,259	20,519	0	0	0	10,259
1994	87,762	441,055	99,092	35,565	61,395	90,230	62,141	29,584	15,417	19,622	29,433	3,270	13,081
1995	7,632	148,432	347,968	365,685	414,480	171,791	50,595	17,012	15,701	9,947	34	34	0
1996	30,294	282,450	920,147	842,317	599,828	357,919	193,394	45,442	0	0	0	0	0
1997	0	12,319	52,120	144,702	357,412	153,680	23,826	23,525	0	0	0	0	0
1998	6,694	369,356	321,092	92,288	47,676	26,863	0	0	0	0	0	0	0
1999	142,863	313,670	256,014	384,755	234,303	139,880	89,014	0	0	0	0	0	0
2000	20,105	1,272,127	803,579	288,209	164,560	14,866	0	0	0	0	0	0	0
2001	22,774	1,032,126	957,732	622,771	224,431	66,596	34,161	11,387	0	0	0	0	0
2002	10,094	90,845	428,674	422,996	309,125	78,858	28,389	268	805	1,745	1,208	1,342	805
2003	0	107,902	413,996	668,782	443,654	214,387	0	0	0	0	0	0	0
2004	15,301	76,507	397,398	324,287	437,034	131,951	25,247	651	1,953	4,232	2,930	3,256	1,953
2005	14,980	818,410	1,207,019	1,009,465	840,137	1,548,482	785,055	138,340	96,547	46,792	21,295	16,284	7,683
2006	25,403	260,089	196,349	803,709	1,249,270	687,601	285,670	22,862	0	0	0	0	0
2007	0	558,915	315,165	303,689	226,315	237,420	123,755	20,461	0	0	0	0	0
2008	113,408	770,232	668,965	602,155	912,938	679,506	242,883	18,901	17,011	56,704	0	0	0
2009	0	290,215	180,608	236,616	273,497	305,371	139,816	8,251	34,381	0	0	0	0
2010	121,195	17,858	99,075	283,320	52,145	234,651	217,270	26,072	60,835	0	17,382	0	0

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
2011	0	184,462	482,240	457,693	361,481	287,590	203,382	127,452	0	21,391	0	0	0
2012	8,164	49,567	31,490	114,550	159,835	189,947	80,035	27,397	6,327	18,339	1,016	680	181
2013	0	306,285	704,634	442,335	157,236	23,454	16,376	5,866	0	0	0	0	0
2014	0	68,411	69,219	276,781	582,216	513,782	63,991	16,614	992	274	137	68	34
2015	0	104,133	526,996	484,142	457,507	273,224	176,715	89,607	1,283	1,013	473	405	0
2016	60,007	773,071	1,218,931	1,193,209	2,359,734	765,753	591,020	154,062	5,001	10,001	0	0	0
2017	0	9,169	53,580	231,271	329,492	604,868	132,370	387,882	22,009	1,866	5,108	754	452
2018	0	4,921	59,048	360,593	760,463	354,737	577,662	66,521	30,088	173	43	43	0
2019	0	19,215	86,290	126,811	417,264	694,016	360,489	260,232	30,851	0	0	0	0
2020	0	57,536	171,953	528,861	271,870	401,494	450,349	161,160	7,969	4,781	0	0	0

Table 5. Relative abundance Indices (thousands of fish) at age for Western Component Pollock, including the simulated eastern Georges Bank (EGB) index. Note that 2016, 2017, 2019 and 2020 include the actual indices of abundance collected by the survey of EGB, instead of the simulated ones.

Year	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1984	1,891	660	1,147	3,959	1,114	117	346	1,308	522	1	0	193
1985	0	169	731	3,794	4,792	1,021	0	434	138	220	304	47
1986	2,735	1,981	2,673	2,370	4,526	2,837	123	68	103	64	72	55
1987	207	358	1,198	3,184	1,693	3,379	1,790	105	196	72	138	176
1988	103	2,338	3,134	7,987	6,602	5,098	2,461	1,014	195	0	39	105
1989	202	236	935	1,712	2,372	2,211	663	390	162	0	41	78
1990	33,633	17,599	8,165	12,529	2,983	764	913	243	137	100	119	53
1991	1,790	3,283	2,819	4,288	4,051	1,250	1,078	450	151	80	20	0
1992	1,033	1,619	2,271	2,247	1,469	282	173	43	89	45	107	0
1993	11,809	14,350	10,021	5,481	2,565	776	29	118	0	0	0	42
1994	688	443	1,277	2,699	2,355	959	281	172	80	29	3	13
1995	669	2,065	1,756	2,653	1,299	390	74	112	69	0	0	0
1996	933	2,285	15,020	12,829	4,254	1,909	242	0	0	0	0	0
1997	508	453	690	2,206	1,027	116	127	0	0	0	0	0
1998	438	465	443	752	723	164	0	42	0	42	0	0
1999	866	872	1,356	797	572	399	0	0	0	0	0	0
2000	2,502	1,352	790	1,074	262	0	33	0	0	0	0	0
2001	6,485	8,937	2,710	970	269	141	37	0	0	0	0	0
2002	525	2,239	1,260	972	307	149	28	1	2	1	1	1
2003	360	1,448	7,594	2,898	776	24	28	0	0	0	0	0
2004	366	3,213	1,969	4,622	1,673	383	1	69	4	47	3	2
2005	885	1,301	2,414	2,383	4,307	1,265	138	97	47	21	16	8
2006	444	1,222	12,674	26,539	10,572	3,968	253	0	0	0	0	0
2007	793	393	1,162	3,937	4,542	888	154	10	0	0	0	0
2008	1,019	909	1,161	5,829	6,652	2,540	172	142	185	0	0	0
2009	1,344	1,424	2,588	4,357	5,884	3,130	36	552	0	0	0	0
2010	45	241	925	174	724	706	67	156	0	31	0	0
2011	702	1,095	1,555	1,315	902	425	187	16	21	0	0	0
2012	988	168	787	1,171	534	170	53	6	18	1	1	0
2013	6,924	4,517	2,492	3,715	1,039	416	72	0	0	0	0	0
2014	2,171	2,093	1,098	1,310	1,067	214	118	27	0	0	0	0
2015	885	907	1,485	933	454	395	143	1	1	0	0	0
2016	2,153	5,460	5,366	10,370	2,973	783	483	38	36	0	0	0
2017	413	951	2,269	1,738	2,608	630	270	82	16	38	0	0
2018	292	368	1,336	3,464	1,469	1,716	273	51	43	0	22	0
2019	148	438	542	1,402	1,865	844	688	104	0	22	28	0
2020	1,231	1,470	2,447	845	907	862	412	52	55	0	0	0

Table 6. Sum of residuals for each model examined across years in ADAPT framework. Dashes (-) show instances where data were not used in the model.

Model	**A**		**B**	**C_sen**	**C**	**D**		**E**		**F_MStat**		**F_M3B**		**F_M4B**		**F_M6B**	
Year	CPUE	RV	RV	RV	RV	RV	Acs	RV	Acs	RV	Acs	RV	Acs	RV	Acs	RV	Acs
1982	-0.71	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1983	-1.79	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1984	-0.70	-5.98	-6.00	-5.03	-4.64	-4.63	-	-11.65	-	-9.15	-	-8.54	-	-8.41	-	-8.50	-
1985	-3.25	-5.66	-5.66	-7.36	-6.18	-6.18	-	-5.38	-	-3.39	-	-2.93	-	-2.46	-	-2.99	-
1986	-0.72	-3.32	-3.34	-10.68	-9.87	-9.88	-	-7.16	-	-4.52	-	-3.89	-	-3.69	-	-3.89	-
1987	-0.42	-5.69	-5.70	-12.70	-11.89	-11.90	-	-6.60	-	-3.97	-	-3.34	-	-3.15	-	-3.36	-
1988	-1.67	3.63	3.62	-0.28	0.38	0.38	-	0.46	-	2.93	-	3.51	-	3.60	-	3.47	-
1989		-4.57	-4.59	-7.88	-7.22	-7.22	-	-6.60	-	-4.17	-	-3.60	-	-3.56	-	-3.68	-
1990	-1.22	4.89	4.87	7.78	8.59	8.59	-	7.50	-	10.00	-	10.54	-	10.53	-	10.35	-
1991	-0.07	1.09	1.08	0.30	0.54	0.55	-	0.62	-	2.77	-	3.12	-	2.74	-	2.83	-
1992	-1.87	-4.96	-4.98	-5.64	-5.39	-5.39	-	-3.80	-	-2.20	-	-2.25	-	-2.90	-	-2.83	-
1993	-0.64	1.62	1.61	5.57	5.71	5.73	-	5.34	-	5.84	-	5.20	-	4.46	-	4.71	-
1994	1.54	0.45	0.44	0.82	0.66	0.68	-	0.86	-	0.72	-	-0.54	-	-1.49	-	-2.02	-
1995	3.05	-0.39	-0.40	2.58	2.41	2.43	-	2.08	-	1.51	-	0.16	-	-0.99	-	-1.22	-
1996	3.77	7.72	7.71	8.11	7.74	7.77	-	7.14	-	6.91	-	5.91	-	5.33	-	5.64	-
1997	1.10	-3.59	-3.60	-3.36	-3.73	-3.70	-	-4.56	-	-4.63	-	-5.54	-	-5.91	-	-5.58	-
1998	0.98	-4.32	-4.33	-3.52	-3.43	-3.40	-	-2.06	-	-2.44	-	-3.62	-	-4.11	-	-4.06	-
1999	-0.90	-0.66	-0.66	-0.83	-0.84	-0.79	-	-0.78	-	-0.94	-	-1.87	-	-1.87	-	-1.55	-
2000	1.49	-2.24	-2.25	-1.74	-2.11	-2.09	-	-1.56	-	-1.92	-	-2.93	-	-2.73	-	-2.88	-
2001	-0.13	0.06	0.04	1.67	1.30	1.33	-	1.07	-	0.75	-	-0.42	-	-0.14	-	-0.54	-
2002	1.48	-3.09	-3.11	-3.21	-3.59	-3.55	-	-11.66	-	-12.19	-	-13.88	-	-13.71	-	-13.98	-
2003	0.67	-0.54	-0.55	-1.40	-1.78	-1.74	-	-2.45	-	-2.91	-	-4.18	-	-3.99	-	-4.29	-
2004	-0.18	3.18	3.18	6.78	6.87	6.90	-	1.39	-	0.54	-	-1.34	-	-1.31	-	-1.43	-
2005	-	-0.04	-0.04	-1.70	-1.71	-1.67	-	14.24	-	13.07	-	11.06	-	11.03	-	11.01	-
2006	-	12.77	12.76	12.54	12.16	12.20	-	11.59	-	10.71	-	9.45	-	9.63	-	9.40	-

Model	**A**		**B**	**C_sen**	**C**	**D**		**E**		**F_MStat**		**F_M3B**		**F_M4B**		**F_M6B**	
Year	CPUE	RV	RV	RV	RV	RV	Acs	RV	Acs	RV	Acs	RV	Acs	RV	Acs	RV	Acs
2007	-	1.85	1.83	1.95	1.53	1.56	-	3.09	-	1.96	-	0.80	-	0.96	-	0.88	-
2008	-	4.39	4.37	9.08	8.92	8.94	-	11.36	-	9.92	-	9.09	-	9.31	-	9.35	-
2009	-	5.70	5.69	8.55	8.13	8.16	-	7.10	-	6.16	-	6.10	-	6.52	-	6.07	-
2010	-	-4.61	-4.63	-6.40	-6.68	-6.66	-	-4.38	-	-5.48	-	-4.42	-	-4.07	-	-4.35	-
2011	-	-0.22	-0.24	-1.16	-1.59	-1.55	-	-0.41	-	-1.33	-	0.33	-	0.57	-	0.13	-
2012	-	-3.86	-3.87	-3.09	-3.46	-3.42	-3.26	-9.83	-3.25	-11.35	-3.80	-9.28	-3.13	-8.98	-3.02	-9.13	-3.71
2013	-	6.02	6.01	8.20	7.82	7.92	-	6.51	-	4.88	-	6.60	-	6.67	-	6.45	-
2014	-	0.40	0.40	2.46	2.06	2.11	-	2.16	-	-0.23	-	1.76	-	1.81	-	2.21	-
2015	-	-4.01	-4.00	-3.51	-3.86	-3.95	-	-7.77	-	-10.33	-	-8.29	-	-8.21	-	-7.62	-
2016	-	5.15	5.19	7.15	7.07	6.86	3.50	7.68	3.40	5.77	2.27	7.47	2.88	7.59	2.91	7.75	2.72
2017	-	1.33	1.42	1.46	1.23	0.86	-1.82	0.37	-1.85	-1.11	-2.53	0.40	-2.15	0.60	-2.10	0.85	-2.19
2018	-	0.49	0.68	0.26	0.21	-0.26	-0.19	-0.95	-0.15	-1.74	-0.22	-0.65	-0.28	-0.44	-0.22	-0.26	-0.40
2019	-	-0.45	-0.05	-1.87	-1.75	-2.38	-3.44	-1.00	-3.21	-1.16	-2.62	-0.58	-3.11	-0.36	-3.03	-0.08	-2.97
2020	-	1.48	2.42	1.19	1.61	0.34	8.06	1.10	7.96	1.86	9.37	1.65	8.16	1.38	7.79	2.78	9.03
Total	-0.20	3.98	5.31	5.11	5.20	2.92	2.85	3.07	2.89	1.14	2.48	1.07	2.38	0.25	2.33	-0.38	2.48

Table 7. Overall residual performance metrics for all models considered. Yellow highlighted rows identify the two final models, with Model J_M4B chosen as a reference model and Model I as a sensitivity. NA = Not Applicable.

Model	Index	SDNR	SumResid	MSSR	ADAPT_MSSR	ASAP_ObjFun
Model A	RV	4.042	3.975	0.937	0.738	NA
Model A	CPUE	-0.402	-0.197	0.240	NA	NA
Model B	RV	5.388	5.311	0.942	1.021	NA
Model C - Sensitivity	RV	4.727	5.106	0.833	1.226	NA
Model C	RV	4.761	5.204	0.853	1.237	NA
Model D	RV	2.678	2.915	0.846	1.141	NA
Model D	Acoustic	4.002	2.850	0.355	NA	NA
Model D - Link	RV	2.815	3.065	0.846	1.141	NA
Model D - Link	Acoustic	4.002	2.850	0.355	NA	NA
Model E	RV	2.780	3.067	0.951	1.172	NA
Model E	Acoustic	4.093	2.893	0.349	NA	NA
Model F - Mstat	RV	1.054	1.142	0.918	1.142	NA
Model F - Mstat	Acoustic	3.314	2.478	0.390	NA	NA
Model F - M3B	RV	0.992	1.066	0.904	1.118	NA
Model F - M3B	Acoustic	3.311	2.377	0.360	NA	NA
Model F - M4B	RV	0.230	0.246	0.898	1.115	NA
Model F - M4B	Acoustic	3.322	2.334	0.344	NA	NA
Model F - M6B	RV	-0.354	-0.376	0.879	1.109	NA
Model F - M6B	Acoustic	3.365	2.485	0.380	NA	NA
Model I	RV	-161.077	-210.660	1.624	NA	4246
Model I	Acoustic	-17.472	-17.068	0.742	NA	NA
Model J - Mstat	RV	-155.348	-203.381	1.607	NA	4352
Model J - Mstat	Acoustic	-16.698	-16.545	0.756	NA	NA
Model J - M3B	RV	-150.899	-199.628	1.626	NA	4418
Model J - M3B	Acoustic	-19.210	-18.014	0.699	NA	NA
Model J - M4B	RV	-151.176	-188.175	1.440	NA	3984
Model J - M4B	Acoustic	-19.260	-18.040	0.698	NA	NA
Model J - M6B	RV	-146.854	-197.748	1.670	NA	4530
Model J - M6B	Acoustic	-17.212	-17.481	0.800	NA	NA

Table 8. Outputs of each model in relation to the estimated q parameter for the summer survey. Yellow highlighted rows identify the two final models, with Model J_M4B chosen as a reference model and Model I as a sensitivity. Dashes (-) show instances where data were not used in the model. RV-Research Vessel, Acs-Acoustic.

Model	Index	Statistic	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13
A	RV	Est.	-	0.0002	0.0005	0.0012	0.0018	0.0021	0.0016	-	-	-	-	-
		Rel. Err.	-	0.145	0.145	0.143	0.143	0.145	0.155	-	-	-	-	-
		Rel. Bias	-	0.005	0.006	0.007	0.008	0.009	0.015	-	-	-	-	-
B	RV	Estimate	-	0.0002	0.0005	0.0012	0.0018	0.0021	0.0016	-	-	-	-	-
		Rel. Err.	-	0.170	0.168	0.168	0.168	0.171	0.183	-	-	-	-	-
		Rel. Bias	-	0.007	0.008	0.010	0.011	0.013	0.021	-	-	-	-	-
C_sen	RV	Estimate	0.0001	0.0002	0.0005	0.0012	0.0017	0.0021	0.0016	0.0022	0.0031	0.0027	0.0030	0.0041
		Rel. Err.	0.188	0.185	0.184	0.184	0.184	0.187	0.198	0.231	0.286	0.334	0.369	0.392
		Rel. Bias	0.012	0.012	0.013	0.015	0.014	0.017	0.022	0.027	0.041	0.056	0.068	0.077
C	RV	Estimate	0.0001	0.0002	0.0005	0.0012	0.0017	0.0021	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024
		Rel. Err.	0.188	0.186	0.185	0.185	0.184	0.187	0.113	0.113	0.113	0.113	0.113	0.113
		Rel. Bias	0.012	0.012	0.013	0.015	0.014	0.017	0.007	0.007	0.007	0.007	0.007	0.007
D		Estimate	0.0001	0.0002	0.0005	0.0012	0.0017	0.0021	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024
		Rel. Err.	0.180	0.178	0.177	0.177	0.176	0.179	0.109	0.109	0.109	0.109	0.109	0.109
	RV	Rel. Bias	0.013	0.012	0.013	0.014	0.014	0.015	0.006	0.006	0.006	0.006	0.006	0.006
		Estimate	0.0013	0.0009	0.0015	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017
		Rel. Err.	0.462	0.464	0.455	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
	Acs	Rel. Bias	0.095	0.092	0.089	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
D_sen		Estimate	0.2024	0.3360	0.7230	1.6500	2.5100	3.0600	2.1200	2.1200	2.1200	2.1200	2.1200	2.1200
		Rel. Err.	0.207	0.204	0.203	0.203	0.203	0.206	0.105	0.105	0.105	0.105	0.105	0.105
	RV	Rel. Bias	0.017	0.016	0.017	0.019	0.019	0.020	0.005	0.005	0.005	0.005	0.005	0.005
		Estimate	0.0014	0.0010	0.0015	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016
		Rel. Err.	0.530	0.533	0.524	0.231	0.231	0.231	0.231	0.231	0.231	0.231	0.231	0.231
	Acs	Rel. Bias	0.124	0.122	0.118	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021
I	RV	Estimate	0.303	0.516	1.009	1.672	1.672	1.662	1.672	1.672	1.672	1.672	1.672	1.672
	Acs	Estimate	0.0018	0.0016	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
J_Mstat	RV	Estimate	0.150	0.272	0.551	0.923	0.923	0.920	0.923	0.923	0.923	0.923	0.923	0.923
	Acs	Estimate	0.0010	0.0008	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
J_M3B	RV	Estimate	0.105	0.196	0.405	0.691	0.691	0.690	0.691	0.691	0.691	0.691	0.691	0.691
	Acs	Estimate	0.0007	0.0006	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007
J_M4B	RV	Estimate	0.139	0.218	0.377	0.644	0.644	0.644	0.644	0.644	0.644	0.644	0.644	0.644
	Acs	Estimate	0.0007	0.0006	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007
J_M6B	RV	Estimate	0.096	0.185	0.394	0.691	0.691	0.691	0.691	0.691	0.691	0.691	0.691	0.691
	Acs	Estimate	0.0008	0.0006	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008

Table 9. ADAPT outputs of each model in relation to the estimated q and α parameters for the CPUE index.

Model	Statistic	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8
Model A	q estimate	6.27E-07	1.11E-05	9.97E-05	1.41E-04	8.95E-05	1.55E-05
Model A	Rel. Err.	3.155	3.115	2.472	1.776	1.011	0.639
Model A	Rel. Bias	4.978	4.851	3.056	1.577	0.511	0.204
Model A	a estimate	1.01	0.85	0.64	0.58	0.57	0.80
Model A	Rel. Err.	0.362	0.443	0.505	0.458	0.314	0.173
Model A	Rel. Bias	0	0	0	0	0	0

Table 10. Total and age-disaggregated acoustic biomass index (mt) for WC Pollock from the RV Survey. LowCI and HighCI columns represent the bootstrapped confidence intervals around the total. Dashes (-) show instances where data were not used in the model.

Year	2	3	4	5	6	7	8	9	10	11	12	13	Total	LowCI	HighCI
2012.5	3,376	492	2,421	3,637	1,237	324	92	-	-	-	-	-	11,578	11,511	11,636
2013.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2014.5	-	-	-	-	-	-	-	-	-	-	-	-	-		-
2015.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2016.5	4,303	5,642	7,798	14,240	3,578	756	576	-	77	-	-	-	36,969	36,758	37,162
2017.5	873	1,898	4,025	3,392	4,770	796	533	95	-	48		-	16,431	16,355	16,504
2018.5	687	692	2,152	6,802	2,607	2,770	452	-	155	-	-	-	16,317	16,271	16,362
2019.5	343	905	1,036	2,118	2,464	1,276	1,008	74	-	52	64	-	9,341	9,298	9,382
2020.5	7,691	7,884	12,282	3,526	2,365	2,956	1,017	339	347	-	-	-	38,061	37,501	39,286

Table 11. Relative error and relative bias associated with estimates of natural mortality (M) for blocks of years for ages 2–4 under the Model B formulation. These outputs are generated as part of a sensitivity run on Model B.

Sensitivity Run	Ages	TimeBlock	Estimate	Rel. Err.	Rel. Bias.
One Block	2–4	1994–2020	0.31	0.612	-0.035
Two Block	2–4	1994–2010	0.25	0.780	-0.045
Two Block	2–4	2011–2020	0.66	0.435	-0.031
Three Block	2–4	1994–2000	0.22	1.071	-0.07
Three Block	2–4	2000–2010	0.29	0.756	-0.033
Three Block	2–4	2011–2020	0.67	0.433	-0.03

Table 12. Natural mortality estimated for each model, by age and year block. Yellow highlighted cells show the parameterization of the chosen reference model.

Model	Year Block	Age Block	Estimate	Rel. Err.	Rel. Bias
Model F - Mstat	1994–2020	2–13	0.384	0.136	-0.080
	1994–2000	2–13	0.496	0.207	-0.007
	2001–2010	2–13	0.507	0.139	-0.003
Model F - M3B	2011–2020	2–13	0.322	0.188	-0.013
	1994–2000	5–13	0.661	0.184	-0.013
	2001–2010	5–13	0.587	0.141	-0.006
Model F - M4B	2011–2020	5–13	0.341	0.212	-0.016
	1994–2000	2–7	0.431	0.288	-0.010
	1994–2000	8–13	0.748	0.218	-0.018
	2001–2010	2–7	0.547	0.173	-0.003
	2001–2010	8–13	0.479	0.262	-0.015
	2011–2020	2–7	0.444	0.196	-0.015
Model F - M6B	2011–2020	8–13	0.163	0.678	-0.029

Table 13. Residual sum of squares for survey trawl, survey acoustic and CPUE indices within each model examined across age. Yellow highlighted rows identify the two selected models, with Model J_M4B chosen as a reference model and Model I as a sensitivity. Dashes (-) show instances where data were not used in the model.

Model	Index	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Age11	Age12	Age13	Total	Mean
A	RV	-	63.5	33.3	30.4	23.6	30.0	27.3	-	-	-	-	-	208.0	34.7
	CPUE	-	9.2	3.0	3.5	4.3	4.7	7.0	-	-	-	-	-	31.6	5.3
B	RV	-	64.0	33.5	30.5	23.5	30.0	27.6	-	-	-	-	-	209.0	34.8
C_sen	RV	78.8	64.4	33.6	30.4	24.3	30.0	27.5	27.4	24.2	18.1	7.8	3.5	369.9	30.8
C	RV	78.9	64.4	33.7	30.4	24.3	30.0	31.8	27.4	25.2	18.4	8.4	6.0	378.8	31.6
D	RV	78.4	63.7	33.1	30.5	24.9	30.4	31.4	25.1	25.2	18.4	8.7	5.9	375.8	31.3
	Acs	5.3	5.4	2.9	1.4	0.2	1.5	1.9	4.0	0.6	0.2	1.5	-	24.8	2.3
D - Link	RV	78.3	63.6	33.2	30.5	25.0	30.4	31.4	25.1	25.2	18.4	8.7	5.9	375.7	31.3
	Acs	5.3	5.4	3.0	2.0	0.1	1.6	1.9	4.2	0.5	0.2	1.4	-	25.5	2.3
E	RV	52.6	44.0	28.5	26.2	20.6	30.4	39.7	52.4	41.2	58.3	17.2	11.1	422.2	35.2
	Acs	4.4	5.9	3.4	2.3	0.2	1.3	1.4	4.0	0.6	0.2	1.5	-	25.1	2.3
F_Mstat	RV	49.9	39.2	24.5	24.5	19.2	29.0	39.7	53.0	41.7	55.3	18.4	13.3	407.6	34.0
	Acs	6.1	6.3	3.6	2.2	0.2	1.7	1.4	3.6	1.0	0.3	1.7	-	28.1	2.6
F_M3B	RV	53.2	39.0	24.0	23.6	18.7	28.6	41.9	48.5	38.1	53.5	18.3	13.8	401.2	33.4
	Acs	6.0	5.6	3.3	2.0	0.2	1.3	1.2	3.4	0.9	0.2	1.7	-	25.9	2.4
F_M4B	RV	50.9	39.7	24.2	23.7	18.8	28.9	43.6	46.8	36.4	51.8	18.7	14.9	398.5	33.2
	Acs	5.0	5.7	3.3	2.0	0.2	1.3	1.2	3.2	1.0	0.2	1.8	-	24.8	2.3
F_M6B	RV	52.1	37.4	22.9	23.2	18.5	30.3	44.8	44.0	33.5	52.7	17.8	12.9	390.1	32.5
	Acs	6.9	6.1	3.5	1.8	0.2	1.4	1.4	3.3	0.9	0.2	1.7	-	27.4	2.5
I	RV	53.2	44.2	28.6	25.9	22.3	30.7	96.3	115.4	79.1	99.9	68.4	57.1	721.0	60.1
	Acs	5.0	6.7	4.3	2.9	0.6	2.8	7.1	12.3	4.3	6.3	1.2	-	53.4	4.9
J_Mstat	RV	50.8	39.3	24.2	23.8	21.0	30.8	101.8	118.9	79.3	94.1	70.2	59.5	713.6	59.5
	Acs	5.0	7.4	4.8	3.2	0.8	3.0	7.3	11.6	4.3	6.0	1.0	-	54.5	5.0
J_M3B	RV	53.4	38.3	25.4	25.9	26.3	37.0	102.2	114.1	75.7	89.0	70.8	63.6	721.8	60.2
	Acs	4.7	5.5	3.5	2.6	0.3	2.0	6.2	13.4	4.3	6.5	1.4	-	50.3	4.6
J_M4B	RV	51.2	38.4	24.1	23.2	21.3	30.4	89.9	103.9	66.0	79.5	57.6	44.3	629.9	52.5
	Acs	5.0	5.9	3.8	2.4	0.5	2.5	6.3	12.4	4.4	6.2	1.1	-	50.4	4.6
J_M6B	RV	52.7	38.6	26.4	27.3	29.8	41.9	104.2	115.4	82.8	91.8	74.7	55.9	741.6	61.8
	Acs	4.9	6.6	4.2	3.2	0.6	1.4	5.1	13.2	5.9	9.5	3.0	-	57.6	5.2

Table 14. Sensitivity runs to investigate the impact of the stock recruitment relationship steepness parameter on the value of the objective function in ASAP. Dashes (-) indicate instances where the model did not converge.

Model	Steepness	ASAP_ObjFun
G	0.2	3,190
G	0.65	2,936
G	0.8	2,996
G	0.99	3,143
H_Mstat	0.65	3,041
H_Mstat	0.9	3,103
H_M3B	0.65	3,190
H_M3B	0.9	3,157
H_M3B	0.99	3,143
H_M4B	0.3	-
H_M4B	0.4	2,991
H_M4B	0.65	3,052
H_M4B	0.9	3,068
H_M6B	0.4	3,230
H_M6B	0.5	3,191
H_M6B	0.65	3,167
H_M6B	0.9	3,314

Table 15. Mohn's rho metrics calculated on spawning stock biomass (SSB) and fishing mortality (F) for Models I and J and five and seven year peels. Bold values identify those which are considered acceptable by Hurtado-Ferro et al. (2015). Yellow highlighted rows identify the two chosen models, with Model J_M4B chosen as a reference model and Model I as a sensitivity.

Model	Five year peel SSB	Five year peel F	Seven year peel SSB	Seven year peel F
Model I - M02	**-0.092**	0.257	**-0.053**	0.271
Model J Mstat	-0.229	0.556	-0.264	0.675
Model J M3B	**-0.073**	**0.197**	**-0.101**	0.272
Model J M4B	**0.062**	**-0.004**	**0.076**	**0.000**
Model J M6B	-0.152	0.348	-0.166	0.431

Table 16. Management objectives and accompanying performance metrics for the 2022 Pollock management strategy evaluation (MSE). NA = Not Applicable; LRP – limit reference point, TAC – total allowable catch.

General intent	Aspirational objective	Measure	Probability	Time
Maintain the stock above the LRP and avoid fishery induced declines to below the LRP	Avoid fishery-induced decline of spawning biomass/abundance below LRP	The probability of the Spawning biomass/abundance falling below the LRP.	Low (5–25%)	Two generations (between now and 12 years)
Adjust level of precaution depending on stock status (DFO SFF Table 1)	Promote stock growth to the Healthy Zone	Spawning biomass/abundance status and trend.	Probability of growth high at LRP (75%) to neutral (50%) at USR	Two generation (between now and 12 years)
Provide stable inter-annual TACs **(Industry)**	Avoid large inter-annual changes in TAC (15%)	Average Number of years in each projection that interannual change in TAC exceeds 15%, in the short, medium and long terms	NA	2023–2030 2023–2036 2023–2045
Maintaining TAC above a certain level **(Industry)**	Maintaining TAC above a certain value (proposed 3000 mt)	Average Number of years in each projection that TAC exceeds 3000 mt in short, medium and long term	NA	2023–2030 2023–2036 2023–2045

Table 17. Scorecard example for Objectives 1 and 2. Table shows proportion of simulations falling below limit reference point (LRP) or above upper stock reference (USR) in the terminal year (2034, two generations away from 2022). MP– management type, OM – operating model.

