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Review of the Assessment Framework for Atlantic Cod in NAFO 3Pn4RS: Population Modelling and Elements Relevant to a Renewed Precautionary Approach and Rebuilding Plan

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Canada

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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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Fisheries and Oceans Canada in the Quebec region undertook in 2021-2022 a review of the assessment framework for the Northwest Atlantic Fisheries Organization (NAFO) 3Pn4RS Atlantic cod (*Gadus morhua*) stock in the northern Gulf of St. Lawrence. A review of assessment inputs, including information on reported and non-reported fishery catches, tagging information and fishery independent monitoring results took place in the spring of 2021. The present document supports the second part of the framework review, which took place in May 2022. That meeting examined some additional assessment model inputs and modelling considerations and principally examined a proposed new model for the assessment of the 3Pn4RS cod stock. The current research document presents the details of that new model and associated model results, as well as results for alternative model formulations, some limited simulation tests and sensitivity evaluations for key model assumptions. We also present methodology for model projections and discuss key uncertainties related to projections of future stock status, particularly as they relate to longer term projections required as part of rebuilding planning. Finally, we review the information available at the time to define revised reference points for the management of the stock and to support the development of a new rebuilding plan for the stock.

INTRODUCTION

In 2021, Fisheries and Oceans Canada (DFO) Science branch in the Quebec region initiated a review of the assessment framework for the stock of Atlantic cod (*Gadus morhua*) in the northern Gulf of St. Lawrence (nGSL; Northwest Atlantic Fisheries Organization Divisions 3Pn4RS). The review was divided into two parts, the first of which took place during the spring of 2021, and the second from May 22-24 2022. The first part of the review examined the main inputs to a revised assessment model, specifically the estimation and compilation of the fishery catch-at-age (Ouellette-Plante et al. 2022a), estimated removals in directed and non-directed commercial fisheries and the recreational fishery (Benoît et al. 2021; Ouellette-Plante et al. 2022b), and abundance indices estimated from fishery-independent surveys (Benoît et al. 2022). The second part of the review, examined some additional assessment model inputs and modelling considerations (Benoît et al. 2024), and principally, examined a proposed new model for the assessment of the nGSL cod stock. The current research document presents the scientific information that was reviewed for this new assessment model. In addition, this document presents the scientific information that was reviewed to address a number of additional terms of reference for the second part of the review, specifically:

- Provide direction on projection methods for future catch options.
- Provide direction for an approach to estimating reference points for this stock.
- Discuss whether the assessment methodology has the potential to support quantitative evaluation of harvest control rules.
- Identify uncertainties and knowledge gaps.
- Identify priority short and medium-term research recommendations to improve data sources, assessment model formulation and estimation, and projection methods.

We begin by first providing a brief background on the factors that motivated the present review of the assessment framework for nGSL cod. Second, we describe the general structure for the proposed revised assessment model, a state-space statistical catch-at-age (SSSCA) model, and present results for a baseline formulation of that model. These results are compared to those produced by the previous assessment, which employed a sequential population analysis model (SPA; Brassard et al. 2020). Third, we present alternative SSSCA model structures that were examined to address somewhat conflicting trends among the five contemporary fishery-independent indices of abundance used in the model. Based on the comparison of the model structures, the one that appears most appropriate for the assessment going forward was selected by the peer review meeting. Fourth, we present an evaluation of the sensitivity of the selected model with respect to certain choices made for its parameterization and present results of some limited simulation testing of the model. Fifth, we present methodology for model projections and discuss key uncertainties related to projections of future stock status, particularly as they relate to longer term projections required as part of rebuilding planning (DFO 2021a). Sixth, we review the information available to define revised reference points for the management of the stock and to support the development of a new rebuilding plan for the stock. It was outside the terms of reference of the May 2022 review to propose specific choices for reference points, which was instead addressed subsequently at the assessment for nGSL cod in February 2023 (DFO 2023; Ouellette-Plante et al. 2025). We note also that subsequent to the May 2022 framework review, the rebuilding plan for the stock was completed (Benoît and Ouellette-Plante 2023; DFO 2024) and that some of the elements presented in this document may no longer be accurate or may not have informed the development of the rebuilding plan. We conclude by summarizing the key uncertainties associated with the revised assessment framework and provide recommendations for additional research that could address them.

BACKGROUND

For more than three decades the assessment of the nGSL stock was undertaken using a SPA model, previously using the ADAPT model of Gavaris (1988), and more recently, the implementation of that model in the National Oceanic and Atmospheric Administration (NOAA) fisheries toolbox (NOAA 2014; Brassard et al. 2016). SPA is essentially an accounting method that assumes that fishery catch-at-age is known without error, and, in its original form, simply back-calculates abundance from the catch-at-age and assumptions on the rate of natural mortality (*M*). Abundance indices are used in SPA to 'tune' the model to estimate abundance and fishing mortality in the terminal year(s). It has historically been common to assume a single value of *M* for all ages and years in SPA models. In 1997, the assessment for nGSL cod began assuming a change in *M* that would have occurred in 1985, from a value of 0.2 to 0.4 (Fréchet and Schwab 1998). This assumption was based in large part on evidence of elevated total mortality rates during the 1994-1996 moratorium, when fishing mortality was very low, as was the case in the neighboring 4TVn stock (Sinclair 2001). In 2003, the assessment began estimating *M* in 5 year blocks of time within the ADAPT framework (Fréchet et al. 2003; see Benoît and Chouinard 2004 for a description of the methods employed). Since the adoption of the NOAA fisheries toolbox (Brassard et al. 2016), *M* has been estimated using an ad hoc tuning procedure that involved iteratively manually changing assumed *M* values with the objective of minimizing model residual error. The major disadvantages of this approach are that it did not account for possible correlations between *M* and estimated parameters of the SPA, and, because the *M* estimation procedure was only applied to the recent period, the results were conditional on decisions made in previous assessments. The assumption of a common *M* value across ages was also a weakness as it is inconsistent with considerable evidence for the size-dependency of *M* (e.g., Lorenzen 1996; Gislason et al. 2010). This assumption can influence the value of important estimated model parameters such as the survey catchability.

The SPA assessment model was associated with model diagnostics that suggested potentially important aspects of model misspecification, notably strong residual and retrospective patterns, and unrealistically elevated estimates of survey catchability (e.g., Brassard et al. 2020). There were also concerns that the approach used may not adequately estimate changes in *M*, which could be important in light of large increases in *M* estimated for the neighboring NAFO 4TVn cod stock, which has reached levels that place that stock at high risk of local extinction (Neuenhoff et al. 2019; Swain et al. 2019). Furthermore, the SPA model assumes that catch-at-age is known without error, which is a tenuous assumption given potentially important unaccounted catch amounts estimated by Ouellette-Plante et al. (2022b). Improving the assessment model for nGSL cod to address these issues was considered a priority given the need to develop a new rebuilding plan for the stock, following the termination of the previous, evidently unsuccessful plan, which ended in 2018. There was also a newly legislated requirement for a plan by April 2024 (Canada Gazette, Part II 2022).

This document presents a new modelling approach for the nGSL cod which attempts to improve on the limitations of the SPA. Details on the various inputs to that modelling are available in other reports and are therefore not presented again here, except where we show model fits to the data. Readers are therefore directed to those other documents, the topics of which are mentioned at the beginning of the introduction: Ouellette-Plante et al. (2022a,b), Benoît et al. (2021, 2022, 2024).

STATE-SPACE STATISTICAL CATCH-AT-AGE MODEL

GENERAL CONSIDERATIONS

The proposed baseline model employs the state-space modelling paradigm, accounting for measurement errors in the inputs/data separately from process error or variability in population dynamics (e.g., Nielsen and Berg 2014; Cadigan 2016a; Stock and Miller 2021). Unlike the popular SAM model, which assumes that process errors act on the entire population equation (all rates affecting changes in abundance at age; Nielsen and Berg 2014; Berg and Nielsen 2016), we assume that process errors are associated with natural mortality rates. This is the approach taken by Cadigan (2016a,b). This choice was guided by the concerns about important, likely directional, changes in *M* for the nGSL stock. Cadigan's (2016a) model is used in the assessment of NAFO 2J3KL cod, where fluctuations in *M* are also of importance for the understanding and management of the stock (e.g., Regular et al. 2022).

There is a trend in stock assessment towards the use of flexible, documented, tested and maintained software packages, as this practice should lead to more reliable and repeatable assessment results (Dichmont et al. 2021). While this approach is highly desirable and may be appropriate for many stock assessments, most user friendly software packages lack the flexibility to account for certain particularities specific to some assessments. These situations motivate the use of bespoke models, which may be based on available source code from available packages. We chose to develop a bespoke model for nGSL based on the model of Cadigan (2016a,b) to allow for the incorporation of a number of features related to nGSL cod, including changes in the spatial coverage of two important surveys, inadequate accounting for changes in catchability of young cod in one survey and somewhat divergent trends in survey indices (Benoît et al. 2024). We also wished to incorporate into the model the results of published tagging-recapture studies that estimated rates of fishing mortality for certain years (Myers et al. 1996).

MODEL STRUCTURE

Population processes

The model is founded on the commonly used cohort model with a 'plus' age group *A*, which is denoted using a + symbol when referring to a specific age :

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

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, where $F_{a,y}$ is the fishing mortality rate and $M_{a,y}$ is the natural mortality rate. The ages for the model are 2-11+ and years are 1973-2020. The last SPA used ages 2 to 13+; however independent analyses and preliminary results with the new model indicated high variability for the older age groups in both fishery and survey catches, including the presence of nil catches in about 5% of instances. The use of an 11+ group improved model diagnostics. The SPA began in 1974 when fishery catch-at-age data became available. Here, we extend back by one year by using survey catch-at-age information available previously not incorporated into the assessment (details below). The model was fit using data ranging to 2020 because validated catch-at-age data for 2021 for all model inputs were not available in time for the framework review.

Recruitment in the model occurs at age 2. The recruitment vector, $R = (N_{2,1}, \dots N_{2,Y})$, is assumed to be a lognormal random vector variable,

$$\log(R) \sim MVN(\mu_R, \Sigma_R), \quad (2)$$

where the parameter vector μ_R of length Y consists of two time-blocks with constant values, one for $y \leq 1990$, and the second for $y > 1990$. These time-blocks were chosen to account for major changes in recruitment levels. Model sensitivities to this choice are presented later in this document. $\Sigma_R$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 ages 2-11+ in the first year (1973) are treated as unknown and free parameters to estimate.

Natural mortality rates, $M_{a,y}$, were assumed to vary as a function of age and, beginning in 1984, also by year for most ages. Information on cohort dynamics contained in survey data is required to estimate temporal variation in natural mortality, which is why we limited this to the period for which long term survey data were available. Although data from surveys conducted in 1973-1976 were included in model fitting (see below; Minet 1978), their limited duration and the 1977-1983 gap with no survey activity precluded estimating credible time variation in *M* prior to 1984 in preliminary model fitting. Values of *M* for ages 2 and 3 were assumed to be temporally invariant. The assumption for age 2 was necessary because recruitment and *M* processes for that age are confounded in the model in the absence of independent information on recruitment. The assumption was also necessary for age 3 given the desire to estimate an unaccounted-for change in survey catchability which occurred in 1990 (Benoît et al. 2024), noting that catchability and natural mortality parameters are typically highly correlated in assessment models.

Natural mortality rates were modelled using assumed age-specific fixed values m_a, and for the relevant ages and years, age-specific mortality process errors, $\delta_{a,y}$:

$$log(M_{a,y}) = log(m_a) + \delta_{a,y}. \quad (3)$$

The following values were assumed for m_a: $m_{a=2}$ = 1.0, $m_{a=3}$ = 0.65, $m_{a=4}$ = 0.45 and $m_{a=5+}$ = 0.15. The value for cod ages 5+ was assumed based on an estimate of total mortality (fishing plus *M*) of 0.25 for the early 1950s presented in Wiles and May (1968), which is consistent with values for other cod stocks in the NW Atlantic at that time (see Benoît et al. 2022 for details). The values for younger ages are based on the average lengths at those ages and the equation of Gislason et al. (2010), assuming von Bertalanffy growth parameters of L_∞=130 and k=0.10, which are reasonable for cod in the NW Atlantic according to FishBase (Froese and Pauly 2022).

The natural mortality process errors were modelled as an AR(1) stochastic process in age and year, and the elements of Σ_M are based on

$$Cov\{\delta_{a,y}, \delta_{a-j,y-k}\} = \frac{\sigma_M^2 \varphi_{M,age}^j \varphi_{M,yr}^k}{(1-\varphi_{M,age}^2)(1-\varphi_{M,yr}^2)}; Corr\{\delta_{a,y}, \delta_{a-j,y-k}\} = \varphi_{M,age}^j \varphi_{M,yr}^k. \quad (4)$$

To improve model convergence and to help ensure identifiability for the simultaneous estimation of natural mortality process errors and temporally varying age-specific fishing mortality (below), we coupled adjoining ages in the estimation of the $\delta_{a,y}$'s. Specifically, common $\delta_{a,y}$ values were estimated for ages 4-5, 6-7, 8-9 and 10-11+. Sensitivity to the ages that were grouped and number of groups was evaluated and is presented below.

Catches at ages 2 to 11+ were modelled using the Baranov catch equation,

$$C_{a,y} = N_{a,y} \frac{\{1 - \exp(-Z_{a,y})\}F_{a,y}}{Z_{a,y}}. \quad (5)$$

The *F*'s are modelled as a stochastic process about a small number of mean values μ_F , which are estimated as fixed effects, similar to recruitment. There are 15 values of μ_F according to blocks of ages and years (Figure 1). These parameters account for large shifts in mean *F* that occurred over time, including as a result of the 1994-1996 and 2003 moratoria.

If *F* is an (A-1)Yx1 vector of all $F_{a,y}$'s for ages 2-11+, then

$$\log(F) \sim MVN(\mu_F, \Sigma_F), \quad (6)$$

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

$$Cov\{\Delta_{F,a,y}, \Delta_{F,a-j,y-k}\} = \frac{\sigma^2_{F,age}\varphi^j_{F,age}\varphi^k_{F,yr}}{(1-\varphi^2_{F,age})(1-\varphi^2_{F,yr})}; Corr\{\Delta_{F,a,y}, \Delta_{F,a-j,y-k}\} = \varphi^j_{F,age}\varphi^k_{F,yr}. \quad (7)$$

Unlike the *M* process errors for which a single age-invariant variance parameter was estimated, a separate $\sigma^2_{F,age}$ parameter was estimated for ages 2-3 combined, 4, 5 and 6+. This choice was motivated by evidence in initial model fits that variation in Δ_F decreased as a function of age for the younger ages. Similar evidence was not observed for *M* process errors, nor did we have a priori expectation for age-related variation.

Myers et al. (1996) present two estimates of *F* derived from tagging experiments for approximately ages 6+ and for which the midpoint of the estimates fall respectively during 1986 and 1987: $\hat{F}_{tag1986} = 0.87\ (SE = 0.30)$ and $\hat{F}_{tag1987} = 1.13\ (0.30)$. We assumed these values to be representative of $F_{6-9,1986}$ and $F_{6-9,1987}$ an included them in the model as normally distributed priors to conform with the manner in which the estimates were presented in the original paper. Although lognormal priors would be more appropriate for *F*, we note that the mean and SE values are such that the density for values <0 is small.

The natural mortality rates, $M_{a,y}$, and fishing mortality rates $F_{a,y}$, are latent (i.e, unobservable) random variables for which we make statistical inferences. As described above, these random variables have probability distributions with a small number of mean and (co)variance parameters that need to be estimated. Survey and catch data are used to estimate these parameters via observation equations described in the next section.

Observation equations

We use marginal maximum likelihood for estimation of model parameters. This involves first modelling the probabilities of the data conditional on the states of recruitments, *M*'s and *F*'s (i.e., observation equations), and then integrating over all the likely states of recruitment, *M*'s and *F*'s to get the marginal distribution of the data on which the marginal likelihood is based. We used the Template Model Builder (TMB) package (Kristensen et al. 2016) to calculate the marginal negative loglikelihood (mnll) for our model and estimated 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 recruitments, *M* and *F*, and the nll's of these effects. 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 described below.

TMB provides predictions of random effects, quantities derived from these random effects (e.g., SSB) and model parameters. TMB also provides generalized delta-method "standard errors" for these derived quantities. The standard errors are actually marginal (with respect to the distributions of recruitments, *M* and *F*) mean squared errors, which are more appropriate for inferences about the values for these and derived quantities than actual standard errors (Zheng and Cadigan 2021).

Fishery catches

We model fishery catch (commercial and recreational fishery landings and commercial discards) and estimates of the catch age-compositions (Benoît et al. 2024) separately because these two data sources originate from different and independent sampling programs. Although the two sets of data are not completely independent, for instance because the catch-at-age estimation involves weighting by landings (Ouellette-Plante 2022a), we ignore the dependency between the two sets for simplicity.

Based on a review of the catch data assembled during the review in 2021 and the apparent quality of those data (Benoît et al. 2021, 2024; Ouellette-Plante et al. 2022b), we decided to fit the landings data using a different likelihood for the years ≤2005 and >2005 in the base model. Sensitivity to this choice was assessed and is presented later.

Expected catch (tonnes) was calculated in the model, using eq 5 to obtain $C_{a,y}$, which was then multiplied by the individual annual age-specific catch weights and summed over age. For *year* ≤2005, we evaluated the likelihood of the input catches using a log-normal likelihood with a mean equal to the expected catch and an assumed standard deviation of 0.1, roughly equivalent to a CV of 10%.

For *year* >2005 we used the censored catch approach (e.g. Cadigan, 2016a,b; Van Beveren et al. 2017). In this approach, the reliability of the catch is quantified by lower and upper bounds that are inputted to the assessment model (Benoît et al. 2024), and 'observed' catch is not directly used to estimate expected catch. 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 (hereafter, censored nll) for the stock assessment model parameters (collected in a vector *θ*) is

$$nll(\theta | L_{lo,y}, L_{hi,y}) = -\sum_{y=1}^{Y} \log\left[\phi_N\left\{\frac{\log(L_{hi,y}) - \log(L_y)}{\sigma_l}\right\} - \phi_N\left\{\frac{\log(L_{lo,y}) - \log(L_y)}{\sigma_l}\right\}\right], \quad (8)$$

where ϕ_N is the cumulative distribution function of a standard normal random variable. The σ_l parameter controls the sharpness of the bounds and is set at $\sigma_l = 0.02$, a value that provides some ability for model estimates to fall outside the specified bounds (Figure 2). The influence of the bounds on the assessment was assessed as part of the sensitivity analyses by changing their width.

