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Analytical Assessment for the Status of Atlantic Cod (*Gadus morhua*) Stock in NAFO Subdivision 3Ps in 2021

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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 status of the cod stock in the Northwest Atlantic Fisheries Organization (NAFO) Subdivision 3Ps was assessed during a Fisheries and Oceans Canada (DFO) Regional Peer Review Process meeting held November 8–12, 2021. An integrated state space model was used to assess the status of the stock and estimate fishing mortality. This model incorporates catch (1959–2020), time varying natural mortality informed by trends in cod condition, and includes abundance indices from bottom trawl surveys conducted by Canada (1983–2005, 2007–19, 2021), France (1978–91), and industry (GEAC, 1998–2005), and standardized catch rate indices from the Sentinel gillnet and line-trawl surveys (1995–2020).

Spawning Stock Biomass (SSB) at January 1, 2021, was estimated to be 31.5 kt (25.3 kt–39.5 kt). The stock is in the Critical Zone (48% of B_{lim} [38–60%]) as defined by the DFO Precautionary Approach (PA) Framework. The probability of being below B_{lim} is >99.9%. The estimated fishing mortality rate (ages 5–8) has generally declined from 0.16 in 2015 to 0.03 in 2021. Natural mortality was estimated to be 0.34 (ages 5–8) in 2021, a decline from higher values in recent years. Recruitment (age 2) estimates have been below the long term average since the mid-1990s. Under multiple catch projection scenarios, there is a probability >99% that the stock will remain below B_{lim} between 2022 and the beginning of 2024. The probability of stock growth to 2024 is 50% with removals of 3,100 t and 75% with removals of 1,600 t, and 93% when there are no removals. Natural mortality plays an important role in projections for this stock. If natural mortality rates are appreciably different from those used, projected outcomes will differ from values reported above.

INTRODUCTION

This document outlines the results of the 2021 analytical assessment of Atlantic Cod (*Gadus morhua*) stock in North Atlantic Fisheries Organization (NAFO) Subdivision (Subdiv.) 3Ps, based on an integrated age-structured population model 'Hybrid'. The population model incorporates scientific data from bottom trawl surveys (Canada, 1983 to 2021; France, 1978–92); an industry association GEAC (1997–2007), the Sentinel Survey (1995–2020) utilizing gillnets and line-trawls near the coast, and landings data. Natural mortality estimates in the model are informed by a cod condition-based index of mortality (M_c). The model provided estimates of biomass, recruitment, natural and fishing mortality for the stock.

HYBRID ASSESSMENT MODEL DESCRIPTION

From 2009 to 2018, the NAFO Subdiv. 3Ps cod stock was assessed using a SURBA (SURvey Based Assessment) model (Cadigan 2010, DFO 2019a) fit to the Canadian research vessel (RV) survey. An assessment framework meeting was held October 8-10, 2019. At this meeting, a range of state-space models for assessing the status of the 3Ps cod stock were examined. Candidate models developed within three different state-space modelling approaches: Champagnat et al. 2024 built using stock assessment package from Nielsen and Berg 2014, Berg and Nielsen 2016 (SAM), a custom model 3PsSSAM (State-space Assessment Model for 3Ps Cod, Cadigan 2023a), and another custom state-space assessment model HYBRID (Varkey et al. 2022) were developed and several model formulations within each of these modelling approaches were presented and reviewed. The goal was to adopt one of the candidate models for assessing the status of the 3Ps cod stock.

The assessment framework meeting decided that a formulation of the HYBRID modelling approach will be used for assessing the stock (Varkey et al. 2022). The HYBRID model is named as such because it uses a variety of features from SAM (mainly the use of random-effects for modelling N and F matrices) and the Northern Cod Assessment Model (Cadigan 2016), mainly the inclusion of expert opinion on reliability of landings time series through the use of censored likelihood. Further, HYBRID uses time-varying natural mortality which is modelled as a function of a scaled fish condition-based mortality index (Regular 2022; Regular et al. 2022). In 2019 and 2020, the NAFO Subdiv. 3Ps cod stock was assessed using the HYBRID model.

This model has the following main features:

1. includes all the available surveys (Canadian RV survey, French ERHAPS [Evaluation des Ressources Halieutiques de la region 3PS survey], industry trawl survey, and gillnet and line-trawl Sentinel surveys);
2. two types of commercial data—fisheries catch-at-age where the age composition is fit using continuation ratio logits, and fisheries landings which are fit using a censored likelihood;
3. Multivariate normal (MVN) random walk for F with age 2 decoupled from the MVN correlation and with a discontinuity in the random walk at the moratorium;
4. time varying M; and
5. the model starts in 1959 which is the first year for which landings data are available. Figure 1 is a summarized presentation of the time-line of all data contributing to the assessment.

INPUT DATA

Fisheries Landings (1959–2020) and Catch-at-age (1959–2020)

Fishery and landing information is outlined in Wheeland et al. In press and references therein. Total landings (Table 1; see Wheeland et al. In press and references therein for more detail on the landings time series) and catch abundance at age (Table 2) are input into the model.

DFO-RV Spring Survey (1983–2021)

Canadian RV (DFO-RV) bottom trawl surveys have been conducted in Subdiv. 3Ps since 1972, however surveys from 1972 to 1982 had poor coverage (Varkey et al. 2024). In 1997, inshore strata were added to the survey; time series from 1983 to 1996 is referred to as the offshore survey and from 1997 to present is referred to as the inshore-offshore DFO-RV time series (Figure 1). Survey methods, survey strata, and results are detailed in Wheeland et al. (In press and references therein). Abundance-at-age (mean number per tow) from the RV survey is input in the HYBRID model (Table 3). DFO-RV spring survey data are also used for computation of maturity at age (Table 4). The beginning of the year stock weights-at-age used in the HYBRID model are estimated based on a time series model (Cadigan 2023b) applied to the mean weights-at-age of fish sampled from the spring survey data (Table 5).

ERHAPS Trawl Survey (1978–91)

France conducted a bottom trawl research survey in Subdiv. 3Ps during February-March of 1978 to 1992 (Bishop et al. 1994). The vessel changed in 1992 and, since data from the two vessels could not be converted, the assessment model included data from 1978–1991 (Table 6). The ERHAPS survey used the same stratification scheme as the Canadian survey, however, only the offshore strata were sampled. A Lofoten otter trawl was used during daylight hours to conduct 30 minute tows and data for unsampled strata were estimated from a multiplicative model based on the results of the Canadian survey for the same strata. More details on the survey is available from Champagnat and Vigneau (In prep[1]).

GEAC Trawl Survey (1998–2005)

An industry-led bottom trawl survey was conducted from 1997 to 2005 and in 2007 (see McClintock 2011 and references therein). This survey also used the stratification scheme of the Canadian and French surveys. An Engel trawl was used, although it did not have a cod-end liner. Tows were 30 minute duration. The 1997 and 2007 data were excluded from the model because of coverage and vessel issues and the assessment model used data from 1998 to 2005 (Table 7).

Sentinel gillnet and line-trawl (1995–2020)

Fixed-gear Sentinel surveys have been conducted at sites along the south coast of Newfoundland from St. Bride's to Burgeo from 1995 through 2020. Gillnets are predominantly operational in Placentia Bay and line-trawls operate mostly in sites west of Burin Peninsula. Survey methodology and standardization approach are summarized in Mello et al. 2018. The Sentinel survey for 2021 was still ongoing at the time of the assessment; hence, data for 2021 are incomplete and not included in the modelling reported below. At the 2020 assessment, a

[1] Champagnat J., and Vigneau J. In prep. ERHAPS: a French survey for cod in 3Ps. IFREMER.

sharp increase in certain index-at-age values were noticed, following which a review of the data processing and standardization of the Sentinel index was done. The review identified two errors in data processing related to the application of aging data to the survey length frequencies and exclusion of data from some survey participants. The main change from the review and following revision was that age 9 and 10 indices from the line-trawl survey were revised upwards for year 2015–17 and downwards for years 2019–20. The updated standardized indices are included in Mello et al. 2022. Standardized catch rates-at-age are input in the assessment model for ages 3–10 from fixed sites in the 5 ½” gillnet (Table 8) and the line-trawl (Table 9) series.

Condition-based M-index (1978–2020)

Biological sampling data from both the DFO-RV spring survey and Sentinel gillnet and line-trawl surveys are utilized to generate an index of natural mortality derived from proportion of cod in poor condition (see Varkey et al. 2022; Regular 2022, and Regular et al. 2022). This condition-based index of natural mortality is presented in Table 10. This time series is available from 1978 to 2021. For the years 1959 to 1977, the average of the first five years of the index was used. Compared to the average value that was used in the previous meetings (0.3), this value has now been updated to 0.39.

MODEL FORMULATION

The state equation follows the parameterization of state equation in the State-space Assessment Model (SAM) (Nielsen and Berg 2014; Berg and Nielsen 2016). The matrices of *log N* (log abundance) are treated as random variables and represent the underlying unobserved state. Age *a* in the model spans from 2 to 14+ and the plus group is represented by *A*. Years (*y*) in the model span from 1959 to 2019. First year abundances (for ages 3 to *A*) are estimated as part of the random variable matrix for $log\ N_{a,y}$. Recruitment (age-2) is modelled to follow a random walk with standard deviation σ_R. The process error is normally distributed with standard deviation σ_P. Age-specific fishing mortality ($F_{a,y}$) and natural mortality ($M_{a,y}$) are used to model the exponential decay in the cohort.

$$log\ N_{2,y} = log\ N_{2,y-1} + \eta_{2,y};\ \eta_{2,y} \sim N(0, \sigma_R) \quad \mathbf{1}$$

$$log\ N_{a,y} = log\ N_{a-1,y-1} - F_{a-1,y-1} - M_{a-1,y-1} + \eta_{a,y}; 3 \le a < A-1;\ \eta_{3:A,y} \sim N(0, \sigma_P\ ) \quad \mathbf{2}$$

$$log\ N_{A,y} = log\begin{pmatrix} N_{A,y-1} * \exp\left(-F_{A,y-1} - M_{A,y-1}\right) + \\ N_{A-1,y-1} * \exp\left(-F_{A-1,y-1} - M_{A-1,y-1}\right) \end{pmatrix} + \eta_{A,y};\ A = 14+ \quad \mathbf{3}$$

PARAMETERIZATION OF F - TIME VARYING FISHERIES SELECTIVITY IN THE MODEL

To account for some of the temporal dynamics in the fishery, time varying selectivity was incorporated into the model. The primary gears used in the fishery for 3Ps cod varied considerably over time with the fishery changing from a predominately offshore fishery heavily exploited by non-Canadian fleets in the 1960s and early 1970s to a fishery based mostly inshore in the later years. Since 1997, most of the Total Allowable Catch (TAC) has been landed by Canadian inshore fixed gear fish harvesters with the remaining catch taken mainly by the mobile gear sector fishing the offshore.

Therefore, we modeled the $F_{a,y}$ matrix is a MVN random walk over years, similar to the implementation in SAM (Nielsen and Berg 2014). We added breaks to the MVN random walk at the beginning of the fishing moratorium. Further, the standard deviation for age 2 is de-coupled from the older ages in the fishery (ages 3+). Correlation in the random walks between ages is enabled through MVN deviations. For the covariance matrix of MVN deviations, we adopt a simple autoregressive (AR1) process for the correlation (ρ) such that similar age groups develop similar trends in fishing mortality.

$$\log(F_{2:A,y}) = \log(F_{2:A,y-1}) + e_{2:A,y};\ e_{2:A,y} \sim MVN_{2:A}(0, \Sigma) \quad \textbf{4}$$

$$\Sigma_{a,\bar{a}} = \rho^{|a-\bar{a}|}\sigma_a^2 \quad \textbf{5}$$

Each element in Σ is a function of the standard deviation of the random walk and the estimated correlation coefficient. This parameterization of *F* allows for flexibility for the shape of the selectivity function over the two dimensional space of ages and years. Selectivity is derived as:

$$s_{a,y} = \frac{F_{a,y}}{\sum_a F_{a,y}} \quad \textbf{6}$$

PARAMETERIZATION OF NATURAL MORTALITY *M*

When information on natural mortality is not available, a base assumption in fisheries stock assessments has been that natural mortality is invariant over age and year and often assigned a value of *M*=0.2 (Hilborn and Liermann 1998). For the neighboring cod stock (Northern cod 2J3KL), *M* is estimated to be higher than 0.2 (Cadigan 2016, DFO 2019b). For this reason, *M*=0.3 was chosen as the base level. Analysis of tagging data for 3Ps cod also suggested *M* levels to be higher than 0.2; although the tagging data is limited to the post-moratorium time period (Robertson 2022). Previous assessments also indicated an increase in total mortality (Ings et al. 2019a, Ings et al. 2019b).

The model applies time-varying $M_{a,y}$, where a trend based on fish condition is applied to a base level *M* (M_{base}= 0.3).

$$M_{a,y} = M_{base}\exp(\delta_{a,y}) \quad \textbf{7}$$

The $\delta_{a,y}$ term is covariate associated estimation such that the resulting *M* follows the trend in the covariate X_y.

$$\delta_{a,y} = mpar_a * X_y \quad \textbf{8}$$

Parameter *mpar* is estimated in the model and describes the effect on covariate X on M. Estimates of *mpar* close to zero suggest none/little influence of covariate on *M*, a positive *mpar* indicates that *M* follows the trend in the covariate and a negative *mpar* indicates an *M* trend opposite to the trend in the covariate. Here, the covariate X_y is a normalized index of *Mc,* a condition-based index of *M* (Table 9).

$$X_y = \frac{Mc_y - \mu_{Mc}}{\sigma_{Mc}} \quad \textbf{9}$$

This scaling allows the treatment of the covariate as an anomaly resulting in estimates above or below the baseline M_{base} provided, similar to the scaling for temperature anomaly for time-varying carrying capacity (Kumar et al. 2013). The mean (μ_{Mc}) and standard deviation (σ_{Mc}) are calculated for the reference period 1978 to 2012; therefore, the normalization of *Mc* is based on a reference period from 1978 to 2012. The *mpar* parameter was estimated by two age groups (2–5 and 6+, roughly corresponding to immature and mature) to allow different age groups to respond differently to the trends in fish condition. A similar implementation of time-varying *M* for the Kootenay lake kokanee population was detailed in Kurota et al. (2016). The final equation for *M* is:

$$M_{a,y} = M_{base} \exp\left(mpar_a * \left(\frac{Mc_y - \mu_{Mc}}{\sigma_{Mc}}\right)\right) \quad \textbf{10}$$

LIKELIHOODS

Surveys

We fit the model to five surveys:

1. the DFO-RV survey,
2. the French ERHAPS survey,
3. the GEAC survey, and
4. the Sentinel gillnet survey.
5. the Sentinel line-trawl survey.

$I_{a,y,s}$ represents the expected index-at-age in survey *s*, *ts***Z* (where instantaneous rate of total mortality *Z = F + M)* represents an adjustment to total mortality to account for the timing of survey in the year (e.g., ts=0.5 for a survey in June; the model year is January to December, although the management year is April to March). The observation error standard deviation $\sigma_{ag,s}$ can be estimated separately for age-group 'ag' and survey '*s*'.

$$\log \hat{I}_{\mathrm{a,y,s}} = \log q_{a,s} + \log N_{a,y} - ts_{y,s} * Z_{a,y} + e_{a,y,s};\ e_{a,y,s} \sim N\left(0, \sigma_{ag,s}\right) \quad \textbf{11}$$

The DFO-RV survey provides annual (except 2006, 2020) records of mean numbers per tow (MNPT) throughout the time series, however survey timing shifted in the early 1990s, and inshore strata were added at the same time as the fishery reopened in 1997. We use an inshore-offshore adjustment (offset for *q*) which is applied only to fish aged 8 and older. The average fraction of fish age 8 and older in the inshore area was less than 5% in the DFO-RV combined inshore-offshore index (DFO-RV-IO). The catchability for fish aged 2 to 7 are estimated independently for the offshore (DFO-RV-OFF) and the DFO-RV-IO survey. For fish aged 8 and older, the catchability in the DFO-RV-OFF is calculated as the catchability of the DFO-RV-IO plus an offset. The offset for *q*-at-age is calculated as the log ratio of the average (median) index-at-age for the combined inshore-offshore region versus the same for the offshore region. A comparison of several approaches to adjust for the addition of inshore strata and estimate catchability for the RV survey series were explored in Varkey et al. 2022. This adjustment was adopted based on fewer assumptions required on the ratio of fish present in the inshore versus offshore, and based on better performance in retrospective analyses (Varkey et al. 2022).

$$log\ q_{8:A,DFO\ RV\ OFF\ 1983:1996} = log\ q_{8,DFO\ RV\ IO\ 1997:2018} + \log q_{offset\ 8:A} \quad \mathbf{12}$$

$$log\ q_{offset\ 8:A} = median\left[-log\left(\frac{I_{DFO\ RV\_IO\ 8:A}}{I_{DFO\ RV\_OFF\ 8:A}}\right)\right] \quad \mathbf{13}$$

Fisheries catch-at-age

Catch is predicted using the Baranov catch equation:

$$\hat{C}_{a,y} = N_{a,y}\left(1 - \exp(-Z_{a,y})\right)^{F_{a,y}}\Big/_{Z_{a,y}} \quad \mathbf{14}$$

In the model fitting exercise, the magnitude of the catch total weights (i.e., landings) and the age composition information in the catch-at-age data were fitted separately. Continuation ratio logits (CRL, Cadigan 2016) are the logit transformation of the conditional probability $\pi_{a,y}$ of proportions at age $P_{a,y}$ in a given year.

$$\hat{P}_{a,y} = \frac{\hat{C}_{a,y}}{\sum_2^A \hat{C}_{a,y}} \quad \mathbf{15}$$

$$\pi_{a,y} = Prob(age = a|age \geq a) = \frac{\hat{P}_{a,y}}{\sum_a^A \hat{P}_{a,y}}, 2 \leq a \leq A \quad \mathbf{16}$$

$$\hat{X}_{a,y} = \log\left(\frac{\pi_{a,y}}{1 - \pi_{a,y}}\right), 2 \leq a \leq A - 1 \quad \mathbf{17}$$

The observed CRLs $X_{a,y}$ are calculated similarly from the proportions-at-age in the observed catch-at-age data. When the estimated catch-at-age was equal to zero, it was replaced by the minimum value in the observed catch-at-age. The continuation ratio logits are fit using a normal likelihood.

$$X_{a,y} = \hat{X}_{a,y} + \epsilon_{a,y}, \epsilon_{a,y} \sim N(0, \sigma_c) \quad \mathbf{18}$$

The standard deviations for the fit to CRL are estimated separately for age groups 2, 3–4, 5–8, and 9+. The decision was based on the comparison of performance of several models at the assessment framework (Varkey et al. 2022).

Fisheries landings

We applied a censored likelihood for landings time series similar to the application in Cadigan (2016). The censored likelihood approach allows the model to include lower and upper bounds for the landings data and thereby include uncertainty in the landings in the estimation process. LB_y and UB_y indicate the lower and upper bounds on landings for a given year, $L_{obs\ 1:Y}$ indicates the reported landings time series, and L_y indicates the predicted landings for the year. Φ_N is the cumulative distribution function (CDF) for a $N(0,1)$ random variable, σ_L is fixed at 0.02, a small value to ensure that predicted landings are unlikely to be estimated outside the provided bounds (Cadigan 2016).

$$l(L_{obs\ 1:Y}|\theta) = \sum_{y=1}^{Y} log \left\{ \Phi_N \left[\frac{\log\left({UB_y}/{L_y} \right)}{\sigma_L} \right] - \Phi_N \left[\frac{\log\left({LB_y}/{L_y} \right)}{\sigma_L} \right] \right\}, 1 \leq y \leq Y \qquad \textbf{19}$$

At the assessment framework meeting in October 2019, the history of the fishery and associated monitoring programs was presented (Carruthers and Ings pers. comm.) The information presented confirmed that at different periods, the available data on landings could be biased higher or lower. For example, it is uncertain if the catch by foreign fleets were reported accurately before the implementation of the Canadian EEZ. Similarly, there is considerable uncertainty during the period of quota negotiation between Canada and France (1987–89). Although the stock was in moratorium during 1993 to 1996, there is uncertainty about bycatch in these years. Information from interviews with current and retired fish harvesters (Carruthers and Ings pers. comm.) suggested that discarding and depredation could have led to underreporting after the fishery reopened in 1997 to the early 2000s.