MP	OM	PropBelowLRP	PropAboveUSR
CC1	OM1	11.0%	69.7%
CC1	OM2	0.0%	100.0%
CC1	OM3	26.0%	48.7%
CC2	OM1	7.1%	77.5%
CC2	OM2	0.0%	100.0%
CC2	OM3	19.1%	57.7%
Islope1	OM1	2.7%	83.6%
Islope1	OM2	0.0%	100.0%
Islope1	OM3	9.7%	66.0%
Islope2	OM1	1.7%	88.6%
Islope2	OM2	0.0%	100.0%
Islope2	OM3	6.7%	72.6%

Table 18. Scorecard example for objective 3. Mean proportion (across simulations) of years within each time period where interannual change in total allowable catch (TAC) exceeded 15% threshold.

MP	OM	Long(2022–2045)	Med (2022–2036)	Short (2022–2030)
CC1	OM1	0.0%	0.0%	0.0%
CC1	OM2	0.0%	0.0%	0.0%
CC1	OM3	0.0%	0.0%	0.0%
CC2	OM1	0.0%	0.0%	0.0%
CC2	OM2	0.0%	0.0%	0.0%
CC2	OM3	0.0%	0.0%	0.0%
Islope1	OM1	5.1%	4.1%	2.4%
Islope1	OM2	4.2%	3.3%	2.0%
Islope1	OM3	5.2%	4.1%	2.4%
Islope2	OM1	5.1%	4.1%	2.4%
Islope2	OM2	4.2%	3.4%	2.1%
Islope2	OM3	5.1%	4.0%	2.4%

Table 19. Proposed candidate reference points and removal references for Western Component Pollock for two natural mortality (M) scenarios (LRP – limit reference point; RR – removal reference, NA - not applicable.

ReferencePoint	Metric	Model	M Assumption (5+)	M Time Period	Value
LRP	0.4BMSY	Model J	0.34	2011–2020	9,738
LRP	0.2B0	Model J	0.34	2011–2020	14,350
LRP	0.4BF40%SPR	Model J	0.34	2011–2022	12,642
LRP	Brecover	Model J	NA	NA	16,701
RR	FMSY	Model J	0.34	2011–2020	0.175
RR	F40%SPR	Model J	0.34	2011–2020	0.187
LRP	0.4BMSY	Model J	0.415	1982–2020	7,583
LRP	0.2B0	Model J	0.415	1982–2020	10,749
LRP	0.4BF40%SPR	Model J	0.415	1982–2020	9,879
LRP	Brecover	Model J	NA	NA	16,701
RR	FMSY	Model J	0.415	1982–2020	0.185
RR	F40%SPR	Model J	0.415	1982–2020	0.220

*Table 20a. Summary of candidate upper stock reference (USR) simulations under a generic harvest control rule (HCR) with a fishing mortality (F) in the critical zone ($F_{critical}$) of 0.00001*RR and two operating models (OM) (OM1 and OM2). Orange highlighted cells show the lowest USR segment where the proportion of simulations below the limit reference point < 5%.*

USR	OM1 40Year	OM2 2Gen	OM2 40Year	OM2 2Gen
14,350	9.60%	7.00%	1.80%	1.30%
15,785	8.20%	6.10%	1.50%	1.30%
17,220	7.10%	5.30%	1.20%	1.00%
18,655	6.20%	4.70%	1.00%	1.00%
20,090	5.20%	4.10%	0.80%	0.80%
21,525	4.40%	3.10%	0.60%	0.50%
22,960	3.60%	2.50%	0.50%	0.50%
24,395	3.00%	1.80%	0.40%	0.40%
25,830	2.40%	1.50%	0.30%	0.30%
27,265	2.10%	1.20%	0.20%	0.30%
28,700	1.80%	1.10%	0.10%	0.20%

Table 21b. Summary of candidate upper stock reference (USR) simulations under a generic harvest control rule (HCR) with a fishing mortality (F) in the critical zone ($F_{critical}$) of 0.06 and two operating models (OM) (OM1 and OM2). Orange highlighted cells show the lowest USR segment where the proportion of simulations below the limit reference point < 5%.

	$F_{critical}$=0.06	
USR	OM1 40Year	OM1 2Gen
14,350	10.7%	10.3%
15,785	9.4%	8.9%
17,220	8.3%	7.7%
18,655	7.2%	7.1%
20,090	6.2%	6.1%
21,525	5.4%	5.6%
22,960	4.5%	4.6%
24,395	3.8%	4.1%
25,830	3.3%	3.6%
27,265	2.7%	2.9%
28,700	2.2%	2.2%

FIGURES

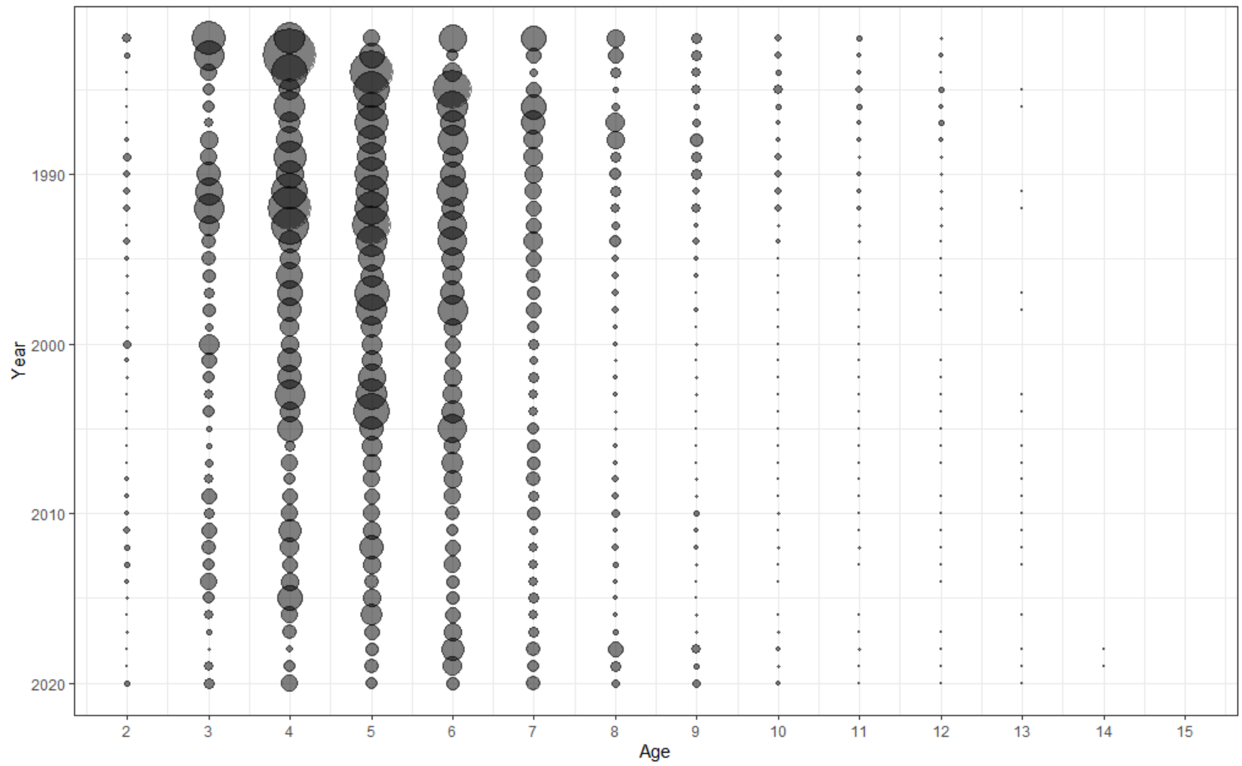


Figure 1. Pollock commercial fishery catch at age updated with corrected ages for 2017–2020. The size of the bubble is proportional to abundance.

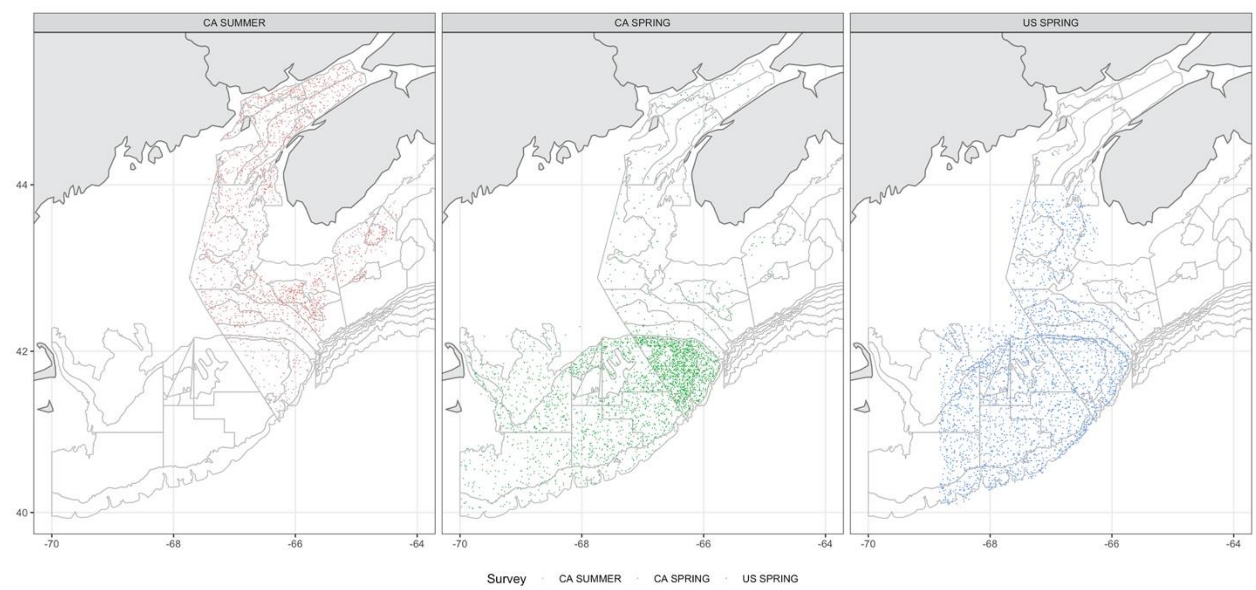


Figure 2. Spatial coverage of the DFO summer (CA summer) and winter (CA spring) research vessel surveys and the US Spring survey in 1983–2021 respectively. The DFO summer survey did not sample eastern Georges Bank consistently.

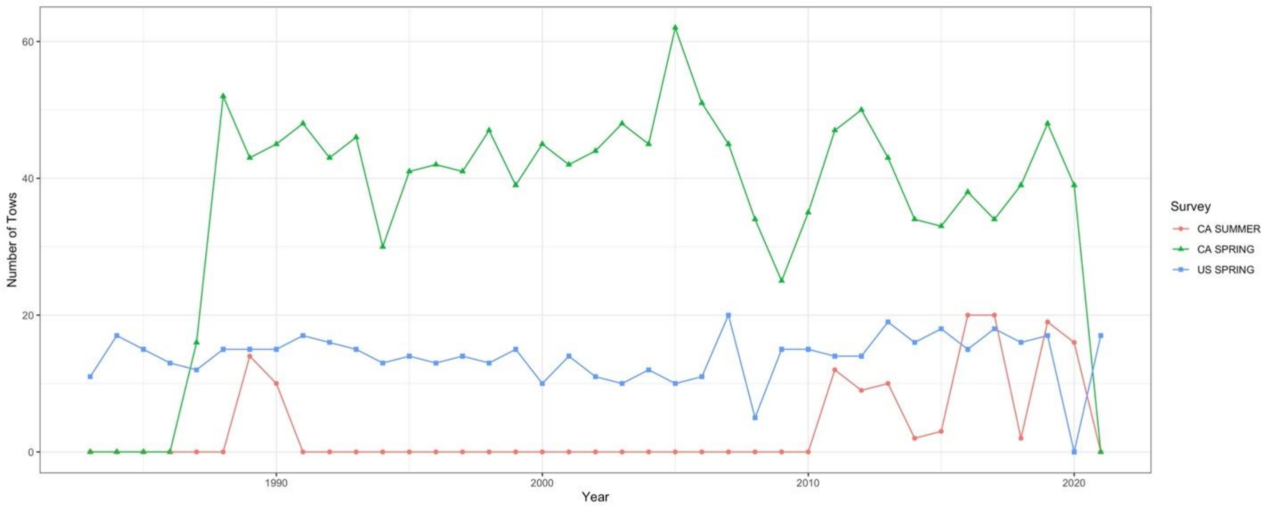


Figure 3. Temporal coverage of the DFO winter (CA spring) and summer (CA summer) research vessel surveys and the US Spring survey on eastern Georges Bank in 1983–2021.

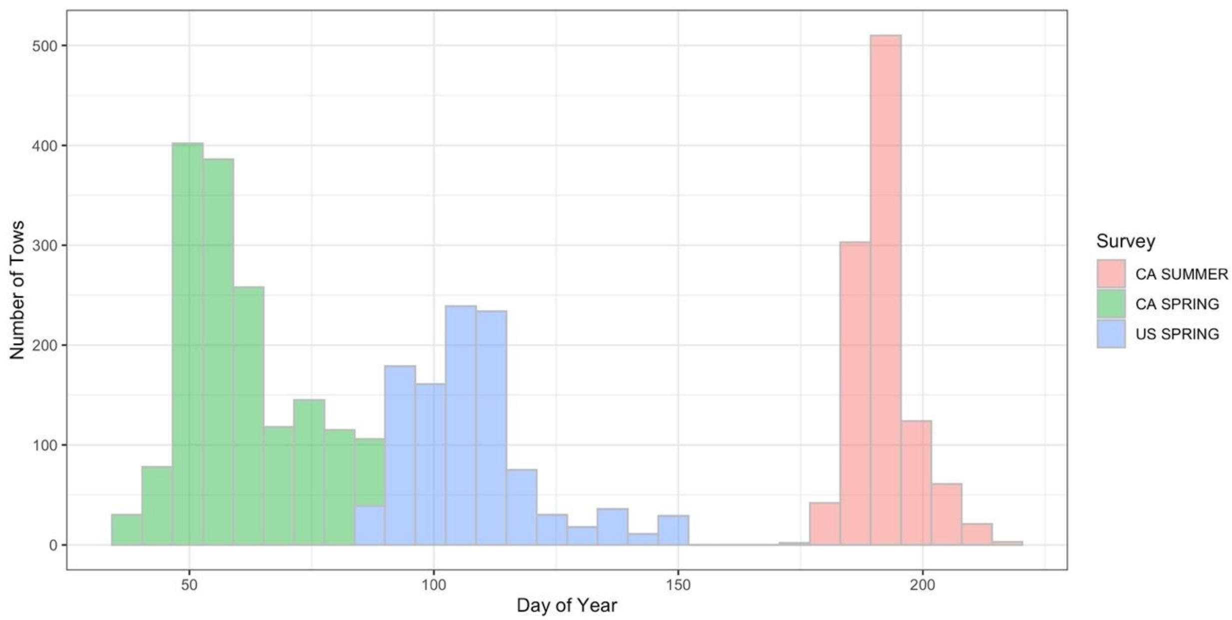


Figure 4. Historical survey dates of the DFO winter (CA spring) and summer (CA summer) research vessel surveys and the US Spring survey.

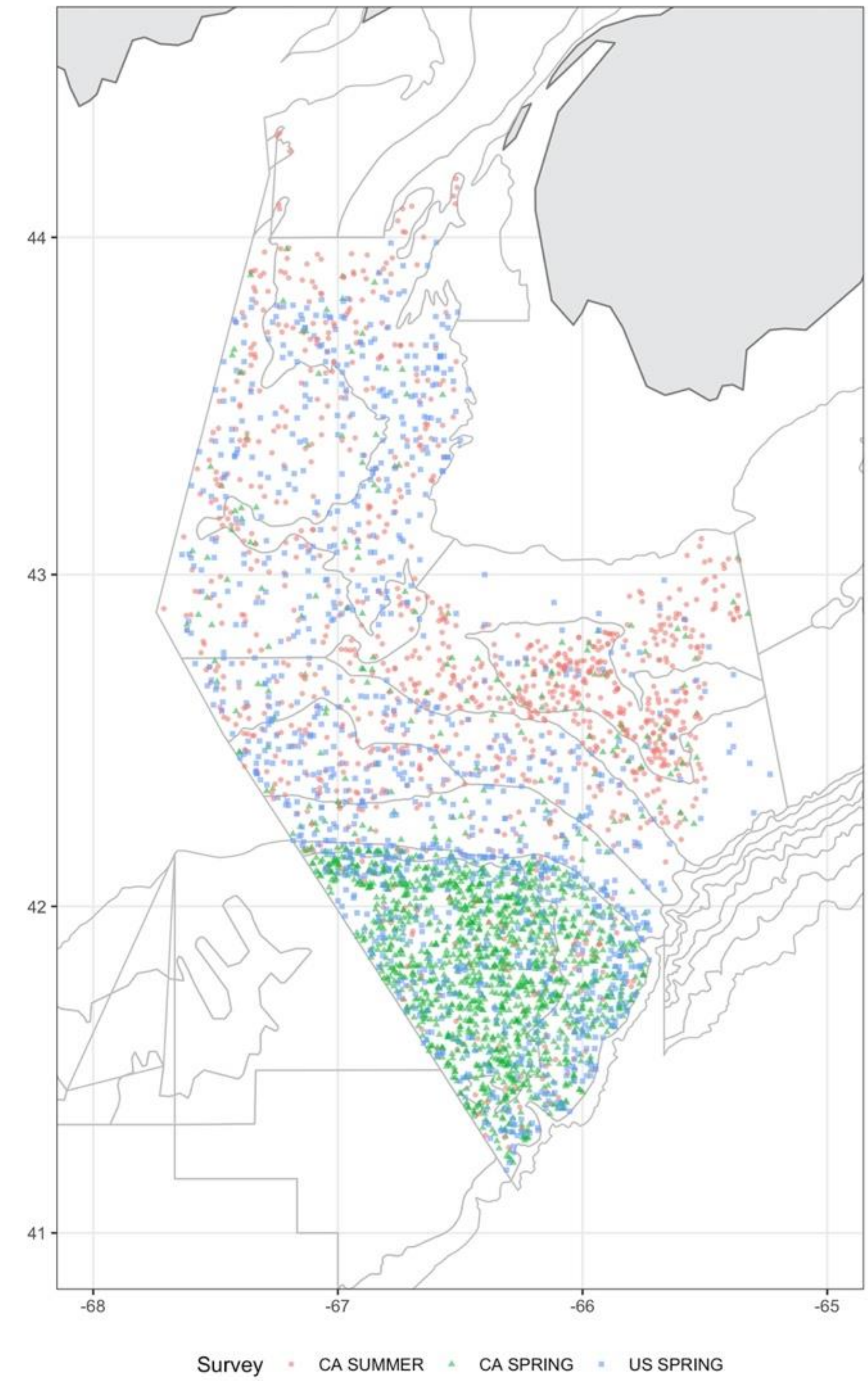


Figure 5. All tow locations within the study area. The study area was restricted to the DFO summer research vessel survey strata 480–485 and 5Z1, 5Z2, and 5Z9. Eastern Georges Bank is composed of 5Z1, 5Z2, and 5Z9 and is the focus of this analysis; 480–485 were included in the analysis to optimize overlap information among the surveys and to improve model performance.

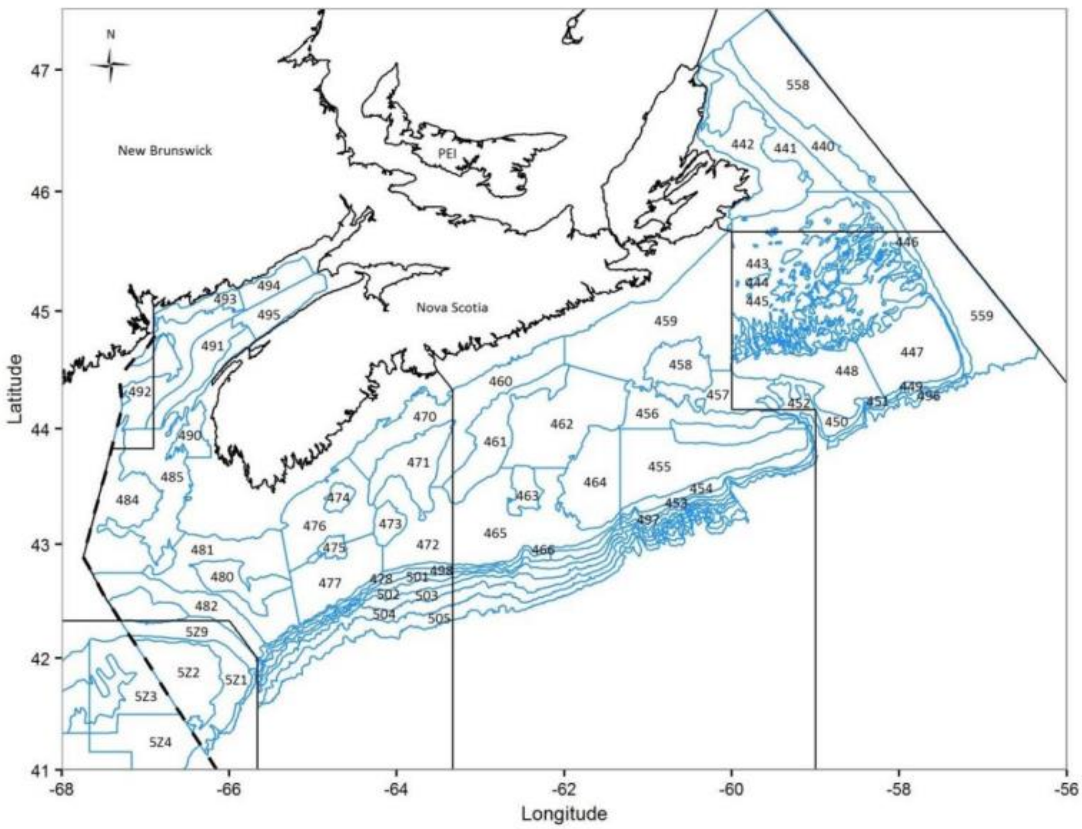


Figure 6. DFO summer research vessel survey strata.

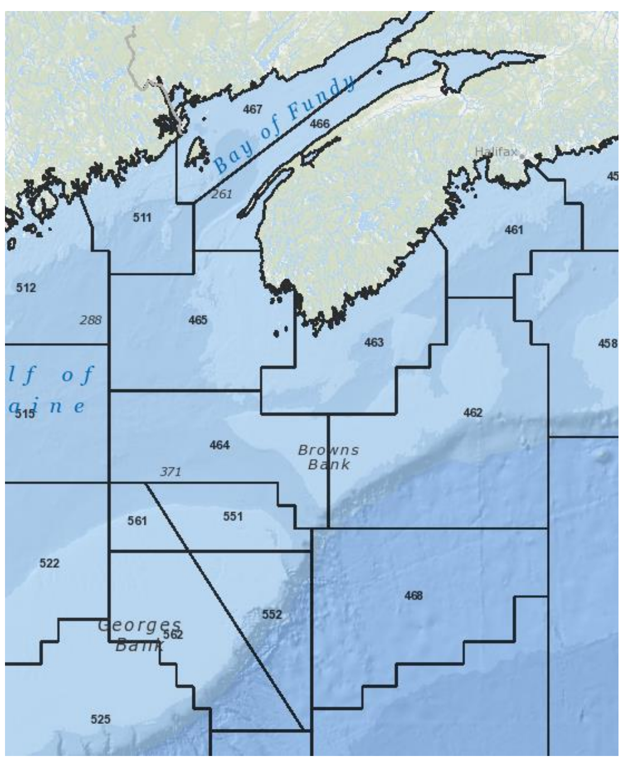


Figure 7. Fisheries statistical reporting areas for the US data. Figure originally from NOAA 2022.

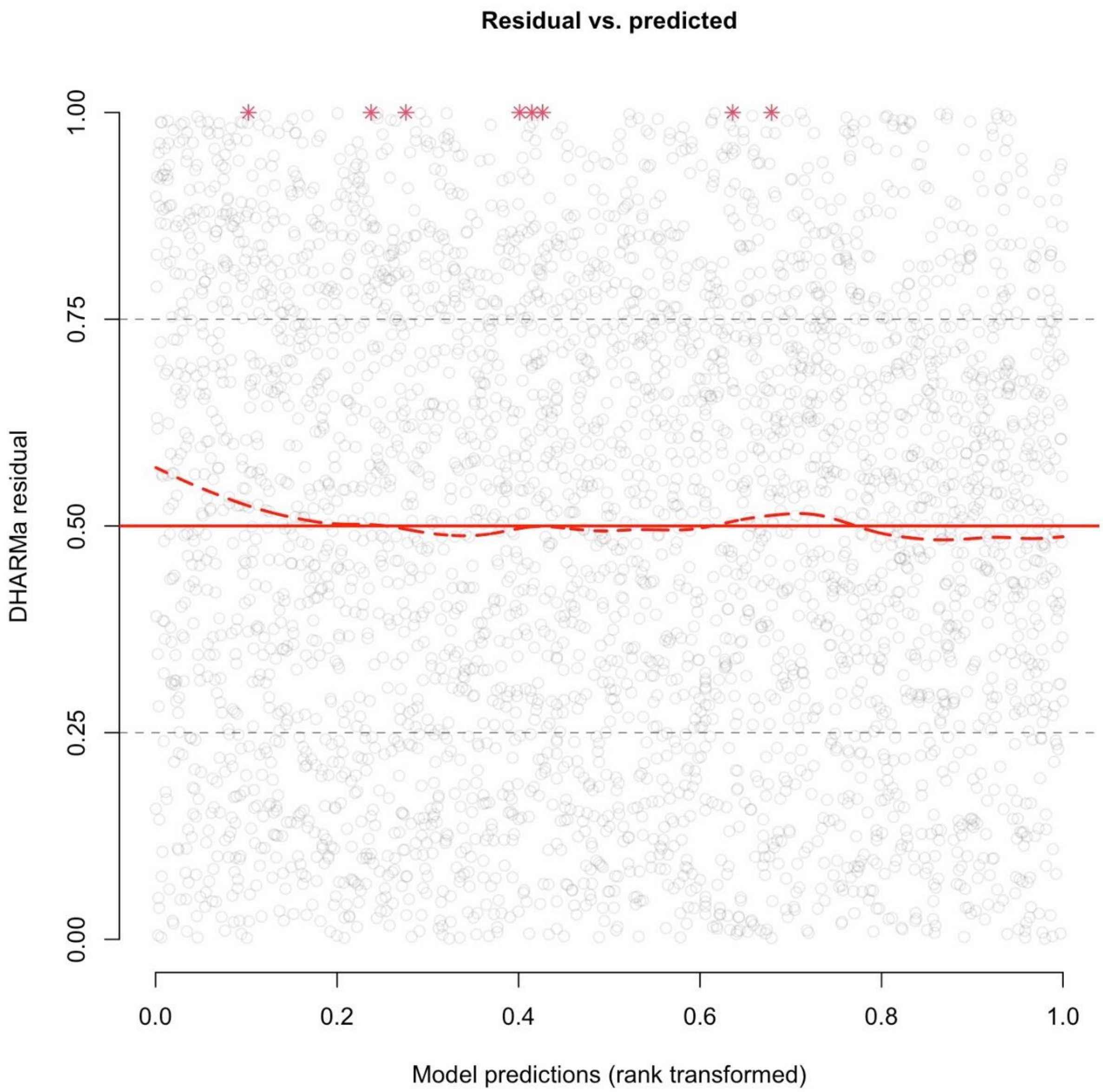


Figure 8. Residual diagnostics conducted by the R DHARMa package. Scaled quantile residuals (black circles) are scattered evenly. The smoothed 50% residual quantiles (segmented red line) align with theoretical quantiles (solid red line).

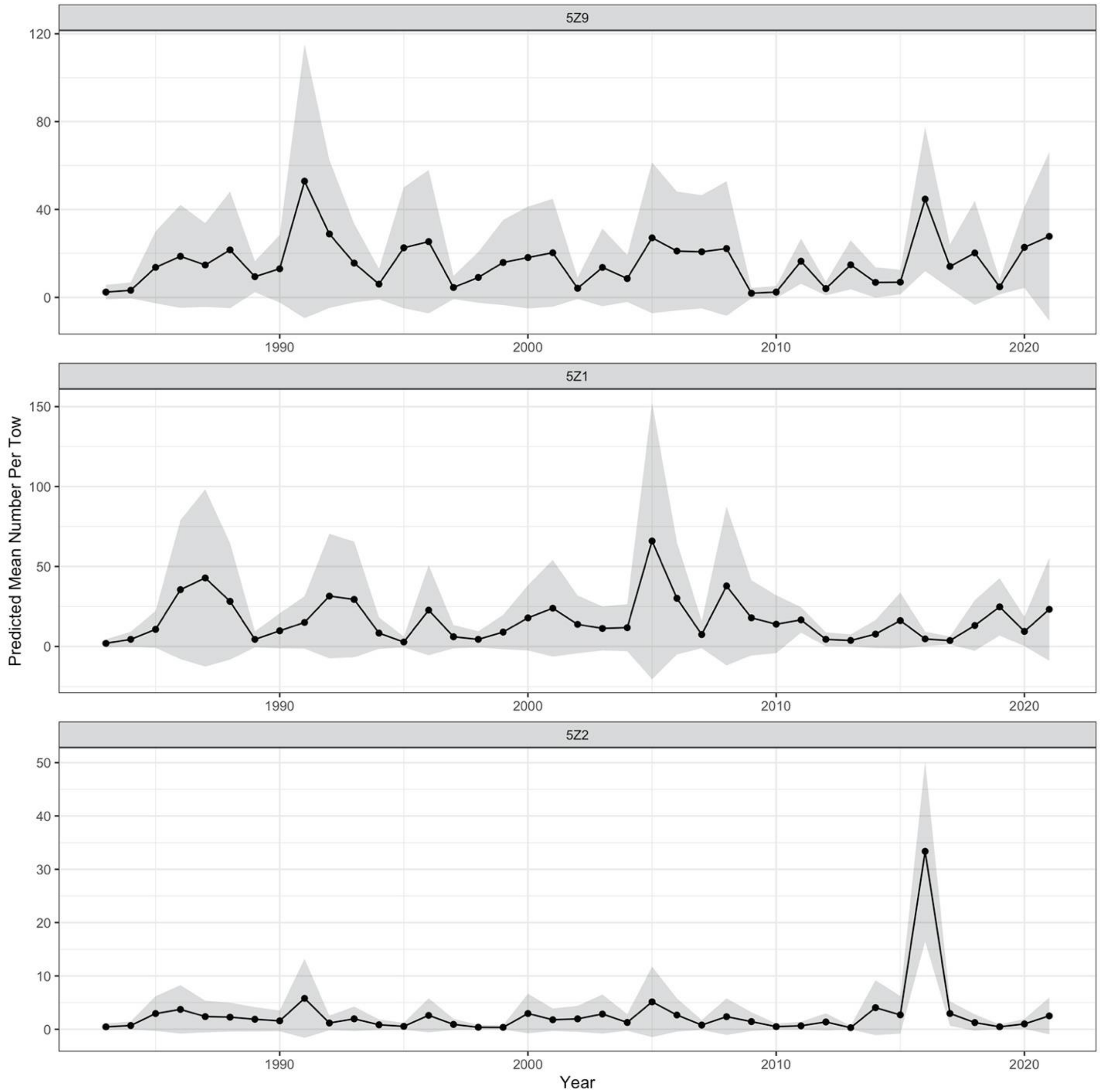


Figure 9. Predicted mean Pollock number per tow for a standard tow in the DFO summer research vessel survey in strata 5Z1, 5Z2, and 5Z9, respectively (grey areas are standard errors).