The time-series of catch proportions (by number) at ages *2,…, 11+*, hereafter the catch age compositions, were modelled using the multiplicative logistic multivariate normal distribution based on the continuation ratio logit (crl) transformation of the proportions (Cadigan 2016a). The crl proportions were computed as follows. We indexed assessment model ages as *a = 1,…,A* where *A = 10*, which corresponds to stock ages *2,…,11+*.

For each age and year, we computed

$$P_{a,y} = \frac{C_{a,y}}{\sum_{a=1}^{A} C_{a,y}}.$$

then

$$\pi_{a,y} = Prob(age = a | age \geq a) = \frac{P_{a,y}}{P_{a,y} + \ldots + P_{A,y}}, \quad a = 1, \ldots, A-1.$$

and the continuation-ratio logit (crl),

$$X_{a,y} = \log\left(\frac{\pi_{a,y}}{1-\pi_{a,y}}\right), \quad a = 1, \ldots, A-1.$$

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 $\sum_{a=1}^{A} P_{a,y} = 1$. The crl is defined only for catch-at-age proportions > 0. All $P_{a,y}$ values were >0 in the nGSL cod data.

The observation equation nll for the vector across indexed ages 1 to *A*-1, X_{oy}, of observed crl's in year *y* is based on

$$X_{oy} = X_y + \varepsilon_{X,y}, \; \varepsilon_{X,y} \sim MVN(0, \Sigma_X), \tag{9}$$

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.

Abundance indices

There are six abundance indices for the nGSL cod model:

- the Minet (1978) bottom-trawl surveys (1973-1976; ages 3-11+),
- the DFO multispecies research vessel (RV) bottom-trawl survey (1985-2020; ages 2-11+; hereafter simply the DFO RV survey),
- the Sentinel bottom-trawl survey (1995-2020; ages 2-11+), and
- three fixed-gear Sentinel indices covering 1995-2020, namely for gillnets (GNS, ages 4-11+), summer longline (LLS1; ages 3-11+) and fall longline (LLS2; ages 3-11+; off southwestern Newfoundland). The youngest ages were excluded for some of the indices because their abundance in the surveys was low and considered too variable.

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

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

The $\exp^{-t_{s,y} Z_{y,a}}$ term projects beginning-of-year abundance to the time of the survey, accounting for in-season mortality. The $q_{s,a}$'s are catchability parameters to estimate and are specified in different manners depending on *s* and *a*, as described below. Given

$$\mu_{s,y,a} = log\{E(I_{s,a,y})\} = log(q_{s,a}) + log(N_{y,a}) - t_{s,y} Z_{y,a}. \tag{11}$$

the observation equation for the indices, for all survey ages and years, including the plus group indices is

$$log(I_{s,a,y}) = \mu_{s,y,a} + \varepsilon_{s,y,a}. \tag{12}$$

We assume the ε observation errors are independent $\varepsilon_{s,y,a} \sim N(0, \sigma_s^2)$. We assumed a single survey specific error variance across all ages and years for each survey, with two exceptions. For both Sentinel longline surveys, a separate variance parameter was estimated for age 3 and for ages 4+ because of higher variability in residual for age 3 in preliminary model runs.

Eq 12 requires $I_{s,a,y}$> 0. The ensemble of survey index data for nGSL contains two instances of zero values. A zero value does not necessarily indicate absence, but rather could be simply related to sampling error at low densities. While approaches are available to account for this as part of model fitting (e.g., Cadigan 2016a), we deemed this extra complexity to be unnecessary given the relatively low incidence of zero values (<0.02% of the data), and chose to simply not fit cases where $I_{s,a,y}$= 0.

Catchability – bottom-trawl indices

Catchabilities for the three bottom-trawl surveys were assumed to follow survey-specific logistic selectivity functions with respect to age,

$$S_{s,a} = \left(1 + \exp\left[\frac{-\log(19)\left(a - {s_s}^{50\%}\right)}{{s_s}^{95\%} - {s_s}^{50\%}}\right]\right)^{-1} \tag{13}$$

where ${s_s}^{50\%}$ and ${s_s}^{95\%}$ are the ages at which 50% and 95% of available cod are selected. These two sets of parameters respectively determine the location and rate of the selectivity function, which has a maximum value of 1. Catchabilities for these three surveys were then calculated as

$$q_{s,a} = S_{s,a} q_{Full,s} \tag{14}$$

where $q_{Full,s}$ is the fully selected (asymptotic) catchability, and is an estimated parameter. The $q_{Full,s}$ were assumed to follow a lognormal distribution. Past assessments for nGSL have recurrently estimated values of $q_{Full,s}$ that far exceed a value of 1. If the surveys covered the entire spatial distribution of nGSL cod, a true value of 1 would be associated with capture of all cod occurring within the area swept by the trawl wings over the length of the haul. Values >1 would imply herding between the trawl doors, which, for the DFO survey, spread about 3 times the width of the wings (McCallum and Walsh 1997). The asymptotic catchability therefore has a maximum value of 3 for that survey. However, this level of herding is not expected for cod, given only minor trawl herding observed in related species (Somerton 2004). Furthermore, the DFO RV survey does not cover many areas where cod occur, in the nearshore, in NAFO 3Pn and in the Mecatina trough, and consequently a value of 3 is not possible. Estimates of large values for fully selected catchability therefore indicate some model misspecification. This may occur for instance if the levels of *M* are mispecified. To help constrain values of $q_{Full,s}$ to around 1, we set a lognormal prior on this parameter for the DFO RV and Sentinel bottom trawl surveys, assuming a mean value for log($q_{Full,s}$) =0 and a fairly wide (permissive) standard deviation of 0.7. Sensitivity to the choice of standard deviation value was evaluated.

In contrast to the DFO RV and Sentinel trawl surveys, for which the indices are in units of swept area abundance, Minet (1978) provided only the relative survey age composition. To account for interannual changes in total survey abundance, we freely estimated fully-recruited catchability parameters for each of the four years of those surveys. These were estimated as fixed effects and the values reflect the estimated total survey abundance, unlike the $q_{Full,s}$ values for the other two trawl surveys which reflect the fraction of the population sampled.

There are doubts concerning the accuracy of conversion factors applied to standardize the DFO RV survey at ages 2 and 3 for the change in vessel and gear that occurred in 1990 (Benoît et al.

2024). We therefore estimated some catchability adjustments in the model by modifying eq 11 (and related equations) such that for s=DFO RV, a=2,3 and y<1990

$$\mu_{s,y,a} = log\{E(I_{s,a,y})\} = log(q_{s,a}) + log(\delta q_{s,a}) + log(N_{y,a}) - t_{s,y}Z_{y,a}. \quad (15)$$

where $\delta q_{s,a}$ are catchability deviations, estimated as fixed effects, one for age 2 and the other age 3.

Catchability – Sentinel fixed-gear indices

Gillnets and longlines often have non-asymptotic selectivity functions, such that the selectivity may decline at older ages (larger sizes). In the absence of information on the shape of the selectivity functions, we freely estimated the $q_{s,a}$ values for the three Sentinel fixed gear indices.

Adjustments for changes in survey coverage – DFO RV and Sentinel bottom-trawl indices

Adjustments are required in the model to account for a change in survey coverage that occurred in 1990 in the DFO RV survey and 2003 in the Sentinel bottom-trawl survey. Adjustments were deemed necessary for ages 2-11+ in the DFO RV survey and only ages 2 and 3 in the Sentinel trawl survey (Benoît et al. 2024). The adjustments, which we call delta-coverage values, $\delta c_{s,a}$, were estimated using abundance index data from the surveys representing the original and current survey sampling areas, for those years in which the current survey area was sampled

$$E\left(log(I_{CURRENT,s,a,y})\right) = log(I_{ORIGINAL,s,a,y}) + \delta c_{s,a} \quad (16)$$

The $\delta c_{s,a}$ parameters were estimated freely using a normal likelihood and survey specific standard deviations, $\sigma_{\delta c_s}$.

BASELINE MODEL RESULTS

In the figures presented in this section and throughout, values reported for age 11 represent age 11+. Estimates of key standard deviation (variance) and correlation parameters for recruitment and mortality processes, and for observation errors are presented in Table 1. These are not necessarily referenced in the results below, which instead focus on demographic parameters of interest and fits to data.

The SSSCA model-estimated SSB values were smaller than those of the former SPA for years prior to 1990, and above the SPA thereafter (Figure 3). There was a closer correspondence between the results of the two models for total biomass prior to 1990, but the differences were greater after 1990. The level of stock depletion from the highs in the early to mid-1980s to recent years is therefore estimated to be less with the SSSCA, about 80% depletion compared to about 90% with the SPA.

The SSSCA model estimated considerably larger number of age 2 recruits compared to the SPA, although the trend was similar (Figure 4). This reflects the large difference in assumed *M* at age 2, *M*=1.0 in the SSSCA and *M*=0.2 in the SPA, which affects survey catchability and which in turn affects the magnitude of abundance related quantities. Survey catchability-at-age was greater for all surveys and ages in the SPA, except for the Sentinel longline index, which is not quite comparable between models (Figure 5). In some instances, such as young cod in the DFO RV survey, the difference was considerable. Note that catchabilities for the Sentinel gillnet survey were a couple orders of magnitude greater in the SPA, which could reflect in part a difference in the units of those indices in the input data, which is something we did not verify. In the SPA, the DFO RV survey catchability function peaks at age 4 and then declines, rather than following an asymptote as assumed in the SSSCA. This likely reflects the assumption of an age invariant *M* in the SPA, which causes the model to interpret the disappearance of older cod in surveys as a decrease in catchability rather than disappearance from the population due to *M*. The estimated catchability functions for the four years of the Minet survey are presented in Figure 6.

A visualization of estimates of age-specific population and catch quantified for the SSSCA is presented in Figure 7. Notably, the biomass-at-age plot displays the passing of several relatively prominent cohorts over the length of the series.

The SSSCA estimated mean fishing mortalities greater than those from SPA for the 1970s and 1980s (Figure 8); however, the SPA estimated a much more pronounced spike in ages 6-9 fishing mortality in the early 1990s, culminating in 1993. While fishing mortalities for ages 4-6 were of similar level and trend in both models, the SSSCA estimated larger increases in *F* during the inter-moratorium period and in the late 2000s. The SSSCA estimated the fishing mortality to be greatest for cod ages approximately 7-10 prior to the first moratorium, but increasingly higher for older cod after 1997 (Figure 9). The standardized *F* deviations from that model are presented in Figure 10. Patterns in the fishery selectivity that emerges from the SSSCA model indicate that the fisheries capturing cod were more broadly selective of fish ages 7+ prior to the 1993 moratorium (Figure 11). Subsequently, the fishery has been more selective of older cod, approximately ages 9+, and since 2008, often most selective of the oldest cod. The pattern post 1993 likely reflects in large part the exclusion of the mobile gear sector which likely captured a relatively higher proportion of smaller / younger fish compared to the fixed gear sector.

Age-specific rates of fishing, natural and total mortality are presented in Figure 12, clearly showing very negligible fishing mortalities at ages 2-4. Estimates of *M* for ages 4-9, which begin in 1984, show an initial decline followed by increases, which indicates that the levels assumed for <1984 were likely reasonable within the context of the model. Estimates of *M* beginning in the late 1980s, were considerably higher than what was assumed/estimated for years prior. For ages 5 to about 9, total mortality fluctuated around a common level over then entire 1974-2020 series, except for the spike from the late 1980s to 1993. For ages 10 and 11+, *M* is estimated to have fluctuated considerably post 1990, with spikes in the late 2010s and 2017 that resulted in very high levels of total mortality. At ages 6-11+, *F* approximated, and generally exceeded *M* in all years prior to 1993, but the reverse occurred after 1993.

In contrast to the SSSCA, the SPA estimated age specific *F*s that fluctuated with greater amplitude (Figure 13). Notably, the SPA estimated a spike in *F* in 1993 for the oldest ages that are implausible or certainly unlikely. For instance at ages 10 and 11+, 95% and 99.3% of cod were estimated to have been killed by fishing, and at ages 7 and 8, about 89%.

The increase in *M* at age 4-11+ beginning in the late 1980s and decreasing in the latter half of the 1990s (Figure 12) is consistent with a period of poor condition in the stock, which has been associated with high *M* (Dutil and Lambert 2000; Lambert 2011). This period may also have been associated with a condition related effect of predation by harp seals (Chassot et al. 2009; Bousquet et al. 2014). However, since the early 2000s, condition of nGSL cod has not been poor, and the fluctuations in *M* in Figure 12 are not consistent with changes in grey or harp seal abundance (DFO 2020, 2022), nor with expectations for predation-related *M* based on trends in the neighboring 4TVn cod stock (Neuenhoff et al. 2019; Swain et al. 2019). Instead, fluctuations in *M* since the early 2000s have corresponded with changes in the total allowable catch (TAC) in the fishery, with decreases in *M* during the 2003 moratorium, and as quotas were reduced around 2010 and again in the most recent years (Figure 14). The association between *M* and TAC are consistent with unaccounted catch in the fishery. This could reflect one or a combination of catch that is unreported by harvesters, or depredation from fishing gear. The latter is a plausible mechanism if one assumes that changes in TAC affect fishing effort, which in turn, affects opportunities for predators to remove cod from the gear. Regardless of the mechanism, the relationship between TAC, *F* and *M* poses some challenges for the assessment, particularly as it relates to projections (details below). Nonetheless, this relationship is such that at the TAC levels just prior to the 2022 review, *M* had been tending towards the low levels expected for the stock and which may have allowed some rebuilding if conditions had persisted (details below).

Catches estimated by the baseline model closely followed input catch up to 2006 as is expected from the assumed ~10% CV for catch error (Figure 15). During the period when catch bounds and a censored nll were assumed, the model estimated catch at a level intermediate to the bounds up to 2009, near the upper bound for 2011-2016 and 2019-2020, and near the lower bound in 2017-2018. Sensitivity to the choice of bounds is discussed later.

In order to explore the possible magnitude of unaccounted fishery catch being subsumed in model estimates of *M*, we assumed that the average of the low values of *M* estimated for 2003 (moratorium) and 2020 could represent an estimate of the true, non-fishing, natural mortality. We took the age-specific difference in annual estimated *M* and these values of non-fishing natural mortality, along with the model estimates of abundance, to make these estimates of unaccounted catch using the Baranov catch equation (green line in the bottom panel of Figure 15). These estimates indicate that catch may have exceeded landings, input catch and model-estimated catch by about 10% in 2000-2001, by about 20-30% around 2007-2009, and 2017-2018 and by upwards of 80-90% in 2012-2016. Of course, these estimates rest on the assumption that true background non-fishing natural mortality was at a constant relatively low level since 2003.

The model estimated catches at the upper bound during the 2010s, when unaccounted catch was estimated to be particularly elevated, suggesting that the assumed bounds may have been constraining, a topic which we addressed later in this document. Nonetheless, estimated catch in most of the other years was lower than the upper bound, despite higher estimated unaccounted catch. We suspect that this may be related, at least in part, to the fact that the input catch age composition is assumed to be an unbiased estimate of the true composition. The censored nll approach assumes that catch is based on this age composition. Potential unaccounted catches that do not conform to the model age composition should therefore be subsumed into *M*. To illustrate the potential for this, we examined the age-specific ratio of *M* and *F* values (Figure 16). The fact that this ratio follows somewhat different trends across different ages indicates that some differences may have existed in the age composition of reported and unaccounted fishery catch.

The baseline model fit the survey abundance indices reasonably well, although it systematically underestimated the Sentinel longline indices at age 3 during the first half of those series (Figure 17). Patterns in model residuals appear generally acceptable, albeit with somewhat higher than expected variability at age 11+ and perhaps ages 2 and 3 (Figures 18 and 19). There is some limited patterning in the residuals, such as a tendency to over estimates abundance at younger ages since the mid-2010s in the DFO RV survey. There is also evidence of a year effect in the Sentinel bottom-trawl survey in 2011 (positive) and 2012 (negative), and to a lesser extent in the DFO RV survey in 2002-2003. Given the low frequency of such year effects and that they occurred in surveys that cover the distribution of, and trends in the stock in similar ways, we did not modify the model to try account for these year effects.

There was little patterning in survey residuals either as a function of year or age (Figure 19). However there were some trends with respect to cohort such that mean residual values declined slightly over cohorts until 2010 in the DFO RV and Sentinel bottom-trawl surveys and throughout the series in the Sentinel fall longline index (LLS2). Meanwhile, in the Sentinel gillnet and summer longline surveys, mean residual values were negative for cohorts born in the 1980s and early to mid-1990s, and largely positive for cohorts born in the late 1990s and 2000s. There were no patterns in standardized residuals as a function of age or year in the Minet surveys (Figure 20).

The model-estimated fishery catch composition (proportions-at-age) fit the input catch composition well (Figure 21). The model tended to underestimate the contribution to an age when the input proportion spiked in a given year, such as at age 11+ in 2017 and 2019. There was no patterning in the standardized crl residuals, with the exception of perhaps lower than expected variability at the youngest ages and higher at age 10 (Figure 22). Overall, there were no patterns in crl residuals with respect to year, age or cohort (Figure 23).

There were essentially no retrospective patterns based on a 7 year peel for average fishing mortality (Figure 24), SSB and recruitment (Figure 25), or *M* (Figure 26). Mohn's rho is a measure of systematic differences, or bias, revealed by a retrospective analysis (Mohn 1999). Values for rho for each of the quantities listed above, and which are indicated in the respective figure panels, are well within the values considered to reflect little bias for a long lived species based on the rule of thumb from Hurtado-Ferro et al. (2015): -0.15 ≤ rho ≤ 0.20.

Overall there was little correlation amongst most model parameters. Figure 27 presents correlations only for those parameters involving one or more absolute values >0.15. The correlations between these specific parameters are largely expected. Survey catchability parameters were highly correlated, which in turn is reflected in correlations with abundance related parameters like those for recruitment and some of the fishing mortality main effects.

ALTERNATIVE MODEL FORMULATION – DISTRIBUTION SHIFT MODEL

An alternative model formulation was considered in an attempt to account for somewhat divergent trends in the bottom-trawl surveys, which cover the offshore and midshore (hereafter simply called offshore), compared to the fixed gear Sentinel surveys, which are limited to the nearshore (see Benoît et al. 2024).

The distribution shift model assumed that the distribution of cod may shift, in an age-dependent manner, with respect to the nearshore zone. In doing so, cod become more available to one group of surveys and less available to the other. This issue had previously been identified and investigated by Cadigan (2004). In the absence of independent information on the distribution of nGSL cod over their distributional range or information on correlates (e.g., environmental) for the shift in distribution, the model assumed that there is an age and time-varying fraction of fish that are only available to one set of surveys, nearshore or offshore. This fraction is assumed to vary smoothly across years and to be correlated among ages.

