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A State-Space Assessment Model for 3NO Cod

by

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Abstract

We present research progress on a state-space assessment model (SSAM) for 3NO cod, which addresses concerns about the reliability of catch statistics, inclusion of a plus group, changes in stock productivity, and inclusion of the EU-Spain survey indices. The SSAM fit the assessment data well and did not have serious retrospective patterns. SSAM estimates of SSB since 1990 were broadly similar to ADAPT estimates. Estimates of SSB during 1960-1990, on the other hand, demonstrated larger differences between the two models as a result of different M assumptions, the inclusion/exclusion of a plus group, and the use of different fish weights-at-age. SSAM and ADAPT estimates of F were also broadly similar and more so at ages 6-9 where the specification of M in each model was more similar. SSAM results were very similar for a range of bounds on fishery catches that were chosen to account for uncertainty in this information for 3NO cod. Hence, we conclude that unless uncertainty in catch statistics is substantially different from our sensitivity runs, this uncertainty will not have much effect on stock status conclusions. Conclusions may, however, be affected by structural uncertainties regarding M. Most of the differences between the SSAM and ADAPT estimates (e.g., recruitment) can be attributed to the different M assumptions and such differences may lead to different conclusions regarding reference points. Current results from the SSAM indicate that poor recruitment occurred below 150 000 t of SSB while the ADAPT indicated 60 000 t. Future research on time-varying M and simulation testing is therefore required before the SSAM should be considered for stock advice.

Introduction

The stock of Atlantic Cod on the southern Grand Bank (Divs. 3NO) collapsed during the early 1990s and has demonstrated little or no sign of recovery since that time, even though the stock has been under a moratorium to directed fishing since 1994. Based on the poor strength of recent year classes, NAFO Scientific Council has stated that the medium-term prospects for the stock are not good (NAFO 2021). Stock productivity has varied over time and under recent conditions even low levels of bycatch may remove most of, or even exceed, the surplus production of the stock (Shelton and Morgan, 2005; Morgan et al. 2014a; 2014b).

The assessment for this stock has long been based on a sequential population analysis using the ADAPT framework (Gavaris, 1988) and the model formulation has not changed in over two decades. Several concerns have been raised in recent years with respect to the use of a VPA to assess this stock (e.g. NAFO 2018; NAFO 2019; Rideout et al. 2021a; 2021b). A major concern is that VPAs assume that there is no uncertainty in the catch data. However, recent assessments have emphasized that the quality of catch information for this stock is poor, with very limited and sporadic sampling of commercial catches for lengths, ages, etc.. Assessments have largely relied on applying age-length keys from one fishing fleet to the length distribution of catches of another fleet, applying age-length keys from one year to a subsequent year, or applying research vessel survey age-length keys to commercial catches. It has repeatedly been suggested that without improved catch information, the catch assumptions of the VPA are likely violated and other modelling approaches should be considered.

Another concern regarding the current 3NO cod VPA is that it only considers ages 3-12 and does not utilize a plus-group to monitor older ages. Instead, fish are artificially removed from the virtual population after age 12. Recruitment to the stock has generally been very low in recent decades but the 2006 year-class tracked through the population as relatively strong and when this year class approached age 12 there was an increased emphasis on the need to include a plus-group to ensure that the artificial removal of fish after age 12 was not significantly and unduly influencing the perception of stock trends and status (NAFO 2018; 2019). Attempts to improve the VPA model diagnostics by including a plus-group were not successful (Rideout et al. 2021a) and the most recent assessment (Rideout et al. 2021b) was still based on the old model formulation, without the plus group. Although the 2006 year-class did not appear to still be strong at older ages, and the plus-group would not have accounted for much of the biomass in recent years, it was still considered important to explore the inclusion of a plus group in any proposed new model formulation.

A further criticism of the current assessment model is that it uses data from three Canadian RV surveys but does not use data from the EU-Spain survey (Garrido et al. 2022) on the tail of the Grand Bank in the NAFO Regulatory Area (NRA). The rationale for this has historically been that the Canadian surveys cover the entire spatial extent of the stock area, whereas the EU-Spain survey only covers the NRA, which is a relatively small portion of the stock area. Hence, concerns have been raised as to whether trends in the EU-Spain survey truly represent stock trends or are just a result of fish moving in and out of the portion of the stock covered by that survey. Previous attempts to use the EU-Spain survey data as an additional input to the assessment VPA resulted in poorer model fits (Morgan 2006; Rideout et al. 2021a). However, it has been noted that in recent years the majority of the stock biomass appears to be located in the NRA and the EU-Spain survey coverage of the NRA is much more intensive than the Canadian surveys (Rideout et al. 2013). It is also worth noting that NAFO SC assessments are not consistent with respect to decisions to use/exclude data from the EU-Spain survey (for example, see the assessment for 3LNO American plaice, Wheeland et al. 2021). Discussions regarding the inclusion/exclusion of the EU-Spain survey have failed to come up with a way to account for only partial stock coverage and the potential confounding impacts of fish movement in and out of the survey area.

Another concern with respect to the current VPA assessment model is that natural mortality is treated as constant (with an assigned value of 0.2) across all ages and years. This is a common assumption in traditional fisheries dynamics models, with data needed to directly estimate M being very rare (Punt et al. 2021). However, life history theory suggests that natural mortality can vary between sexes as well as over time (Punt et al. 2021) and should decrease with age as a result of outgrowing potential predators (Lorenzen 2000). NAFO Scientific Council recommended exploring more flexible models to address the shortcomings of the current VPA, including the potential to not impose assumptions about stationary natural mortality (NAFO 2021).

We present a bespoke state-space stock assessment model (SSAM) to address the issues that have been identified for 3NO cod; that is, our model: 1) accounts for potential uncertainty in total fishery catch estimates and the age composition estimates of this catch; 2) includes a plus group at age 10; 3) includes process error in population dynamics that can account for variable productivity; 4) includes indices from the three Canadian RV surveys and the EU-Spain survey. SSAMs account for measurement errors in the data separately from process error or variability in population dynamics (see e.g., Nielsen and Berg, 2014, Cadigan, 2016; Perreault et al., 2020; Stock and Miller, 2021), which is an improvement to approaches that treat the fishery catch-at-age data as known with negligible error. SSAMs are considered to be an essential part of the next generation stock assessment package (Punt et al., 2020). The 3NO cod model is customized for the stock but most of the procedures and programming modules have been tested with other stocks or included in the software we used (described below).

Methods

We first describe the data available for the stock assessment model which will motivate some modelling choices.

Data

This stock has been under a moratorium to directed fishing since 1994 and therefore recent reported landings (bycatch) have been very low compared to levels prior to the 1990s (Figure 1). Methods used by NAFO Scientific Council to estimate landings have changed over time (Brodie 2013) and in at least some cases uncertainties associated with methods have been used to inform catch bounds (i.e. rather than point estimates) for assessment purposes (e.g. Perrault et al. 2020). Sufficient information is not available to evaluate the accuracy of the landing's estimates.

Data from sampling of the length and age-compositions of the catches have been used to estimate catch-at-age (C@A) in abundance (Figure 2 and Figure 3) from the landings estimates. The catch at age time series for this stock suggests that catch-at-age 2 prior to 1987 was always zero (Figure 3), despite data for catches of age 2 fish in some older reports (e.g. Pinhorn and Wells 1975). We assume that these zero values are a reporting error and treat the data as missing rather than zeros. While some cohorts have clearly tracked through the age-compositions (Figure 4 and Figure 5), sometimes there are relatively large catch proportions at older ages even for cohorts that were relatively weak at younger ages. The latter may be due to measurement errors rather than variable population dynamics, and these errors seem larger at ages 2-3 and 11-13. Cohorts since 2008 have not tracked well through the C@A (Figure 5) which may be due to low between-year variation in cohort strength as well as poor age sampling.

Unfortunately, the length and age compositional data sources and the algorithms used to derive the C@A throughout the entire time-series are not available to us. This limits our ability to effectively account for age-composition measurement errors in a SSAM. A pragmatic and partial solution is to aggregate data for poorly sampled ages. However, too much aggregation will result in a loss of information about cohort strength and morality rates. Figure 3 - Figure 5 suggest that 10 is a good age to aggregate C@A and include as a plus group in a SSAM. An additional benefit of aggregating for ages 10+ is that there are then very few zero's in the C@A (Figure 3). This is important because our observation model for the catch age-compositions assumes all proportions are non-zero and zero's are either treated as missing (i.e. catches of age 2 cod prior to 1987) or replaced with a small positive value.

The survey indices available to include for estimating a SSAM are shown in Figure 6 - Figure 8. Age 13 is a plus group age for the Spring, Fall, and EU-Spain surveys in these figures. The Juvenile survey indices are a short historical series that will probably have little impact on SSAM estimates. The trends in the EU-Spain indices at ages 9-13 are different than the Canadian Fall and Spring indices (Figure 7). Between-survey correlations of log index deviations (from their age-specific means) also demonstrate better correlations between the three surveys at ages 1-8 (Figure 9 and Figure 10) than at ages 9-13 (Figure 11). Indices with zero values were treated as missing in these figures. At ages 1-4 the indices are all reasonably correlated between surveys. At ages 5-7 the Spring and Fall indices have less correlation with each other than they do with the EU-Spain indices (Figure 10), but the reverse occurs at age 8 and ages 9-13 (Figure 11). All the surveys have tracked some cohorts well (Figure 12), except the Spring and Fall indices at age 1 for the Campelen converted years (Spring, 1984-1995; Fall, 1990-1994). However, cohorts do not seem to track as well at older ages, and the Spring indices do not seem to track cohorts as well as the Fall and EU-Spain survey indices. There are many zero values in the survey indices (Figure 8), and further aggregation from 13+ to 10+ will reduce this problem when fitting SSAM's using log index values.

Other assessment inputs are the stock weights (see Cadigan and Rideout, 2022) and catch weights, and the proportion mature-at-age (Figure 13).

Natural Mortality Rate

Natural mortality rates (Ms) are often considered to be among the most important parameters in a fish stock assessment, but they are also among the most difficult parameters to estimate using commonly available data (Punt at al., 2021). We treat Ms as model inputs, although our SSAM will involve process errors that can partially account for uncertainty about M values. We used the Lorenzen method to specify M from body weight estimates (Lorenzen, 1996),

$$M_{ay} = M_o W_{ay}^{b}, \tag{1}$$

where $M_{a,y}$ is the natural mortality at age a in year y, $W_{a,y}$ is the stock weight-at-age, M_o is a scaling parameter, and b is an allometric scaling factor. The basic idea with Eq. (1) is that M's for small fish are larger because of predation effects. We use b = -0.305 which is the value for ocean systems in Lorenzen (1996). This value was also used in Miller and Hyun (2018) and Kumar et al. (2020).

The scaling parameter was chosen so that $\min_{a,y} M_{ay} = 0.15$. The M values are shown in Figure 14. We consider these values to be "preliminary" and they should be updated if better information is available.

Stock Assessment Process Model

The stochastic cohort model with a plus age group A is

$$\log(N_{a,y}) = \begin{cases} \log(N_{a-1,y-1}) - Z_{a-1,y-1} + \delta_{a,y}, & a < A, \\ \log\{N_{a-1,y-1}\exp(-Z_{a-1,y-1}) + N_{a,y-1}\exp(-Z_{a,y-1})\} + \delta_{a,y}, & a = A, \end{cases} \quad y = 1, \dots, Y, \tag{2}$$

where $N_{a,y}$ is stock abundance at age a in year y, $Z_{a,y} = F_{a,y} + M_{a,y}$ is the total mortality rate, $F_{a,y}$ is the fishing mortality rate, and $\delta_{a,y}$ is process error. For the 3NO cod SSAM, the ages are 1-10+ and years are 1959-2019. Equation (2) is the typical cohort model used in fish stock assessment.

The recruitment vector, $R = (N_{1,1}, \dots N_{1,Y})$, is assumed to be a lognormal random vector variable,

$$\log(R) \sim MVN(\mu_R, \Sigma_R), \tag{3}$$

where the $Yx1$ parameter vector μ_R consists of three time-blocks with constant values: 1) $y < 1970$, 2) $1971 \le y \le 1991$, and 3) $y > 1991$. These time-blocks were chosen to account for major changes in recruitment levels. Σ_R is the stationary covariance matrix of an AR(1) process defined by σ_R and φ_R. The correlation between $\log(R_i)$ and $\log(R_j)$ is $\varphi_R^{|i-j|}$.

The numbers at age's 1-10+ in the first year are treated as unknown and free parameters to estimate. They are technically modelled as random effects with no distribution (i.e. a flat improper distribution). The δ process errors are assumed to be independent for all ages and years and have a normal distribution with mean zero and variance σ_δ^2.

Catches at ages 2 to 10+ are modelled using the Baranov catch equation,

$$C_{a,y} = N_{a,y}\frac{\{1 - \exp(-Z_{a,y})\}F_{a,y}}{Z_{a,y}}. \tag{4}$$

There are no reported catches at age 1 so we assume that F is zero at this age. F's are modelled as a stochastic process about a small number of mean values μ_F similar to recruitment. The μ_F's are mapped to 6 values for blocks of ages and years (see Figure 15) to account for shifts in mean F because of the moratorium on fishing that started in 1994, and because ages 2 and 3 cod are historically not targeted the same as older and larger sized cod. The F deviations at age 2, $\Delta_{F,2,y} = \log(F_{2,y}) - \mu_{F2,y}$, are modelled as independent normal random variables, $\Delta_{F,2,y} \sim N(0, \sigma_{F2}^2)$. If $\boldsymbol{F}$ is an *(A-2)Yx1* vector of all $F_{a,y}$'s for ages 3-10+, then

$$\log(\boldsymbol{F}) \sim MVN(\mu_F, \Sigma_F), \tag{5}$$

Similar to the process errors, $\Delta_F = \log(\boldsymbol{F}) - \mu_F$ is modelled as an AR(1) stochastic process in age and year, and the elements of Σ_F are based on

$$Cov\{\Delta_{F,a,y}, \Delta_{F,a-j,y-k}\} = \sigma_{F,3+}^2 \varphi_{F,age}^j \varphi_{F,yr}^k ; Corr\{\Delta_{F,a,y}, \Delta_{F,a-j,y-k}\} = \varphi_{F,age}^j \varphi_{F,yr}^k . \tag{6}$$

Note that there is no correlation between F deviations at age 2 and those at ages 3 and older.

Our SSAM internally calculates the catch-at-age in abundance and biomass, and we sum over ages to calculate total catch-weight each year.

The stock size N's and fishing mortality rate F's are latent (i.e. unobservable) random variables that we make statistical inferences for. These random variables have probability distributions with a small number of mean and covariance parameters that need to be estimated. We use survey and catch data to estimate these parameters via observation equations that we describe in the next section.

Observation equations

We use marginal maximum likelihood for estimation of model parameters. This involves 1) modelling the probabilities of the data conditional on the states of N's and F's (i.e. observation equations), and then 2) integrating over all the likely states of N's and F's to get the marginal distribution of the data which the marginal likelihood is based on. The Template Model Builder (TMB) package (Kristensen et al. 2016) is a state-of-the-art tool for this purpose, and we use this software to calculate the marginal negative loglikelihood (mnll) for our 3NO cod SSAM. We estimate model parameters using the *nlminb()* function in R. The mnll is derived from a "joint" nll which is the sum of conditional nll's of the data given N and F, and the nll's of N and F. TMB uses the Laplace approximation to integrate the joint nll over the random effects to calculate the mnll. The conditional nll's of the data are the observation equations.

TMB also provides predictions of random effects and functions of random effects and model parameters (i.e. derived quantities), and provides generalized delta-method "standard errors" for these derived quantities. The standard errors are actually marginal (with respect to the distributions of N and F) mean squared errors which are more appropriate for inferences about the values of N and F than actual standard errors (i.e. Zheng and Cadigan, 2021). These derived quantities can include those that are the focus of stock assessment, such as spawning stock biomass (*SSB*), average F's for some ages, etc.

A critical part of a realistic and reliable stock assessment model is to use observations equations that effectively account for sampling variability and other measurement errors in the data. However, in stock assessment this is a major challenge because the "data" used for SSAM estimation are themselves the results of complex estimation procedures. The uncertainty in these assessment inputs is difficult to quantify accurately and often not available in practice. This is the case for 3NO cod. Pragmatic assumptions and simplifications are required to make progress. The validity of these assumptions must be examined during model fitting which creates an additional layer of model building (e.g. selecting observation likelihoods) in addition to the stochastic process equations to describe stock dynamics. However, there are some basic principles to follow, such as that the conditional nll's of independent data sources are simply the sum of nll's of each data source.

Fishery Catches

We model reported landings and estimates of the catch age-compositions separately because these two data sources come from different and mostly independent sampling programs, although catch-at-age may be aggregated across fleets using relative landings estimates so there are some complex dependencies in these data sources that we ignore for simplicity.

There are uncertainties and possible biases in fishery landings information that are difficult to quantify. We use the censored likelihood approach (e.g. Cadigan, 2016; Van Beveren et al., 2017; Perreault et al., 2020) to address these uncertainties. The censored likelihood is based on subjective assumptions about potential inaccuracies in landings. However, we examine the sensitivity of key assessment outputs to a range of assumptions about these inaccuracies. The reliability of the landings is quantified by lower and upper bounds that are assessment model inputs. In fact, our SSAM does not directly use 3NO cod landings estimates; we only use the bounds. If L_y denotes the true but unknown landings in year *y*, and $L_{lo,y}$ and $L_{hi,y}$ are the lower and upper bounds (i.e. the data), then the conditional censored nll landings observation equation for the stock assessment model parameters (collected in a vector θ) is

$$nll(\theta|L_{lo,y}, L_{hi,y}) = -\sum_{y=1}^{Y} \log\left[\phi_N\left\{\frac{\log(L_{hi,y}) - \log(L_y)}{\sigma_l}\right\} - \phi_N\left\{\frac{\log(L_{lo,y}) - \log(L_y)}{\sigma_l}\right\}\right], \tag{7}$$

where ϕ_N is the cumulative distribution function of a standard normal random variable and the σ_l parameter controls the sharpness of the bounds (effect illustrated in Figure 15). We set $\sigma_l = 0.02$ such that the nll surface is almost flat within the landings bounds and increases rapidly outside of the bounds. Hence, the assessment estimation will only keep predicted landings within or just outside of the bounds, and otherwise predicted landings will be estimated to be consistent with other data sources. We can control how much influence the bounds on landings have on the assessment by changing the width of the bounds.

The time-series of catch abundance proportion at ages *2,…, 10+*, which we refer to as the catch age compositions, are modelled using the multiplicative logistic multivariate normal distribution based on the continuation ratio logit (crl) transformation of the proportions, which are computed as follows. We index assessment model ages as *a = 1,…,A* where *A = 9*, which corresponds to stock ages *2,…,10+*.

1. For each age and year, compute $P_{a,y} = \frac{C_{a,y}}{\sum_{a=1}^{A} C_{a,y}}$.
2. Compute $\pi_{a,y} = Prob(age = a|age \geq a) = \frac{P_{a,y}}{P_{a,y}+\dots+P_{A,y}}$, $a = 1, \dots, A-1$.
3. Compute the continuation-ratio logit (crl), $X_{a,y} = \log\left(\frac{\pi_{a,y}}{1-\pi_{a,y}}\right)$, $a = 1, \dots, A-1$.

The crl is applied to both the observed and the model predicted catches. Note that there are only *A-1* crl's derived from *A* catch proportions because catch proportions only contribute *A-1* independent observations since $\sum_{a=1}^{A} P_{a,y} = 1$.

Prior to 1987 for 3NO cod there are no catches reported at age 2 so the crl's are derived from ages 3 to 10+ in this time-period. However, our SSAM predicts catches at age 2 in this time-period but these are not used for fitting the catch age compositions. In effect, our model assumes these age 2 catches are missing but not zero.

If other observed catch-at-age proportions are zero then the crl is not defined. For 3NO cod, estimated catches at ages 2, 3, 8 and 10+ in 1995, and age 2 in 1994, were zero (see Fig. 3). These values were replaced with half the minimum non-zero estimated catch. Note that catches were aggregated at ages 10-13+ in Fig. 3, and many of the zero's at older ages in this figure are not an issue because the 10+ aggregated catch is not zero.

The observation equation nll for the vector X_{oy} of observed crl's in year *y* is based on

$$X_{oy} = X_y + \varepsilon_{X,y},\ \ \varepsilon_{X,y} \sim MVN(0, \Sigma_X), \tag{8}$$

Where X_y is the vector of model predicted crl's and Σ_X is AR(1) in form, with variance parameter σ_X^2 and correlation φ_X. That is, we assume the crl errors are AR(1) correlated within years but independent between years.