The ensuing discussion at the framework meeting (in October 2019) was used to determine agreed upon updated lower and upper bounds for representing current understanding of the uncertainty in the landings. (Table 1, Figure 2).

MODEL DIAGNOSTICS

Similar to the model fits at the previous assessment, model predictions of recruits (age 2 fish) in the RV survey are below the observed indices (Figure B1). The fits to age groups 5 and older is good. The error plots for the RV data show that the model does not show any major year or age effects but does show recent cohort effects (Figure B2). The model fits the younger age indices from the Sentinel line-trawl and Sentinel gillnet surveys more closely than it fits the indices in the RV survey (Figure B3 and B4). The Sentinel line-trawl indices in recent years have shown large increases for the older ages. For example, indices for age 8, 9, and 10 are near the time series high for the index series. The Sentinel gillnet indices also show increase in age 9 and age 10 indices. The model predictions follow the increase, but not to the same levels as the indices. This is noted in the recent increasing trend of the mean line of the standardized residuals plotted against year (Figure B5). The error plots for the Sentinel gillnet series show clear year effects in the early part of the time series (Figure B6); this coincides with the early phase of the Sentinel program which was initiated while the fishery was in a moratorium. When the fishery reopened, there was a TAC of 10, 20, and 30 kt in 1997, 1998, and 1999, respectively. Model fits to the French and GEAC surveys are shown in Figures B7 and B8.

IMPACT OF ADJUSTMENTS IN PROPORTION MATURE-AT-AGE

A computational error was found in the calculation of proportion mature-at-age derived from the DFO-RV data and used in the 2019 assessment. This error was corrected, and updated values were presented at the 2021 assessment.

Differences in estimates of percent mature at age due to the coding error are presented in Figure 3. Most differences were well below 1%, and inconsequential to subsequent analyses. A few notable changes occurred, particularly in ages 4–6, with the new estimates differing from the previous estimates by as much as -6% to +14%. Estimates of SSB based on both the previous and new maturity-at-age numbers suggest no meaningful impact of the coding error on stock size estimates or trends (Figure 4); annual differences ranged from 0 to 2.9%).

MODEL OUTPUTS

Model results indicated that SSB declined from the beginning of the time series in 1959 (234 kt) to values near the Limit Reference Point (LRP) by the mid-1970s (Figure 5; Table 10). Subsequently, SSB increased and was estimated to be above 100 kt over 1981 to 1988, but this period was followed by a continuous decline to less than 40 kt in 1993. The SSB was below the LRP from 1991 to 1994. Following the start of the moratorium (1993), SSB started to increase, but by 1999 had started declining again. From about 2001 to 2006, SSB was relatively stable at values that were just below the LRP. SSB decreased in the mid-2000s, and has been stable at a low level (near 30 kt) since 2009. The SSB estimated for the beginning of year 2021 was 32 kt (95% CI = 24 to 42 kt). This estimate is at the upper end of the range projected at the last assessment (projection 2021 = median 25 kt, range 18 to 35 kt). With an assumed catch of 1,346 t for calendar year 2021, the SSB in the beginning of year 2022 is estimated to be 31.5 kt (48% of the LRP).

Recruitment (Figure 6; Table 11) peaked in 1965–66 at approximately 200 million age 2 fish, then generally declined until the late 1970s when there were about 50 million age 2 cod in the population. During most of the 1980s, recruitment was variable between 70 and 150 million fish. From 1993 onward, recruitment was generally low at values around 25 to 40 million fish with particularly low values (~9 million) during 2016–17. Recruitment levels have increased since, reaching near 25 million in 2021.

The assessment model provides estimates of both fishing mortality (F) and natural mortality (M). The estimated fishing mortality rate for ages five to eight generally increased from 1959 (F=0.23) to the mid-1970s (peaked at 0.41 in 1975) leading up to the extension of jurisdiction in 1977, then declined rapidly to approximately 0.28 and remained at similar values until the mid-1980s (Figure 7; Table 12). Fishing mortality estimates generally increased again until the moratorium in 1993. Average F was near zero (<0.02) during the moratorium (1993–97) when removals were only from bycatch. The estimated fishing average mortality rate for ages 5–8 has generally declined from 0.15 in 2017 to 0.05 in 2020. Ages 5-8 are typically the dominant ages in the fishery, and average F for this age-range is 0.03. However, in 2020, catch-at-age was dominated by age 9+s (~45% by weight) reflecting the dominance of a single year class (2011) in the population and the fishery. F for age 9+ in 2021 is estimated at 0.07.

Generally, M was near 0.33 from 1959 to 1980, then declined to near 0.27 through the early 2000s. M subsequently increased considerably and estimates over the last 10 years (2012 to 2021) have averaged near 0.37, reaching a time series high at 0.41 in 2019 (Figure 8). M in 2021 is estimated to be 0.34.

Retrospective patterns: The model responded to the large increase in Sentinel index for the older ages with an increase in the estimates of catchability parameters for the Sentinel gillnet and line-trawl surveys compared to the estimates from the previous assessments (Figure 9). The catchability parameters for the other surveys did not show much change between the 2020 and the 2021 assessment (Figure 10). The retrospective patterns for the previous two assessments show a positive revision in the SSB estimates. The main cause for the revision is the change in the Sentinel index trends between years. The 2018 Sentinel index which was used in the 2019 assessment had the lowest values in the time series for ages 3, 4, and 5. In 2019, the index values were relatively high for older ages compared to the indices in 2018. Another source of the revision in estimates is the update to the condition-based index of M between the 2019 assessment and subsequent assessments.

MODEL PROJECTIONS

The model is projected forward with the following assumptions:

1. Catch weights-at-age, stock weights-at-age, selectivity, condition-based M indices, and recruitment are the average of respective values from 2019–21.
2. Maturity is the projected maturity for years 2022–24 from the cohort-based maturity model.
3. Catch for 2021 was assumed to be 1,346 t.

Projection of the stock to 2024 was conducted assuming fishery removal scenarios of 0, 0.5, 1.0, 1.5, and 1.75 times an assumed total catch of 1,346 t. An additional projection of 2.3 times was performed at the meeting. Under these scenarios, there is a high probability (>99%) that the stock will remain below B_{lim} between 2022 and the beginning of 2024 (Table 12). Removals of 3,096 t result in a 50% probability and removals of 1,346 t result in a 79% probability of growth in projected SSB from beginning of year 2022 to 2024 (Table 12). At no removals, the probability is 93% (i.e., none of the scenarios result in 95% probability) for positive growth trajectory of the stock from 2022.

SOURCES OF UNCERTAINTY

The 2018 Sentinel line-trawl indices were at time series lows for ages 3 to 5 while the 2019 indices were comparatively much higher for several age groups. The increase in index, especially of older ages in the index led to the revision of the trajectories for several years for these cohorts. Inclusion of the 2019 Sentinel data led to an upward revision of stock status. The review and revision of the 2019 Sentinel indices decreased some of the indices for the older ages. The 2020 Sentinel indices for several of the older ages continue to be high. Although this index covers only a small portion of the stock, it shows good internal consistency and for this reason, the model is sensitive to the Sentinel line-trawl index. Conversely, the DFO-RV survey covers most of the stock area, but in comparison shows lesser internal consistency. The model under-estimates the index for the young ages in the DFO-RV survey in the post-2010 period, mainly because the model fits the younger age indices from the Sentinel line-trawl and Sentinel gillnet surveys more closely than it fits the indices in the RV survey for the younger ages. However, the model fits well to all other ages (6–14+) in the DFO-RV survey and all ages in other surveys plus the catch-at-age. This issue is a source of uncertainty that requires further research.

CONCLUSIONS

The 3Ps cod stock status was assessed using an integrated state space model that includes several surveys of which the DFO-RV and Sentinel gillnet and line-trawl surveys are ongoing. However, there was no DFO-RV survey in spring 2020.Time-varying natural mortality for the stock is modelled to follow trends in an index based on cod condition sampled from both these surveys.

Natural mortality for ages 5–8 has been high over the last decade, averaging 0.37 from 2012 to 2021. In 2021, the estimated natural mortality is 0.34. The estimated fishing mortality rate (ages 5–8) decreased from 0.15 in 2017 to 0.03 in 2021. Natural mortality plays an important role in projections for this stock. If natural mortality rates are appreciably different from those used, projected outcomes will differ from values reported above.

Recruitment estimates (age 2 fish) reached a time series low of approximately 9 million fish over 2016–17 but have been increasing since then. In 2021, recruitment is estimated to be around

25 million fish, equivalent to the average recruitment since 1993 but still well below the time series average of 74 million fish.

Assuming a catch of 1,346 t in 2021, the projected SSB at the beginning of 2022 is 31.5 kt (25.3 kt–39.5 kt), indicating that the stock is in the Critical Zone (48% of the LRP [38–60%]) according to the DFO Precautionary Approach (PA) Framework. Based on model projections, the probability of the stock being below the LRP in 2023 and 2024 is greater than 99.9%, and it has been below the LRP since the early 2000s.

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TABLES

Table 1. Total landings and lower and upper bounds (in tonnes). Lower and upper bounds were determined based on multipliers specified for different time periods in the fishery (Figure 2).

Year	Landings (t)	Lower Bound	Upper Bound
1959	60,170	54,153	78,221
1960	77,285	69,557	100,471
1961	86,824	78,142	112,871
1962	55,239	49,715	718,11
1963	51,821	46,639	67,367
1964	56,567	50,910	73,537
1965	51,853	46,668	67,409
1966	66,207	59,586	86,069
1967	62,774	56,497	81,606
1968	77,556	69,800	100,823
1969	63,799	57,419	82,939
1970	76,858	69,172	99,915
1971	62,448	56,203	81,182
1972	44,213	39,792	57,477
1973	52,641	47,377	68,433
1974	46,712	42,041	60,726
1975	35,373	31,836	45,985
1976	37,133	25,993	48,273
1977	32,245	22,572	41,919
1978	27,221	24,499	35,387
1979	33,006	29,705	42,908
1980	37,568	33,811	48,838
1981	38,892	35,003	50,560
1982	33,902	30,512	44,073
1983	38,451	34,606	49,986
1984	36,950	33,255	48,035
1985	51,367	46,230	66,777
1986	57,990	52,191	75,387
1987	59,204	29,602	88,806
1988	43,382	21,691	65,073
1989	39,540	19,770	59,310
1990	41,405	20,703	62,108
1991	43,589	21,795	65,384
1992	35,895	17,948	53,843
1993	15,216	7,608	22,824
1994	661	654	859
1995	821	813	1,067
1996	1,057	1,046	1,374

Year	Landings (t)	Lower Bound	Upper Bound
1997	9,420	9,326	12,246
1998	20,156	19,955	26,203
1999	27,997	27,717	36,397
2000	25,100	24,849	32,630
2001	16,546	16,380	21,509
2002	15,319	15,166	19,915
2003	15,260	15,108	19,838
2004	14,414	14,270	18,738
2005	14,776	14,628	19,208
2006	13,157	13,026	17,105
2007	12,959	12,829	16,847
2008	11,773	11,655	15,305
2009	9,762	9,664	12,691
2010	8,299	8,216	9,129
2011	6,876	6,807	7,563
2012	5,087	5,036	5,596
2013	4,366	4,322	4,803
2014	6,887	6,818	7,576
2015	6,460	6,395	7,106
2016	7,246	7,173	7,970
2017	6,641	6,574	7,305
2018	4,737	4,690	5,211
2019	3,528	3,493	3,881
2020	2,228	2,206	2,451
2021	1,346	1,333	1,481

Table 2. Numbers-at-age (000s) for the commercial cod fishery in NAFO Subdiv. 3Ps from 1959 to 2020.

Year	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
1959	1,001	13,940	7,525	7,265	4,875	942	1,252	1,260	631	545	44	1
1960	567	5,496	23,704	6,714	3,476	3,484	1,020	827	406	407	283	110
1961	450	5,586	10,357	15,960	3,616	4,680	1,849	1,376	446	265	560	91
1962	1,245	6,749	9,003	4,533	5,715	1,367	791	571	187	140	135	389
1963	961	4,499	7,091	5,275	2,527	3,030	898	292	143	99	107	284
1964	1,906	5,785	5,635	5,179	2,945	1,881	1,891	652	339	329	54	233
1965	2,314	9,636	5,799	3,609	3,254	2,055	1,218	1,033	327	68	122	165
1966	949	13,662	13,065	4,621	5,119	1,586	1,833	1,039	517	389	32	75
1967	2,871	10,913	12,900	6,392	2,349	1,364	604	316	380	95	149	55
1968	1,143	12,602	13,135	5,853	3,572	1,308	549	425	222	111	5	506
1969	774	7,098	11,585	7,178	4,554	1,757	792	717	61	120	67	220
1970	756	8,114	12,916	9,763	6,374	2,456	730	214	178	77	121	181
1971	2,884	6,444	8,574	7,266	8,218	3,131	1,275	541	85	125	62	57
1972	731	4,944	4,591	3,552	4,603	2,636	833	463	205	117	48	45
1973	945	4,707	11,386	4,010	4,022	2,201	2,019	515	172	110	14	29
1974	3,025	8,265	7,080	4,780	2,457	1,625	1,053	490	241	63	42	22
1975	675	3,301	2,557	4,655	5,357	874	778	233	169	51	20	4
1976	443	4,161	7,601	3,178	2,251	796	222	84	47	29	13	3

Year	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
1977	552	7,718	7,976	4,409	1,008	308	276	108	48	57	26	12
1978	216	4,474	5,347	3,004	1,509	513	253	318	77	58	35	17
1979	130	1,669	12,064	4,567	1,839	720	252	49	36	4	3	4
1980	188	1,597	4,846	7,864	3,447	1,080	366	107	77	43	13	41
1981	1,074	3,616	2,745	3,914	5,210	1,663	576	190	142	127	22	6
1982	190	4,447	4,337	1,757	3,063	3,560	672	208	54	16	7	6
1983	754	2,733	9,536	3,008	1,471	1,050	1,256	293	109	49	21	6
1984	359	4,241	4,984	4,852	1,695	533	436	354	47	25	6	2
1985	160	2,839	7,950	5,406	4,994	1,624	606	654	267	98	18	8
1986	1,442	8,677	8,914	9,077	3,822	2,204	832	306	198	78	46	21
1987	375	3,474	3,455	7,380	4,912	1,448	619	423	229	119	79	62
1988	1,104	6,967	4,991	2,056	2,393	1,606	960	528	314	110	57	22
1989	1,241	5,902	6,370	3,463	1,843	1,705	1,239	749	129	109	34	21
1990	425	7,592	5,925	3,873	1,615	756	875	784	333	181	197	84
1991	1,370	3,087	6,052	4,004	1,339	449	206	251	211	177	119	127
1992	278	3,712	2,035	3,156	1,334	401	89	38	52	13	14	5
1993	1	30	152	72	79	41	19	2	2	0	0	0
1994	0	0	39	102	34	26	5	0	0	0	0	0
1995	2	16	19	77	117	38	13	8	1	0	0	0
1996	14	455	1,345	602	769	922	254	113	124	7	13	0
1997	83	298	964	1,605	946	1,512	1,371	233	110	55	16	3
1998	49	677	1,333	2,139	2,479	1,155	901	849	203	127	23	10
1999	23	408	828	1,539	1,573	1,696	589	507	977	133	45	28
2000	76	576	844	1,162	1,172	796	720	269	186	199	25	11
2001	112	591	1,416	1,283	1,009	788	451	372	112	79	81	8
2002	18	363	1,051	2,063	1,278	644	353	277	156	58	46	73
2003	66	144	714	1,826	1,855	665	281	165	82	44	14	18
2004	70	427	634	1,106	1,653	1,236	598	157	114	45	25	6
2005	47	279	927	992	911	1,155	727	324	95	40	24	7
2006	63	279	756	1,122	875	540	575	485	178	54	42	18
2007	9	212	642	1,314	1,069	653	351	329	208	110	27	12
2008	20	131	914	1,037	841	469	223	102	93	66	45	12
2009	8	404	590	1,301	741	399	208	80	24	68	34	9
2010	28	152	922	912	893	362	169	64	27	21	8	6
2011	10	80	202	723	646	398	143	64	22	32	4	9
2012	10	166	458	393	495	361	149	56	22	16	4	7
2013	6	59	785	796	367	564	218	132	28	32	5	2
2014	2	289	298	893	610	262	303	72	32	7	3	0
2015	2	78	912	649	797	385	102	128	38	21	10	2
2016	0	18	262	1,408	512	472	211	74	46	11	19	4
2017	2	27	102	425	1,033	316	111	49	15	5	1	1
2018	7	28	103	431	1,043	312	110	49	15	5	1	1
2019	6	28	69	151	262	595	207	103	54	14	6	4
2020	0	15	261	1,297	518	454	197	61	42	5	16	1

Table 3. CAN-RV survey mean number per tow.

