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2018 Stock Assessment Modelling Framework for 4X5Y Cod

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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

The 2018 stock assessment modelling framework review for 4X5Y Cod was held on November 6–8, 2018. It was the second of two Maritimes Region of Fisheries and Oceans Canada peer-review meetings for 4X5Y Cod. This meeting was preceded by the Assessment Framework for 4X5Y Atlantic Cod: Part 1 – Review of Data Inputs, held on March 27–28, 2018. This research document summarized the conclusions from the ‘data inputs’ meeting and described the methodologies developed for estimating current stock status, reference points, and short term projection for providing multi-year catch advice. A 10-year, medium-term projection was conducted to evaluate the recovery potential. Guidance on inter-framework review activities, existing data gaps, and research recommendations in the future were documented.

Both a Virtual Population Analysis (VPA) model and State-space Assessment Model (SAM), with assumed constant natural mortality (M), were used to demonstrate the fitting problems caused by the unexplained high mortality reflected in the survey and fishery data. To resolve the retrospective pattern and other model fitting issues observed in past 4X5Y Cod stock assessments, the VPA models with random walk in M by different age groups were explored. A VPA model (3MFfirst) was recommended as the new framework model for the 4X5Y Cod stock assessment. There was a clear temporal increasing trend in M on older age groups (ages 5+); it has steadily increased from 0.37 in 1983 to about 1.5 since 2011. The high M estimated in the VPA models could be aliasing fish moving to adjacent areas or deeper waters, under-reported landings, and unreported discards, as well as natural mortality caused by biotic and abiotic factors.

For the biomass limit reference points, considering the unstationary natural mortality of ages 5+ Cod, the equilibrium Maximum Sustainable Yield (MSY)-based reference points was considered not appropriate. The $S_{b_{50/90}} = 22,193$ mt was recommended as the biomass limit reference points for 4X5Y Cod. Given the estimated poor stock status, the fishery catch advice would be as low as possible to rebuild this stock. The fishing reference point was not developed. A 10-year projection showed that there would be little chance of stock recovery under high M and low recruitment, even with zero catch.

INTRODUCTION

In 2018, the Maritimes Region of Fisheries and Oceans Canada (DFO) initiated a two-part framework assessment review of 4X5Y Cod. The first part focused on commercial fishery and survey data inputs, which were evaluated during a meeting conducted at the St. Andrews Biological Station, March 27–28, 2018, and are documented in Andrushchenko et al. (2022).

The main conclusions from the data input review are provided below. For details see Andrushchenko et al. (2022).

STOCK STRUCTURE

Although assessed together, Atlantic Cod in the Bay of Fundy (NAFO areas 4Xqrs5Yb) and Scotian Shelf (NAFO areas 4Xmno) areas of the management unit exhibit distinctly different growth rates, with western fish (Bay of Fundy) growing faster than those from the east (Scotian Shelf). In general, a two-stock component structure within 4X5Y seems to persist, with a mixing area in 4Xp and some movement taking place between adjacent management areas.

COMMERCIAL FISHERY

Use of pre-1980 catch data is limited to total amounts, as catch sampling prior to 1980 excluded the Bay of Fundy region, rendering any age or size stratification of the catch within the 4X5Y area inaccurate prior to 1980. Assessing Bay of Fundy and Scotian Shelf Cod separately would require additional work to address misreporting throughout the 1980s, or a time series starting post 1990.

Insufficient levels of observer coverage and lack of systematic, unbiased sampling, continue to be the major impediments to quantifying the magnitude of Cod bycatch/discards in non-groundfish fisheries.

RESEARCH VESSEL SURVEY

The RV survey has undergone several vessel and gear changes throughout the time series since 1970, but problems during comparative fishing between RV Lady Hammond to the RV Alfred Needler in 1983, and uncertainties about the relative fishing power of the two vessels, resulted in unreliable Cod conversion factors (Clark and Brown 1996, Mohn 1999). Without reliable conversion factors, abundance and biomass trends prior to 1983 are not comparable to subsequent years. Given the lack of reliable fishery catch-at-age data from the 1970s, coupled with unreliable survey conversion factors prior to 1983, it was concluded that pre-1983 survey data should be excluded from the population models of 4X5Y Cod.

It was also agreed that the Individual Transferable Quota (ITQ) Survey between 1996 and 2011 be excluded from the 4X5Y stock assessments, based on several in-depth evaluations of the ITQ survey data (Clark and Emberley 2009, Claytor et al. 2014).

MODELING FRAMEWORK REVIEW AND OBJECTIVES

The objectives of the modelling framework meeting are to assess a model(s) to monitor stock status and productivity, including:

1. Determine the methodology that can be used to reliably estimate the current stock size and fishing mortality levels of 4X5Y Cod.

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2. Define the biomass limit reference point under the DFO Precautionary Approach Framework and, if applicable, the fishing mortality reference point.
 3. Determine a forecasting methodology for population trajectories under current productivity, and feasible harvest levels provided by fishery management.
 4. Investigate data limited methods that could test the robustness of any proposed catch advice to uncertainties in stock assessment.
 5. Identify ecosystem-level variables contributing to changes in spatial distribution of 4X5Y Cod.
 6. Provide recommendations on the schedule for ongoing assessment of 4X5Y Cod. Identify indicators which would be used to characterize stock status in years between stock assessments, and events that could trigger an earlier-than-scheduled assessment.
 7. Identify uncertainties and knowledge gaps.

From the above objectives, this working paper is intended to address 1–3, 6, and 7.

HISTORY OF STOCK ASSESSMENT

Previous assessments of the 4X5Y Cod stock have been modelled using the DFO summer survey calibrated Virtual Population Analysis (ADAPT), the history of which is detailed in Andrushchenko et al. (2022). The last analytical assessment of 4X5Y Cod was conducted in 2008, in which several models were examined to investigate changes in survey catchability, natural mortality, and the exclusion of the ITQ survey (Clark and Emberley 2009). The accepted model assumed no change in survey catchability, estimated an increase in M from 0.2 to 0.76 on older Cod (ages 4+) since 1996, and excluded the ITQ survey from the assessment (Clark and Emberley 2008). Later, the output from this model was used in the 2011 Recovery Potential Assessment (RPA) for 4X5Y Cod. Considering the poor status of the stock, and continued advice by DFO Science to keep fishery catches as low as possible, multiple stock status updates have been provided since then; catch advice has been decided by fishery management by monitoring the trend of DFO Summer Research survey provided in the stock status updates (DFO 2015, DFO 2017, DFO 2018).

DATA FEATURES THAT MODELS NEED TO FIT/EXPLAIN

DATA QUALITY

Data quality is compromised due to a lack of conversion factors between the research vessels Cameron and Needler, ageing issues with younger ages (1–2), and sampling issues with pre-1980s fishery catch data. Restricting data to post-1980s survey and fishery data in the assessment might result in a loss of the fish productivity information and potentially impact the calculation of reference points.

Additional major issues for the stock were summarized at the data input framework meeting with under- and mis-reported landings as well as unquantified discards due to low observer coverage. The year and magnitude of the misreported catches and discards were unknown. Moreover, possible unstationary natural mortality added more challenges to modelling the population dynamics of this mixed stock.

SURVEY ABUNDANCE INDICES

The combined survey abundance indices in the Bay of Fundy and western Scotian Shelf from 1983 to 2017 were shown in Table 1. The Coefficient of Variation values (CVs) for each age were shown in Table 2. CVs ranged from 28% to 44% for ages 1–7, but with higher CVs for ages 8+, and more zero catches for ages 6+ in recent years. The survey abundance showed clear downward trends and age truncation since the mid-1990s, although a small amount of older fish were caught in 2016 and 2017 (Figure 1). Considering the higher CVs associated with the survey catch, and many missing catches in the older age groups, the survey catch at ages 1–6 was used as the abundance indices for the model exploration (Table 1).

To track the age structure information in the survey abundance indices, the Standardized Proportions at Age (SPA) was used to show cohort patterns (Figure 2). The cohorts of 1992, 1998, 2001, 2003, 2007, 2010, and 2013 were above average, and there was presumably a year effect in the 2017 survey. A few ages showed above-average catch, which was not consistent with the cohort strength signals shown in other years of the survey catch.

FISHERY CATCH-AT-AGE

The 1983–2017 combined Bay of Fundy and Scotian Shelf fishery catch-at-age was shown in Table 3. Compared to survey abundance indices, the fishery catch-at-age showed deeper downward trends and age truncation in recent years (Figure 3). The Standardized Proportions at Age (SPA) of fishery catch-at-age indicated similar information on relative cohort strength as the survey (Figure 4).

Considering the small contribution of the older age groups (7+) to the total fishery catch (ranging from 0.2% to 10% by number except for 2016 up to 16%), an age-aggregated ages 7+ group was used in the model input (Table 3).

FISHERY SELECTIVITY CHANGES

The spatial distribution of the 4X5Y Cod fishery has changed over time. Historically, the proportion of Cod landings from the Scotian Shelf have been greater than those from the Bay of Fundy, but the proportions have switched with the redistribution of fishing effort starting in the late 1990s and early 2000s. More recently, the contributions from the two areas have become equivalent (Table 4; Figure 12 in Andrushchenko et al. 2022). The contribution of landings from 4Xp was relatively low (approximately 10%) during the 1970s and 1980s, but increased steadily to account for 30% of the 4X5Y Cod landings in the late 2000s.

Fishery selectivity has likely changed over time as a result of shifts in the spatial and seasonal distribution of the fishery and the use of different gear types. For instance, longline and otter trawl gears tend to catch Cod of similar size, with length frequencies peaking between 50 and 60 cm for both gears, across all areas of the 4X5Y management unit (Andrushchenko et al. 2022). In contrast, gillnet tends to catch larger cod, reflecting the selectivity of the 5.5" mesh size, with size frequencies peaking between 65 and 70 cm.

Clark (2014) proposed implementing a ratio method to calculate relative fishery selectivity from the age or length composition, from the fishery and survey data, with the assumption of no temporal changes in survey selectivity. As such, these ratio values could be used to detect temporal changes of fishery selectivity, relative to the survey. Fishery and survey data from 1983–2017 indicated that the fully selected age of fishery shifted from age 3 to 4 in the post-1995 period, whereas the survey fully selected age was at age 3. It also showed a flat-topped Partial Recruitment (PR) for ages 4–6, in both time periods (Figure 5).

This information was used to understand the possible fishery PR changes (dome- or flat-shaped PR) and to help determine next steps of model development.

RELATIVE F AND SURVEY Z

Relative fishing mortality at age (Relative F) was calculated as the ratio of fishery catch-at-age over the survey catch-at-age (Figure 6). Relative F has declined for younger ages (1–5) in the mid-1990s, whereas older ages (6+) have been variable.

Total mortality (Z) at-age was calculated from the DFO summer survey catch-at-age. Survey Z on ages 4+ have been higher since 1990s, despite the substantially decreased relative F (Figure 7).

Furthermore, catch curve analyses of log-transformed relative abundance data from each cohort in successive years were used to calculate the survey Z for each cohort. This calculation has the merit of removing the confounding effects of differential year-class strength on the interpretation of catch curve results. Using age 3 as the fully recruited age, Figure 8 showed higher Z for older ages (6+) across all the cohorts in recent years, which was consistent with the above survey Z calculations.

Conflicting signals from the relative F and Z trends implies there may be other factors than the reported landings contributing to the total mortality in the population dynamics.

BASIC VPA MODEL

A basic ADAPT Virtual Population Analysis (VPA) model was run to identify the possible issues when there were conflicting signals in the data. In this model, natural mortality (M) was fixed at 0.2 over all ages and years, and fishery catch-at-age was assumed to be known without error. The data inputted to this model were fishery catch-at-age 1 to 7+ (1983–2017) and DFO summer survey swept area abundance indices-at-age 1 to 6 (1983–2017). Zero observations in the abundance indices were treated as missing values. The survey catchability (q) was fixed as flat-topped at ages 3–6, based on the above data analysis. Fishing selectivity on the 7+ age group was set as equal to age 6. The objective function was the discrepancy between the logarithm of the observed and predicted abundance indices-at-age, which were assumed to be log-normally distributed. The Residuals check showed a clear pattern, with the model overestimating the population numbers in the early years, and underestimating the population numbers in the recent years (Figure 9). This was caused by the conflicting signals between relative F and Z trends, under the assumption of accurate fishery catch-at-age and constant M.

SAM MODEL

The State-space Assessment Model (SAM) has been used by the International Council for the Exploration of the Sea (ICES) for many stocks ([ICES 2017](#)). Instead of an assumption of accurate fishery catch in the basic VPA model, both survey and fishery catch-at-age were assumed to follow a lognormal observation error. In addition, a multiplicative lognormal process error was assumed in the stock-state equations:

$$\log N_{a+1,y+1} = \log N_{a,y} - F_{a,y} - M_{a,y} + \xi_{a,y}, \text{ where } \xi_{a,y} \sim N(0, \sigma_s^2)$$

Where a, y index age, and year, respectively. $\xi_{a,y}$ was the process error. The process error represented that full knowledge of F and M may not provide full knowledge of cohort survival from one year to the next, it could also represent migrations. Large σ_s^2 , or one-sided deviations from stock equation, can be used to diagnose model-fitting problems.

Recruitment can be modeled as a stochastic process via a stock-recruitment relationship, or as a free parameter. In the model applied to the 4X5Y Cod,

$$\log R_y = \log R_{y-1} + \varepsilon_y, \text{ where } \varepsilon_y \sim N(0, \sigma_R^2)$$

Where the logarithm of recruitment followed a random walk.

The fishing mortality vector $F_y = (F_{1,y}, F_{2,y}, \dots, F_{6,y})$ was assumed to follow a correlated random walk:

$$\log F_{y+1} = \log F_y + \psi_y, \text{ where } \psi_y \sim N(0, \Sigma)$$

Where ψ_y followed a multivariate normal distribution. In the model applied to the 4X5Y Cod, an AR(1) correlation structure was assumed. For any combination of ages ($a \neq \tilde{a}$),

$$\Sigma_{a,\tilde{a}} = \rho^{|a-\tilde{a}|} \sqrt{\Sigma_{a,a} \Sigma_{\tilde{a},\tilde{a}}}$$

Survey catchability, correlation parameters, process, and observation variances were objectively estimated by the maximum likelihood method, by integrating over the unobserved state variables.

For details of the SAM model, see Nielsen and Berg (2014). The application of SAM model to 4X5Y Cod data was implemented using the R package "[stockassessment](#)".

A basic run of the SAM model was conducted using 4X5Y Cod fishery and survey data. The data input for this model was the same as the above basic VPA model, with a flat-topped survey catchability for ages 3–6, and a constant M of 0.2 over all ages and years. Fishing selectivity for the 7+ age group was set as equal to age 6.

The model covered and showed a large variance associated with the fishery catch and strong patterns in the residuals (Figure 10). It indicated a systematic change in catch reporting had occurred over time, which implied substantial overreporting of catch in the early years and underreporting of catch in recent years. To date, there was no evidence to support the possibility of substantial amounts of overreported catch in the early years. The 7-year peel retrospective analysis showed strong retrospective patterns; the retro rho was 0.70 for SSB (ages 4+ biomass) and -0.36 for F4–7 (number weighted average of fishing mortality of ages 4 to 7), shown in Figure 11.

The basic VPA and SAM model mainly differed in the assumption of observation error in fishery catch-at-age. However, both models showed diagnostic problems with a fixed M = 0.2 assumption.

VPA MODELS WITH RANDOM WALKS IN M

A VPA model with time-varying natural mortality (M) was fit to 4X5Y Cod data to address the conflicting signals reflected by the survey and fishery data. Instead of assuming a constant M, this model allowed natural mortality to vary with time by age groups. Simulation tests of these VPA models for Eastern Georges Bank Cod and Southern Gulf of St. Lawrence Cod resulted in reliable conclusions about changes in M (Swain 2013, Swain and Benoit 2015). For 4X5Y Cod, considering the possible bias in reported catch, M could be aliasing natural mortality, under-reported catch, discards, or fish emigration to other areas.

In this model, the input data were the same as the above basic VPA model. Instead of an assumption of constant M, M was modelled as a random walk increment for different age groups per year.

$$M_{j,1983} = Minit_j$$

$$M_{j,y} = M_{j,y-1} e^{Mdev_{j,y}} \text{ if } y > 1983$$

Where j represented age group and y represented indexed year. $Minit_j$ was M for age group j for the first year (1983). $Minit_j$, $Mdev_{j,y}$, as well as other model parameters (survey catchability at age and terminal year (2018) of population abundance at age), were estimated by minimizing an objective function with the following components: 1) a component for the discrepancy between observed and predicted values of the abundance indices at age, which were assumed to be log-normally distributed; 2) a penalty for departures of $Minit_j$ from its prior value (normal priors for $Minit_j$ were set at mean of 0.2 and a standard deviation of 0.05 for all the age groups); and 3) a penalty for departures of $Mdev_{j,y}$ from its prior value. A normal prior for $Mdev_{j,y}$ was set at a mean of 0 and a standard deviation Msd of 0.05. The value of Msd affected the degree to which the random walk was constrained. For model details, see Swain (2013).

In this model, survey catchability was assumed to be time-invariant and flat-topped for ages 3 to 6.