Survey Indices

Let $I_{s,a,y}$ denote the observed age-based abundance index for survey s. Let t be the midpoint of the survey dates which is expressed in a fraction of the year. The model predicted index is

$$E(I_{s,a,y}) = q_{s,a} N_{y,a} \exp^{-t_{s,y} Z_{y,a}}. \tag{9}$$

The $\exp^{-t_{s,y} Z_{y,a}}$ term projects beginning-of-year abundance to the time of the survey. The $q_{s,a}$'s are catchability parameters to estimate, possibly with constraints or blocking among ages (see below). Let

$$\mu_{s,y,a} = log\{E(I_{s,a,y})\} = log(q_{s,a}) + log(N_{y,a}) - t_{s,y} Z_{y,a}. \tag{10}$$

The index observation equation is

$$log(I_{s,a,y}) = \mu_{s,y,a} + \varepsilon_{s,y,a}. \tag{11}$$

We assume the ε observation errors are independent $\varepsilon_{s,y,a} \sim N(0, \sigma_{s,a,y}^2)$. The error variances are blocked for all ages and years for each survey, but these variances can be split further if residual diagnostics indicate a need for this. We use Equation (11) for all survey ages and years, including the plus group age for plus group survey indices. Within-year correlation in errors is common and our SSAM can be easily modified to account for such correlations.

We drop Canadian Fall survey indices at age 1 prior to 1995 because these indices were based on the Engel trawl survey which had very low catchability for age 1 cod and do not provide reliable stock trend information. We also drop Spring survey indices at age 1 prior to 1996 for the same reason. Otherwise, there are some indices with zero values that are treated as missing because they cannot be used with Equation (11). For the fall survey (e.g. Figure 8) there are 3 zero indices at age 8 in 2008, and ages 9 in 1996 and 2009. For the EU-Spain survey there are 7 zero indices at ages 1 in 1997, age 7 in 2002, age 8 in 2003, age 9 in 1997 and 2001, and age 10+ in 1997 and 2005. Other index observations models that support zero's could be used (e.g. Perreault et al., 2020); however, there are not many of these zero's and we don't think this will make much difference with the 3NO cod SSAM formulation and the age 10+ group.

Stock assessment model estimation of mortality rates is usually more reliable if at least one survey has asymptotic catchability. For the 3NO cod SSAM we assume the fall survey q's are asymptotic as that survey covers the whole stock area and the trawl selectivity is expected to be flat-topped.

The EU-Spain survey covers a relatively small part of the total 3NO area, although as we indicated in the Introduction section, in recent years the majority of the stock biomass has been located in the NRA which is covered by the EU-Spain survey. However, this also suggests that the fraction of the stock available to this survey may have changed over time. We accommodate potential q-drift for the EU-Spain survey by using a separable q-model,

$$log(q_{s,a,y}) = log(q_{s,a}) + \gamma_{s,y}, \qquad \text{s = EU-Spain survey}, \tag{11}$$

where the $\gamma_{s,y}$'s are modelled as a zero mean normal random-walk with variance σ_γ^2. The $q_{s,a}$'s for the EU-Spain survey are treated as fixed-effects parameters to estimate just like the other surveys, Hence, the EU-Spain survey q's can change from year-to-year but the ratio of q's for any two years are assumed to be the same for all ages.

Average fishing mortalities at ages 4-6 and ages 6-9 are reported in annual for assessments of 3NO cod. These averages are N-weighted. We use TMB to derive delta methods standard errors for these N-weighted averages.

Prior to 1994 we assume the bounds on landings are: $L_{lo,y} = 0.9L_{obs,y}, L_{hi,y} = 2L_{obs,y}$, where $L_{obs,y}$ are the reported landings. Since 1994 we assume $L_{lo,y} = L_{obs,y}$. We explore three options for $L_{hi,y \geq 1994}$:

1. M1: $L_{hi,y} = 1.25L_{obs,y}$
2. M2: $L_{hi,y} = 1.5L_{obs,y}$
3. M3: $L_{hi,y} = 2.0L_{obs,y}$

Assessment Model Results

We focus on the landings bounds formulation M2 and compare assessment model results with models M1 and M3 at the end of this section.

Total biomass and SSB estimates (Figure 17) are substantially higher than ADAPT estimates prior to 1975 but are more similar since 1995. The SSAM has a plus group at age 10 whereas the ADAPT model only accounts for ages 2-12; hence, some differences in biomass are expected. SSAM age-specific estimates of abundance and biomass (Figure 18) demonstrate that the 10+ group has never been large in terms of numbers but it was large in terms of biomass in the first part of the assessment time-series. Comparisons with ADAPT age-specific estimates provided at the end of this section (Figure 33 and Figure 35) demonstrate that there are plus group differences in abundance compared to ADAPT, but differences in stock-weights (comparison provided in Cadigan and Rideout, 2022) also contribute to the biomass differences in Figure 17

Uncertainty in SSAM biomass estimates is also substantially higher in the first part of the assessment time-series (Figure 17). We expect this is because there are no survey indices in this period to provide information about biomass levels.

Average values of F (Figure 19) are broadly comparable, although the SSAM estimates usually have less inter-annual variation which is expected because this model assumes F's are correlated across years and ages (also see Figure 20 and Figure 21), and that there are measurement errors in the catches so the model does not have to fit the catches exactly. The ADAPT model F-values fit catches exactly.

Recruitment estimates from the SSAM are substantially different than those from ADAPT (Figure 22). This is mostly due to the substantially different M's used by the two models, but also due to the different ages that recruitment represents; that is, age 1 for the SSAM and age 2 for ADAPT. The recruitment trends relative to the mean during 1970-1990 are more similar, although the relative size of some cohorts differed substantially between the SSAM and ADAPT. The predicted log-recruitment deviations (Figure 23) show some temporal patterns and further refinement of the SSAM recruitment model, possibly including a stock-recruitment relationship, may be warranted. However, the recruitment values are strongly affected by the choice of M and we suggest that the priority should be to first get more accurate estimates of M at all ages, and whether M changes over time, before fine-tuning how recruitment is modelled as a function of SSB.

As indicated in the Methods section, we constrained Fall survey catchabilities (q's) to be asymptotic (Figure 24). In effect, we blocked q's to be equal for ages 2-10+ for the Fall survey because in preliminary runs the q's decreased if the blocking was applied at older ages. Partly because of this blocking, the fully selected q for the Fall survey is estimated with high precision. The Spring survey q's are estimated freely for each age and the estimates also have relatively high precision. Therefore, biomass confidence intervals are relatively narrow in time-periods with survey indices (Figure 17). Uncertainty in the EU-Spain survey q's is relatively high, in part because these indices cover fewer years than the DFO Spring and Fall surveys, but also because of the SSAM q-drift applied to the Spanish indices. The q-drift estimates (Figure 25) indicate that the catchability of the Spanish survey indices increased overall during 1997-2015 but declined since then.

An important feature of SSAM's is the process error. Predictions of these errors for 3NO cod are mostly negative at ages 4-10+ since about 2000 (Figure 26 and Figure 27). This indicates that cohorts have declined more than caused by SSAM Z's. A possible reason for this is an increase in M compared to the assumed values used in the model.

There are some retrospective patterns in assessment results (Figure 28 and Figure 29), although retrospective estimates are usually contained within the confidence intervals for the full time-series. This indicates that this SSAM has reasonably accounted for uncertainty in 3NO cod stock dynamics. Other model fit diagnostics are provided in Appendix A (Figure A1 - Figure A8). They do not indicate serious model misspecification.

The choice of landings upper bounds since 1994 had little impact on SSB (Figure 30) or average F's (Figure 31). Model M1 and M3 fit the data similarly and retrospective patterns (Figure A9 - Figure A12) were similar to M2 (Figure 28 and Figure 29).

The M2 biomass levels are smaller than Fall and Spring survey swept-area biomass estimates (Figure 32) but the differences are not substantial and could be caused by biases in the swept area calculations; in particular, the area swept by a trawl. Figure 32 does not indicate the scale of the M2 biomass estimates is seriously wrong.

Differences in ADAPT and SSAM estimates of total biomass and SSB are partly related to differences in estimates of abundance (Figure 33). These differences were small at ages 6-10+ since 1995 (Figure 34), except for the size of the 2006 cohort at ages 8 and 9, and in the 10+ group. Differences in abundance at younger ages are strongly influenced by the different M assumptions used in the ADAPT assessment and the SSAM. Differences in biomass estimates at older ages are larger than the differences in abundance (compare Figure 33 and Figure 35) and this is because of the differences in stock weights used in these two models. However, since 1995, biomass-at-age from both approaches (Figure 36) are more similar in most years. A significant difference in the SSAM model compared to the ADAPT assessment is the historic size of the 10+ group which may be much less of an issue more recently because of apparently poorer survival of 3NO cod.

The stock-recruit patterns from ADAPT (Figure 37) are substantially different than the SSAM (Figure 38 ;M2 formulation). The SSAM suggests a much higher breakpoint for good recruitment. Recruits per spawner (RPS) from ADAPT do not decline at higher levels of SSB which is opposite of what density-dependance theory predicts. The time trends in RPS should follow the opposite pattern of the bottom panel in Figure 37. The SSAM RPS results (Figure 38) are more consistent with basic density-dependence theory, although RPS when SSB > 150 Kt still seems high relative to values at lower SSB's. Another related factor is that the recruitment estimates will be sensitive to assumed values of M, and if M at juveniles ages in the 1960's and 1970's was lower than the values we assumed, compared to recent M's, then this will impact the RPS relationship and bring it even more in line with density dependence theory. This would also have large impacts on reference points. As is often the case in stock assessment, the values we chose for M are somewhat speculative and better information about M would facilitate a more realistic stock assessment.

Discussion

The state-space assessment model (SSAM) we developed for 3NO cod addressed concerns about the reliability of catch statistics, inclusion of a plus group, changes in stock productivity, and inclusion of the EU-Spain survey indices. However, SSAM estimates of SSB since 1990 were still broadly similar to ADAPT estimates. Estimates of SSB during 1960-1990, on the other hand, demonstrated larger differences between the two models as a result of different M assumptions, the inclusion/exclusion of a plus group, and the use of different estimates of fish weights-at-age. We did not parse the specific impacts of these changes. SSAM and ADAPT estimates of F were also broadly similar and more so at ages 6-9 where the specification of M in each model was more similar. The SSAM results were very similar for a range of bounds on fishery catches that were chosen to account for the amorphous uncertainty in this information for 3NO cod. Hence, we conclude that unless uncertainty in catch statistics is substantially different from our sensitivity runs, this uncertainty will not have much affect on stock status conclusions.

The SSAM fit the data well. There were no substantial residual patterns in the fits to survey indices or fishery age compositions. As a result, the SSAM did not have serious retrospective patterns. The scale of the SSAM biomass estimates was about 75% of the DFO Fall RV survey swept-area biomass values which is reasonably close. This implies that the fully selected swept-area Q was about 1.3 and this difference from 1 could easily be accounted for by errors in the swept-area biomass estimation. The good fitting of the SSAM was achieved by using 1) process error, and 2) drift in the EU-Spain survey Q (to account for the fact the EU-Spain survey covers only a small portion of the stock area and therefore selectivity can change if fish move in/out of the survey area). The cost of using these modelling devices is increased uncertainty. Although we did not simulation test the model to check for bias and the accuracy of the uncertainty evaluations, the retrospective fitting indicated that confidence intervals captured estimation uncertainty. However, simulation testing should be conducted before implementing a new stock assessment model. The simulation self-test (e.g. Deroba et al., 2015) is a minimum requirement and this should be conducted in the future before the 3NO cod SSAM is considered for stock advice.

An important difference between the 3NO cod SSAM and ADAPT was in the relationship between recruitment and parental SSB, and implications for biomass limit reference points. The SSAM results indicated poor recruitment occurred below about 150 000 tonnes of SSB, whereas the ADAPT model results indicated poor recruitment below about 60 000 tonnes. This difference is due to the combined effects of including a plus group in the assessment model, different estimates of stock weights, different choices for M, and including process error in the SSAM. The relationship between stock size and subsequent recruitment is notoriously difficult to estimate. Ideally, we expect the relationship to exist for SSB and egg production, but lacking the necessary data to estimate egg production, we use recruitment at an older age as a proxy. Conceptually, stock abundance at age one should provide a better proxy for egg production than abundance at older ages. However, a problem is that we expected natural mortality to be higher and have more interannual variation for younger ages, but we have little information about this. For example, if M at age 1 has shifted over time (higher or lower) then this will have a direct impact on the stock-recruit relationship. This is a source of uncertainty that the SSAM does not account for and suggests that the SSAM and ADAPT stock-recruit relationships are highly uncertain, especially for the purpose of finding breakpoints in the relationship. Defining recruitment at an older age only compounds this problem because of variation in M between age 1 and an older age (e.g. age 3). MSY-based reference points may be less sensitive to tenuous assumptions about M at young ages.

Our 3NO cod SSAM has process error which may partially account for time-variation in M, but not completely. The process errors only directly affect the cohort survival equation and do not directly affect the Baranov catch equation. M should affect both equations. This is what Aldrin et al. (2019, 2020) recommended. Cadigan (2016) included multiplicative process error for M but used extensive tagging data to help estimate how M has changed over time for cod in NAFO Divisions 2J3KL. In the 2022 assessment framework of cod in NAFO Divisions 3Pn4RS, a state-space model was accepted (pending minor revisions) with time-varying M and implemented without using tagging data for model fitting, although time-varying (age-invariant) M has been a part of the 3Pn4RS cod assessment since the late 1990s. However, including time-varying M can lead to convergence issues and possibly a lack of robustness (ICES, 2020), so this type of model is not always straight-forward to develop. The state-space assessment model for 3Ps cod (DFO, 2021) used information on changes in body condition as an index of M, partially motivated by the positive relationship between the fraction of 2J3KL cod in poor condition and the assessment model estimates of M (Regular et al., 2022). This has also recently been investigated for Icelandic cod (Björnsson et al, 2022). Assessment models for other stocks are currently being developed that include estimation of time-varying M. Zhang et al. (2020) found large-scale synchronized dynamics of oscillating but overall decreasing juvenile cod mortality rates during 1994-2016 for stocks off the coasts of Newfoundland and Labrador. Extending their investigations to include updated and longer survey index time-series and potential drivers of M variation could inform the specification of M at young ages in the 3NO cod SSAM. Hence, we conclude that the treatment of M in our 3NO cod SSAM requires further research.

Another issue involves the treatment of age composition information. In many stock assessments (e.g. Stock synthesis; Methot and Wetzel, 2013), the age-composition sampling information and sample sizes are used when modelling the uncertainty in composition data. The sample sizes are often highly influential on fishing mortality rate estimates. However, this information is not readily available for 3NO cod, especially for fisheries prior to the 1990's. The approach we implemented was a pragmatic solution but it does not directly account for the sampling uncertainty in age compositions. Our approach is the 'poor cousin' of the state-of-the-art for modelling age compositions. Also, age-compositions of catches have borrowed some information from surveys in the same year, and fishery sampling in previous years. Hence, there is a lack of independence in the age-compositions that our model has only partially addressed. Ideally, a model should use length composition data and age-length keys for the various fleets where the data exists. A fully integrated model does not need regular age sampling but the model estimation is improved when annual information is available.

The Spanish survey q-drift estimates suggests that the fraction of the stock in the NRA increased during 1997-2015 but has declined since then. It will be useful to investigate if the DFO RV spring/fall spatial survey information also indicate that the stock distribution in 2016-2019 shifted away from the NRA. Spring/Fall centers of gravity time-series could give this information. This will provide some validation, or not, of the Spanish survey q-drift estimates.

Although the maturities are modelled by cohort, there are still some large between-year changes in maturity and further analyses of this temporal variation seems useful (e.g., Cadigan et al., 2014; Zheng et al., 2020). The same can be said for length-at-age and weight-at-length, the latter of which is currently under way to understand how 3NO cod condition has varied over space, time, and size.

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Figures

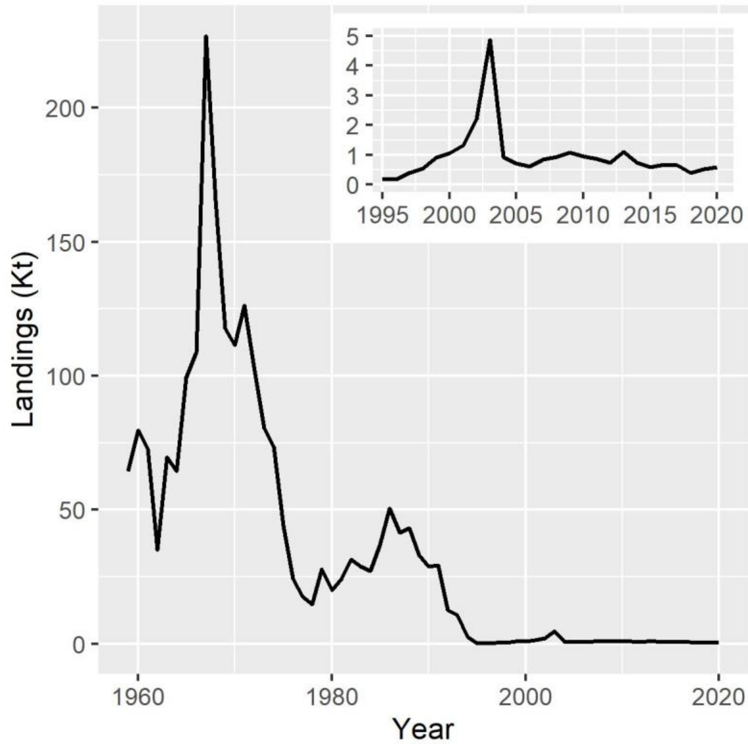

Figure 1. Estimates of total fishery landings of cod in NAFO Divisions 3NO. The inset figure shows landings since 1995.

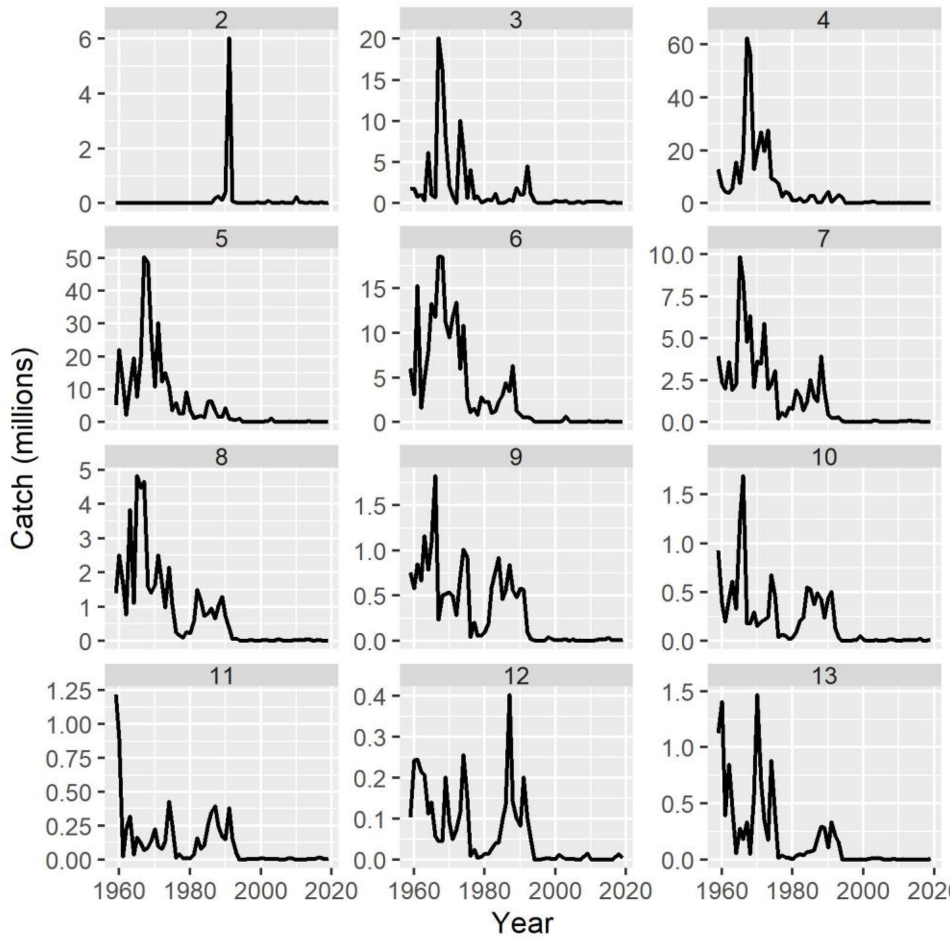

Figure 2. Estimated catch abundance at age for cod in NAFO Divisions 3NO. Age 13 is a plus group.