Year	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
1983	10.01	6.52	1.14	3.72	1.62	0.48	0.89	1.61	0.75	0.36	0.14	0.06	0.05
1984	5.40	2.33	1.55	0.63	2.11	0.77	0.37	0.46	0.71	0.18	0.15	0.06	0.03
1985	7.74	14.88	12.57	9.96	3.28	2.66	0.79	0.48	0.42	0.42	0.49	0.21	0.12
1986	6.62	5.65	6.48	7.95	6.33	2.13	1.47	0.84	0.29	0.24	0.29	0.17	0.10
1987	8.48	5.67	4.97	13.82	8.31	3.35	1.29	0.69	0.28	0.23	0.16	0.17	0.16
1988	9.13	5.93	2.96	2.84	6.50	5.84	3.65	1.49	0.84	0.74	0.35	0.16	0.15
1989	6.50	4.66	3.17	1.51	1.16	2.15	1.21	0.67	0.37	0.41	0.13	0.11	0.05
1990	1.48	9.82	14.49	10.89	5.67	3.84	3.14	1.15	0.71	0.32	0.16	0.12	0.09
1991	27.69	5.03	10.00	11.24	5.75	2.84	1.58	1.19	0.74	0.56	0.22	0.11	0.07
1992	1.80	6.95	2.11	4.15	2.03	1.03	0.53	0.26	0.24	0.08	0.04	0.01	0.01
1993	0.00	1.99	4.04	1.49	1.35	0.47	0.10	0.04	0.03	0.04	0.01	0.00	0.01
1994	1.63	1.46	4.31	6.10	1.73	1.62	0.50	0.08	0.04	0.03	0.02	0.01	0.01
1995	0.31	1.16	1.67	13.08	19.65	4.40	5.75	2.19	0.25	0.20	0.01	0.07	0.03
1996	1.08	3.67	3.62	1.32	2.69	2.91	0.54	0.46	0.09	0.09	0.02	0.00	0.00
1997	1.68	2.44	1.01	0.46	0.25	0.26	0.21	0.12	0.04	0.01	0.00	0.00	0.00
1998	1.28	6.28	7.40	4.91	3.53	1.73	2.19	2.43	0.38	0.26	0.06	0.03	0.00
1999	3.05	2.52	2.26	2.41	2.12	1.54	0.39	0.68	0.52	0.07	0.02	0.02	0.01
2000	3.84	6.66	3.52	2.24	1.75	1.11	0.80	0.31	0.28	0.46	0.11	0.00	0.01
2001	2.88	11.44	10.58	3.71	1.74	1.08	0.66	0.60	0.32	0.43	0.80	0.10	0.05
2002	1.53	3.72	7.08	4.95	2.58	1.73	0.85	0.45	0.31	0.07	0.11	0.16	0.01
2003	2.62	2.24	3.67	5.88	3.51	1.34	0.63	0.28	0.16	0.17	0.04	0.09	0.01
2004	2.24	2.50	1.85	1.93	3.49	3.61	1.08	0.68	0.57	0.67	0.13	0.09	0.02
2005	1.63	7.32	7.27	3.49	2.08	1.52	1.20	0.41	0.09	0.15	0.06	0.03	0.03
2007	2.34	5.33	3.26	2.11	1.14	0.76	0.35	0.56	0.37	0.12	0.10	0.07	0.04
2008	4.09	4.30	3.27	1.99	1.22	0.50	0.34	0.12	0.14	0.08	0.04	0.02	0.01
2009	2.47	8.64	5.81	4.91	2.65	1.53	0.84	0.18	0.15	0.18	0.32	0.12	0.01
2010	2.76	7.75	13.95	5.87	3.53	1.27	0.25	0.08	0.03	0.03	0.07	0.01	0.00
2011	4.63	6.37	2.56	5.46	2.04	1.42	0.49	0.09	0.08	0.00	0.02	0.01	0.01
2012	3.99	11.21	6.37	3.34	3.39	1.76	0.94	0.16	0.25	0.01	0.04	0.00	0.01
2013	19.94	12.11	16.14	5.83	4.04	2.72	2.06	0.48	0.24	0.06	0.01	0.00	0.01
2014	5.21	11.03	4.54	2.23	1.11	0.41	0.83	0.42	0.06	0.00	0.01	0.00	0.01
2015	4.90	8.47	10.97	2.87	1.17	0.92	0.31	0.43	0.06	0.01	0.00	0.00	0.00
2016	2.58	5.98	4.62	4.71	2.00	0.69	0.22	0.12	0.14	0.01	0.00	0.00	0.00
2017	3.22	4.34	3.99	3.57	2.62	0.62	0.38	0.09	0.04	0.05	0.00	0.00	0.00
2018	5.40	4.56	2.59	1.73	2.22	2.29	0.23	0.19	0.17	0.13	0.01	0.00	0.00
2019	6.73	6.77	4.32	2.00	1.20	0.90	0.31	0.13	0.04	0.04	0.00	0.01	0.00
2021	9.69	5.15	2.88	1.23	1.04	0.45	0.63	0.35	0.25	0.13	0.03	0.00	0.00

Table 4. Estimated proportion mature at age.

Year	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
1959	0.001	0.004	0.014	0.068	0.194	0.470	0.757	0.914	0.972	0.991	0.997	0.999
1960	0.000	0.003	0.015	0.061	0.180	0.470	0.757	0.914	0.972	0.991	0.997	0.999
1961	0.000	0.000	0.011	0.054	0.227	0.400	0.757	0.914	0.972	0.991	0.997	0.999
1962	0.001	0.001	0.001	0.046	0.174	0.569	0.669	0.914	0.972	0.991	0.997	0.999
1963	0.000	0.004	0.010	0.011	0.173	0.441	0.856	0.860	0.972	0.991	0.997	0.999
1964	0.001	0.003	0.019	0.078	0.110	0.474	0.747	0.964	0.949	0.991	0.997	0.999
1965	0.000	0.005	0.018	0.091	0.413	0.574	0.795	0.917	0.992	0.983	0.997	0.999
1966	0.000	0.003	0.025	0.104	0.349	0.853	0.937	0.944	0.976	0.998	0.994	0.999
1967	0.000	0.001	0.016	0.126	0.428	0.741	0.980	0.994	0.986	0.994	1.000	0.998
1968	0.001	0.000	0.007	0.085	0.444	0.829	0.938	0.997	0.999	0.997	0.998	1.000
1969	0.001	0.004	0.001	0.044	0.342	0.816	0.969	0.988	1.000	1.000	0.999	1.000
1970	0.000	0.007	0.021	0.013	0.240	0.750	0.961	0.995	0.998	1.000	1.000	1.000
1971	0.001	0.001	0.034	0.090	0.129	0.684	0.949	0.993	0.999	1.000	1.000	1.000
1972	0.003	0.005	0.010	0.162	0.317	0.625	0.937	0.992	0.999	1.000	1.000	1.000
1973	0.005	0.014	0.026	0.078	0.510	0.686	0.949	0.990	0.999	1.000	1.000	1.000
1974	0.002	0.020	0.060	0.124	0.420	0.849	0.912	0.995	0.999	1.000	1.000	1.000
1975	0.002	0.009	0.070	0.227	0.432	0.860	0.968	0.980	1.000	1.000	1.000	1.000
1976	0.000	0.007	0.037	0.218	0.575	0.804	0.981	0.994	0.996	1.000	1.000	1.000
1977	0.001	0.001	0.028	0.136	0.508	0.862	0.957	0.998	0.999	0.999	1.000	1.000
1978	0.003	0.003	0.006	0.110	0.392	0.793	0.966	0.992	1.000	1.000	1.000	1.000
1979	0.000	0.011	0.018	0.042	0.345	0.726	0.934	0.992	0.998	1.000	1.000	1.000
1980	0.001	0.000	0.040	0.096	0.244	0.692	0.916	0.981	0.998	1.000	1.000	1.000
1981	0.012	0.005	0.005	0.139	0.388	0.706	0.906	0.978	0.995	1.000	1.000	1.000
1982	0.001	0.034	0.028	0.056	0.385	0.790	0.947	0.976	0.995	0.999	1.000	1.000
1983	0.000	0.006	0.089	0.145	0.420	0.708	0.957	0.992	0.994	0.999	1.000	1.000
1984	0.000	0.001	0.024	0.214	0.505	0.899	0.904	0.993	0.999	0.999	1.000	1.000
1985	0.000	0.001	0.007	0.093	0.433	0.860	0.991	0.973	0.999	1.000	1.000	1.000
1986	0.000	0.002	0.005	0.037	0.299	0.681	0.973	0.999	0.993	1.000	1.000	1.000
1987	0.000	0.001	0.013	0.037	0.178	0.640	0.857	0.995	1.000	0.998	1.000	1.000
1988	0.000	0.000	0.011	0.082	0.223	0.554	0.881	0.944	0.999	1.000	1.000	1.000
1989	0.001	0.002	0.005	0.095	0.372	0.681	0.876	0.969	0.979	1.000	1.000	1.000
1990	0.000	0.006	0.023	0.073	0.493	0.797	0.941	0.976	0.992	0.992	1.000	1.000
1991	0.002	0.003	0.052	0.240	0.540	0.901	0.963	0.992	0.996	0.998	0.997	1.000
1992	0.004	0.016	0.051	0.341	0.807	0.946	0.988	0.994	0.999	0.999	1.000	0.999
1993	0.000	0.021	0.096	0.461	0.831	0.982	0.996	0.999	0.999	1.000	1.000	1.000
1994	0.000	0.003	0.114	0.411	0.932	0.979	0.999	1.000	1.000	1.000	1.000	1.000
1995	0.002	0.006	0.039	0.434	0.821	0.995	0.998	1.000	1.000	1.000	1.000	1.000
1996	0.007	0.015	0.069	0.330	0.821	0.968	1.000	1.000	1.000	1.000	1.000	1.000
1997	0.004	0.034	0.092	0.502	0.856	0.965	0.995	1.000	1.000	1.000	1.000	1.000
1998	0.003	0.022	0.149	0.403	0.931	0.986	0.994	0.999	1.000	1.000	1.000	1.000
1999	0.000	0.016	0.103	0.465	0.818	0.995	0.999	0.999	1.000	1.000	1.000	1.000
2000	0.003	0.004	0.085	0.375	0.812	0.968	1.000	1.000	1.000	1.000	1.000	1.000
2001	0.004	0.025	0.074	0.345	0.758	0.955	0.995	1.000	1.000	1.000	1.000	1.000
2002	0.003	0.026	0.159	0.635	0.751	0.942	0.991	0.999	1.000	1.000	1.000	1.000
2003	0.008	0.019	0.144	0.583	0.974	0.945	0.988	0.998	1.000	1.000	1.000	1.000
2004	0.004	0.044	0.104	0.516	0.911	0.999	0.990	0.998	1.000	1.000	1.000	1.000

Year	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
2005	0.003	0.021	0.213	0.408	0.870	0.987	1.000	0.998	1.000	1.000	1.000	1.000
2006	0.005	0.014	0.105	0.610	0.804	0.977	0.998	1.000	1.000	1.000	1.000	1.000
2007	0.002	0.021	0.064	0.385	0.901	0.960	0.996	1.000	1.000	1.000	1.000	1.000
2008	0.006	0.011	0.086	0.250	0.770	0.981	0.993	0.999	1.000	1.000	1.000	1.000
2009	0.014	0.034	0.069	0.297	0.619	0.947	0.997	0.999	1.000	1.000	1.000	1.000
2010	0.007	0.061	0.169	0.323	0.654	0.888	0.990	0.999	1.000	1.000	1.000	1.000
2011	0.002	0.036	0.233	0.538	0.754	0.894	0.975	0.998	1.000	1.000	1.000	1.000
2012	0.002	0.019	0.170	0.589	0.869	0.951	0.974	0.995	1.000	1.000	1.000	1.000
2013	0.001	0.017	0.138	0.528	0.871	0.974	0.992	0.994	0.999	1.000	1.000	1.000
2014	0.003	0.006	0.109	0.573	0.859	0.969	0.995	0.999	0.999	1.000	1.000	1.000
2015	0.001	0.017	0.057	0.469	0.918	0.971	0.993	0.999	1.000	1.000	1.000	1.000
2016	0.002	0.011	0.084	0.398	0.865	0.989	0.995	0.999	1.000	1.000	1.000	1.000
2017	0.000	0.013	0.074	0.320	0.878	0.979	0.999	0.999	1.000	1.000	1.000	1.000
2018	0.001	0.002	0.089	0.374	0.708	0.988	0.997	1.000	1.000	1.000	1.000	1.000
2019	0.001	0.009	0.026	0.409	0.816	0.926	0.999	1.000	1.000	1.000	1.000	1.000
2020	0.001	0.009	0.063	0.273	0.831	0.970	0.985	1.000	1.000	1.000	1.000	1.000
2021	0.001	0.009	0.063	0.352	0.842	0.972	0.996	0.997	1.000	1.000	1.000	1.000

Table 5. Beginning of the year weights-at-age (stock weights in kg) modeled from the weights-at-age derived from the Canadian RV survey.

Year	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
1959	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1960	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1961	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1962	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1963	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1964	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1965	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1966	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1967	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1968	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1969	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1970	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1971	0.296	0.686	1.250	1.814	2.468	3.186	4.252	5.482	6.763	8.576	10.011	15.049
1972	0.290	0.640	1.144	1.638	2.235	3.052	4.305	5.637	6.836	8.449	9.714	14.674
1973	0.287	0.623	1.096	1.593	2.159	2.755	3.824	5.174	6.441	7.998	9.210	13.975
1974	0.295	0.677	1.183	1.702	2.345	2.970	3.851	5.130	6.583	8.357	9.621	14.462
1975	0.309	0.736	1.370	1.938	2.642	3.391	4.358	5.406	6.815	8.896	10.435	15.495
1976	0.298	0.756	1.458	2.199	2.957	3.762	4.923	6.062	7.142	9.177	11.076	16.639
1977	0.268	0.650	1.336	2.101	3.029	3.813	4.967	6.225	7.294	8.784	10.475	16.491
1978	0.249	0.557	1.079	1.821	2.736	3.686	4.752	5.930	7.089	8.518	9.547	15.458
1979	0.261	0.604	1.076	1.744	2.808	3.920	5.364	6.588	7.799	9.520	10.602	16.204
1980	0.276	0.636	1.180	1.744	2.683	3.983	5.601	7.289	8.481	10.248	11.598	16.900
1981	0.276	0.624	1.137	1.717	2.375	3.340	4.966	6.669	8.256	9.835	11.069	16.036
1982	0.276	0.660	1.190	1.772	2.516	3.203	4.538	6.469	8.259	10.439	11.558	16.422
1983	0.251	0.609	1.159	1.696	2.377	3.120	4.015	5.465	7.436	9.728	11.473	15.961
1984	0.245	0.581	1.117	1.744	2.401	3.118	4.147	5.130	6.669	9.285	11.298	16.356

Year	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
1985	0.232	0.563	1.051	1.665	2.445	3.133	4.138	5.294	6.264	8.338	10.801	16.611
1986	0.219	0.531	1.004	1.544	2.295	3.142	4.104	5.210	6.362	7.715	9.567	16.395
1987	0.222	0.504	0.941	1.471	2.116	2.921	4.067	5.067	6.093	7.624	8.608	15.322
1988	0.225	0.519	0.907	1.411	2.062	2.749	3.859	5.099	6.000	7.414	8.633	14.322
1989	0.225	0.549	0.982	1.423	2.071	2.812	3.828	5.111	6.377	7.711	8.831	14.189
1990	0.200	0.482	0.895	1.311	1.766	2.380	3.306	4.291	5.421	6.984	7.872	12.438
1991	0.206	0.443	0.805	1.249	1.709	2.143	2.974	3.946	4.843	6.313	7.577	11.560
1992	0.243	0.502	0.819	1.259	1.834	2.346	3.054	4.072	5.124	6.488	7.862	12.283
1993	0.242	0.576	0.918	1.248	1.807	2.472	3.310	4.155	5.250	6.802	8.000	12.891
1994	0.219	0.519	0.951	1.237	1.579	2.144	3.077	3.981	4.728	6.160	7.432	12.063
1995	0.223	0.499	0.910	1.382	1.693	2.027	2.884	3.983	4.841	5.911	7.139	11.886
1996	0.231	0.501	0.860	1.312	1.888	2.185	2.759	3.774	4.888	6.107	6.898	11.714
1997	0.249	0.551	0.927	1.333	1.930	2.630	3.206	3.870	4.963	6.596	7.591	12.115
1998	0.255	0.577	1.004	1.406	1.926	2.655	3.813	4.427	5.019	6.608	8.083	12.568
1999	0.272	0.595	1.065	1.536	2.048	2.675	3.872	5.278	5.770	6.717	8.125	13.177
2000	0.274	0.587	1.005	1.480	2.028	2.581	3.533	4.851	6.255	7.033	7.544	12.621
2001	0.271	0.596	1.000	1.413	1.978	2.588	3.441	4.446	5.764	7.620	7.886	11.979
2002	0.255	0.601	1.045	1.442	1.928	2.562	3.475	4.338	5.293	7.026	8.540	11.671
2003	0.244	0.564	1.050	1.500	1.956	2.474	3.408	4.345	5.141	6.439	7.874	11.714
2004	0.261	0.563	1.029	1.596	2.162	2.672	3.525	4.582	5.564	6.764	7.803	12.324
2005	0.268	0.601	1.026	1.565	2.299	2.961	3.850	4.830	6.020	7.503	8.397	13.026
2006	0.252	0.572	1.017	1.442	2.089	2.920	3.965	4.889	5.867	7.478	8.602	12.878
2007	0.227	0.540	0.968	1.437	1.934	2.665	3.937	5.059	5.962	7.307	8.603	12.865
2008	0.200	0.467	0.866	1.298	1.819	2.313	3.348	4.649	5.716	6.888	7.814	12.034
2009	0.221	0.467	0.844	1.328	1.872	2.472	3.297	4.473	5.929	7.401	8.210	12.294
2010	0.235	0.520	0.849	1.301	1.928	2.565	3.559	4.461	5.802	7.823	8.995	12.889
2011	0.244	0.504	0.854	1.160	1.666	2.331	3.267	4.273	5.159	6.848	8.537	12.422
2012	0.250	0.537	0.850	1.208	1.543	2.107	3.113	4.119	5.197	6.401	7.845	12.458
2013	0.208	0.515	0.846	1.111	1.491	1.822	2.635	3.686	4.716	6.082	6.928	11.624
2014	0.211	0.459	0.876	1.204	1.505	1.939	2.510	3.433	4.624	6.024	7.159	11.502
2015	0.209	0.469	0.776	1.249	1.634	1.956	2.667	3.268	4.294	5.896	7.079	11.468
2016	0.199	0.451	0.767	1.072	1.650	2.073	2.636	3.400	3.996	5.362	6.792	11.200
2017	0.204	0.430	0.735	1.060	1.423	2.103	2.807	3.366	4.155	4.992	6.179	10.885
2018	0.217	0.468	0.749	1.089	1.514	1.949	3.058	3.826	4.373	5.512	6.092	10.936
2019	0.209	0.459	0.748	1.008	1.418	1.893	2.591	3.821	4.583	5.371	6.245	10.230
2020	0.213	0.495	0.835	1.150	1.500	2.011	2.833	3.620	5.077	6.206	6.683	10.602
2021	0.209	0.503	0.909	1.278	1.701	2.103	2.981	3.919	4.764	6.815	7.659	11.024

Table 6. ERHAPS survey mean number per tow.

Year	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
1978	0.62	1.32	2.6	1.73	1.01	0.75	0.44	0.25	0.19	0.02	0.03	0.01	0.03
1979	0.46	0.41	2.21	7.73	3.47	1.93	1.02	0.4	0.23	0.31	0.1	0.11	0.23
1980	5.47	1.27	0.37	1.98	3.35	1.23	0.5	0.21	0.16	0.13	0.08	0.08	0.13
1981	0.14	3.78	3.81	3.96	5.74	4.35	1.23	0.92	0.36	0.12	0.11	0.05	0.1
1982	9.21	1.5	6.38	6.12	4.65	3.49	4.07	1.21	0.67	0.32	0.12	0.16	0.08
1983	8.31	4.16	2.29	5.55	4.7	3.5	2.13	1.6	0.58	0.19	0.15	0.06	0.05
1984	9.43	6.22	12.27	7.12	15.45	4.55	1.73	2.52	1.8	0.5	0.13	0.11	0.1
1985	4.38	11.56	5.96	3.14	0.85	1.56	0.91	0.62	0.69	0.87	1.05	0.1	0.18
1986	6.93	4.03	14.55	25.35	20.74	8.73	6.67	3.69	0.76	0.56	0.69	0.21	0.31
1987	16.29	9.09	2.24	6.56	9.87	6.57	2.33	1.53	0.75	0.16	0.28	0.12	0.23
1988	11.69	11.71	7.25	2.85	5.14	3.69	1.26	0.61	0.28	0.28	0.13	0.12	0.26
1989	18.89	12.25	6.27	4.44	2.66	3.39	1.55	0.77	0.21	0.1	0.05	0.05	0.06
1990	2.39	18.26	20.11	7.66	2.46	0.73	1.00	0.44	0.26	0.11	0.09	0.03	0.06
1991	12.14	7.08	12.96	12.68	7.56	2.42	1.07	0.91	0.62	0.06	0.15	0.03	0.03

Table 7. GEAC survey mean number per tow.