For the 7+ age group, two different alternative methods for calculating fishing mortality were conducted:

1. Fratio: $F_{7+} = F_6$.
2. Ffirst: $F_6 = \text{mean}(F_{3-5})$ for pre-1995 and $F_6 = \text{mean}(F_{4-5})$. This reflected the fishery selectivity changes in the mid-1990s, observed in the above data analysis.

As M in random walk was modelled by age groups, the following models with M by 2 or 3 age groups were explored and compared:

- 2M age groups models: Ages 1–5 and 6+ (referred to “2MFratio” and “2MFfirst” models).
- 3M age groups models: Ages 1–2, 3–4 and 5+ (referred to “3MFratio” and “3MFfirst” models).

For each model, the uncertainties of model parameters were derived using Markov Chain Monte Carlo (MCMC) method resampling algorithm. An MCMC chain of length 1,000,000 was run, and samples were taken systematically every 500 iterations, which resulted in a posterior sample size of 2,000. The fit of the models were evaluated by checking residuals and conducting retrospective analyses.

FRATIO MODELS

The 2MFratio and 3MFratio models had similar fits to the survey data and both showed residual patterns (Figure 12). The models overestimated the biomass for ages 3–4 when compared to the survey. The 7-year peel retrospective analysis indicated retrospective pattern (Figure 13 and Figure 14). For the 2MFratio model, the retro rho value was -0.28 for SSB, and as high as 0.65 for F4–7; for the 3MFratio model, the retro rho value was -0.28 for SSB and 0.62 for F4–7.

FFIRST MODELS

The 3MFfirst model showed better fit-to-survey biomass compared to the 2MFfirst model (Figure 15). The estimated SSB, F4–7, survey q and M were shown in Figure 17. The retro rho was -0.13 for SSB and -0.01 for F4–7, from the 7-year peel retrospective analysis. The VPA output and residuals from this model were shown in Figures 17 and 18, and Table 4. The 95% credibility intervals associated with M , recruitment at age 1, SSB, F4–7, and survey q , as well as terminal year SSB distribution, were shown in Figures 19 and 20. There was a clear temporal

increasing trend in M for the older age group (M5+), especially after 1995, which has gone above 1 and has reached around 1.5 since 2011. In contrast, the changes in M1–2 and M3–4 were small.

The 2MFfirst model failed to converge in one single-year run in the retrospective analysis. By changing the standard deviation in the prior of *Mdev* for ages 1–2, from 0.05 to 0.1, this model converged for all of the retrospective runs, with a retro rho value of -0.09 for SSB and 0.005 for F4–7. The estimates from this model were compared to the 3MFfirst model, and there was little difference in the model-fit-to-survey biomass (Figure 15). SSB, F4–7, and M5+, as well as age-pattern in fishing mortality (Figure 21), were similar with the 3MFfirst model. However, in contrast to the slightly increasing trend of M1–2 and M3–4 from the 3M Ffirst model, the estimated M1–4 from the 2MFfirst model showed a gradual increase, starting around 0.2 from 1983 to 2006, and then quickly increased to around 0.5 in recent years. With the increase in M1–4, the estimated recruitments from the 2MFfirst model were higher than the 3MFfirst model in recent years (Figure 21).

Although different conclusions could be drawn on the natural mortality of the younger age groups (ages 1–4) and recruitment for the 4X5Y Cod stock, both models showed that M on older age groups (ages 5+) has gone up as high as about 1.5 since 2010. A comparison between survey-abundance indices at age 1 with survey-q-adjusted recruitment, estimated from the 2MFfirst and 3MFfirst model, showed that the 2MFfirst model overestimated the recruitments in recent years (Figure 22), reflecting the higher *Mdev* of ages 1–2 in the 2MFfirst model set up.

This comparison was presented at the peer review meeting on November 6–8, 2018, and it was agreed that the 3MFfirst model should be used as the new framework stock assessment model of 4X5Y Cod. The reference points calculated, based on this model, were described in next section.

From the 3MFfirst VPA model, spawning-stock biomass (ages 4+) of 4X5Y Cod has declined throughout the 1990s and 2000s, and has stabilized at a very low level since 2010. Recruitment has been low since the mid-1990s and has remained below 5 million fish since 2015 (Table 4). The early decline in the 1980s was most likely due to high fishing mortality and the proceeding declines due to increases in the natural mortality of older (ages 5+) fish and low recruitment levels (Figure 19). The results implied compensatory mortality of ages 5+ Cod with the period of low biomass associated with high natural mortality.

REFERENCE POINTS

The Terms of Reference for the 2018 modelling framework of 4X5Y Cod requested the biomass Limit Reference Point (LRP) be defined, under the DFO Precautionary Framework (DFO 2009), and, if applicable, the fishing Limit Removal Reference point (LRR). A Recovery Potential Assessment (RPA) for the 4X5Y Cod was carried out in 2011, using output from the 2008 assessment model, to provide the information and scientific advice necessary to meet requirements under the *Species at Risk Act* (SARA). It was concluded that the 4X5Y Cod was in the critical zone (DFO 2011). With the updated stock status and productivity from the new framework model, the Reference Points were re-developed.

The DFO Precautionary Approach Framework (DFO 2009) defines LRP as the stock level, below which, serious harm is occurring to the stock. “Serious harm” has been interpreted as “impaired recruitment”, or any changes to the biological or productivity properties of the stock, that decrease the likelihood of rebuilding or recovery (DFO 2016). No single method of identifying LRP is suitable for every stock (Myers et al. 1994). Best practices, when defining

reference points, should evaluate as many diagnostic measures as possible. At the 2002 National Workshop on Reference Points for Gadoids (DFO 2002), five computational methods were considered for defining LRP in terms of SSB. These five methods were (DFO 2002):

1. $B_{recover}$: the lowest historical biomass level from which the stock has recovered readily.
2. $Sb_{50/90}$: the SSB corresponding to the intersection of the 50th percentile of the recruitment observations and the replacement line for which 10% of the stock-recruitment (S-R) points are above the line.
3. BH_{50} : the SSB at which expected average recruitment is one half of the maximum recruitment predicted by assuming an underlying B-H stock-recruit relationship (i.e., the recruitment that is 50% of the value at the asymptote).
4. RK_{50} : the lower SSB at which expected average recruitment is one half of the maximum recruitment predicted by assuming an underlying Ricker-type stock-recruit relationship (i.e., the recruitment that is 50% of the value at the peak of the dome).
5. NP_{50} : estimate of the lowest SSB where the expected median recruitment is one half of the maximum recruitment calculated by non-parametric analysis (i.e., the recruitment that is 50% of the largest median recruitment achievable at any SSB within the range of historic observations).

At the workshop, there was consensus that a comparison amongst the five LRP candidates provided some insight into the certainty of advice.

The LRR is the maximum acceptable removal rate for the stock in the Healthy Zone; it must be less than or equal to F_{MSY} (DFO 2009). Equilibrium F_{MSY} could be calculated using the Sissenwine-Shepherd age-structured production model (Sissenwine and Shepherd 1987), which incorporates a stock-recruitment relationship with the per-recruit analysis, or a proxy for F_{MSY} , using $F_{0.1}$ and $F_{40\%}$ from the per-recruitment analysis. The difference of the F_{MSY} , calculated from these models, could be explained by different assumptions on recruitment dynamics. Per-recruitment analysis assumes the recruitment is constant. Calculations using reference-point estimates that do not incorporate variation in recruitment are likely to result in unexpected population declines, or even collapse, when productivity is low (Morgan et al. 2014). When there is a positive Stock-Recruitment (SR) relationship, per-recruit analyses will tend to overestimate F_{MSY} , since it does not consider the feedback between conserving biomass in the water, to increase recruitment and yield, later on (Duplisea 2012).

The output from the 3MFfirst model was used to determine the 4X5Y Cod reference points. Considering the significant changes in natural mortality since the mid-1990s, the recent time period (1995–2017) average of M, PR, fishery weight-at-age, spawning stock weight-at-age, and maturity-at-age were used for the per-recruit analysis. In order to have enough stock and recruitment data to fit an appropriate SR relationship, with an assumption of no evolutionary changes in the life-history caused by short time-period of natural mortality changes, the long time-series (1983–2016) SR data was used in the calculations for both models. Recruitment was modelled using the Hockey-stick, Beverton-Holt, and Ricker models, separately.

Table 5 showed the equilibrium F_{MSY} calculated from different SR models (Figure 23), and proxies for F_{MSY} , from the per-recruit analysis (Figure 24). The equilibrium F_{MSY} can vary widely, depending on the stock-recruitment dynamics included, and can interact with natural mortality in an opposite way, with the per-recruit analysis. In contrast with the high values of $F_{0.1}$ and $F_{40\%spr}$ from the per-recruit analysis, the equilibrium F_{MSY} calculated from the production model was extremely low. For the Hockey-stick model, it showed that even under no fishing, the cohort cannot replace itself, and the stock would collapse. For the Ricker model, there was no MSY

associated reference points. For the B-H model, the estimated F_{MSY} is 0.01. The fishing mortality that would lead to stock collapse ($F_{collapse}$) was very low for both the Ricker and B-H model, which were 0.018 and 0.025, respectively. This can be explained by the negligible positive surplus production of this stock due to the extremely high natural mortality.

The Ricker and B-H models showed that the equilibrium SSBs under no fishing were 15,000 mt and 17,197 mt, respectively. For $B_{recover}$, there was no historical biomass level from which the stock has recovered readily. Considering that the MSY-based reference points may be unreliable for this stock due to unstable M , $Sb_{50/90} = 22,193$ mt (Figure 25; Table 5), the SSB corresponding to the intersection of the 50th percentile of the recruitment observations and the replacement line for which 10% of the S-R points are above the line, was recommended as the LRP for 4X5Y Cod. This value was thought to be more conservative, as it was higher than the equilibrium SSB under no fishing, calculated from the Ricker and B-H models. This implies that, under the current high natural mortality scenario, even with zero catch, the stock will remain in the critical zone and cannot rebuild above LRP.

As LRR was the removal reference for stocks in the Healthy Zone, and considering the current stock status of 4X5Y Cod, a new LRR was not recommended. The science catch advice would be to keep the fishery catch as low as possible.

PROJECTION AND RISK ANALYSIS

The Terms of Reference for this framework requested the development of a forecasting methodology for population trajectories under current productivity and feasible harvest levels provided by fishery management. Due to current, low-stock productivity and poor stock status of 4X5Y Cod, the scientific catch advice would be to keep the fishery catch as low as possible for rebuilding this stock. However, considering the possibility that current reported landings might not be the driving factor of the population dynamics of this stock, and the utilization of other commercial fisheries resources, the forecasting methodology for population trajectories under a constant low-catch scenario of 300 mt was provided here for illustration purposes only.

The projection shown here was to illustrate how this outlook can be provided in terms of consequences with respect to alternative catch quotas in 2019 and 2020 had they been pursued at the beginning of 2018. These projections assume that the current productivity conditions will persist over the projection period. The most recent 5-year average of natural mortality and recruitment, and the recent 3-year average of fishery weight-at-age, beginning-of-year population weights-at-age, and fishery PR were used as inputs for the projection. The catch in 2018 was assumed to be equal to the 825 mt quota.

Uncertainty about current biomass generates uncertainty in forecast results, which was expressed here as the credibility intervals for the projected biomass and fishing mortality for the VPA models (Figure 26).

10-YEAR MEDIUM TERM PROJECTION

During the meeting, a 10-year projection with zero fishery catch and assumed various levels of ages 5+ M was requested to project the SSB trajectory and to evaluate the likelihood that the stock will recover. In these projections, recent 3-year average weight-at-age, as well as recent 5-year average of PR, recruitment, and M of ages 1–4 were used.

Table 6 and Figures 27 and 28, showed the projections with different assumed reduced, aged 5+ M scenarios. The SSB was projected to remain essentially unchanged over the 10-year time period, until 5+ M was reduced to below 0.63, which was 40% of the current natural mortality level (Figure 28). There would be little probability of this stock recovering to the cautious zone

over next 10 year period, unless ages 5+ M was reduced to 0.31, which was 20% of the current natural mortality level. These results were consistent with the above-equilibrium analysis.

GUIDANCE ON INTER-FRAMEWORK REVIEW

Given the two-year quota management structure, it was expected that the 4X5Y Cod assessment would follow a two-year cycle, with a fishery- and survey-indicator update in the non-assessment years. The update is expected to follow the same format as the previous updates (DFO 2017), with an additional section discussing whether exceptional circumstances have triggered a framework for the following year. Given the current status of the stock, the proposed trigger mechanisms were focused on detecting a positive change in the current stock productivity dynamics and were defined as follows:

1. The 3-year median abundance for ages 7 through 9 is above 0 for all three ages.
2. If the q-adjusted, 3-year-median, survey-biomass index falls outside of the 95% confidence interval of the projection.
3. If the 3-year median of the age 7+ group abundance index falls outside of the 95% confidence interval of the projection.

Meeting at least one of the three conditions above would result in a model review.

DATA GAP AND RESEARCH RECOMMENDATIONS

Although 4X5Y Cod is regarded as a data-rich stock with age-structured fishery and survey information, it exhibits some difficult problems in modelling stock dynamics. The high M used in the VPA models could be aliasing fish moving to adjacent areas or deeper waters where the fishery or survey cannot catch them, under-reported landings, and unreported discards, as well as unstationary natural mortality caused by biotic and abiotic factors.

Increased observer coverage on the Cod bycatch fishery would improve the reliability of Cod discard estimates. A new sex-specific seal stock assessment model, more research on the seasonal and spatial distribution of seals, as well as diet composition, would help to characterize the possible impact of Grey Seal predation on 4X5Y Cod. Research on other biotic and abiotic factors, which could possibly be linked to elevated M, would help facilitate a better understanding of the population dynamics of 4X5Y Cod.

Considering the confounding impacts of non-stationary M, missing catch, and stock mixing, the mixing rate of the two Cod spawning components in 4X5Y was not quantified at this framemark. Due to lack of reliable conversion factors and fishery catch-at-age data in the earlier time period (1970–1982), the productivity during this period, and its impact on reference, points is unknown.

ACKNOWLEDGEMENTS

We thank Doug Swain for providing the ADMB source Code to run VPA models with random walks in M.

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TABLES

Table 1. DFO summary survey abundance indices (1,000s) for 4X5Y Cod since 1983.

YEAR/AGE	1	2	3	4	5	6	7	8	9
1983	141	1,085	4,226	2,369	1,480	946	389	0	77
1984	820	5,746	3,390	2,362	1,820	688	482	63	58
1985	495	8,760	4,331	1,527	1,451	766	483	267	165
1986	768	1,333	2,920	1,226	314	549	448	217	97
1987	392	2,348	618	1,180	528	260	245	304	75
1988	2,630	3,926	9,246	1,496	1,548	496	210	244	91
1989	794	6,089	3,420	2,549	420	489	108	27	82
1990	515	873	5,523	2,463	2,321	240	414	80	42
1991	614	1,727	1,131	3,086	1,094	751	128	116	19
1992	252	2,731	1,569	681	1,710	471	460	124	85
1993	369	955	2,518	925	129	265	52	61	0
1994	1,258	3,313	2,739	1,605	449	36	195	88	70
1995	122	847	4,779	1,477	598	274	94	91	34
1996	339	839	2,048	5,527	880	753	148	0	56
1997	349	569	1,189	1,444	2,462	321	194	100	0
1998	211	1,929	1,808	1,418	1,022	1,371	225	116	6
1999	382	787	1,291	882	850	194	297	46	0
2000	432	1,497	830	999	409	325	157	148	0
2001	150	1,053	2,891	951	646	44	60	0	31
2002	4,329	1,990	2,573	2,501	520	324	122	19	98
2003	43	3,014	546	1,082	752	191	78	20	19
2004	31	272	2,977	319	325	113	27	8	0
2005	246	1,750	384	1,870	224	223	39	0	29
2006	102	813	1,844	398	354	162	20	0	0
2007	300	1,307	707	1,028	113	410	25	0	0
2008	277	1,086	346	309	277	27	0	0	0
2009	545	3,133	4,817	877	356	420	0	0	0
2010	206	408	424	648	99	10	89	0	0
2011	245	682	343	614	282	17	0	18	0
2012	292	1,567	456	202	99	24	0	0	11
2013	94	351	589	272	65	0	0	0	0
2014	100	456	565	393	21	0	0	0	0
2015	135	1,186	446	524	195	27	0	0	0
2016	250	648	1,916	179	143	22	7	0	0
2017	50	178	331	438	426	18	52	62	7

Table 2. Coefficient of Variation (CV) of DFO summary survey abundance indices for 4X5Y Cod since 1983. A dash (-) indicates no data.