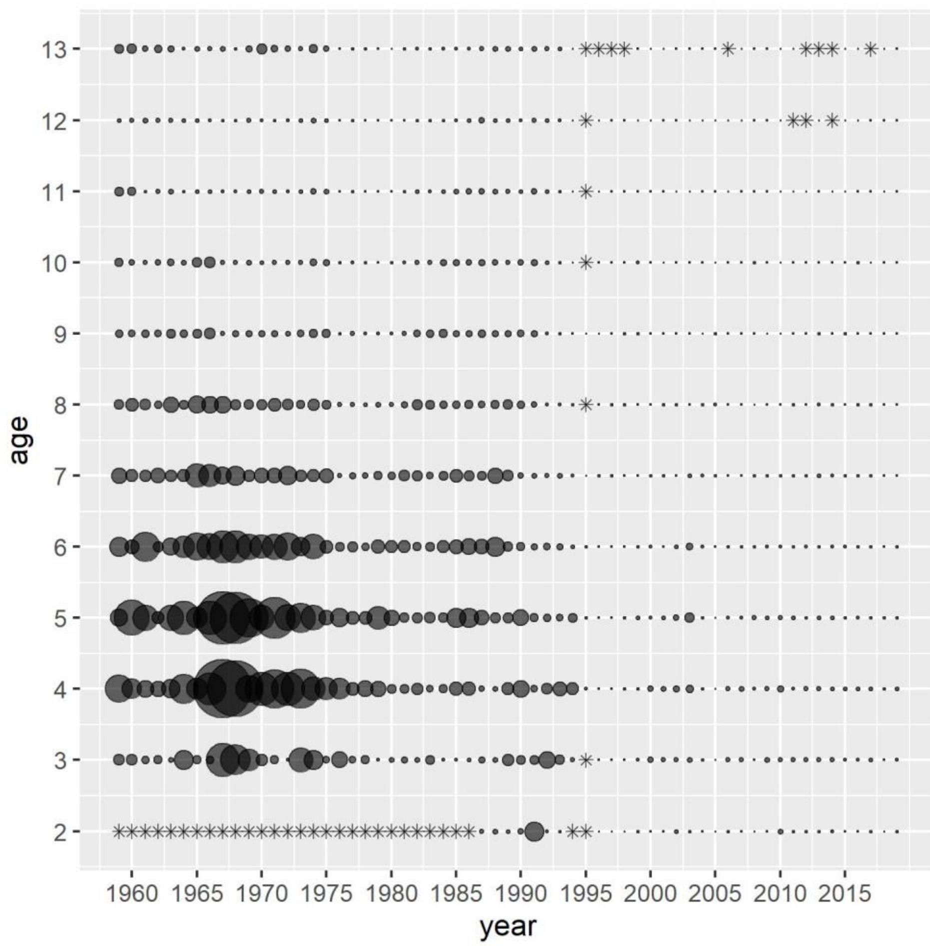

Figure 3. Bubble plot of catch abundance at age for cod in NAFO Divisions 3NO. The area of a bubble is proportional to the size of the catch, and zeros are indicated by a *.

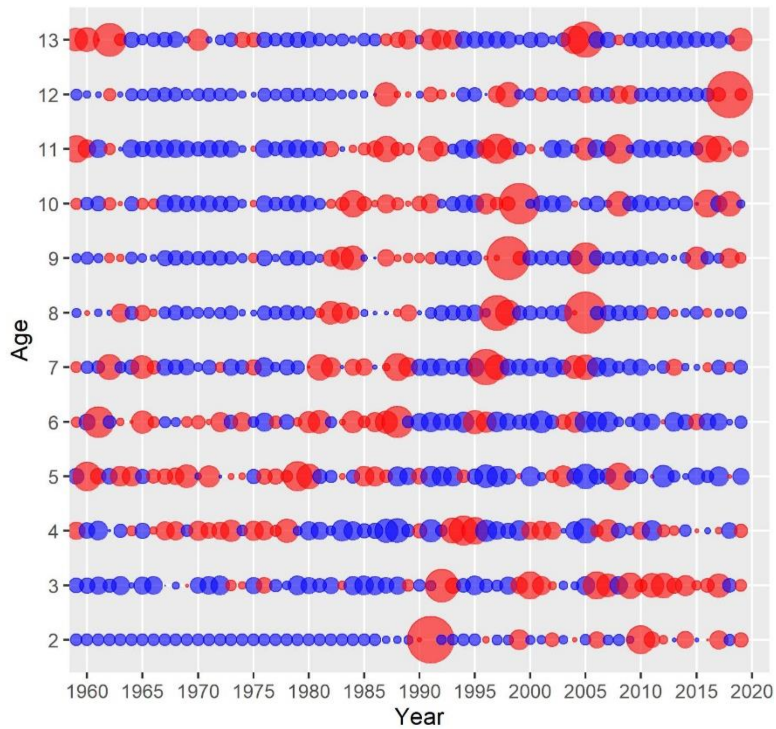

Figure 4. Standardized proportion-at-age (SPAY) for the catch-at-age. The area of a bubble is proportional to the absolute value of the standardized proportion. Red is positive and blue is negative.

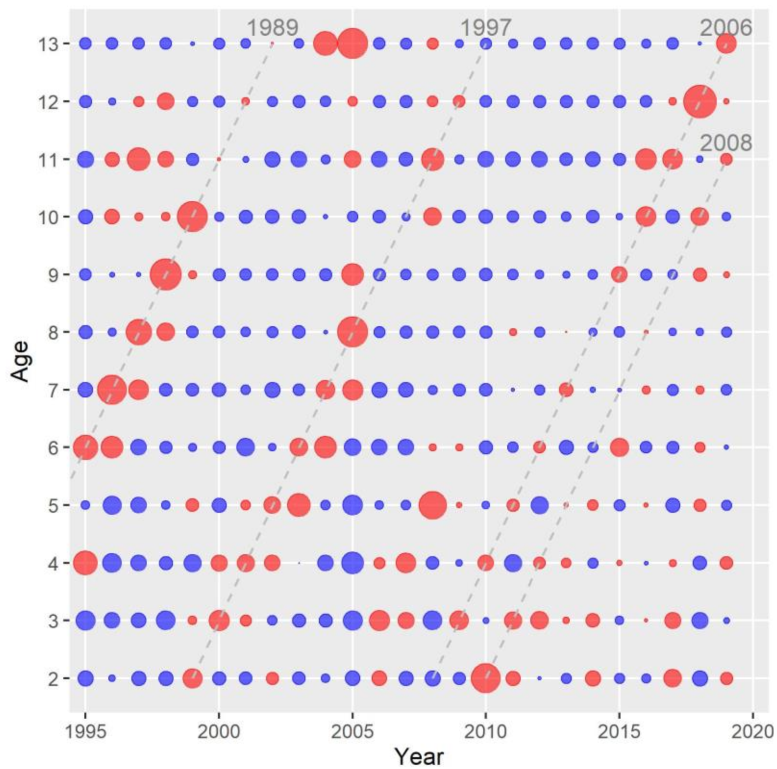

Figure 5. Standardized proportion-at-age (SPAY) for the catch-at-age since 1995. The area of a bubble is proportional to the absolute value of the standardized proportion. Red is positive and blue is negative. Dashed lines follow several pronounced cohorts.

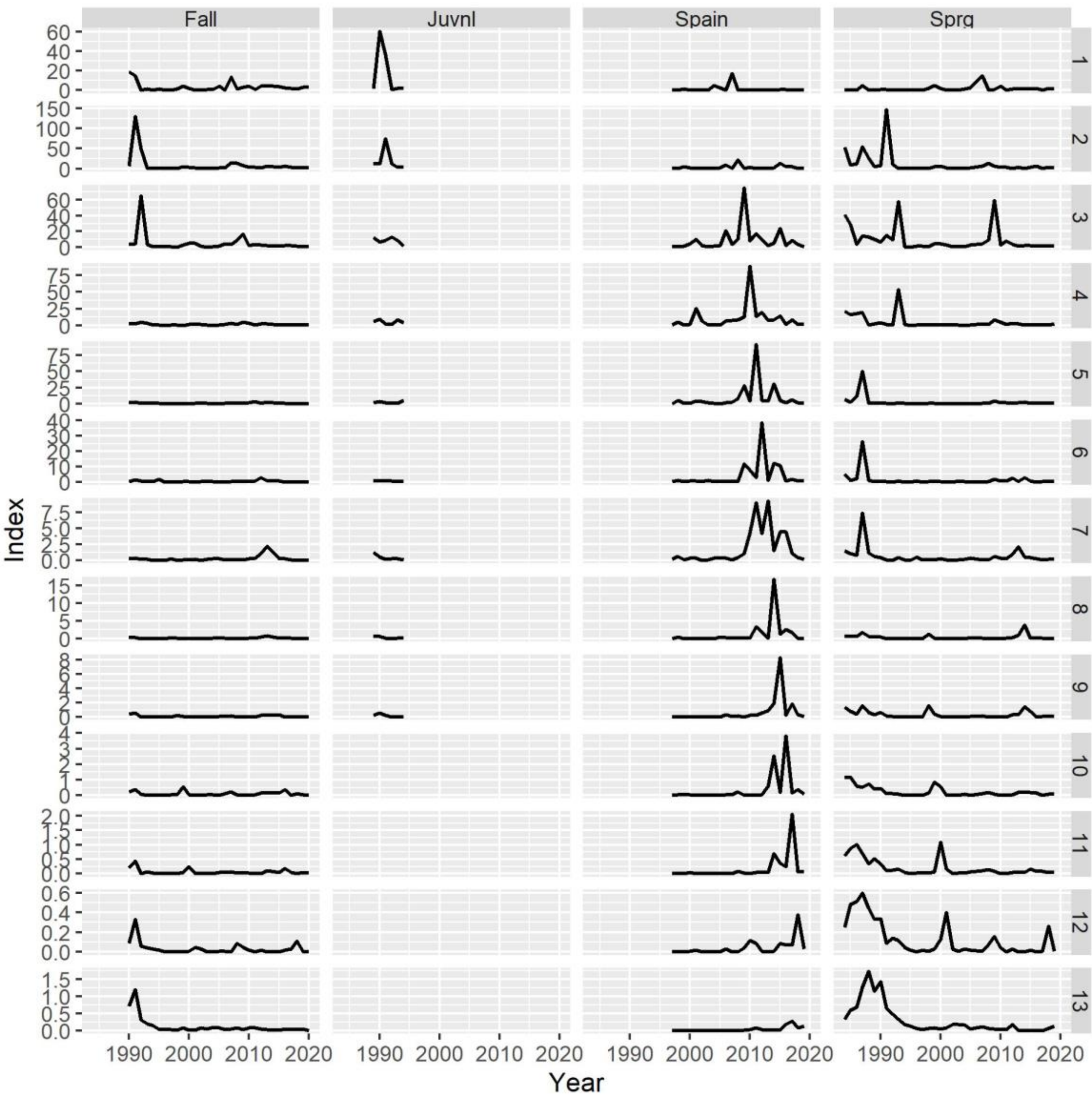

Figure 6. Survey indices (mean number per tow) time-series for cod in NAFO Divisions 3NO. Columns are for different surveys and rows are for ages.

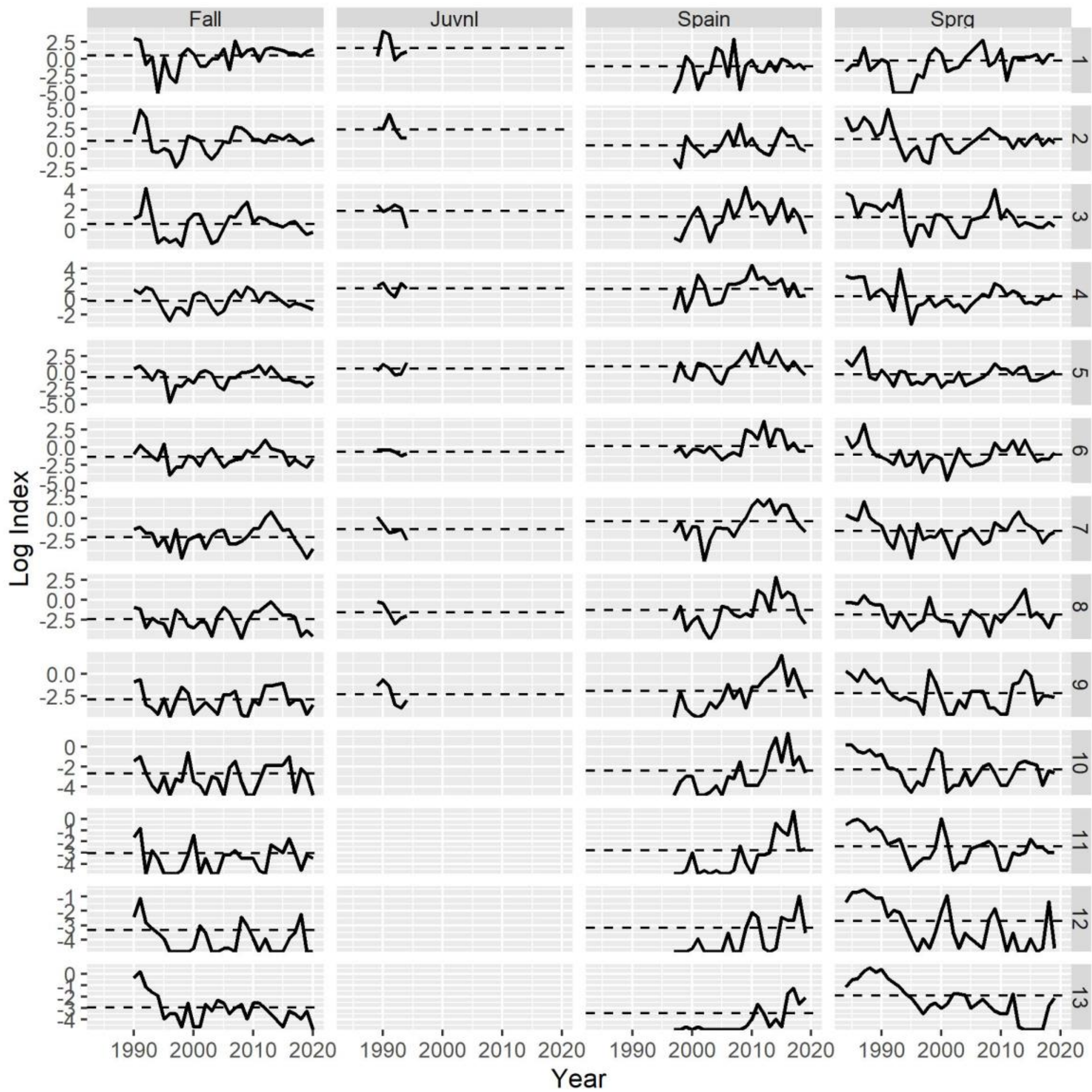

Figure 7. Survey indices (log mean number per tow) time-series for cod in NAFO Divisions 3NO. Columns are for different surveys and rows are for ages. Horizontal lines indicate the series average (but zero's removed).

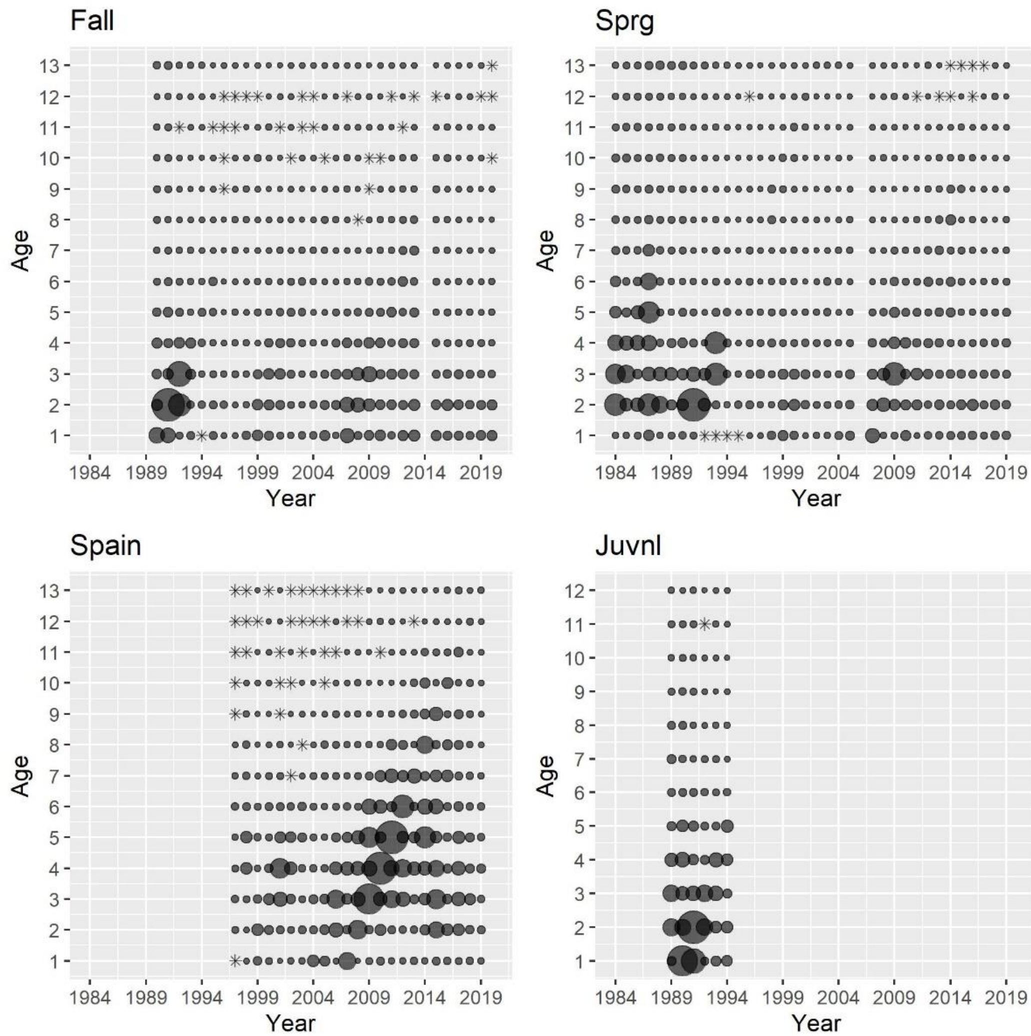

Figure 8. Mean number per tow at age for cod in NAFO Divs. 3NO from RV surveys. The area of a bubble is proportional to the size of the survey index (mean number per tow), and zeros are indicated by a *.

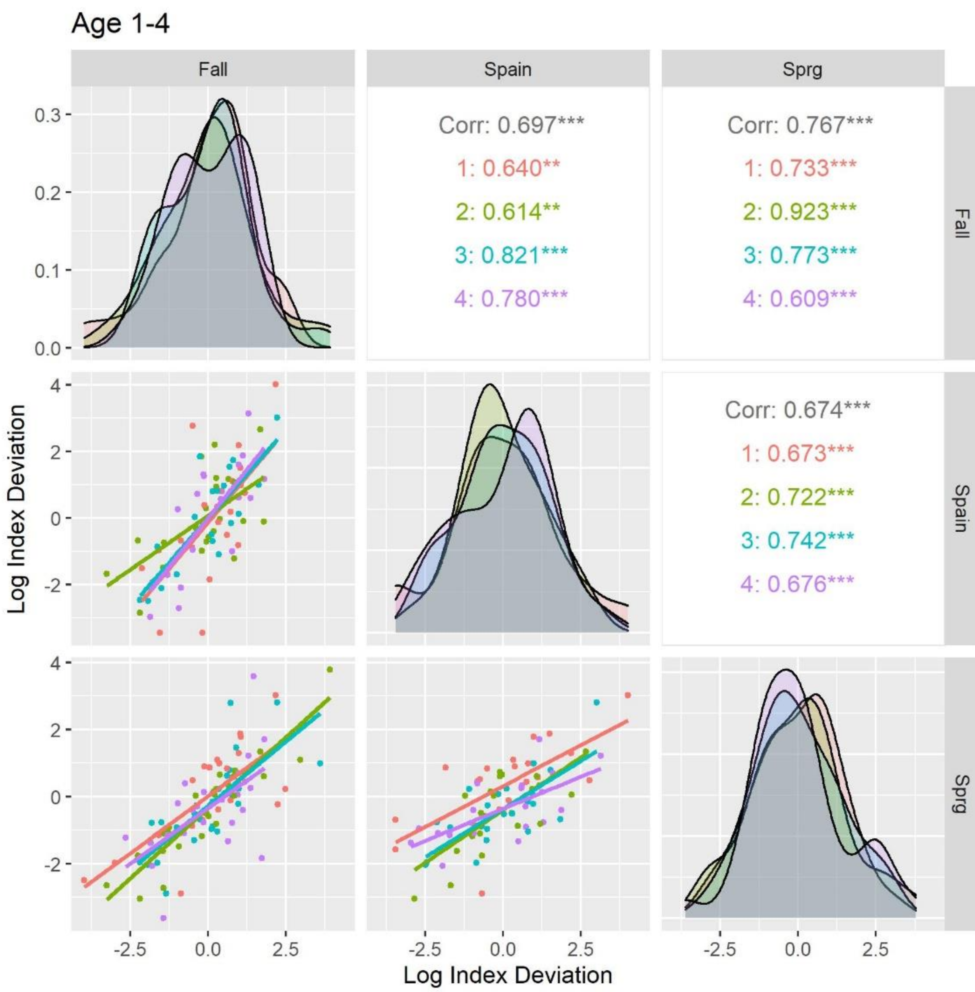

Figure 9. Between-survey correlations of log indices for ages 1-4. Correlations are listed in the upper triangle panels and the colors correspond to ages. The main correlation in black is for all ages 1-4.