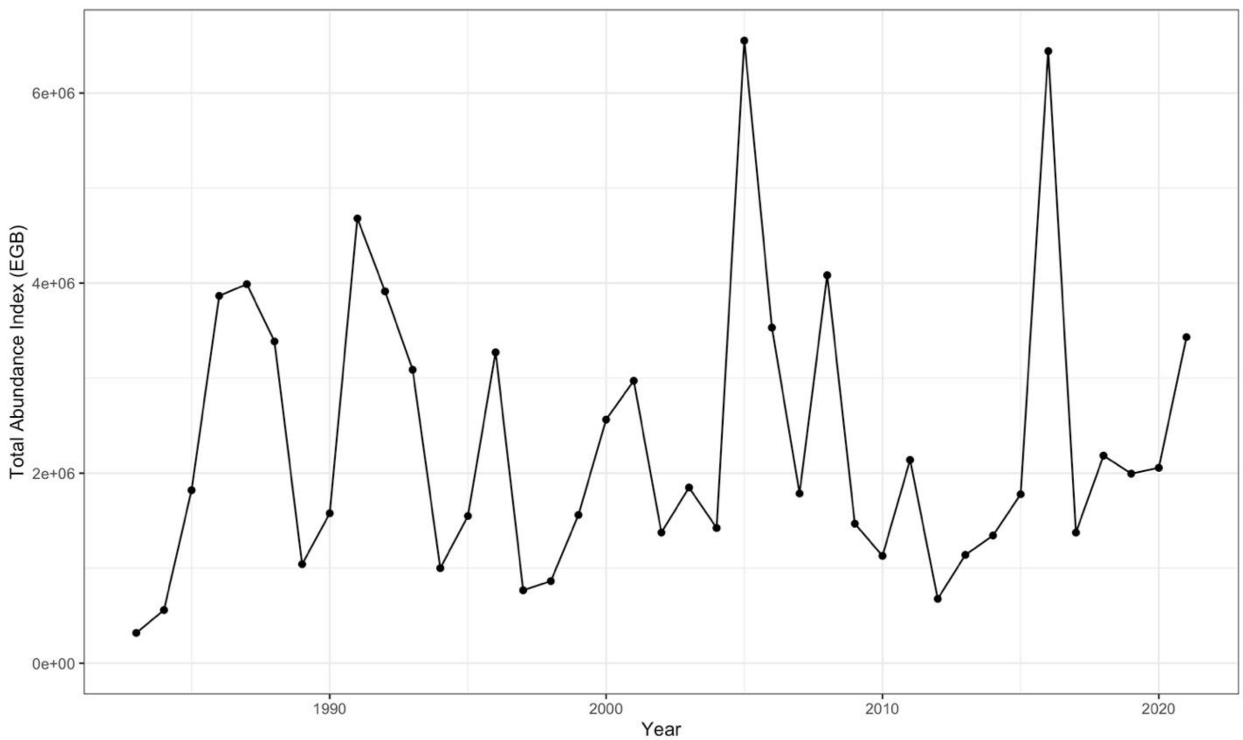


Figure 10. Predicted total Pollock population abundance for eastern Georges Bank (strata 5Z1–9 combined).

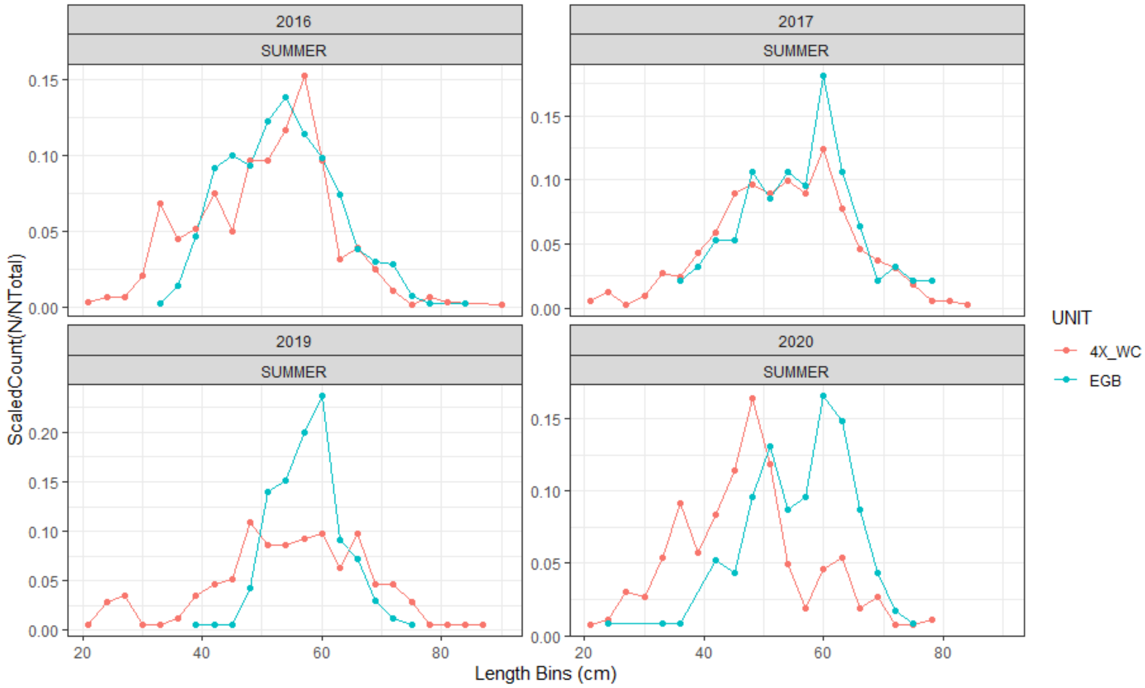


Figure 11. Scaled length frequency distribution of Pollock sampled on the DFO summer research vessel survey in the four years of minimum coverage of eastern Georges Bank (EGB) by year. Colour of lines showed the scaled length frequency distribution of EGB and the Western Component portion of 4X.

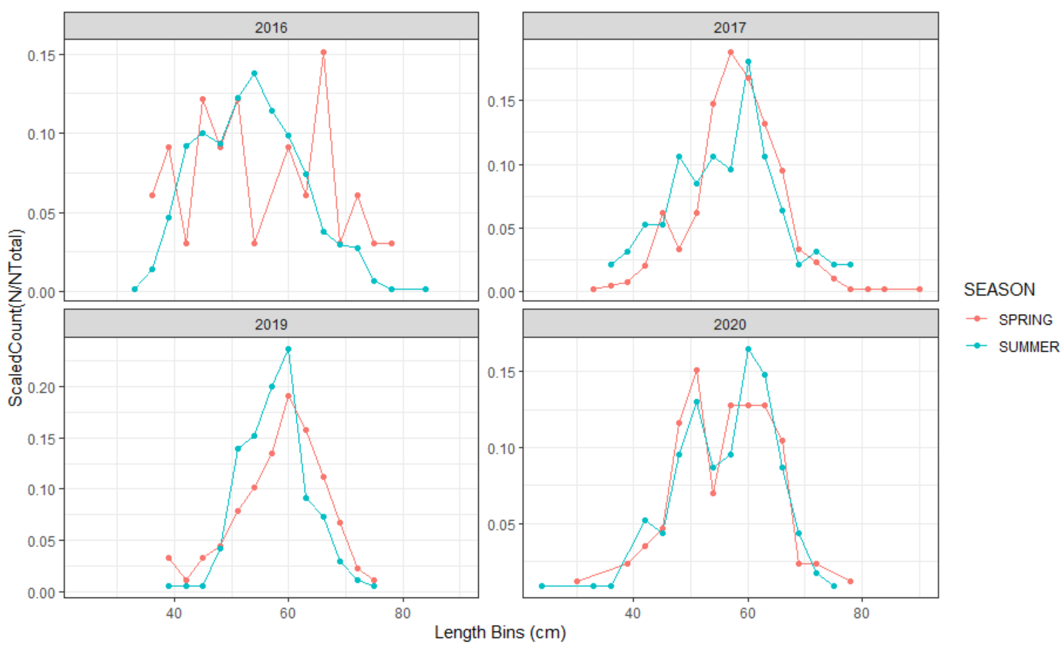


Figure 12. Scaled length frequency distribution of Pollock sampled on eastern Georges Bank (EGB) in four years where minimum coverage of EGB was completed (facets). Colour of lines showed the scaled length frequency distributions of DFO summer and winter surveys.

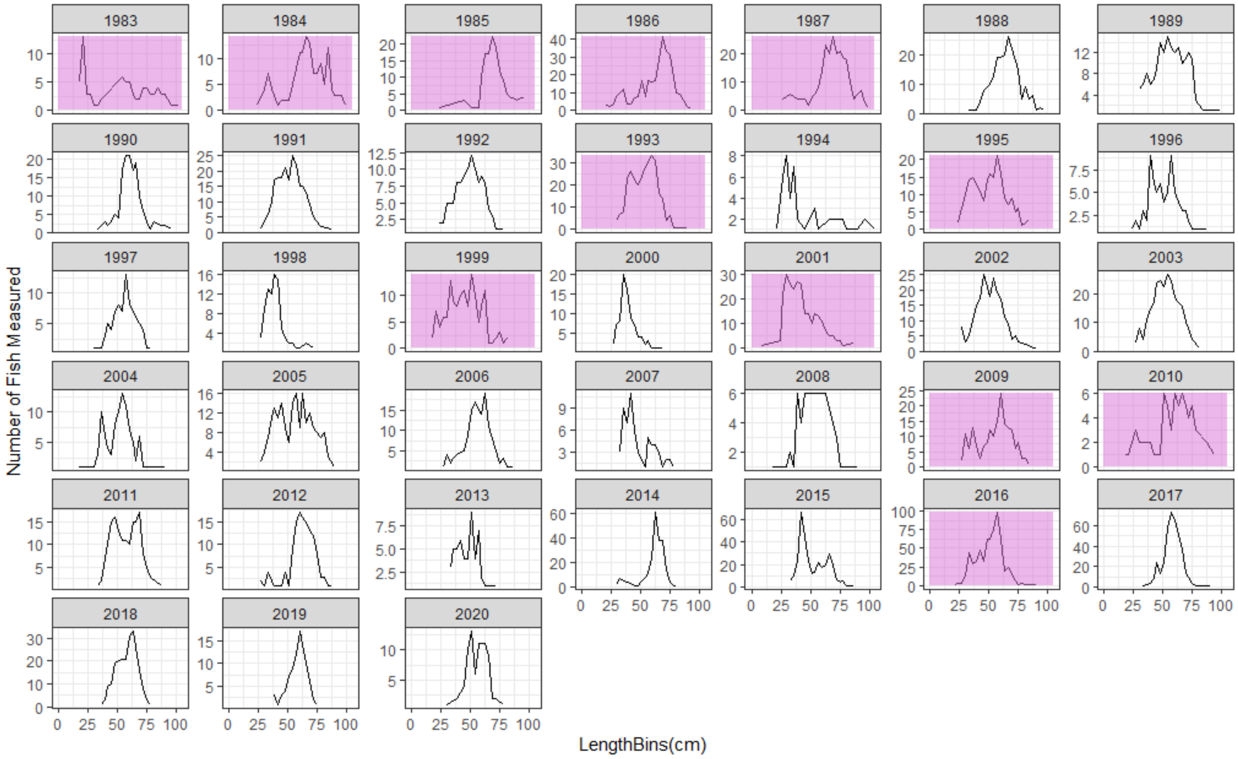


Figure 13. Pollock length frequency distributions applied to the DFO summer survey on eastern Georges Bank. Pink facets denote years when the length frequency distribution is from the western component portion of 4X; the white facets denote years when the length frequency distribution is from the DFO winter survey.

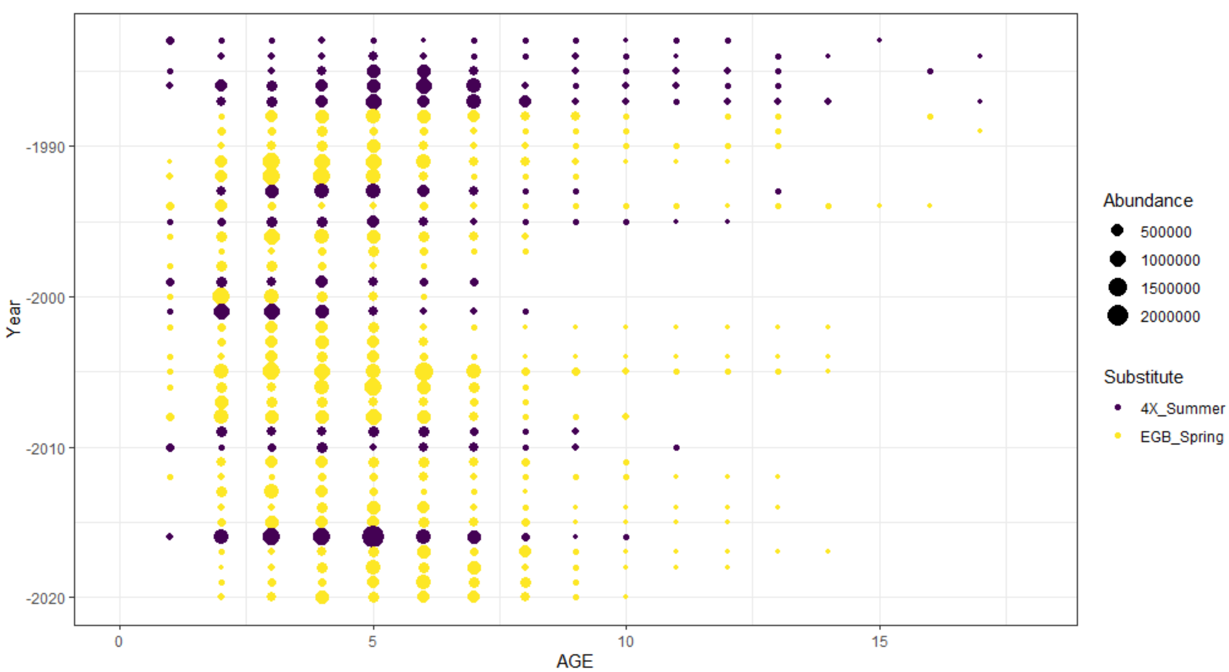


Figure 14. Pollock abundance-at-age indices for the modeled DFO surveys of Eastern Georges Bank. Size of bubble is indicative of total abundance. Colour identifies the source of length frequency applied to the total abundance.

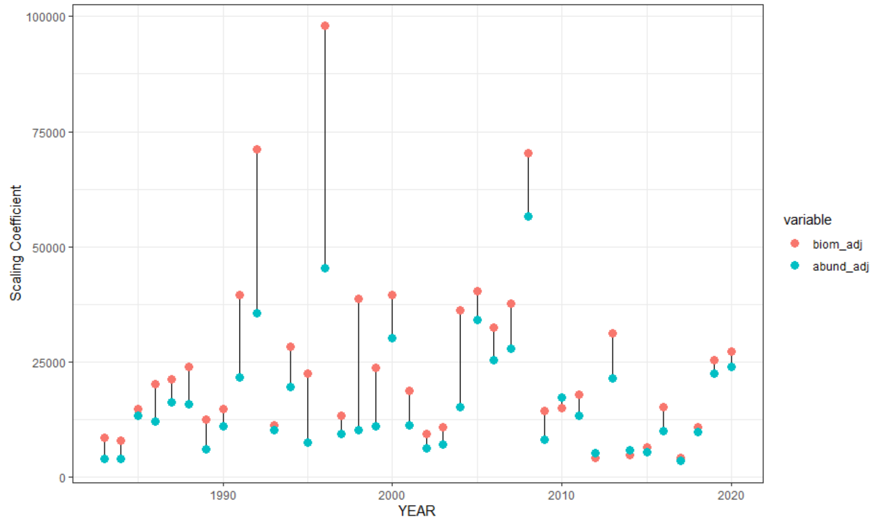


Figure 15. Scaling coefficient calculated for Pollock biomass and abundance on eastern Georges Bank.

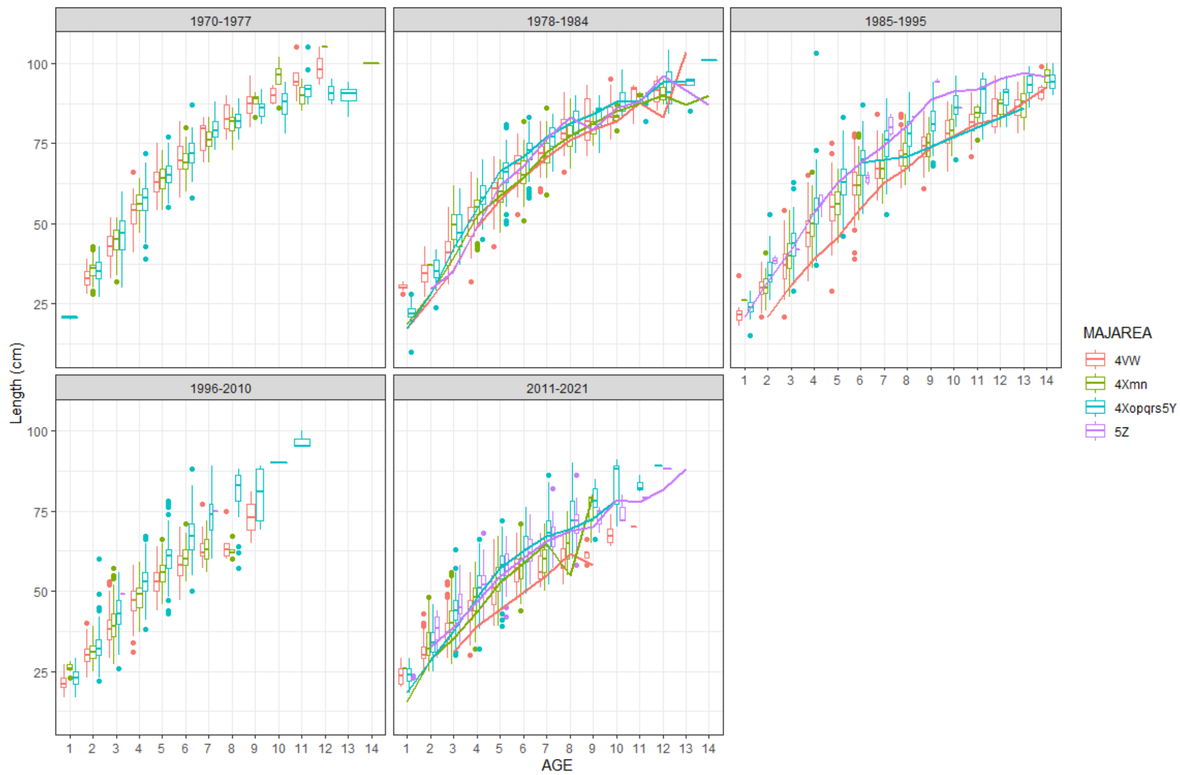


Figure 16. Length at age for Pollock by unit area (denoted by colours) and time periods (denoted by facets) from the DFO winter survey. Lines denote the mean value. Boxplots show the data distribution around that mean.

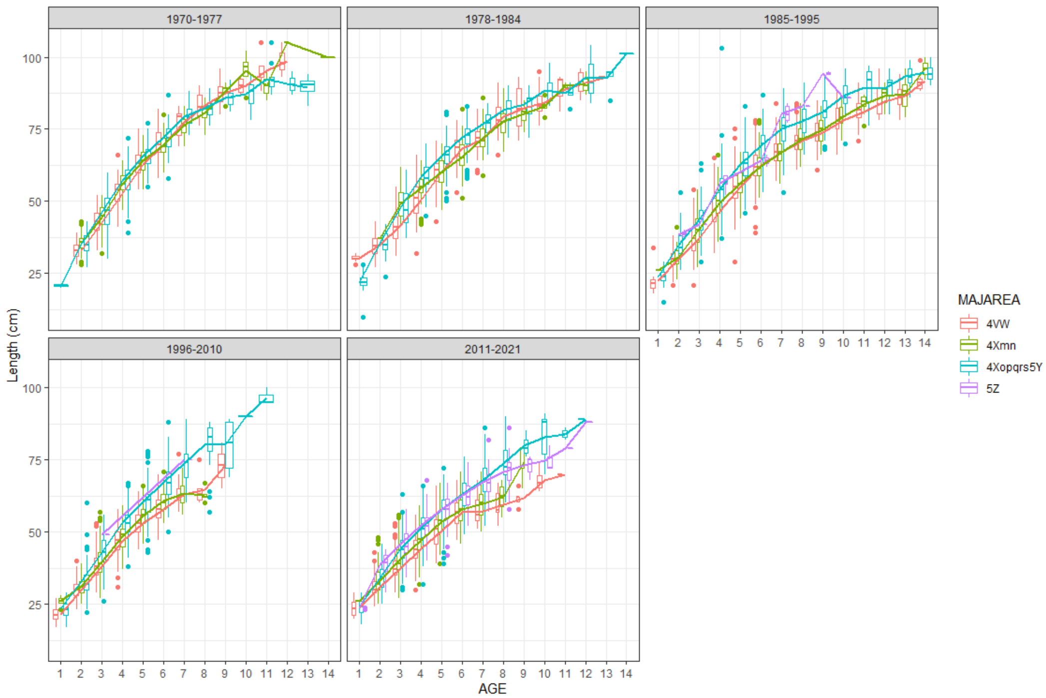


Figure 17. Length at age for Pollock by unit area (denoted by colours) and time periods (denoted by facets) from the DFO summer survey. Lines denote the mean value. Boxplots show the data distribution around that mean.

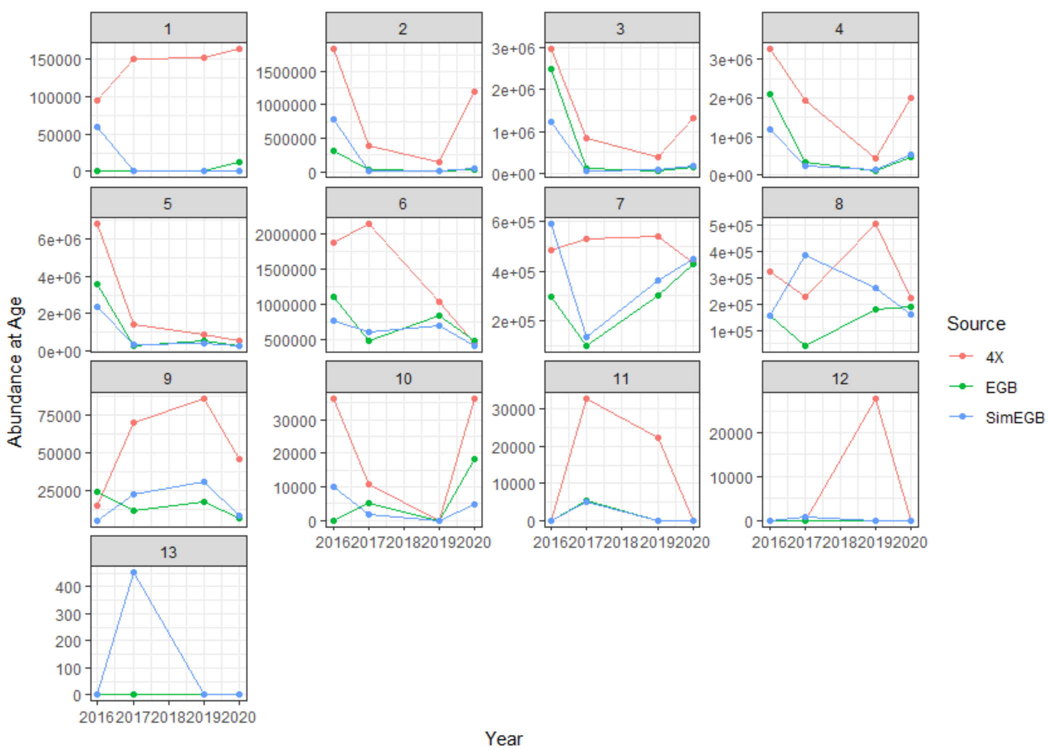


Figure 18. Relative Pollock abundance at age (facets) for NAFO areas 4Xopqrs5Y (red), eastern Georges Bank (green) and the simulated eastern George Bank (blue) indices, in the four years the DFO summer survey had full coverage of eastern Georges Bank (2016, 2017, 2019, 2020).

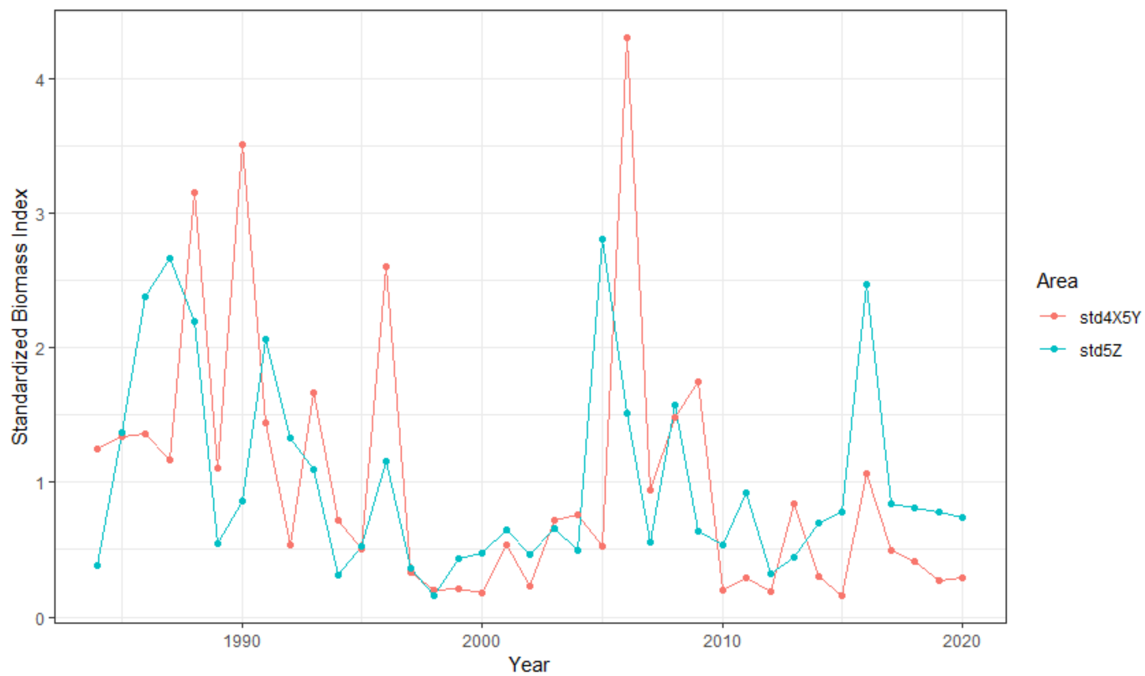


Figure 19. Relative Pollock biomass indices for DFO summer survey strata in NAFO areas 4Xopqrs5Y (red) and the simulated relative biomass index for eastern Georges Bank (blue). Indices have been standardized to appear on the same scale by dividing them by their respective averages from 1984–2020.

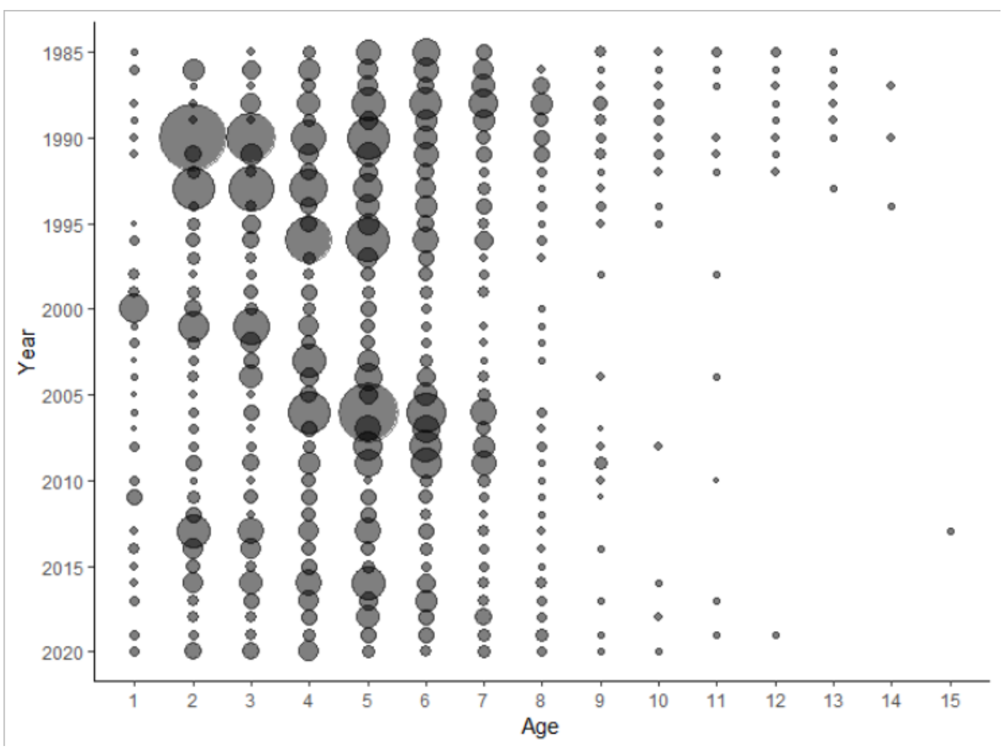


Figure 20. Area-weighted mean Pollock number at age per tow from the DFO summer survey used in the 2011 MSE as age-specific indices of abundance.