YEAR/AGE	1	2	3	4	5	6	7	8	9
1983	0.58	0.28	0.21	0.14	0.30	0.29	0.27	-	0.45
1984	0.37	0.31	0.32	0.25	0.25	0.21	0.27	0.71	0.68
1985	0.38	0.42	0.33	0.25	0.19	0.21	0.27	0.31	0.45
1986	0.66	0.27	0.24	0.22	0.26	0.19	0.26	0.29	0.67
1987	0.51	0.18	0.19	0.21	0.21	0.36	0.29	0.29	0.41
1988	0.34	0.57	0.46	0.57	0.29	0.29	0.40	0.46	0.71
1989	0.25	0.26	0.20	0.19	0.20	0.33	0.37	1.00	0.51
1990	0.36	0.31	0.19	0.17	0.22	0.26	0.24	0.49	0.61
1991	0.32	0.21	0.18	0.16	0.18	0.20	0.27	0.49	0.84
1992	0.26	0.26	0.12	0.14	0.18	0.23	0.26	0.35	0.71
1993	0.48	0.24	0.14	0.16	0.45	0.34	0.47	0.51	-
1994	0.30	0.18	0.30	0.16	0.18	0.34	0.45	0.41	0.51
1995	0.46	0.29	0.21	0.21	0.18	0.30	0.46	0.49	1.00
1996	0.25	0.58	0.32	0.43	0.50	0.40	0.25	-	0.81
1997	0.28	0.24	0.26	0.22	0.17	0.38	0.21	0.65	-
1998	0.42	0.22	0.20	0.19	0.19	0.17	0.30	0.41	1.00
1999	0.27	0.17	0.19	0.22	0.20	0.27	0.29	0.73	-
2000	0.31	0.19	0.28	0.26	0.24	0.25	0.41	0.52	-
2001	0.60	0.24	0.25	0.22	0.22	0.51	0.43	-	1.00
2002	0.93	0.72	0.42	0.24	0.24	0.29	0.38	1.00	0.50
2003	0.72	0.76	0.37	0.32	0.26	0.26	0.45	0.61	1.00
2004	-	0.37	0.44	0.31	0.42	0.52	1.00	1.00	-
2005	0.55	0.33	0.54	0.24	0.51	0.42	0.72	-	1.00
2006	0.51	0.31	0.16	0.35	0.20	0.36	0.53	-	-
2007	0.37	0.42	0.23	0.35	0.45	0.42	0.56	-	-
2008	0.40	0.21	0.28	0.23	0.27	0.39	-	-	-
2009	0.07	0.61	0.45	0.42	0.33	0.42	-	-	-
2010	0.24	0.28	0.25	0.24	0.63	1.00	0.51	-	-
2011	0.35	0.34	0.20	0.21	0.26	0.48	-	0.65	-
2012	0.34	0.76	0.28	0.32	0.39	0.53	-	-	1.00
2013	1.03	0.49	0.50	1.91	-	-	-	-	-
2014	0.68	0.26	0.32	0.32	0.80	-	-	-	-
2015	0.39	0.21	0.37	0.32	0.36	0.60	-	-	-
2016	0.41	0.28	0.30	0.35	0.35	0.76	0.71	-	-
2017	0.54	0.29	0.24	0.22	0.37	1.00	0.58	0.83	1.00
Average	0.44	0.34	0.28	0.31	0.31	0.39	0.41	0.58	0.74

Table 3. Fishery catch at age for 4X5Y Cod since 1983.

YEAR/AGE	1	2	3	4	5	6	7+
1983	9	1,031	3,689	2,433	2,057	1,205	915
1984	33	917	2,393	3,081	1,930	965	805
1985	0	711	1,674	1,569	2,324	1,284	863
1986	0	251	2,789	1,941	994	1,008	806
1987	0	861	902	2,053	1,087	523	1,001
1988	0	403	3,517	1,659	1,553	656	549
1989	17	655	2,560	3,656	632	562	343
1990	0	144	2,863	2,805	2,462	497	464
1991	2	391	1,535	5,092	1,777	1,364	467
1992	0	751	3,391	1,878	3,276	878	654
1993	0	881	3,490	2,045	660	672	309
1994	0	475	2,280	2,233	887	195	242
1995	0	135	2,146	1,081	582	130	84
1996	0	50	883	2,594	441	212	57
1997	0	59	1,126	1,556	1,193	199	110
1998	0	234	886	1,021	615	441	87
1999	0	72	834	543	347	264	149
2000	0	218	575	905	247	189	103
2001	0	114	1,187	595	378	75	71
2002	0	22	365	1,099	221	138	64
2003	0	73	249	557	519	96	121
2004	0	33	1,029	367	291	153	46
2005	0	66	148	830	173	89	60
2006	0	42	760	215	491	103	37
2007	0	214	341	927	122	175	29
2008	0	427	492	401	594	75	76
2009	7	192	878	272	98	114	18
2010	0	39	185	88	8	6	2
2011	0	37	124	187	162	46	13
2012	0	65	246	116	66	49	24
2013	0	61	297	158	22	13	5
2014	0	31	213	195	38	5	1
2015	0	29	60	126	67	7	0
2016	0	0	7	113	47	51	41
2017	0	4	35	117	85	23	19

Table 4. VPA output from the 3MFfirst model.

Year	M1-2	M3-4	M5+	F4-7	SSB	recruitment
1983	0.20	0.22	0.37	0.28	84,995	21,247
1984	0.20	0.22	0.39	0.28	76,487	25,359
1985	0.20	0.22	0.41	0.31	75,716	16,565
1986	0.20	0.22	0.43	0.27	68,244	45,670
1987	0.20	0.22	0.45	0.26	73,735	30,297
1988	0.20	0.22	0.47	0.28	61,731	39,675
1989	0.20	0.22	0.50	0.20	70,549	13,457
1990	0.20	0.22	0.52	0.25	93,843	19,502
1991	0.20	0.22	0.55	0.33	104,394	26,362
1992	0.20	0.22	0.59	0.46	74,285	20,283
1993	0.20	0.22	0.63	0.32	48,610	43,544
1994	0.20	0.22	0.67	0.27	55,309	16,801
1995	0.20	0.22	0.73	0.14	53,554	14,090
1996	0.20	0.22	0.81	0.14	77,893	8,686
1997	0.21	0.22	0.90	0.17	81,252	16,675
1998	0.21	0.23	1.00	0.19	56,493	11,622
1999	0.21	0.23	1.11	0.15	37,220	22,639
2000	0.21	0.23	1.21	0.15	35,159	12,707
2001	0.21	0.24	1.29	0.13	38,487	10,429
2002	0.21	0.24	1.33	0.13	45,692	18,935
2003	0.21	0.24	1.37	0.14	49,760	5,289
2004	0.21	0.25	1.37	0.11	40,398	16,811
2005	0.21	0.25	1.34	0.11	40,256	6,110
2006	0.21	0.25	1.31	0.14	30,299	7,174
2007	0.22	0.26	1.30	0.14	25,776	10,234
2008	0.22	0.26	1.29	0.21	20,512	4,649
2009	0.22	0.27	1.32	0.11	14,881	2,449
2010	0.22	0.27	1.38	0.15	16,957	3,975
2011	0.22	0.28	1.47	0.14	12,402	12,670
2012	0.22	0.28	1.58	0.15	8,133	5,980
2013	0.22	0.28	1.65	0.10	6,237	2,540
2014	0.22	0.28	1.64	0.05	8,567	7,341
2015	0.22	0.28	1.56	0.04	19,374	4,102
2016	0.22	0.28	1.50	0.05	13,161	2,773
2017	0.22	0.28	1.48	0.09	10,297	1,925

Table 5. The estimated Reference Points using outputs from the 3MFfirst model.

3MFfirst model	Estimated Reference Points
F_{MSY} proxies <ul style="list-style-type: none"> • F_{0.1} • F_{40%_{spr}} • F_{MSY} (HS) • F_{MSY} (Ricker) • F_{MSY} (B-H) 	<p>0.62</p> <p>0.56</p> <p>no equilibrium</p> <p>no maximum</p> <p>0.01</p>
F_{collapse} <ul style="list-style-type: none"> • HS • Ricker • B-H SSB_{F=0} (mt) <ul style="list-style-type: none"> • Ricker • B-H • HS 	<p>no equilibrium</p> <p>0.018</p> <p>0.025</p> <p>15,000</p> <p>17,197</p> <p>no equilibrium</p>
LRP(mt) <ul style="list-style-type: none"> • S_{b50/90} 	<p>22,193</p>

Table 6. The 10-year projected spawning biomass (mt) of 4X5Y Cod under different assumptions of M for 5+ ages.

Natural Mortality (M)	YEAR									
	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
M = 1.57	8,246	6,401	6,525	8,073	8,494	8,597	8,625	8,627	8,628	8,628
M = 1.41	8,617	6,827	6,878	8,316	8,798	8,947	8,981	8,989	8,989	8,990
M = 1.26	9,057	7,330	7,327	8,626	9,195	9,398	9,443	9,461	9,462	9,463
M = 1.1	9,573	8,005	7,926	9,113	9,734	9,989	10,058	10,092	10,100	10,100
M = 0.94	10,127	8,920	8,750	9,833	10,468	10,789	10,918	10,960	10,981	10,987
M = 0.79	10,820	10,013	9,910	10,851	11,512	11,943	12,135	12,211	12,250	12,271
M = 0.63	11,647	11,442	11,559	12,397	13,095	13,688	13,968	14,124	14,199	14,243
M = 0.47	12,596	13,295	13,877	14,807	15,653	16,465	16,933	17,234	17,429	17,550
M = 0.31	13,724	15,789	17,208	18,662	20,016	21,276	22,255	22,946	23,460	23,797

FIGURES

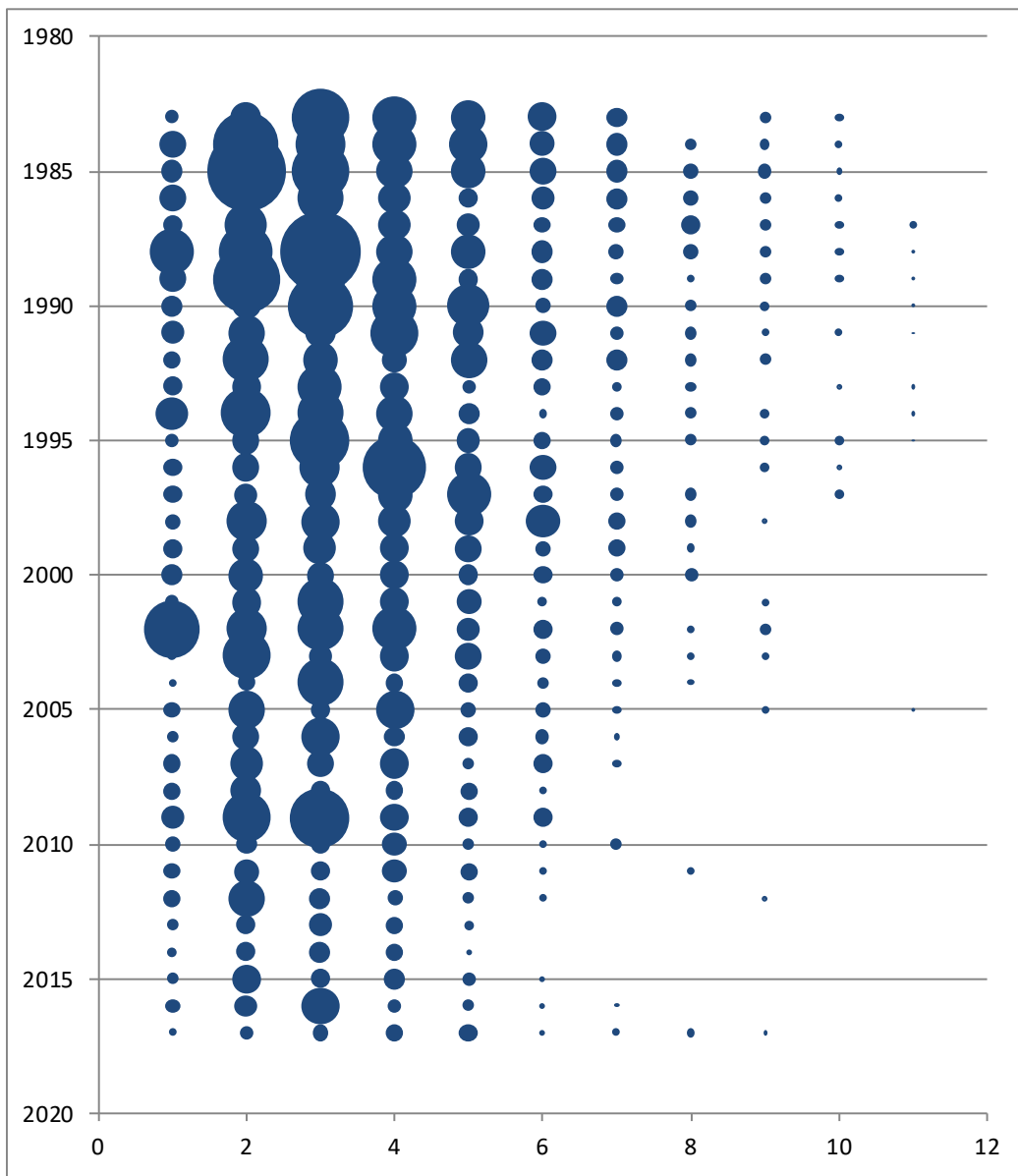


Figure 1. 4X5Y Cod abundance indices from the DFO summary survey (1983–2017).

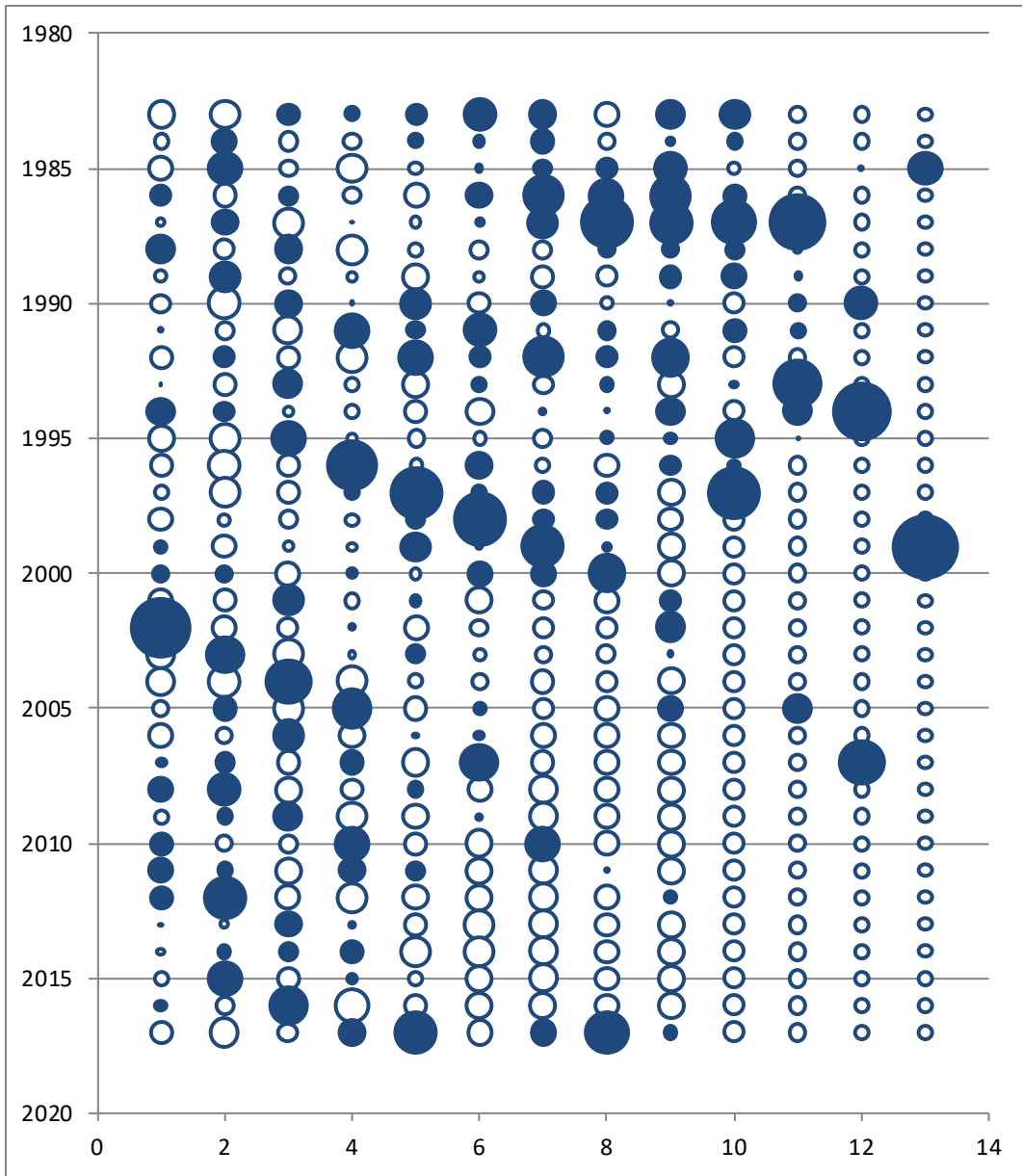


Figure 2. Standardized proportion-at-age of 4X5Y Cod survey abundance indices. Open bubbles represent below-average values and shaded bubbles are above-average.