Year	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
1998	0.06	0.4	1.76	2.32	1.81	0.35	1.64	3.4	0.4	0.04	0.13	0.22	0.04
1999	0.34	1.14	1.71	2.83	3.58	3.27	0.51	1.43	1.36	0.17	0.1	0.02	0
2000	1.64	7.24	2.86	3.35	5.18	5.89	3.99	1.14	5.83	7.14	0.79	0.11	0.17
2001	0.21	12.47	26.74	3.75	2.14	1.62	1.34	0.96	0.1	0.44	0.58	0.08	0.1
2002	0	1.26	16.88	18.47	2.9	1.39	1.18	0.91	0.46	0.09	0.27	0.3	0
2003	0.22	0.41	2.46	8.34	9.28	1.32	0.73	1.32	0.48	0.24	0	0.16	0.18
2004	0.08	0.68	0.8	1.07	2.98	1.18	0.15	0.12	0.18	0.13	0.05	0	0.2
2005	0.05	1.74	1.15	0.43	0.31	0.74	0.5	0.08	0.04	0.09	0.04	0	0

Table 8. Sentinel GN standardized catch rate indices at age.

Year	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10
1995	0.019	0.078	4.088	8.867	5.387	2.517	0.380	0.147
1996	0.021	0.285	2.740	12.574	10.269	2.936	0.876	0.067
1997	0.014	0.248	5.336	5.311	9.463	7.657	1.129	0.630
1998	0.003	0.059	1.123	7.738	3.481	2.737	1.691	0.315
1999	0.000	0.007	0.828	1.328	1.969	0.709	0.231	0.216
2000	0.011	0.028	0.313	0.748	0.741	1.015	0.338	0.114
2001	0.023	0.166	0.429	0.925	0.721	0.405	0.391	0.184
2002	0.004	0.039	0.530	0.847	0.808	0.348	0.162	0.182
2003	0.026	0.074	0.248	1.075	0.518	0.183	0.096	0.035
2004	0.004	0.045	0.238	0.881	0.873	0.422	0.152	0.029

Year	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10
2005	0.000	0.027	0.140	0.575	0.670	0.394	0.299	0.053
2006	0.004	0.053	0.307	0.593	0.515	0.583	0.254	0.145
2007	0.003	0.060	0.417	1.063	0.745	0.398	0.275	0.189
2008	0.000	0.095	0.270	1.053	0.878	0.442	0.216	0.092
2009	0.019	0.019	0.267	0.652	1.160	0.228	0.180	0.058
2010	0.010	0.062	0.369	0.796	0.675	0.344	0.114	0.179
2011	0.007	0.007	0.110	0.349	0.637	0.256	0.203	0.021
2012	0.007	0.046	0.159	0.551	0.590	0.452	0.145	0.085
2013	0.134	0.074	0.520	1.131	0.477	0.529	0.321	0.022
2014	0.004	0.042	0.491	0.533	0.338	0.550	0.258	0.118
2015	0.004	0.071	0.109	0.569	0.472	0.187	0.172	0.071
2016	0.000	0.004	0.307	0.405	0.462	0.348	0.307	0.082
2017	0.000	0.111	0.298	0.978	0.439	0.762	0.197	0.086
2018	0.000	0.035	0.157	0.483	1.550	0.506	0.292	0.077
2019	0.003	0.006	0.083	0.415	0.566	1.409	0.305	0.291
2020	0.006	0.038	0.470	0.457	0.379	0.291	0.720	0.204

Table 9. Sentinel LT standardized catch rate indices at age.

Year	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10
1995	0.008	0.015	0.051	0.074	0.020	0.018	0.004	0.001
1996	0.008	0.029	0.029	0.046	0.049	0.014	0.008	0.002
1997	0.006	0.023	0.025	0.016	0.017	0.024	0.003	0.002
1998	0.008	0.018	0.023	0.017	0.006	0.010	0.013	0.002
1999	0.008	0.020	0.027	0.016	0.008	0.005	0.005	0.002
2000	0.013	0.029	0.027	0.018	0.008	0.007	0.002	0.001
2001	0.019	0.034	0.025	0.015	0.008	0.005	0.003	0.001
2002	0.015	0.031	0.028	0.010	0.006	0.002	0.001	0.001
2003	0.003	0.038	0.043	0.022	0.009	0.004	0.001	0.001
2004	0.010	0.010	0.039	0.021	0.011	0.004	0.002	0.000

Year	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10
2005	0.008	0.022	0.014	0.014	0.012	0.005	0.002	0.001
2006	0.010	0.019	0.029	0.021	0.014	0.013	0.004	0.002
2007	0.011	0.020	0.017	0.015	0.009	0.006	0.005	0.002
2008	0.006	0.029	0.024	0.020	0.010	0.008	0.003	0.003
2009	0.007	0.016	0.028	0.016	0.006	0.004	0.002	0.001
2010	0.004	0.018	0.013	0.015	0.007	0.002	0.001	0.000
2011	0.010	0.015	0.021	0.019	0.012	0.004	0.002	0.000
2012	0.009	0.017	0.016	0.015	0.014	0.005	0.002	0.000
2013	0.003	0.014	0.017	0.010	0.006	0.005	0.002	0.001
2014	0.004	0.005	0.015	0.014	0.006	0.007	0.003	0.001
2015	0.001	0.010	0.010	0.012	0.011	0.004	0.004	0.002
2016	0.002	0.006	0.016	0.011	0.011	0.007	0.001	0.002
2017	0.001	0.008	0.014	0.016	0.008	0.007	0.004	0.002
2018	0.000	0.004	0.008	0.013	0.010	0.006	0.004	0.002
2019	0.002	0.008	0.008	0.016	0.019	0.015	0.004	0.001
2020	0.003	0.008	0.018	0.023	0.017	0.018	0.011	0.005

Table 10. Condition-based index of natural mortality (M_c) used to scale M within the HYBRID model.

Year	Condition-based index of M
1978	0.444
1979	0.431
1980	0.422
1981	0.352
1982	0.341
1983	0.341
1984	0.277
1985	0.258
1986	0.239
1987	0.211
1988	0.228
1989	0.231
1990	0.244
1991	0.275
1992	0.291
1993	0.302
1994	0.384
1995	0.308
1996	0.230

Year	Condition-based index of M
1997	0.205
1998	0.186
1999	0.165
2000	0.200
2001	0.258
2002	0.236
2003	0.202
2004	0.171
2005	0.187
2006	0.237
2007	0.210
2008	0.273
2009	0.413
2010	0.425
2011	0.347
2012	0.429
2013	0.518
2014	0.508
2015	0.494
2016	0.611
2017	0.482
2018	0.415
2019	0.537
2020	0.476

Table 11. Spawning stock biomass (in thousand tonnes).

Year	SSB	Low	High
1959	233.7	163.6	333.8
1960	222.5	156.9	315.6
1961	222.6	160.3	309.1
1962	212.0	149.2	301.2
1963	194.0	136.0	276.6
1964	176.9	125.8	248.8
1965	170.2	124.2	233.4
1966	160.9	120.8	214.3
1967	149.2	115.3	193.3
1968	159.9	128.5	199.0
1969	146.1	117.2	182.2
1970	131.9	105.7	164.7
1971	124.6	97.8	158.8
1972	111.6	89.5	139.2
1973	90.7	71.9	114.3
1974	83.9	65.2	107.8
1975	92.0	66.2	127.8
1976	84.7	59.0	121.5
1977	80.0	58.3	109.9
1978	70.8	55.0	91.1
1979	79.7	65.5	96.9
1980	98.8	82.9	117.8
1981	112.2	94.3	133.4
1982	124.9	103.3	150.9
1983	111.7	94.2	132.4
1984	121.6	102.3	144.5
1985	129.7	109.4	153.9
1986	124.1	103.5	148.8
1987	114.6	95.2	137.8
1988	101.7	83.8	123.3
1989	92.0	75.7	111.9
1990	73.0	60.7	87.9
1991	63.8	53.4	76.2
1992	51.0	41.0	63.3
1993	37.7	31.9	44.6
1994	42.3	34.2	52.3
1995	75.1	60.2	93.7
1996	70.6	58.8	84.7
1997	75.9	64.4	89.5
1998	86.4	74.8	99.9
1999	79.8	65.5	97.1

Year	SSB	Low	High
2000	65.2	57.0	74.5
2001	50.9	41.6	62.2
2002	50.2	41.9	60.0
2003	52.1	45.9	59.2
2004	53.4	46.8	60.8
2005	52.0	46.2	58.5
2006	50.9	45.3	57.2
2007	45.1	40.2	50.7
2008	36.7	32.6	41.3
2009	31.6	28.0	35.5
2010	27.4	24.2	31.0
2011	27.0	23.7	30.9
2012	27.1	23.4	31.4
2013	25.3	21.8	29.3
2014	27.8	24.0	32.3
2015	27.1	23.1	31.7
2016	28.3	24.2	33.1
2017	30.6	26.1	35.8
2018	31.6	26.7	37.4
2019	30.1	25.2	36.0
2020	32.6	26.2	40.6
2021	31.7	24.2	41.5
2022	31.5	25.4	39.6

Table 12. Model estimated Numbers-at-age (in millions), 1959–2021.

Year	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Age11	Age12	Age13	Age14+
1959	137.77	108.45	188.22	50.90	45.45	33.30	6.71	9.04	6.91	6.96	3.73	0.59	0.01
1960	129.41	104.73	77.87	128.90	33.84	23.55	18.56	4.40	4.97	3.61	4.23	1.90	0.37
1961	128.28	94.47	82.12	51.50	74.81	17.25	16.26	9.25	2.79	2.67	1.96	2.82	1.18
1962	136.13	93.28	72.95	59.37	31.20	39.58	10.02	7.15	4.70	1.47	1.40	1.07	2.41
1963	171.93	95.36	63.57	50.20	35.37	17.95	20.81	6.60	3.46	2.51	0.81	0.80	2.06
1964	200.64	132.10	63.82	39.27	30.53	17.97	10.46	10.28	4.63	1.80	1.52	0.45	1.62
1965	211.32	156.12	95.02	38.02	23.55	15.32	10.19	5.83	4.54	3.03	0.85	0.81	1.09
1966	204.65	154.35	114.70	61.26	20.54	15.65	6.18	5.25	3.20	1.83	2.07	0.42	0.93
1967	166.78	164.14	118.52	72.94	34.59	11.50	7.34	2.97	2.42	1.57	0.67	1.31	0.71
1968	134.02	126.28	122.40	82.10	37.01	17.06	6.19	3.89	1.54	1.27	0.76	0.26	1.66
1969	106.30	94.35	94.52	78.97	42.91	19.51	7.56	2.95	2.11	0.71	0.64	0.36	0.97
1970	113.07	71.85	65.65	62.96	45.20	22.22	9.15	3.32	1.21	0.92	0.33	0.29	0.56
1971	95.01	92.34	48.17	39.46	31.38	24.23	9.83	4.02	1.70	0.57	0.45	0.17	0.36
1972	79.95	71.32	68.13	28.47	19.95	16.54	10.86	4.16	1.77	0.83	0.28	0.21	0.24
1973	97.24	52.56	52.10	45.81	14.84	10.66	6.57	4.94	1.87	0.76	0.40	0.13	0.21
1974	101.60	77.35	32.95	34.64	22.66	7.17	4.88	2.84	2.00	0.80	0.32	0.17	0.17

Year	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Age11	Age12	Age13	Age14+
1975	91.95	75.32	55.03	17.10	18.61	13.84	2.88	2.00	1.15	0.82	0.33	0.14	0.16
1976	86.01	68.57	55.46	36.12	11.62	7.75	4.52	1.21	0.82	0.50	0.35	0.15	0.15
1977	54.53	74.64	52.45	37.26	19.94	5.23	2.53	2.59	0.67	0.46	0.30	0.21	0.18
1978	37.54	40.08	66.25	34.34	17.62	7.96	2.65	1.61	1.53	0.36	0.28	0.17	0.26
1979	46.75	24.09	31.86	57.97	22.63	9.33	4.34	1.49	0.91	0.74	0.20	0.16	0.30
1980	73.75	36.05	17.97	24.81	36.75	13.58	5.23	2.30	0.92	0.60	0.38	0.13	0.34
1981	57.51	67.00	30.51	13.83	17.60	21.77	7.10	3.16	1.36	0.58	0.40	0.20	0.29
1982	102.48	41.91	57.84	22.12	8.68	11.17	15.32	3.91	1.85	0.82	0.36	0.24	0.30
1983	126.65	79.45	33.85	44.93	14.08	5.87	5.57	7.88	2.44	1.09	0.50	0.23	0.33
1984	129.96	88.73	60.38	28.02	26.91	9.11	3.56	3.43	4.12	1.47	0.65	0.30	0.38
1985	105.37	98.29	70.60	43.57	19.60	16.28	5.87	2.37	2.37	2.31	1.11	0.43	0.50
1986	120.02	68.24	74.84	49.42	34.18	12.85	9.07	3.60	1.59	1.42	1.26	0.66	0.63
1987	137.62	81.63	40.26	47.87	32.47	19.85	6.71	4.65	2.10	0.98	0.84	0.72	0.81
1988	150.58	91.58	52.72	22.04	29.44	18.22	7.80	3.34	2.36	1.13	0.60	0.46	0.79
1989	138.26	108.08	60.86	30.88	11.22	11.85	7.57	4.16	1.73	1.24	0.54	0.33	0.61
1990	78.32	106.15	75.39	36.30	14.24	6.08	6.17	3.79	2.07	0.83	0.62	0.25	0.50
1991	101.20	49.01	69.95	39.71	16.29	5.49	2.68	3.15	1.76	0.89	0.39	0.30	0.37
1992	58.55	74.63	27.38	34.86	15.55	4.65	1.38	0.93	0.85	0.42	0.23	0.09	0.21
1993	29.01	46.36	50.08	13.27	13.25	4.68	1.37	0.35	0.14	0.13	0.06	0.04	0.04
1994	36.51	19.35	39.43	36.60	7.85	5.91	1.80	0.60	0.16	0.06	0.05	0.02	0.03
1995	33.30	30.74	12.85	30.12	30.87	7.28	4.59	1.30	0.28	0.12	0.03	0.03	0.03
1996	29.05	29.54	31.51	10.42	15.86	16.32	3.96	2.18	0.76	0.19	0.10	0.02	0.03
1997	26.81	21.02	22.09	26.14	7.76	8.64	8.18	2.28	1.18	0.52	0.12	0.07	0.03
1998	27.83	19.91	16.32	15.12	13.73	5.25	6.17	5.68	1.39	0.67	0.31	0.09	0.05
1999	38.10	20.69	12.92	12.56	9.77	8.35	3.27	2.80	2.93	0.71	0.32	0.14	0.07
2000	42.98	31.24	15.36	9.18	7.74	5.31	4.51	1.61	1.36	2.00	0.35	0.13	0.10
2001	32.91	35.28	25.40	10.68	6.42	4.45	2.57	1.99	0.70	0.72	0.96	0.15	0.11
2002	21.26	26.35	22.93	16.86	6.88	3.66	2.18	1.13	0.91	0.32	0.36	0.44	0.09
2003	26.96	13.13	17.68	14.49	11.25	4.33	1.81	0.95	0.55	0.43	0.14	0.17	0.24
2004	28.17	21.52	9.63	10.23	10.06	6.96	2.32	0.90	0.46	0.31	0.19	0.07	0.20
2005	27.80	22.21	15.63	7.42	6.08	6.19	3.71	1.46	0.47	0.29	0.16	0.09	0.14
2006	30.82	21.81	15.55	11.40	5.71	3.72	3.83	2.13	0.85	0.26	0.15	0.08	0.11
2007	24.40	25.62	14.78	10.55	6.86	3.59	1.92	2.09	1.17	0.47	0.14	0.08	0.10
2008	25.60	16.50	18.69	9.47	7.27	4.03	2.05	1.01	1.01	0.57	0.25	0.07	0.09
2009	20.70	20.84	11.72	12.91	6.59	3.82	1.80	0.86	0.44	0.42	0.26	0.12	0.08
2010	26.54	13.16	16.56	8.57	7.94	3.24	1.44	0.59	0.32	0.15	0.16	0.10	0.07
2011	28.47	21.52	8.51	11.94	6.20	4.17	1.47	0.63	0.22	0.12	0.06	0.06	0.07
2012	21.93	23.23	15.18	5.67	7.20	4.16	2.02	0.66	0.28	0.09	0.06	0.02	0.06
2013	23.72	14.33	17.63	11.04	4.38	4.01	2.23	0.92	0.27	0.13	0.05	0.02	0.04
2014	14.54	19.38	9.09	13.02	6.86	2.36	2.55	1.06	0.41	0.10	0.06	0.02	0.03
2015	11.78	9.27	17.61	6.78	8.17	3.93	1.33	1.25	0.39	0.15	0.04	0.02	0.02
2016	9.40	8.34	7.16	16.55	5.83	4.97	2.16	0.72	0.56	0.13	0.07	0.02	0.02

Year	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Age11	Age12	Age13	Age14+
2017	9.88	6.14	6.63	6.77	14.02	3.67	2.46	1.05	0.34	0.18	0.04	0.03	0.01
2018	14.94	6.20	5.10	4.57	5.75	9.49	2.57	1.07	0.50	0.15	0.07	0.02	0.02
2019	17.43	11.59	5.18	4.08	3.64	3.87	6.05	1.77	0.68	0.27	0.07	0.04	0.02
2020	20.78	12.24	8.39	3.97	3.56	2.61	2.34	4.35	1.07	0.38	0.14	0.04	0.03
2021	24.54	15.38	9.00	6.03	2.93	2.23	1.67	1.41	2.41	0.63	0.22	0.08	0.04

Table 13. Model estimated Average fishing (F), natural (M), and total (Z) mortality (ages 5 to 8).

Year	Average F	Average M	Average Z
1959	0.23	0.33	0.57
1960	0.24	0.32	0.56
1961	0.26	0.34	0.60
1962	0.25	0.33	0.58
1963	0.25	0.33	0.58
1964	0.28	0.33	0.61
1965	0.29	0.33	0.63
1966	0.30	0.32	0.62
1967	0.28	0.32	0.60
1968	0.30	0.32	0.63
1969	0.33	0.33	0.66
1970	0.33	0.33	0.66
1971	0.36	0.33	0.69
1972	0.37	0.33	0.71
1973	0.35	0.32	0.67
1974	0.36	0.33	0.69
1975	0.41	0.34	0.75
1976	0.29	0.32	0.61
1977	0.27	0.32	0.59
1978	0.28	0.34	0.61
1979	0.25	0.33	0.58
1980	0.28	0.35	0.62
1981	0.29	0.32	0.62
1982	0.27	0.32	0.59
1983	0.26	0.31	0.57
1984	0.26	0.30	0.56
1985	0.29	0.29	0.58
1986	0.31	0.29	0.60
1987	0.36	0.28	0.64
1988	0.39	0.28	0.67
1989	0.37	0.29	0.66
1990	0.37	0.29	0.66
1991	0.43	0.30	0.73
1992	0.46	0.30	0.76

Year	Average F	Average M	Average Z
1993	0.39	0.30	0.69
1994	0.01	0.31	0.32
1995	0.01	0.31	0.31
1996	0.01	0.28	0.29
1997	0.09	0.28	0.37
1998	0.21	0.27	0.48
1999	0.30	0.27	0.57
2000	0.30	0.28	0.58
2001	0.25	0.29	0.54
2002	0.22	0.29	0.52
2003	0.21	0.28	0.50
2004	0.23	0.27	0.50
2005	0.27	0.27	0.55
2006	0.21	0.29	0.50
2007	0.19	0.28	0.48
2008	0.22	0.30	0.51
2009	0.22	0.33	0.56
2010	0.20	0.34	0.55
2011	0.18	0.31	0.50
2012	0.15	0.35	0.50
2013	0.12	0.36	0.48
2014	0.14	0.36	0.50
2015	0.15	0.37	0.52
2016	0.14	0.38	0.52
2017	0.15	0.38	0.52
2018	0.11	0.35	0.46
2019	0.09	0.41	0.50
2020	0.05	0.37	0.42
2021	0.03	0.34	0.37

Table 14. Risk of projected SSB being below the LRP under 6 scenarios of catch removals (catch multiplier = 1 is assumed catch of 1,346 t) over 2022–24. B_y represents SSB in projection year.