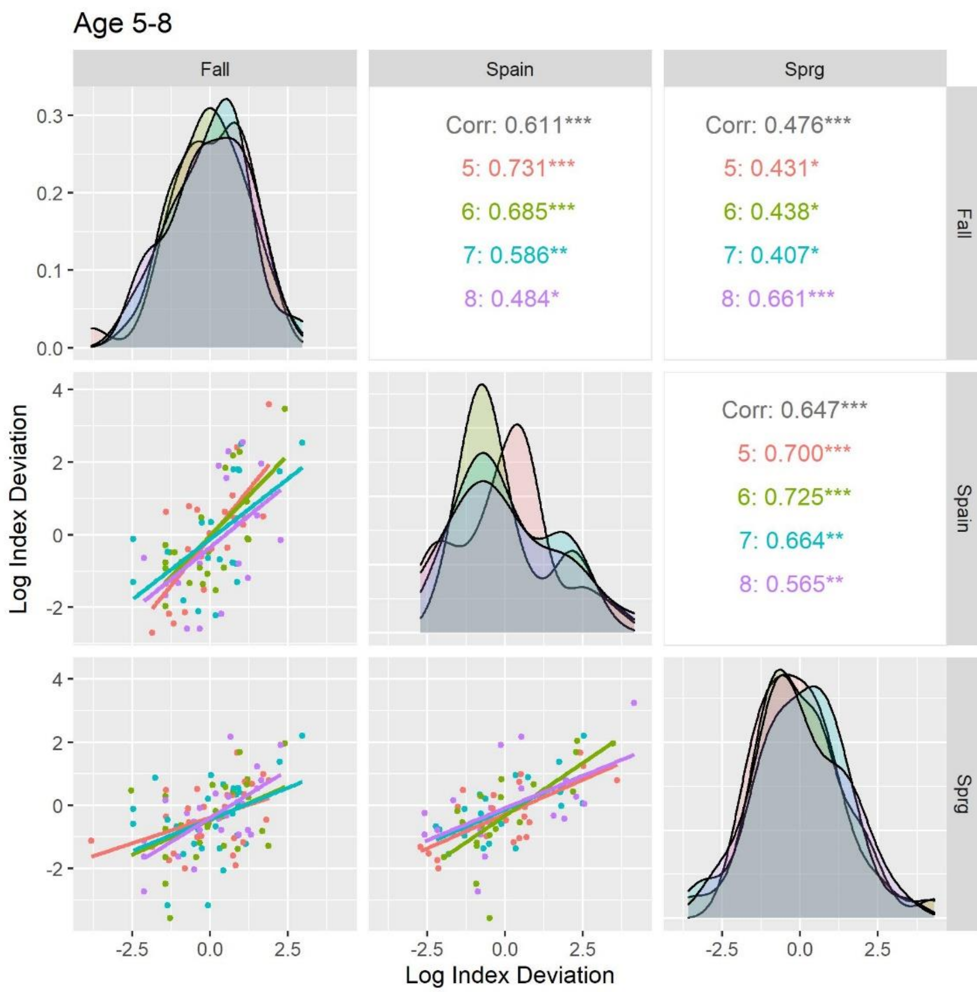

Figure 10. Between-survey correlations of log indices for ages 5-8. Correlations are listed in the upper triangle panels and the colors correspond to ages. The main correlation in black is for all ages 5-8.

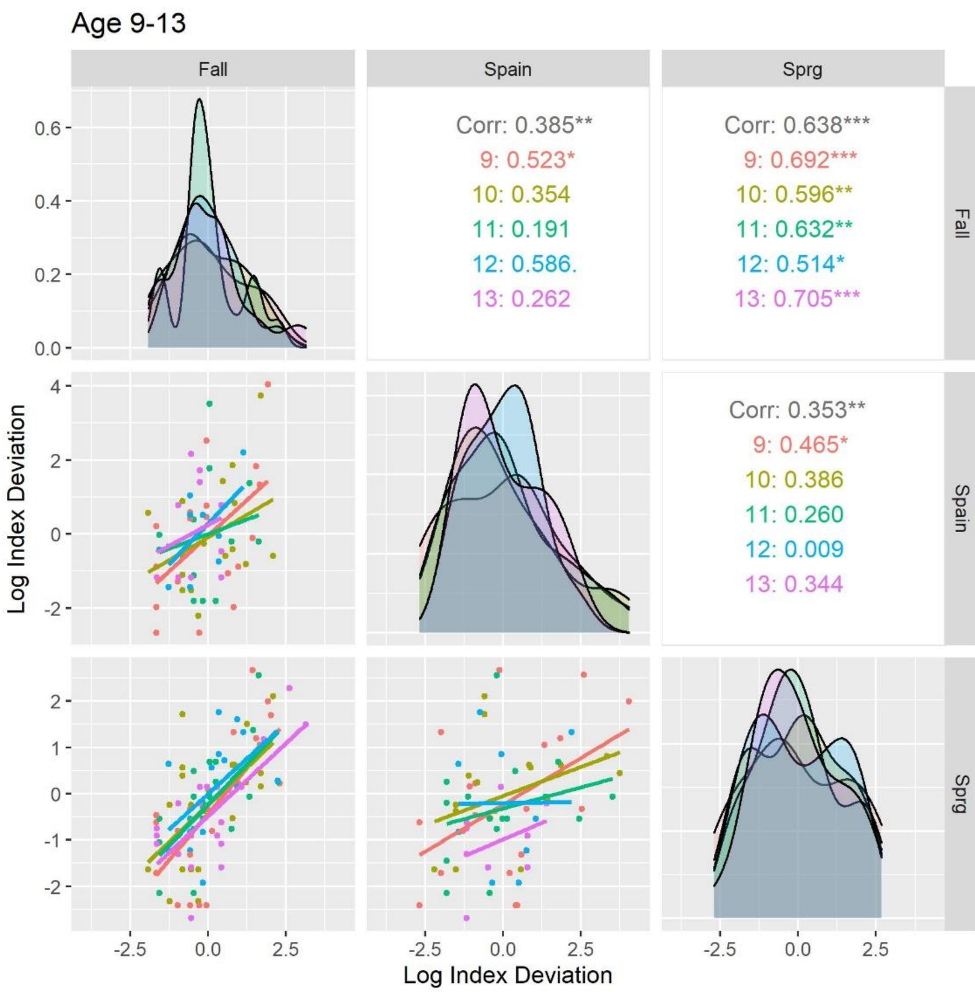

Figure 11. Between-survey correlations of log indices for ages 9-13. Correlations are listed in the upper triangle panels and the colors correspond to ages. The main correlation in black is for all ages 9-13.

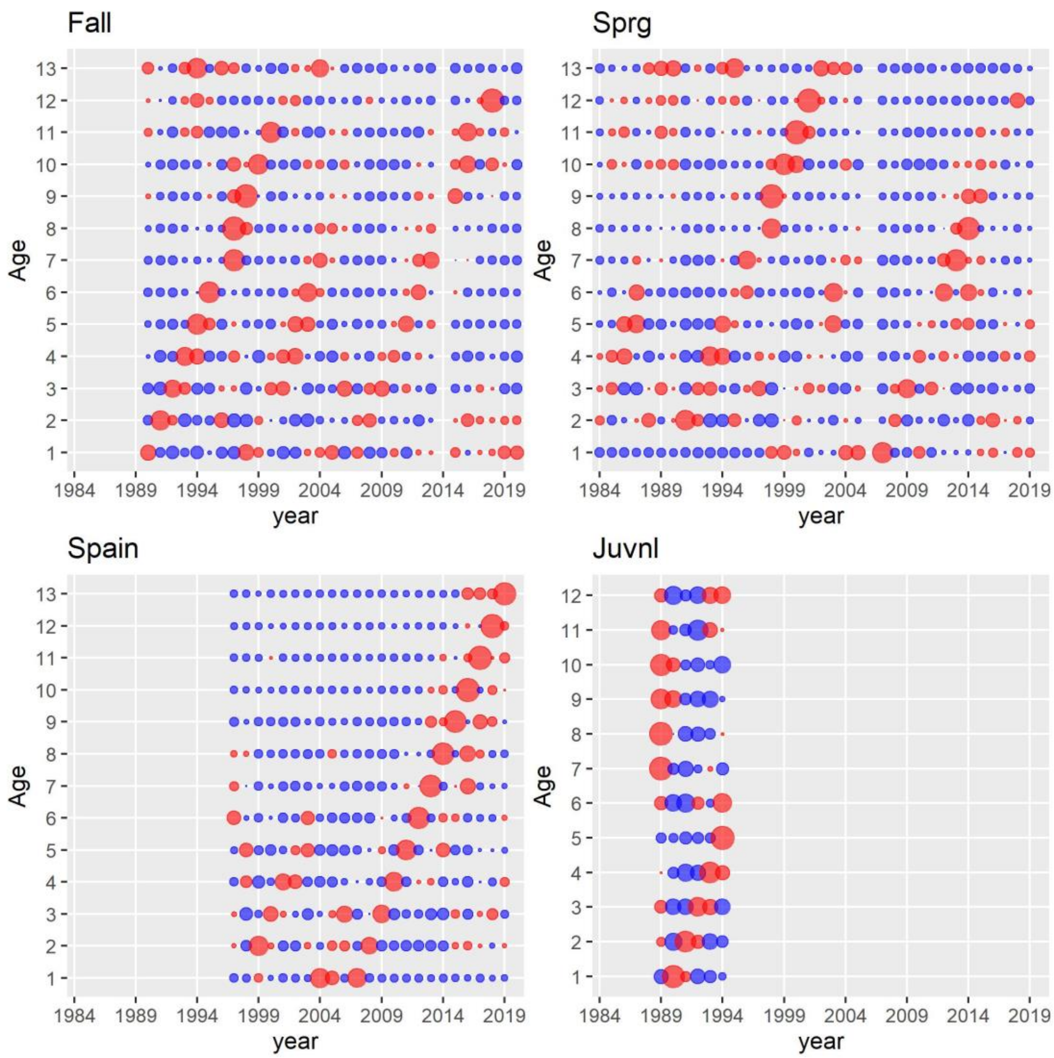

Figure 12. Standardized proportion-at-age (SPAY) for cod in NAFO Divs. 3NO for each survey index time-series. The area of a bubble is proportional to the absolute value of the standardized proportion. Red is positive and blue is negative.

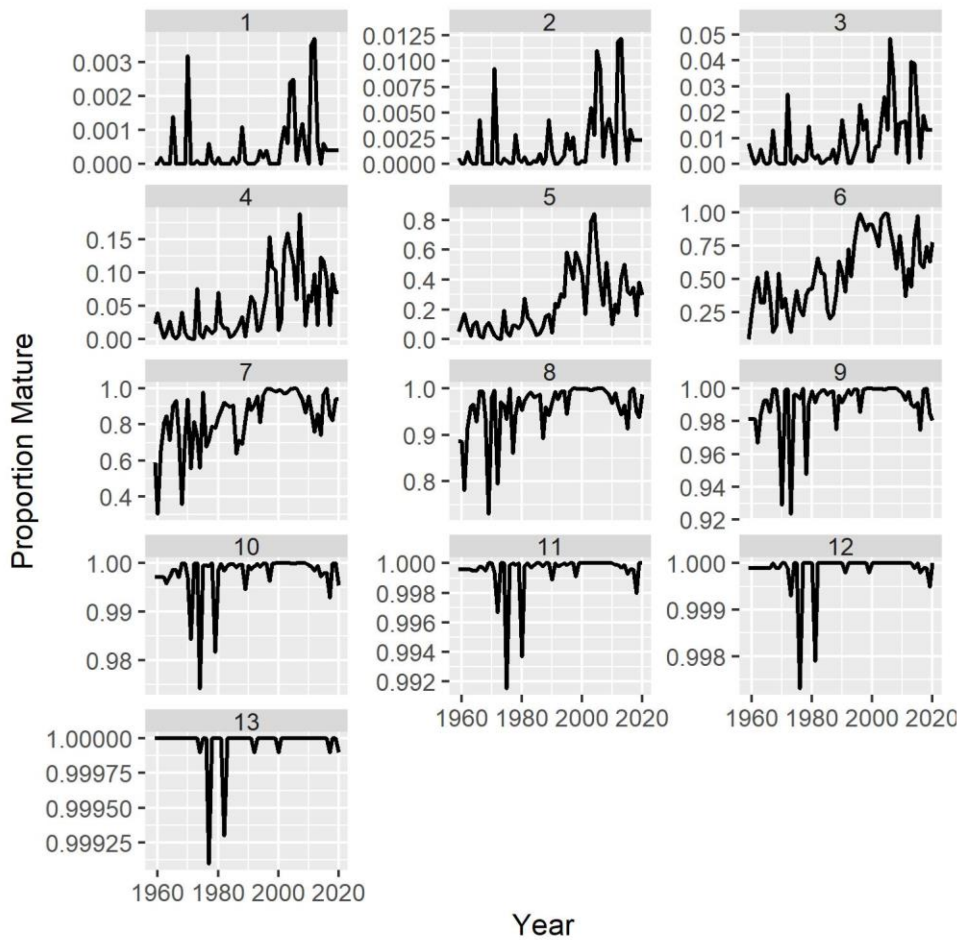

Figure 13. Proportion mature at age for cod in NAFO Divs. 3NO.

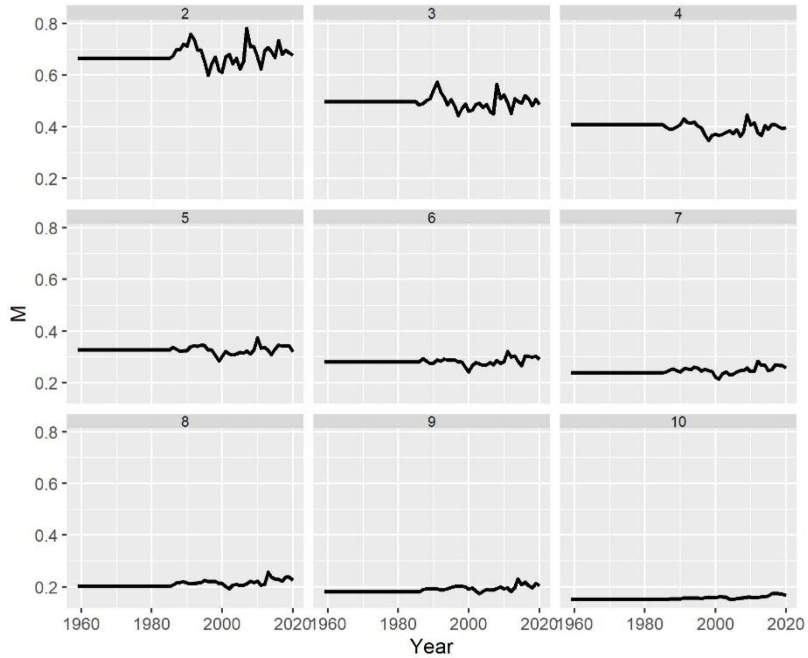

Figure 14. Preliminary M values.

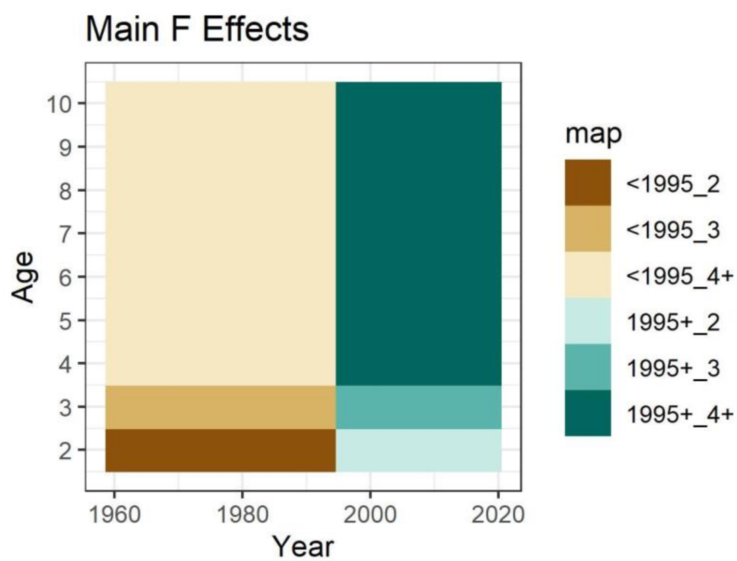

Figure 15. Illustration of the six age-year blocks used in the estimation of F. Note that ages 2 and 3 are historically not targeted the same as older and larger fish, and the moratorium on directed fishing started in 1994. Each color block has an F main effect parameter.

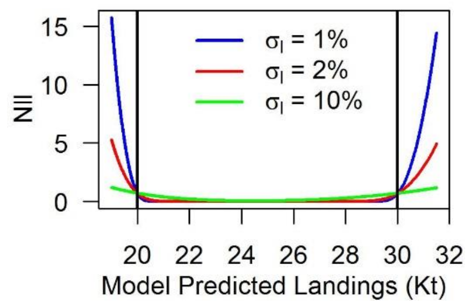

Figure 16. Censored nll's for a range of model predicted landings, using three choices of $\boldsymbol{\sigma_l}$. Vertical solid black lines indicate the lower and upper bounds.

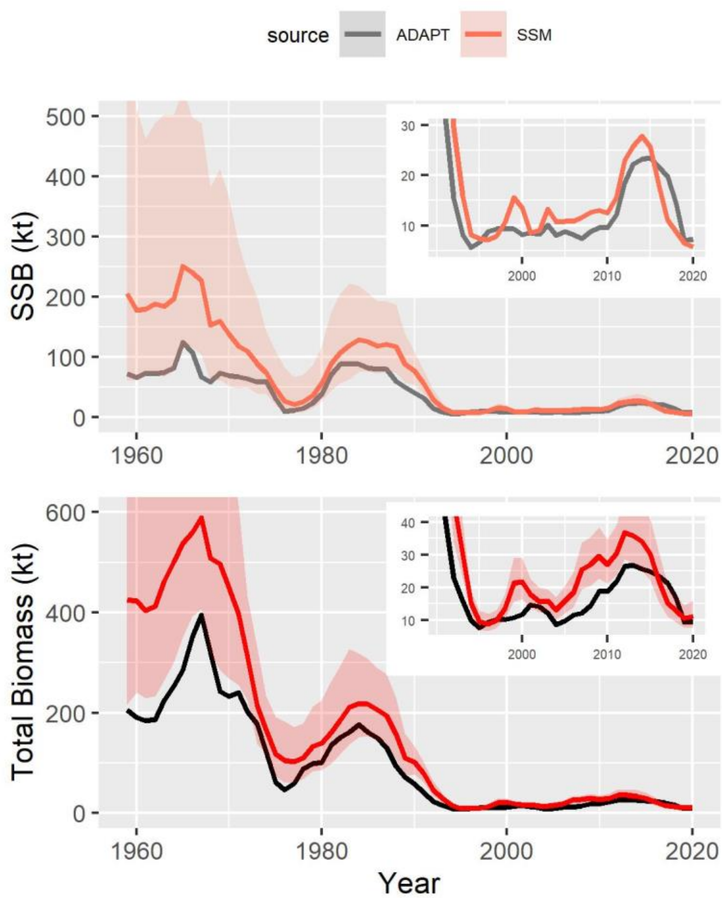

Figure 17. M2 estimates of SSB and total biomass compared to ADAPT results. Line colors indicate assessment models which are defined at the top. Shaded regions indicate 95% confidence intervals. Inset figures focus on estimates since 1990.