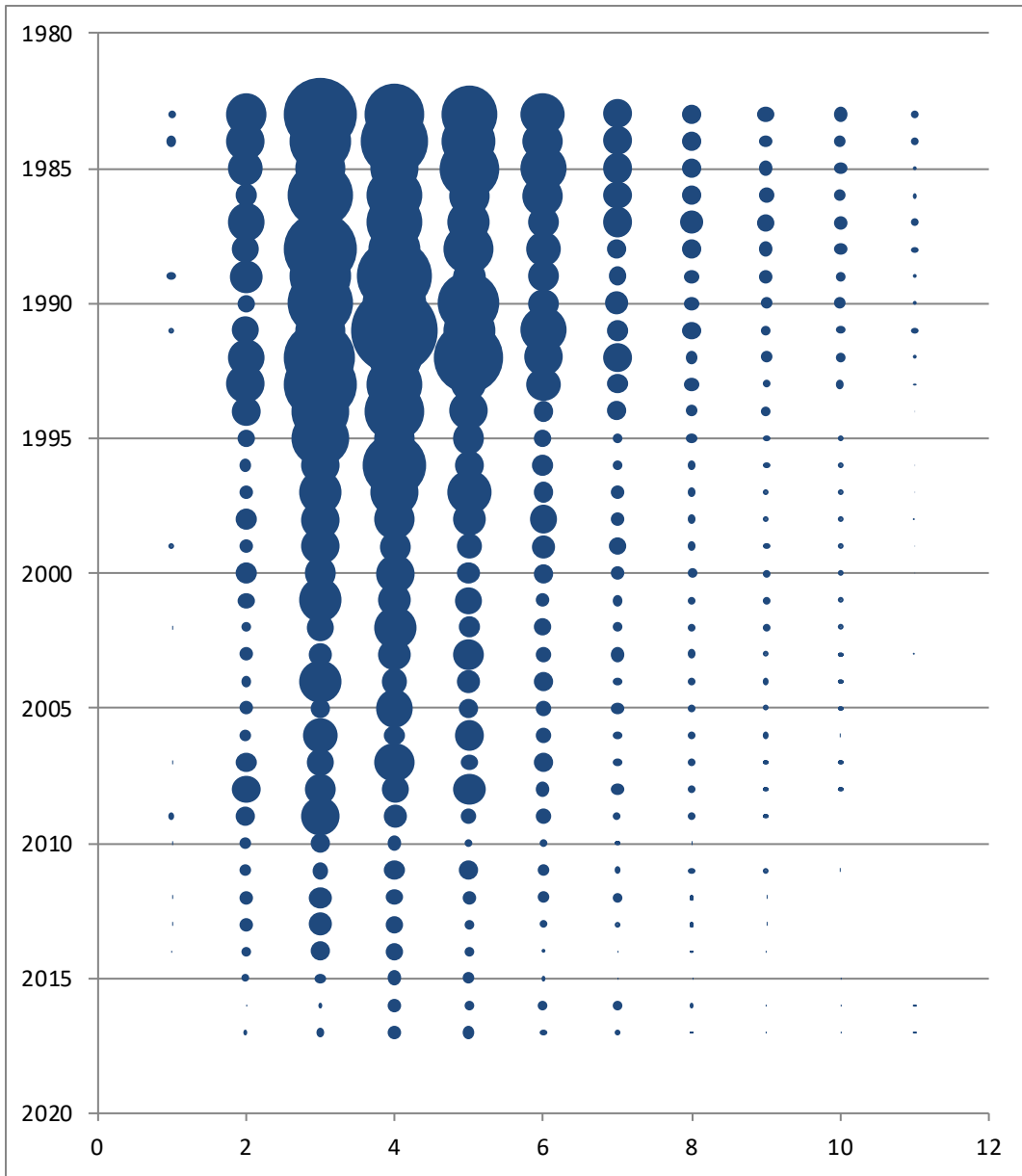


Figure 3. Fishery catch-at-age of 4X5Y Cod from 1983 to 2017.

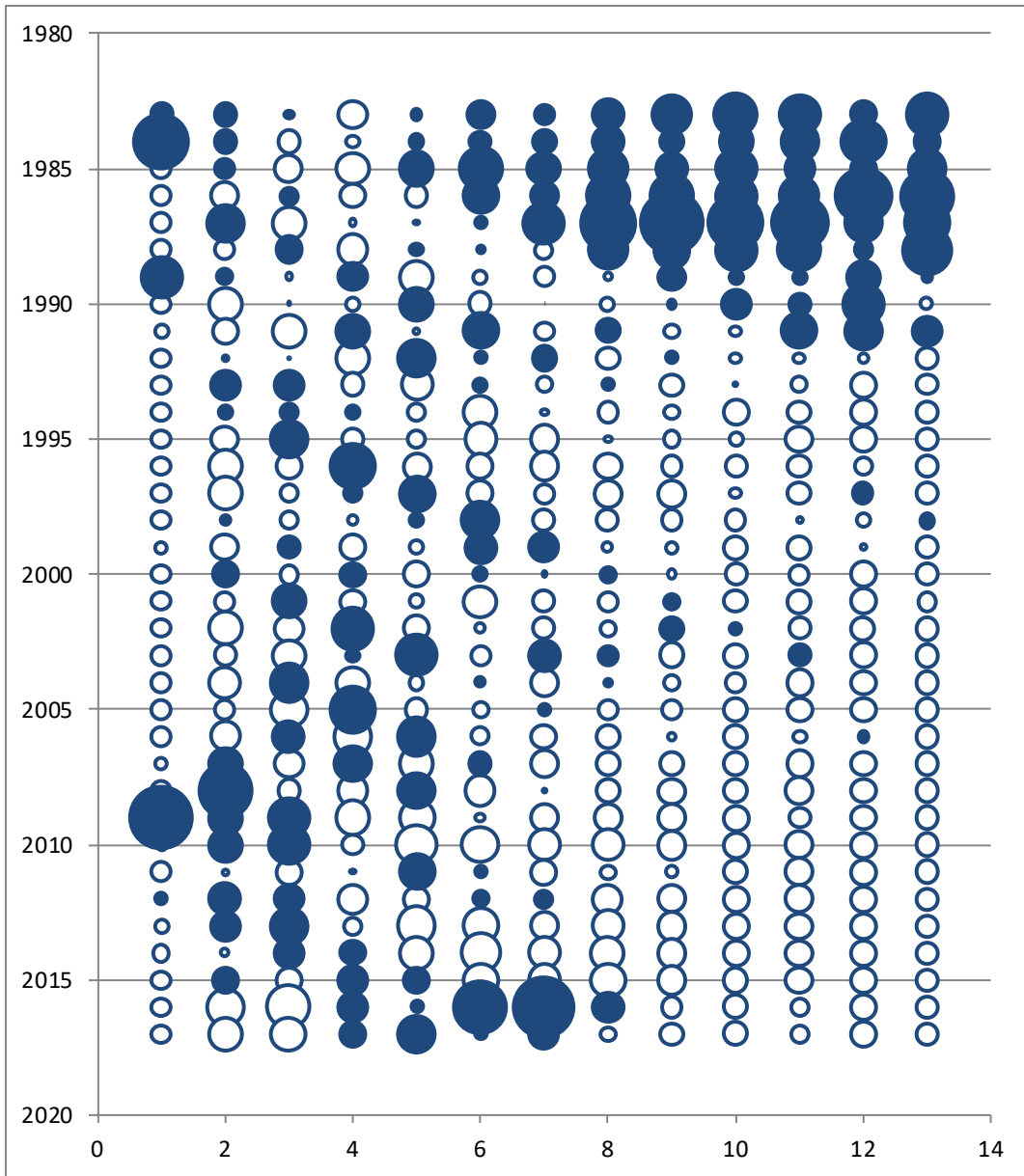


Figure 4. Standardized proportion-at-age of 4X5Y Cod fishery catch-at-age. Open bubbles represent below-average values and shaded bubbles are above-average.

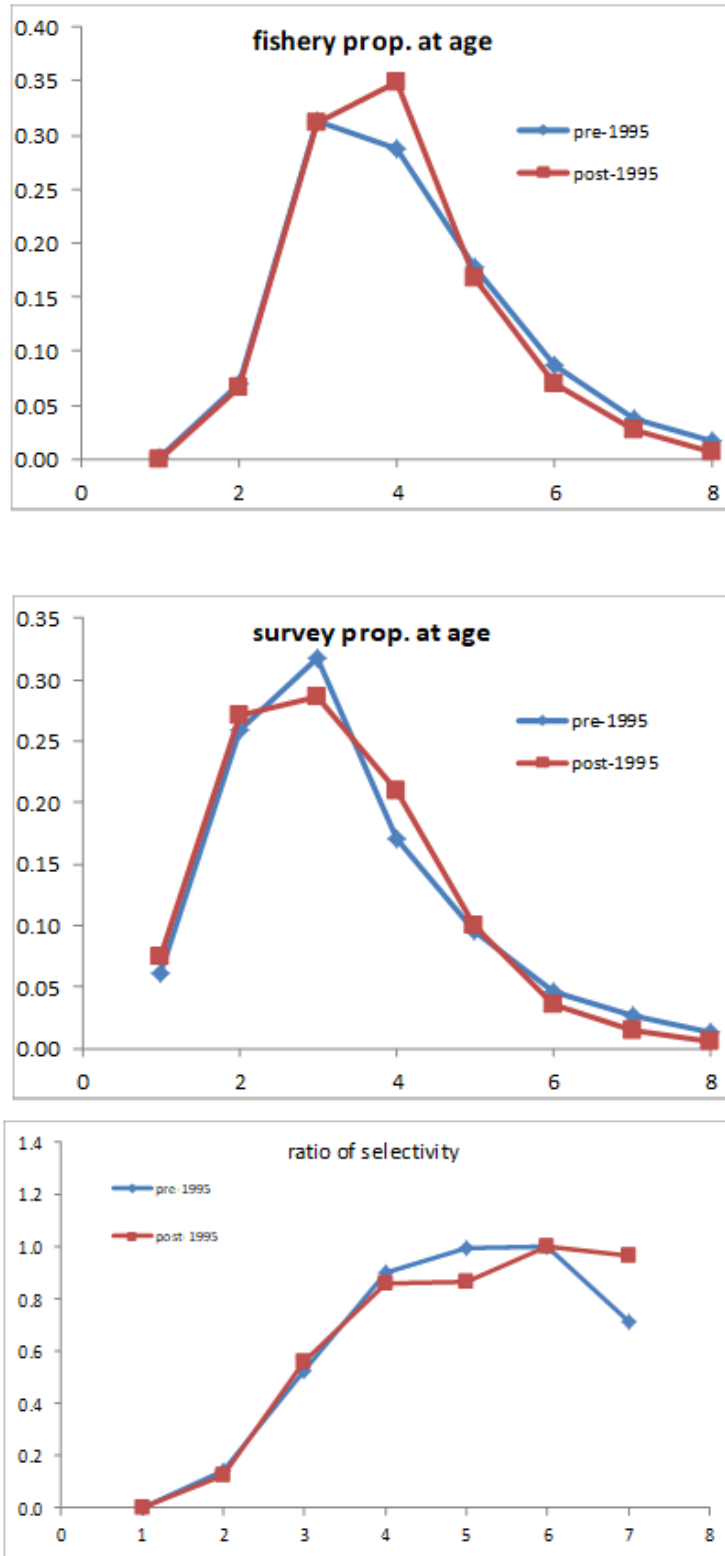


Figure 5. Fishery (top panel) and survey (middle panel) proportion-at-age, and fishery relative selectivity (bottom panel) for 2 time periods (pre-1995; post-1995).

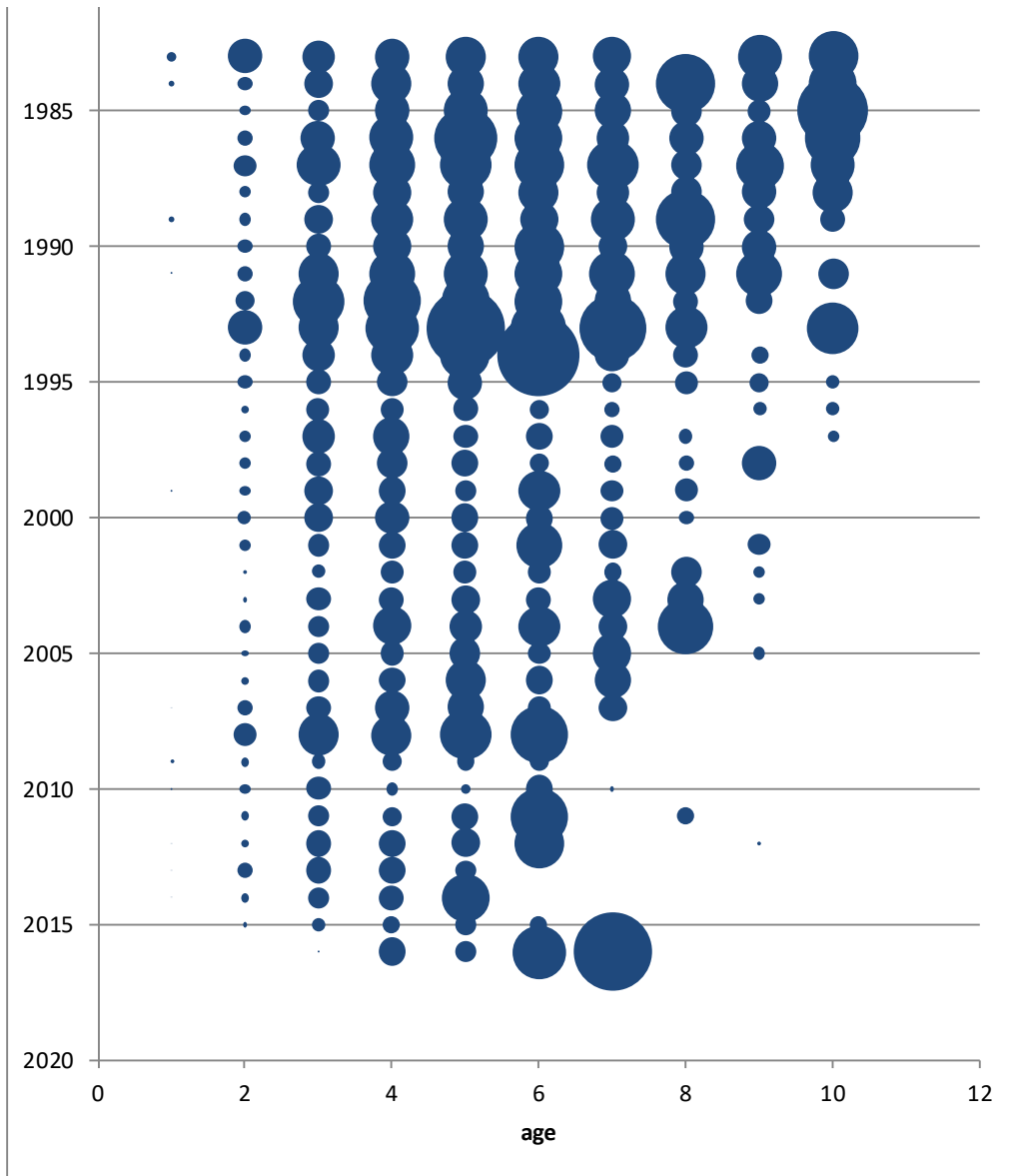


Figure 6. Relative fishing mortality for 4X5Y Cod from 1983 to 2017.

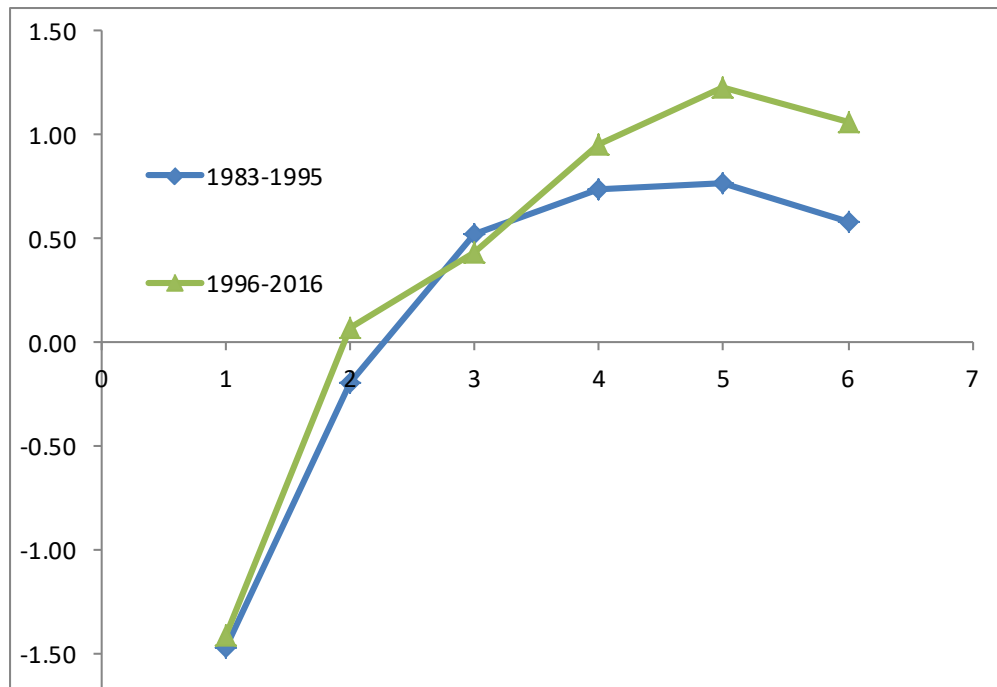


Figure 7. Z for 2 time periods (1983–1995; 1996–2016) using RV survey data.