Model description

The distribution shift model assumes no changes to the population equations used in the baseline model (eqs. 1-7); the cod population is assumed to be homogenous, with respect to demographic rates, recruitment and mortalities. However, the distribution of cod over space is not necessarily homogenous, such that availability to surveys can differ between the nearshore and offshore zones. Consequently, only the observation equations for surveys are modified. Furthermore, because information is required in the data to estimate the relative availability between the two zones, only the observation equations applied to survey data for years ≥1995 are affected; i.e., the years for which there were data for nearshore zone, corresponding to years when the Sentinel surveys were active.

The model assumes a latent (unobserved) time and age-varying fraction of fish, $p_{a,y}$ that becomes unavailable to one set of surveys when it becomes available to the other set. This assumes that the surveys cover mutually exclusive areas, which is practically true for the DFO

RV survey and the summer Sentinel fixed gear indices (GNS and LLS1). This is somewhat less the case for the Sentinel mobile gear survey, which extends a little into the nearshore zone, but we assess the evidence for distinctness between that survey and the nearshore surveys using model comparisons. It may also not be correct for the Sentinel fall index LLS2 (details below).

Let

$$p_{a,y} = 2 \cdot logit(\Delta p_{a,y}) - 1 \quad (17)$$

where $\Delta p_{a,y}$ is an age and year specific deviation. Eq 17 ensures that the fraction $p_{a,y}$ is contained over the interval [-1,1], such that a value of 0 indicates that the proportion of the population in each area is equal to the respective long term averages, a negative value indicates a population shift into the nearshore compared to the long term and a positive value a shift into the offshore.

The deviations $\Delta p_{y,a}$ are then modelled as an AR(1) stochastic process in age and year,

$$Cov\{\Delta p_{a,y}, \Delta p_{a-j,y-k}\} = \frac{\sigma^2_{P,3+}\varphi^j_{P,age}\varphi^k_{P,yr}}{(1-\varphi^2_{P,age})(1-\varphi^2_{P,yr})}; Corr\{\Delta p_{a,y}, \Delta p_{a-j,y-k}\} = \varphi^j_{P,age}\varphi^k_{P,yr}. \quad (18)$$

This ensures that the proportion $p_{a,y}$ varies smoothly in time and that there is a correlation amongst ages, which is expected given age and length dependent distribution patterns commonly observed in fish populations.

The proportions were then applied as catchability deviations in the observation equation (eq 11) such that if survey *s* is considered a nearshore survey:

$$\mu_{s,y,a} = log\{E(I_{s,a,y})\} = log(q_{s,a}) + \log(1 - p_{y,a}) + log(N_{y,a}) - t_{s,y}Z_{y,a}. \quad (19)$$

and if survey *s* is considered an offshore survey:

$$\mu_{s,y,a} = log\{E(I_{s,a,y})\} = log(q_{s,a}) + \log(1 + p_{y,a}) + log(N_{y,a}) - t_{s,y}Z_{y,a}. \quad (20)$$

We also considered the possibility that certain surveys might sample the entire population. For instance, the Sentinel fall longline survey index LLS2, covers a time and area where cod begin to assemble prior to overwintering in the deeper waters of NAFO 3Pn. Similarly, as noted above, the Sentinel bottom-trawl survey might effectively approximately sample the entire population. For these situations, the observation eq 11 was applied. We fit models making different assumptions for these two surveys and used AIC to determine which seemed to have the most support in the data.

There is no information to independently estimate $p_{a,y}$ for age 2 because that age is not included in the Sentinel fixed gear indices, and information is more limited for age 3 because the Sentinel gilllnet index does not include that age. We therefore examined the relative fit of models that assumed a common age 2-3 value versus a common age 2-4 value, across different models making different assumptions about whether the LLS and Sentinel trawl surveys were whole population surveys or not. There was greatest support for grouping ages 2-4, with the smallest delta AIC value being 5.6 (comparisons not shown). Grouping ages 2-4 also improved model convergence; the age 2-3 model associated with the additional 5.6 AIC units had a maximum gradient component (mgc) for the negative log-likelihood of 0.00113 whereas the model grouping ages 2-4 had a mgc of 0.00018.

Results

The best model assumed that both the DFO RV and Sentinel trawl surveys were offshore surveys and that the Sentinel fall longline survey LLS2 sampled the entire population (AIC = 3,182.5). This reflects a better fit compared to the baseline model which was associated with a larger AIC value of 3,315.9. Distribution shift models that assumed that the Sentinel mobile survey sampled the whole population (AIC = 3,201.4) or that LLS was a nearshore survey (AIC = 3,205.3) had less support.

Estimated distribution shift catchability deviations ranged between 0.4 and -0.4, values which are non-negligible (Figure 28). Trends in the deviations were age dependent. Of note is a greater availability of young fish to the offshore in the 2016-2020 period, and of older fish in the early 2000s and around 2010 for ages 10-11+. These patterns clearly reflect the diverging trends that were observed in the survey data when comparing the fixed gear and trawl surveys (see Benoît et al. 2024).

Allowing for the catchability deviations in the model resulted in largely imperceptible differences with the baseline model most of the estimated quantities including SSB and total biomass (Figures 3, 29), recruitment (Figures 4, 30), average fishing mortality (Figures 8, 31), and age-specific mortalities (Figures 12, 32). The estimates of the survey catchability functions for the Sentinel GNS and LLS1 indices differed a little between models, and had slightly wider confidence intervals for the distribution shift model (Figures 5, 33). Estimates for the other surveys were less affected.

The largest differences between the baseline and distribution shift models concerned residuals for the survey indices. Patterns in residuals were improved somewhat for the younger ages ≤ 6 in the recent 10 years in the DFO RV survey and the Sentinel GNS and LLS1 surveys (Figures 18, 34). This is perhaps more clearly shown in Figure 35, where there is a reduced trend in residuals as a function of cohort for these surveys compared with the baseline model (Figure 19).

Fits to the input catch proportion-at-age were nearly identical for both models (Figures 21, 36).

There were some moderate retrospective patterns in the estimates of the catchability deviations, although the sign of the bias was different for the younger versus older ages (Figure 37). The seventh peel of the 7 year peel retrospective analysis did not properly converge (mgc value of 0.014), which appeared to be related to problems associated with estimating the catchability deviations (results not shown). We did not investigate what modifications would be required to obtain proper convergence given that we do not recommend this model be used as the assessment model, at least at the present stage of development.

Retrospective patterns for the other quantities were very similar to the baseline model, as is shown for example for SSB (Figures 25 and 38; results for most other quantities not shown). However, there was a stronger retrospective pattern for recruitment for the distribution shift model (Figure 38 bottom panel). This is very likely a result of the strong catchability deviations on age 2 in the recent period (Figure 28), which makes estimated recruitment susceptible to shifts in estimated deviations.

Recommendations

The distribution shift model provides a better overall fit to the data based on AIC and patterns in the residuals for some surveys. However, including the deviations has little effect on the estimation of quantities of interest for the assessment including SSB, biomass, abundance, recruitment and mortality rates. It is therefore not clear whether this added complexity is useful for the routine assessment model. For instance, projections from the distribution shift model for formulating catch advice would require also projecting shifts in distribution, which would represent another time-varying rate to project in addition to recruitment and natural mortality. Furthermore, additional investigation is required to understand what prevented proper model convergence in the 7 year peel of the retrospective analysis.

We therefore recommend against choosing this model for routine assessment of the nGSL cod stock. Nonetheless, we believe that this model could be useful as a secondary or research model that could be used to evaluate some causes of discrepancies between survey indices and model results that arise over time, and could be used along with additional data to explore the evidence for changes in cod distribution, perhaps in relation to environmental drivers and density-dependence. The discrepancies between survey indices highlighted in Benoît et al. (2022) and reflected here in the estimates of catchability deviations underscore the need for abundance indices that cover the distributional area of the stock and that are not susceptible to changes in availability. A spatial statistical model that integrates data from the different surveys to produce a single index, if properly validated, would be highly useful in that regard.

SIMULATIONS

The baseline model was subjected to self-simulation, using the *SIMULATION*() function available in TMB. In this type of simulation, data similar to the input data (catch, catch composition, survey indices) are simulated from the fitted model, and the model is fit to those simulated data. This is used to determine whether parameters are estimable and whether they might be inaccurately estimated. Correspondence between the original model fit and the fits to simulated data also confirms that the model was correctly coded.

Model independent simulation testing is advocated for models with random walks, like our *M* process errors (Deroba et al. 2015). These were beyond the scope of the present work. However we note that the ability to estimate trends in *M* in both age and size structured SPA and SSSCA models has previously been demonstrated in simulation studies (Chouinard et al. 2005; Swain and Benoît 2015; Cao and Chen 2022).

SIMULATION METHODS

We simulated 100 runs of data generation and model fitting, which took about 30 hours to implement, thereby limiting the number feasible. It is not clear how to simulate catch bounds used in the censored nll. Instead we assumed a lognormal likelihood for catches in all years, but added a second, larger catch variance parameter for the years 2006+ to be consistent with the spirit of the catch bounds.

The first set of simulations revealed small biases in certain estimated parameters and derived quantities (results presented below). We initially thought that these biases may reflect non-linear bias associated with the use of model random effects (Thorson and Kristensen 2016). Biases are expected especially for derived quantities that depend on random effects in a non-linear manner. The TMB package includes functionality to correct for such bias, although the implementation can require considerable computation time. Our results revealed trivial amounts of bias in model parameters (results not shown). Noticing that the biases occurred in quantities affected directly or indirectly by survey catchabilities and noting that the use of a prior on the fully recruited catchability for the trawl surveys could have influenced the results, we ran a second set of simulations assuming a small standard deviation value of 0.05 on the prior for the DFO RV survey.

SIMULATION RESULTS

Plots of the results of the simulation study for a small number of parameters and derived quantities are presented in Appendix A.

In the first set of simulations, the baseline model over-estimated survey catchability-at-age for all five surveys by about 10% relative to the simulations (Figure A1.1). This was associated with underestimation of abundance related quantities such as SSB and recruitment (Figure A1.2), and therefore also an overestimation of fishing mortality (Figure A1.3). Making the prior highly informative for the DFO RV survey fully recruited catchability (q) dramatically improved the correspondence between the original estimated model results and the results of the simulations (rightmost panels in the figures in Appendix A). We do not know whether the difference between the two sets of simulations might reflect a feature of the simulation algorithm as implemented in TMB or whether biases truly exist when the standard deviation of the prior is larger. Even if the estimated biases are correct and are a feature of the model, we judge their magnitude to be small (10%) and therefore not of concern. Furthermore, we note that the biases appear to be consistent over the model time series, which suggests internal consistency among model parameters and quantities, such that decision making using the model should not be affected by the small biases.

SENSITIVITY TO ALTERNATIVE FORMULATION AND PARAMETERIZATION ALTERNATIVE FORMULATION AND PARAMETERIZATION

We examined the sensitivity to some of the choices made in model formulation and parameterization as regards the age groups used to estimate the *M* process errors, the specific years used to define the two blocks of time for the log-recruitment means (eq. 2), the use of the Myers et al (1996) *F* priors, assumptions on errors in the input catch, which we term catch-error runs, and assumptions for the survey catchability functions (age-specific selectivity and the prior on RV survey asymptotic catchability). These constitute some of the main factors that could affect model suitability and model estimates of key abundance quantities and demographic rates.

M GROUPS

The baseline model estimates *M* process errors for four groups of ages. We examined models with three groups (ages 3-5, 6-8 and 9-11+; and ages 4, 5-7 and 8+) and two groups (ages 3-6 and 7+) of ages. The baseline model resulted in the lowest AIC (3315.9), compared to the three *M* group models (AIC 3,320.1 and 3,323.2 respectively) and the two *M* group model (AIC = 3,333.6). Estimates of age-specific natural (Figure 39) and fishing mortality (Figure 40) were generally very similar between model formulations. Other model parameters and quantities were also nearly identical and those results are not shown. Given the similarity in results we did not examine different combinations of ages for the groups.

Models with four different age groups were also attempted following suggestions from participants at the peer review meeting, specifically for ages 4, 5-6, 7-9 and 10+, and for ages 4, 5-7, 8-9 and 10+, but both models failed to converge.

Overall we conclude that the use of the original four age groups was supported.

MEAN RECRUITMENT YEAR BLOCKS

The previous assessment for the stock estimated an important drop in annual mean recruitment beginning in 1991 (Brassard et al. 2020). This motivated the choice of estimating separate mean log recruitment values for years ≤1990 and >1990. Sensitivity to the choice of time-blocks around the pivotal year in which mean recruitment dropped was assessed by fitting the baseline model with two alternative mean recruitment block definitions, i) $y \leq 1989$ and $y > 1989$, and ii) $y \leq 1991$ and $y > 1991$. Recruitment estimates were very similar for the baseline model and two sensitivity runs (Figure 41). The estimated standard deviation for log recruitment deviations, σ_R, was 0.305 for the baseline run, 0.321 for sensitivity run i) and 0.385 for sensitivity run ii). The larger standard deviation for sensitivity run ii), which likely results from including a low recruitment year in the first time-block, is evident in the greater dispersion of log recruitment deviations and wider confidence intervals for estimated recruitment (Figure 41). Overall, these results confirm that the time-blocks chosen for the baseline model are suitable, and certainly preferable to those in sensitivity run ii).

The change in mean recruitment coincides with the change in vessel and gear that occurred in 1990 for which the model estimated catchability adjustments for ages 2 and 3 (see eq 15). There were therefore concerns that choice of recruitment time-blocks could affect the estimates of the catchability adjustments. Indeed, there is some unavoidable sensitivity for these estimates, with an approximately 6-7% difference between the baseline model and sensitivity run (i) and a 11-13% difference between the baseline model and sensitivity run (ii):

Time-blocks	Age 2	Age 3
≤1990 and >1990 (baseline)	0.458	0.517
≤1989 and >1989 (i)	0.429	0.487
≤1991 and >1991 (ii)	0.518	0.576

Setting aside sensitivity run (ii) which was clearly less suitable on the basis of a larger estimated σ_R, the difference between the baseline model and sensitivity run (i) is relatively small and unlikely to be consequential for other model parameter estimates.

TAGGING *F* PRIOR

Excluding the Myers et al (1996) *F* priors reduced somewhat the estimated mean *F* for ages 6-9 in 1986 and 1987 compared to the estimates from the baseline model (Figures 8, 42). Overall *F* values at age were impacted little by the exclusion (results not shown). Excluding the priors had an unexpected impact on the fully-recruited catchability to the DFO RV survey, reducing the value from about 1.9 in the baseline model to 1.6 (Figures 5, 43). This had a knock on effect on the fully-recruited catchability to the other surveys. The change in catchability was associated with a change in the scale of SSB (Figure 44). When the priors were excluded SSB was greater over the entire series. The ratio of the lowest and highest SSB was 0.07 for the baseline model and 0.11 when the priors were excluded, indicating that the degree of estimated depletion was somewhat different between the two formulations. In contrast, estimated recruitment at age 2 was very similar between formulations (Figure 44). Model fits to the survey, catch and catch composition data were nearly identical in the two model formulations (not shown). Overall, although the choice to include the priors affects the scale of estimated SSB, the results of the assessment (relative stock status and trends) are affected much less. There is no compelling reason to exclude the results of the tagging study analysis reported by Myers et al. (1996) from the assessment, as those results are relevant to the stock. Furthermore, the assumption of *M*=0.2 used by Myers et al. (1996) is supported by the estimates of *M* in the model. We therefore believe that the priors should be retained for subsequent modelling.

ASSUMPTIONS ON ERRORS IN INPUT CATCH

Two separate runs were made in which we widened the uncertainty on catch inputted into the model. In the first run, we applied the censored nll to the catch for the entire 1973-2020 series, assuming catch bounds for years ≤ 2005 that ranged from 90% of input catch as the lower bound and 400% input catch for the upper bound. For the remaining years, we multiplied the original upper catch bound by 4. The choice of multiples of 4 was arbitrary, but chosen to represent a large increase in catch uncertainty. This run assumes that catch under-reporting could have been important in all years and particularly since 2006. In the second run, we retained the revised assumption for catch bounds for years since 2006, but reverted to the lognormal likelihood for catches in years ≤ 2005, however increasing the standard deviation on log-catch from a value of 0.1 to 0.5. In this run, log catch in the early part of the series could equally be under or overestimated, noting that this could also have been achieved by decreasing the value of the lower catch bound.

First run - censored-likelihood and wide upper catch bounds

In this run, catch was estimated to be somewhat above input catch for 1973-1994, generally well above input catch in 1993-1998 and 2003-2020 and at the level of input catch in 1999-2002 (Figure 45). The level of estimated catch since the 2003 moratorium was substantially greater than in the baseline runs, and unsurprisingly, unaccounted catch subsumed in *M* was a smaller fraction of total estimated catch (Figure 46). The total unaccounted catch estimated by the model for the recent period is substantial, close to five times the reported landings in some years, which seems implausible given the level of monitoring in the commercial fisheries. Even with considerably increased magnitude for the upper catch bound, model-estimated catch was near the catch bound in some years.

The scale of average fishing mortalities differed only a little in this run compared to the baseline model, although high frequency variation was smoothed over considerably (Figures 8, 47). The spike in *F* in 1992-1993 was spread over both year and the average *F* was a little higher post 2000. While estimated total mortality-at-age was similar to the baseline model, the level of natural mortality was reduced somewhat, especially in some years (Figures 12, 48).

There was an unexpected reduction in the fully recruited catchability to the DFO RV survey, to a value of 1.28, with knock on reductions in catchability to the other surveys (Figures 5, 49). This resulted in an increase in the level of SSB and age 2+ biomass, as well as wider confidence intervals on the estimates for the 1980s (Figures 3, 50). However the scale for recruitment differed little between this run and the baseline model, and the trend in recruitment was very similar (Figures 4, 51).

Model fits to the catch composition data (Figure 52) and the survey data (not shown) were very similar between this run and the baseline model (Figure 21). It therefore appears that it is mainly the scale in the model that was affected by changing the catch bounds and employing the censored likelihood for the entire series, as reflected by the change in survey catchability and estimated catch. This is also reflected in the correlations amongst model parameters, which were increased considerably compared to the baseline model (Figures 27, 53). In addition to those shown in Figure 53, there were large correlations between the estimated numbers in 1973 and the parameters defining the catchability functions for the Minet surveys.