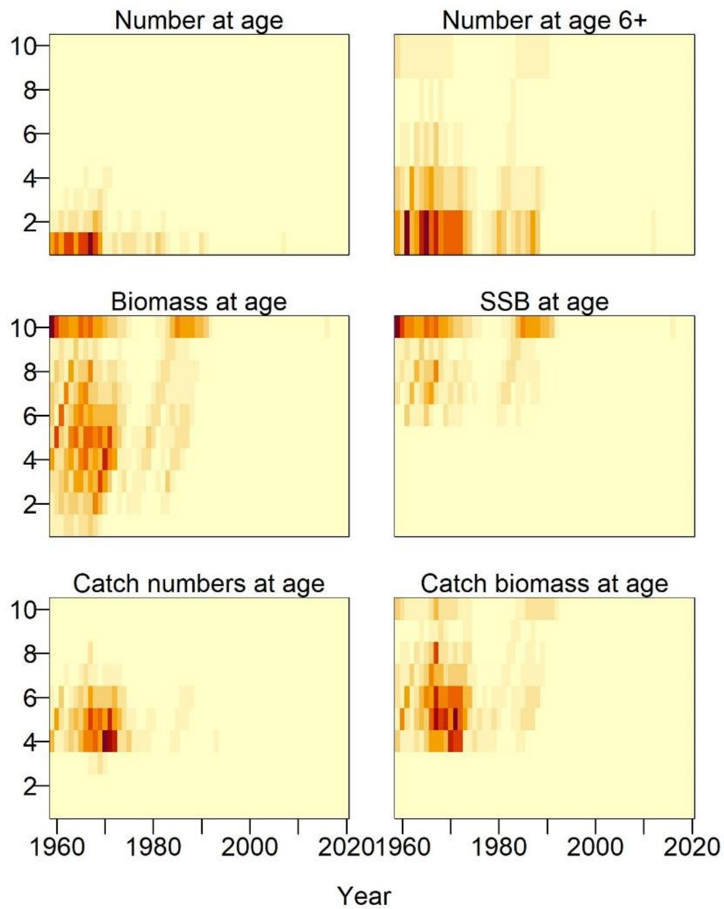

Figure 18. M2 estimates of age-based quantities defined at the top of each panel. Darker colors indicate higher estimates. Catches are model predicted.

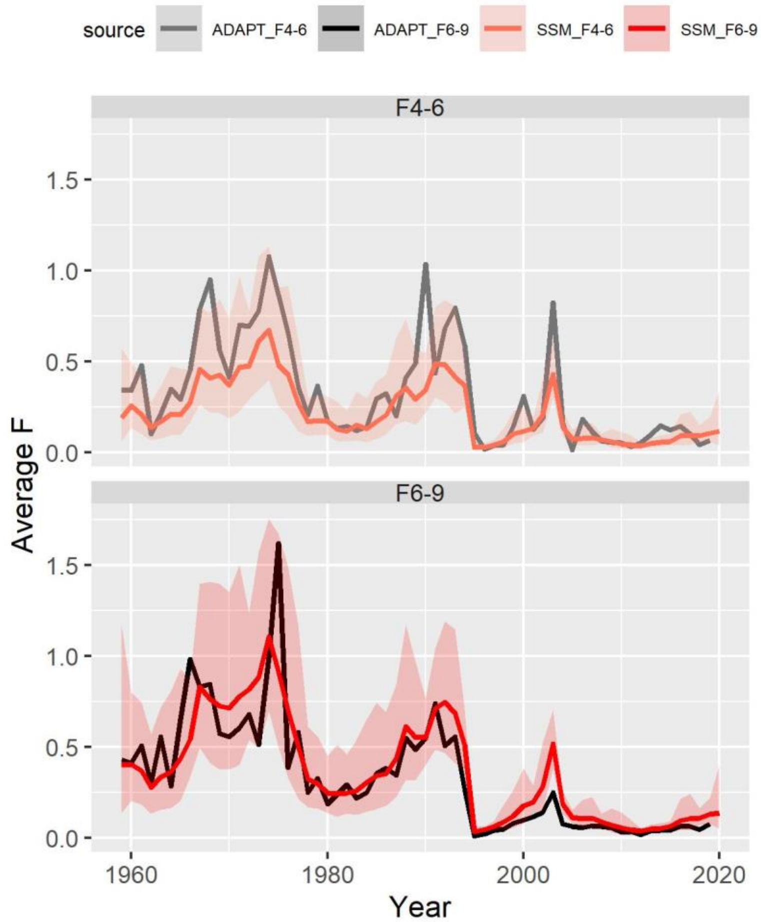

Figure 19. M2 estimates of average F at ages 4-6 and 6-9 compared to ADAPT results. Line colors indicate assessment models which are defined at the top. Shaded regions indicate 95% confidence intervals.

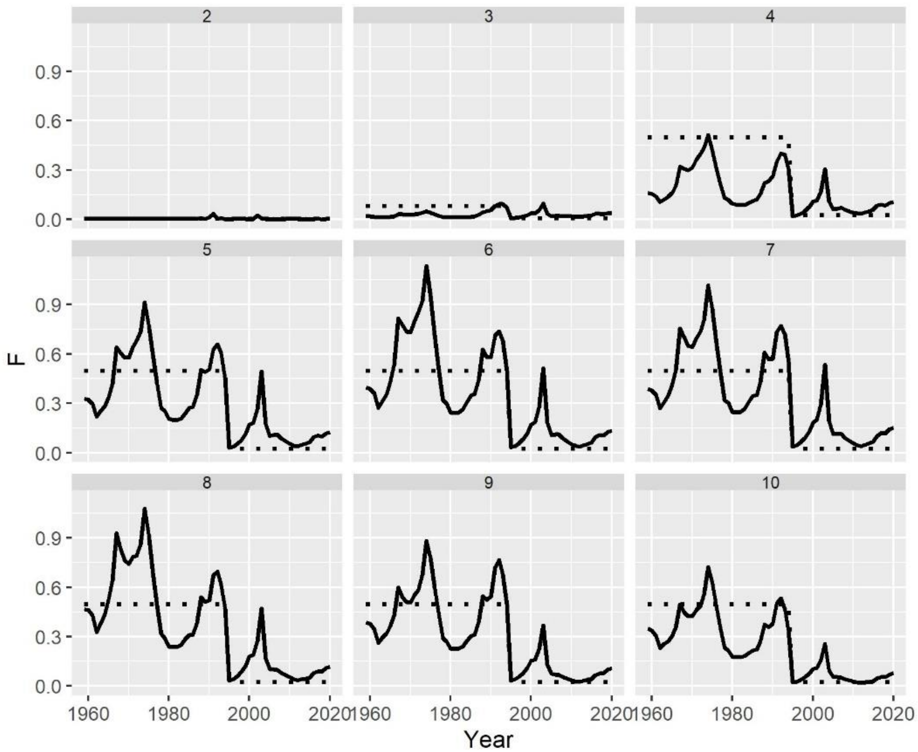

Figure 20. M2 estimates of fishing mortalities at age age (panels). The dotted lines indicate the mean F's indicate for time-blocks.

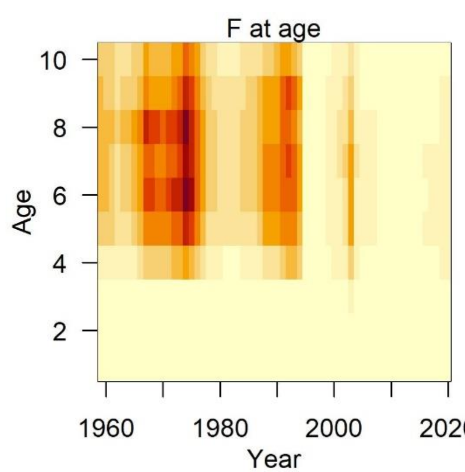

Figure 21. M2 illustration of F's. Darker colors indicate higher estimates.

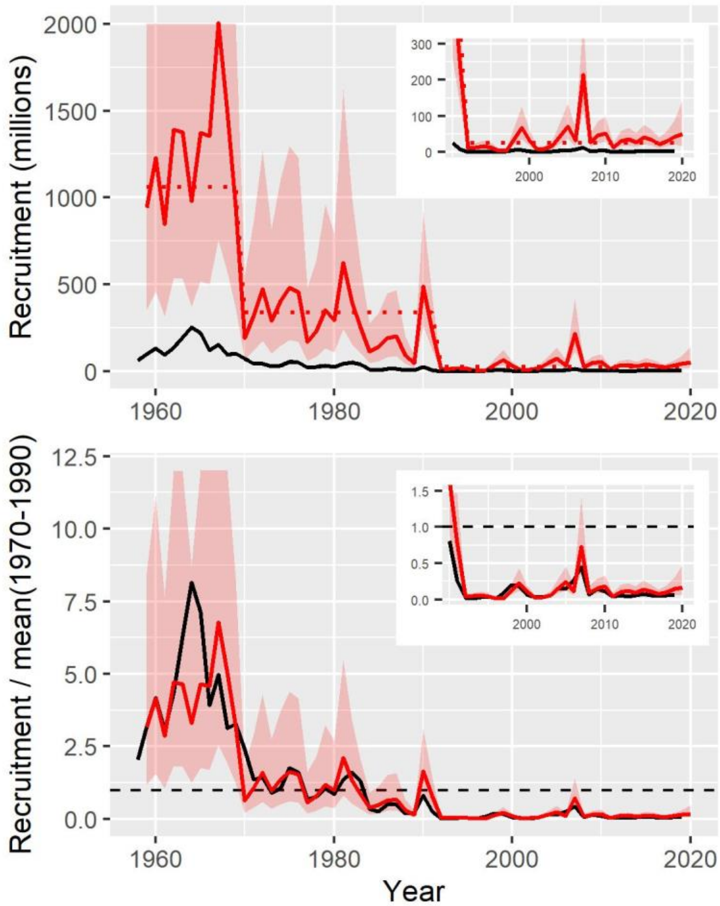

Figure 22. Top panel: M2 estimates of recruitment (red lines) at age 1 compared to ADAPT results (black lines). The dashed red lines indicate the recruitment means estimate for three time-blocks. Shaded regions indicate 95% confidence intervals. Inset figures focus on estimates since 1990. ADAPT recruitment is at age 2 and it was back shifted one year to indicate the same cohorts as the SSAM. Bottom panel: Recruitment relative to the mean for each series (i.e. SSAM and ADAPT) during 1970-1990.

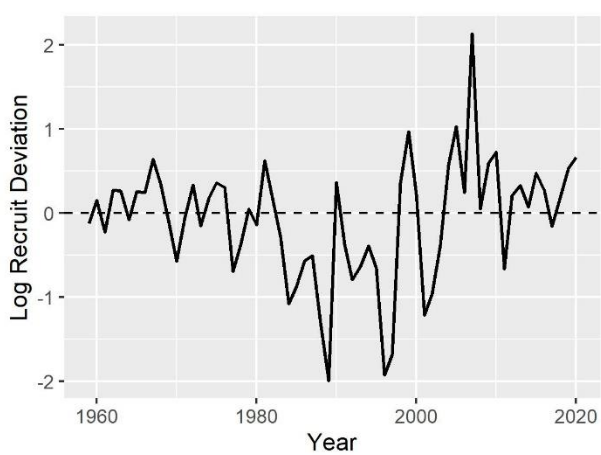

Figure 23. M2 recruitment deviations.

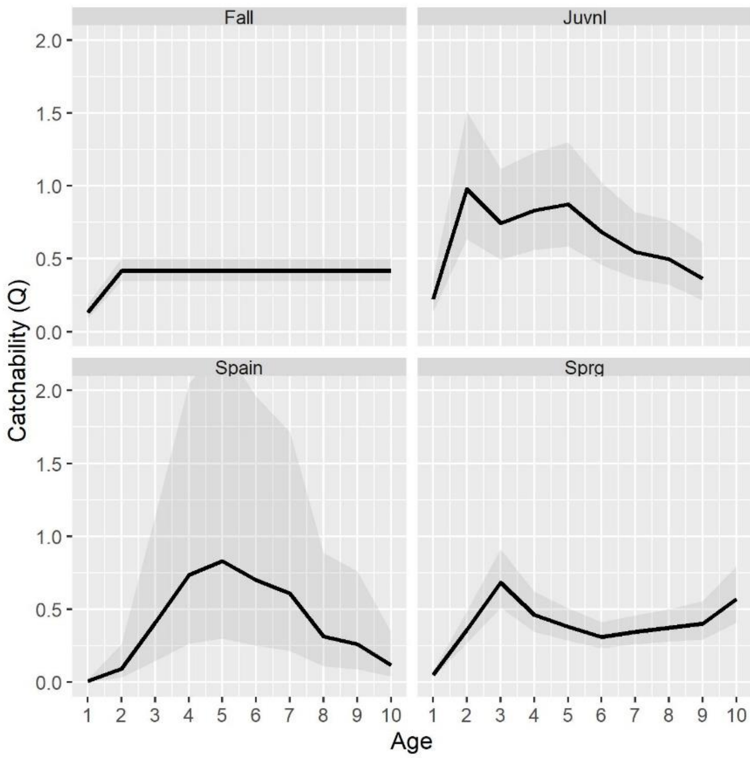

Figure 24. Estimates of survey index catchabilities. Shaded regions indicate 95% confidence intervals.

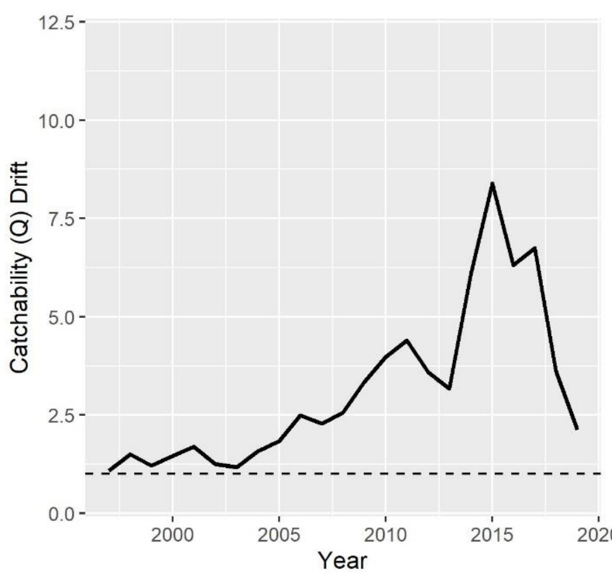

Figure 25. M2 estimates of q-drift for the Spanish survey indices. A dashed line at one is shown for reference.

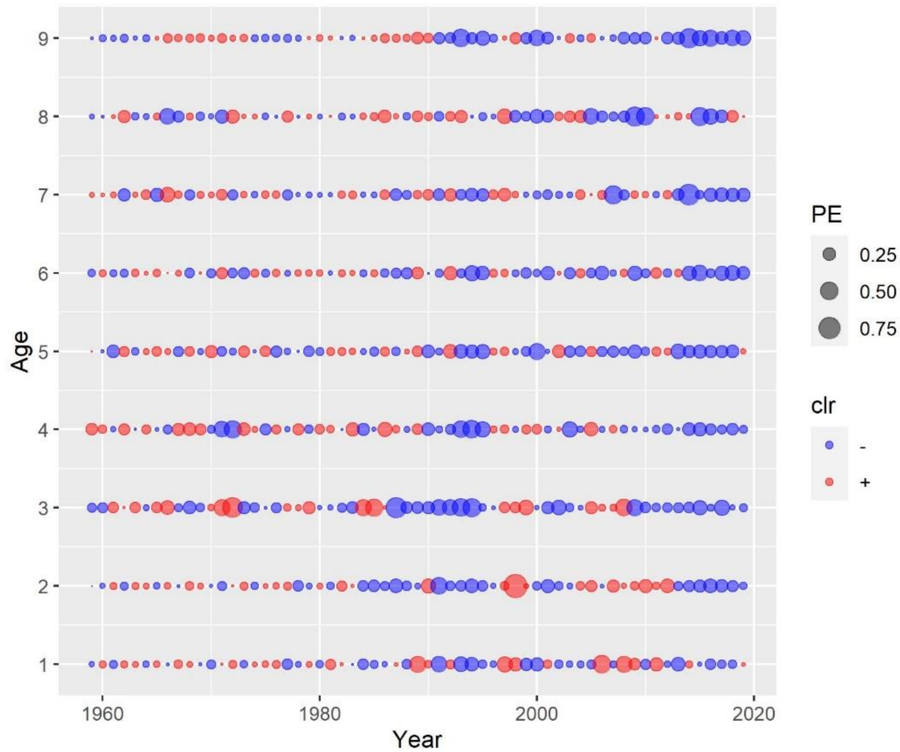

Figure 26. M2 process error predictions. The area of a bubble is proportional to the absolute value. Red is positive and blue if negative.

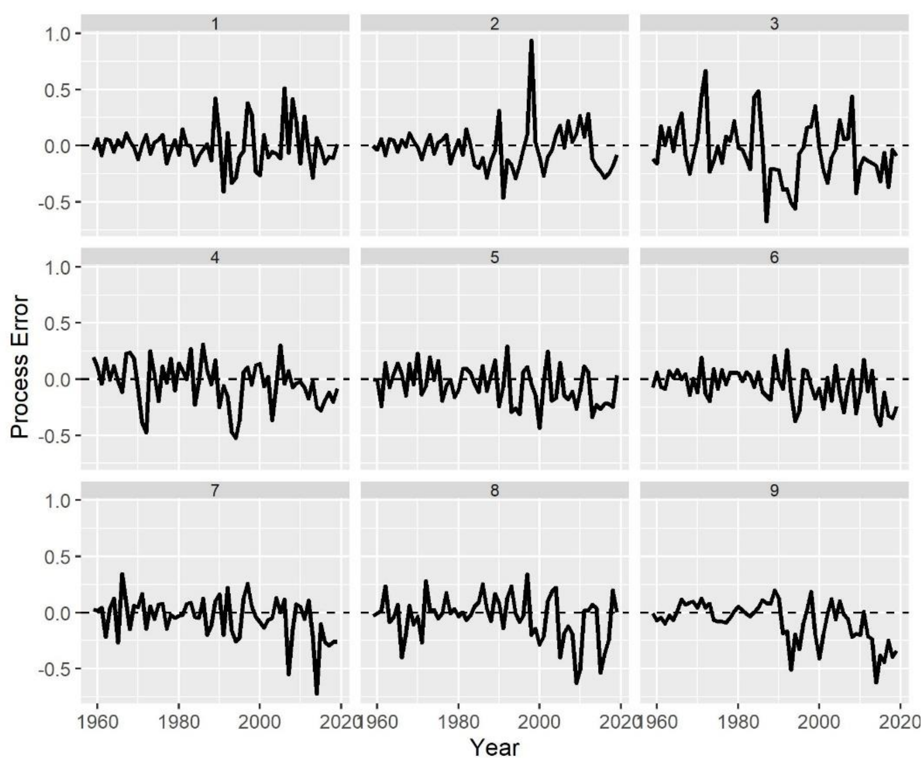

Figure 27. M2 process error predictions for each age (panels).

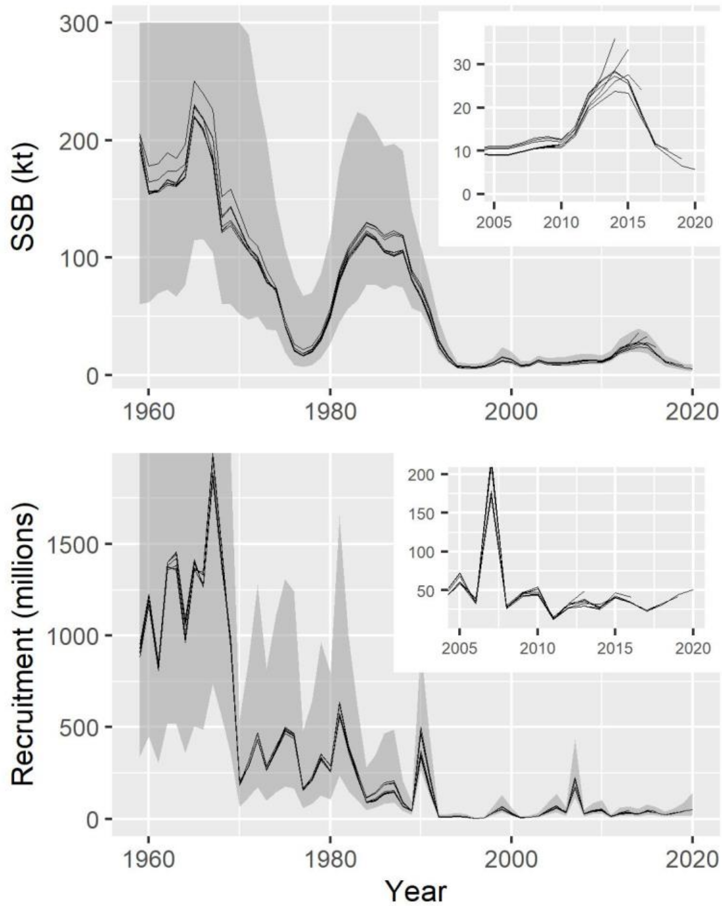

Figure 28. M2 retrospective estimates of SSB (top panel) and recruitment (bottom panel). Shaded regions indicate 95% confidence intervals based on the full time-series of data. Inset figures show trends since 2005.