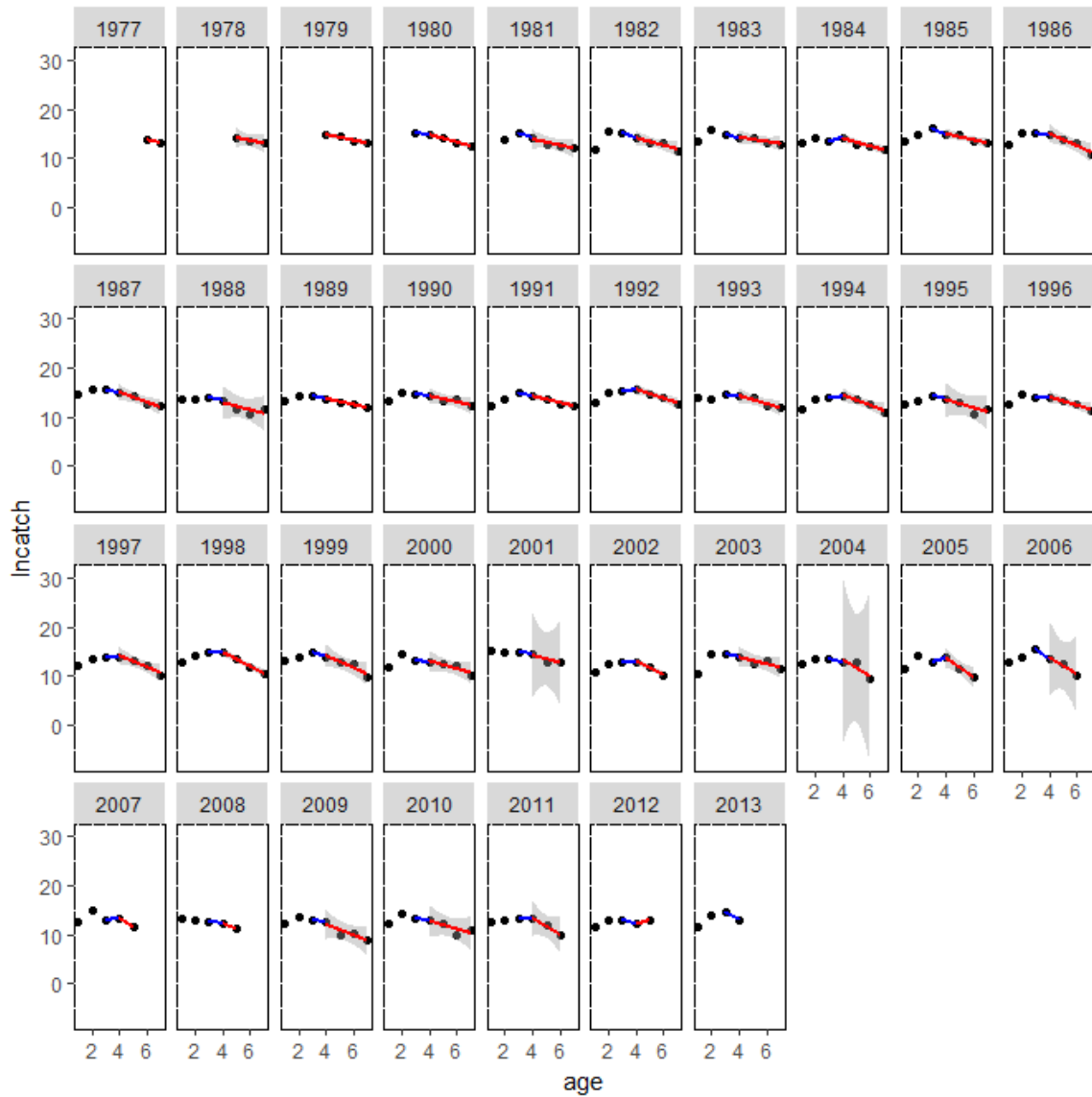


Figure 8. Catch curve analysis of each cohort using the DFO summer RV survey abundance indices. Blue lines show ages 3–4, red lines show older ages.

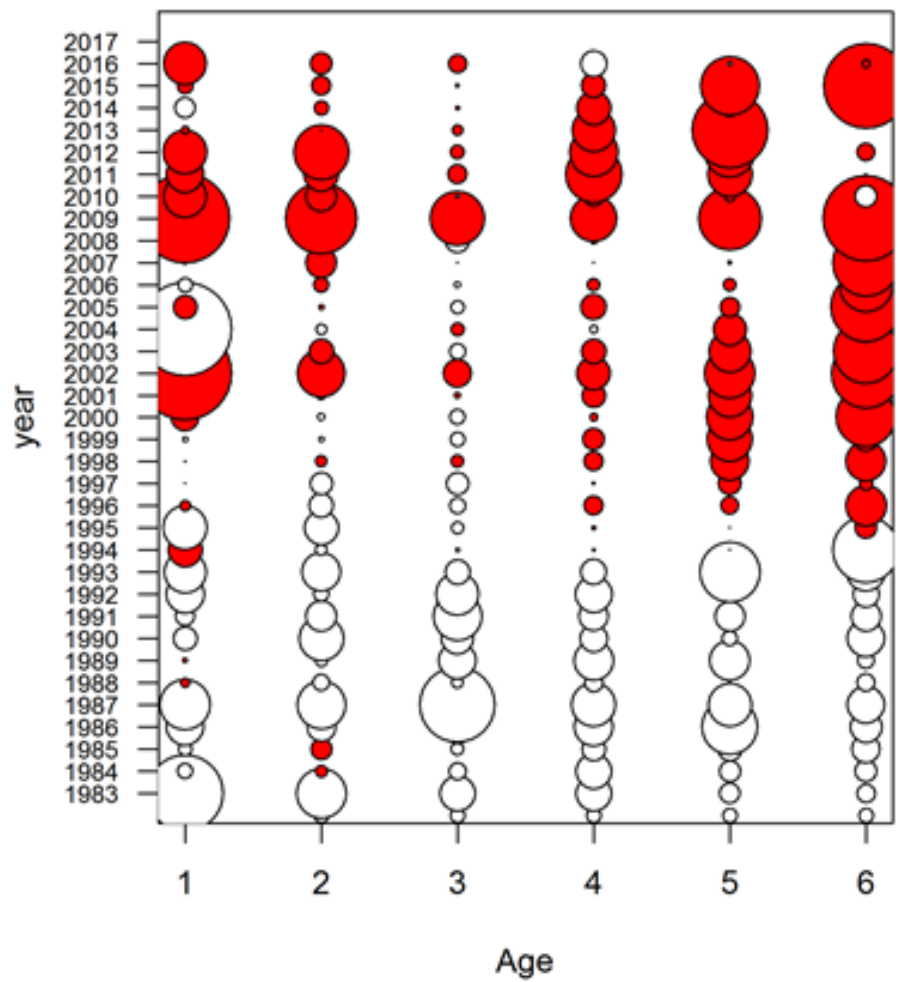


Figure 9. Residuals from the basic VPA model run using data from 1983 to 2017.

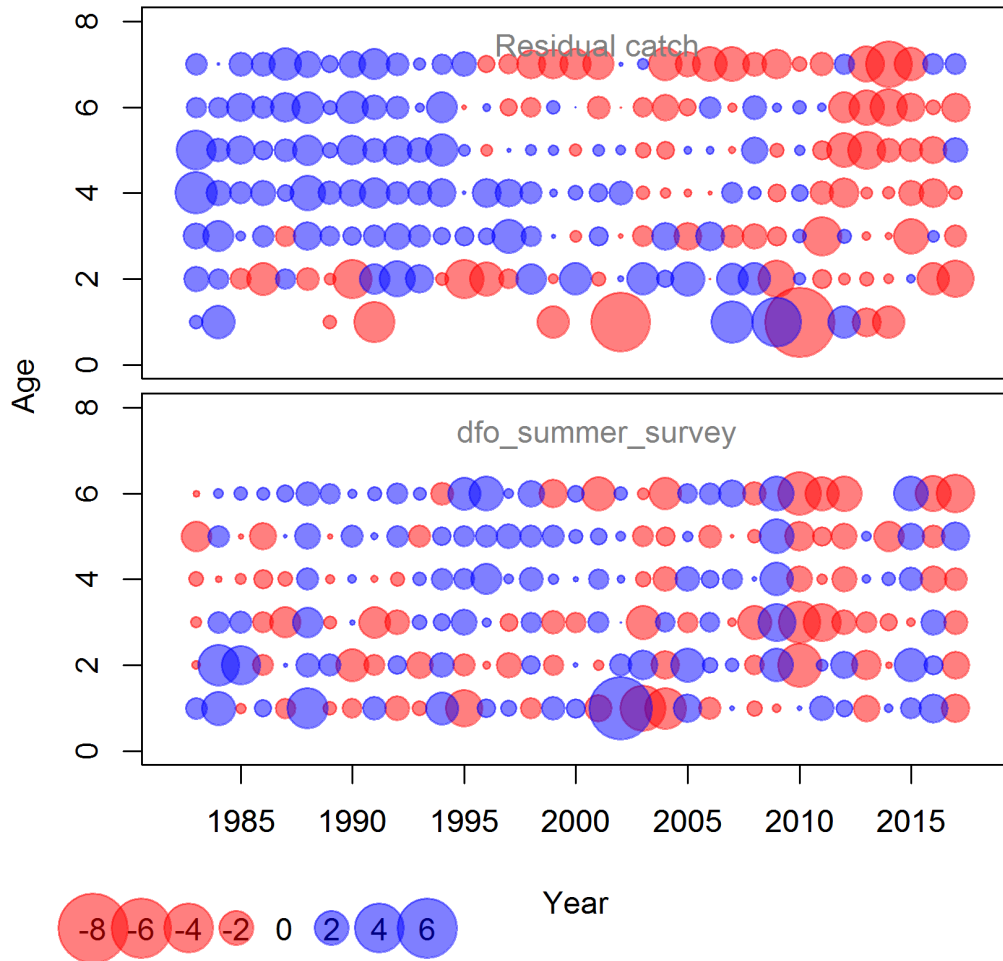


Figure 10. Normalized residuals for the basic run of the SAM model.

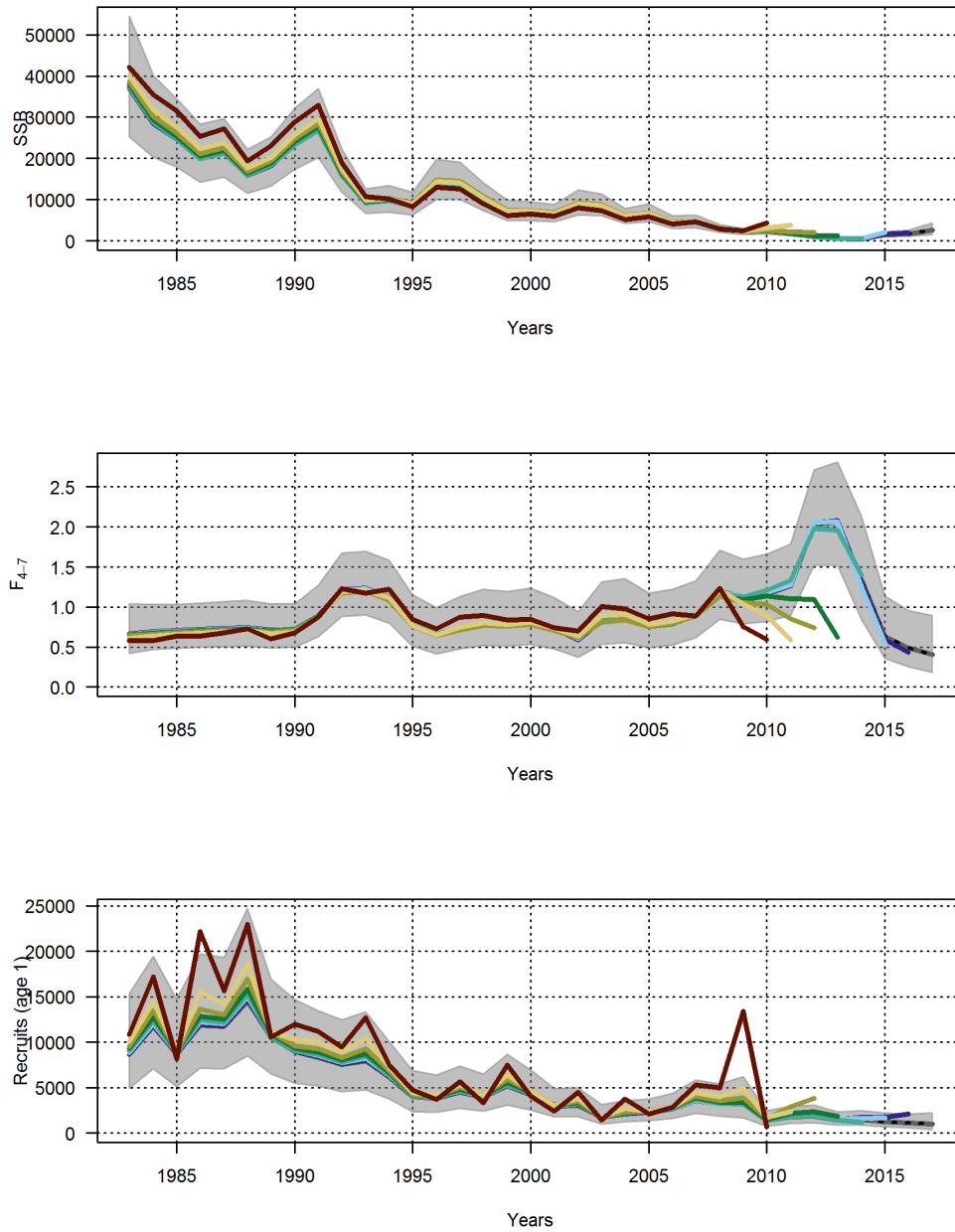


Figure 11. Retrospective analysis from the basic run of the SAM model.

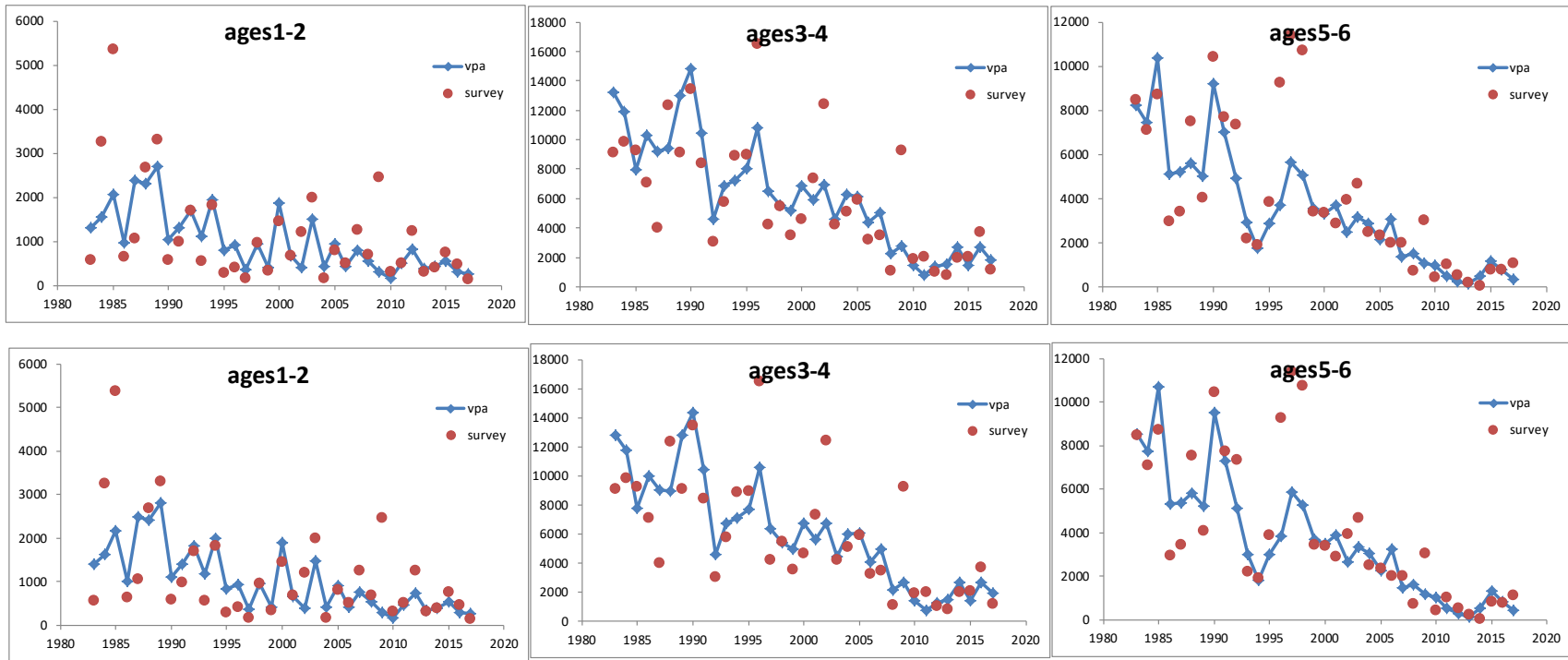


Figure 12. Model fit compared to survey biomass for the 2MFratio (upper panel) and 3MFratio models (bottom panel).