Catch Multiplier	Projected Catch (t)	Probability of growing out of the critical zone P(B_y>LRP)		Probability of growth from current levels P(By>projected B2022)	
		2023	**2024**	**2023**	**2024**
2.3	3,096	<0.1%	<0.1%	40%	50%
1.75	2,356	<0.1%	<0.1%	51%	63%
1.5	2,019	<0.1%	<0.1%	57%	69%
1	1,346	<0.1%	<0.1%	68%	79%
0.5	673	<0.1%	<0.1%	78%	87%
0.001	1	<0.1%	<0.1%	84%	93%

FIGURES

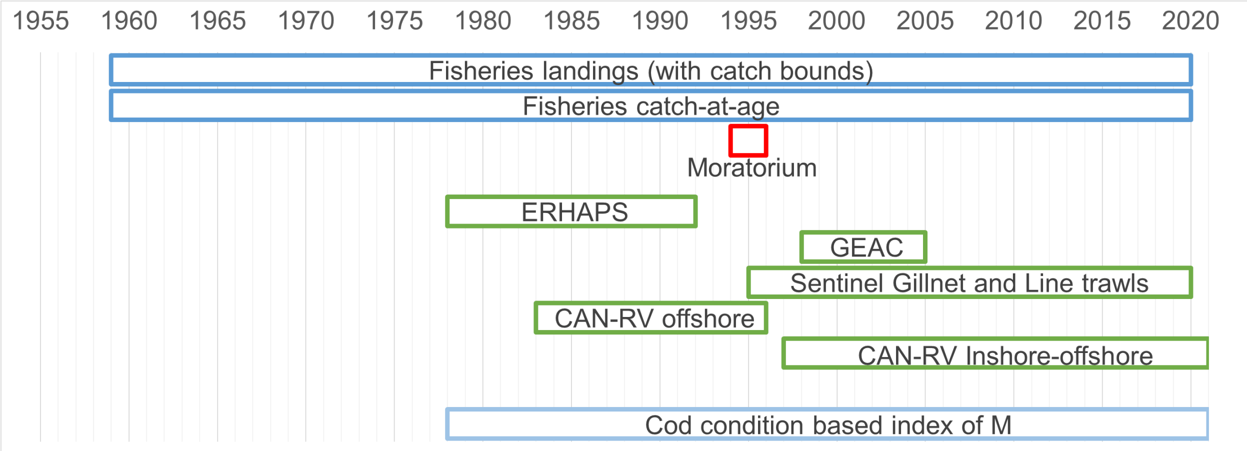

Figure 1. Time-line of data inputs for the assessment.

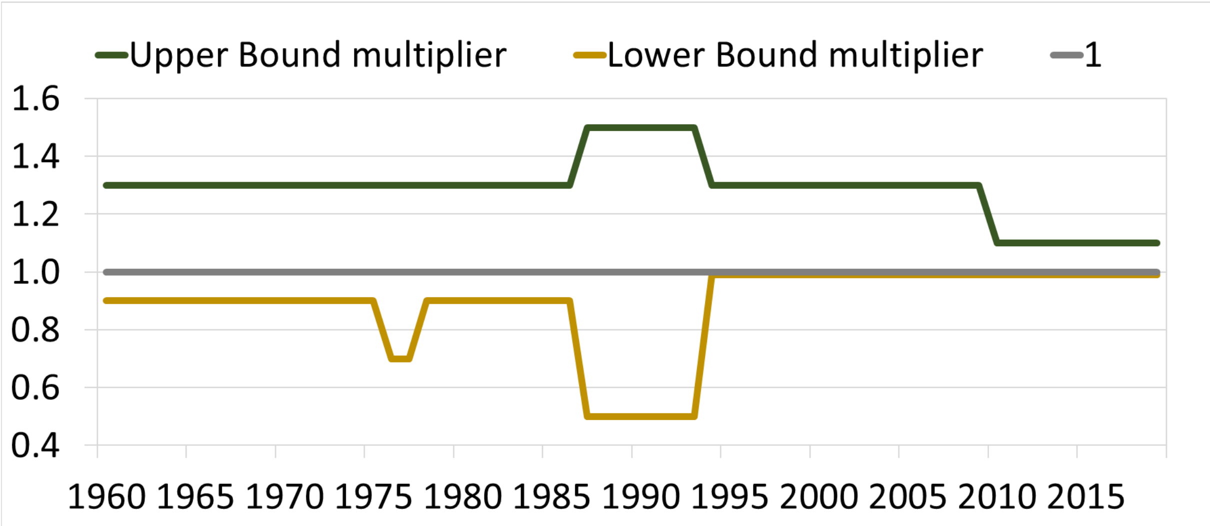

Figure 2. Landings bounds decided at the Framework meeting for 3Ps cod in October 2019.

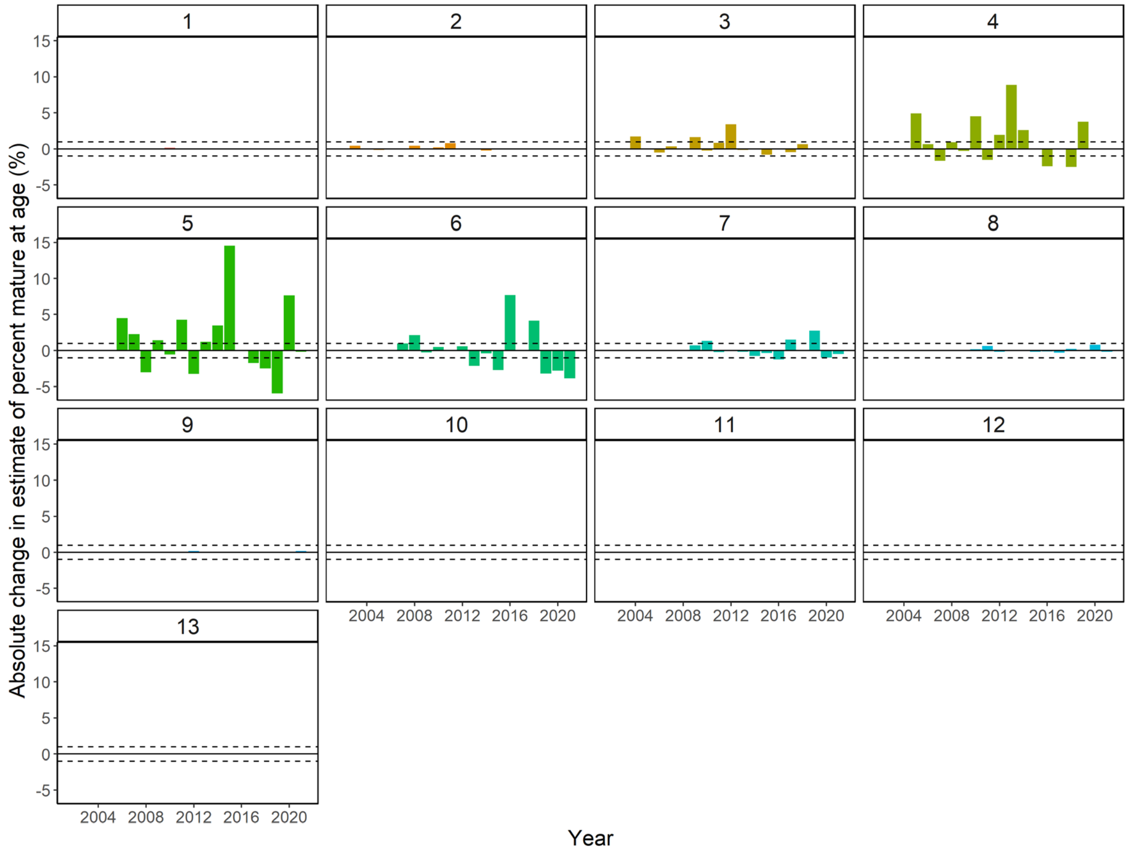

Figure 3. Differences in the absolute estimates of proportion mature at age following the identification of a coding error for values used in the previous assessment of this stock. Dashed lines indicate a change of +/-1%. There were no differences in values prior to 2002.

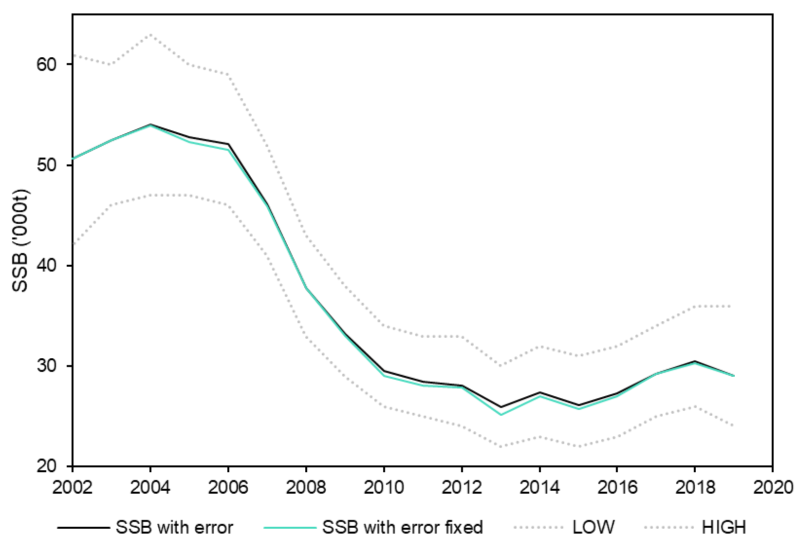

Figure 4. Comparison of SSB from the 2020 assessment (blue line) with SSB recalculated with the revised values for proportion mature (pmat). There were no differences in pmat prior to 2002. LOW and HIGH indicate confidence intervals in SSB estimates from the earlier assessment.

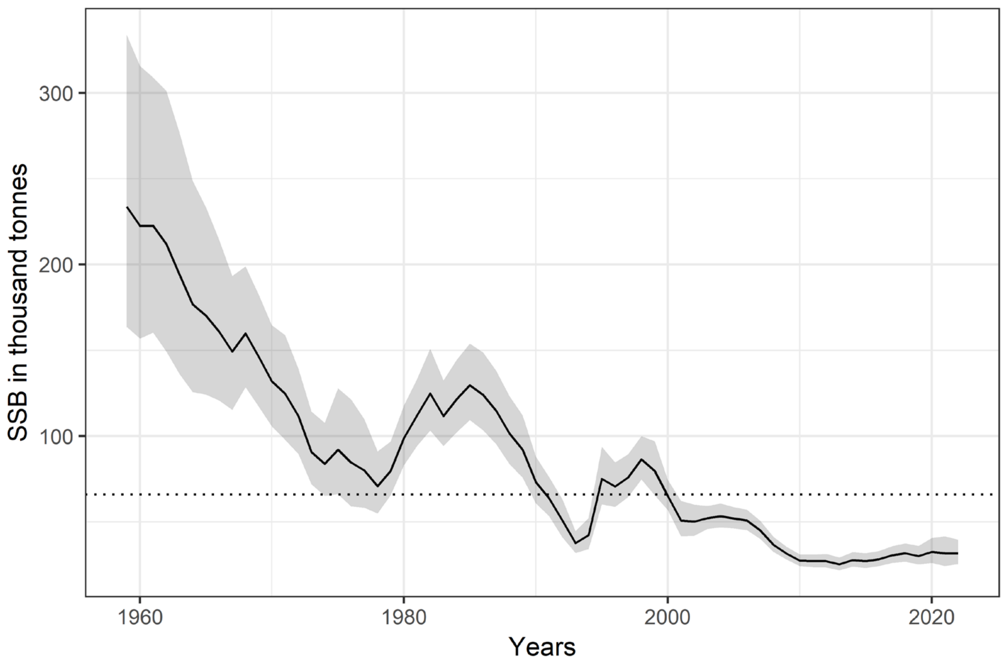

Figure 5. Estimates of SSB (median estimate with 95% confidence interval) for the period 1959 to 2022. Dashed line indicates B_{lim} This reference point represents the boundary between the Critical and Cautious Zones of DFO's Precautionary Approach framework.

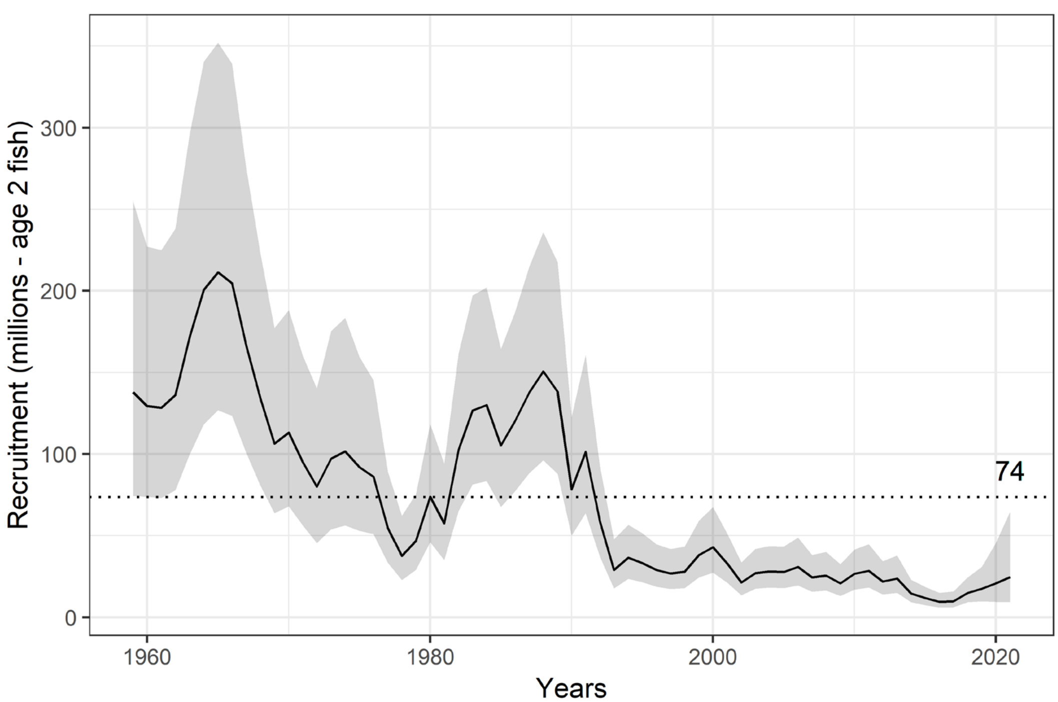

Figure 6. Estimates of recruitment for the period 1959 to 2021.The dotted line represents the time-series average of 74 million fish.

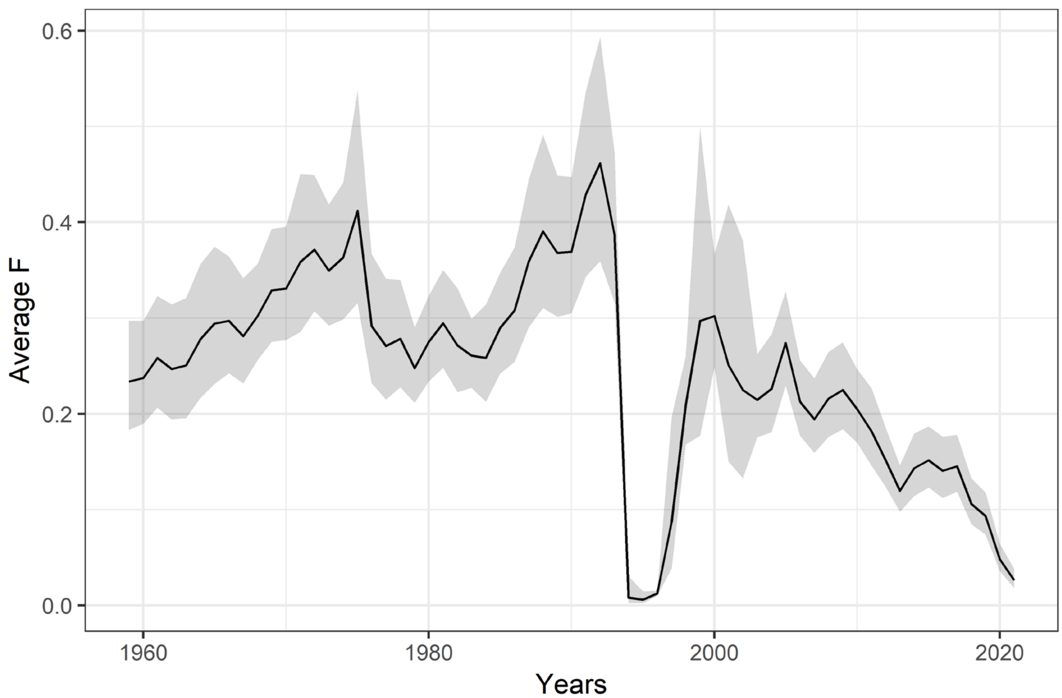

Figure 7. Average F (ages 5 to 9) estimates for 3Ps cod between 1959 and 2021.

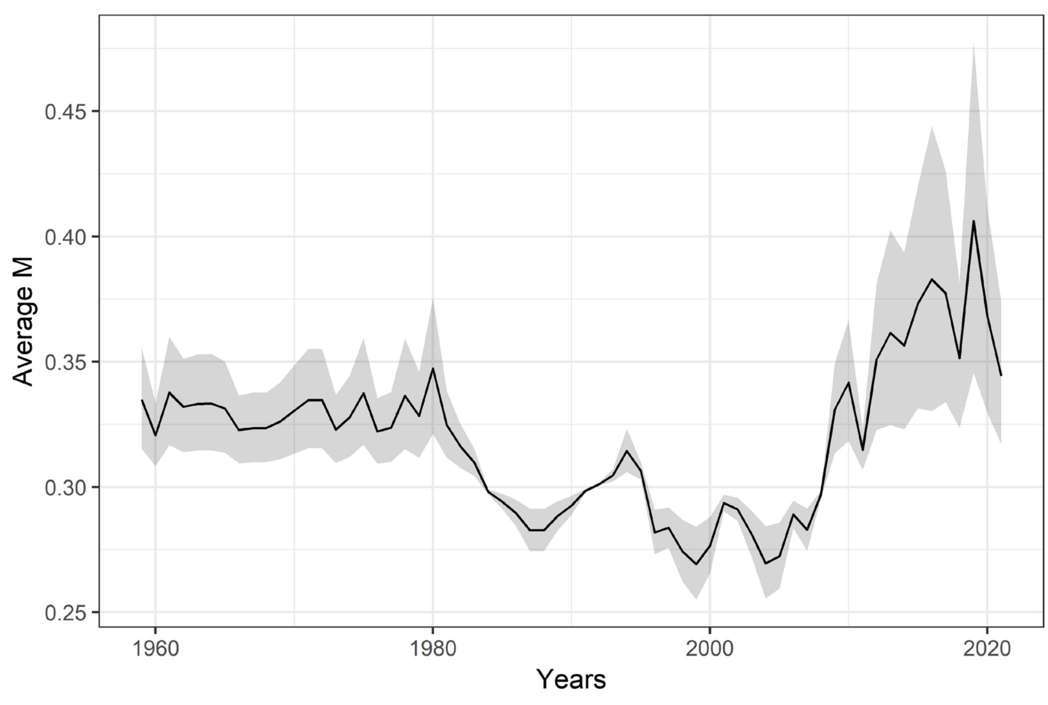

Figure 8. Natural mortality (Average M, ages 5 to 9) of 3Ps cod between 1959 and 2021. M is set at a base level of M=0.3 and scaled within the model based on the index of condition shown in Table 7.