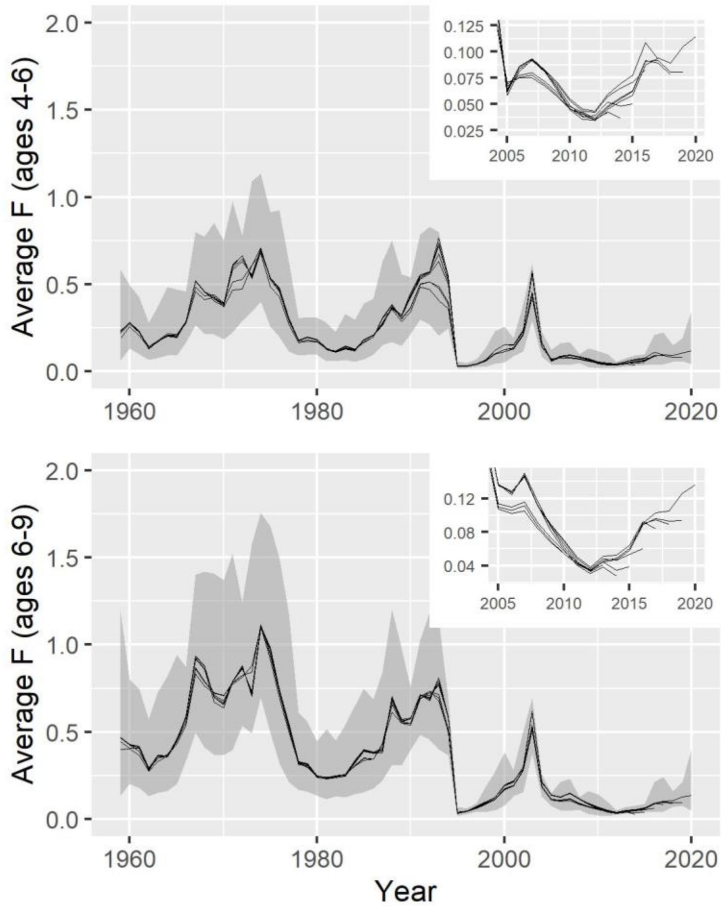

Figure 29. M2 retrospective estimates of average F at ages 4-6 (top panel) and 6-9 (bottom panel). Shaded regions indicate 95% confidence intervals based on the full time-series of data. Inset figures show trends since 2005.

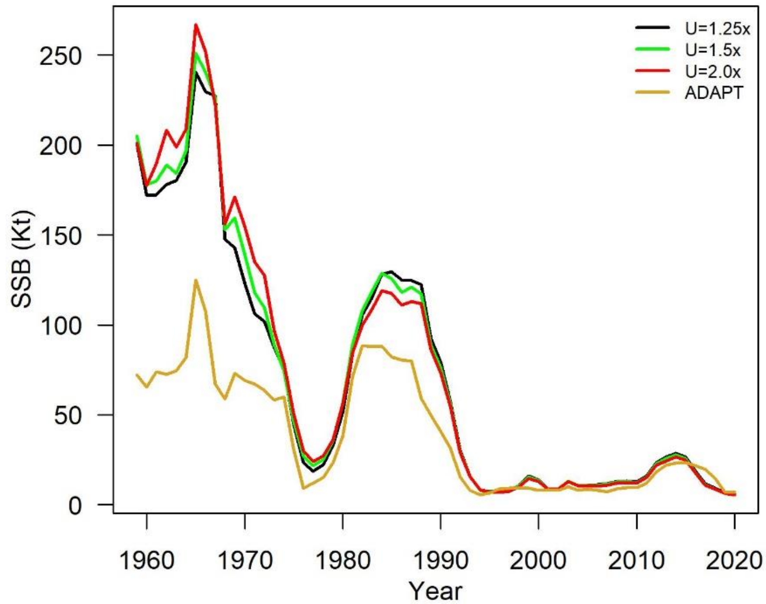

Figure 30. Comparison of SSB from three SSAM's (M1-M3) with different upper bounds on landings since 1994 (U option line colors shown in legend). ADAPT estimates of SSB at ages 2-12 are shown for reference.

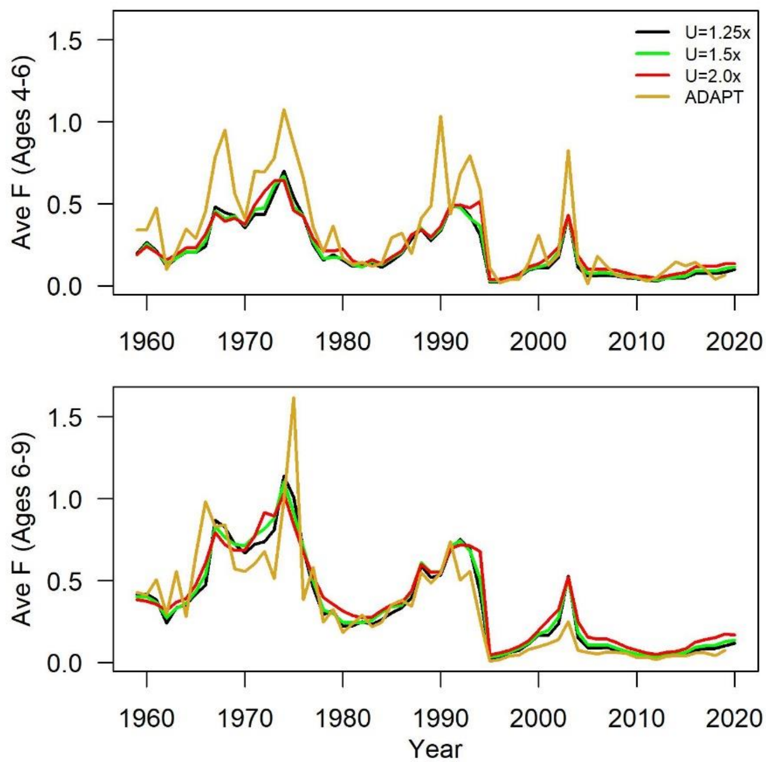

Figure 31. Comparison of average F at ages 4-6 (top panel) and 6-9 (bottom panel) from three SSAM's (M1-M3) with different upper bounds on landings since 1994 (U option line colors shown in legend) and ADAPT.

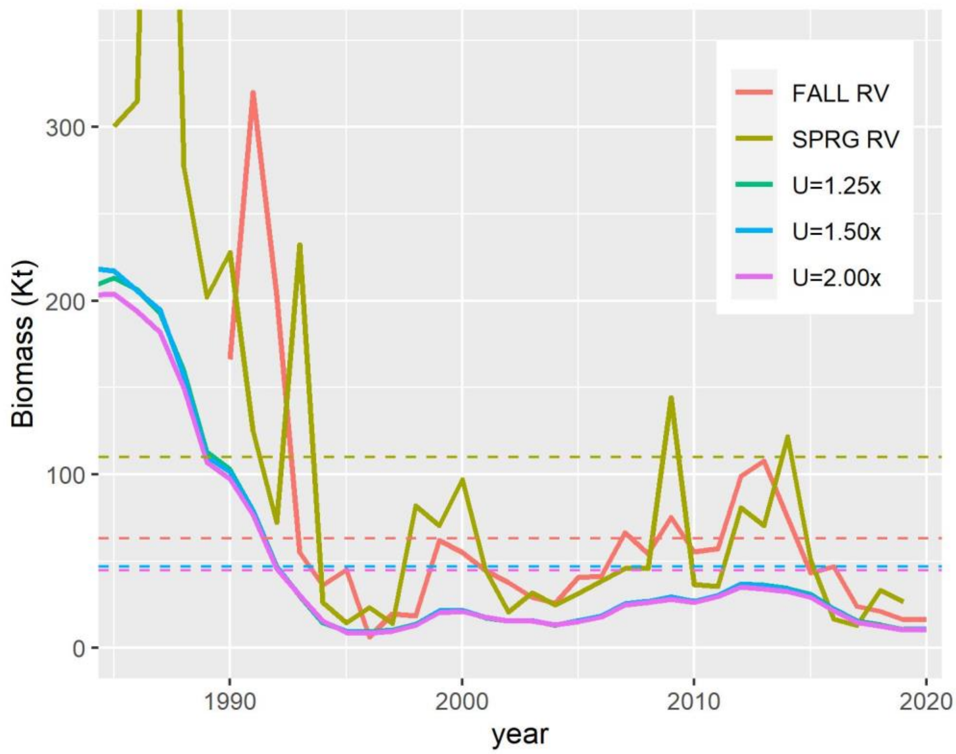

Figure 32. Comparison on M1-M3 (U = 1.25x, 1.5x, and 2.0x respectively) SSAM estimates of stock biomass and swept-area biomass for the Fall and Spring DFO RV surveys. Horizontal lines indicate the series averages. Line colors correspond to model or survey and are defined in the legend.

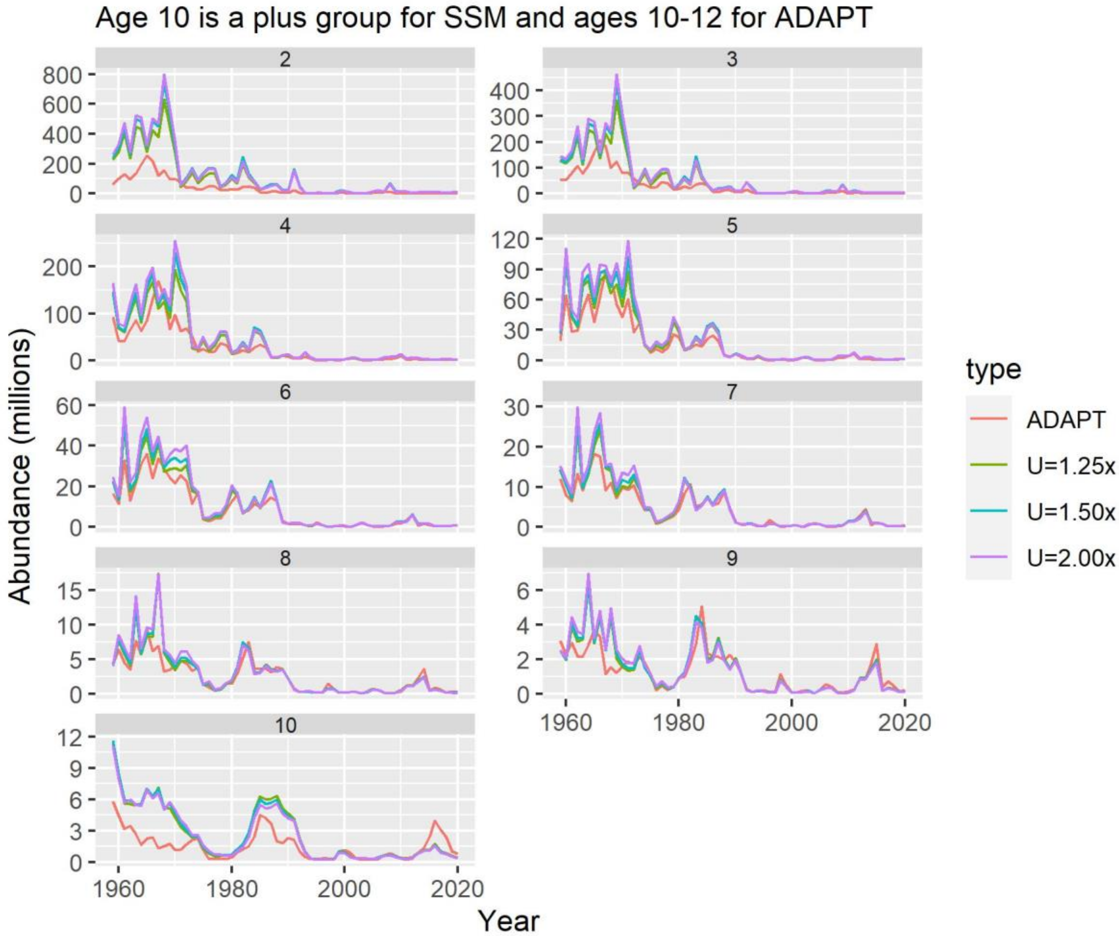

Figure 33. Comparison of 3NO cod abundance-at-age from three SSAM's (M1-M3) with different upper bounds on landings since 1994 (U option line colors shown in legend) and ADAPT estimates.

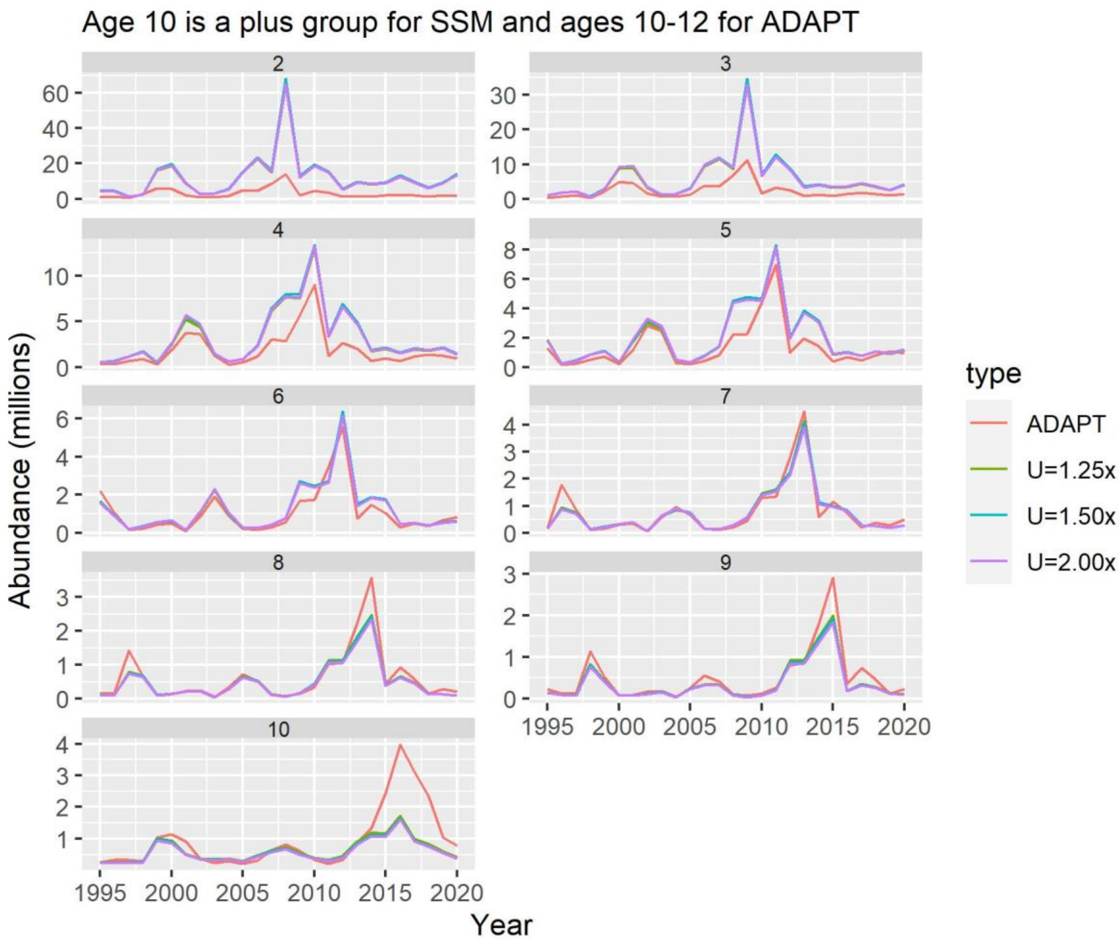

Figure 34. Comparison of 3NO cod abundance-at-age since 1995 from three SSAM's (M1-M3) with different upper bounds on landings since 1994 (U option line colors shown in legend) and ADAPT estimates.

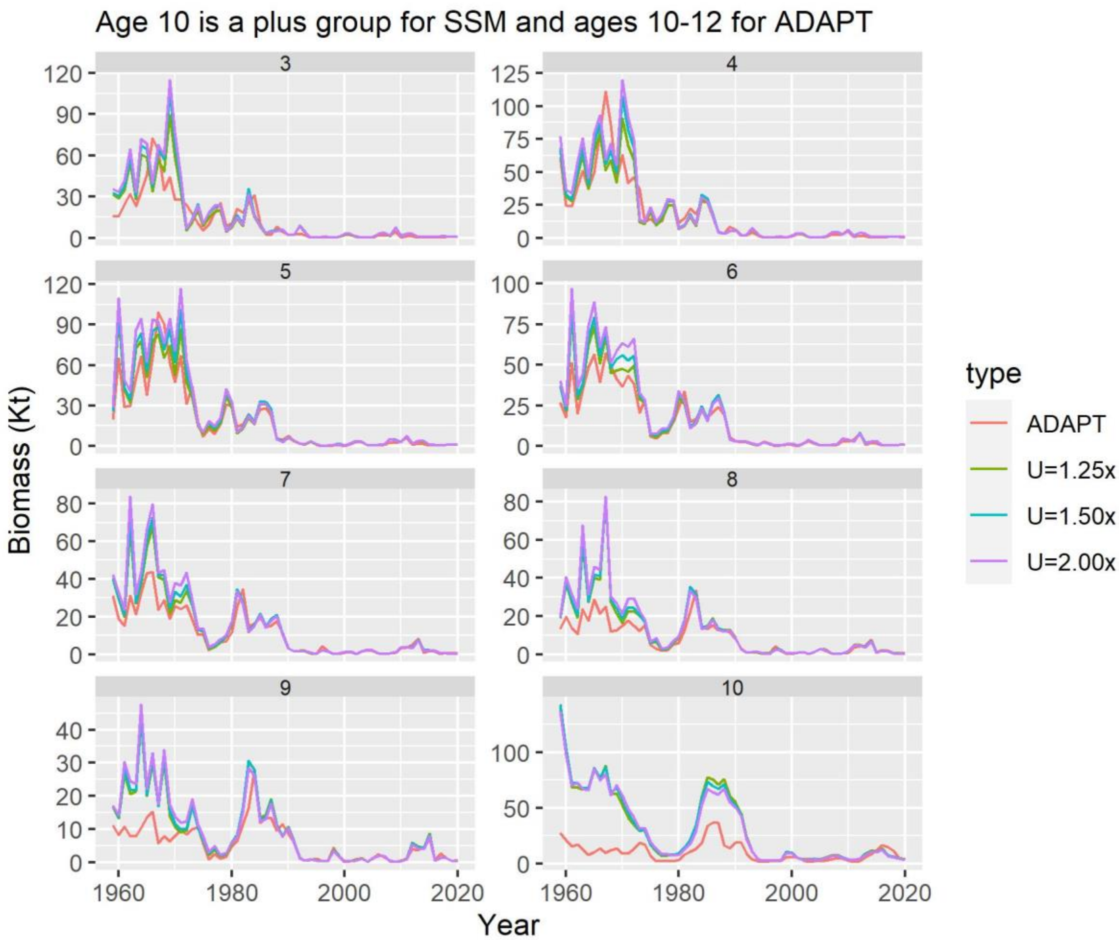

Figure 35. Comparison of 3NO cod biomass-at-age from three SSAM's (M1-M3) with different upper bounds on landings since 1994 (U option line colors shown in legend) and ADAPT estimates.