Second run - lognormal likelihood with wide variance for 1973-2005

In the second run of catch-error runs, catch was estimated to be below input catch in most years prior to 2003. Estimated catch for subsequent years was often much lower than in the first catch error run (Figures 45, 54). The two runs resulted in very similar estimates of average fishing mortality for ages 4-6 and 6-9 (Figures 47, 55); however age-specific estimates of *F* were considerably different at most ages (Figures 48, 56). Fishing mortality-at-age, and even total mortality, had larger values in many years. Ignoring spikes and dips in estimated *F* and *Z*, average fishing mortality since 2000 fluctuated around levels comparable to those prior to 2000 for the older ages. Meanwhile, estimated *M* was much lower at all ages, generally fluctuating just above the assumed m_a values.

The second catch error run resulted in survey catchabilities that were similar to the first run, hence lower than in the baseline model (Figure 57). Estimated abundance and biomass quantities were nearly identical to those in the first catch-error run (results not shown).

Summary for catch-error runs

The results of the catch-error runs appear to indicate that a discrepancy in input catches for the first portion of the series compared to the second portion may underlie the relatively elevated estimated value for the DFO RV survey catchability in the baseline model and in the existing SPA. To reduce the fully recruited catchability towards the assumed prior, the model appears to seek to increase considerably the estimated catch for the most recent period with respect to estimated catch in the first portion of the series. In the first catch-error run, this was manifested by estimated catches that in some years were very close to the assumed upper bound in the 2010s, while in the second run, this was manifested by estimated catches that were below the input values for much of the 1970-2002 period, yet above for much of the 2010s. The results for the runs excluding the Myers' priors appear to also support the contention that catch discrepancies affected the survey catchabilities, as they resulted in a reduction in *F* for part of the 1980s and in a reduction in survey catchability.

It is not clear how the discrepancy identified above can be resolved with the existing catch information alone, as the available information has recently been reviewed in considerable detail and the inputs used here constitute the current best possible (Ouellette-Plante 2022a,b). Incorporating the results from the tagging experiments undertaken during the past two decades into the model might help to attenuate the discrepancy (Ouellette-Plante 2022b). Exploring this could be a research priority. However, expectations should be tempered as regards the benefits of incorporating the tagging information for the nGSL assessment. As indicated by Ouellette-Plante et al. (2022b), there appear to be some problems with the tagging data, including a non-negligible proportion of tag returns with likely incorrect recapture year. Furthermore, it is not clear whether tags are returned when tagged cod are captured in the recreational fishery, and certainly they are not identified as such in the data. Also, we question whether tags are reported for cod that are captured in catches that are otherwise not declared. Given the amounts of unaccounted catch implied by estimates from the baseline model, let alone the catch-error runs, failure to report tags for otherwise unaccounted catches could result in substantial biases in estimated fishing mortality rates in the model, and therefore also *M*.

During the peer review meeting for the model framework, participants questioned why the model in baseline and catch sensitivity runs tended to attribute 'excess' mortality to *M* rather than to catch, despite having the capacity to ascribe to catch. Although this question warrants further investigation, it appears this may be a result of incorrectly assuming that missing or incorrectly specified catch has the same age composition as that assumed for reported catch. A comparison of the estimated relative composition of mortality across ages for *F* as a function of *M* shows an inconsistent correlation at different ages, for 2004-2020 (Figure 58). To the extent that *M* is subsuming unaccounted catch, this result indicates that mortality is distributed differently across ages compared to fishing mortality. Strong constraints on the age composition of unaccounted catch in the model, coupled with flexibility to accommodate time varying patterns in age-specific *M*, are such that excess mortality is more likely to be ascribed to *M*. Fundamentally, unaccounted catch is only expected to have the same age composition as accounted catch if misreporting rates are uniform or random across fishing fleets and sectors, or for instance, if these fleets and sectors fish with similar selectivity, which is unlikely. In contrast, if misreporting rates differ among fleets, the age composition of accounted for and unaccounted for catches may differ. Notably, the age composition of catches in the recreational fishery are likely to differ from other fleets, given notable differences in the gear employed. This poses a modelling challenge that is unlikely to be resolvable in the absence of additional data or information on the age composition of unaccounted for catches, or making other assumptions in the model. Allowing for the annual age composition of unaccounted catches to be estimated by the model would result in strong confounding with time varying age-specific *M*. Possible solutions include:

- Assuming that the age composition of *M* estimated during moratorium years applies to the remaining years and estimating the age composition of unaccounted catch; however, this would assume that time trends in actual *M* are not age-specific;
- Increase fishery and compliance monitoring to reduce the incidence of catch misreporting; however, while this could be an effective solution prospectively, it does not address the problem historically; and,
- Try to improve estimates of age-specific *M* using data from other sources such as tagging, acknowledging the existing challenges with the tagging program (Ouellette-Plante 2022b).

In the absence of better information or guidance from the peer review, we proceeded with the baseline model formulation for the assumptions on catch.

LOGISTIC SURVEY CATCHABILITY ASSUMPTION

A review meeting participant was concerned that the assumption of a logistic function for RV and Sentinel mobile survey catchabilities may be too constraining and may affect model performance. In response, we undertook sensitivity runs in which catchability-at-age was freely estimated for all ages up to a given age, above which catchability was assumed constant. This approach ensured that catchability reached an asymptote, as is expected for trawl surveys. Three variants were undertaken, assuming constant catchability for ages 5+, 7+ and 9+ respectively for both surveys. Estimated catchability-at-age differed little between the baseline model and the three sensitivity variants for the Sentinel mobile survey (Figure 59). Patterns were also similar across model runs for the RV survey, although the model estimated an increasingly wider hump in catchability at intermediate ages as model flexibility was increased. Given that the differences amongst variants were not large and in the absence of plausible explanations for a peak in catchability at intermediate ages in the RV survey, the meeting concluded that the logistic function assumption was suitable.

PRIOR ON RV SURVEY CATCHABILITY

Sensitivity to the choice of standard deviation (s.d.) on the prior for the fully selected (asymptotic) RV survey catchability (eqn 14) was assessed by running a model assuming a value of 0.1, which is considerably more restrictive than the value of 0.7 assumed for the baseline model.

Unsurprisingly, the model estimated an asymptotic catchability for the RV survey much closer to a value of one in the sensitivity run compared to the baseline model (Figures 5, 60). Asymptotic or maximum catchability values for the other surveys were also smaller, although age-specific patterns were very similar between baseline and sensitivity runs. The changes in survey catchability resulted in a corresponding increase in both SSB and age 2+ biomass estimates (Figures 3, 61). Recruitment values were also greater and there were some differences in interannual but not long term trends (Figures 4, 62). The correlation for log-recruitment deviates was approximately 11% lower in the sensitivity run (Table 1), which could explain the small differences in recruitment trends.

The tighter prior on asymptotic RV survey catchability resulted in a decrease in age-specific fishing mortality, and a generally corresponding increase in age-specific *M*, resulting generally in only small changes in total mortality *Z* (Figures 12, 63). This result is not unexpected given that reductions in survey catchability values are expected to result in increased abundance and biomass estimates, which in turn results in decreased fishing mortality for a given amount of catch. Furthermore, because the survey catches-at-age provide a lot of information on *Z* (see Benoît et al. 2022), and because survey age-specific catchabilities differed little between model runs (Figure 60), model estimates of *Z* weren't expected to change much. The standard deviation for log-*M* deviations was about 12% higher in the sensitivity run compared to the baseline model (Table 1), reflecting the greater variability in *M* required by the model to explain patterns in *Z*. This result corroborates those of other sensitivity runs in suggesting that high survey catchability values favored by the baseline model and the previous SPA assessment model may reflect challenges in ascribing apparent high mortality that isn't well accounted for by fishery catch.

Estimates for other key standard deviation and correlation parameters (Table 1), and other model estimated quantities and residuals (result not shown) differed little between baseline and model runs.

Given that the sensitivity run resulted largely in changes to the scale of estimated abundance, biomass and *M*, rather than to trends, and in the absence of better information to specify the prior on RV survey asymptotic catchability, the baseline model was retained.

Problems with unreported or unaccounted catches appear to be the most likely explanation for the persistence of an estimated asymptotic q value >1 in the new model and previous SPA, based on the various foregoing sensitivity analyses. An alternative explanation is that DFO RV survey (and Sentinel mobile survey) abundance and biomass are overestimated by the current survey design, such that the model is attempting to 'correct' for this bias with elevated q values. As noted earlier in this document, herding of cod is an unlikely explanation. The survey design is also very unlikely to overestimate trawlable abundance. All else being equal, stratified random surveys are design unbiased. The survey is very unlikely to sample cod from other stocks, incorrectly attributing them to nGSL cod (Benoît et al. 2021). In fact, the RV survey does not sample nearshore strata, nor NAFO 3Pn strata, that are important for nGSL cod, and both mobile gear surveys do not sample other potentially higher density areas such as the Mecatina trough, rendering them more likely to underestimate rather than overestimate abundance.

PROJECTIONS

Projections are used in stock assessment to evaluate the probabilities of achieving different management outcomes as a function of management actions, typically choices for TAC, and the characteristics of the stock and the fishery as estimated by the assessment model. The SSSCA model is well suited for short-term projections because it can project the uncertainty and temporal autocorrelation in key characteristics, notably recruitment, *M* and relative fishery Iselectivity as implied in the estimated age-specific *F* values. In short-term projections, the relative values of these characteristics will reflect correlation with the last values estimated in the assessment. In longer-term projections, projected values will tend towards mean values equivalent to those in the assessment, thus the mean recruitment since 1991, the assumed m_a values for mortality, and the *F* main effects for the most recent period (Figure 1). These values may not be appropriate the future. For instance, if there is a relationship between recruitment and SSB, mean recruitment should change if there are important changes in mean SSB. Likewise, a change in the nature of the fishery could change the fishery selectivity. These issues are not germane to the SSSCA and concern all assessment models. Longer term projections thus require more assumptions and perhaps the exploration of different scenarios. This type of exercise was beyond the scope of the assessment framework review. We therefore considered only short-term projections of 10 years. Furthermore, we present results only to illustrate the projections from the model and therefore only examined two scenarios, a status quo scenario of

2,000 t of total fishery catch (including unaccounted catch) and an approximately 'lowest catch levels possible' scenario of 100 t annually.

Recruitment was projected using the estimated AR(1) covariance recruitment deviation and 1991+ mean recruitment parameters from the model. A stock recruitment relationship is not well defined for the nGSL stock, and there is little basis for projecting recruitment at intermediate SSB levels (Figure 64). Projecting recruitment as we did is likely conservative with respect to an increasing SSB. Careful consideration is required before choosing an alternative means of projecting recruitment (Van Beveren et al. 2021).

Natural mortality was projected using the age and year AR(1) covariance parameters for the *M* process errors. Because the most recent estimates of *M* were low, values in the stochastic projections will also tend to be low. This will be reasonable for projections involving fishery catch amounts similar to those in the most recent year, but will not be reasonable for projected TACs of greater magnitude because of the greater amount of unaccounted catch subsumed into *M* described above. Incorporating this phenomenon into projections is not straightforward and would require assumptions about how the magnitude of unaccounted catch scales with the catch options.

Rather than projecting the age dependent *F*s from the model, we estimated the mean partial recruitment-at-age for the last year within the model, and projected partial recruitment from the estimated values.

Projections were undertaken outside the model estimation in TMB to avoid potentially influencing the estimation of parameters. Instead, projections were undertaken in R using the parameter estimate vector and the parameter covariance matrix.

The projections for the two catch scenarios suggest a high probability of stock increase whereby there is a >50% chance of SSB exceeding 100,000 t in 10 years and >90% chance of exceeding the current SSB level over 10 years (Figures 65 and 66). Similarly, the abundance of cod age 5+ is projected to increase at a moderate rate for the next two years, and then slightly more rapidly to years 3 and 4. There was little difference in projection results for the two scenarios, as the assumed catch levels in the projections are small relative to SSB, particularly once the 2018 cohort recruits to the mature population. The relative abundance of that cohort has been especially large in the DFO RV survey since 2019 (Figure 67).

The positive outlook for the nGSL stock in the projections is clearly a function of the strong 2018 year class (Figure 4), both for its contribution to subsequent stock growth but also because projected recruitment is correlated with that high 2020 age 2 value. The positive outlook is also a result of the relatively low total mortality rates estimated for 2020, which at ages 6+ were estimated to be at the lowest level since the 2003 moratorium (Figure 12). A recent assessment update showed that mortality rates increased considerably subsequently, consequently, the strong 2018 cohort did not contribute to stock growth and in fact SSB declined (Ouellette-Plante et al. 2025).

RELEVANT INFORMATION FOR REFERENCE POINTS AND REBUILDING

The revised model has resulted in a change in the scale of stock characteristics relevant to establishing reference points and has provided a better understanding of interannual changes in *M*, a key determinant of stock productivity. As a result, the values of reference points used for the management of nGSL cod need to be updated, possibly using a different approach from the past. Furthermore, the nGSL cod stock was also the subject of a rebuilding plan which was in place from May 2013 to May 2018 . This plan was not previously published and is therefore presented for reference in Appendix B. The development of a renewed rebuilding plan was, among other things, delayed in anticipation of the current review of the assessment framework for nGSL cod. Most importantly, the requirement for a revised rebuilding plan was legislated by regulation to be completed by April 2024 (Canada Gazette, Part II, 2022).

The science advisory review associated with the present document was intended to review the assessment framework for nGSL and its subsequent operationalization. It was not meant to propose specific candidate reference points or associated management and rebuilding framework. These items were addressed subsequently (Benoît and Ouellette-Plante 2023; DFO 2023; Ouellette-Plante et al. 2025). However the terms of reference for the May 2022 review included the following items, which are addressed in the current section:

- Provide direction for an approach to estimating reference points for this stock.
- Discuss whether the assessment methodology has the potential to support quantitative evaluation of harvest control rules.

We interpreted these terms of reference more generally to also include the context of an eventual rebuilding plan.

The elaboration of a precautionary approach for an exploited stock should be based on an understanding of state (e.g., SSB) and productivity (i.e., recruitment, growth, *M*) that is as extensive as possible, and ideally, which accounts for or at least acknowledges past periods of low and high productivity. An examination of long-term dynamics is required to minimize the risks associated with the so-called shifting baselines syndrome (Pauly 1995). To that end, we utilised the highly useful data and information on the historical productivity and exploitation dynamics of the nGSL stock available in the papers by Wiles and May (1968; details below) and Myers et al (1996) to extend the assessment model back to 1966, and to derive estimates of SSB that are representative of 1953 and 1958. These historical estimates are based on more assumptions and on data that are more uncertain, compared to what is used in the proposed assessment model described in the previous sections (i.e., with data starting in 1973). Consequently, we recommend against including these 'historical' data and estimates in the operational stock assessment model going forward. However, these 'historical' estimates provide a useful perspective on stock dynamics and productivity during the period of industrialization of the fishery, including the introduction of bottom trawls in the mid to late-1950s (Wiles and May 1968). They also provide estimates of fishing mortality that appear to have sustained the stock from the late 1960s to the mid-1980s, when rates of natural mortality were likely similar to the estimated values for the most recent years, at levels of SSB and recruitment that were greater than present. As such, the extended assessment modelling that includes these historical estimates should be useful in defining relevant reference points and a relevant rebuilding plan.

In addition to considering long term evidence for stock productivity, we also considered approaches for defining key reference points using the contemporary assessment, based on stock and recruitment, and based on accepted proxies. Some results were presented and discussed to stimulate reflection on possible reference points, which were subsequently more formally proposed and reviewed at the winter 2023 assessment for nGSL cod (DFO 2023; Ouellette-Plante et al. 2025). While this might have stimulated discussion on the appropriateness of different approaches, a discussion and review of specific reference point values was outside the terms of reference for the May 2022 assessment framework review.

METHODS

Extended assessment model

Wiles and May (1968) present results for the age composition from surveys that covered blocks of years, specifically for 1947-1951, 1957-1961 and 1962-1966 (results also presented in Benoît et al. 2022). Based on the availability of fishery catch-at-age information in their paper, and the relative amounts of survey sampling in each year that they report, we took these survey results to represent respectively the years 1953, 1958 and 1966. This is clearly a great simplification that necessarily blurs possible cohort dynamics (e.g., strong year classes), but was necessary practically and should nonetheless reflect average conditions for the period surrounding those years.

In their paper, Wiles and May (1968) present results for fishery catch-at-age, or catch-at-length which we converted to catch-at-age using the growth function they provide, for different fleets: bottom-trawls, longlines, and traps. We weighted catch-at-age values reported by them for specific years or groups of years, by the relative catch made by each fleet, as reported in Brassard et al. (2020) for 1964-1966, and as reported in Table 1 of Wiles and May (1968) for the previous years, with adjustments for landing in NAFO 3Pn as described below. We grouped results for years such that a catch-at-age was constructed to approximate the true catch-at-age for 1953, 1958, and 1966.

The mean estimates of fishing mortality estimated by Myers et al. (1996) from tagging experiment for 1957-1958 and 1964-1967 were adjusted for an assumed *M* of 0.15 as suggested by the authors, and were assumed to represent 1958 (*F*=0.20 ± 0.15) and 1966 (*F*=0.37 ± 0.15) . For 1953, we arbitrarily assumed *F*=0.10 given the 1947-1951 survey estimate of total mortality (*Z*=0.25, see Benoît et al. 2022). We assumed that these *F* values represented average age 6-9 *F*, as we did in the baseline model.

For simplicity, we assumed that the 1973 catch and stock weights, and the maturity ogive also applied to the prior years. We nonetheless compared the results with those obtained using the stock weights and ogives from Wiles and May (1968). These were not used in the initial estimates because we do not know when the values changed in the population between the mid-1960s to mid-1970s.

The age-specific fishing mortalities were assumed to follow the AR(1) age and year correlations estimated for the remainder of the modelled period, 1973-2020. A selectivity function and asymptotic catchability was estimated for the surveys using the approach used in the baseline model.

Annual landings for 1964-1972 were taken from Brassard et al. (2020). Landings for the years prior were taken from values reported in Wiles and May (1968) for NAFO Divisions 4RS, which were prorated to account for landings made in 3Pn by applying the ratio of 4RS:3Pn landings calculated from the values for 1964-1968.