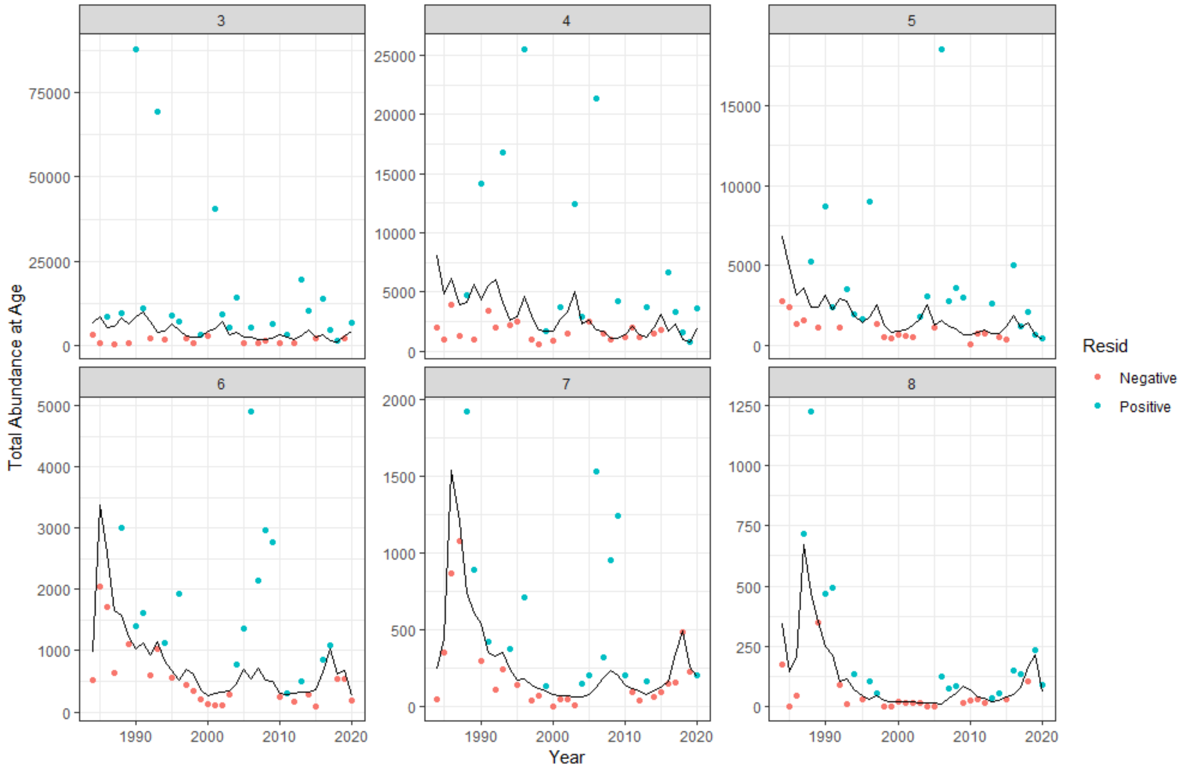


Figure 21. DFO summer survey model fit for Model A at each age (facet) and year (x axis).

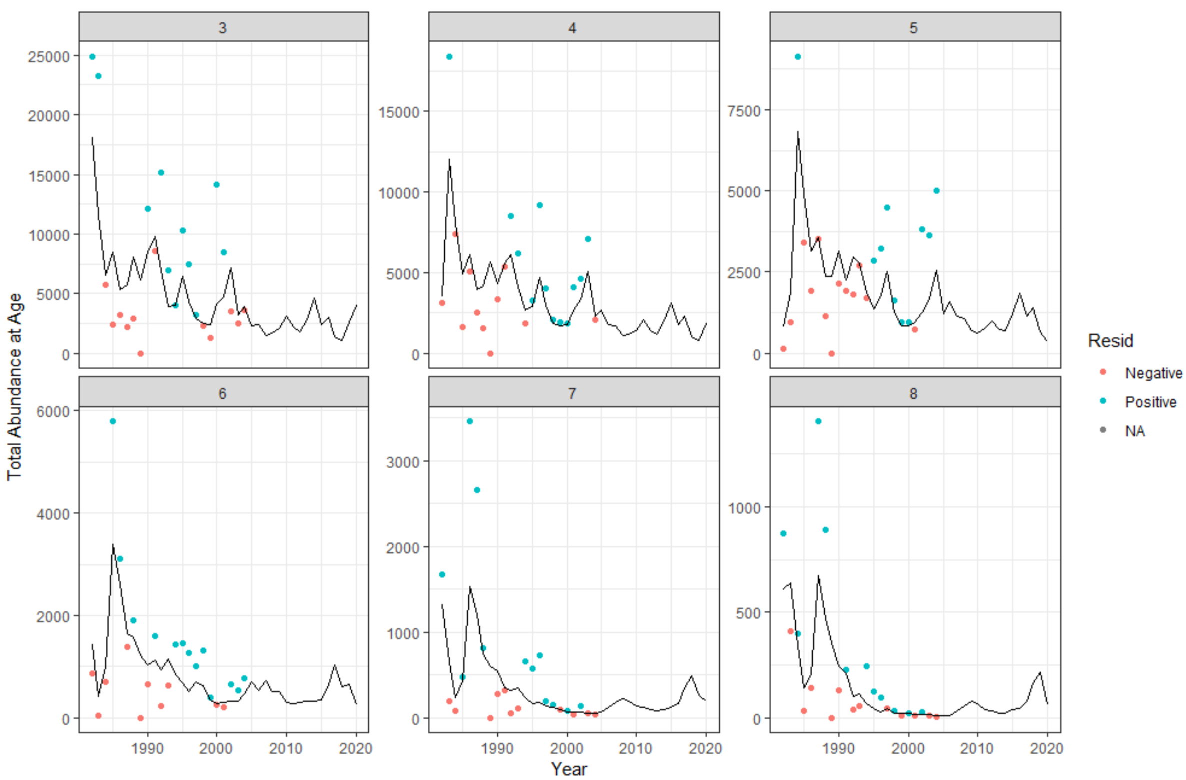


Figure 22. Pollock CPUE commercial index model fit for Model A at each age (facet) and year (x axis).

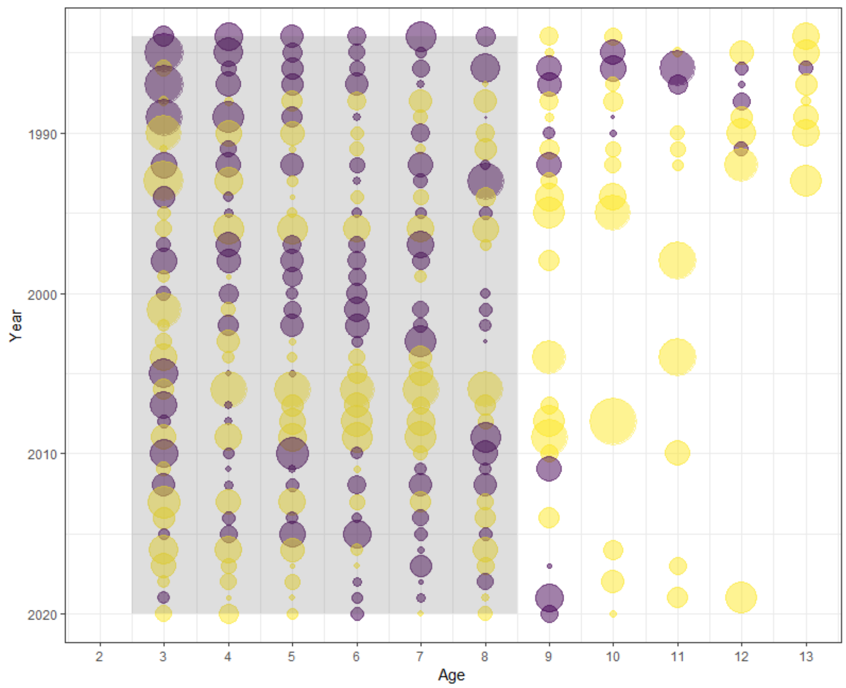


Figure 23. Pollock survey residuals for Model A with size of bubble proportional to the magnitude of the residual and colour indicative of negative (purple) or positive (yellow) values. The grey box identifies ages for which an age-specific q is estimated. Residuals outside of the grey box are calculated assuming a flat top selectivity.

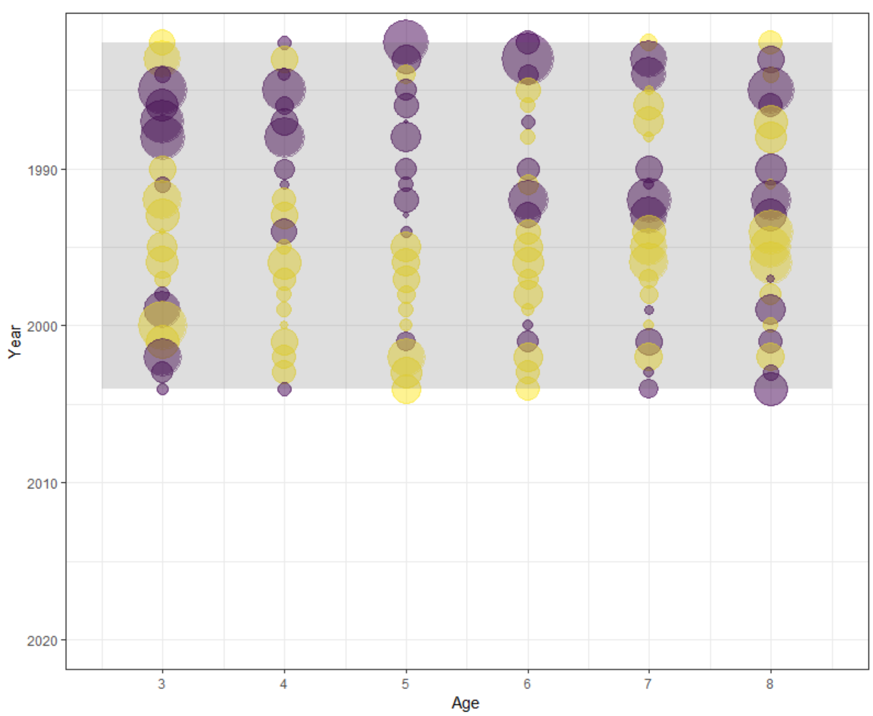


Figure 24. Pollock CPUE residuals for Model A with size of bubble proportional to the magnitude of the residual and colour indicative of negative (purple) or positive (yellow) values. The grey box identifies ages for which an age-specific q is estimated. Residuals outside of the grey box are calculated assuming a flat top selectivity.

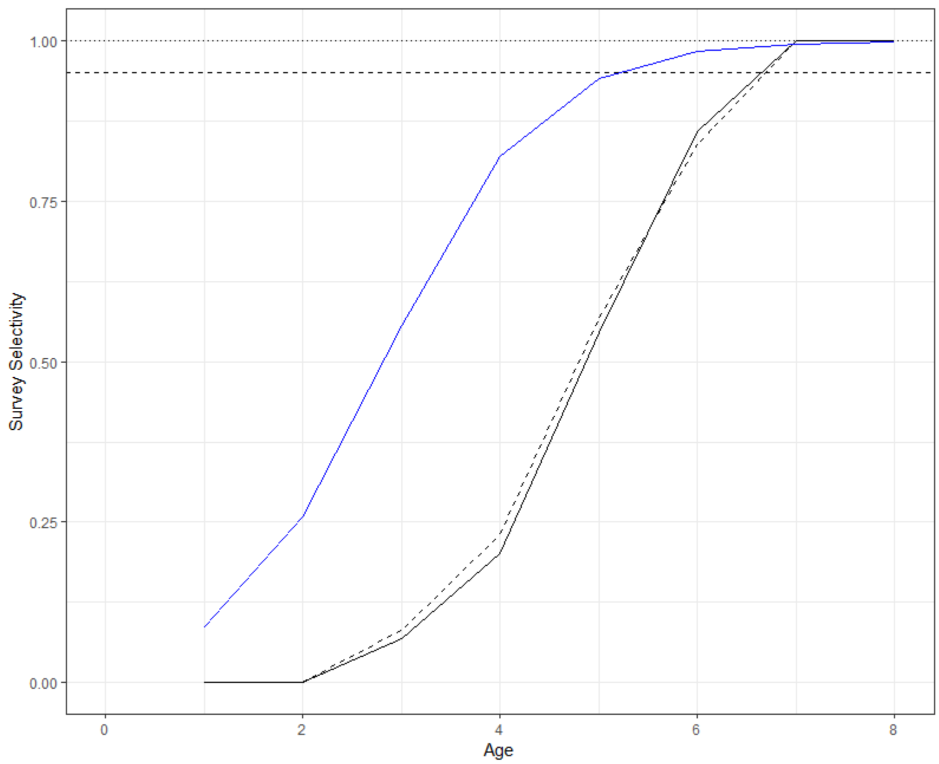


Figure 25. Comparison of survey selectivity for Pollock derived from the catchability (q) outputs of the 2011 VPA (black solid), the 2022 VPA Model A (black, dashed) and the model-independent catch-based method (blue).

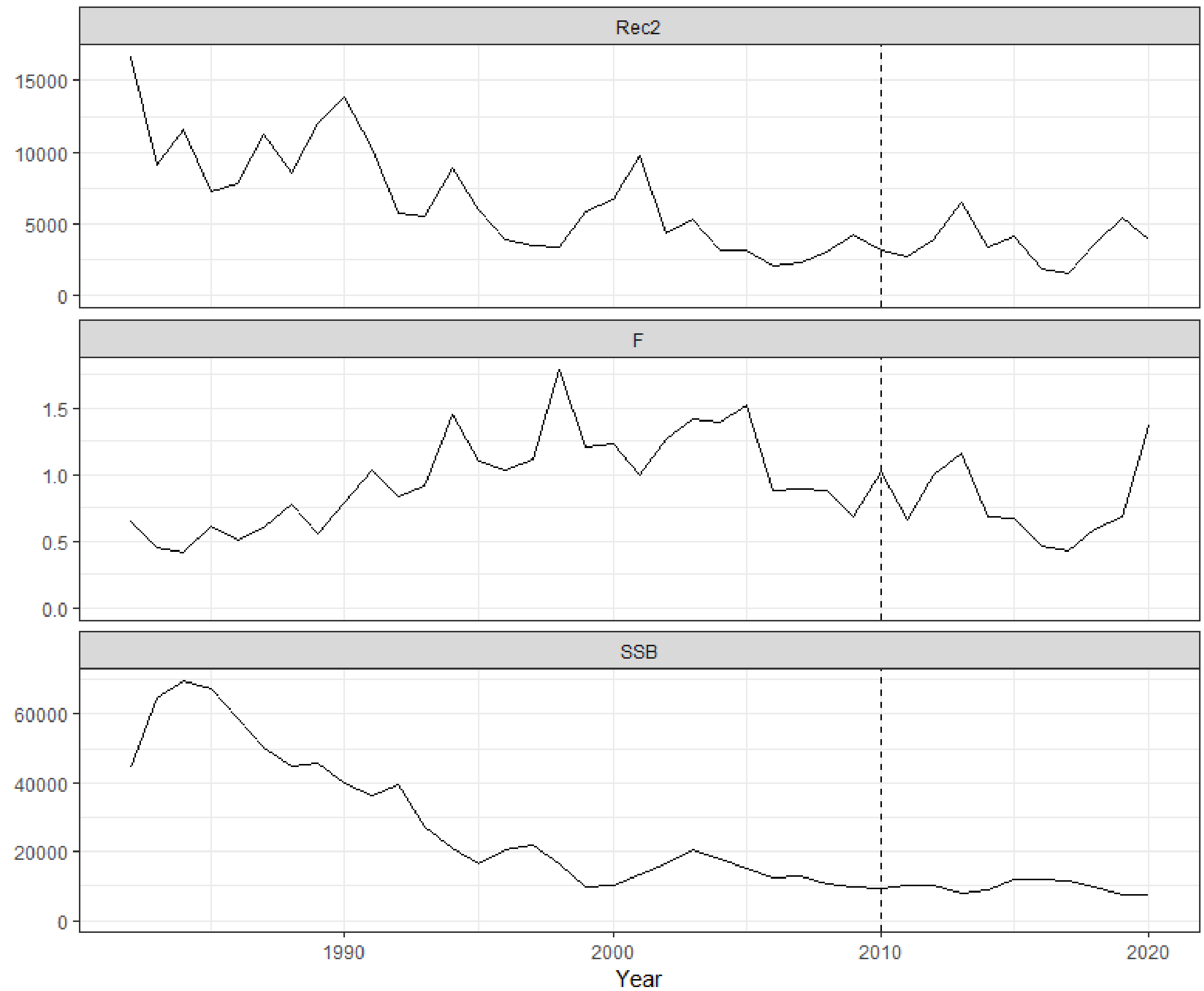


Figure 26. Age 2 Pollock recruitment (thousands of fish), the fishing mortality on ages 6 through 9 and SSB (ages 4+) from the original VPA Model A, updated with data through 2020.

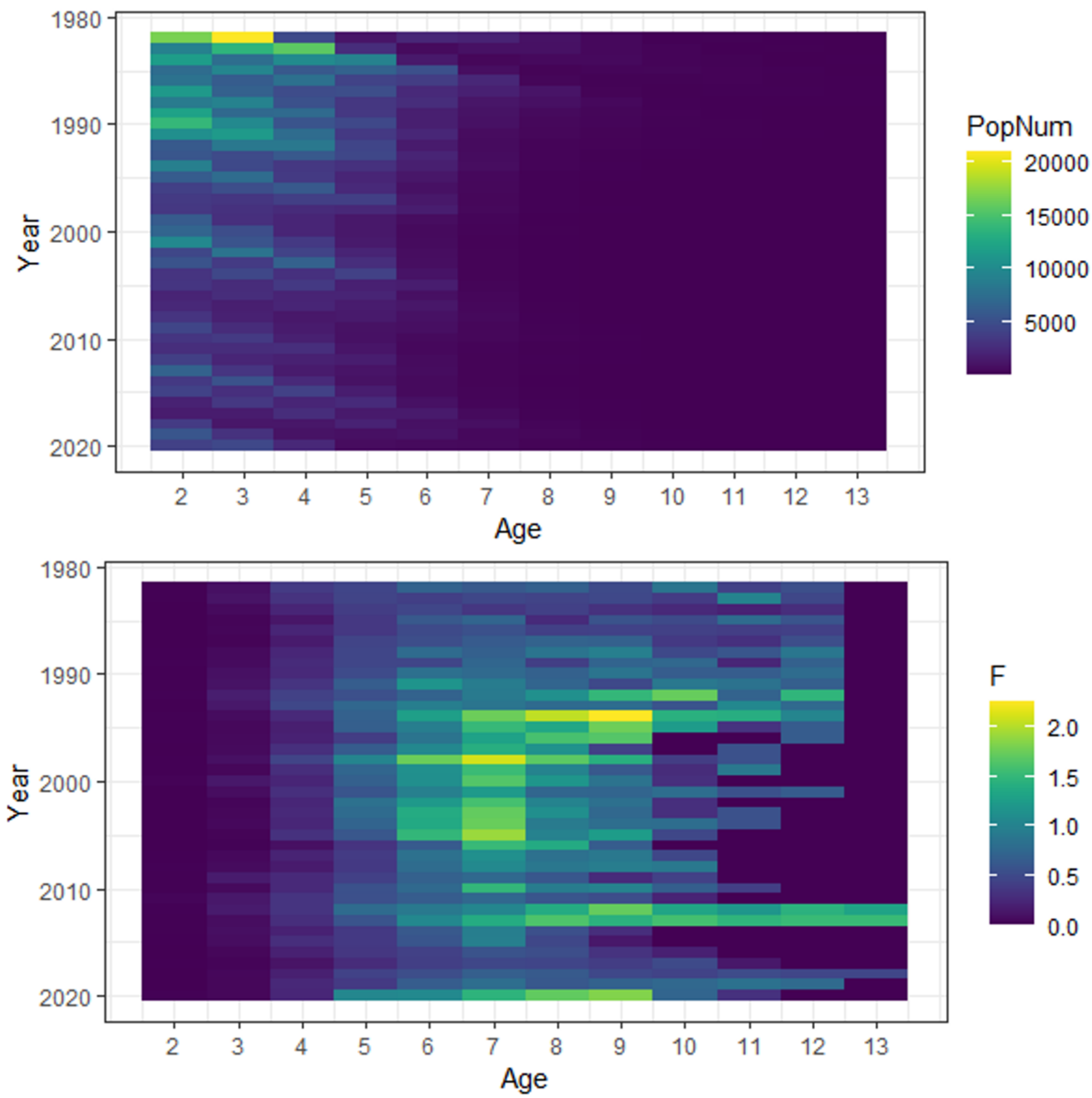


Figure 27. Pollock population abundance- at-age (top plot) and fishing mortality-at-age (bottom plot) output from Model A.

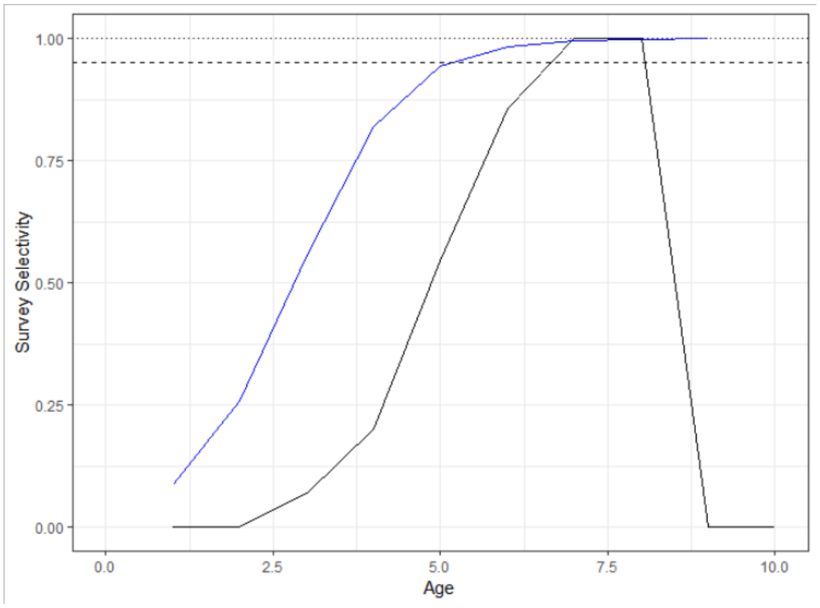


Figure 28. Comparison of Pollock survey selectivity derived from the catchability (q) outputs of the 2011 VPA (black) and the model-independent catch-based method (blue).

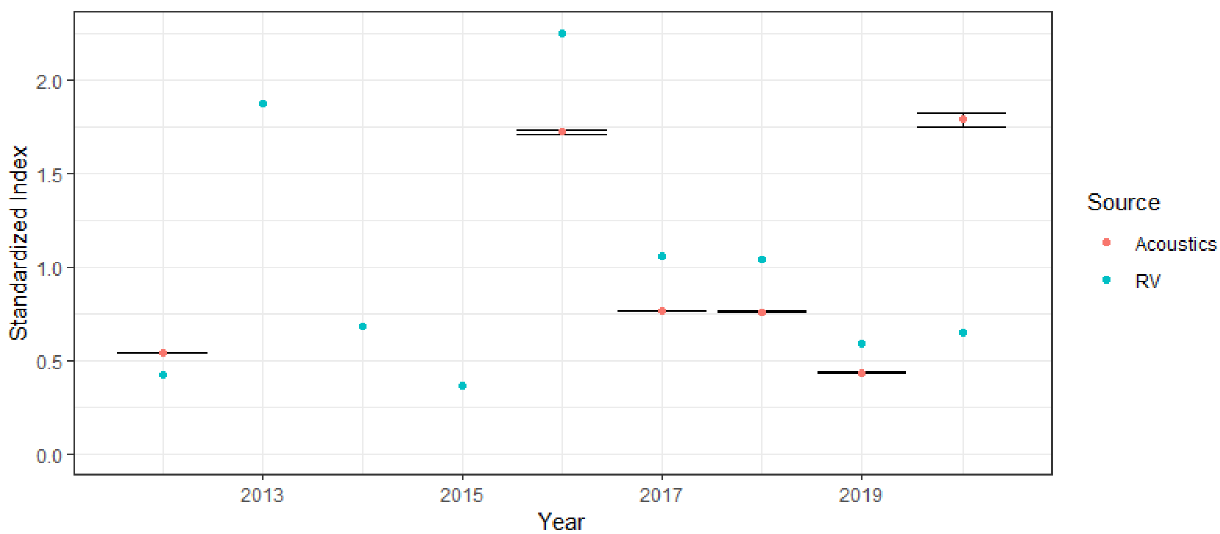


Figure 29. Relative indices of Pollock biomass from the DFO summer survey trawl (blue; kg/tow) and acoustic (red; kgs) data sources. The indices were standardized to appear on the same scale by dividing each point by their respective index average value between 2012 and 2020.

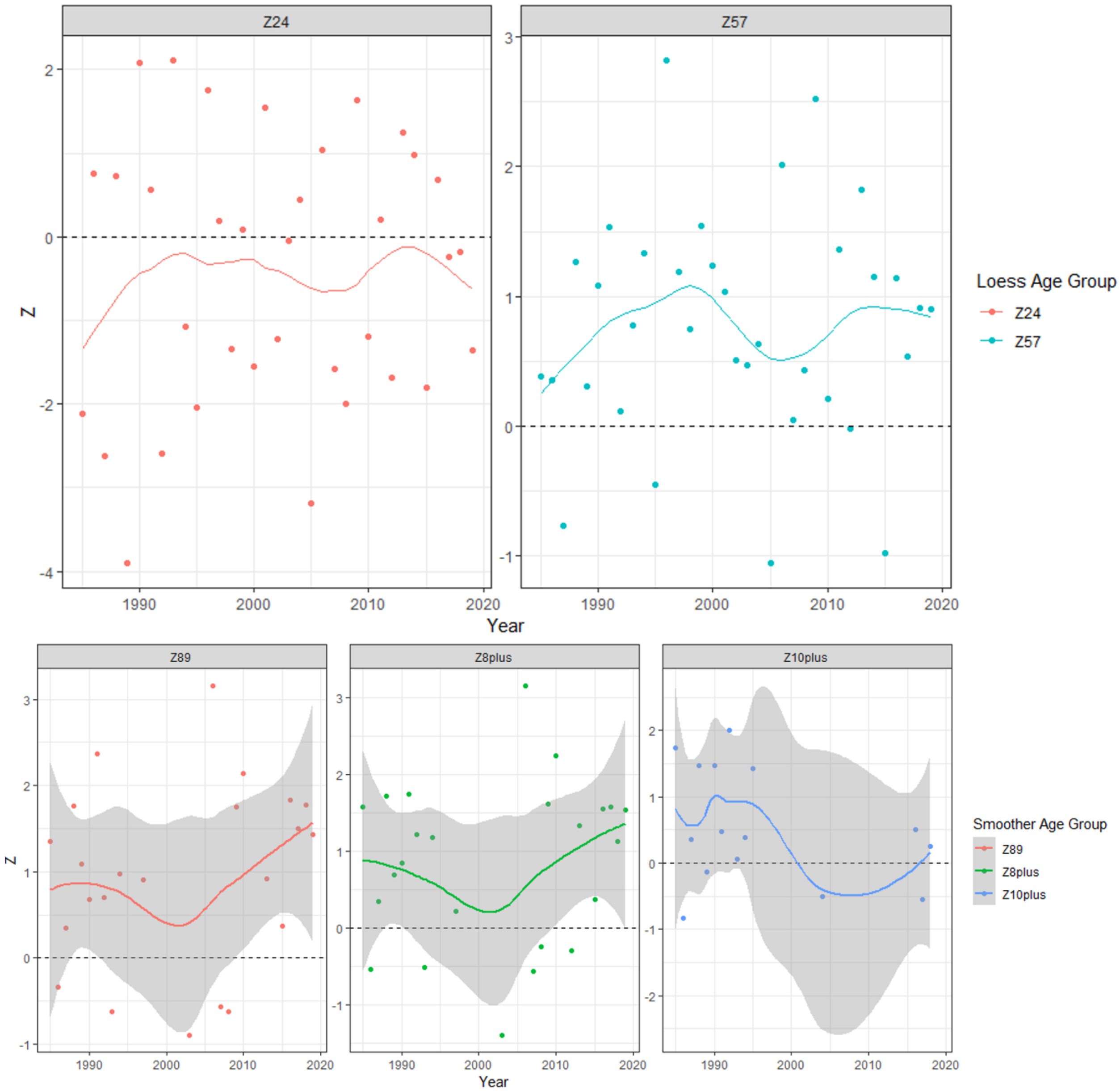


Figure 30. Pollock total mortality (Z) calculated by various age groups, as depicted by both facets and colours. Points represent raw values and lines represent a loess smooth. Figure from DFO (2022).

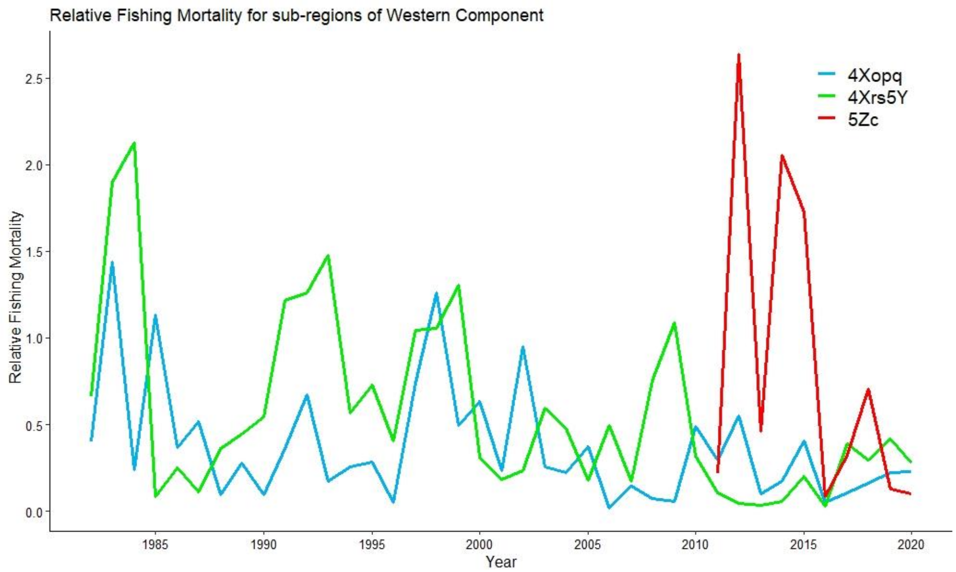


Figure 31. Relative fishing mortality (total landings / total biomass) for different spatial units of Pollock, denoted by various colours. Western Component refers to NAFO areas 4Xopqrs5ZY.