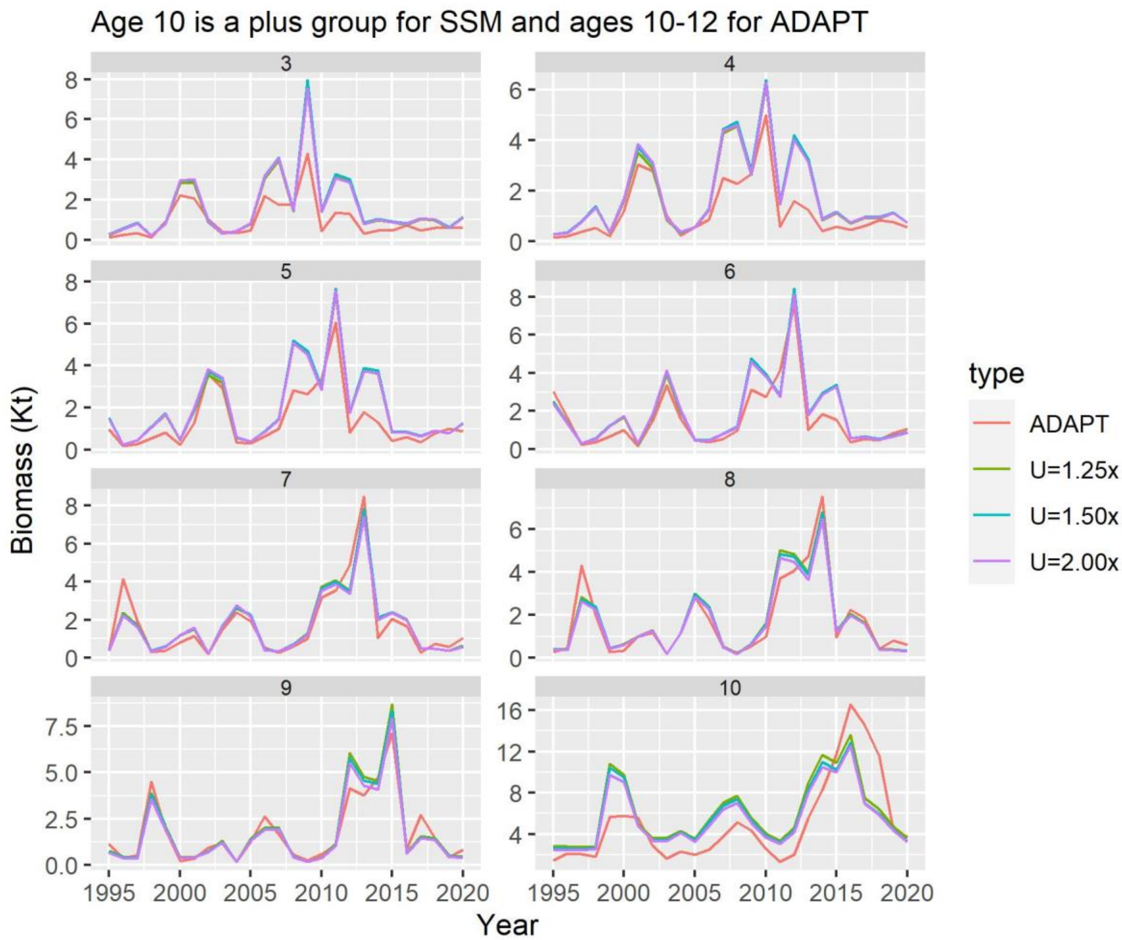

Figure 36. Comparison of 3NO cod biomass-at-age since 1995 from three SSAM's (M1-M3) with different upper bounds on landings since 1994 (U option line colors shown in legend) and ADAPT estimates.

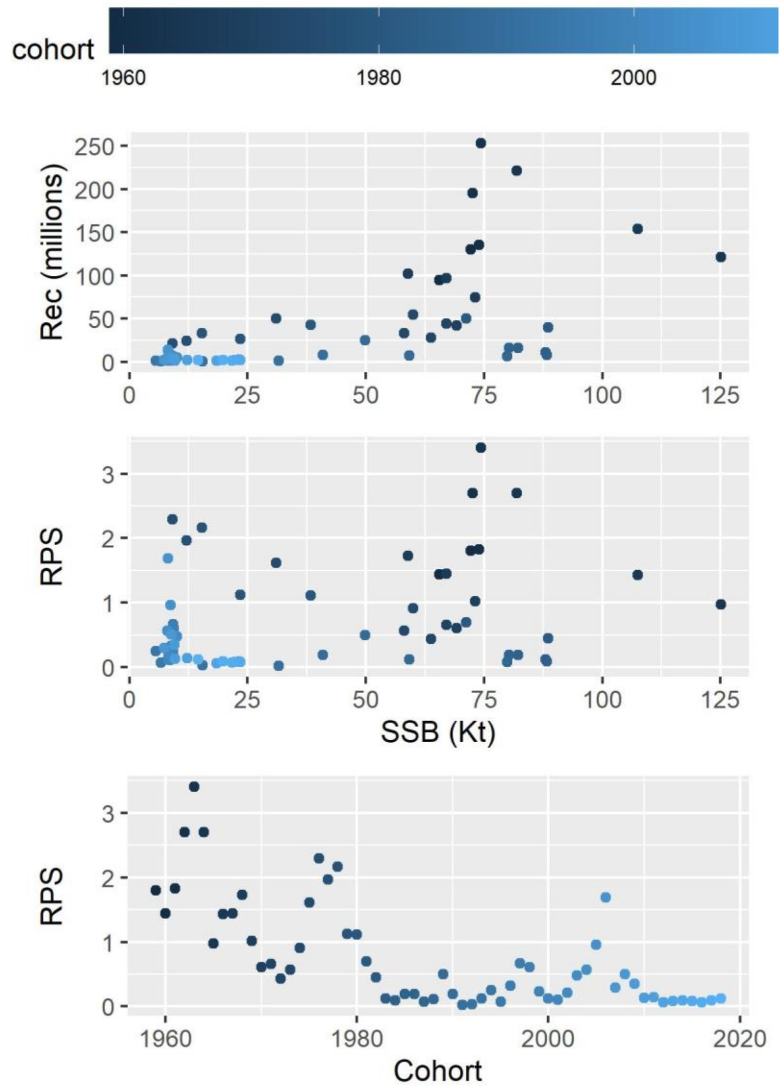

Figure 37. Stock-recruit relationship from ADAPT. Top panel: recruitment versus SSB; middle panel: Recruits per spawner (RPS) versus SSB; bottom panel: RPS versus year. Plotting symbol colors indicate cohort which is described at the top of the figure.

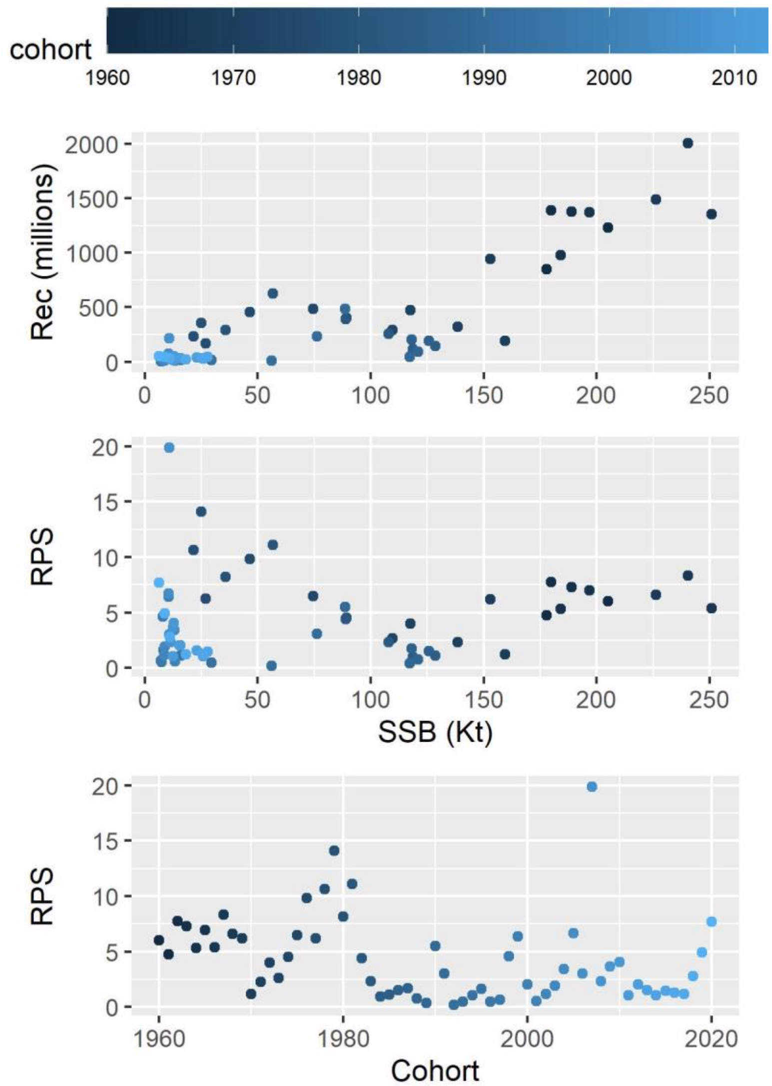

Figure 38. Stock-recruit relationship from SSAM M2. Top panel: recruitment versus SSB; middle panel: Recruits per spawner (RPS) versus SSB; bottom panel: RPS versus year. Plotting symbol colors indicate cohort which is described at the top of the figure.

Appendix: SSAM Diagnostic Figures

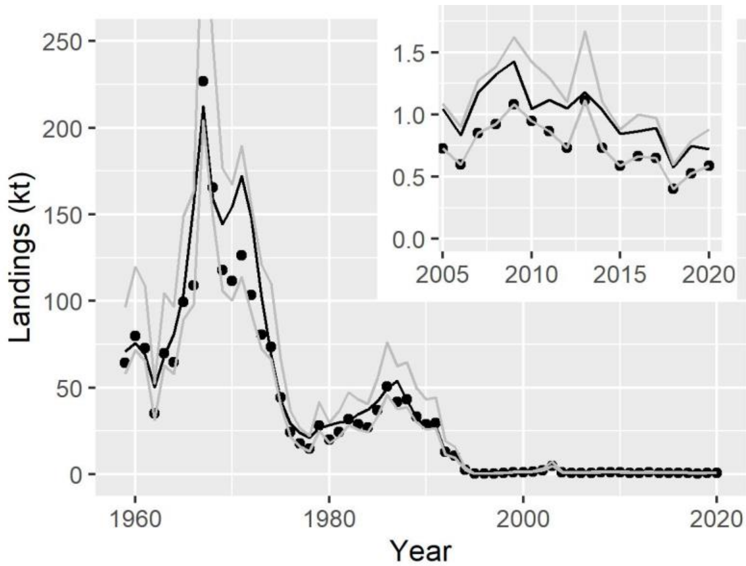

Figure A1. Grey lines are the landings bounds and the black lines are M2 model predicted landings. Points are reported landings which are not used by the SSAM. The inset figure shows trends since 2005.

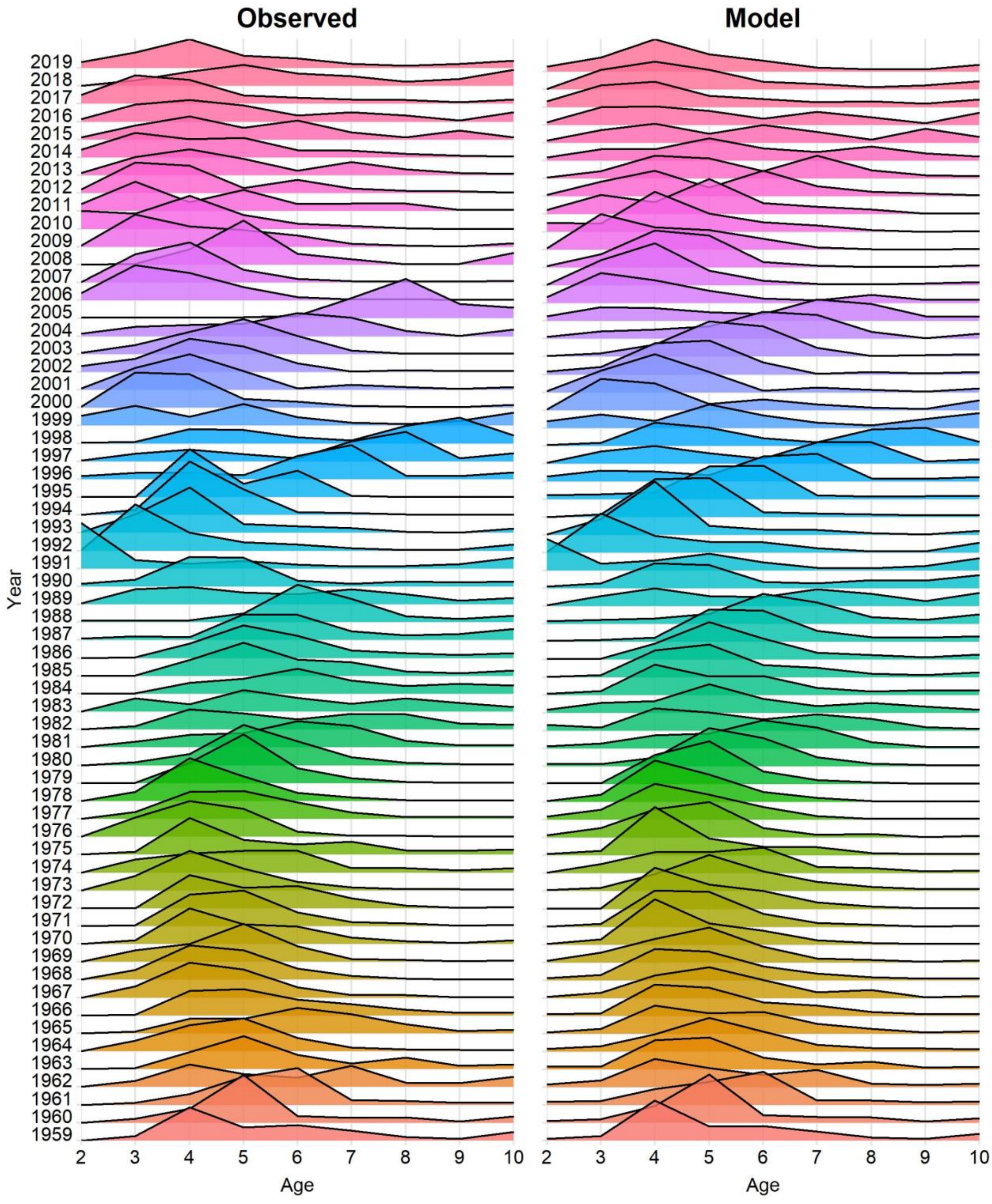

Figure A2. Observed (left) and M2 model predicted (right) catch-at-age.

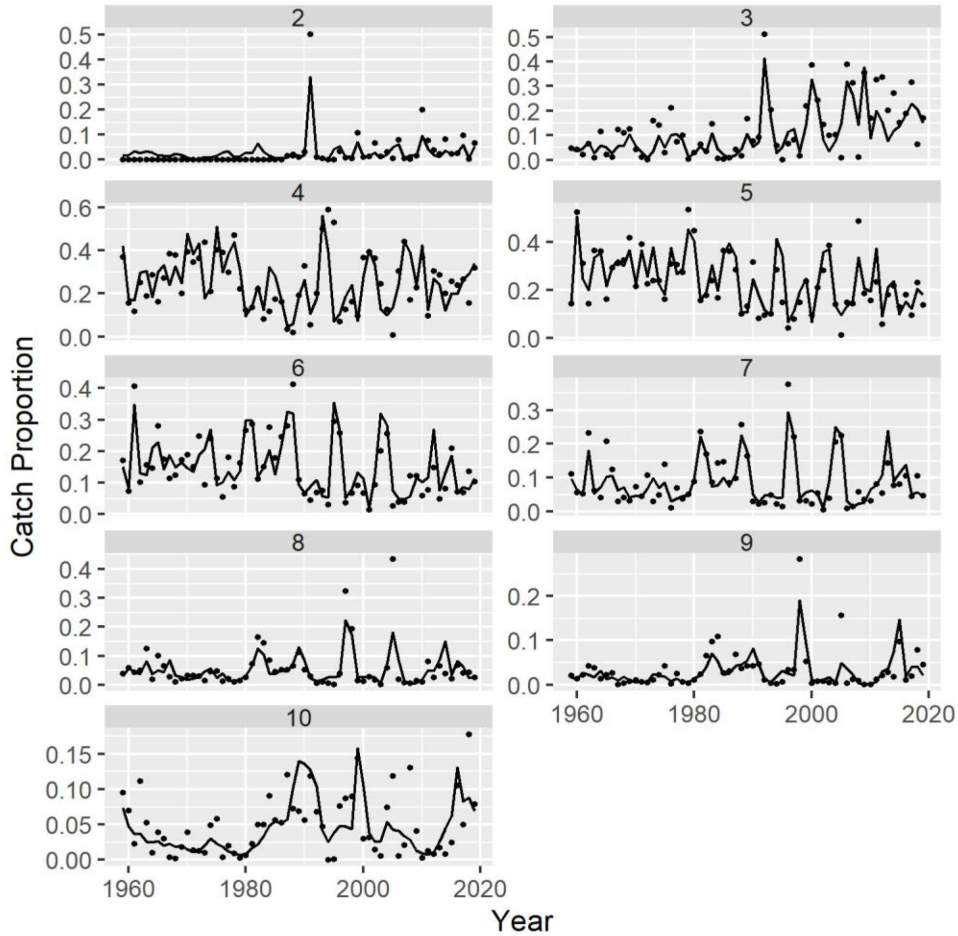

Figure A3. Observed (points) and M2 model predicted (lines) catch proportion-at-age.

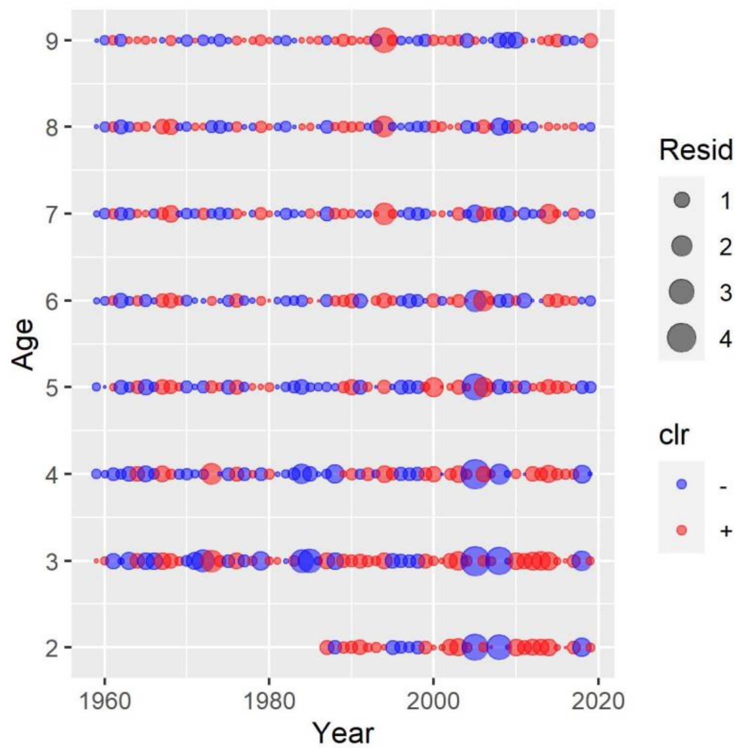

Figure A4. M2 catch age composition crl residuals. The area of a bubble is proportional to the absolute value. Red is positive and blue is negative.

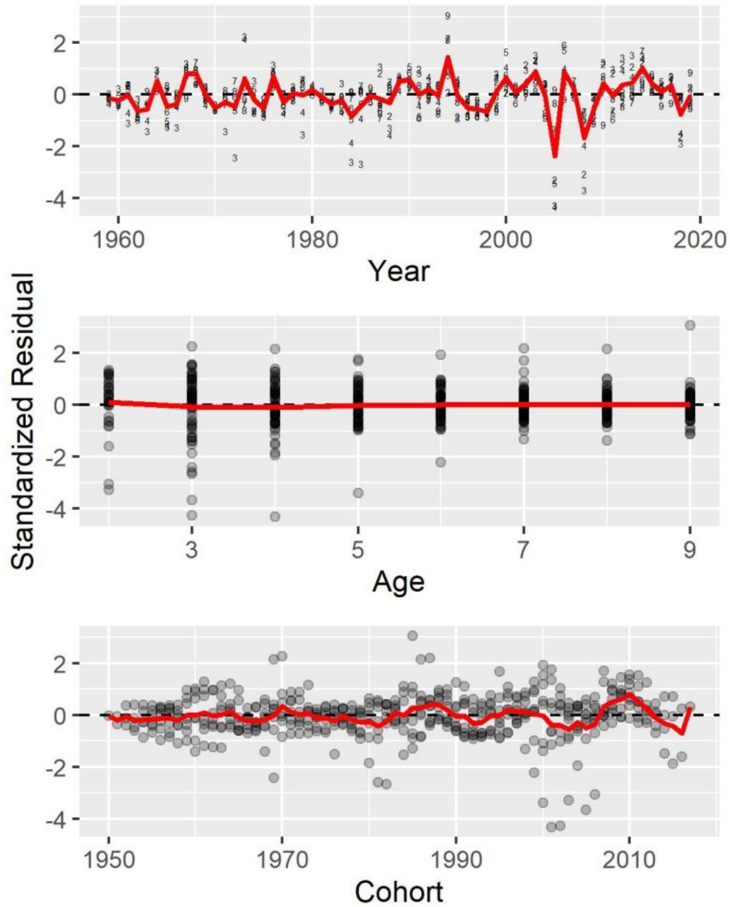

Figure A5. M2 catch age composition crl residuals versus year (top panel; age is the plotting symbol), age (middle panel), and cohort (bottom panel). Red lines connected the means for age year/age/cohort.