A model incorporating the data and information assumed for 1966 converged, but models extending further back did not. We therefore estimated SSB values for 1953 and 1958 using a different approach. For 1958, we assumed that the fishery partial recruitment function implied by the age-specific *F*s in 1966 also applied to 1958. In making this assumption, we had all the information required to calculate abundance at age using the Baranov catch equation, and then to calculate SSB. We could not assume the 1966 fishery partial recruitment function for the 1953 estimate because bottom trawls were not active in the fishery then. Instead, we assumed only that ages 6-9 were fully recruited. Abundance at other ages was derived using the survey selectivity function estimated for 1966 in the extended model.

Other approaches for reference points

An extensive review by Myers et al. (1994) on limit reference points (LRP) for recruitment overfishing, and subsequent DFO advice (Rivard and Rice 2003; Shelton and Rice 2002), favored approaches based on stock sizes that result in 50% of the maximum predicted average recruitment due to their robustness and ease of understanding and communication. This was the basis for setting the current LRP for nGSL cod (Duplisea and Fréchet 2011). Additional approaches included the use of $B_{recover}$, the lowest historical biomass level from which the stock recovered under favorable environmental conditions. For example, $B_{recover}$ was chosen to establish the LRP for the neighboring NAFO 4TVn stock (Chouinard et al. 2003).

The process of selecting the current LRP for the nGSL stock involved fitting a large number of parametric and non-parametric functions to the SSB-recruitment output from the assessment model, as an objective means of estimating the stock sizes that result in 50% of the maximum predicted average recruitment (Duplisea and Fréchet 2011). That approach does not appear relevant presently because the stock and recruitment output from the baseline model provides very little information on recruitment at intermediate stock sizes (Figure 64). While there is some evidence that average recruitment declined as SSB increased from about 135,000 t, consistent with the depensatory dynamics of a Ricker function, the SSB that maximizes average recruitment is difficult to define from the model outputs. Furthermore, the shape of the SSB-recruitment function between SSB levels of about 50,000 to 130,000 t, which would define the SSB producing 50% maximum recruitment, is essentially unknown. Model estimates of stock SSB and recruitment from the short period when the stock collapsed in the late 1980s and 1990s (labelled years in Figure 64) are unlikely to be a good basis for defining the SSB-recruitment function. Those years were characterized by poor physiological condition of adults that is not entirely accounted for in SSB, high abundance of at least one important pelagic fish predator of cod eggs and larvae, Atlantic mackerel (*Scomber scombrus*), and below average bottom-temperatures that may have contributed to higher mortality in settling and settled juveniles (Figure 68; Dutil and Lambert 2000; Lambert 2011; DFO 2021b; Galbraith et al. 2021). These are all factors that have been identified previously as likely negative contributors to reproduction or recruitment for cod (Swain and Sinclair 2000; Duplisea and Robert 2008; Lambert 2011; Bryhn et al. 2022), and all of which are currently at more favorable values (Figure 68). It therefore seems likely that recruitment at intermediate SSB levels could be higher under current conditions than what is indicated by the existing model outputs. It is also difficult to gauge from Figure 64 whether stock-recruitment dynamics since 1991 might reflect an Allee effect. However, the estimated abundance at age-2 of cod from the 2018 cohort is comparable to that of some cohorts born prior to 1991 from much larger SSB (Benoît and Ouellette-Plante 2023), suggesting an Allee effect might not be likely. Overall, because the degree to which recruitment might be improved is difficult to gauge, we did not pursue approaches for defining an LRP based on the stock-recruitment function. Likewise, because nGSL cod have not undergone depletion-recovery dynamics since the stock has been monitored, it is not possible to define an LRP based on $B_{recover}$.

Instead, we considered proxies that are often used to define reference points for fishing mortality and stock status. These are derived from calculations of yield-per-recruit (*YPR, kg*) and spawner-per-recruit (*SPR, kg*),

$$YPR = \sum_{a=0}^{A} cw_a f_a F\, Z_a^{-1}(1 - e^{-Z_a})e^{-Z_a a}$$

$$SPR = \sum_{a=0}^{A} sw_a mat_a e^{-Z_a a}$$

where $Z_a = f_a F + M_a$

and cw_a and sw_a are the weight (kg) of an individual at age *a* in the fishery (catch weight) and the population (stock weight), respectively, f_a is the fishery selectivity at age, *F* is the fully recruited fishing mortality, and Z_a, M_a and mat_a are respectively the total mortality, natural mortality and proportion mature at age *a*.

YPR is evaluated for a range of *F* values to obtain a *YPR* function. The value of *F* associated with an instantaneous slope of that function that is 10% the slope at the origin (*F*=0) defines the fishing mortality reference point *F0.1*, which was used to manage cod stocks in Atlantic Canada in the past[1]. *F0.1* considers only mortality and catch weight at age and is therefore an unsuitable reference point for recruitment overfishing (Gabriel and Mace 1999). However, *F0.1* is often established to prevent growth overfishing, and if it is suitable for that purpose it should also be sufficient to prevent recruitment overfishing, as pointed out by Shelton and Rice (2002). This reasoning is also relevant for reference points based on *SPR*.

The values of *F* that result in some fraction of maximum *SPR* at equilibrium are used as proxies for fishing mortality reference points. $F_{SPR35\%}$, the fishing mortality resulting in 35% of maximum *SPR* is a commonly used value assumed to be a robust estimator of F_{MSY}, the fishing mortality that will produce maximum sustainable yield, though some have argued that $F_{SPR40\%}$ may be preferable (see Gabriel and Mace 1999). Multiplying the value of *SPR* (35%) by average recruitment provides an approximation of B_{MSY}, the equilibrium biomass that is achieved if a stock is fished at F_{MSY}. In turn, DFO's fishery decision-making framework incorporating the precautionary approach (DFO 2009) states that values representing 80% and 40% of B_{MSY} may be suitably proxies for an upper stock reference point and an LRP respectively.

We calculated *YPR* and *SPR* derived reference points assuming both current conditions (2020) and those that prevailed during the early to mid-1980s (1980-1985) when there was a large fishery on the stock and the stock appeared to be in a relatively healthy state. The age-related functions that define *YPR* and *SPR*, including the fishery selectivity function, differ considerably between those two periods (Figure 69). It is not clear to us that the changes in the biological characteristics are necessarily reflective a change in productivity that may be difficult to reverse, given that the stock continued to experience important fishing-related losses even following the first moratorium, and because the estimation that *M* is trending downwards recently. Consequently, it seems relevant to also consider productivity and fishery conditions from the 1980s.

RESULTS AND DISCUSSION

Extended assessment model

SSB was estimated to have fluctuated around a value of 150,000 t from 1966 to the mid-1970s in the extended model, and the subsequent dynamics were as estimated in the baseline model (Figure 70). The SSB estimate for 1966 was affected little by the choice of weights and the maturity ogive used in the calculation (Figure 71). Although the weights at age from before 1967 were greater, maturity was delayed, and evidently the two differences essentially canceled out for the numbers at age in 1966. The SSB value for 1958 was around 330,000 t, while the value for 1953 was about 225,000 t (Figure 70).

Estimates of recruitment from the extended model indicate a dip that occurred from about 1969-1972, and which reached values comparable to the largest recruitment estimated for the 2010s (Figure 72). The new recruitment values from the extended model result in a slight increase in the dispersion of recruitment as a function of stock SSB, for values of SSB between 125,000 and 160,000 t (Figure 73).

The mean fishing mortalities for ages 4-6 and 6-9 were estimated to have fluctuated without much trend from 1966 to the mid to late 1980s, before rising steeply beginning in the late 1980s

[1] Canadian Senate. 2003. Straddling fish stocks in the Northwest Atlantic. A Report of the Standing Senate Committee on Fisheries and Oceans. June 2003.

(Figure 74). Patterns in *F*-at-age did not vary substantially during those first 20 years (Figure 75).

The reduction in SSB from the 1958 value to the 1966 value, and the subsequent SSB variation (Figure 70), constitute a trend that closely resembles that estimated for Northern cod (NAFO 2J3KL) based on surplus production type modelling (Rose 2004; Schijns et al. 2021). Schijns et al. (2021) estimated that around 1960, Northern cod (NAFO 2J3KL) SSB was at a value 1.5 times B_{MSY} and, by the mid to late 1960s, around B_{MSY}. There is evidence that these relative values might be relevant for nGSL cod. Assuming that the average of the 1953 and 1958 estimates constitutes 1.5 times B_{MSY} results in a rough estimate of B_{MSY} = 185,000 t. This value is of a similar scale to the mean estimated SSB value for 1966-1985 of 168,340 t (Figure 70). That level of SSB was produced during a period of time when mean fishing mortality fluctuated without trend (Figure 74) and resulted in landings that fluctuated about a mean of 86,350 t; values that were sustained (on average) over 20 years and are among the largest in the 65 year record (Figure 76). It may therefore be the case that the nGSL stock happened to be fished for a 20 year period at a level approximating F_{MSY} (0.49 for ages 6-9) and which resulted in an SSB approximating B_{MSY}. Using the proxies from the DFO framework (2009), this reasoning would result in values for the LRP equal to 74,000 t, if based on 1.5 times the 1953/1958 average, or 67,340 t[2] based on mean SSB for 1966-1985).

Reference point proxies

Compared to the 1980s, the current fishery selects for older fish and present values for *M* that are greater (Figure 69). This results in a *YPR* function that does not reach a maximum value and only tends to an asymptote as *F* is increased, compared to a *YPR* function representative of conditions in the early to mid-1980s that reaches a peak value for an *F*~ 0.3 (Figure 77). The *YPR* functions result in an estimated value of *F0.1* of 0.361 for the present period and 0.182 for the 1980s. While this suggests that the stock can be fished harder today than 25 years ago, it is associated with considerably reduced yield, < 50%. The *SPR* analysis produced estimates of an F_{MSY} proxy ($F_{SPR35\%}$) that are of comparable magnitude: 0.41 for current conditions and 0.196 for the 1980s.

Assuming recruitment equal to the mean recruitment <1991 estimated in the baseline model, we estimate the following values for B_{MSY} and the *LRP* associated with fishing at $F_{SPR35\%}$ (Figure 77):

	B_{MSY}	*LRP*
Current conditions	164,770 t	65,907 t
Early to mid-1980s conditions	426,130 t	170,450 t

The reference points associated with the *SPR* function for the early to mid-1980s are clearly very conservative, with the B_{MSY} value lying well above the historical SSB values we derived above (Figure 70), and how those values relate to the estimated stock and depletion dynamics estimated by Schijns et al. (2021) for Northern cod, a stock that very likely experienced a similar exploitation history.

[2] A correction for the difference in asymptotic catchability between the baseline and extended model would later be applied by Ouellette-Plante et al. (2025), resulting in an LRP value of 71,970 t. Proposed target and upper stock reference points were similarly adjusted.

Discussion – Reference points and rebuilding

Although they are based on very different reasoning, the potential fishing mortality and stock status reference points from the extended model correspond in magnitude to those from *YPR* and *SPR* proxies. While this is largely a coincidence, it has the benefit of reducing the range of choices. Although the values derived from the extended model are to some extent based on *ad hoc* reasoning, they benefit from being rooted in some understanding of the exploitation history of the stock. In the context of nGSL cod, this may be favorable in many respects compared to approaches to setting reference points based on simulations at equilibrium or tenuous assumptions about stock-recruitment dynamics.

The terms of reference for this review sought an evaluation of whether the new framework could support the quantitative evaluation of harvest control rules. Although the new modelling revealed uncertainties associated with removals from the population, particularly in the most recent decades, we believe that the model and model-based projections are suited to help guide the development of a complete precautionary approach for the stock, including harvest control rules. Furthermore, while some key uncertainties remain, such as concerns about recruitment dynamics at intermediate stock sizes, the framework also appeared suitable for supporting the development of a new rebuilding plan. We illustrate this with a very brief example to conclude this section.

At its core, a rebuilding plan requires a rebuilding target and a rebuilding timeline. Defining these is the responsibility of DFO Fisheries Management sector, although DFO Science provides a supporting role (DFO 2021a). A rebuilding target should be set at a level that is far enough above the LRP to have a high probability of the stock being above it (DFO 2021a). Other jurisdictions, including the United States and New Zealand (MF 2008; NOAA 2025), and international agreements such as the United Nations Fish Stocks Agreement (United Nations 1995), use B_{MSY} as a rebuilding target. We used this assumption for our example, and assumed that the objective was met when there was at least a 50% chance of SSB being above that target. We used B_{MSY} = 168,340 t derived from the results of the extended model as the rebuilding target.

International best practice is to estimate the minimum time required to reach the rebuilding target with zero fishing mortality (Tmin), and to establish a maximum rebuilding time of 2-3 times Tmin (DFO 2021a). We used the projections from the baseline model to estimate Tmin, which under current productivity conditions is about 15 years. We then made projections for the nGSL stock assuming total removals of 100 t/year, to simulate a 'lowest catch possible' scenario, and undertook a series of simulations to identify the annual removals that would result in a 50% probability of reaching the rebuilding target within 30 years, or 2 times Tmin.

The 'lowest catch possible' scenario resulted in achieving the rebuilding target in 15-16 years, while annual total removals of 13,000 t resulted in projections consistent with the intention of the second scenario (Figure 78). The 100 t/yr and 13,000 t/yr scenarios resulted in a 50% probability of SSB above the LRP (0.4 x B_{MSY}) in about 3 and 8 years respectively, although this level of probability does not constitute a large chance of truly being above the LRP or that the stock may fall back below if a rebuilding plan were to be terminated. As discussed above in the section on projections, these scenarios may be conservative in that they do not include compensatory recruitment dynamics.

While these projections were provided simply as an example, they indicated that there are reasonable prospects to rebuilding the nGSL cod stock at the time of the review in 2022. It was acknowledged this may take more than a decade, particularly depending on the level of fishing mortality to which it is subjected. Subsequent work undertaken in developing the rebuilding plan provided somewhat different prospects (Benoît and Ouellette-Plante 2023).

ACKNOWLEDGEMENTS

We thank Kunasekaran 'Kanna' Nirmalkanna for his assistance with coding the age and year autocorrelation function for natural mortality in the projections and Elisabeth Van Beveren for her help with projections coding. We thank Caroline Senay and Daniel Duplisea their constructive review of the penultimate draft of this document.

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TABLES

Table 1. Key standard error and correlation parameter estimates for model components (with reference to the associated equation number) of the baseline model and the sensitivity run with a more constrained prior on the survey catchability parameter.

			Baseline model		Constrained RV q prior model		
Parameter	Component	Eqn	Estimate	SE	Estimate	SE	Percent difference
σ_R	Recruitment	2	0.305	0.055	0.284	0.047	6.89
φ_R	Recruitment	2	0.442	0.187	0.393	0.178	11.09
σ_M	Natural mort.	4	0.896	0.199	1.002	0.222	11.83
$\varphi_{M,age}$	Natural mort.	4	0.885	0.048	0.898	0.042	1.47
$\varphi_{M,yr}$	Natural mort.	4	0.922	0.035	0.940	0.028	1.95
$\sigma_{F,ages\ 2-3}$	Fishing mort.	6, 7	2.352	0.372	2.286	0.360	2.81
$\sigma_{F,age\ 4}$	Fishing mort.	6, 7	1.465	0.188	1.440	0.180	1.71
$\sigma_{F,age\ 5}$	Fishing mort.	6, 7	0.808	0.117	0.800	0.110	0.99
$\sigma_{F,ages\ 6+}$	Fishing mort.	6, 7	0.466	0.052	0.465	0.051	0.21
$\varphi_{F,age}$	Fishing mort.	6, 7	0.791	0.038	0.788	0.038	0.38
$\varphi_{F,yr}$	Fishing mort.	6, 7	0.843	0.038	0.835	0.040	0.95
σ_X	crl resid.	9	0.280	0.022	0.280	0.022	0
φ_X	crl resid.	9	0.269	0.121	0.268	0.121	0.37
σ_{RV}	crl resid.	12	0.512	0.021	0.515	0.021	0.59
$\sigma_{Sen\ GNS}$	survey resid.	12	0.547	0.029	0.547	0.029	0
$\sigma_{Sen\ LLS1,age\ 3}$	survey resid.	12	1.121	0.162	1.119	0.162	0.18
$\sigma_{Sen\ LLS1,ages\ 4+}$	survey resid.	12	0.462	0.025	0.463	0.025	0.22
$\sigma_{Sen\ LLS2,age\ 3}$	survey resid.	12	1.126	0.164	1.117	0.162	0.80
$\sigma_{Sen\ LLS2,ages\ 4+}$	survey resid.	12	0.427	0.023	0.428	0.023	0.23
$\sigma_{Sentinel\ mobile}$	survey resid.	12	0.514	0.025	0.515	0.025	0.19

FIGURES

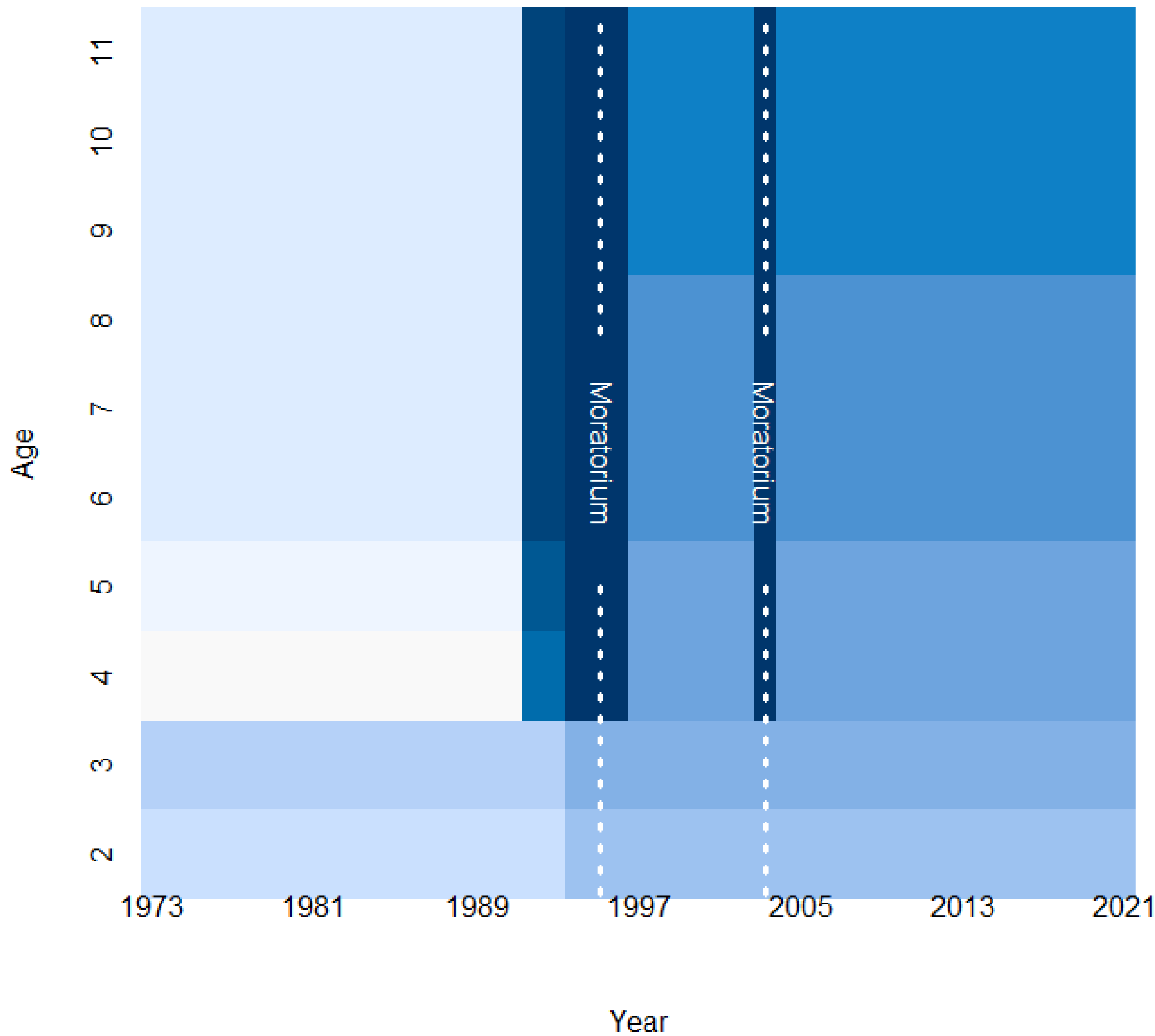


Figure 1. Fishing mortality main fixed effects. Each color represents a different estimated parameter value.