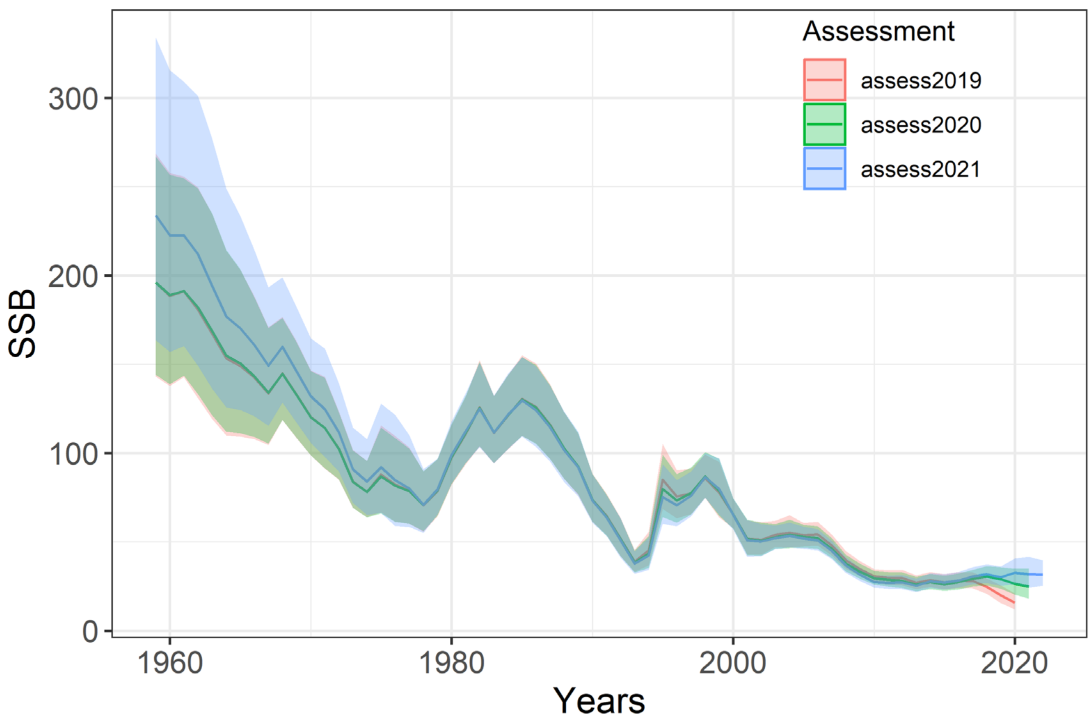

Figure 9. Assessment retro for Spawning Stock Biomass (SSB in thousand tonnes)

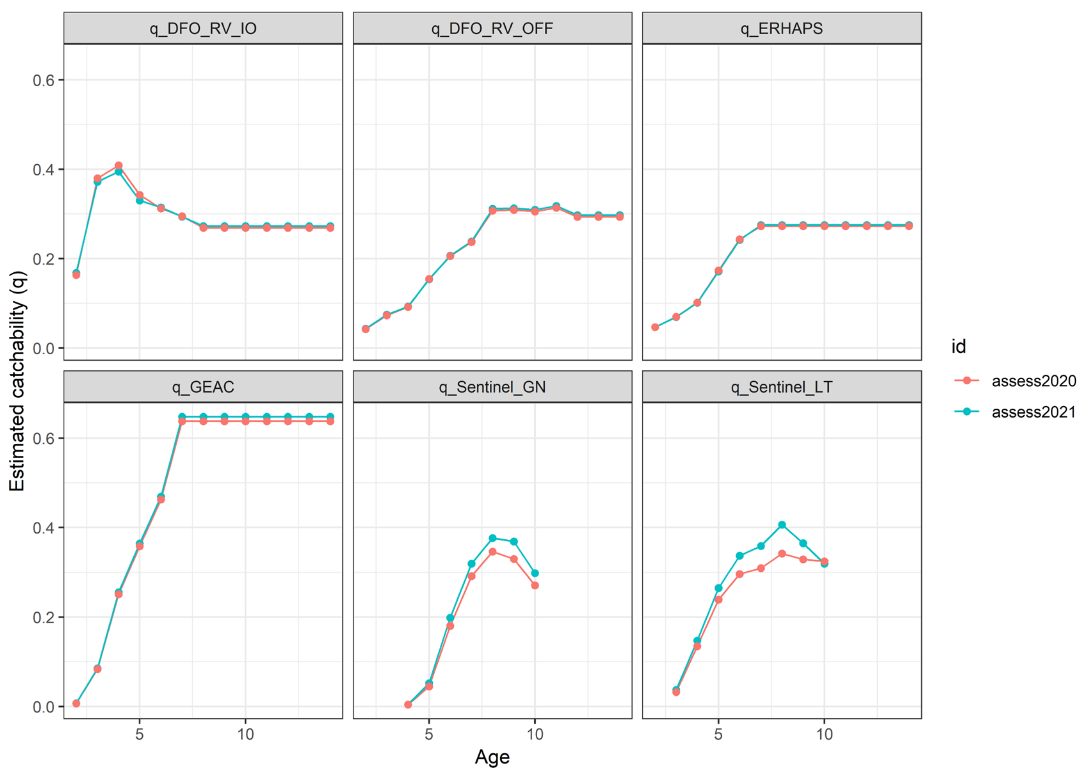

Figure 10. Catchability parameter estimates from the 2020 and 2021 assessment.

APPENDIX A – SAM MODEL UPDATE 2021

SAM MODEL DESCRIPTION

The stock assessment model (SAM) model for 3Ps cod stock was developed with the stock assessment package (from Nielsen and Berg 2014, Berg and Nielsen 2016), and has been described extensively in Champagnat et al. 2024. The model formulation follows Champagnat et al. 2024 description of 'Sentinel run' (run 143).

Input data and parametrization

The input data used in 2021 cod 3Ps assessment are the same as for the HYBRID model with regard to fisheries landings (1959–2020), catch, weight and maturity-at-age (1959–2020), Research surveys (CAN-RV Spring Survey, ERHAPS Trawl Survey), GEAC Trawl Survey and Sentinel gillnet and line-trawl (1995–2020). In the HYBRID model, the plus group is set at 14 while for SAM, the plus group is set at 12 and the model differs in the parametrization of the Natural Mortalities and some other elements of the State-Space Assessment Model (SAM) as follows:

-	SAM	Hybrid
Fit to commercial data	Catch-at-age directly	Landings and proportion at age using continued ratio logits
Treatment of 0's	Changed into NA and estimated	Censored likelihood to inform on 0 +espsilon
Random effects	F and N	F and N. Break to the MVN for F at the beginning of the moratorium. Separation of age 2 from the MVN.
RV survey: Inshore-Offshore (IO) & Offshore (OFF)	Q for ages > 7 equally in the 2 scientific surveys	Q for ages 8 and older adjusted in the 2 scientific surveys
Uncertainty in landings	No uncertainty (although possible to introduce a proxy)	Uncertainty treated with censored likelihood
Natural mortality (M)	Set at 0.3 all years and all ages	Condition-based M
Plus group	12	14

Model outputs

Sentinel indices Influence

Sentinel line-trawl index has a very low standard deviation estimate (Table A1), which points that the model is fitting substantially to this index, although its influence decreased in the latest assessment compared to the run presented to the framework in 2019. To assess the influence of that series, leave out fleet runs were performed (e.g., running the same model but with one survey out). Contrary to last year's assessment and due to the most recent increase in the survey indices at age, the run without Sentinel line-trawl index is the one displaying the lowest SSB (Figure A1), which figures out that this index is driving now the stock estimates upward. The Sentinel gillnet index has the highest standard deviation estimate from the 6 reference fleets. This survey has thus a very low influence on the final estimate and leaving it out of the final run displays SSB, F and Recruitment lines confounded with those of the final run (Figure A1).

Surveys influence

The standard deviation estimates (Table A1) of the two Spring DFO-RV surveys (Inshore/Offshore (1997 to present), Offshore [pre-1997]) and French ERHAPS survey show a remarkable similarity (0.75–0.79) which means they are contributing equally to the final estimates. The leave out exercise (Figure A1) shows that the DFO-RV survey is the most influential for the last decade SSB and R.

Updated RUN

The final run presented at the 3Ps cod assessment 2021 meeting was parametrized as described in the first section.

The stock spawning biomass displays a slow but steady upward trend since its lowest value in history at the beginning of the 2010's (Figure A4). The final estimate for 2021 is 33.3 kt (Table A2), which is about 50% of the LRP as defined in 2019.

Population weighted fishing mortality has overall decreased since 2000 and 2021 estimate is 0.04, the lowest value in the time series, excluding the moratorium period (Figure A5; Table A2).

Recruitment estimates (abundance of age-2 fishes) are low since 2002. After 2011 and 2012 strong year classes, it has decreased and reached the lowest values of the series before beginning a return to average values over the last 20 years. The DFO spring survey has been tracking few more young fishes since 2018 resulting in the slight increase of recruitment estimates (Figure A6). It is to be noted that the survey did not take place in 2020 due the covid pandemic.

Model diagnostics are similar to results discussed at the framework meeting, with some evidences of year-effect in the survey fit and some conflict between DFO RV survey and Sentinel line-trawl indices.

Quality of the assessment

Process residuals for the population are well described (Figure A2) and those for fishing mortality display some large bubbles in the mid-1990's, probably as a side effect of the moratorium.

The retrospective runs (Figure A3) do not show any directional patterns during the last 5–6 years, which is much welcome given the difficulty with such patterns in the early 2010's. Indeed, this confirms the difficulty of assessing the real magnitude of the 2011 year class until these fish were 5–6 years old, as highlighted with the retrospective figure for recruitment.

Projection with SAM

Projection of the stock to 2024 was conducted assuming catch removal will be within ± 30% of current value (2020 landings). Recruitment was assumed to be the mean of the age-2 estimates over 2012–19, weights at age, mortality at age and fishing selectivity were assumed to equal the average of those over 2017–21. The proportions mature at age were projected forward from the cohort-specific model estimates. Six projection scenarios were conducted, using multipliers of 0.7, 0.85 1.0, 1.15, and 1.3 on current landings, with a constant value assumed for each year projected. All projections with assumed landings show SSB in 2024 to be equal or higher than SSB in 2021 (Tables A3–A5). Where catch is increasing, fishing mortality is doing so at a stronger pace, a 30% increase (15% increase scenario) or multiplied by two (30% increase scenario).

Tables

Table A1. Standard deviation parameters estimated for SAM run.

Standard deviation parameters	Standard run 2019	Standard run 2021
Recruitment	0.35	0.32
Survival/population	0.22	0.18
Age2 F	0.68	0.69
Age3–4 F	0.97	0.96
Age5+ F	0.65	0.64
Age2 catch	1.62	1.67
Age3–4 catch	0.64	0.67
Age5+ catch	0.26	0.28
OFF	0.74	0.75
IO	0.81	0.79
GEAC	0.98	0.97
ERHAPS	0.75	0.77
Sentinel GN	2.74	2.74
Sentinel LT	0.38	0.45

Table A2. Estimates, upper and lower bounds of SSB F and R from SAM.

Variable	Year	Estimate	Lower – Upper bound
SSB	2019	27.5	22.0–34.4
	2020	31.0	23.8–40.4
	2021	33.3	25.0–44.2
F	2019	0.09	0.07–0.12
	2020	0.04	0.03–0.06
	2021	0.04	0.01–0.16
Recruitment	2019	16.1	9.4–27.6
	2020	19.3	9.4–39.7
	2021	22.4	9.2–54.7

Table A3. Estimates, upper and lower bound of SSB and fishing mortality in 2022 from SAM projection.

Variable	Catch scenario	SAM Estimate	SAM Lower bound	SAM Upper bound
SSB	0	34	24	45
	-30%	34	25	45

Variable	Catch scenario	SAM Estimate	SAM Lower bound	SAM Upper bound
	-15%	33	24	45
	Status quo	33	24	46
	+15%	33	24	46
	+30%	33	23	46
F	0	0	0	0
	-30%	0.015	0.003	0.094
	-15%	0.024	0.004	0.138
	Status quo	0.032	0.005	0.210
	+15%	0.043	0.007	0.254
	+30%	0.058	0.010	0.323

Table A4. Estimates, upper and lower bound of SSB and fishing mortality in 2023 from SAM projection.

Variable	Catch scenario	SAM Estimate	SAM Lower bound	SAM Upper bound
SSB	0	38	26	52
	-30%	37	27	52
	-15%	36	24	51
	Status quo	35	23	50
	+15%	34	22	50
	+30%	34	21	49
F	0	0	0	0
	-30%	0.009	0.001	0.102
	-15%	0.019	0.002	0.156
	Status quo	0.031	0.003	0.261
	+15%	0.047	0.005	0.410
	+30%	0.072	0.007	0.628

Table A5. Comparative estimates, upper and lower bound of SSB and fishing mortality in 2024 from SAM projection.

Variable	Catch scenario	Estimate	Lower bound	Upper bound
SSB	0	42	29	62
	-30%	40	28	58
	-15%	39	24	58
	Status quo	37	22	56

Variable	Catch scenario	Estimate	Lower bound	Upper bound
	+15%	36	19	56
	+30%	35	15	54
F	0	0	0	0
	-30%	0.006	0.000	0.081
	-15%	0.014	0.001	0.159
	Status quo	0.028	0.002	0.317
	+15%	0.051	0.004	0.723
	+30%	0.086	0.007	1.086

Figures

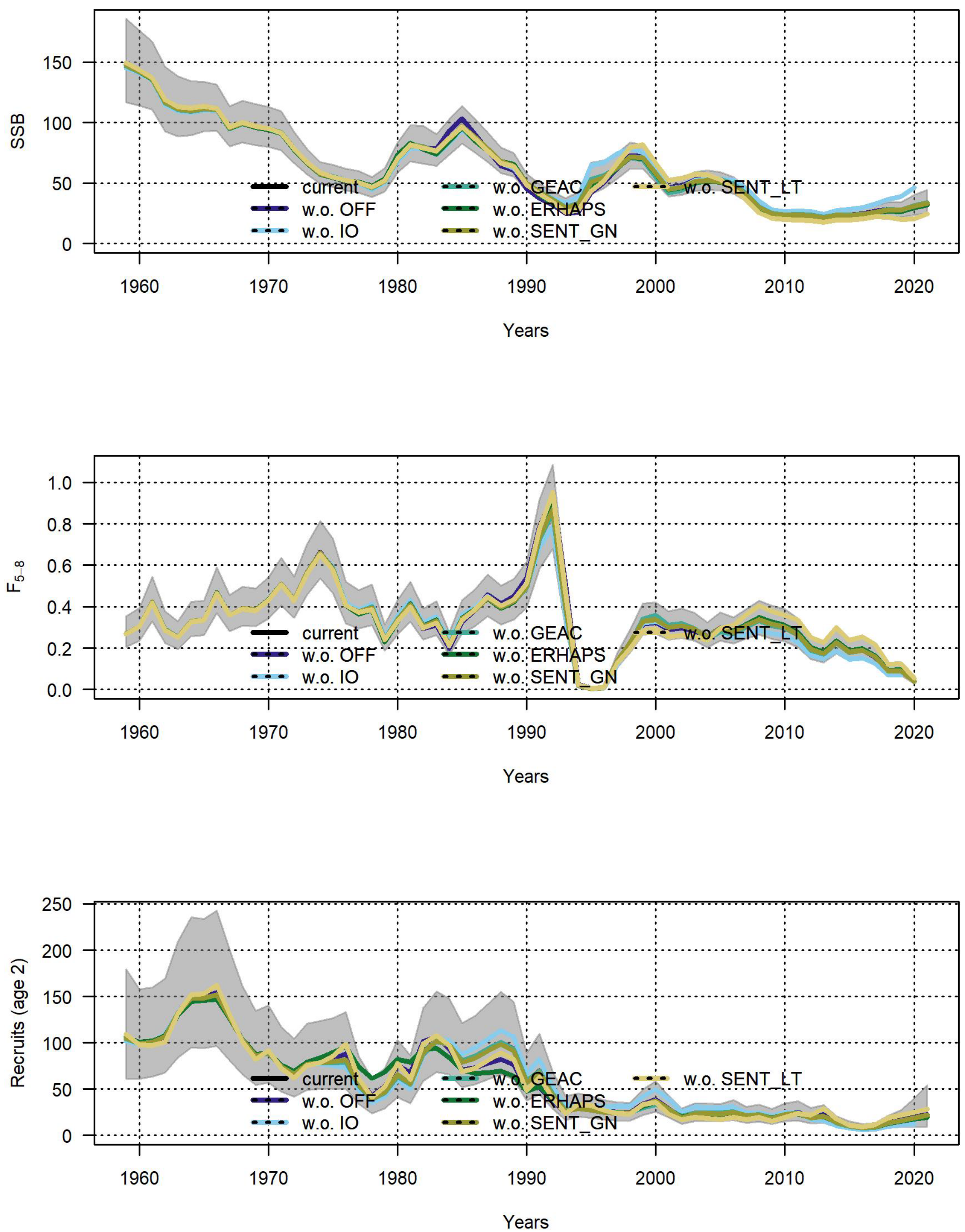

Figure A1. Trends in SSB, average fishing mortality and recruitment (age-2) estimated by SAM for current run and leave out fleet runs.

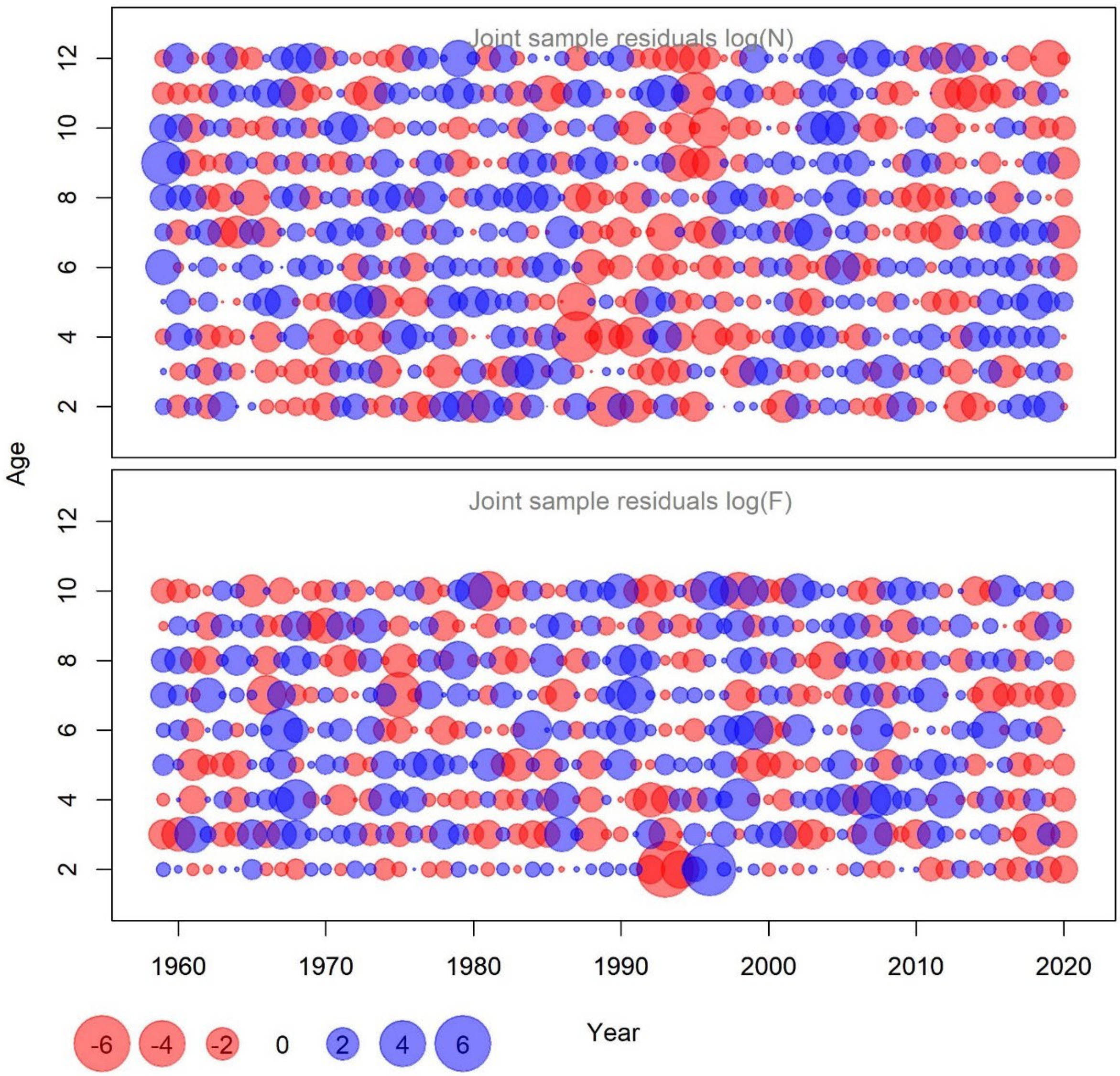

Figure A2. Process residuals for population (top) and fishing mortality (down).