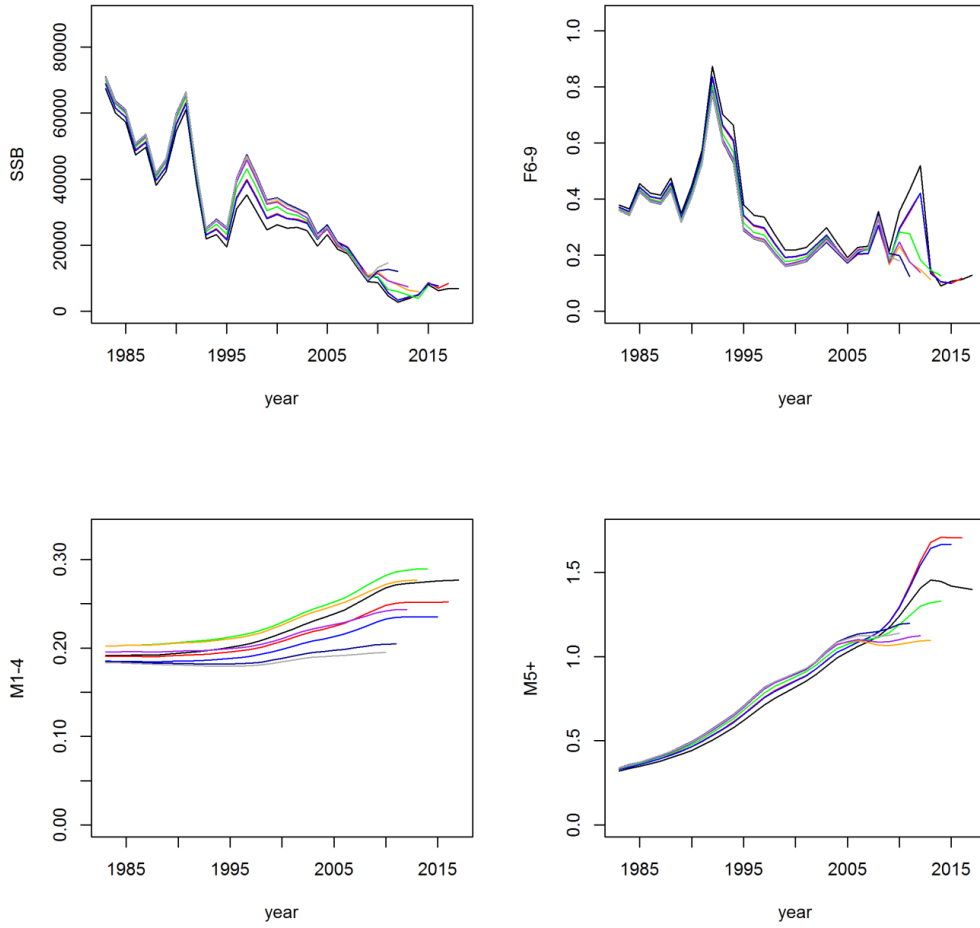


Figure 13. Retrospective analysis for the 2MFratio model.

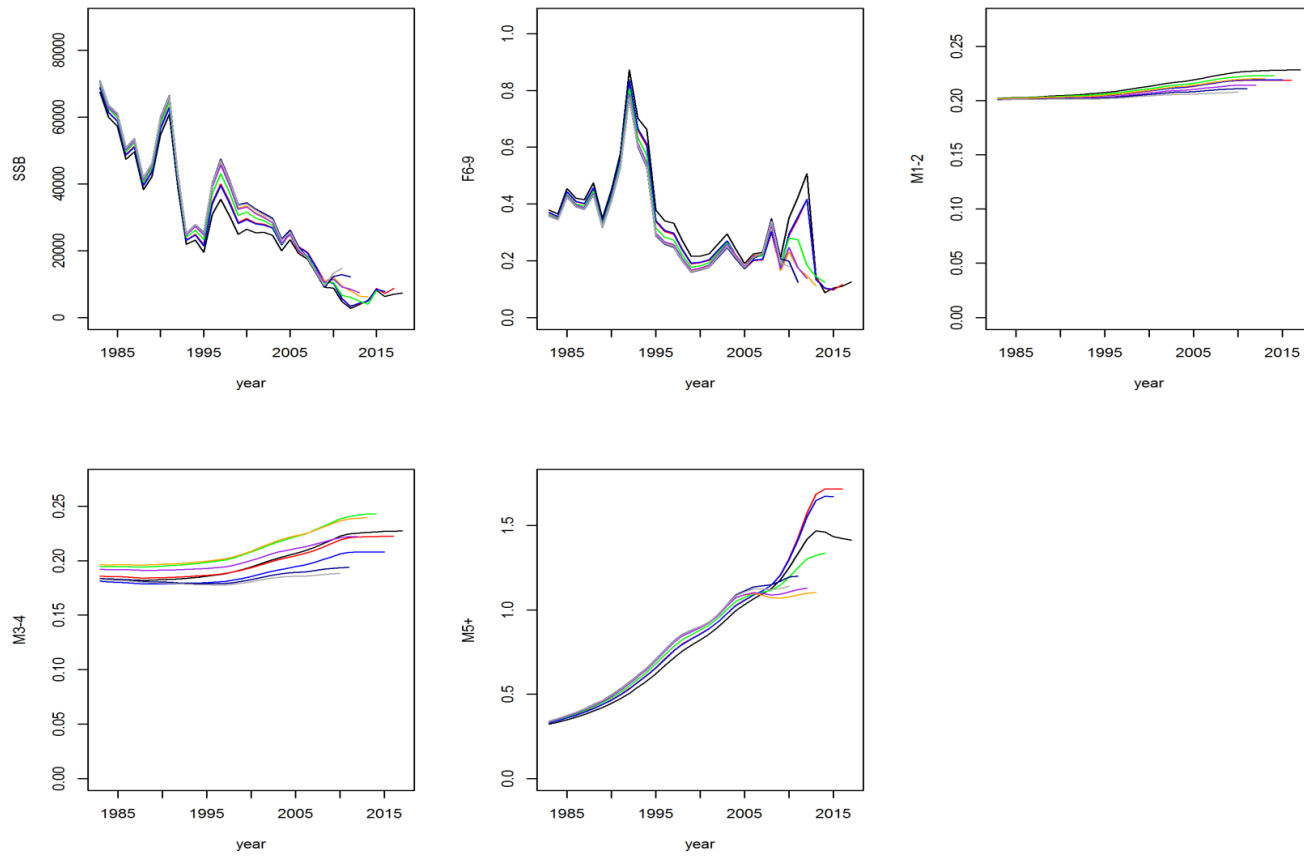


Figure 14. Retrospective analysis for the 3MFratio model.

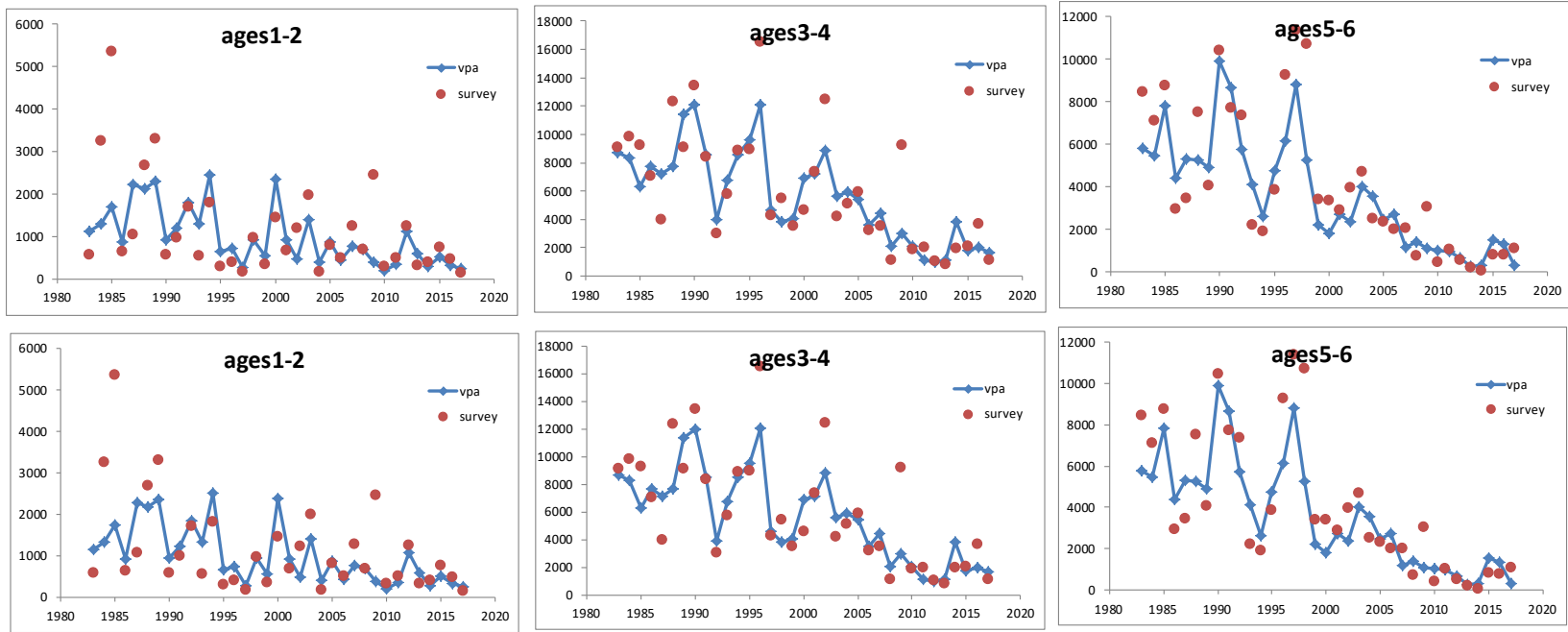


Figure 15. Model fit compared to survey biomass for the 2MFfirst ($Mstd1 = 0.1$; upper panel) and 3MFfirst (bottom panel) models.

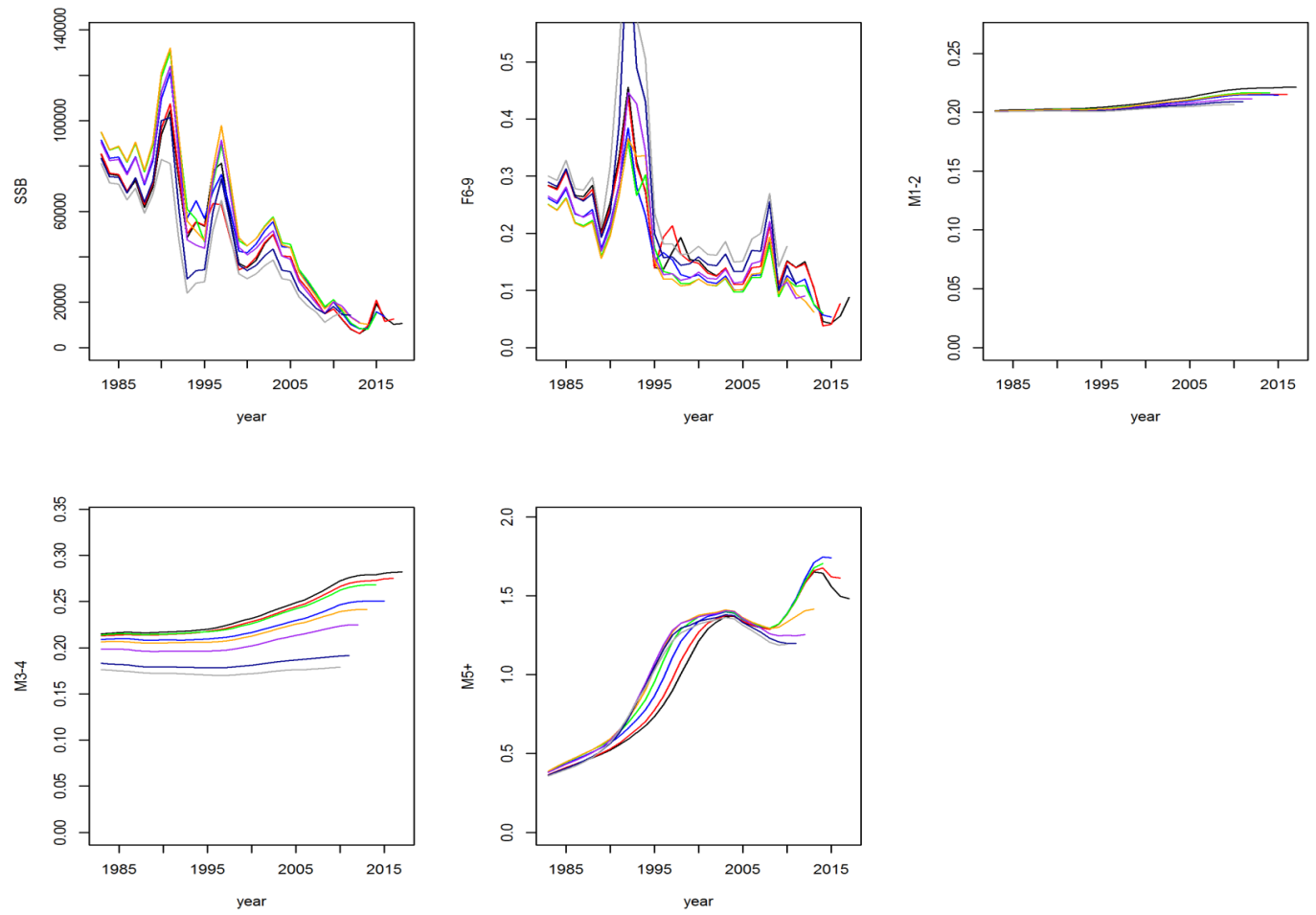


Figure 16. Retrospective analysis for the 3MFfirst model.

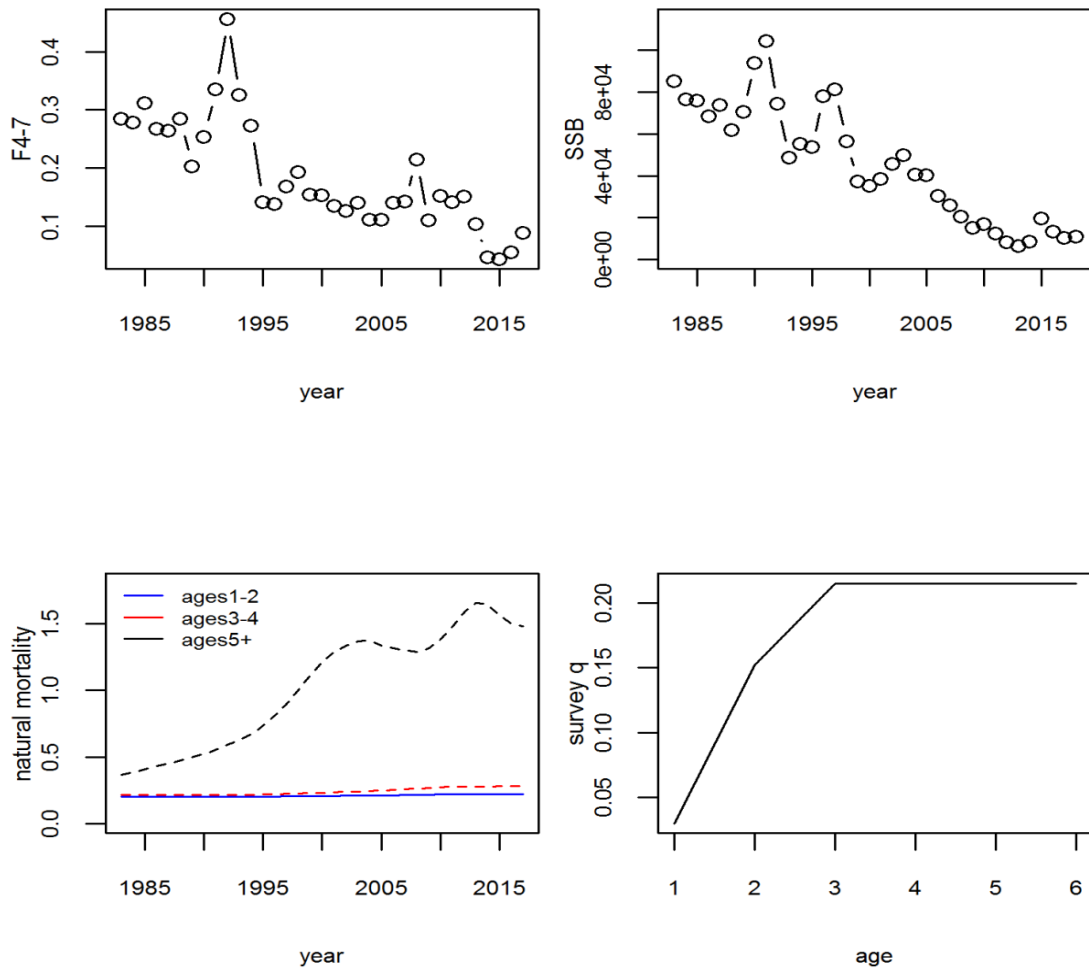


Figure 17. Model output from the 3MFfirst model.