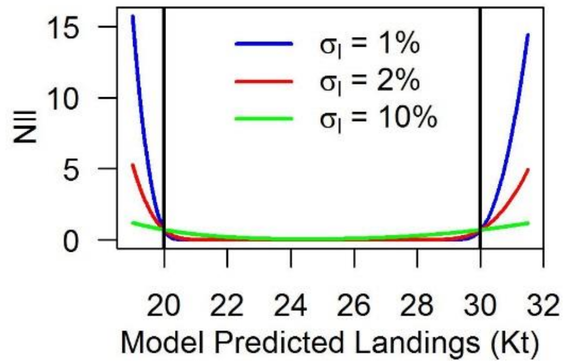


Figure 2. Illustration of the censored nll's for a range of model predicted landings, using three choices of $\boldsymbol{\sigma_l}$. Vertical solid black lines indicate the lower and upper bounds (redrawn from Cadigan 2023).

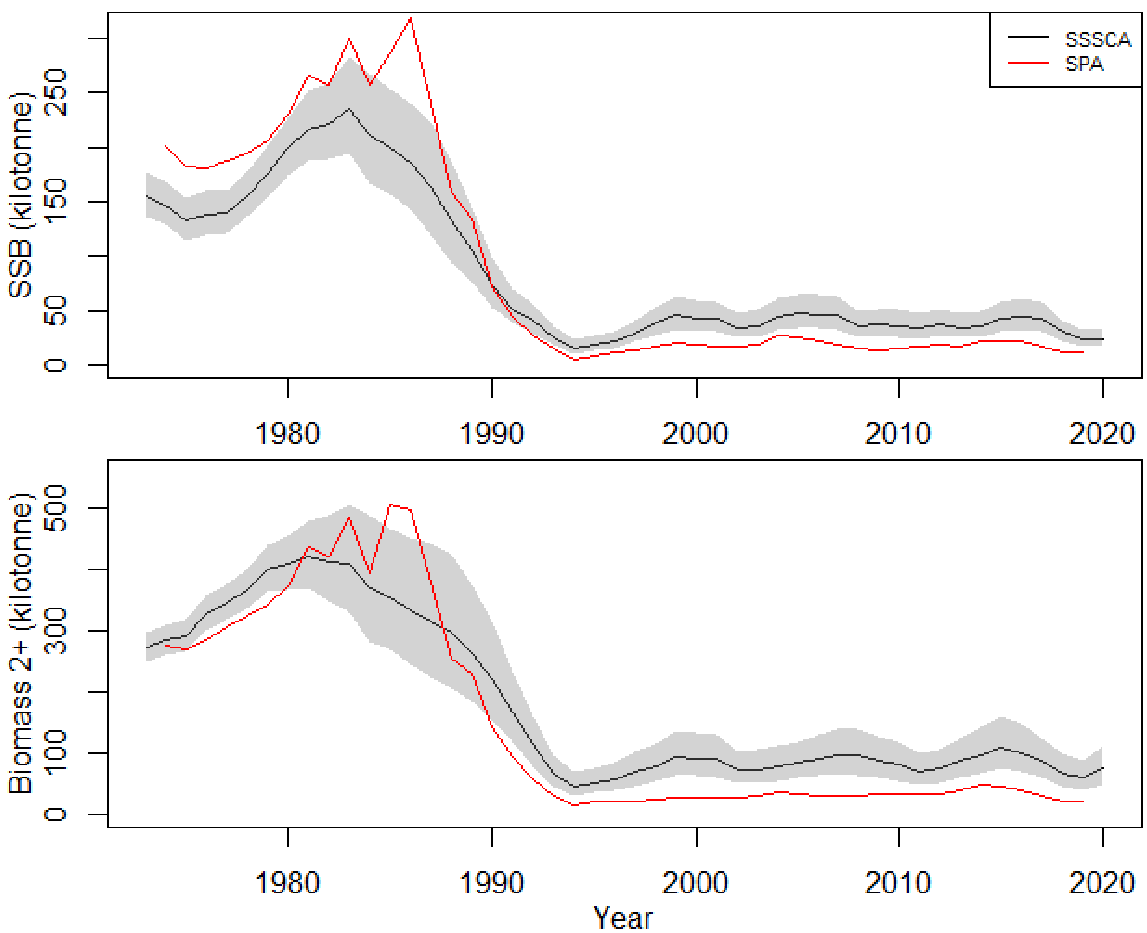


Figure 3. Baseline model (SSSCA) estimates of spawning stock biomass (SSB) and age 2+ biomass, with 95% confidence interval (shaded region), compared to values from the 2019 assessment using the SPA. In this and subsequent figures, confidence intervals for the SPA are not plotted because the principal comparison is on the predicted level and trend, and to keep the plots as simple as possible.

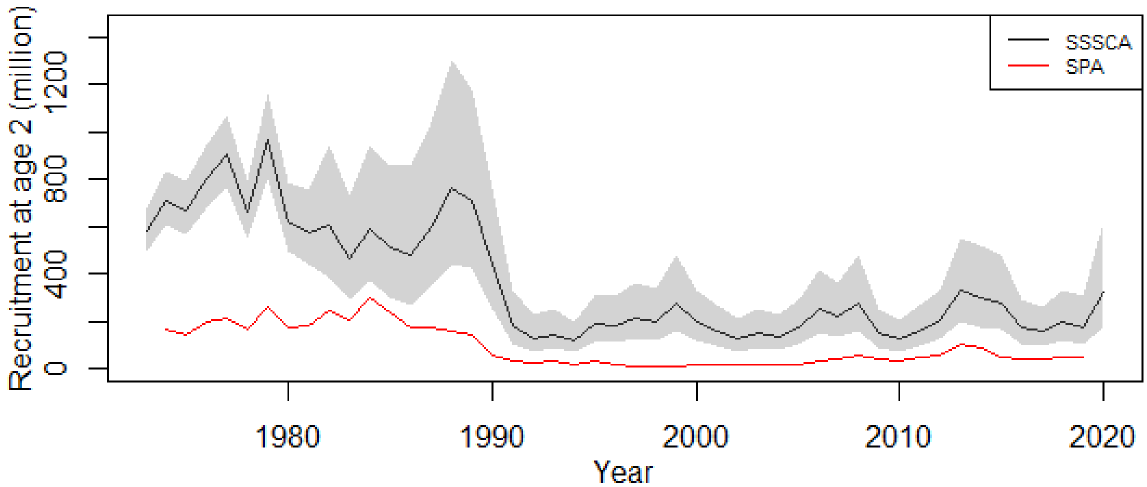


Figure 4. Baseline model (SSSCA) estimates of recruitment (numbers at age 2), with 95% confidence interval (shaded region), compared to values from the 2019 assessment using the SPA.

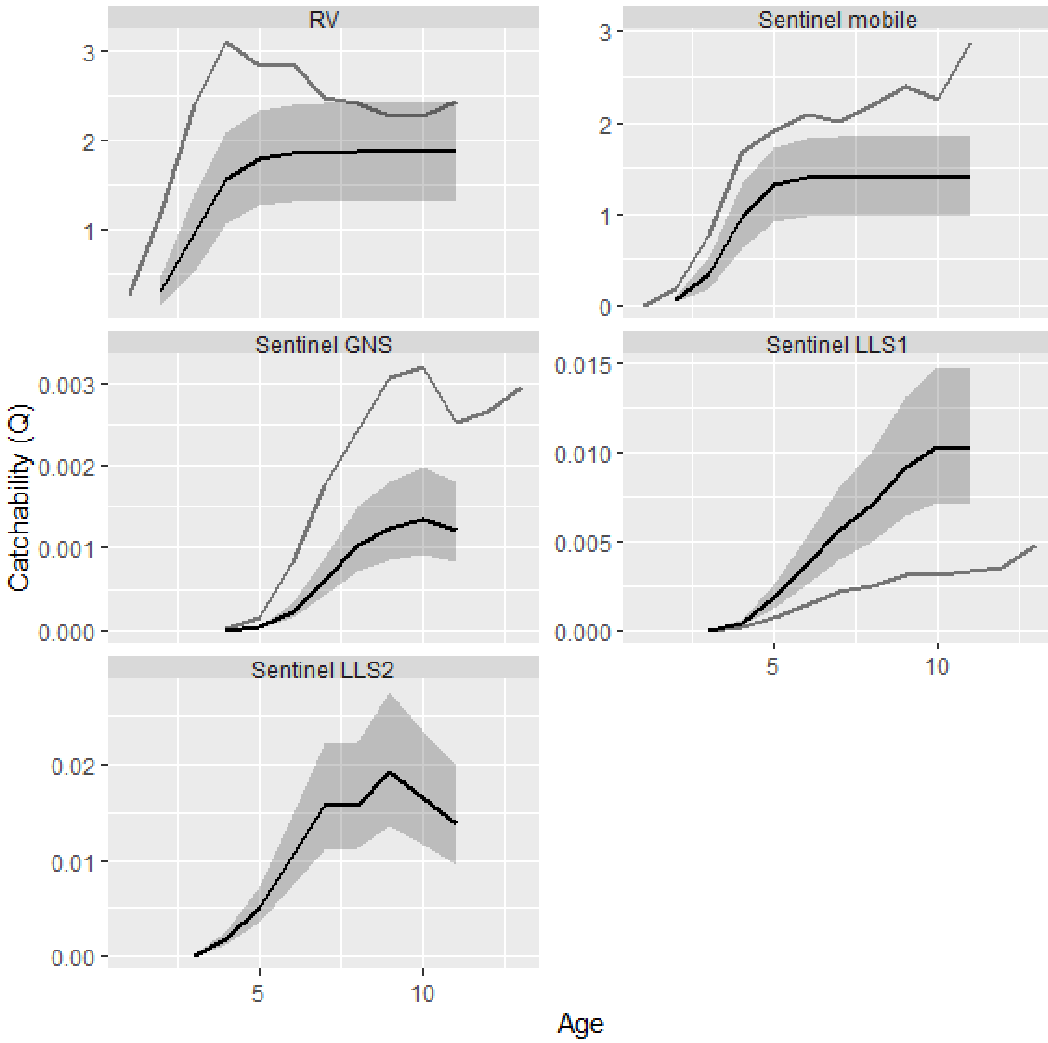


Figure 5. Baseline model estimates of age-specific catchability to the five main surveys, with 95% confidence intervals (black line and shaded region), compared to values from the 2019 assessment using the SPA (grey line). The Sentinel Longline 1 (LLS1) index in the present model is most similar to the SPA Sentinel longline index and the two are therefore plotted together. Note that for the Sentinel Gillnet (GNS) and LLS1 the values from the SPA model were divided by 100 for plotting. Note also that the SPA uses a 13+ group.

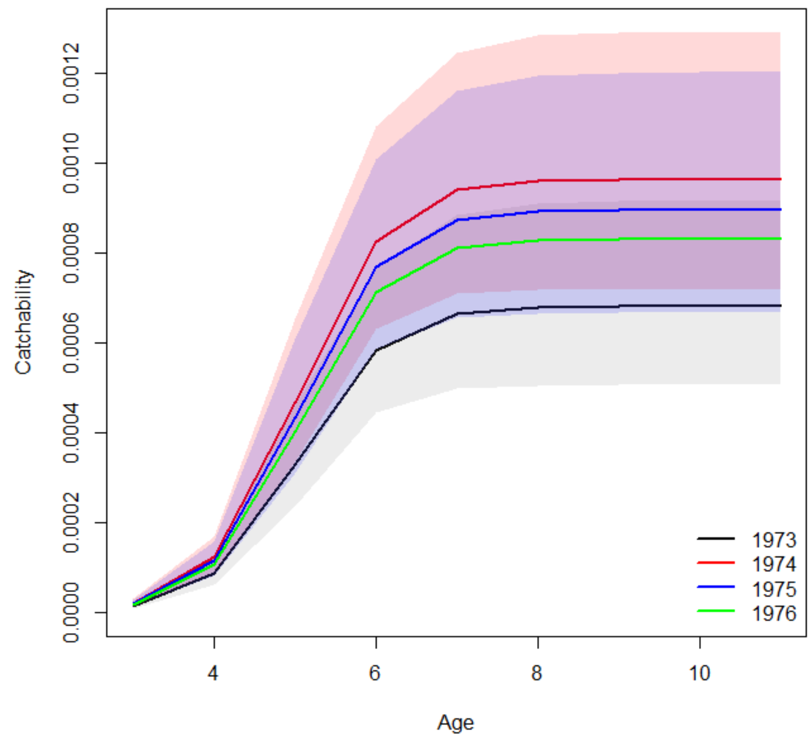


Figure 6. Baseline model estimates age-specific catchability to the Minet (1978) surveys, with 95% confidence interval (shaded region). The confidence interval for 1976 was of similar width to that for 1975 and was omitted to enhance the clarity of the presentation.

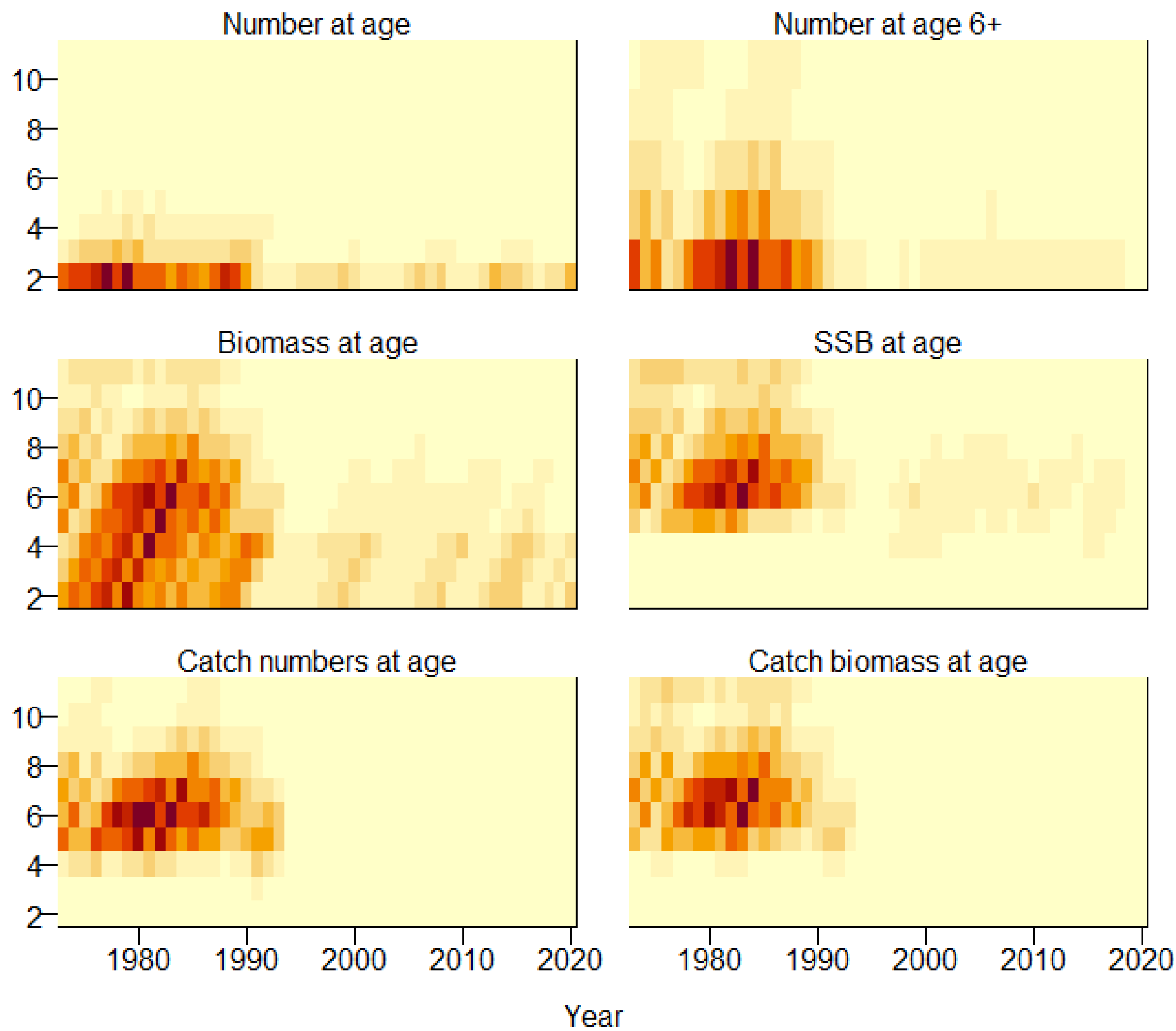


Figure 7. Baseline model estimates of age-based quantities defined at the top of each panel. Darker colors indicate higher estimates. Catches are model predicted, not the input fishery catch-at-age.