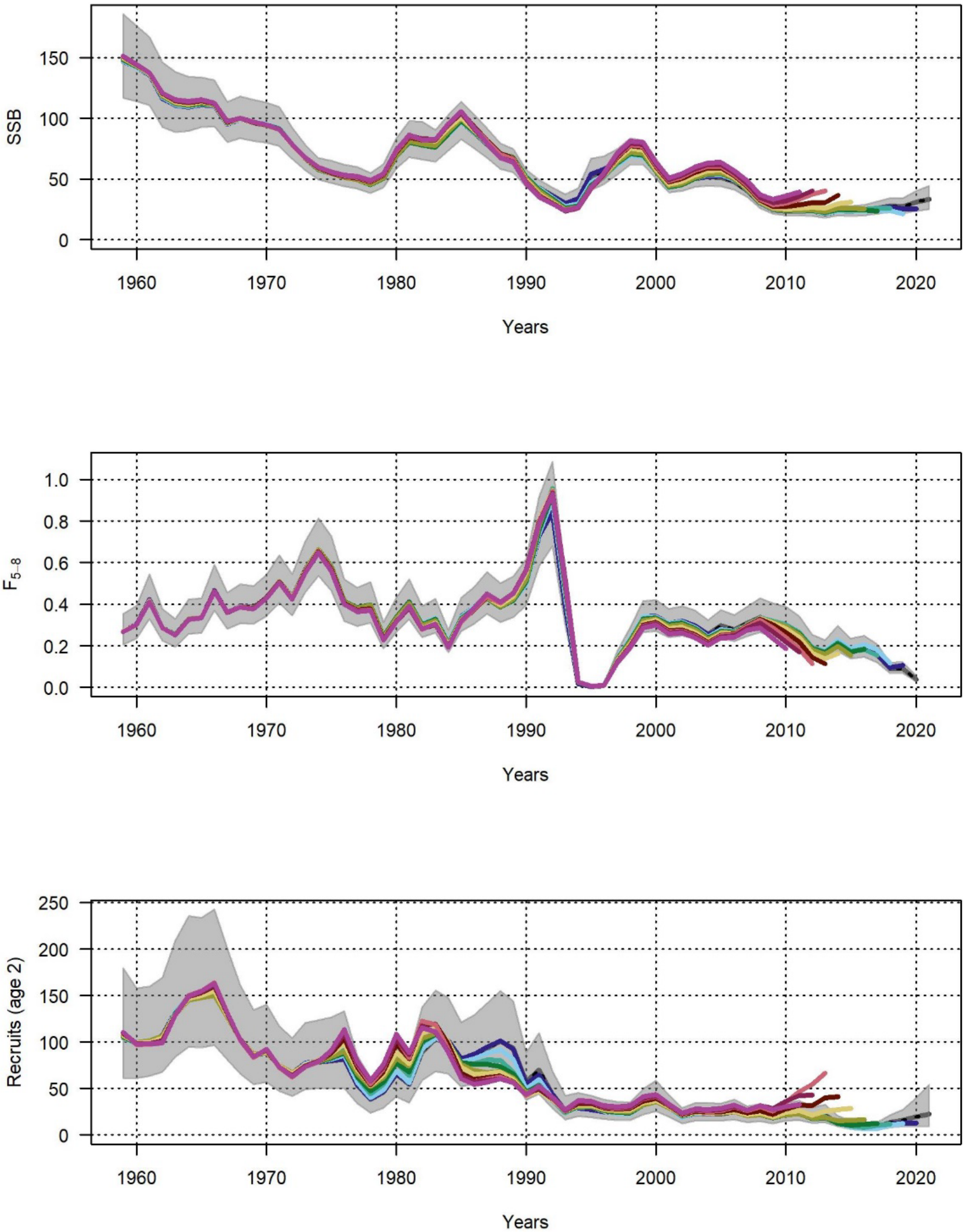

Figure A3. Plots of retrospective runs for SSB, average fishing mortality and recruitment (age-2) estimated by SAM.

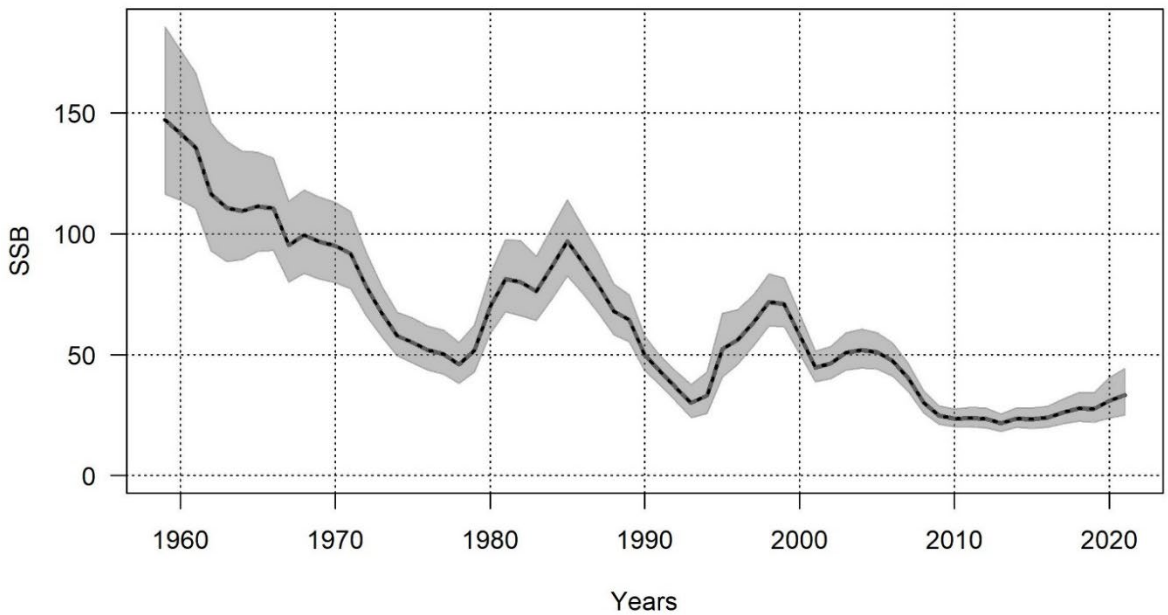

Figure A4. Estimates and confidence intervals for SSB from SAM run.

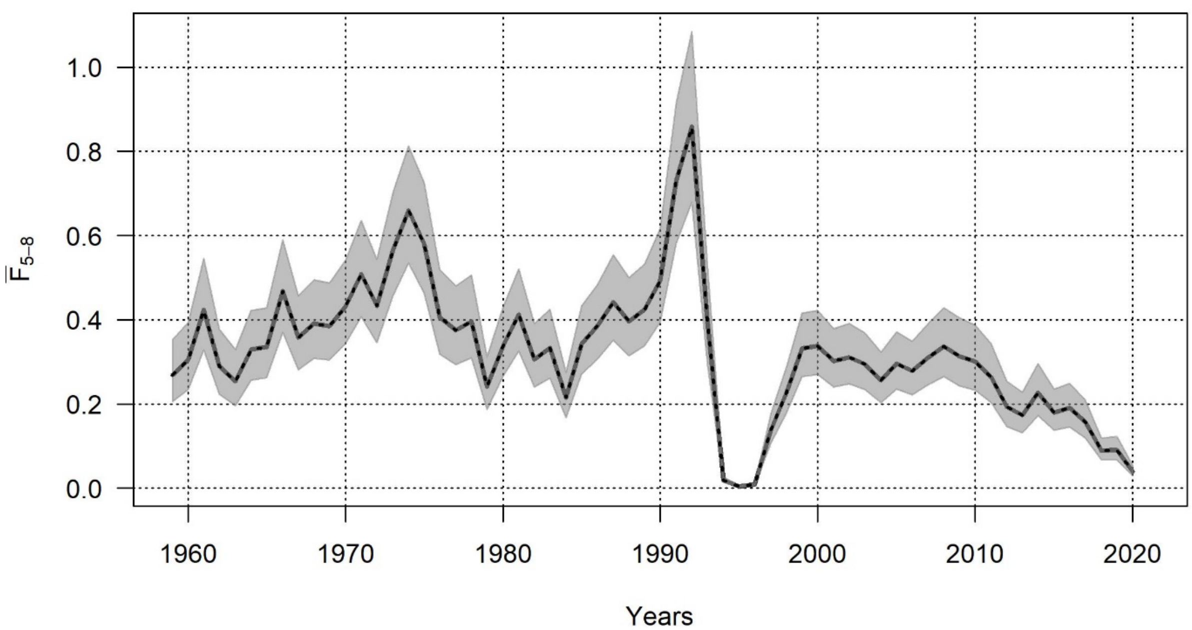

Figure A5. Estimates and confidence intervals of average fishing mortality from SAM run.

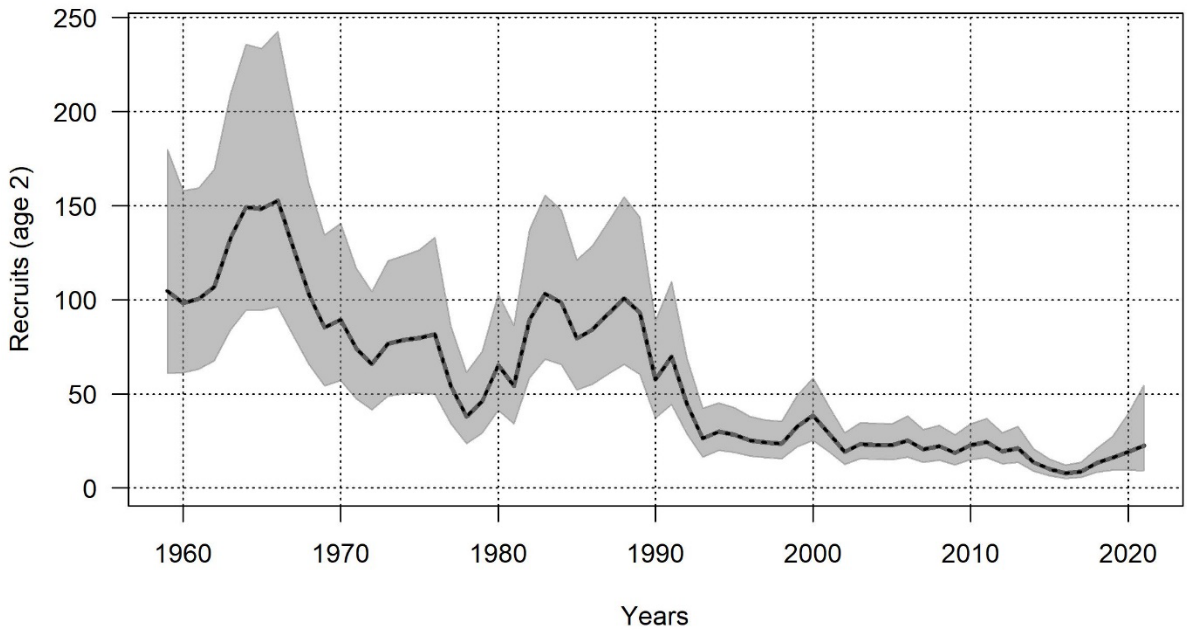

Figure A6. Estimates and confidence intervals of recruitment (age-2) from SAM run.

APPENDIX B – MODEL DIAGNOSTICS

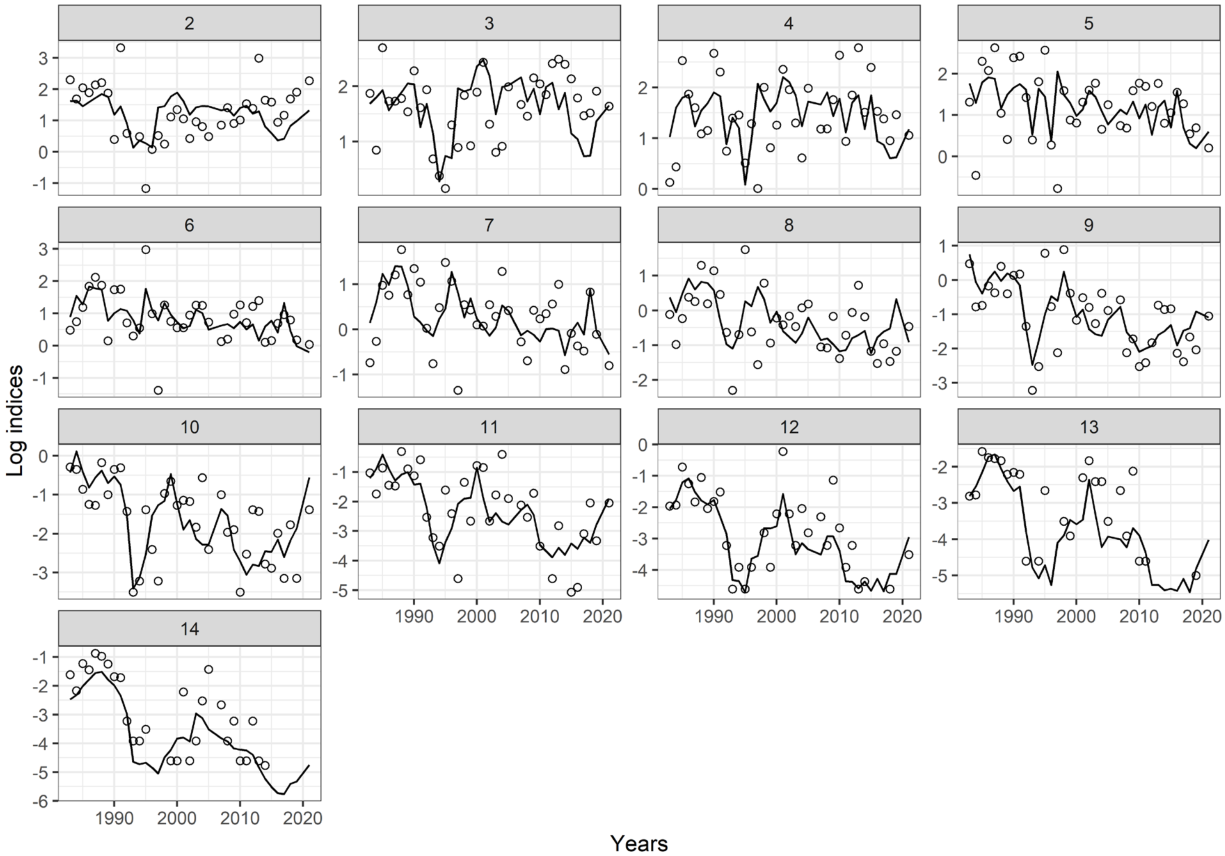

Figure B1. Model fits at age to the DFO Spring RV survey in NAFO Subdiv. 3Ps.

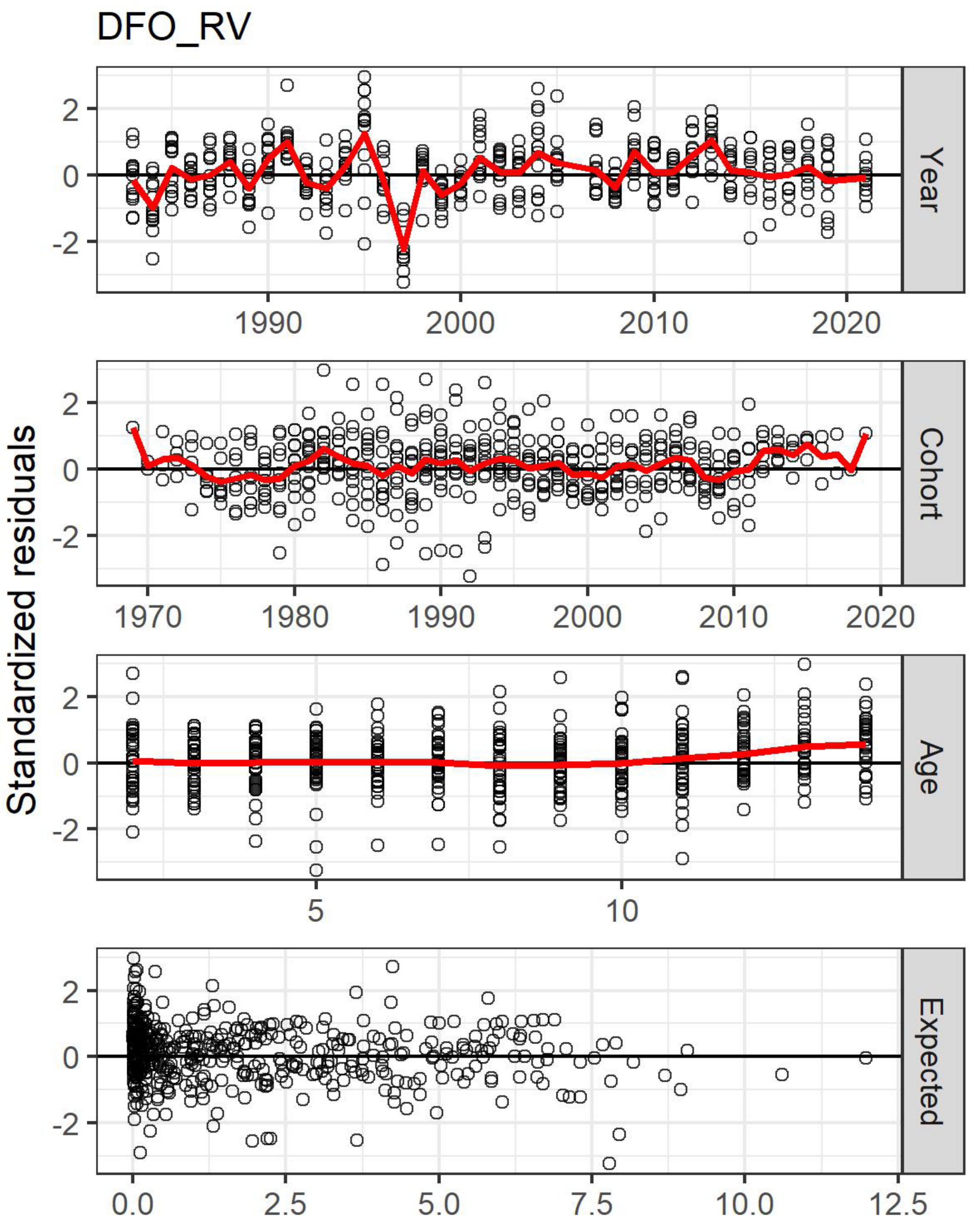

Figure B2. Standardized residuals of indices obtained from the DFO RV survey are plotted against year, cohort, age, and predicted log-index for the three divisions. A solid line representing the mean is drawn on each plot.