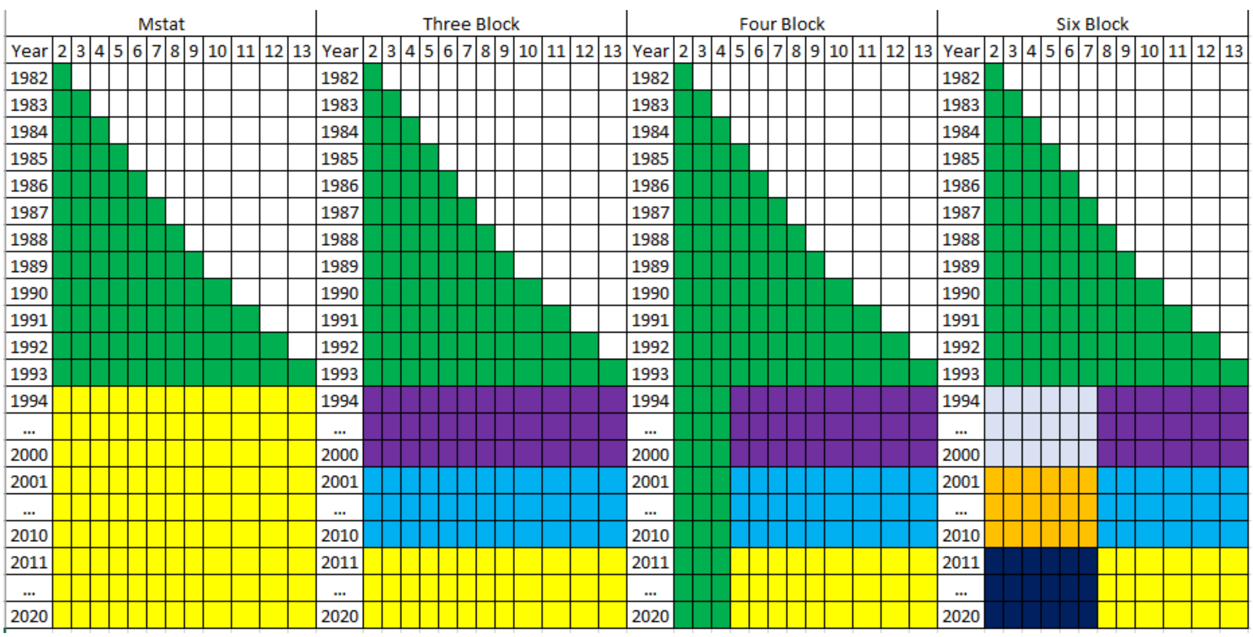


Figure 32. Pollock natural mortality block parameterization for Model F, each colour denotes a block of common mortality estimated by the model. Green blocks indicate a fixed mortality set at 0.2.

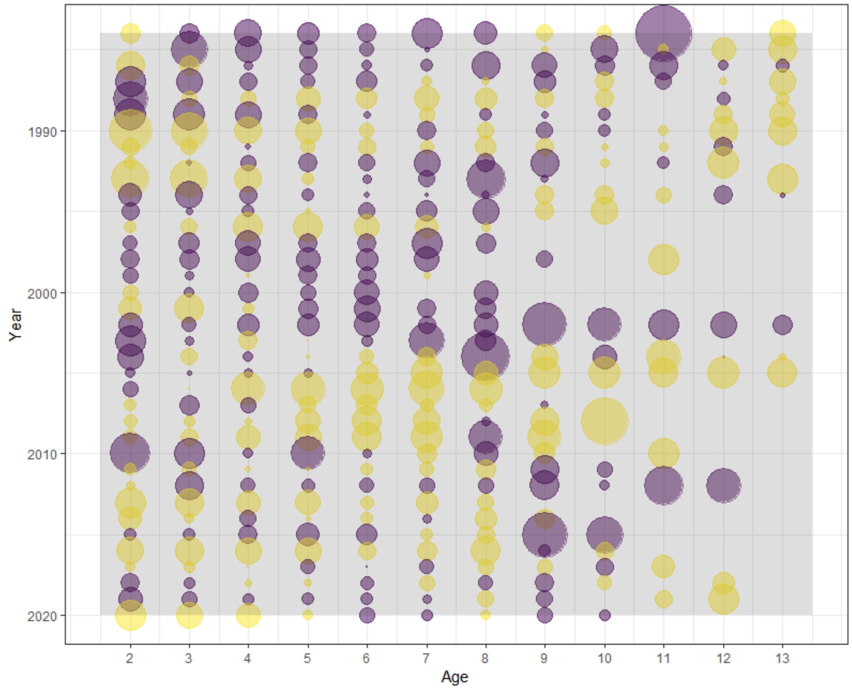


Figure 33. DFO summer survey residuals for Model F – M6Block with size of bubble proportional to the magnitude of the residual and colour indicative of negative (purple) or positive (yellow) values. The grey box identifies ages for which an age-specific q is estimated.

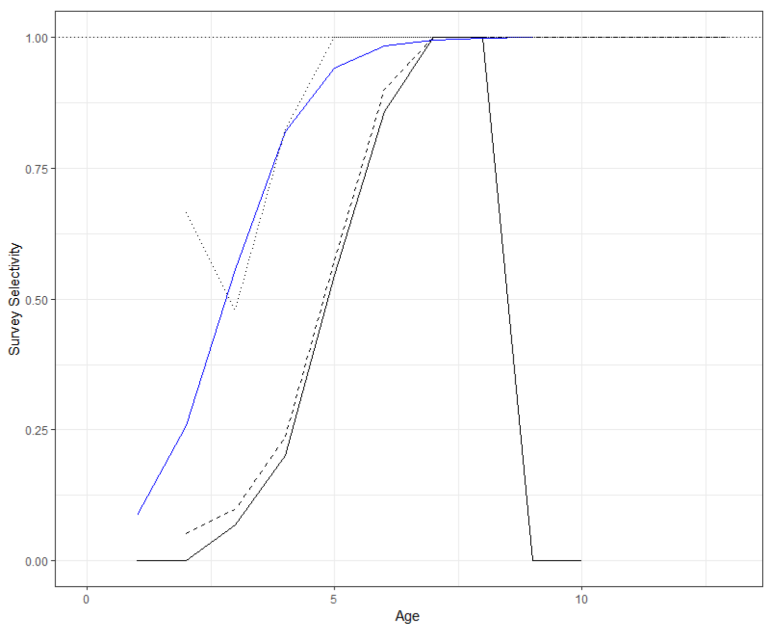


Figure 34. Comparison of survey selectivity derived from the catchability (q) outputs of the 2011 VPA (black solid), the 2022 VPA Model F Mstat (black, dashed) with no common selectivity specified between ages, and the model-independent catch-based method (blue).

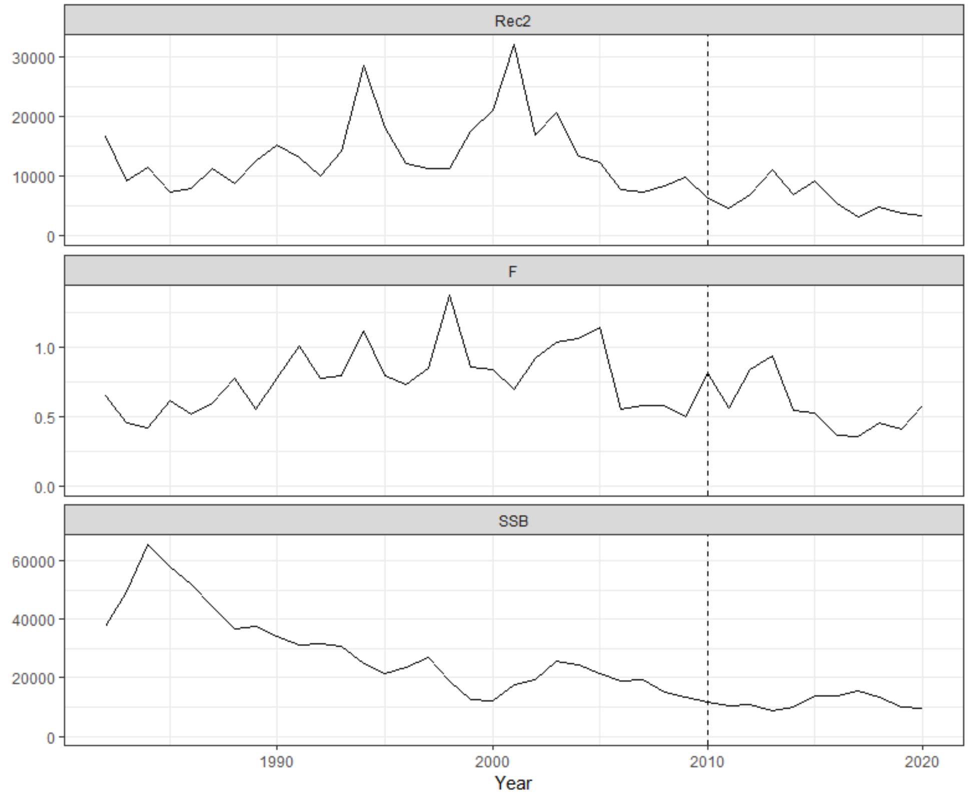


Figure 35. Age 2 recruitment (Rec2, thousands of fish), the fishing mortality (F) on ages 6 through 9 and biomass (SSB, ages 4+) from Model F – M3Block.

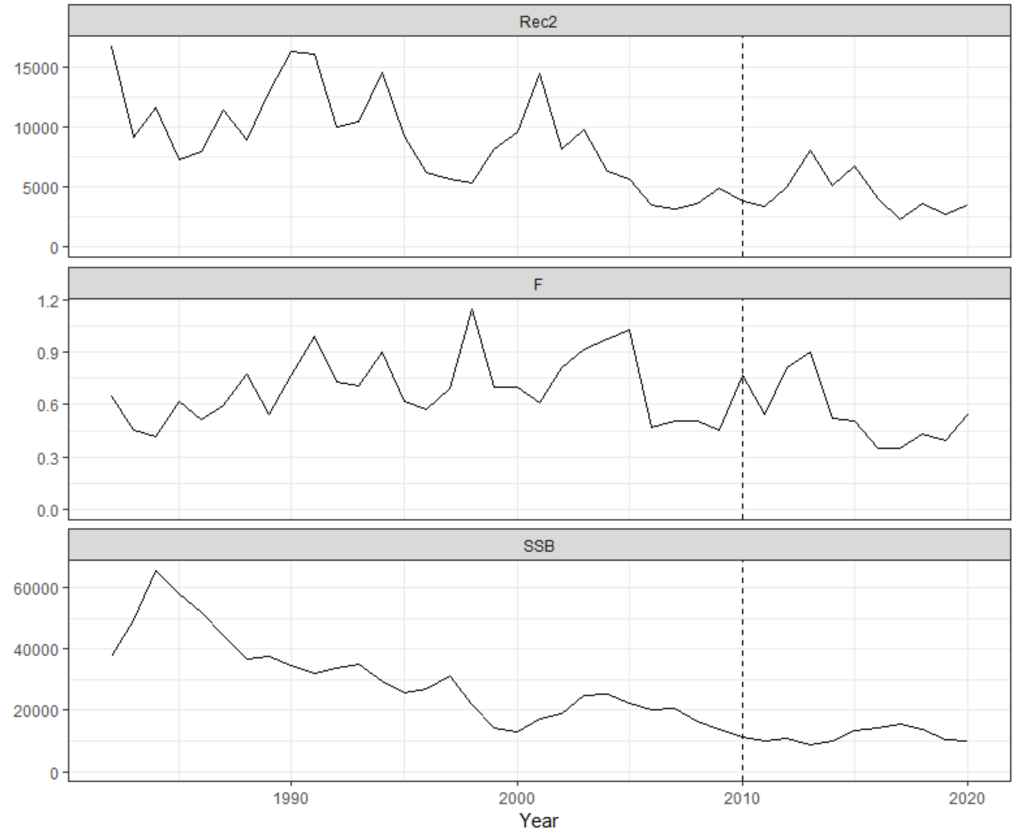


Figure 36. Age 2 recruitment (Rec2, thousands of fish), the fishing mortality(F) on ages 6 through 9 and biomass (SSB, ages 4+) from Model F – M4Block.

Figure 37. DFO summer survey observed (points) to predicted (line) abundance for Model I at each age (facet) and year (x axis).

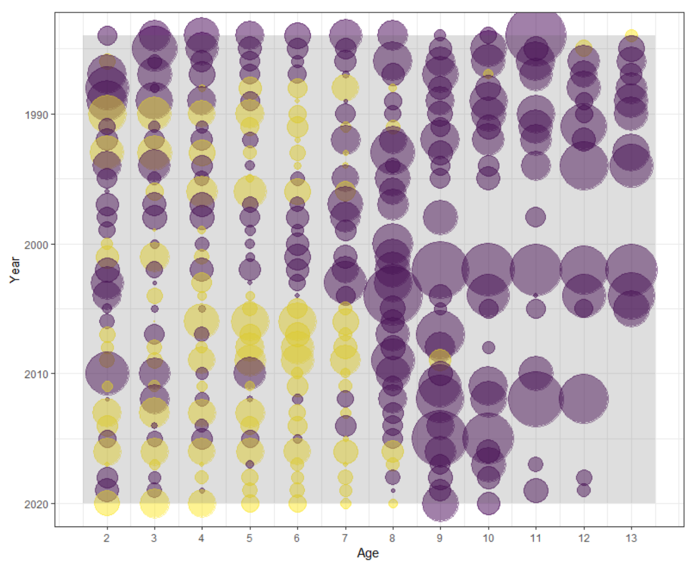


Figure 38. DFO summer survey residuals for Model I with size of bubble proportional to the magnitude of the residual and colour indicative of negative (purple) or positive (yellow) values. The grey box identifies ages for which an age-specific q is estimated.

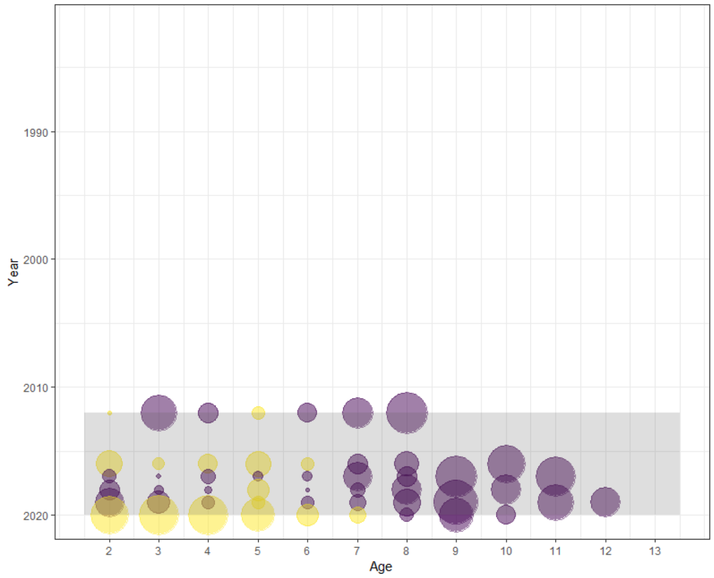


Figure 39. Acoustic Survey residuals for Model I with size of bubble proportional to the magnitude of the residual and colour indicative of negative (purple) or positive (yellow) values. The grey box identifies ages for which an age-specific q is estimated.

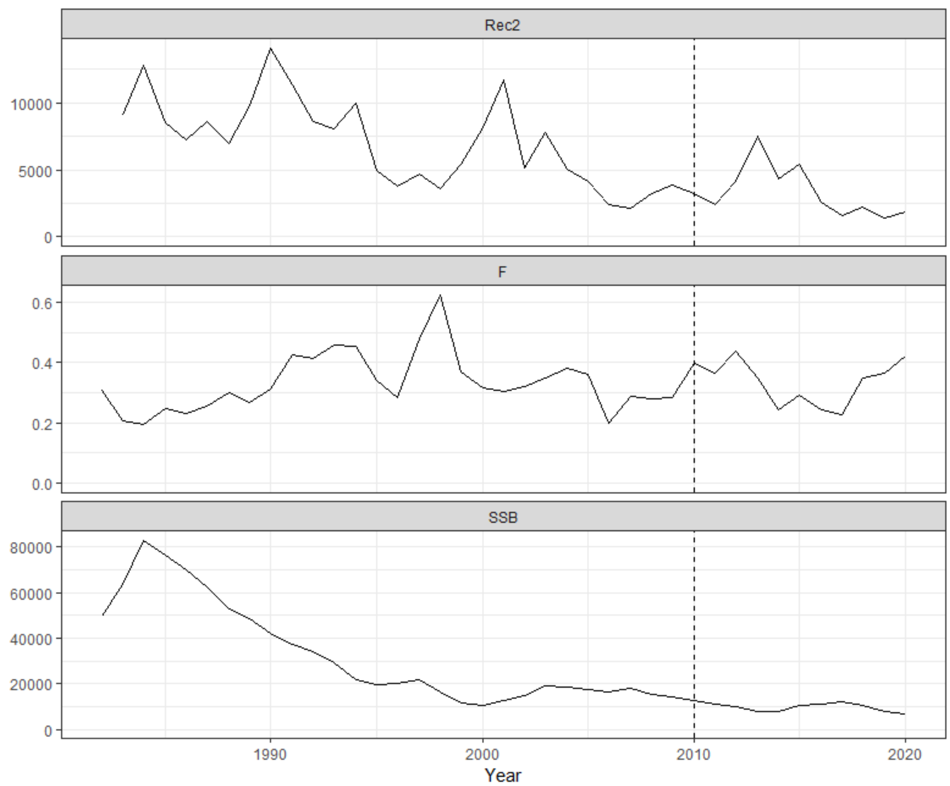


Figure 40. Age 2 recruitment (Rec2, thousands of fish), the fishing mortality (F) on ages 6 through 9 and biomass (SSB, ages 4+) from Model I.

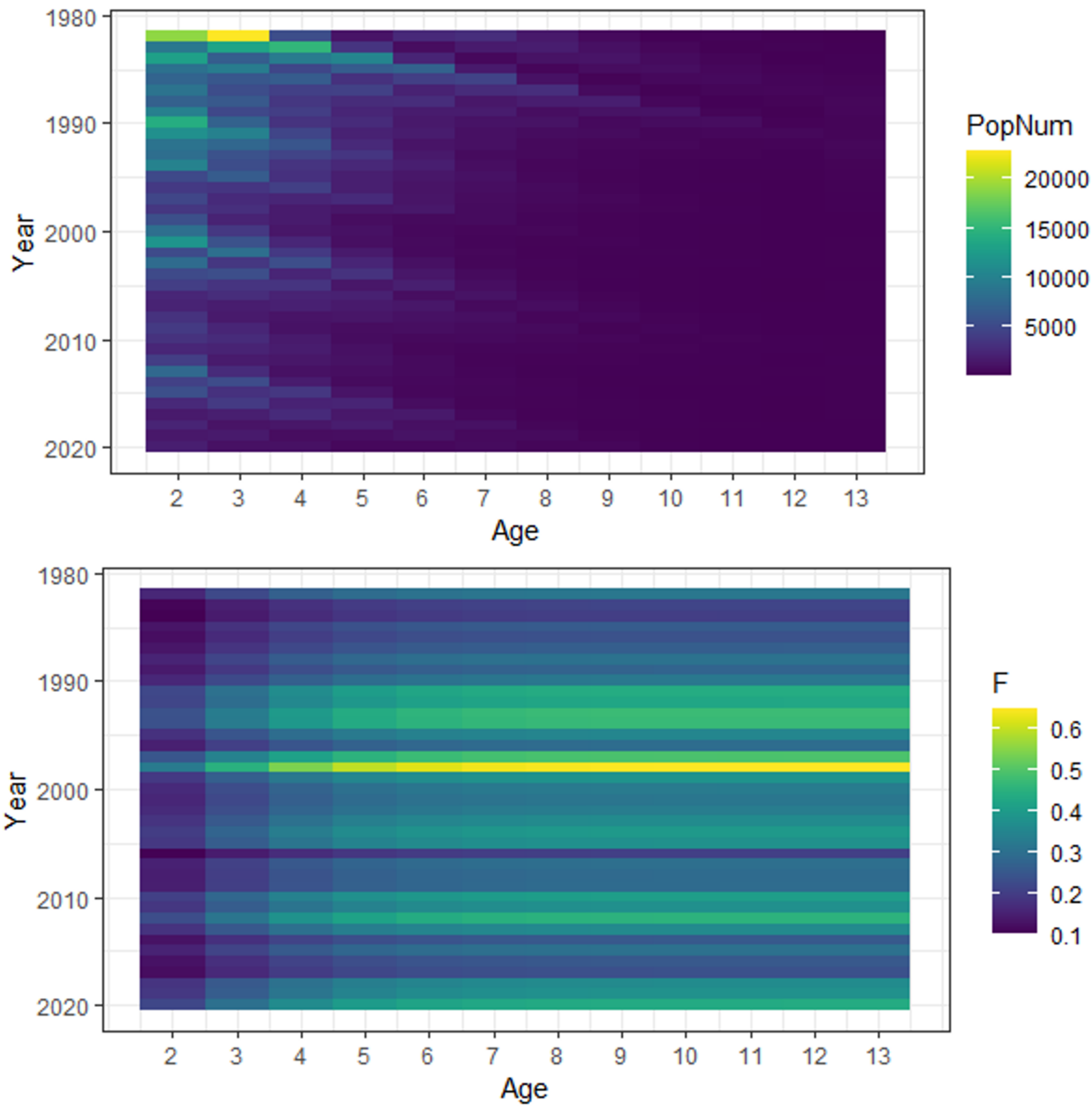


Figure 41. Population abundance-at-age (top plot) and fishing mortality-at-age (F, bottom plot) output from Model I.

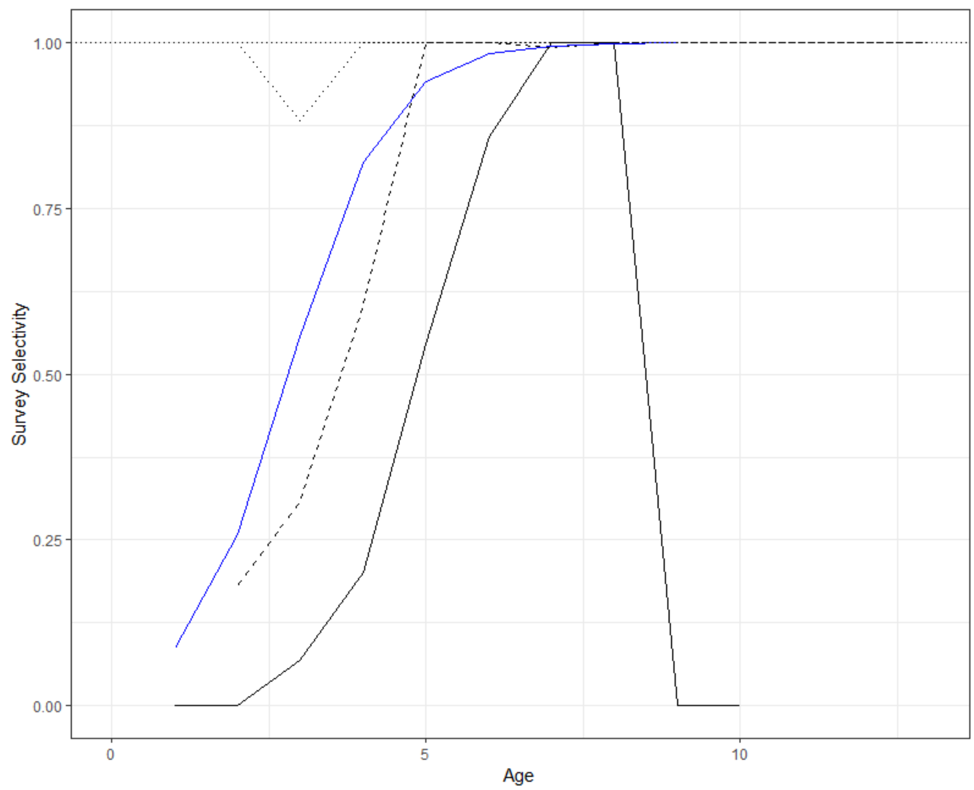


Figure 42. Comparison of survey selectivity derived from the catchability (q) outputs of the 2011 VPA (black solid), the 2022 VPA Model I (black, dashed) with a common selectivity specified on ages 8–13, and the model-independent catch-based method (blue). The fine dashed line shows the final selectivity estimated on the Acoustic Index in Model I.

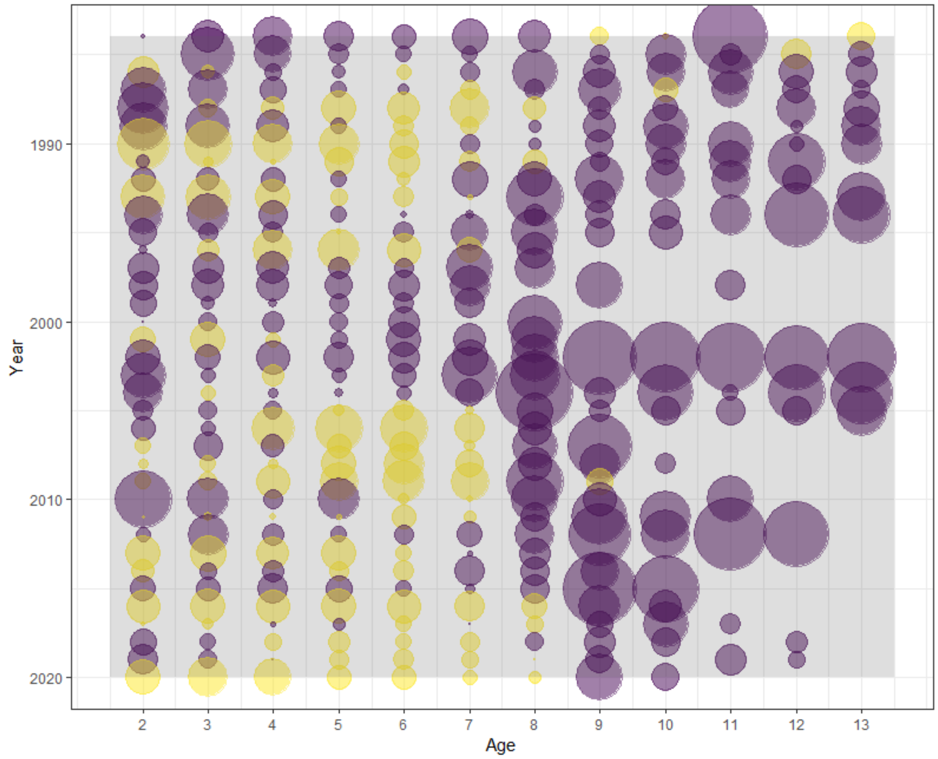


Figure 43. DFO summer survey residuals for Model J_MStat with size of bubble proportional to the magnitude of the residual and colour indicative of negative (purple) or positive (yellow) values. The grey box identifies ages for which an age-specific q is estimated.

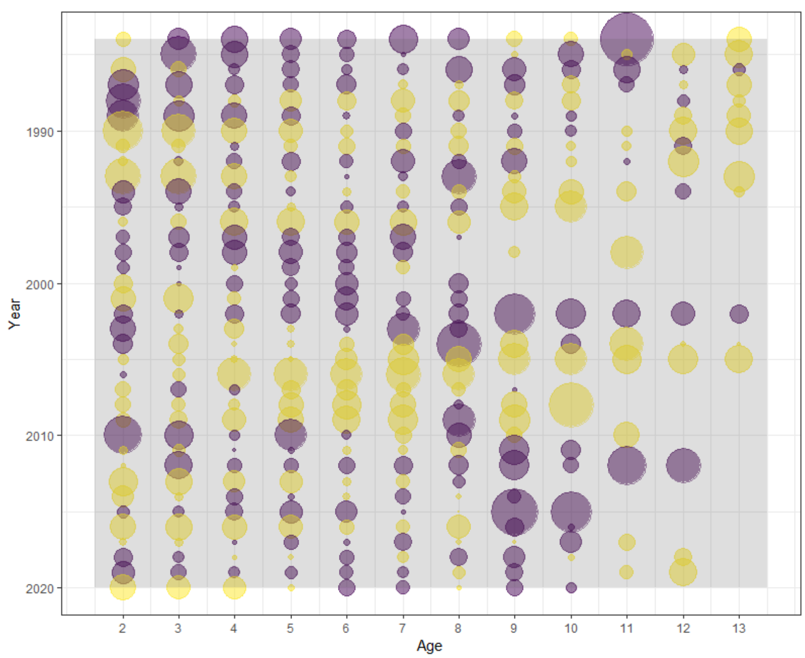


Figure 44. DFO summer survey residuals for Model F – Mstat with size of bubble proportional to the magnitude of the residual and colour indicative of negative (purple) or positive (yellow) values. The grey box identifies ages for which an age-specific q is estimated.