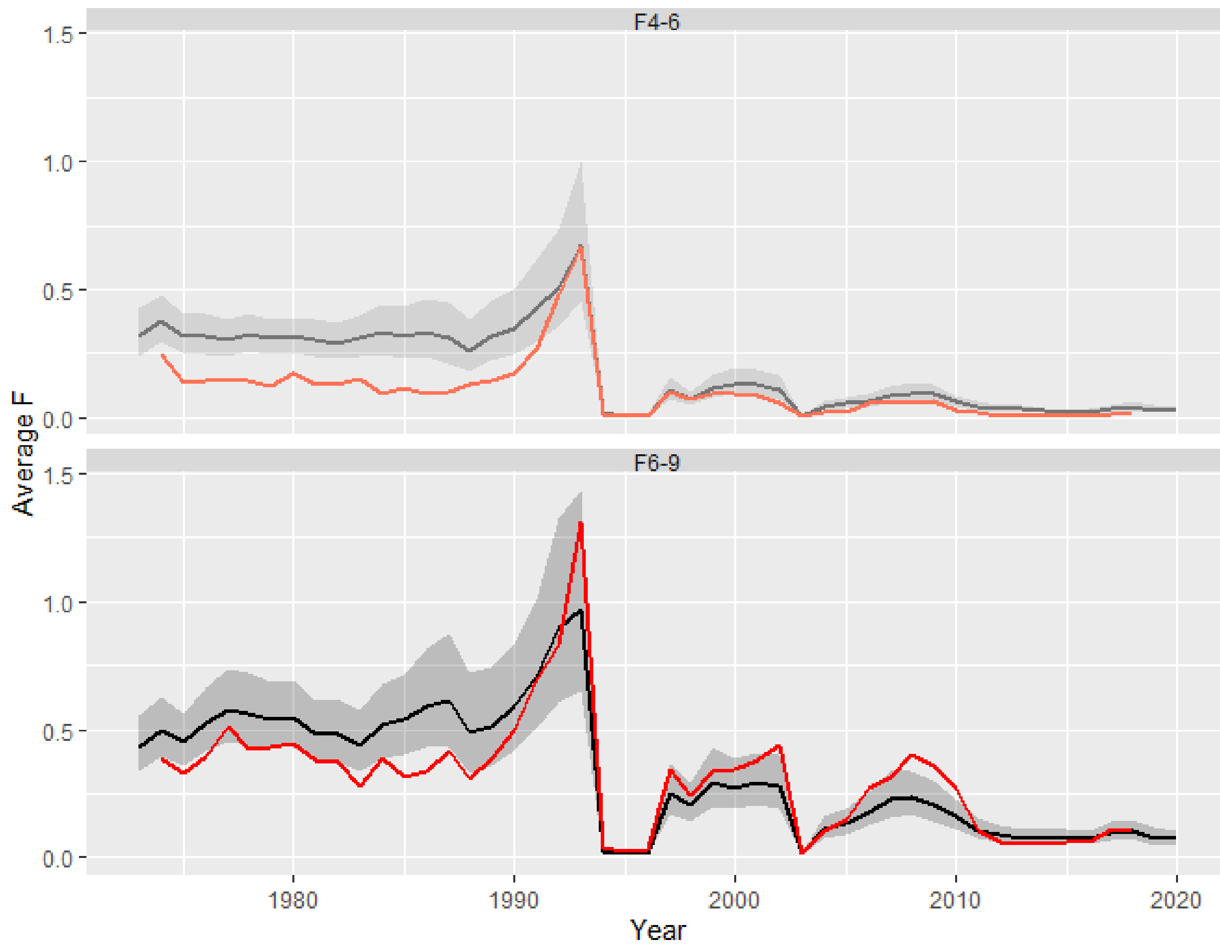


Figure 8. Baseline model estimates of average fishing mortality F at ages 4-6 and 6-9 (panels), with 95% confidence interval (dark line and shaded region), compared to values from the 2019 assessment using the SPA (red line).

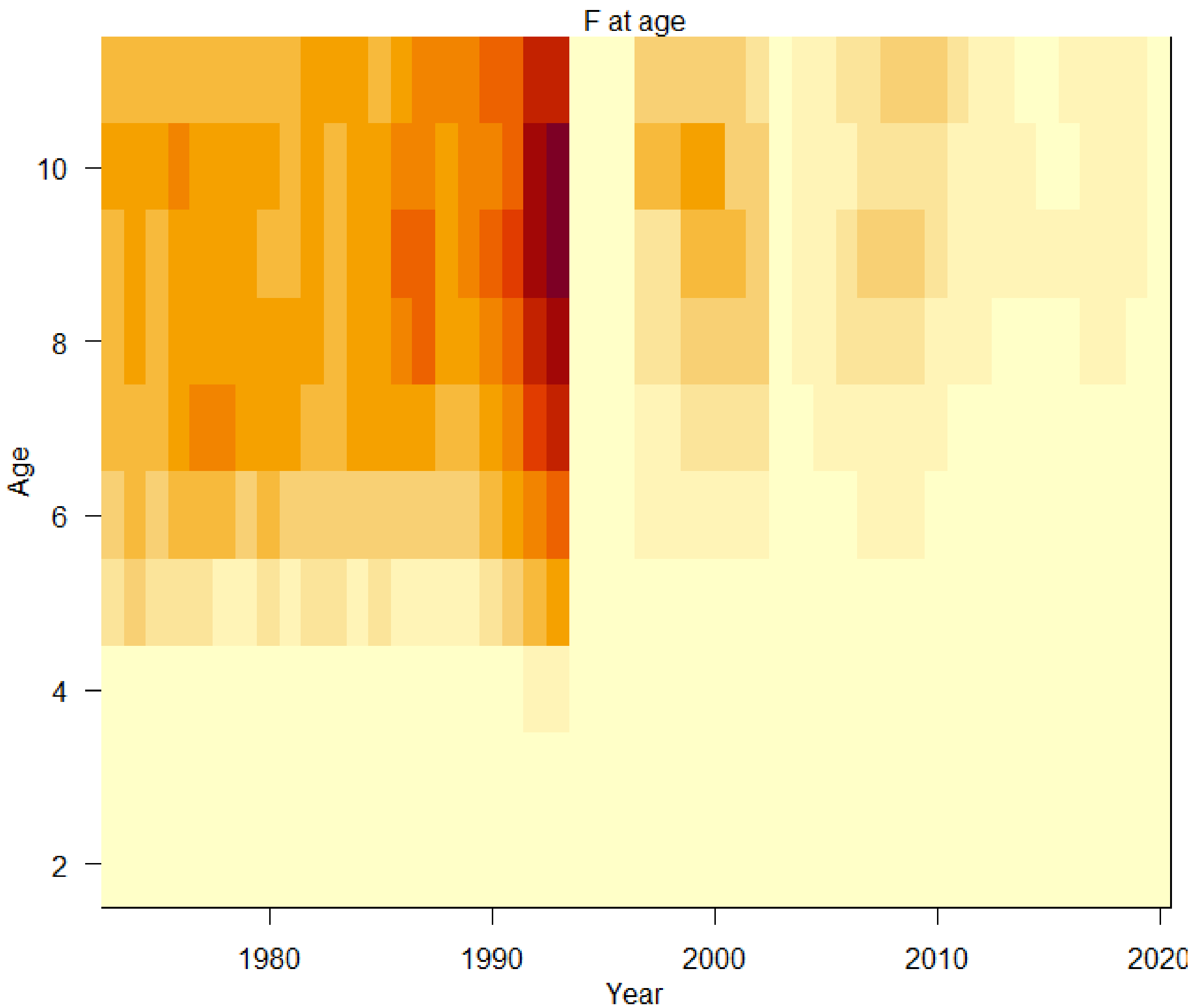


Figure 9. Illustration of baseline model estimates of fishing mortality at age, where darker colours indicate higher values. For an alternative depiction of these estimates, see figure 12.

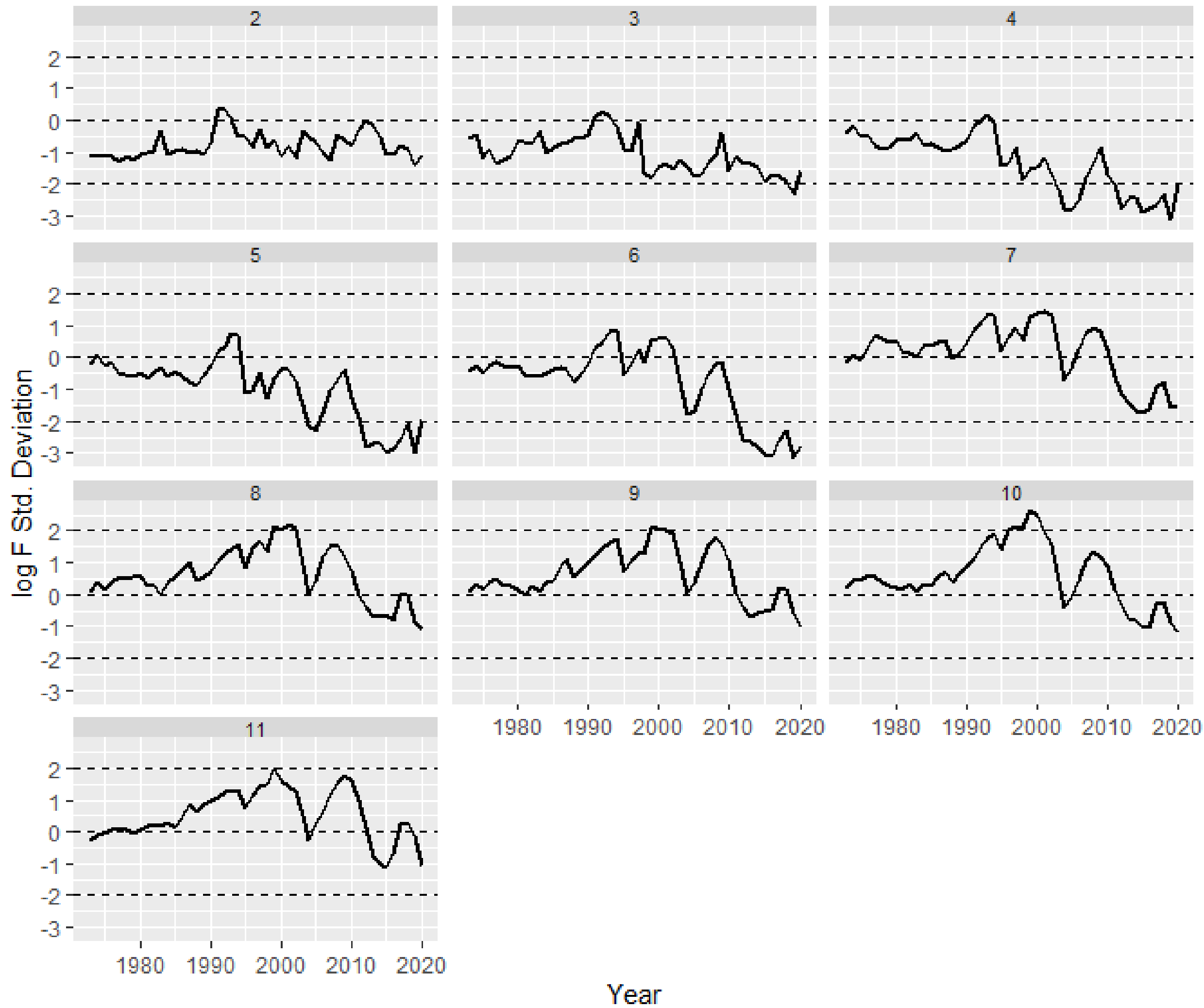


Figure 10. Baseline model estimates of standardized log F deviations (standardized Δ_F), by age (panels).

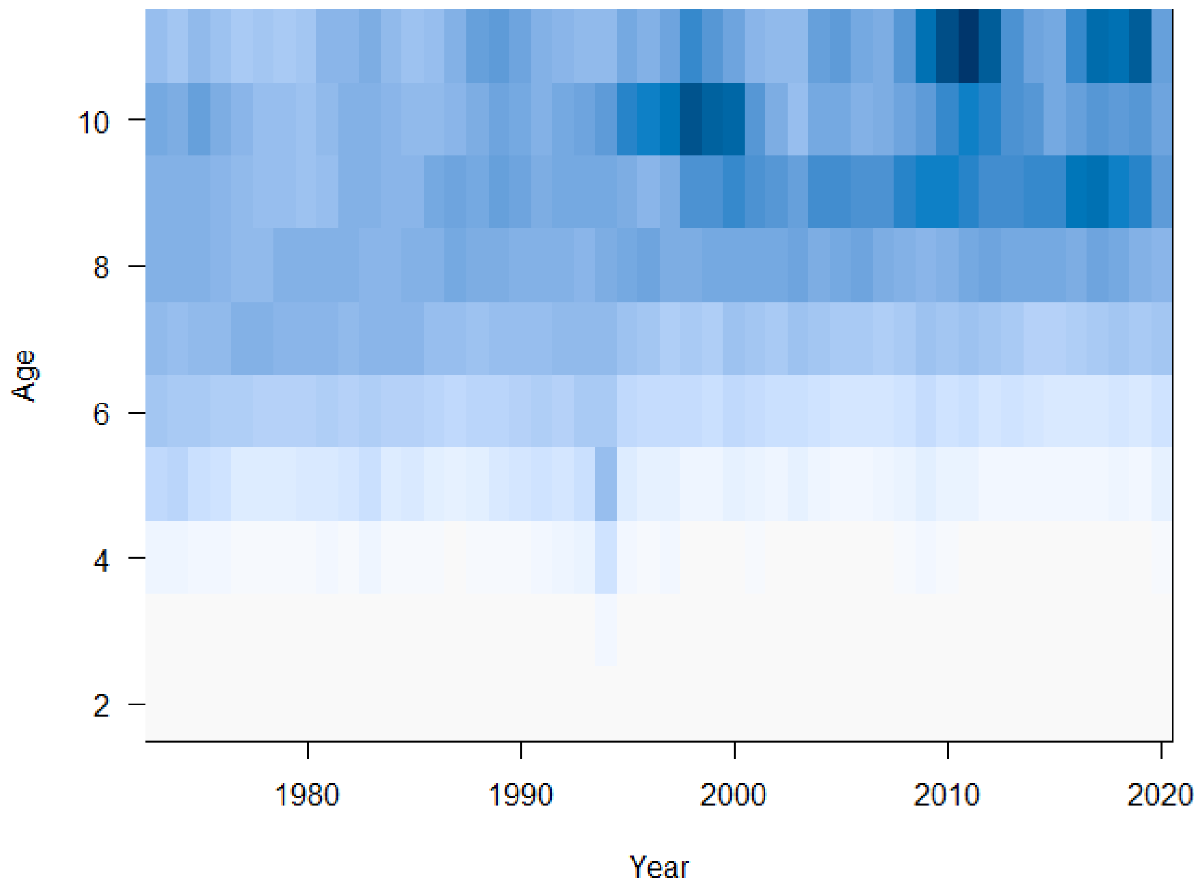


Figure 11. Fishery relative selectivity for the baseline model, calculated for each year as age-specific F divided by the average F for ages 6-9. Darker colours indicate higher values.

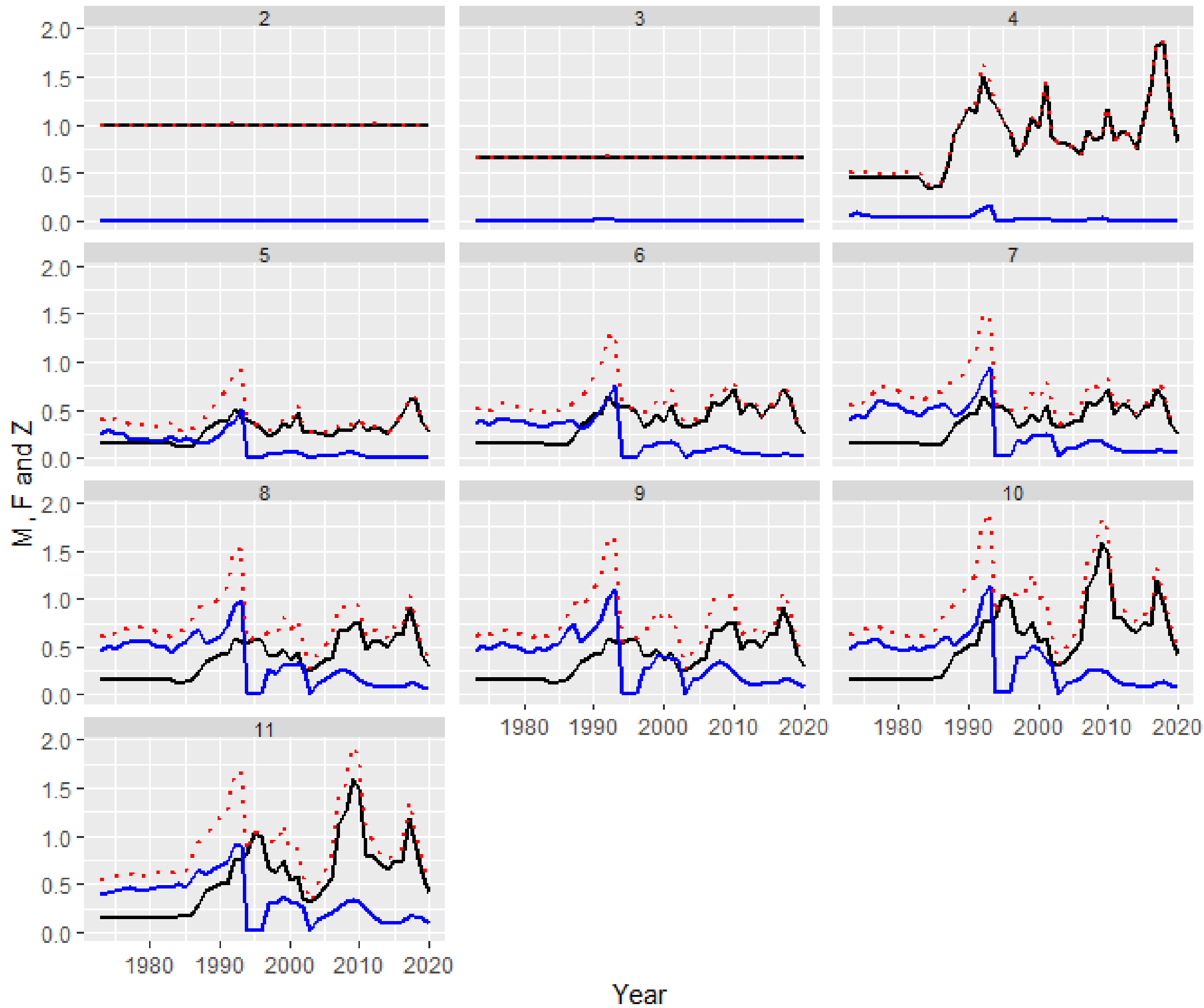


Figure 12. Baseline model estimates of age-specific natural mortality (M, black lines), fishing mortality (F, blue lines), and total mortality (Z= M+F; dotted red lines).