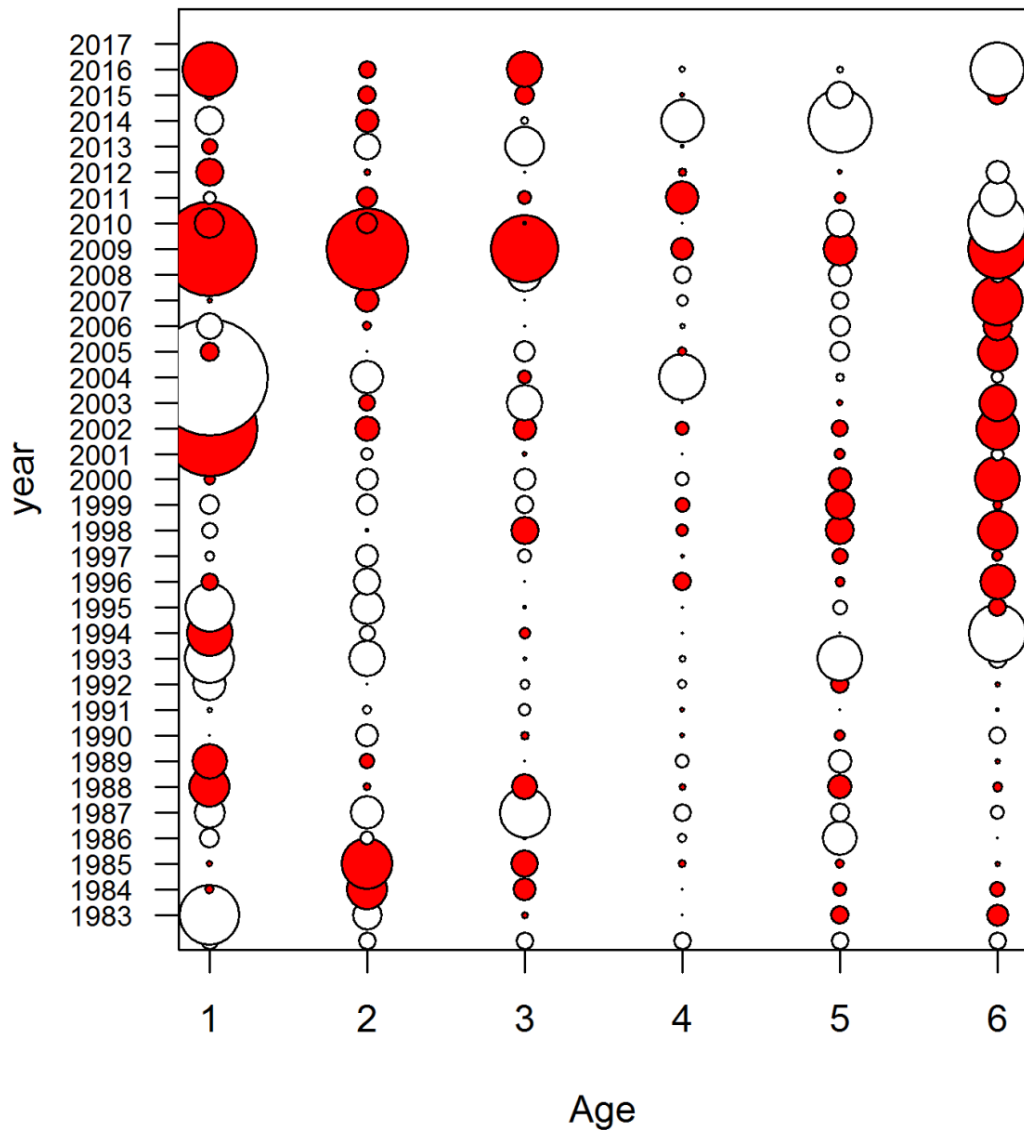


Figure 18. Residuals of the 3MFratio model.

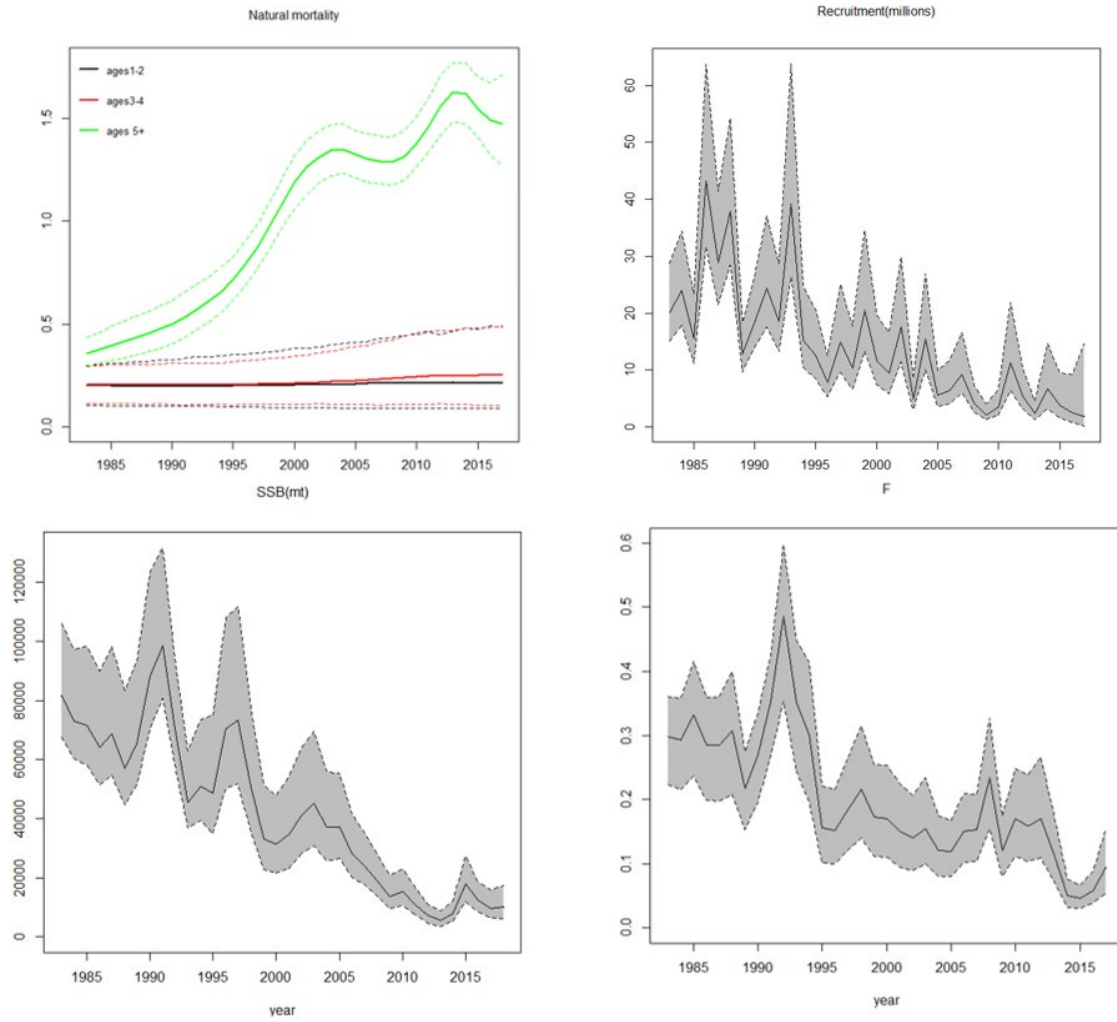


Figure 19. 95% Credibility Intervals of M , recruitment, SSB, and F_{47} from the 3MFfirst model.

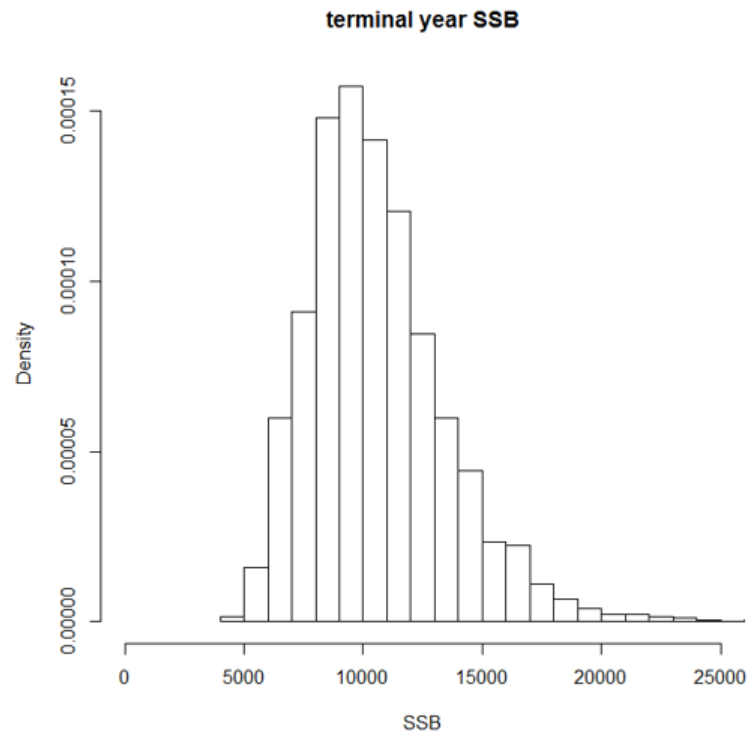
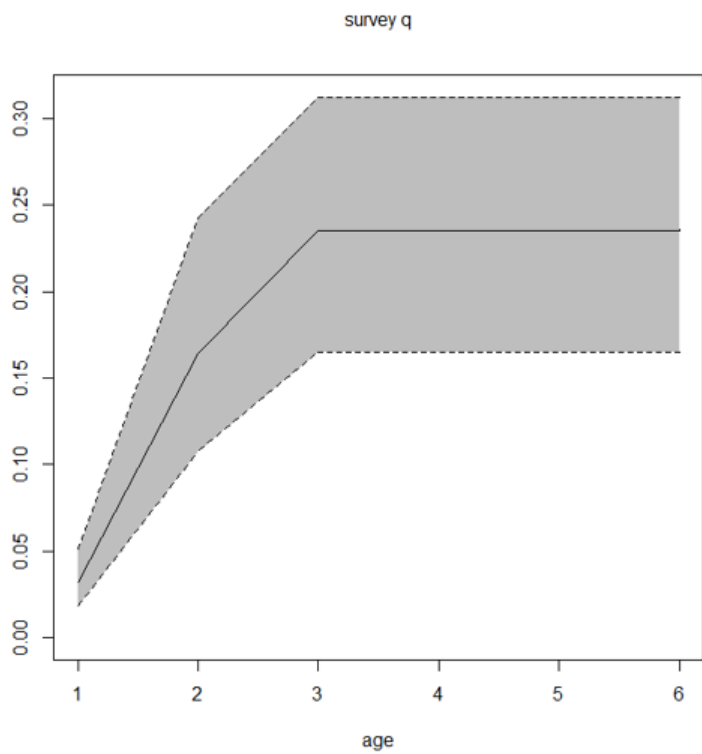


Figure 20. Estimated survey q with 95% Credibility Interval and terminal year (2018) SSB distribution from the 3MFfirst model.

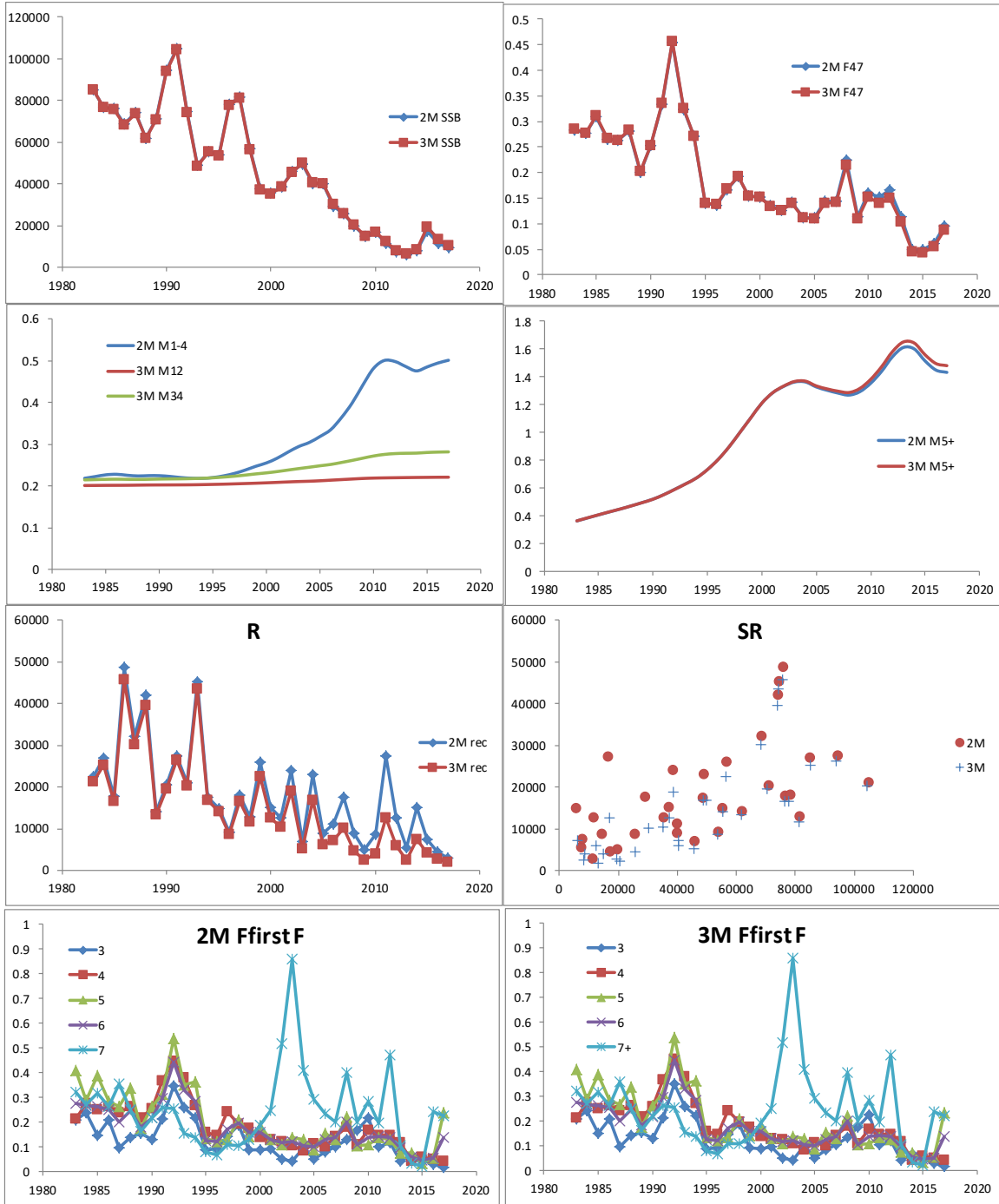


Figure 21. Comparison of model output from the 2Mfirst and 3Mfirst models.

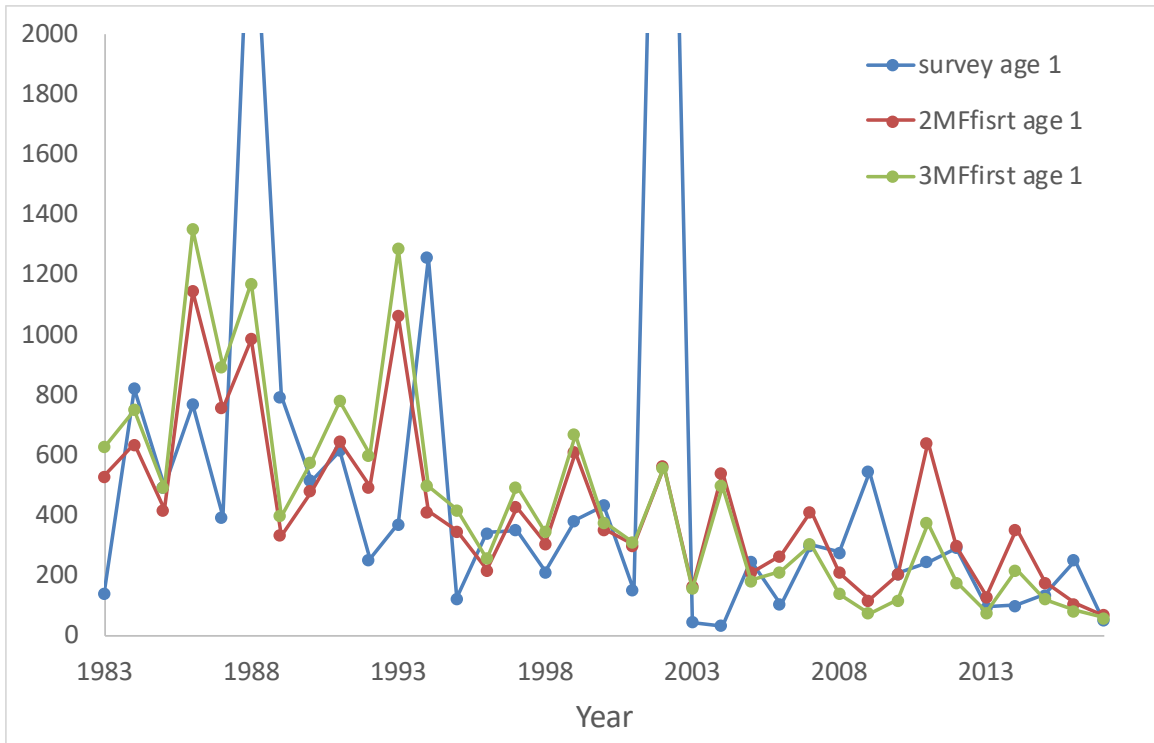


Figure 22. Survey abundance indices at age 1 compared to survey q adjusted age 1 estimated from the 2MFfirst and 3MFfirst model.