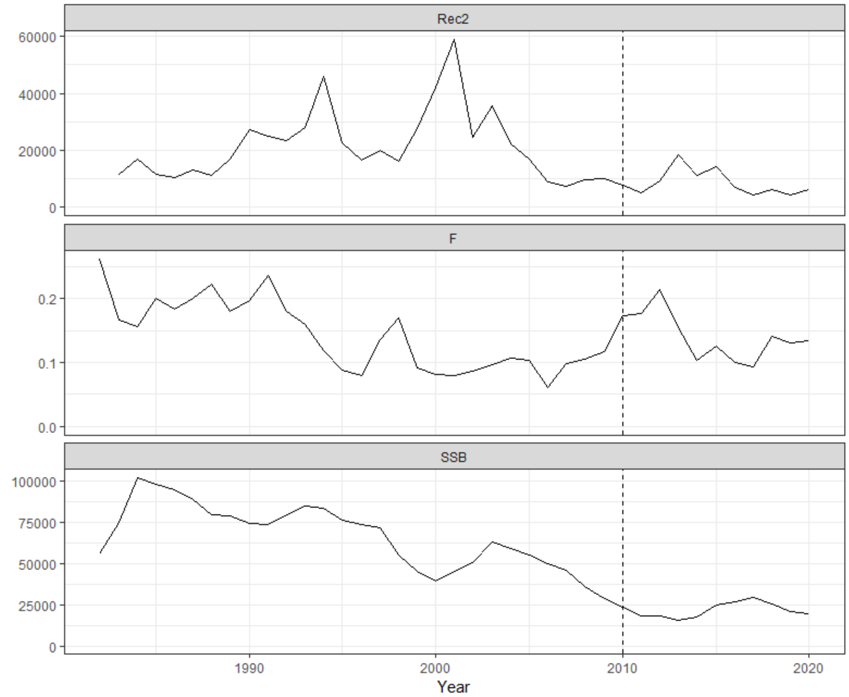


Figure 45. Age 2 recruitment (Rec2, thousands of fish), the fishing mortality (F) on ages 6 through 9 and biomass (SSB, ages 4+) from Model J_M3B.

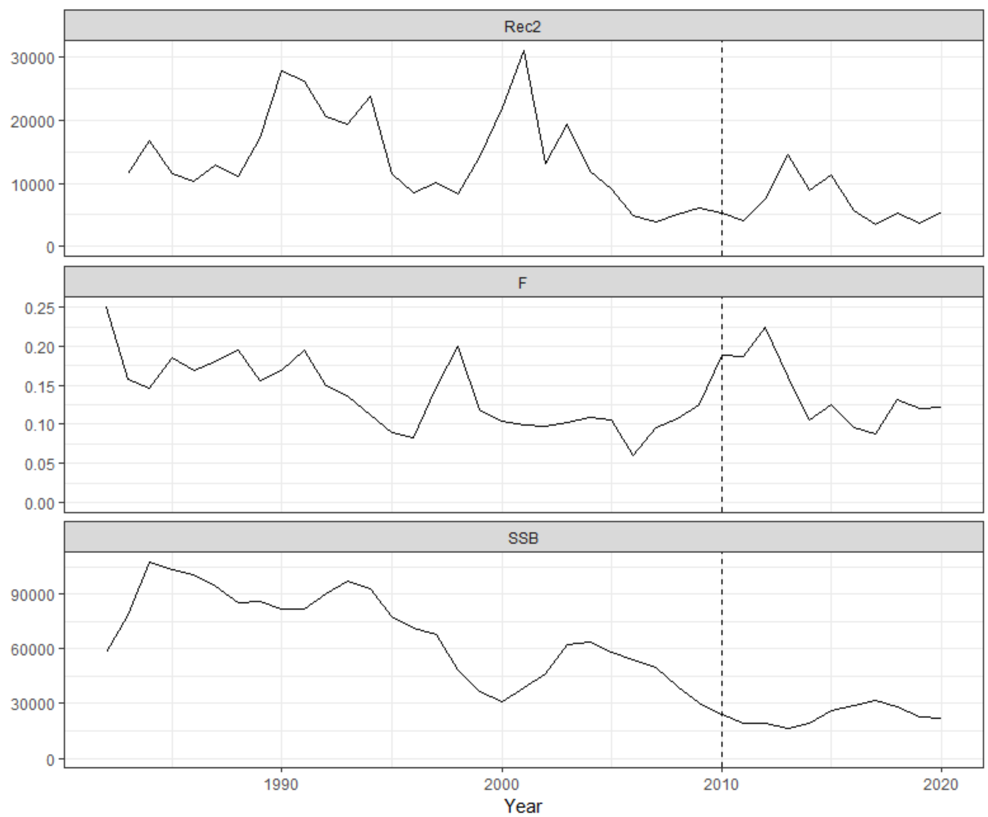


Figure 46. Age 2 recruitment (Rec2, thousands of fish), the fishing mortality (F) on ages 6 through 9 and biomass (SSB, ages 4+) from Model J_M4B.

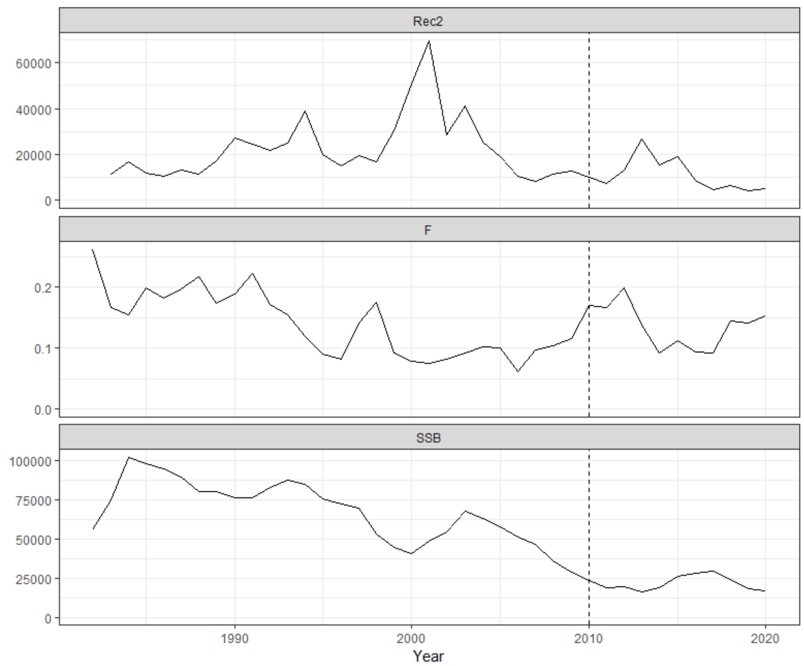


Figure 47. Age 2 recruitment (Rec2, thousands of fish), the fishing mortality (F) on ages 6 through 9 and biomass (SSB, ages 4+) from Model J_M6B.

Figure 48. DFO summer survey observed (points) to predicted (line) abundance for Model J_M4B at each age (facet) and year (x axis).

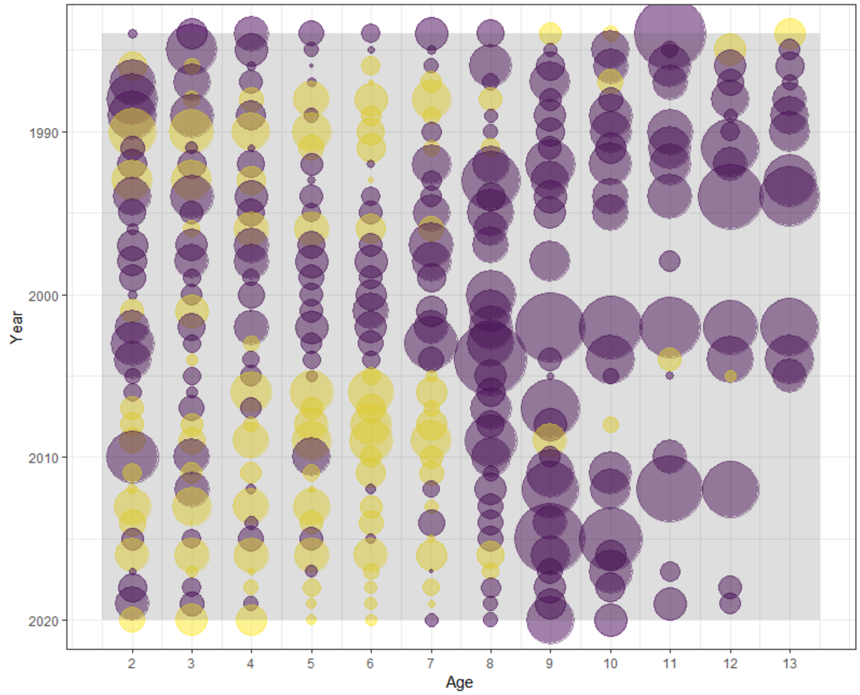


Figure 49. RV bottom trawl survey residuals for Model J_M4B with size of bubble proportional to the magnitude of the residual and colour indicative of negative (purple) or positive (yellow) values. The grey box identifies ages for which an age-specific q is estimated.

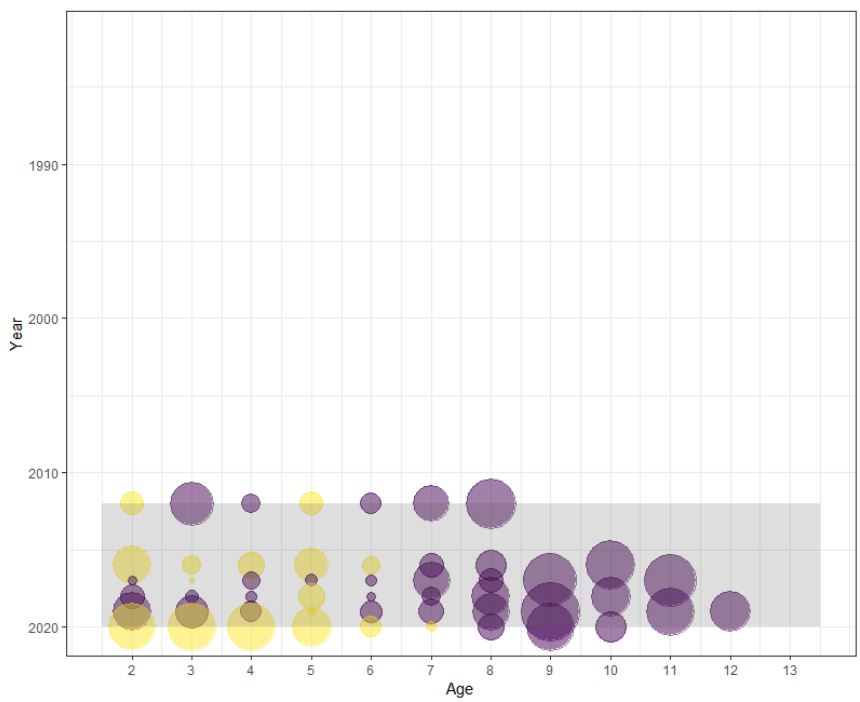


Figure 50. Acoustic survey residuals for Model J_M4B with size of bubble proportional to the magnitude of the residual and colour indicative of negative (purple) or positive (yellow) values. The grey box identifies ages for which an age-specific q is estimated.

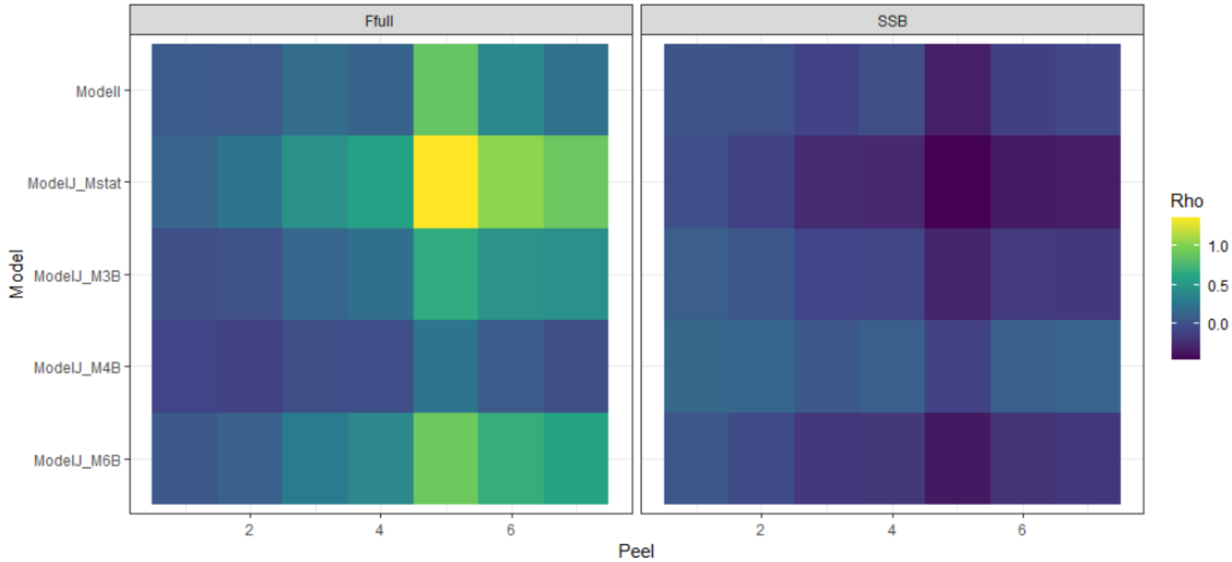


Figure 51. Visualization of the annual Mohn's rho values for models I and J for fishing mortality (Ffull, Left) and biomass (SSB, right).

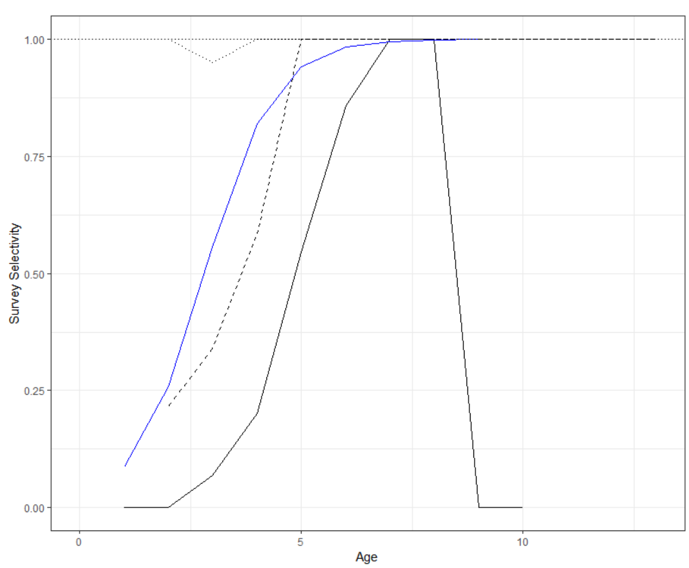


Figure 52. Comparison of survey selectivity derived from the catchability (q) outputs of the 2011 VPA (black solid), the 2022 Model J_M4B (black, dashed), and the model-independent catch-based method (blue). The fine dashed line shows the final selectivity estimated on the acoustic index in Model J_M4B.

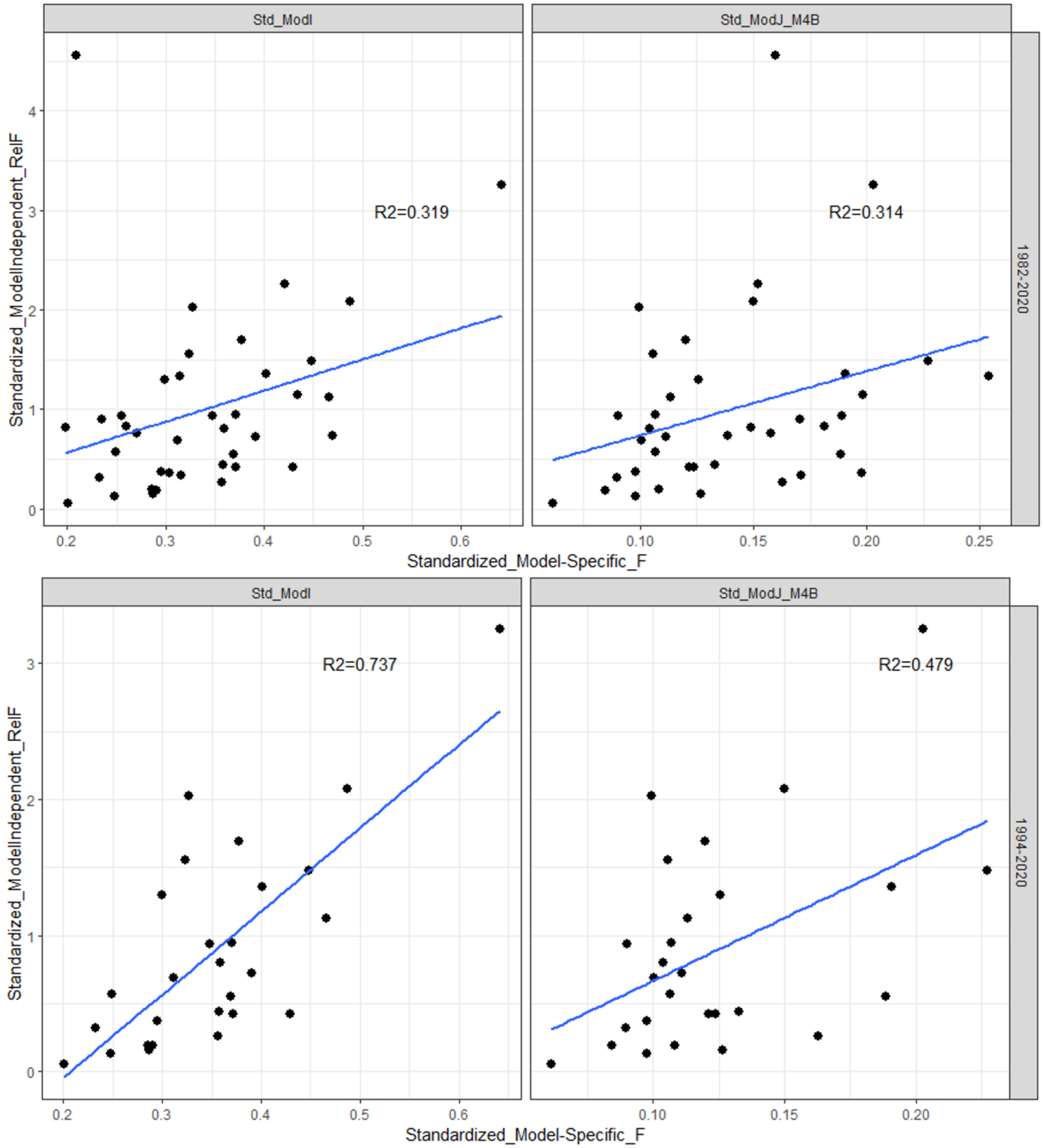


Figure 53. Correlations calculated for the final two models (columns) for a complete time series (top row) and a recent time series (bottom row). Blue line shows the regression line.

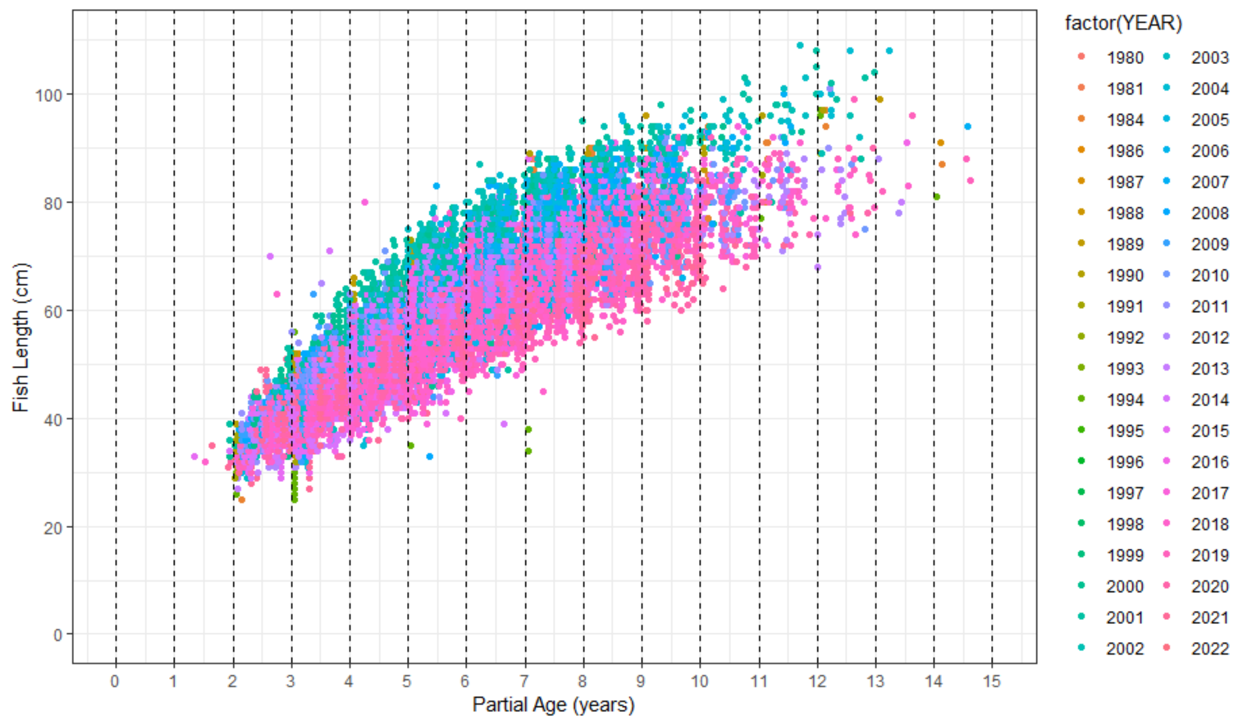


Figure 54. Length at age for Western Component Pollock from all readily available data sources (port samplers and survey). Partial age is calculated assuming a February 1st birthdate.

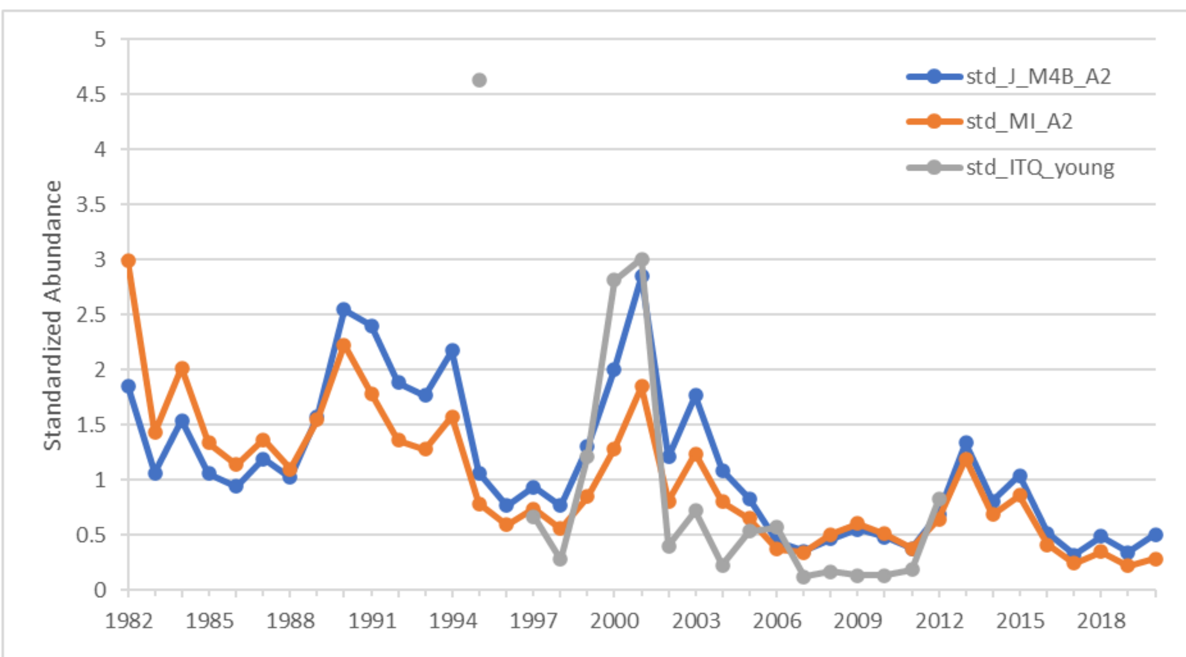


Figure 55. Pollock abundance at age 2 from Models I (orange lines) and J_M4B (blue lines), and index of abundance for fish lengths 30–43 cm from the ITQ survey (grey). All three indices have been standardized by their respective means from 1995 to 2012 to appear on the same axis.

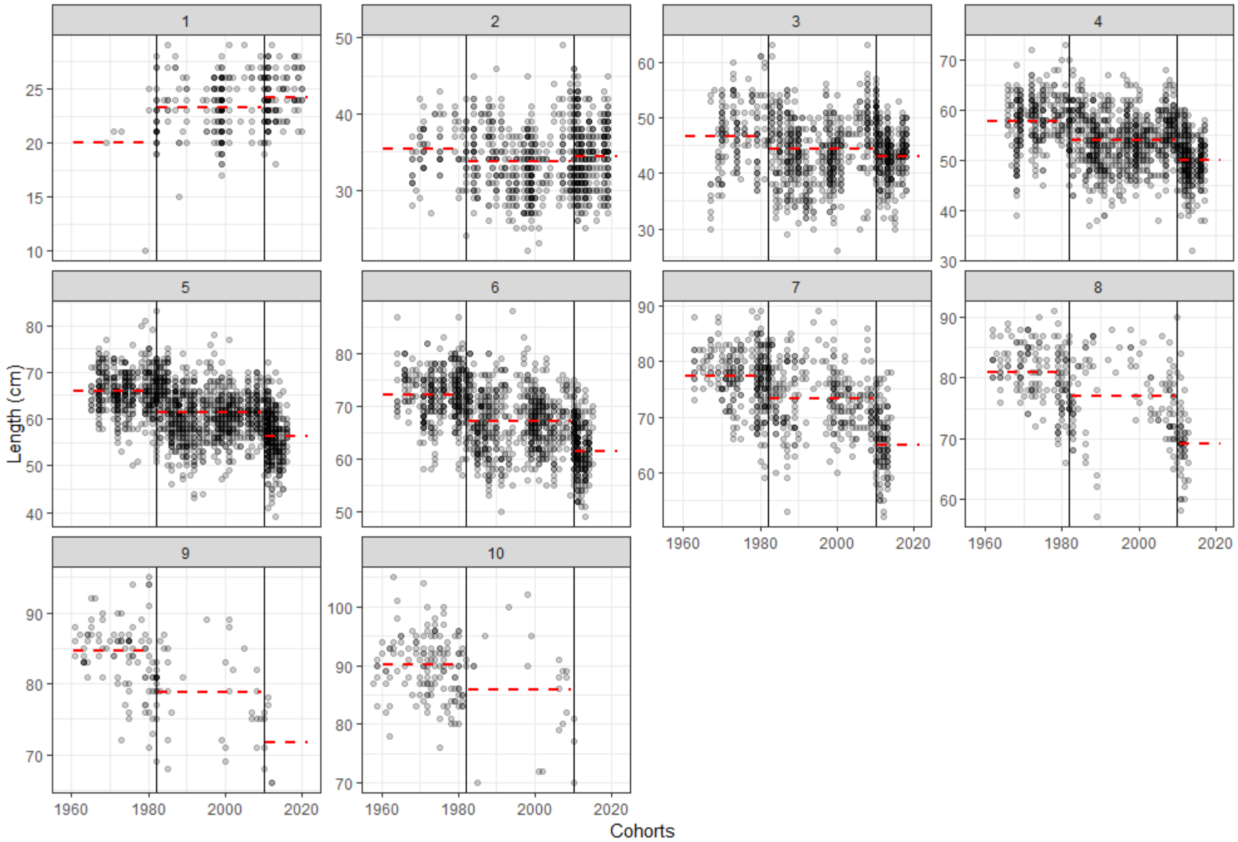
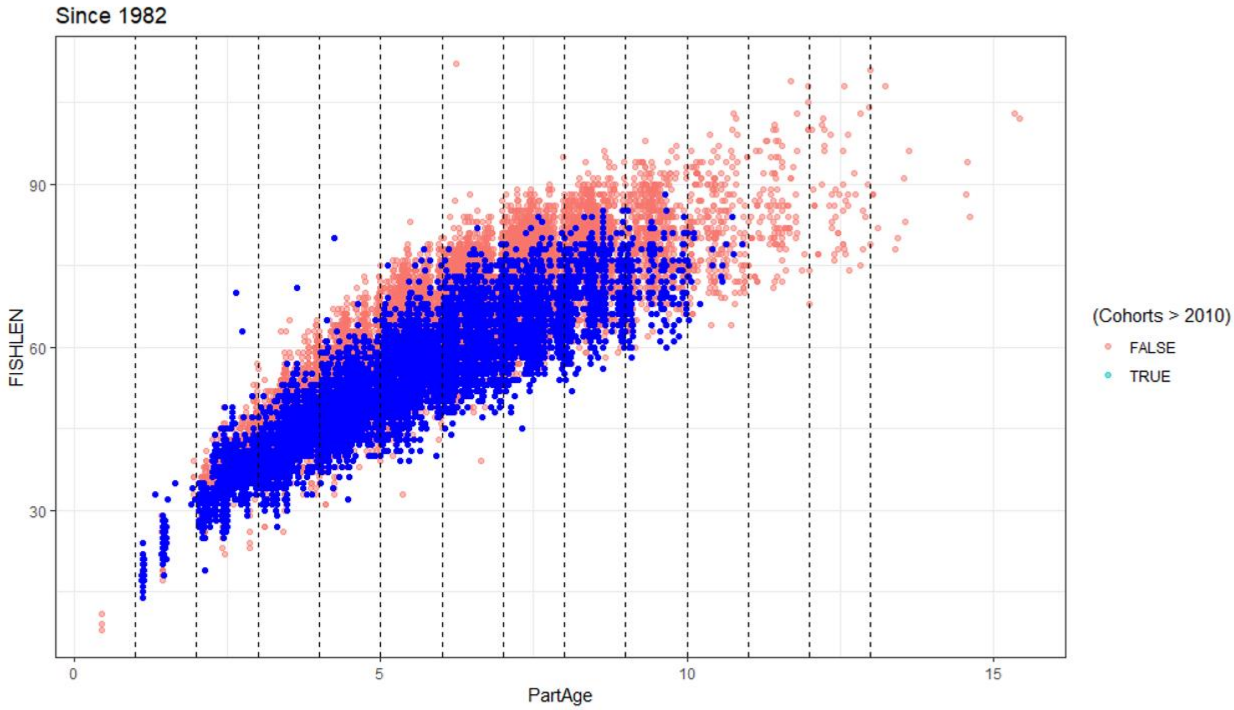


Figure 56. Length (points) at age (facets) by cohort for Pollock caught on the DFO summer survey in NAFO areas 4Xopqrs5. Vertical lines identify the period breaks and the horizontal dashed red line show the mean length at age for each time period.