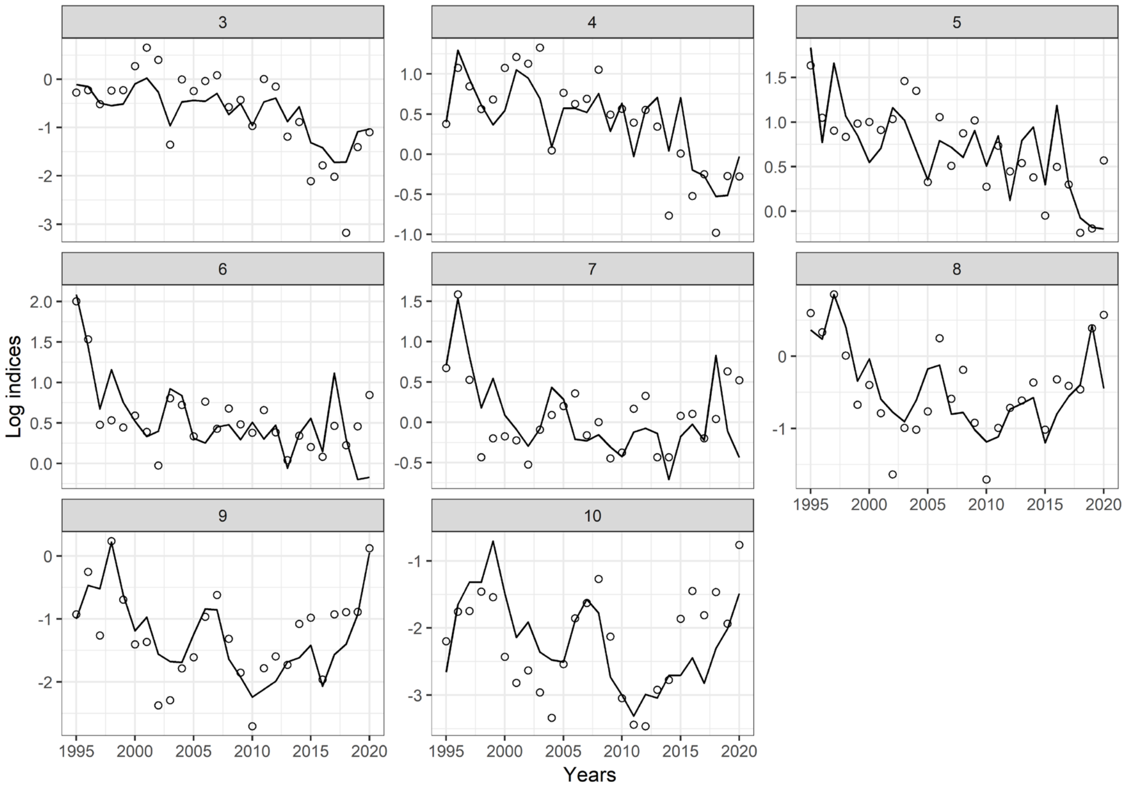

Figure B3. Model fits at age to the Sentinel line-trawl index.

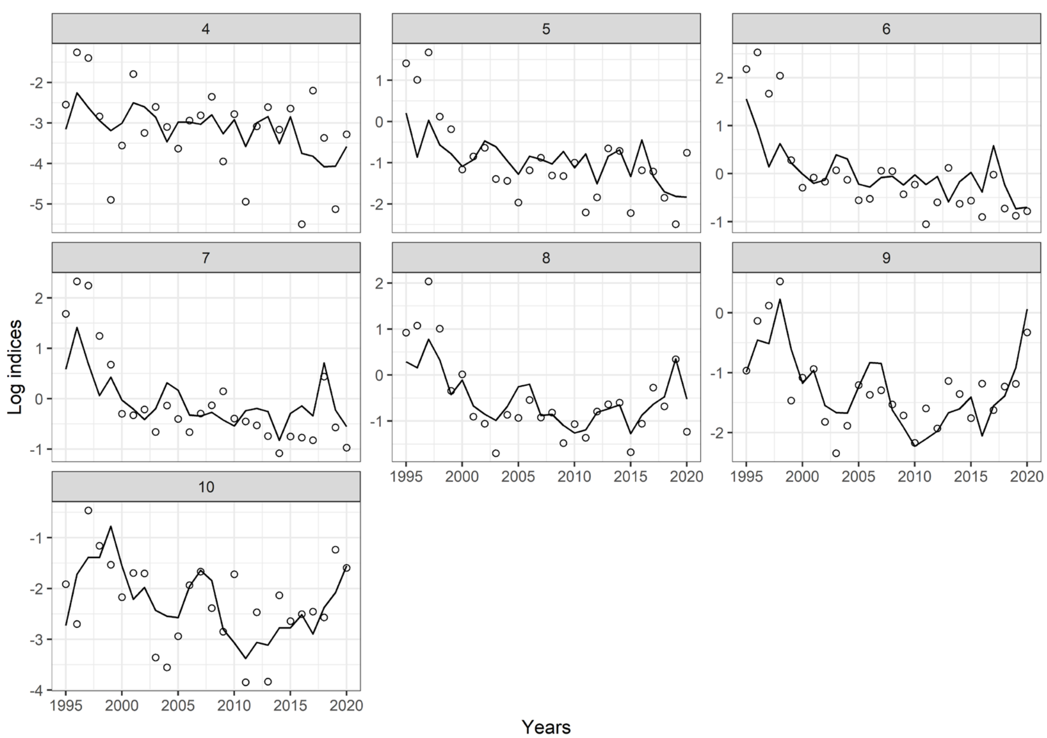

Figure B4. Model fits at age to the Sentinel GN index.

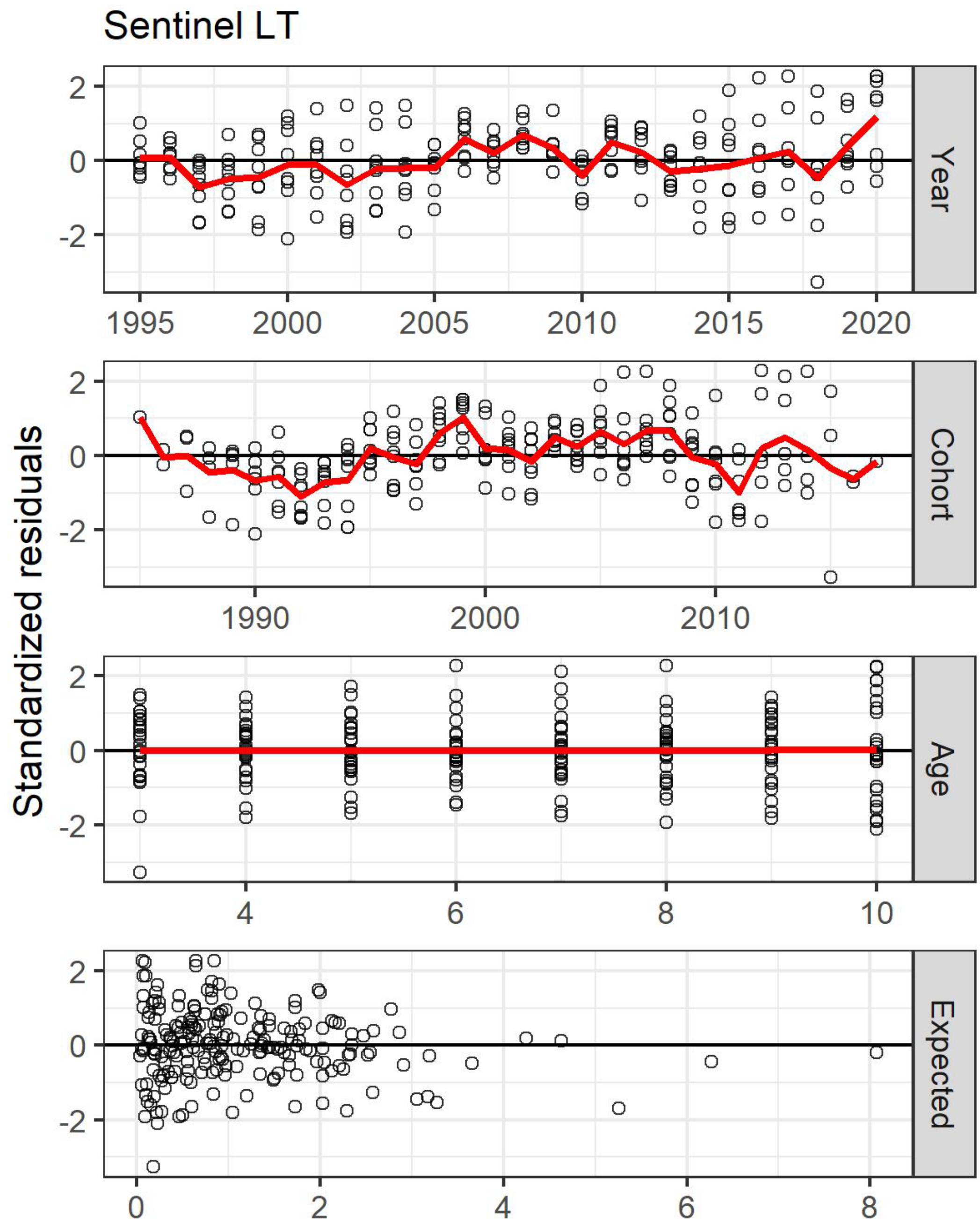

Figure B5. Standardized residuals of indices obtained from the Sentinel line-trawl survey are plotted against year, cohort, age, and predicted log-index for the three divisions. A solid line representing the mean is drawn on each plot.

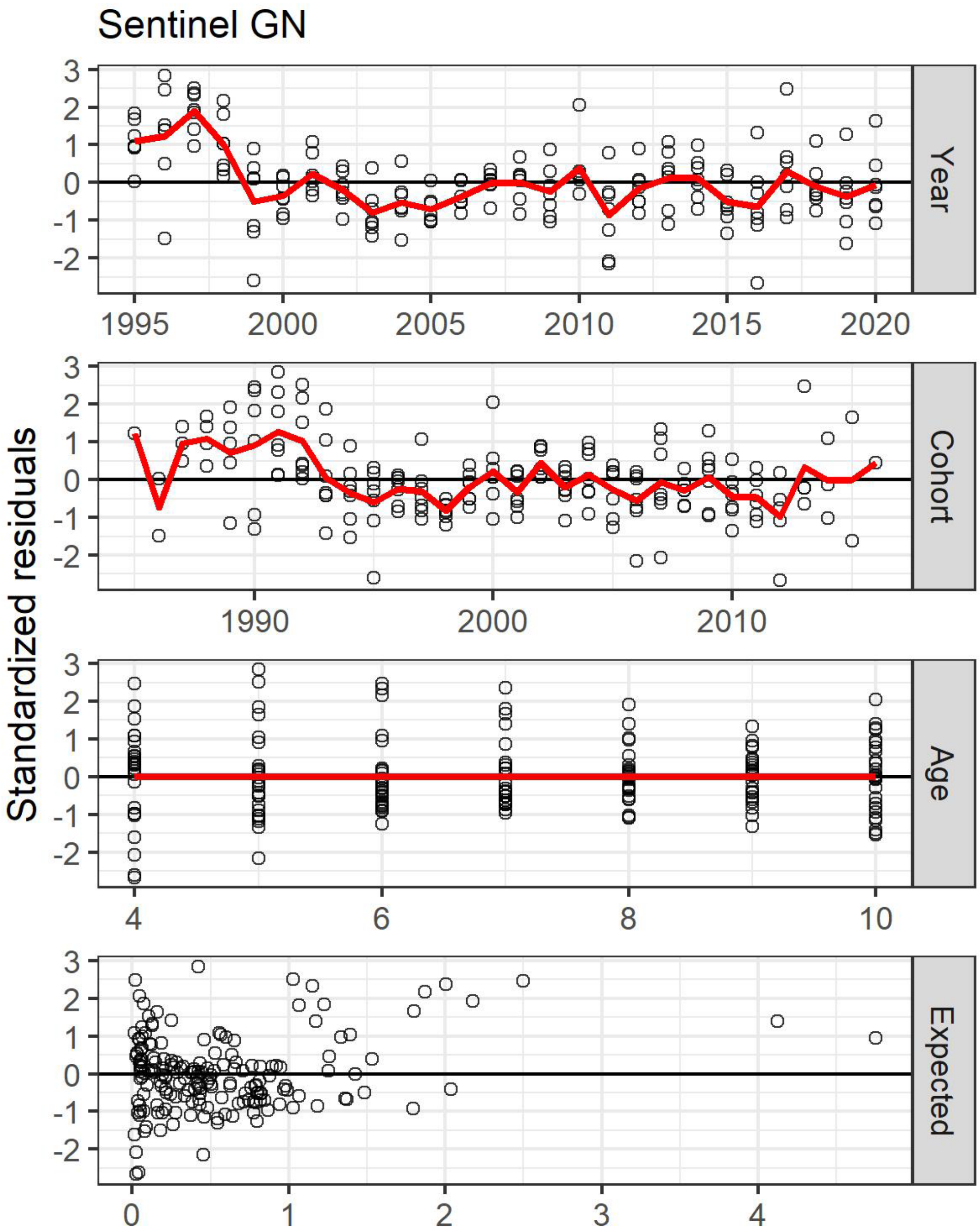

Figure B6. Standardized residuals of indices obtained from the Sentinel gillnet survey are plotted against year, cohort, age, and predicted log-index for the three divisions. A solid line representing the mean is drawn on each plot.

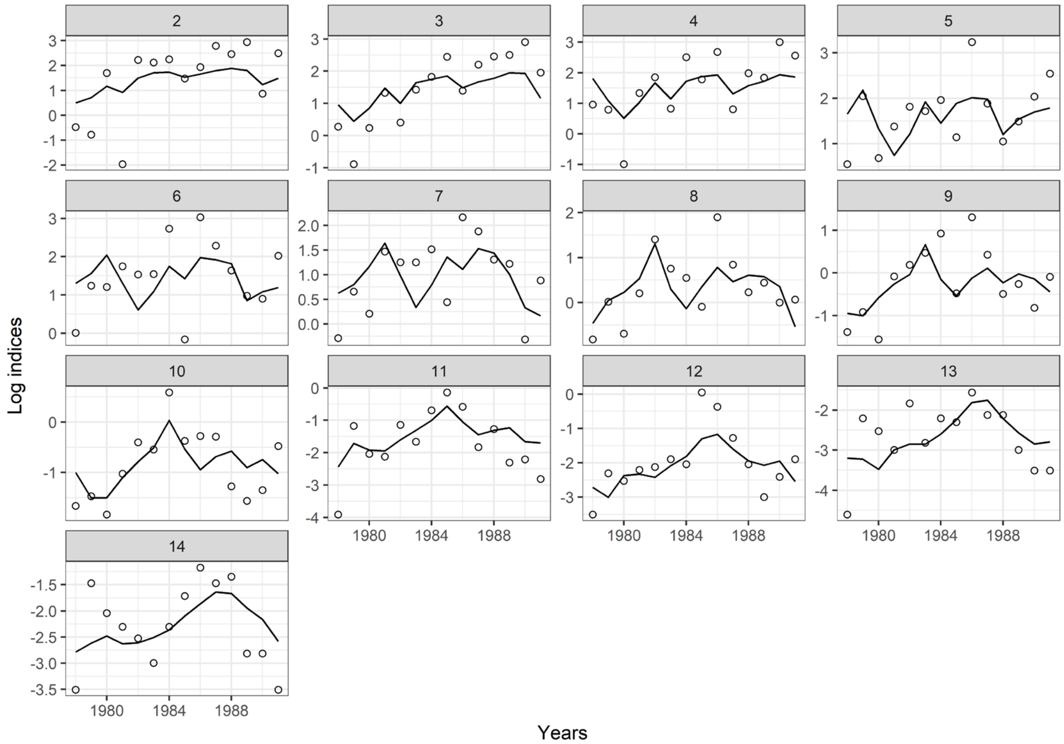

Figure B7. Model fits at age to the French EHRAPS survey.

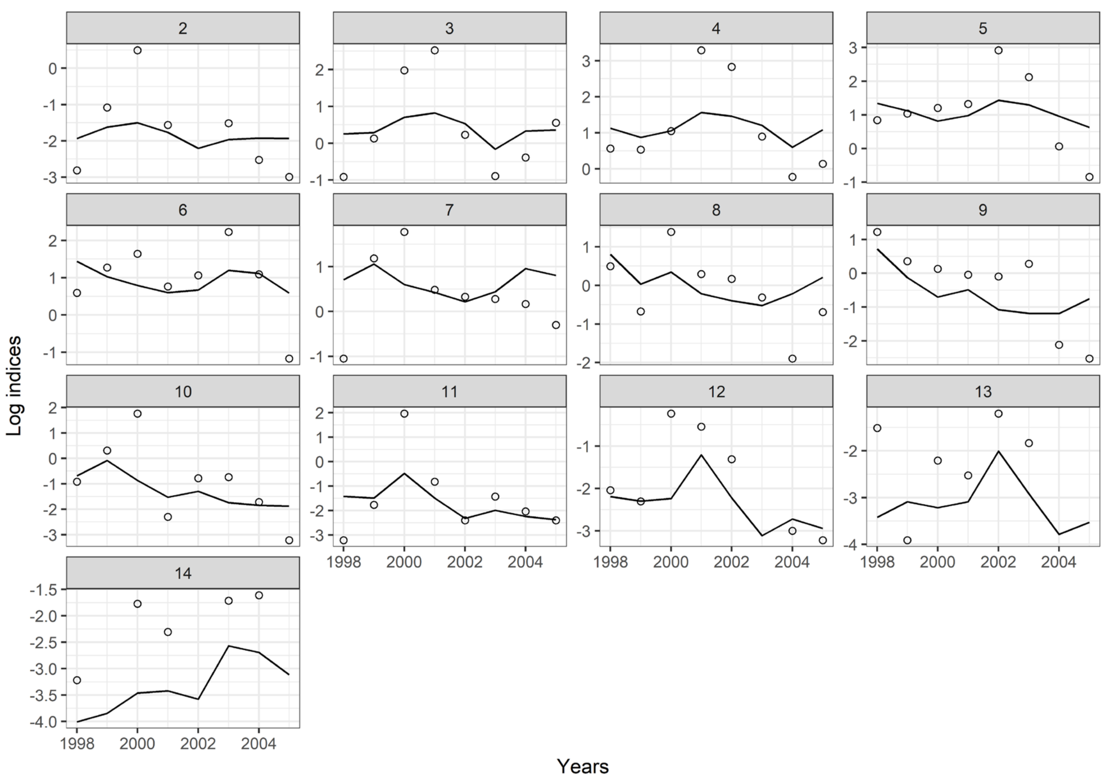

Figure B8. Model fits at age to the GEAC survey.