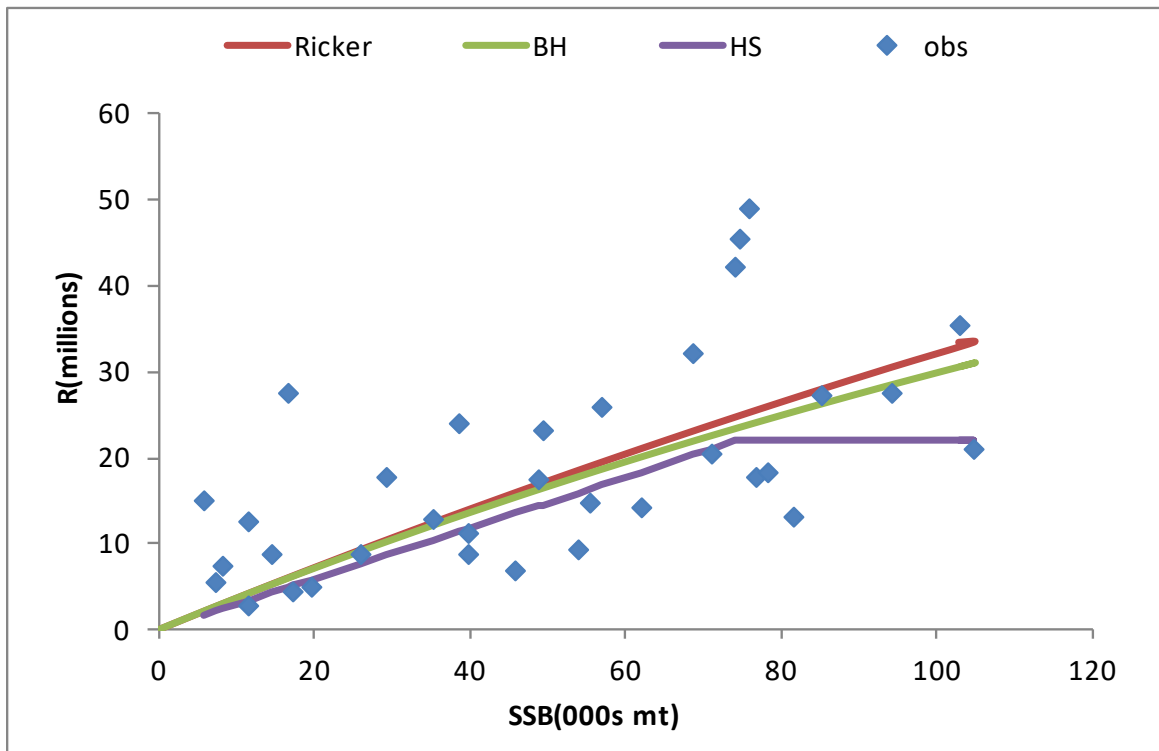


Figure 23. Stock-recruitment relationship of 4X5Y Cod.

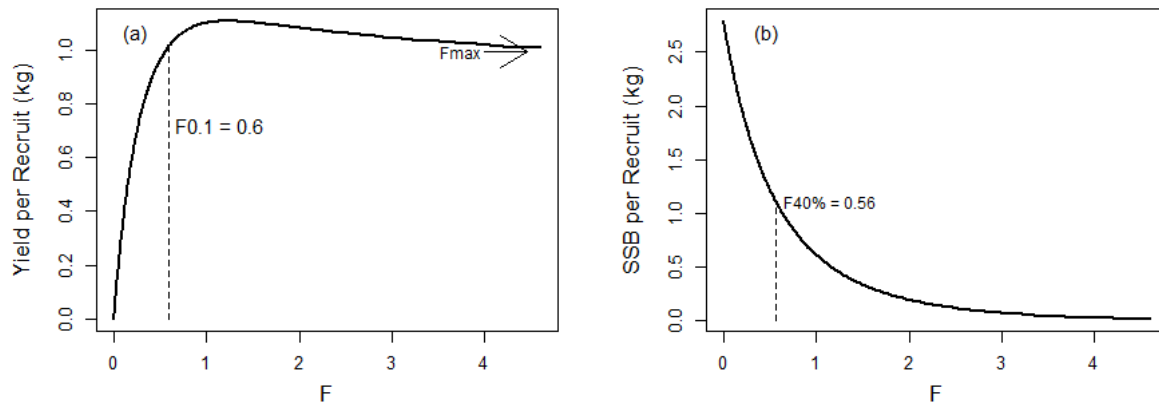


Figure 24. Per-recruit analysis using 3MFfirst model output.

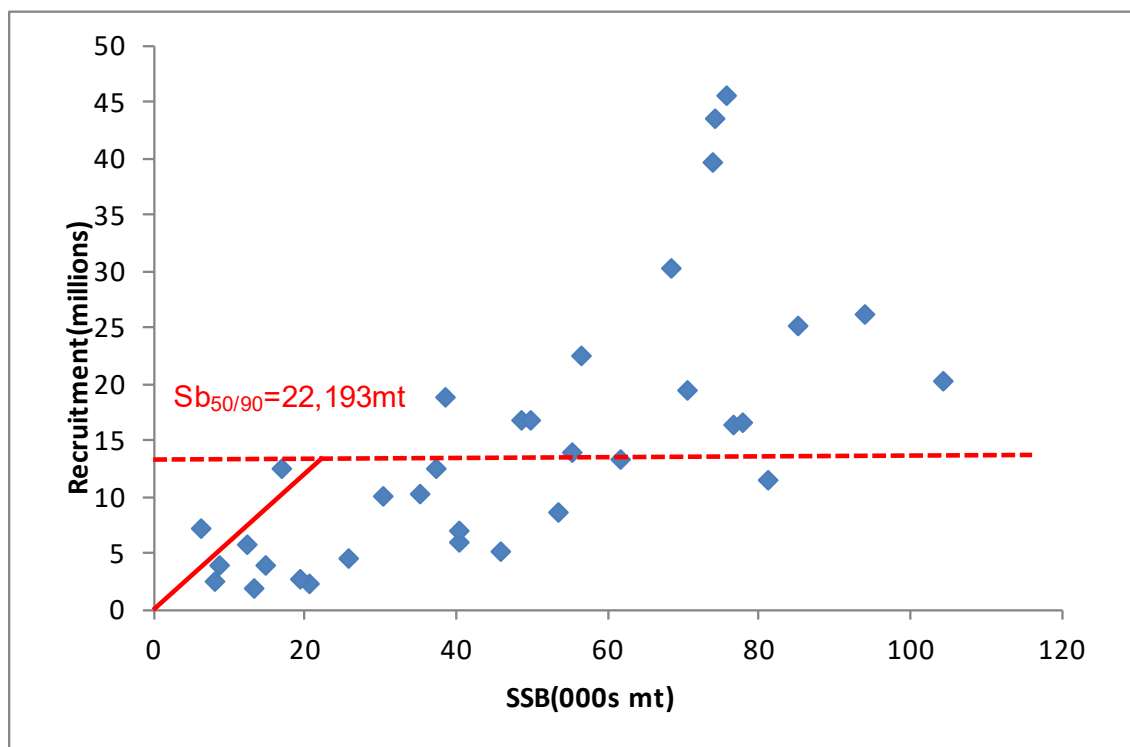


Figure 25. $Sb_{50/90}$ using output from the 3MFfirst model.

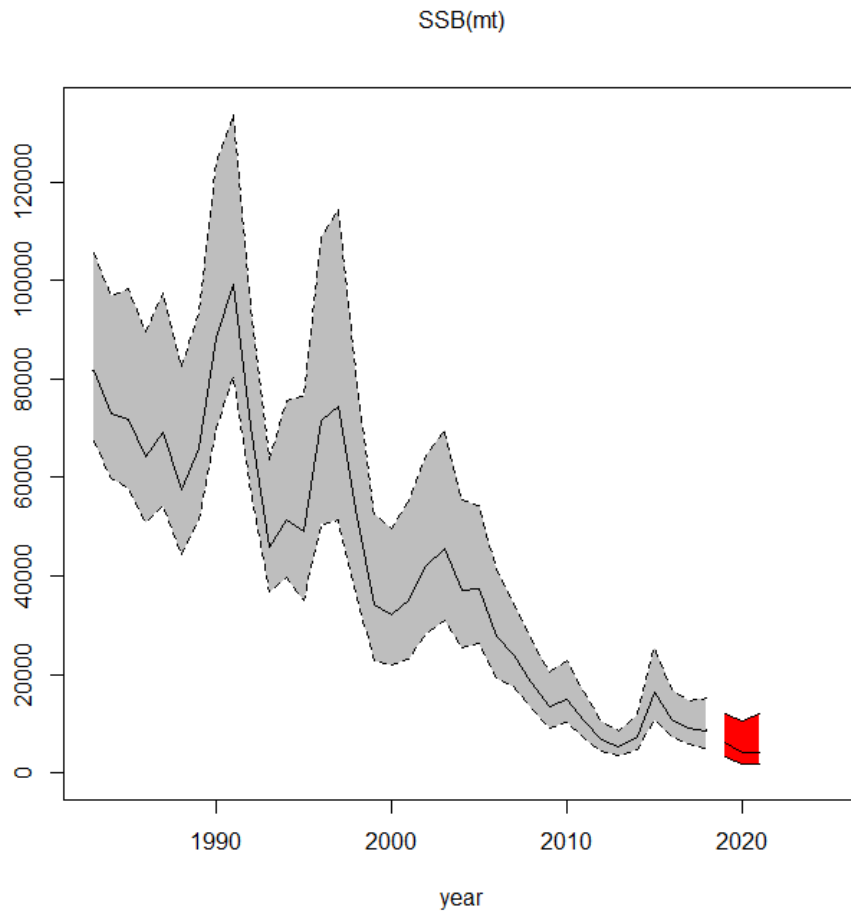


Figure 26. Illustrative projection from the VPA 3MFfirst model, the red shaded color showed the 95% credibility interval from 2,000 posterior samples.

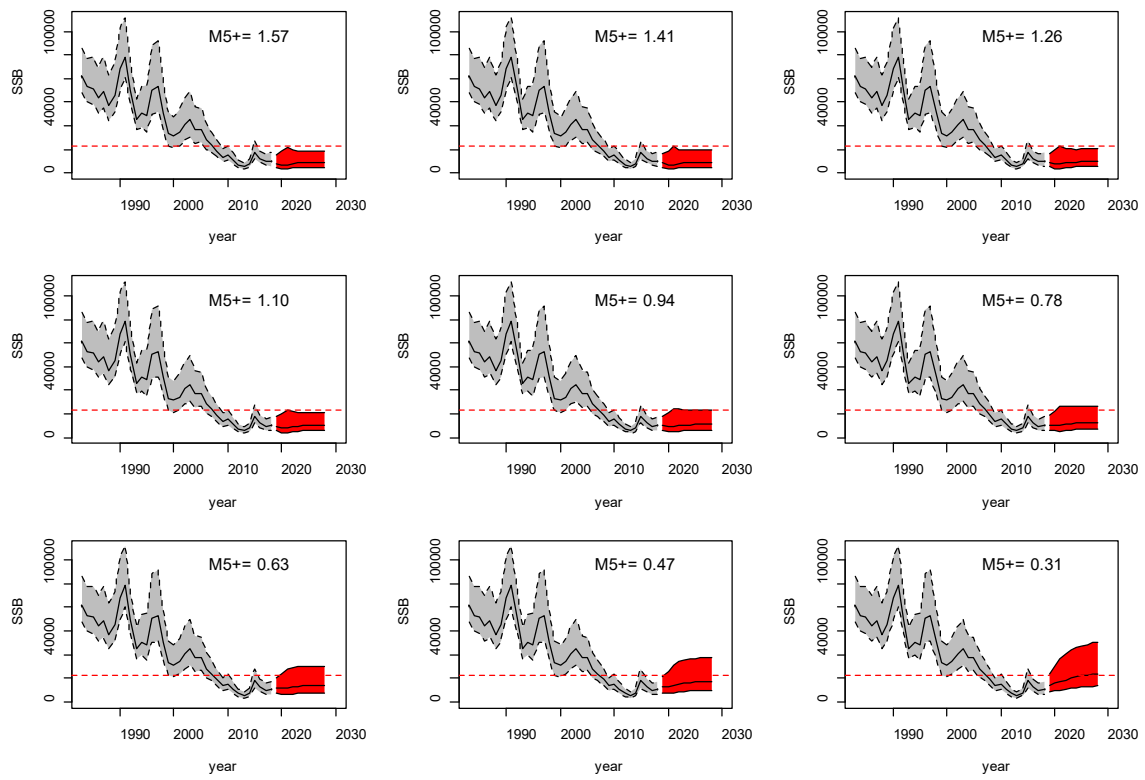


Figure 27. The 10-year projected spawning-stock biomass trajectory under different assumption scenerios on M of ages 5+.

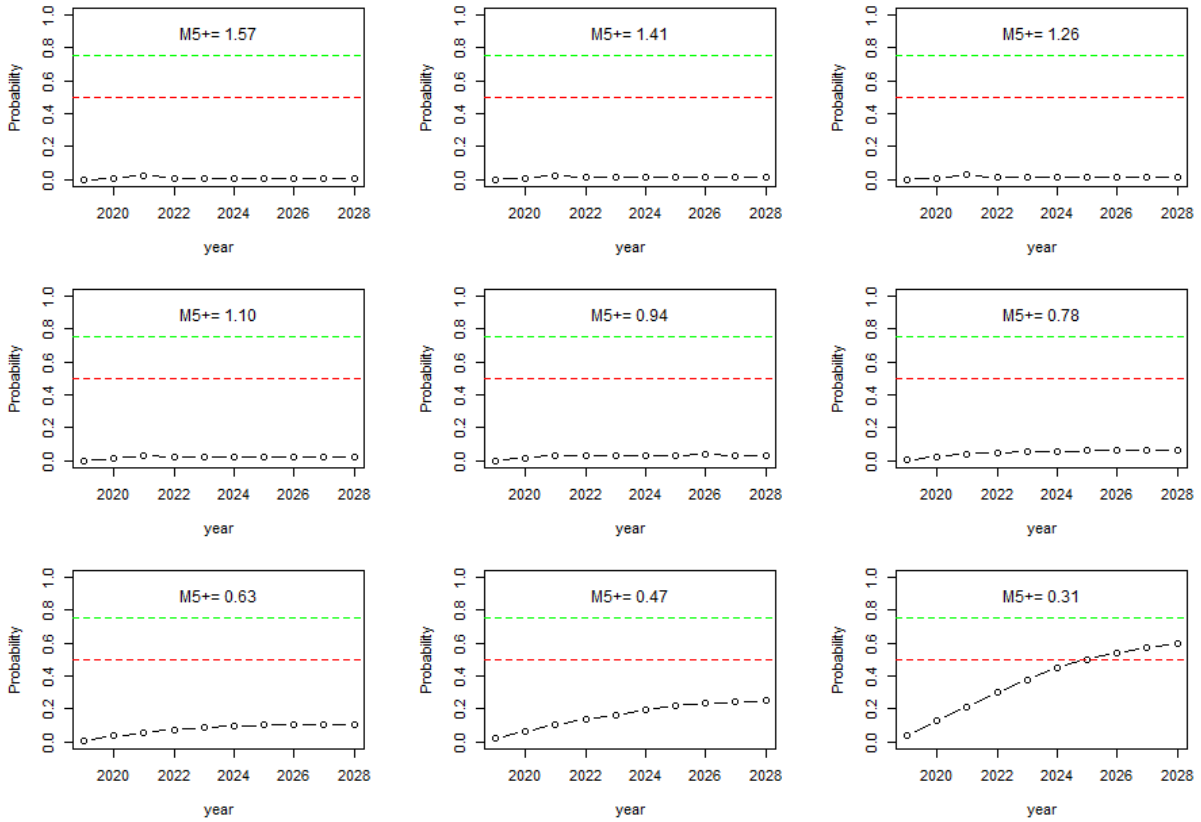


Figure 28. The probability of spawning-stock biomass exceeding limit reference points in the next 10 years under different assumption scenarios on M of ages 5+. The red and green lines show are 50% and 75% probability, respectively.