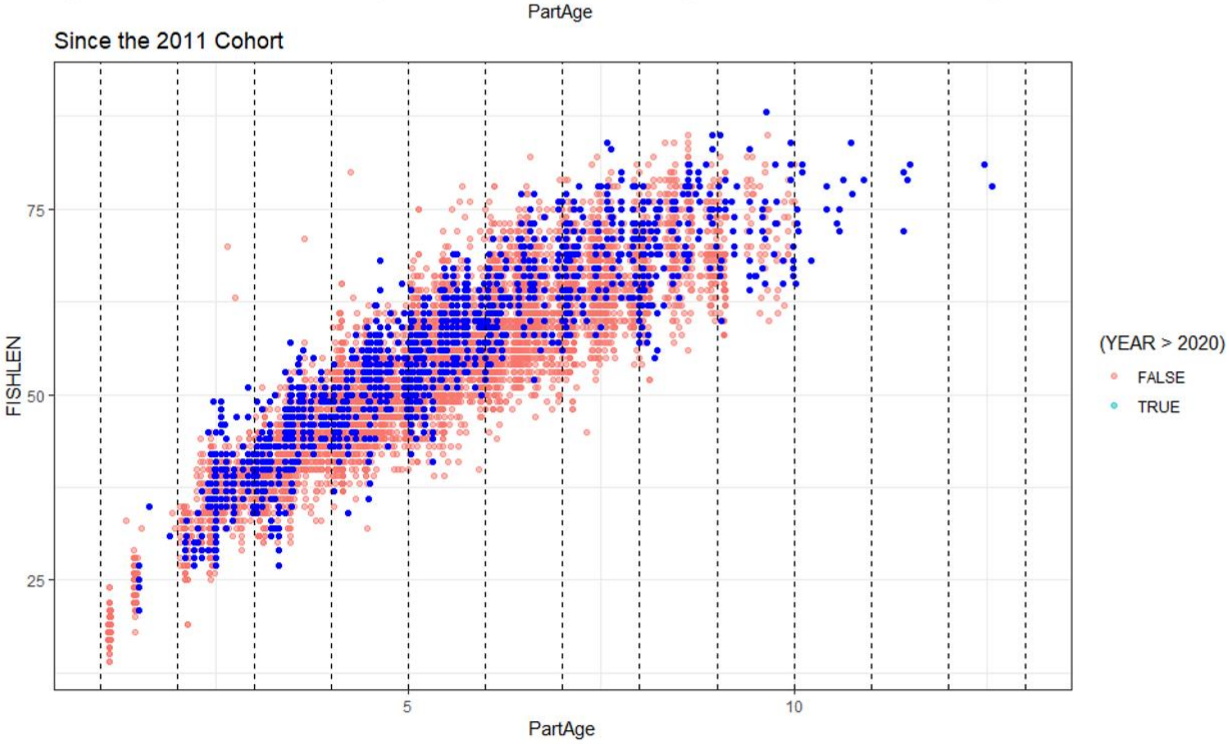


Figure 57. Length at age for WC Pollock since 1982 (top panel) and since the 2011 cohort (bottom panel) from all available port samples, observer and ecosystem survey databases. Partial age is calculated based on the proportion of the year which has passed since the birth date of the fish. Pollock are assumed to have a February 1 birthdate.

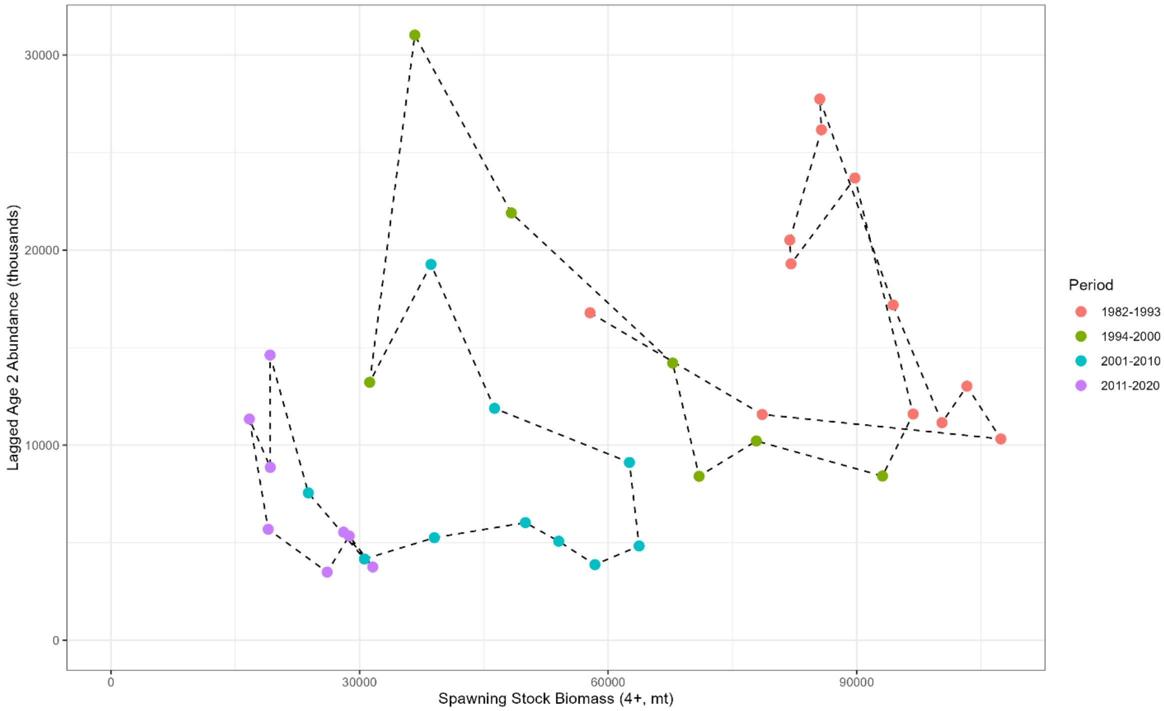


Figure 58. Spawning stock biomass (mt) and recruitment (thousands) for Model J_M4B. Recruitment has been lagged by two years. Colour of points indicates groups of years to help identify years. Dashed line identifies adjacent years.

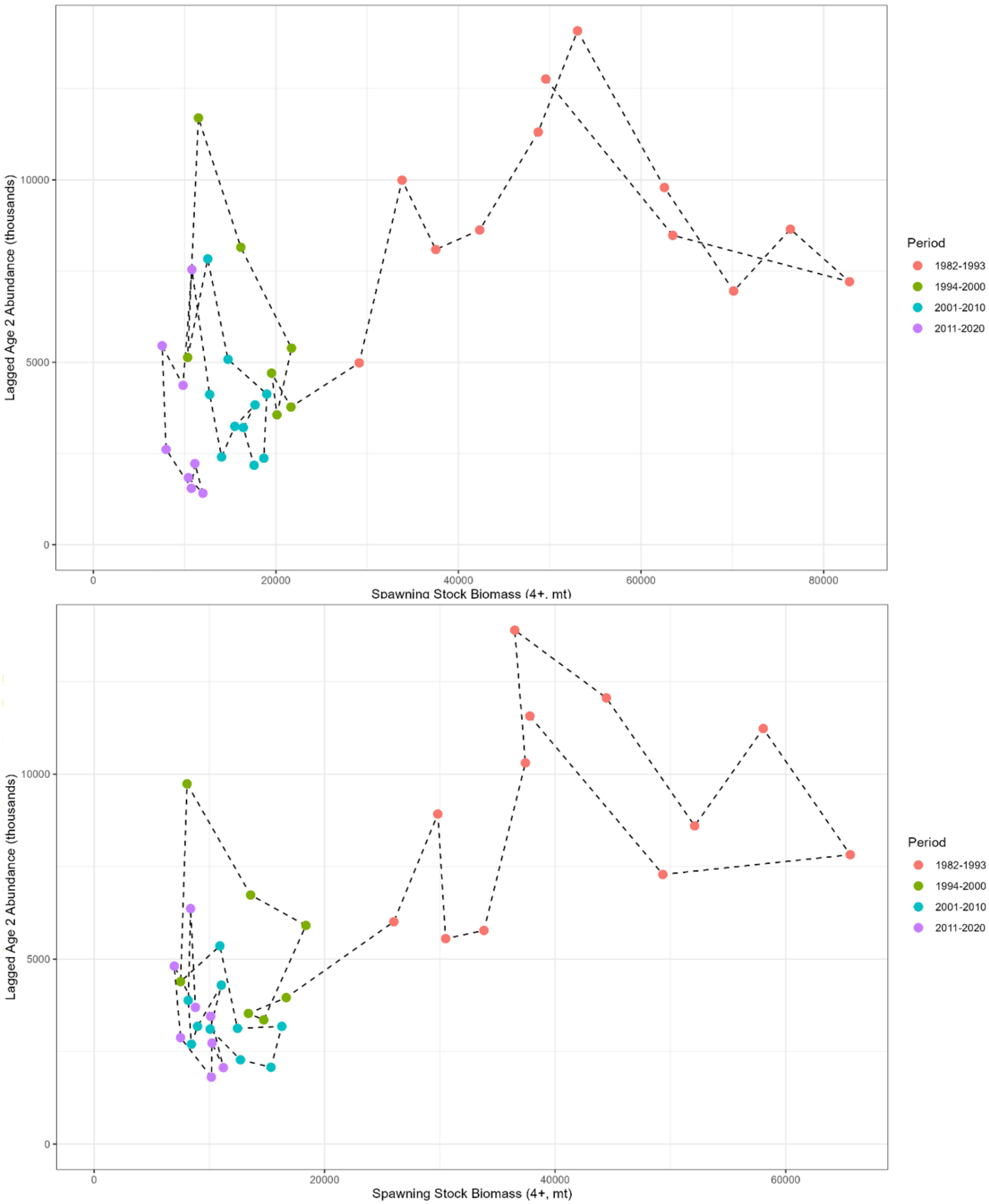


Figure 59. Spawning stock biomass (mt) and recruitment (thousands) for sensitivity models I (Upper Panel) and E (Lower Panel), shown for demonstration purposes only. Recruitment has been lagged by two years. Colour of points indicates groups of years to help identify years. Dashed line identifies adjacent years.

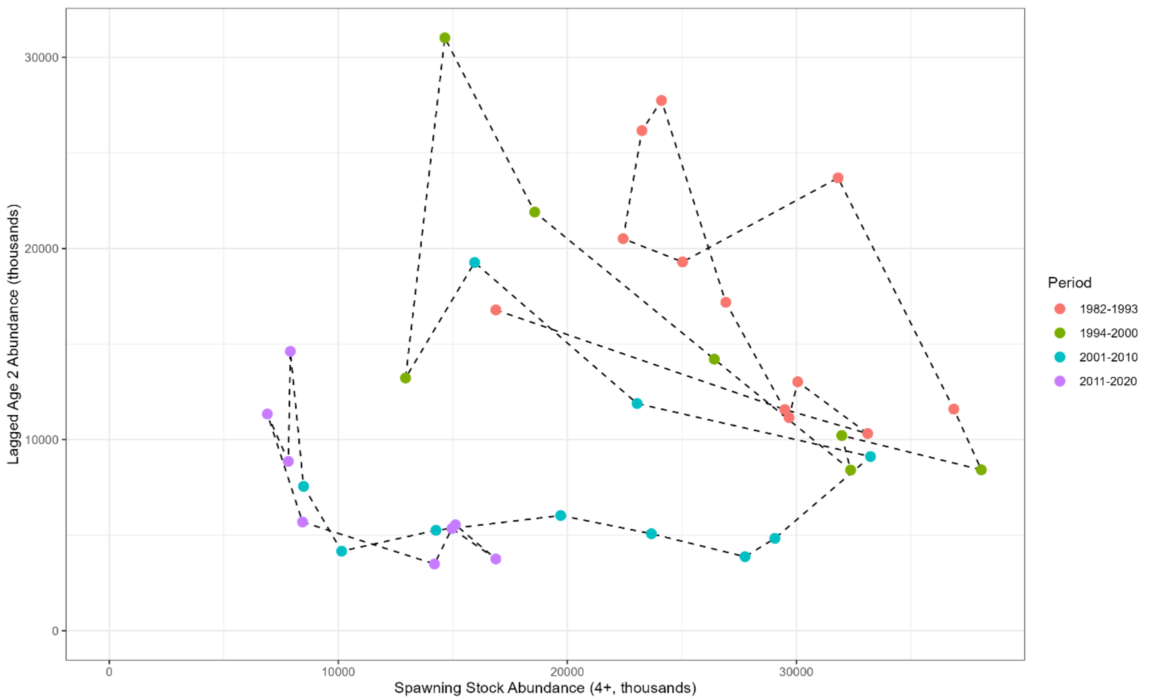


Figure 60. Spawning stock abundance (4+, thousands) and recruitment (thousands) for Model J_M4B. Recruitment has been lagged by two years. Colour of points indicates groups of years to help identify years. Dashed line identifies adjacent years.

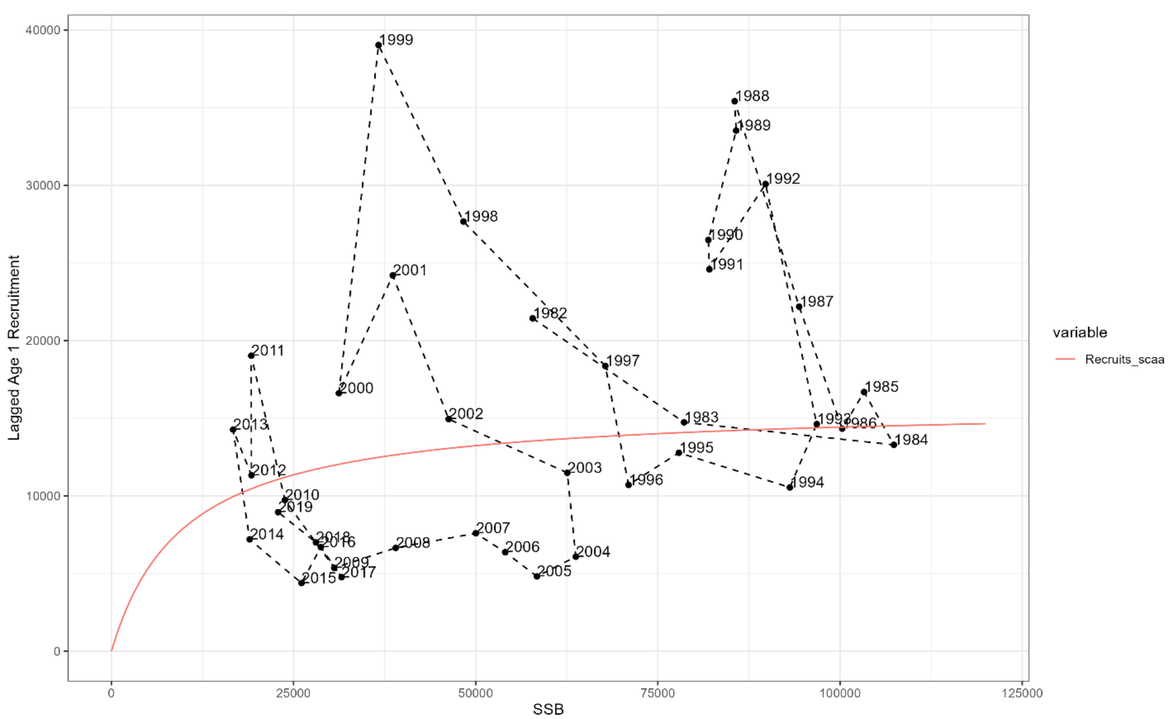


Figure 61. Recruitment (Age 1, lagged) and spawning stock biomass outputs from J_M4B. Colour of points is consistent between panels. Solid lines show the stock recruitment relationship from the SCAA. Dashed line connects adjacent years.

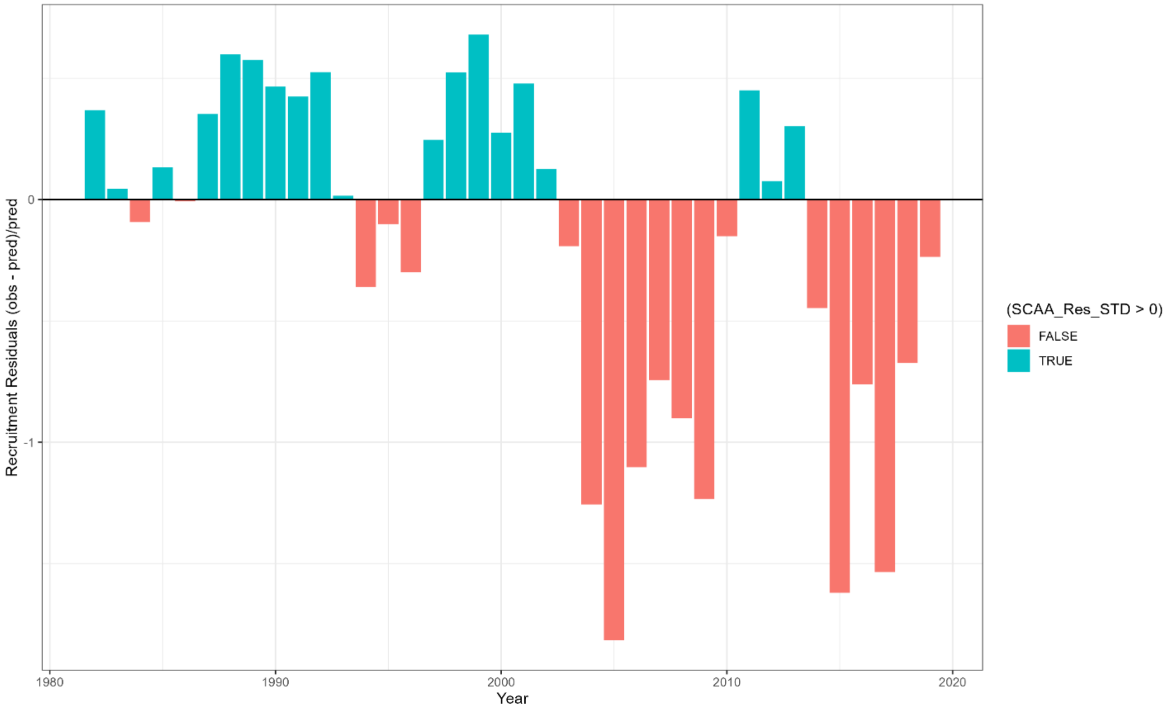


Figure 62. Standardized recruitment residuals from J_M4B to a Beverton-Holt stock recruitment relationship. Colour indicates positive and negative residuals.

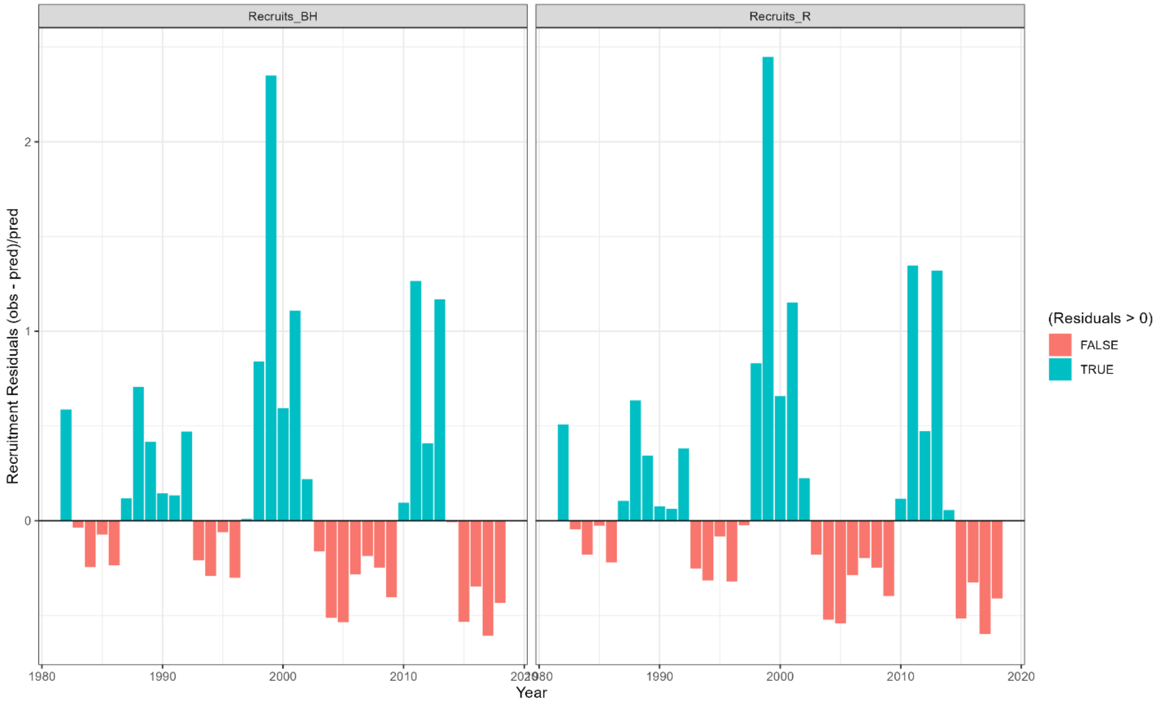


Figure 63. Recruitment (Age 2, lagged two years) and spawning stock biomass (upper panel) and standardized residuals to the stock recruitment Relationship (lower panel) for sensitivity Model I.

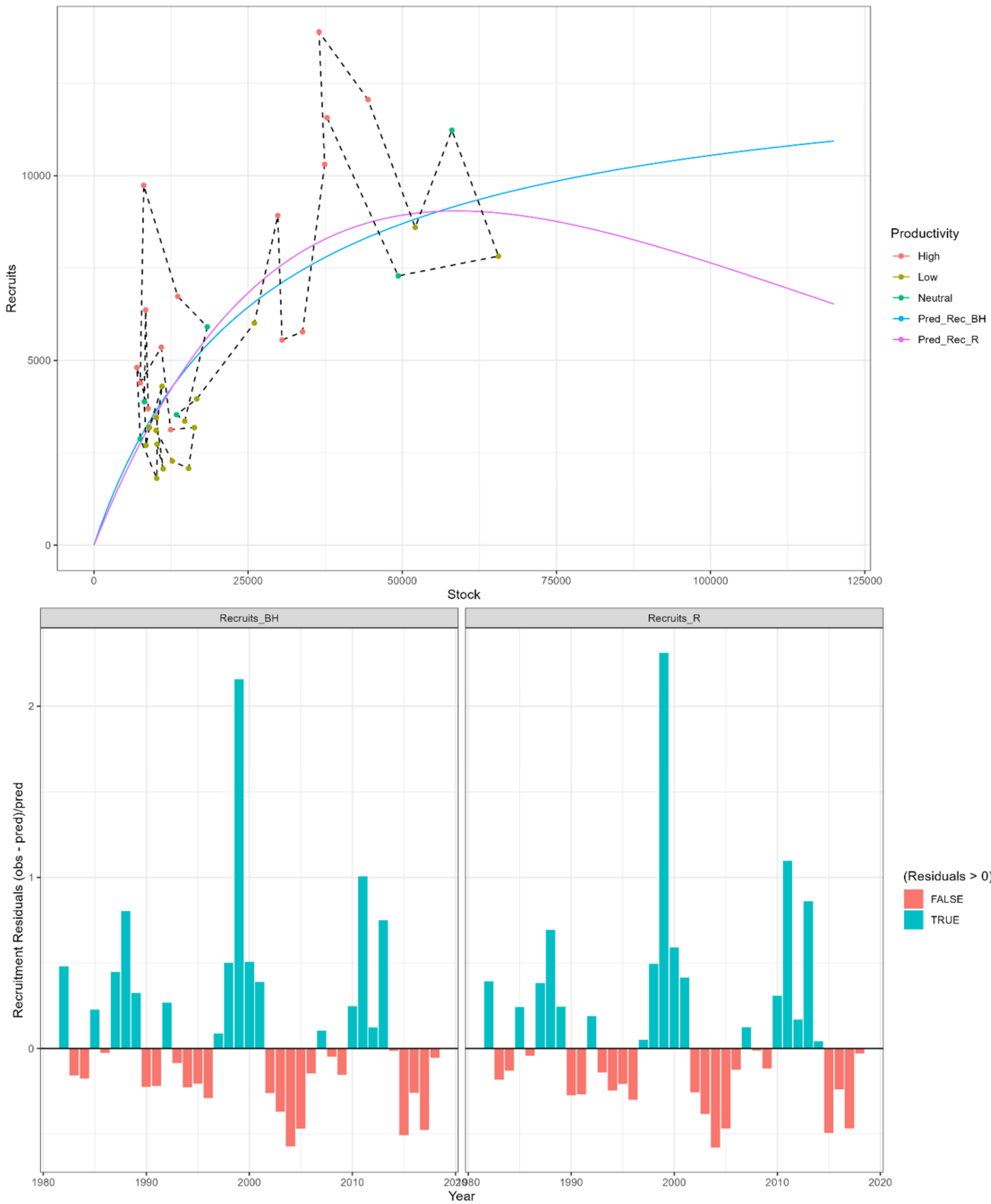


Figure 64. Recruitment (Age 2, lagged two years) and spawning stock biomass (upper panel) and standardized residuals to the stock recruitment relationship (lower panel) for sensitivity Model E. Note that as Model E is a VPA, the stock-recruitment relationship was fit to the data post-hoc.

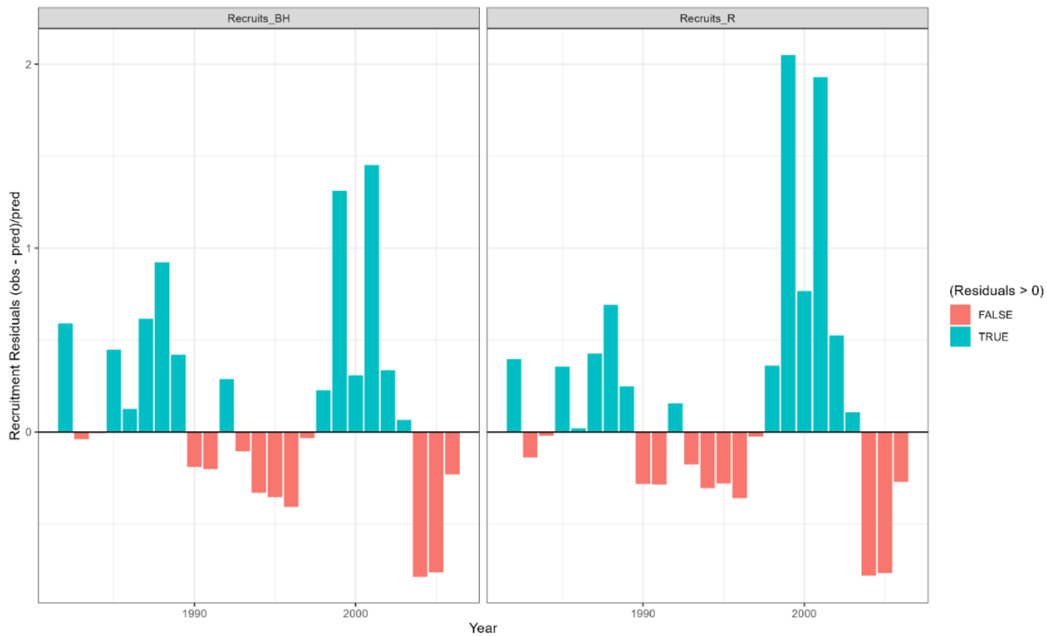


Figure 65. Recruitment (Age 2, lagged two years) and spawning stock biomass (upper panel) and standardized residuals to the stock recruitment relationship (lower panel) for the 2011 MSE. Note that this was a VPA, so the stock-recruitment relationships were fit to the data post-hoc.

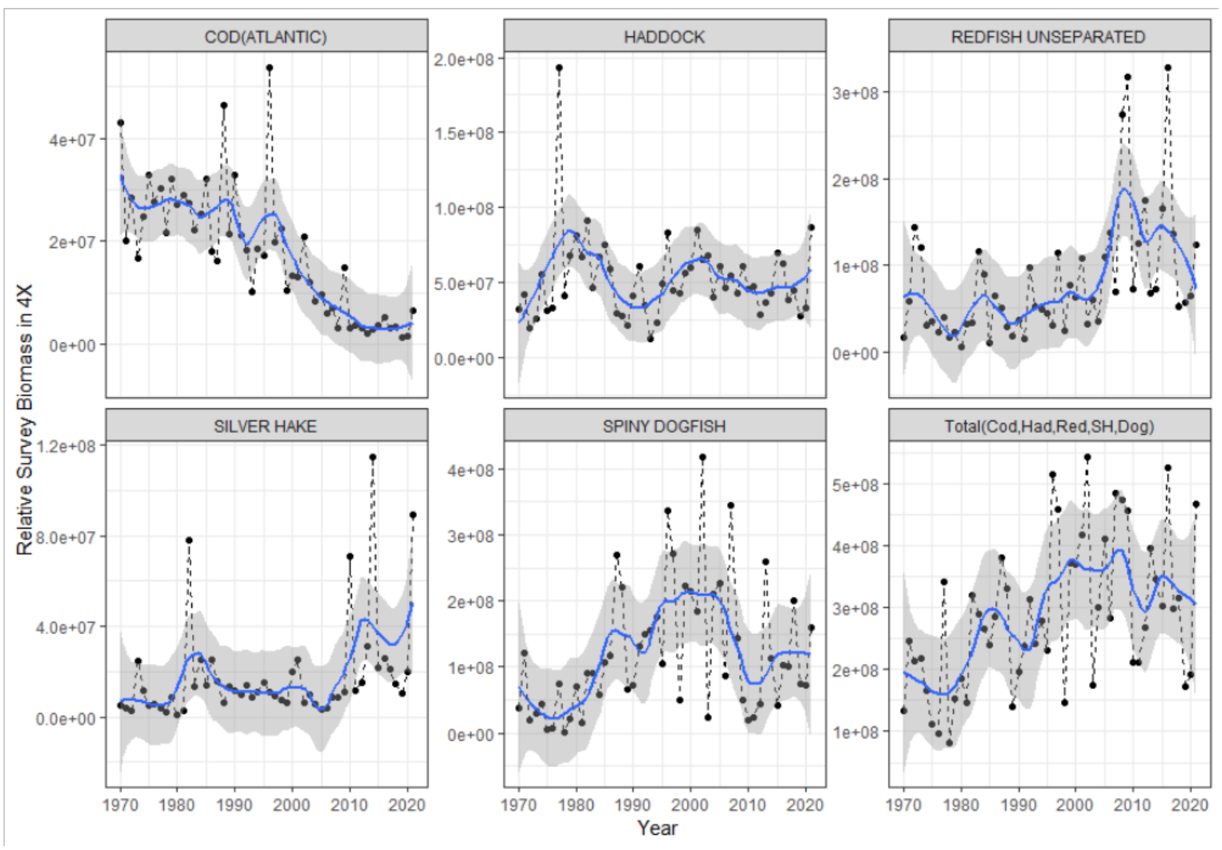


Figure 66. Approximate biomass trends from the DFO summer survey for strata 469–498 (NAFO 4X5Y) for various species considered to be either predators or competitors of Pollock.