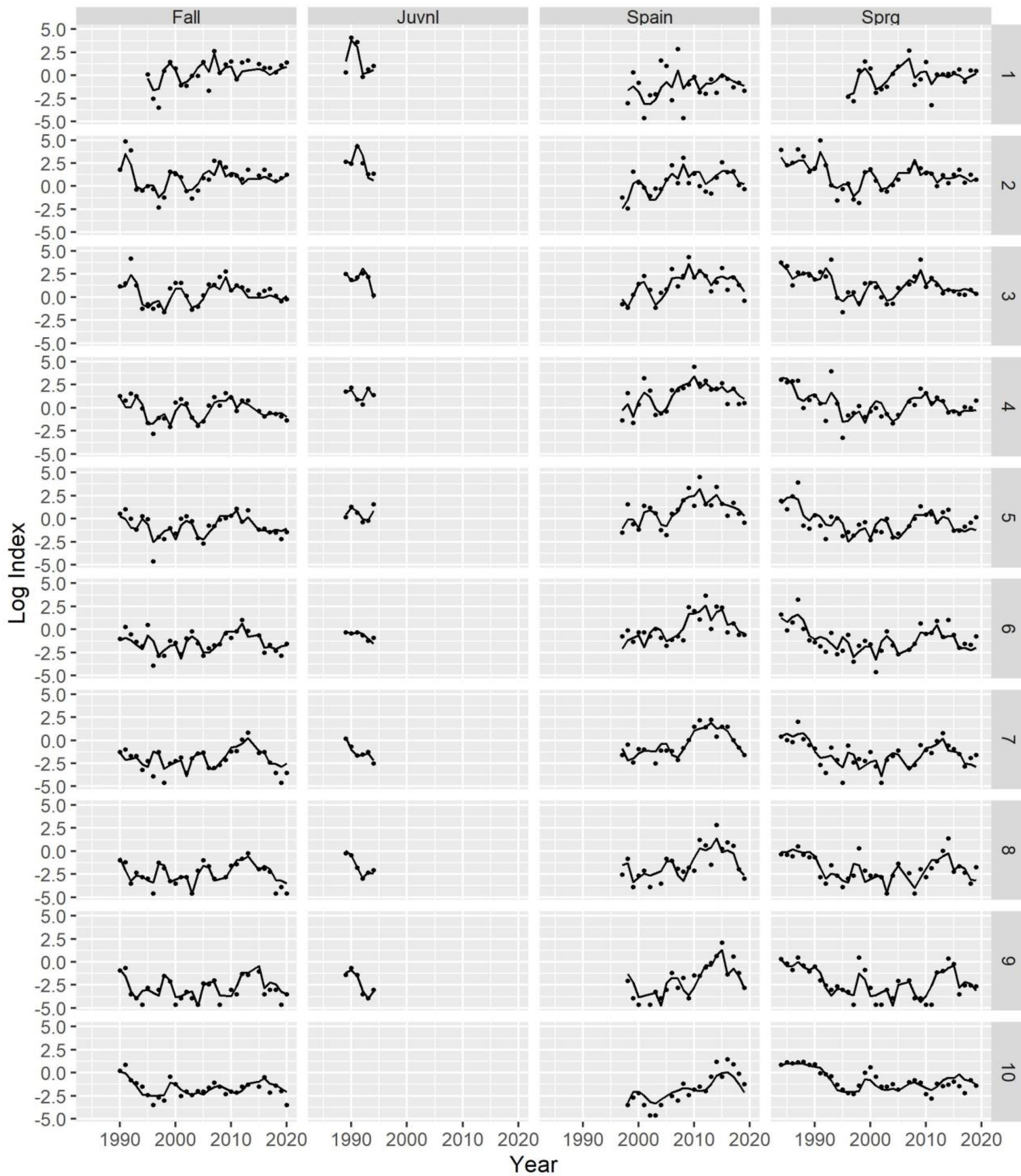

Figure A6. Observed (points) and M2 model predicted (lines) survey (columns) log-index at each age (rows).

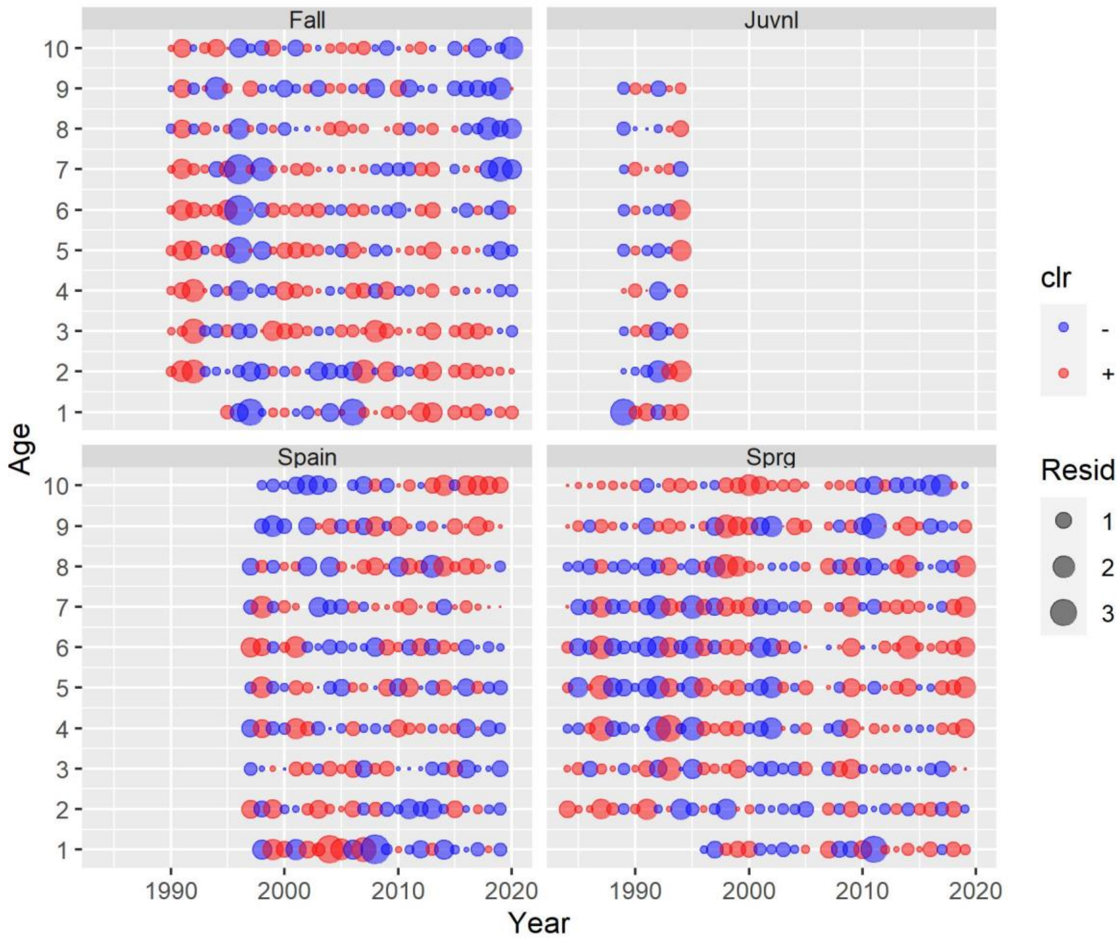

Figure A7. M2 index residuals for each survey (panels). The area of a bubble is proportional to the absolute value. Red is positive and blue is negative.

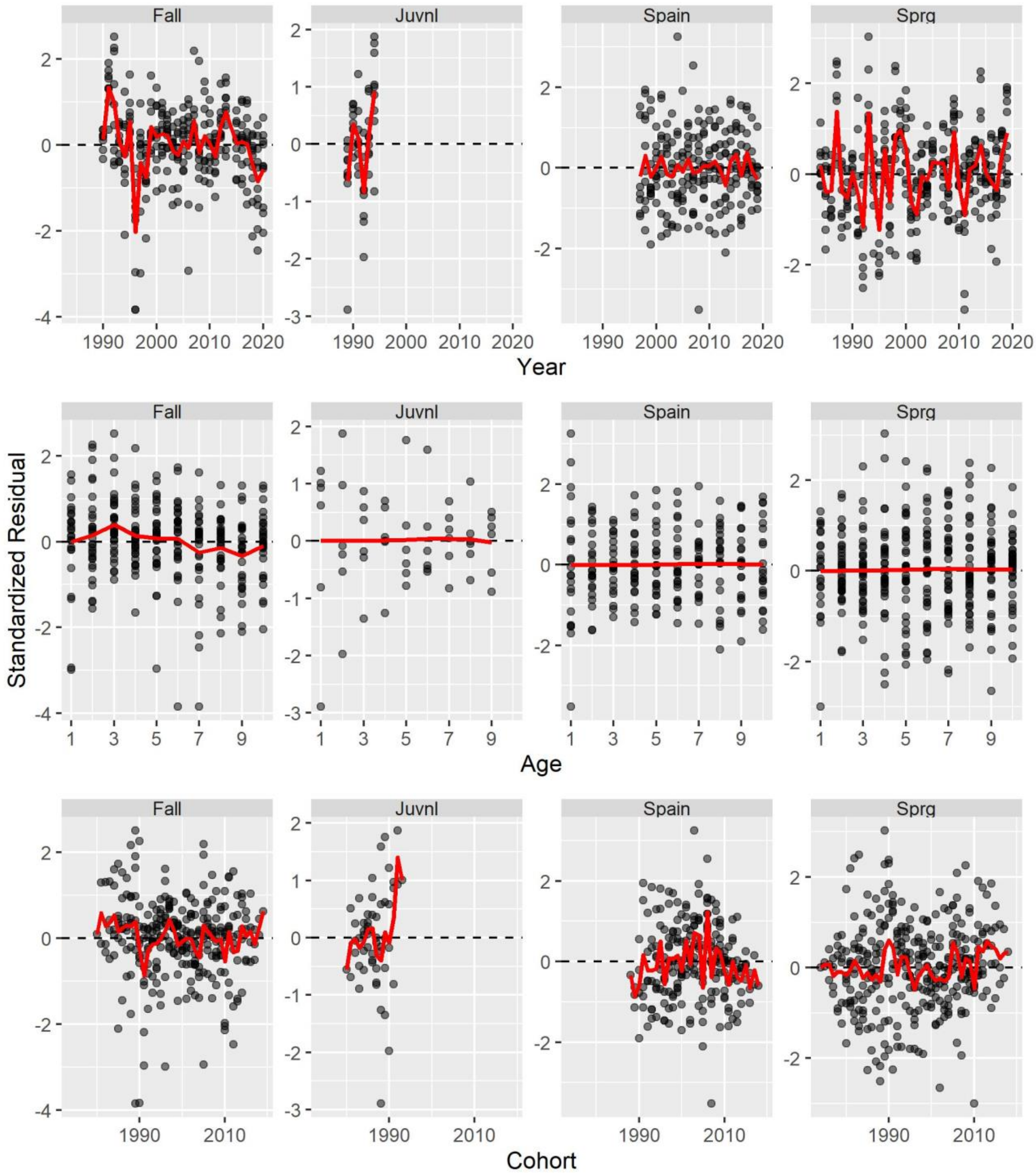

Figure A8. M2 index residuals for each survey (columns) versus year (top row), age (middle row), and cohort (bottom row). Red lines connected the means for age year/age/cohort.

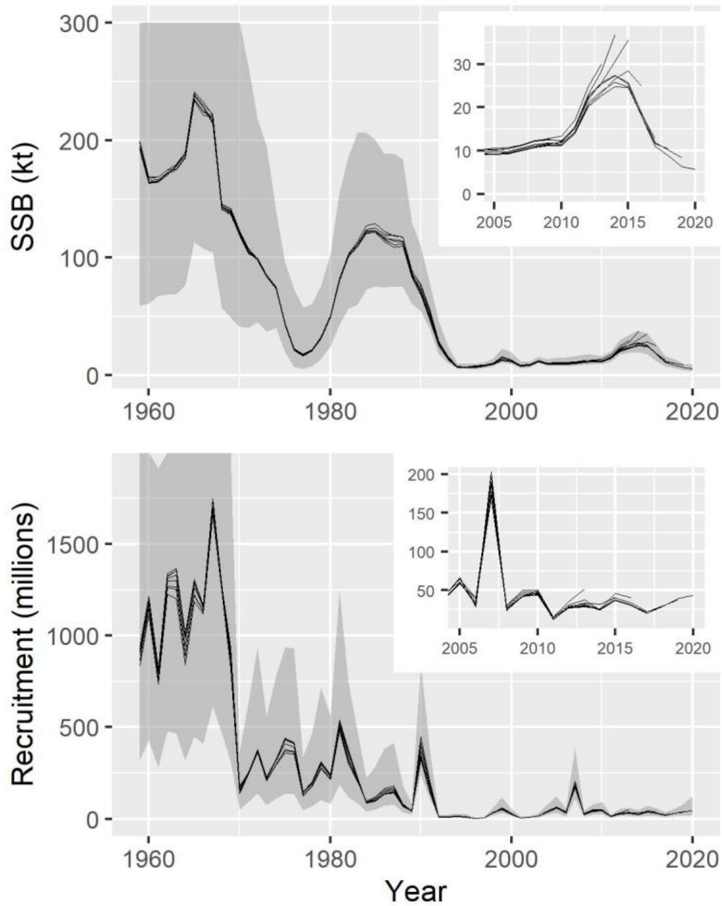

Figure A9. M1 retrospective estimates of SSB (top panel) and recruitment (bottom panel). Shaded regions indicate 95% confidence intervals based on the full time-series of data. Inset figures show trends since 2005.

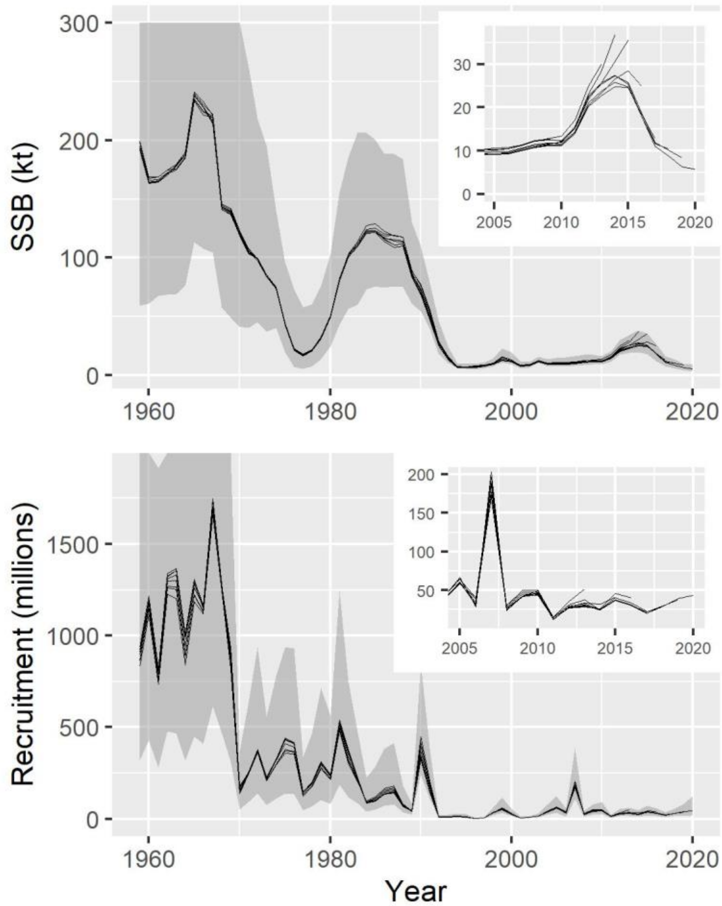

Figure A10. M1 retrospective estimates of average F at ages 4-6 (top panel) and 6-9 (bottom panel). Shaded regions indicate 95% confidence intervals based on the full time-series of data. Inset figures show trends since 2005.

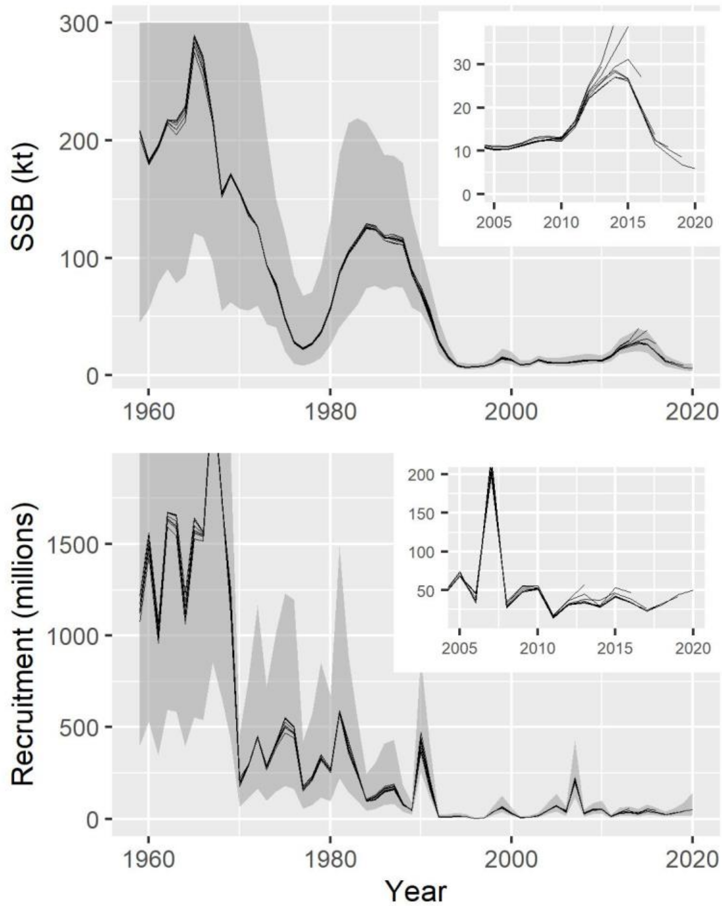

Figure A11. M3 retrospective estimates of SSB (top panel) and recruitment (bottom panel). Shaded regions indicate 95% confidence intervals based on the full time-series of data. Inset figures show trends since 2005.

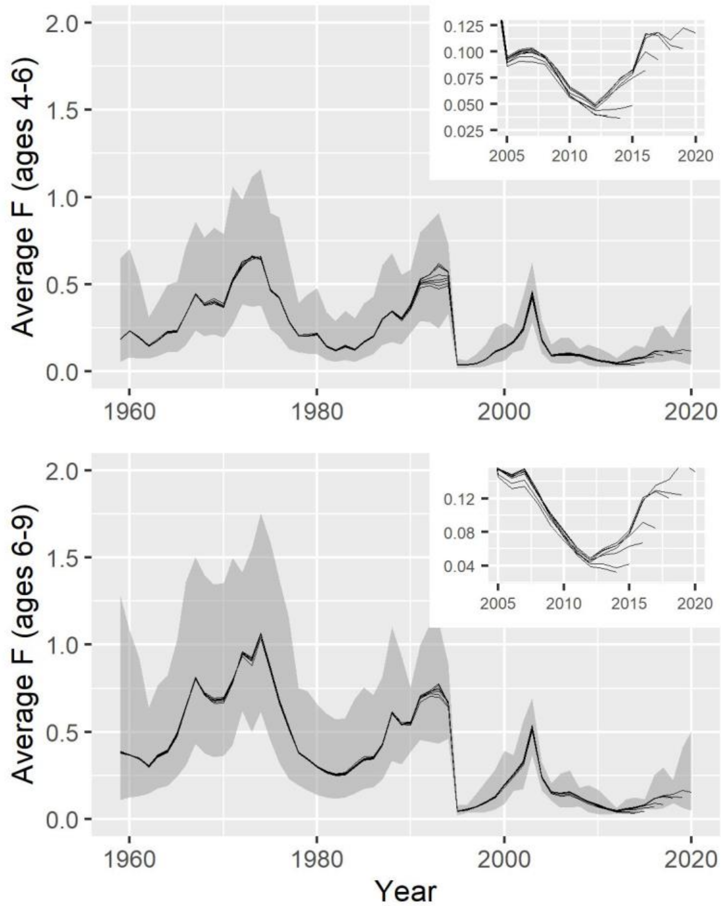

Figure A12. M3 retrospective estimates of average F at ages 4-6 (top panel) and 6-9 (bottom panel). Shaded regions indicate 95% confidence intervals based on the full time-series of data. Inset figures show trends since 2005.