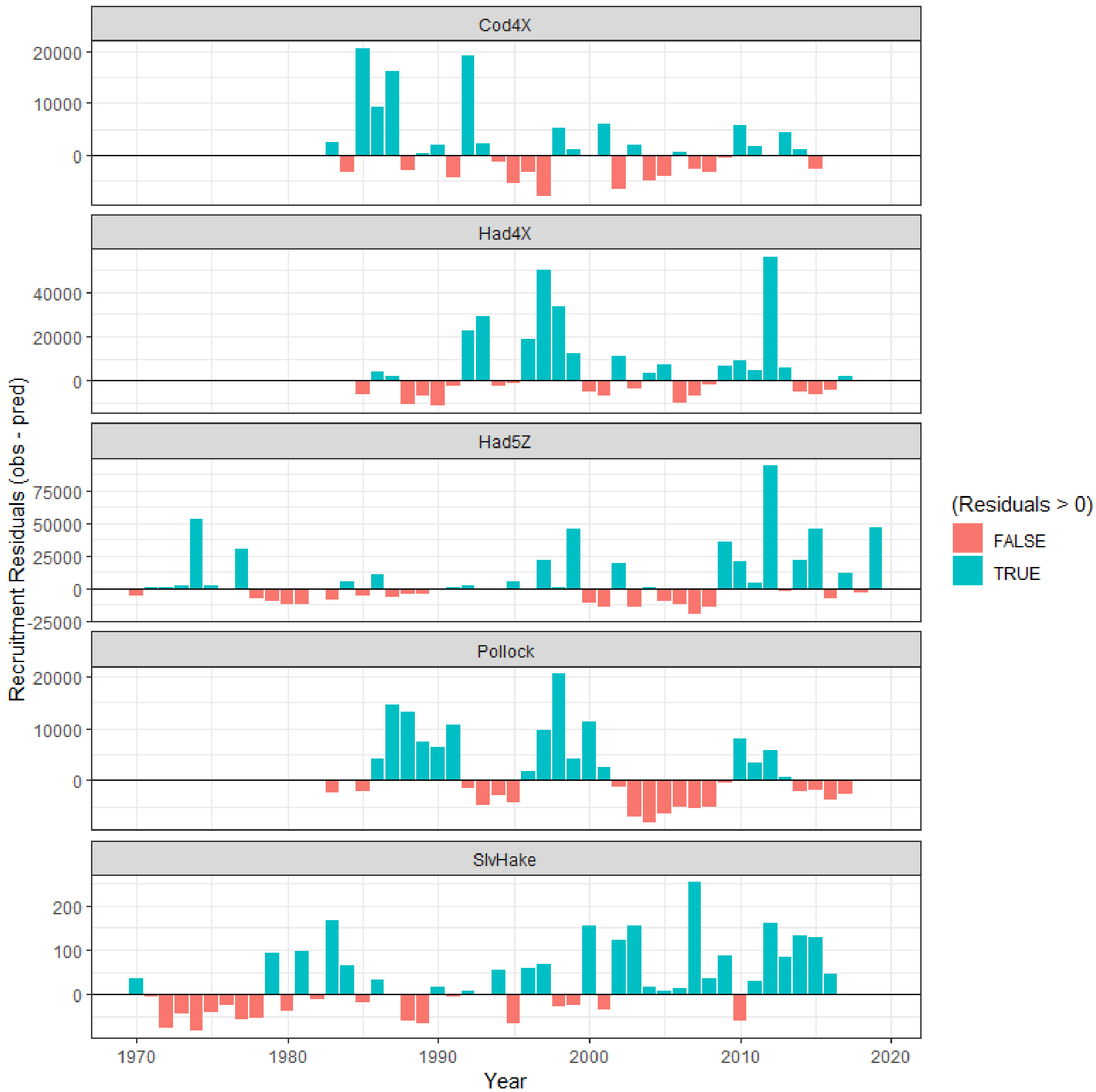


Figure 67. Residuals in recruitment of various groundfish species from a Ricker stock-recruitment relationship. Stock-Recruitment data were obtained from model outputs when possible (5Z Haddock, 4X5Y Cod, Silver Hake), and the DFO summer survey when not possible (4X5Y Haddock). Note that the 2013 years for both 5Z and 4X5Y Haddock were artificially adjusted down to make the residuals in other years visible; the actual values for those years exceed 90,000. Recruitment estimates were lagged accordingly, to coincide with the biomass that produced them.

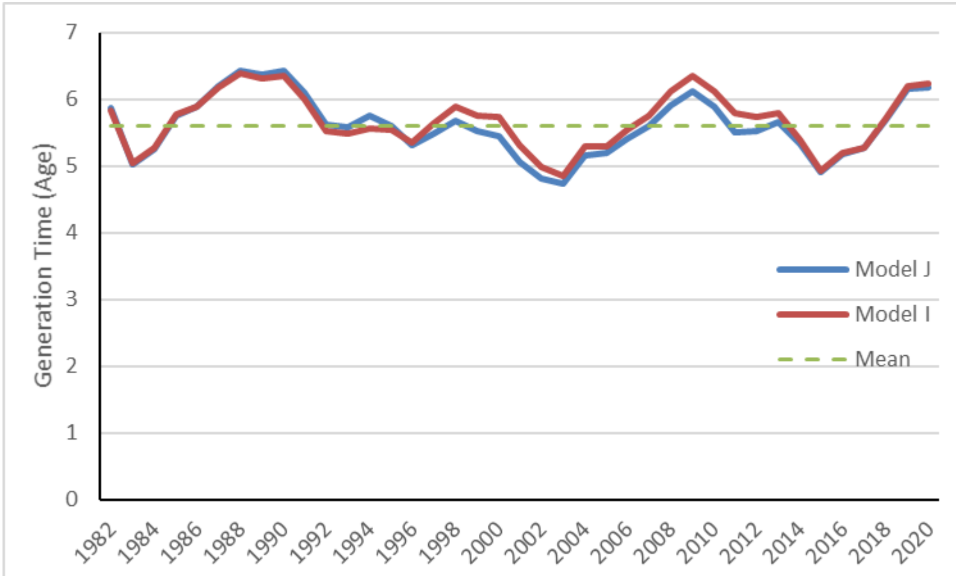


Figure 68. Generation time for Models I and J_M4B over time.

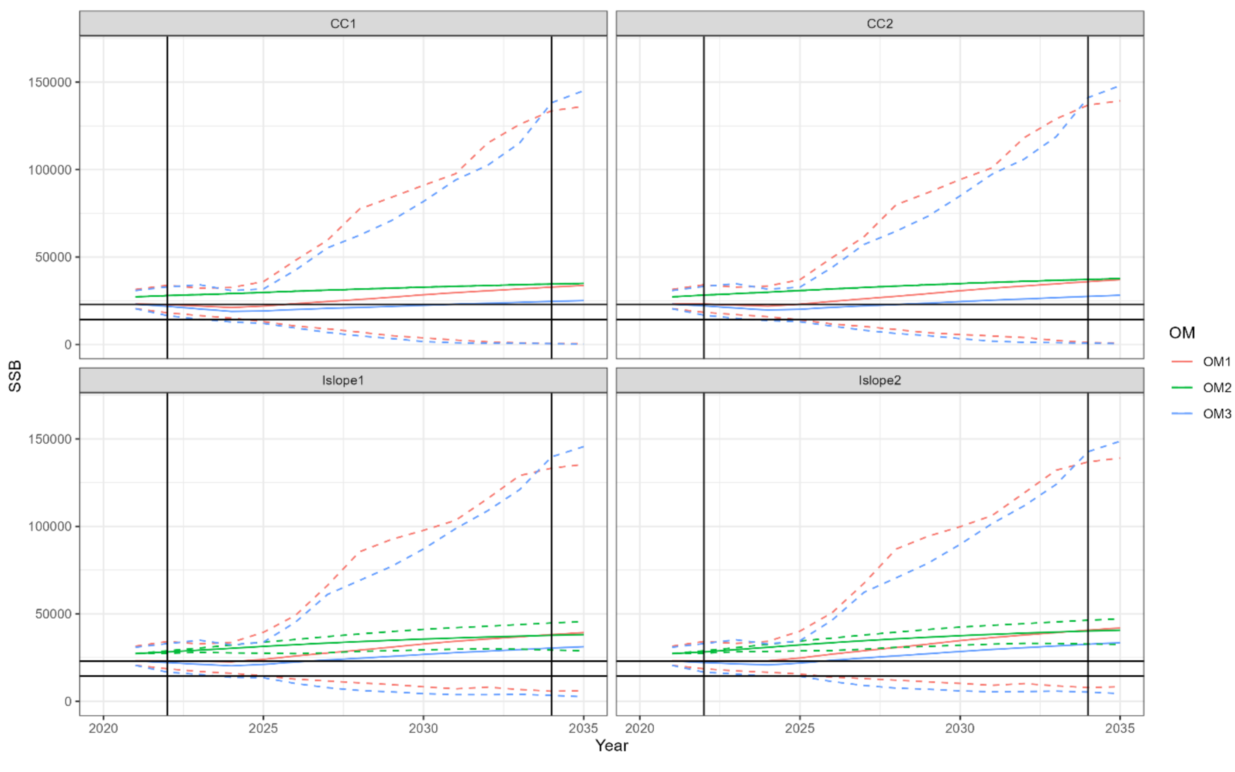


Figure 69. Example outputs for a sample of three OMs and four MPs. These are not representative of actual runs and are just here for example purposes and interpretation of the subsequent scorecard plots.

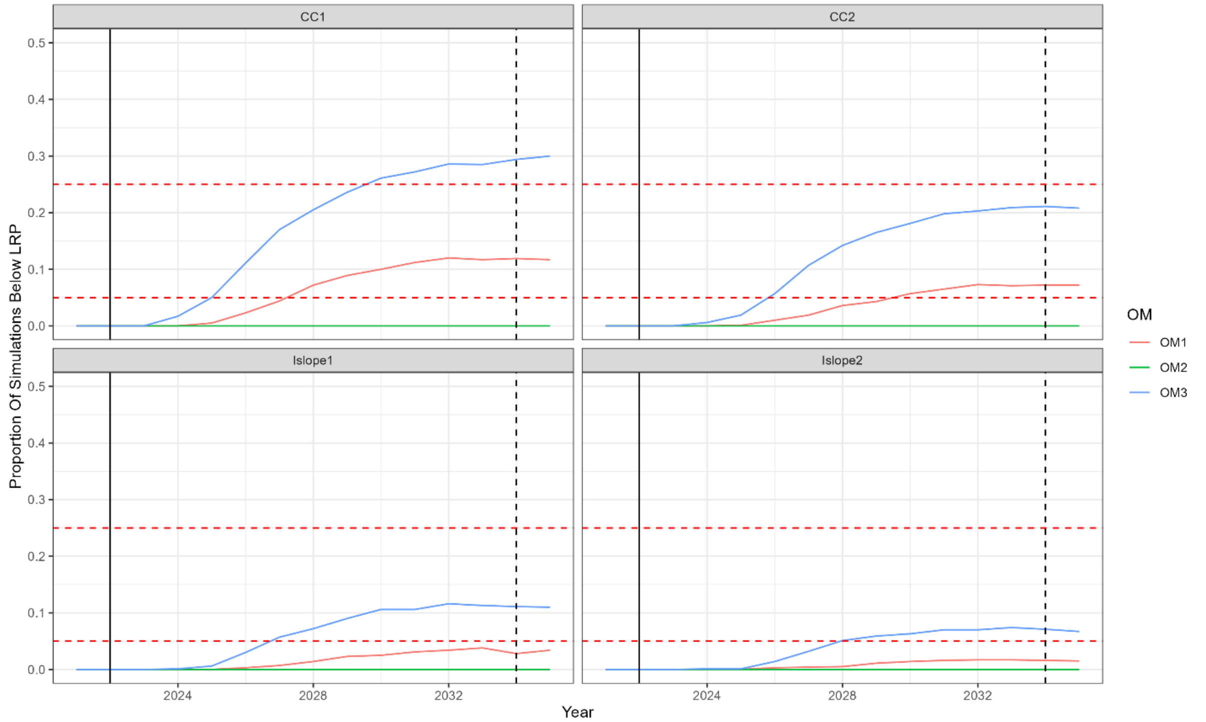


Figure 70. Example scorecard figure showing the performance of each MP (facets) against Objective 1.

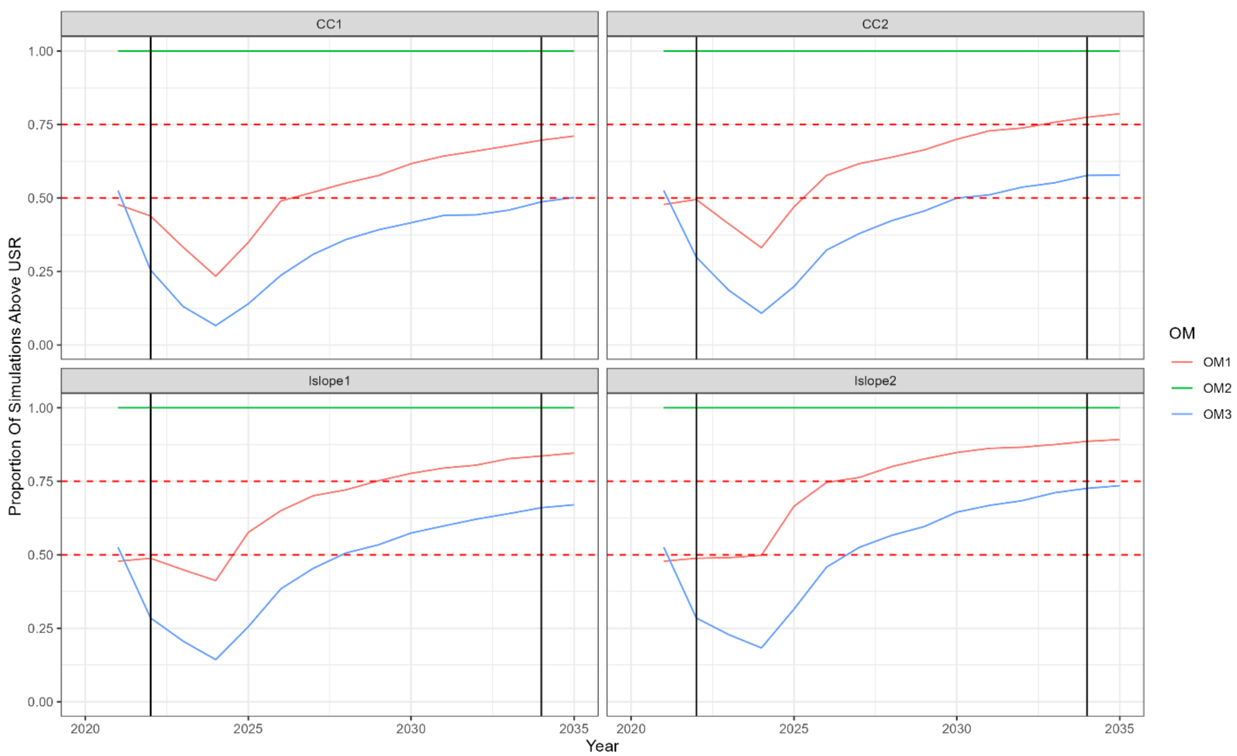


Figure 71. Example scorecard figure showing the performance of each MP (facets) against Objective 2.

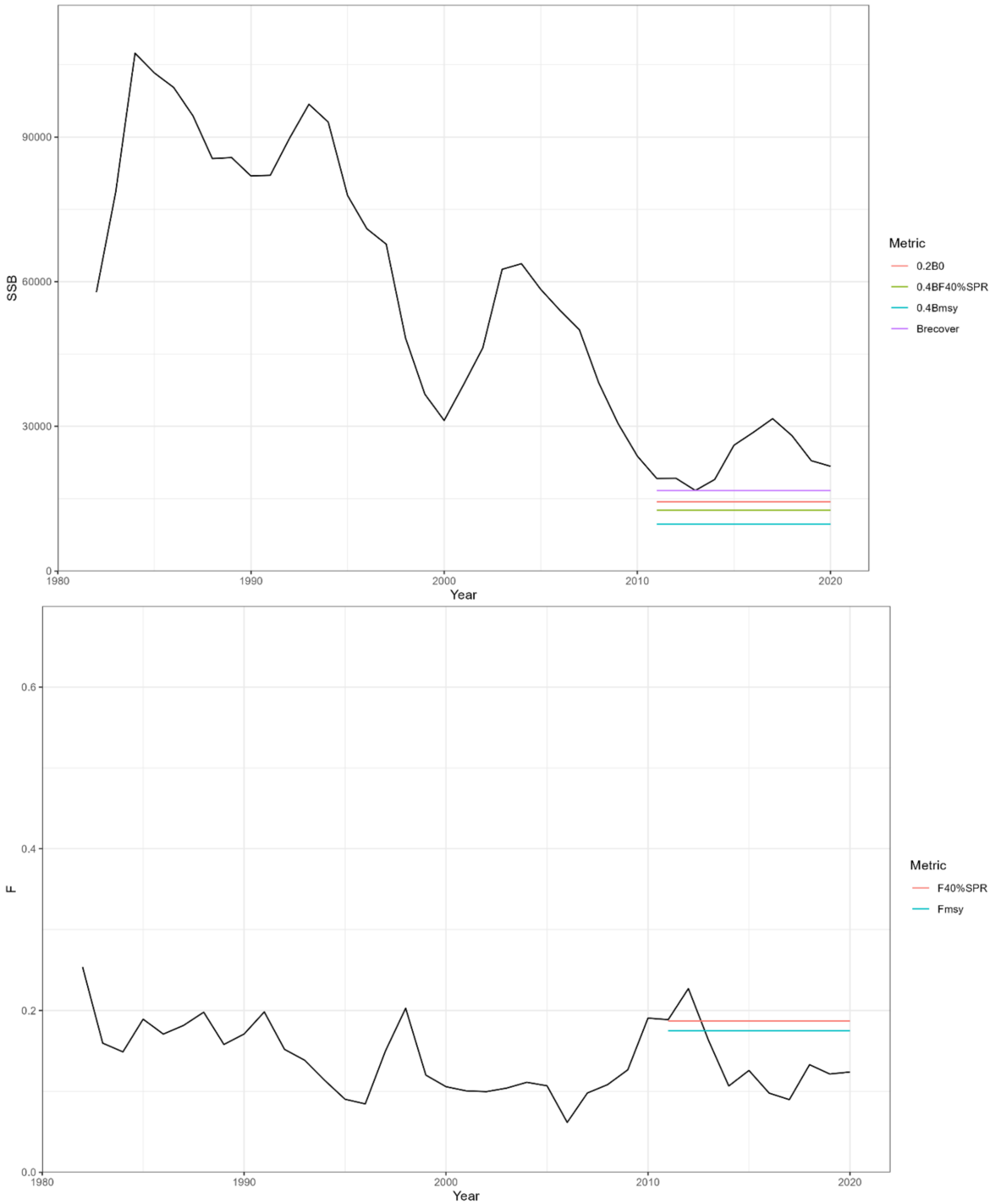


Figure 72. Spawning stock biomass (top panel) and fishing mortality (bottom panel) trends from Model M_J4B, along with their respective candidate reference point and removal reference metrics under the recent M scenario (0.340).

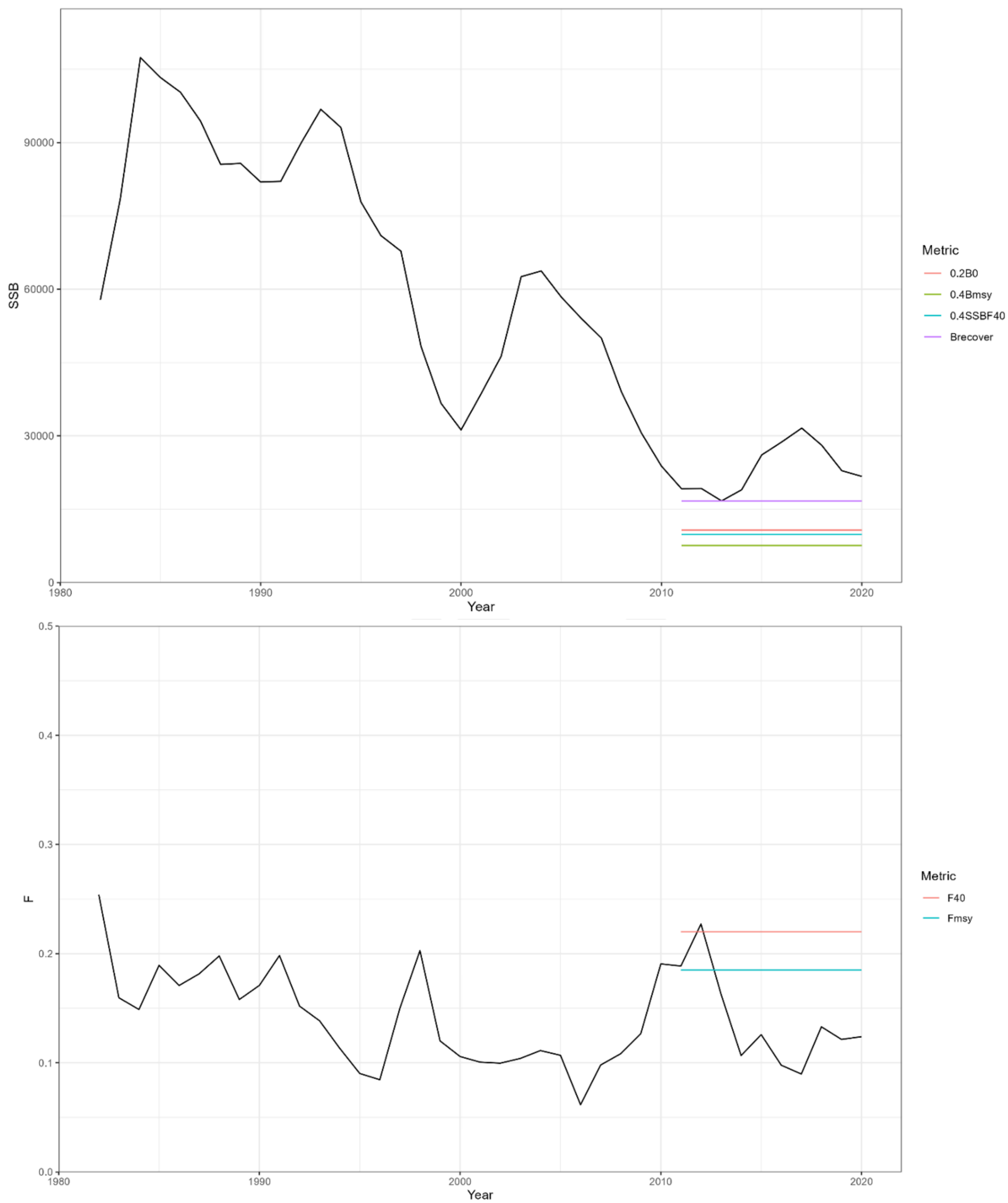


Figure 73. Spawning stock biomass (top panel) and Fishing mortality (bottom panel) trends from Model M_J4B, along with their respective candidate reference point and removal reference metrics under the series mean M scenario (0.415).

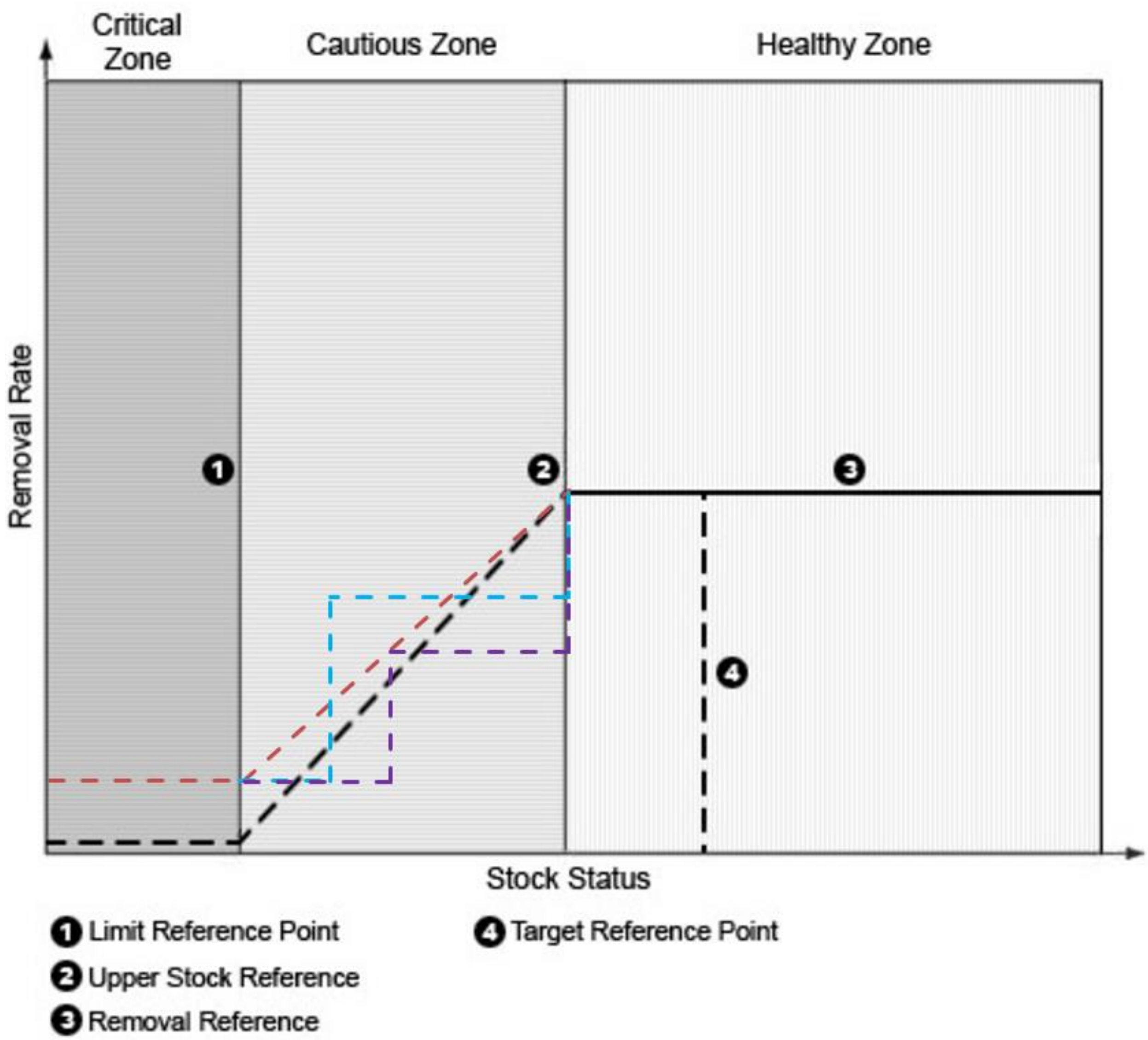


Figure 74. Precautionary Approach figure (originally from DFO 2009) showing HCR variations. Black shows HCR with a low F in the critical zone. Red shows the generic HCR with a higher F in the critical zone. Purple shows a HCR with Fs equivalent to or lower than the red. Blue shows an example of a HCR which exceeds Fs prescribed by the red.

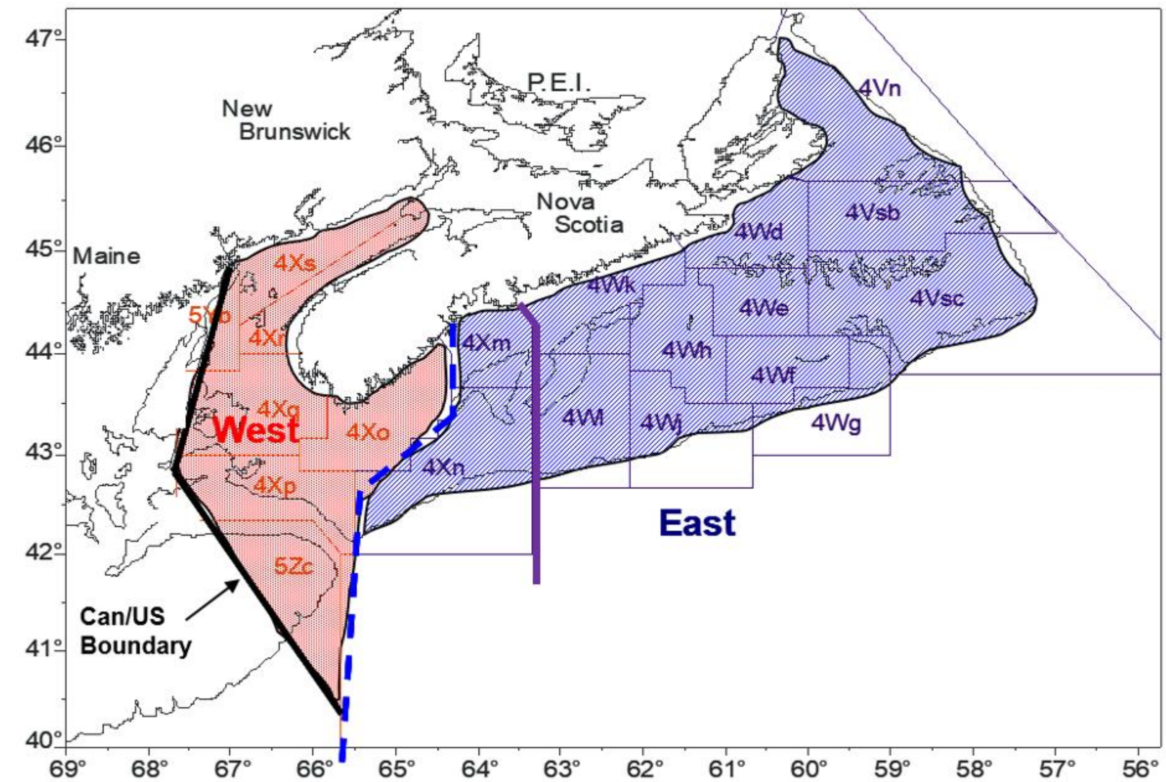


Figure 75. Spatial division of the Eastern and Western Component Pollock in the Maritimes Region. Dashed blue line delineates the division between East and West for the assessment units. Purple solid line delineates the division between East and West for the Management Units.