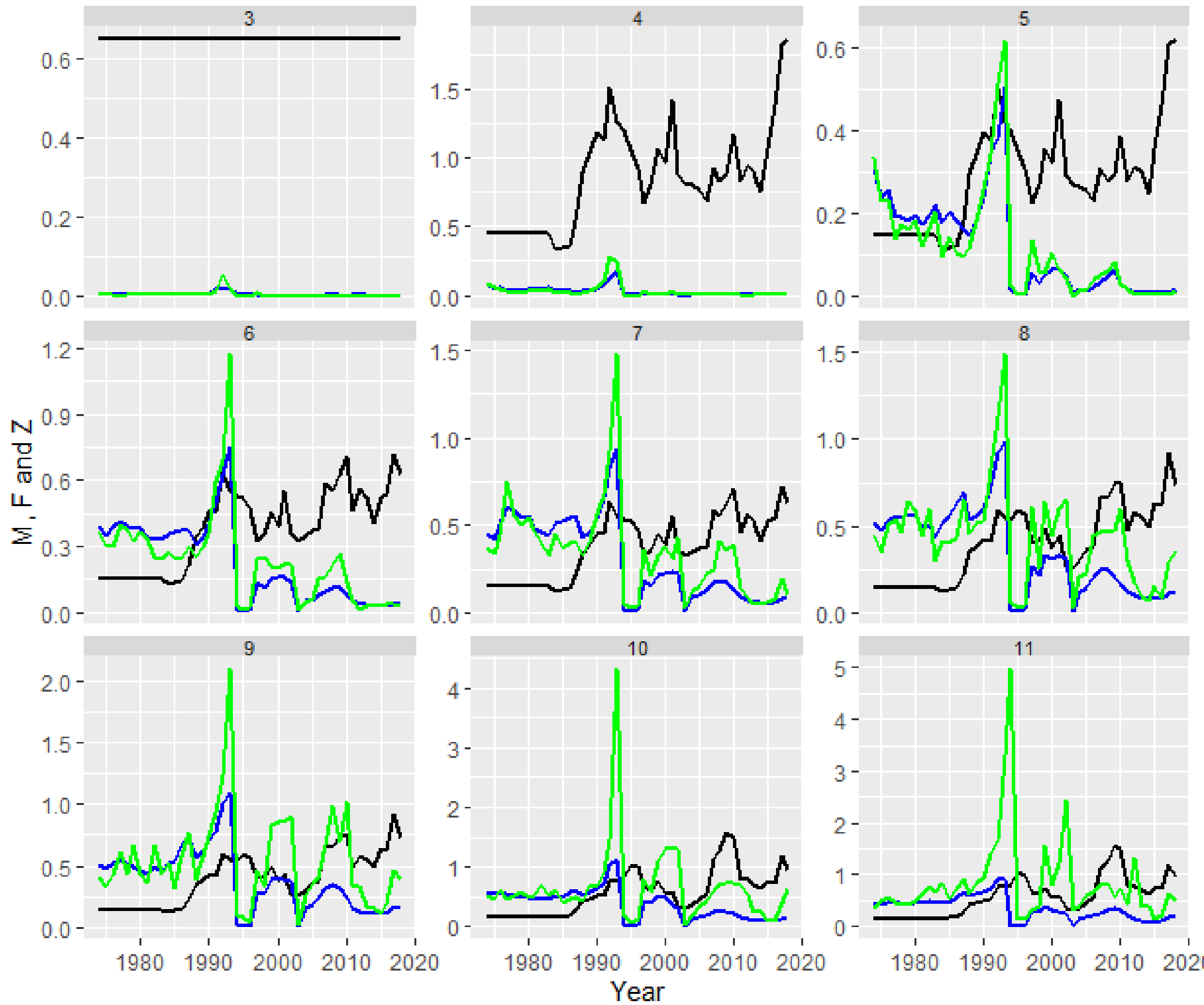


Figure 13. Baseline model estimates of age-specific fishing mortality (F, blue lines) and natural mortality (M, black lines), compared to fishing mortality values from the 2019 assessment using the SPA (F, green lines). Note that the F value for the SPA at age 11+, was derived as an abundance weighted average of F for individual ages given the SPA employed an age 13+ group.

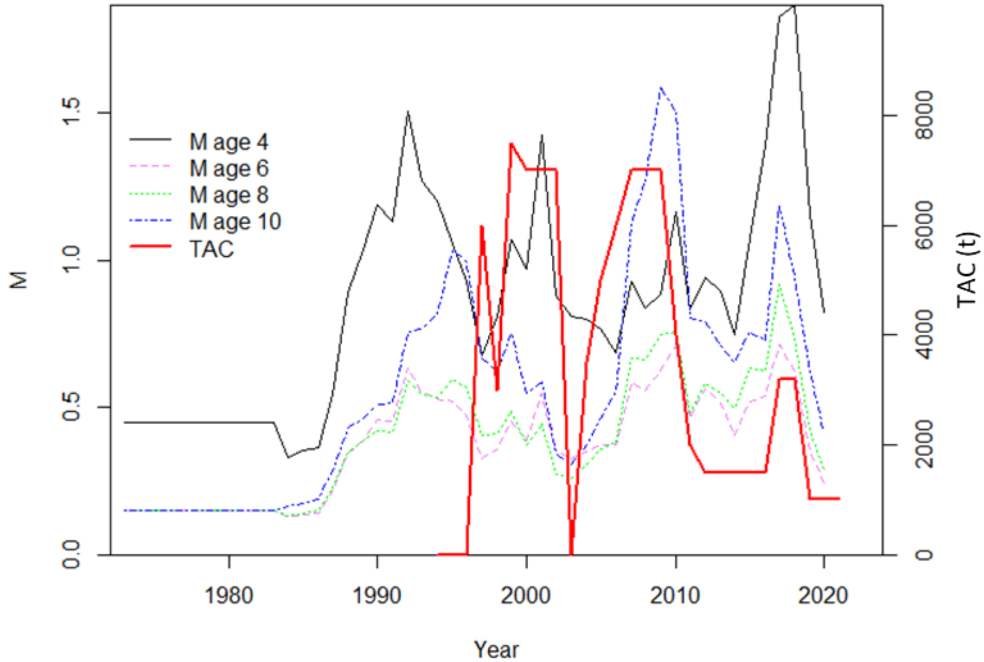


Figure 14. Baseline model estimates of natural mortality (M) for some ages along with the total allowable catch in tonnes (TAC, red line, secondary y-axis).

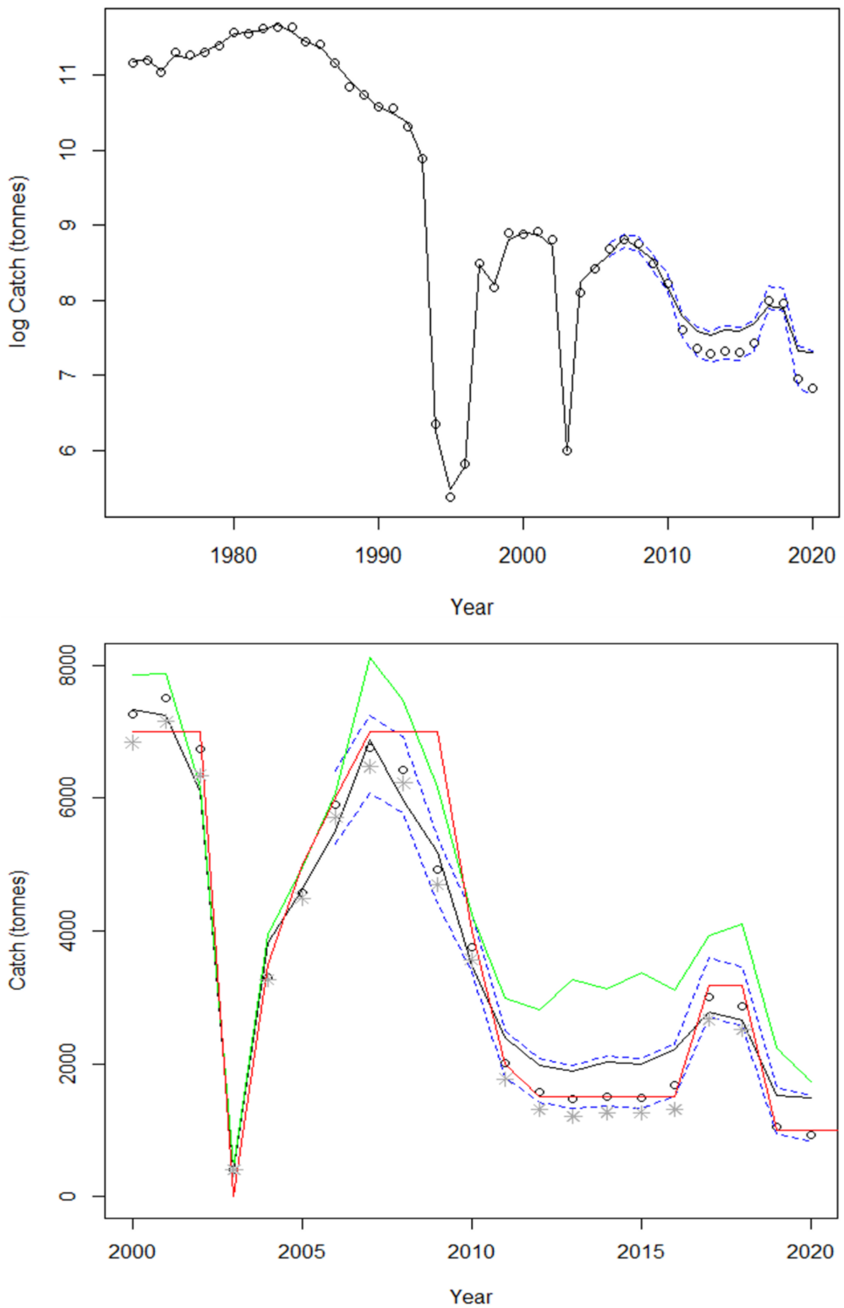


Figure 15. Top panel: Baseline model predicted catch (black line), compared to input catch (points) and catch bounds (dashed blue lines) for 1973-2020 (note the log scale). Bottom panel: Input and predicted catch and catch bounds for 2000-2020 (lines and symbols as above), with the addition of the landings (grey asterisk), the total allowable catch (TAC; red line) and the sum of model predicted catch and surplus unaccounted catch inferred from M (green line).

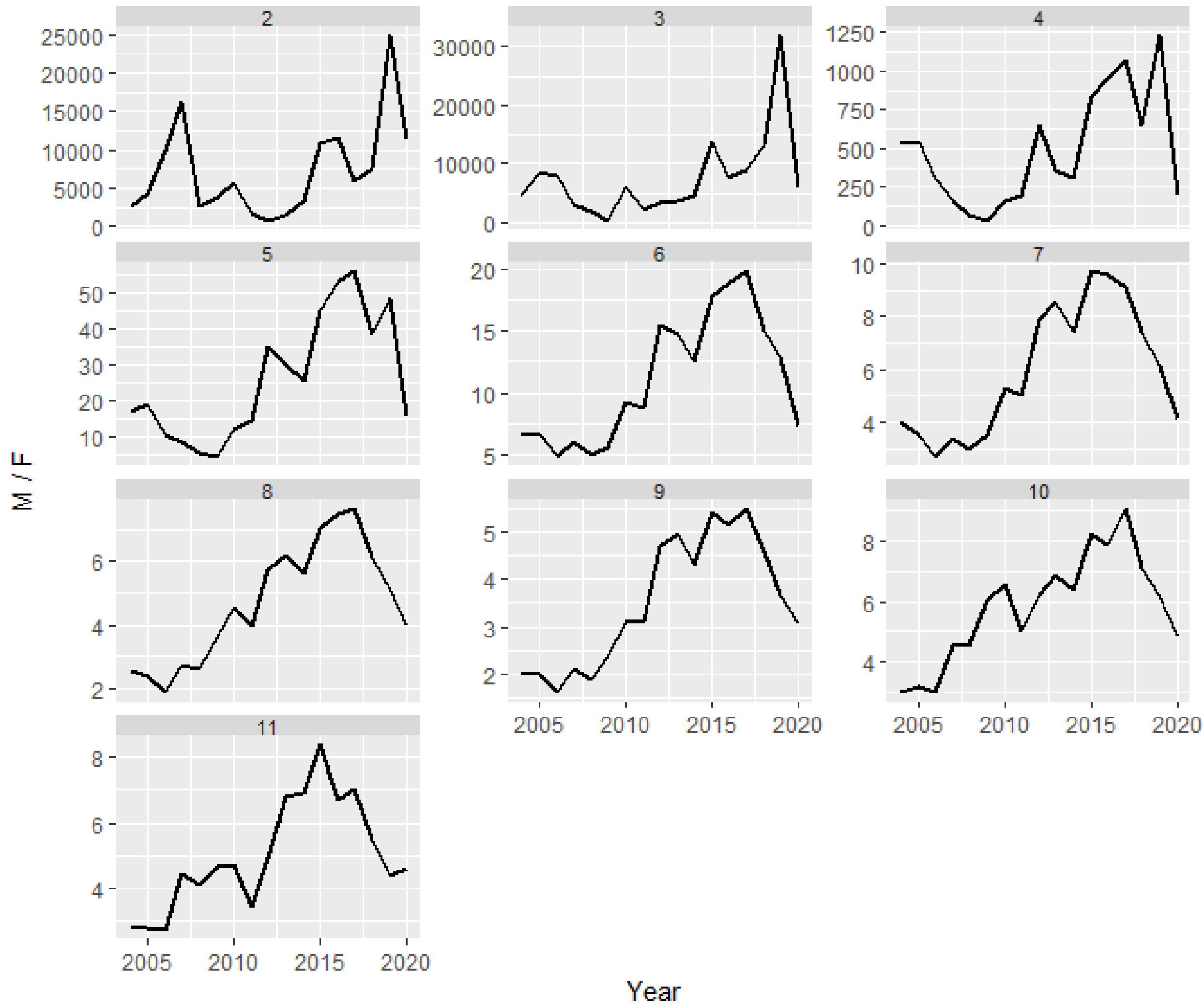


Figure 16. Ratio of age-specific (panels) natural and fishing mortality estimates since 2004.

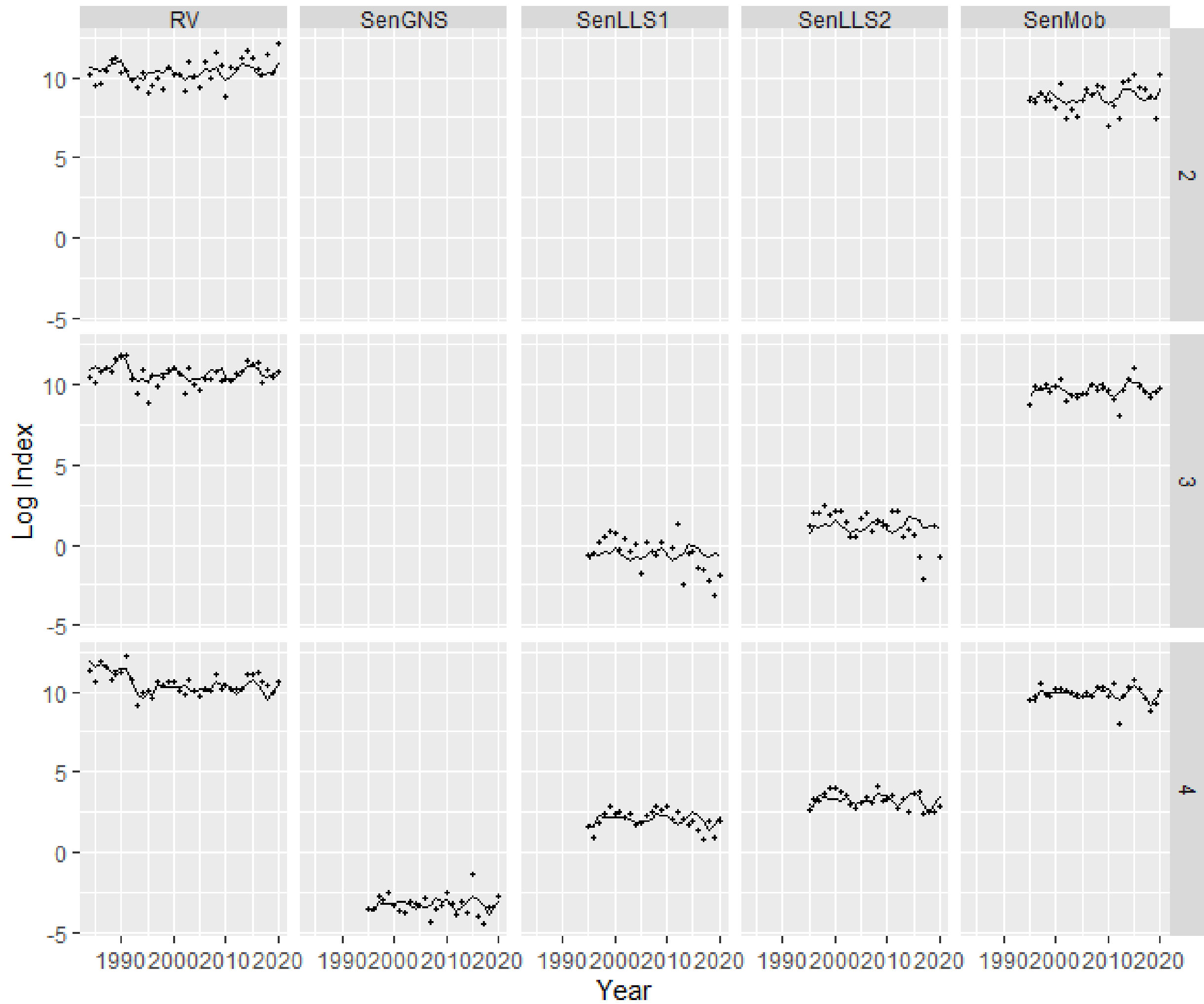


Figure 17. Baseline model fits to the log indices at age (rows) for each of the five major survey indices (columns). Points represent the observations and the line the model fit. Panels are empty when an age was not included in the model for a particular survey.

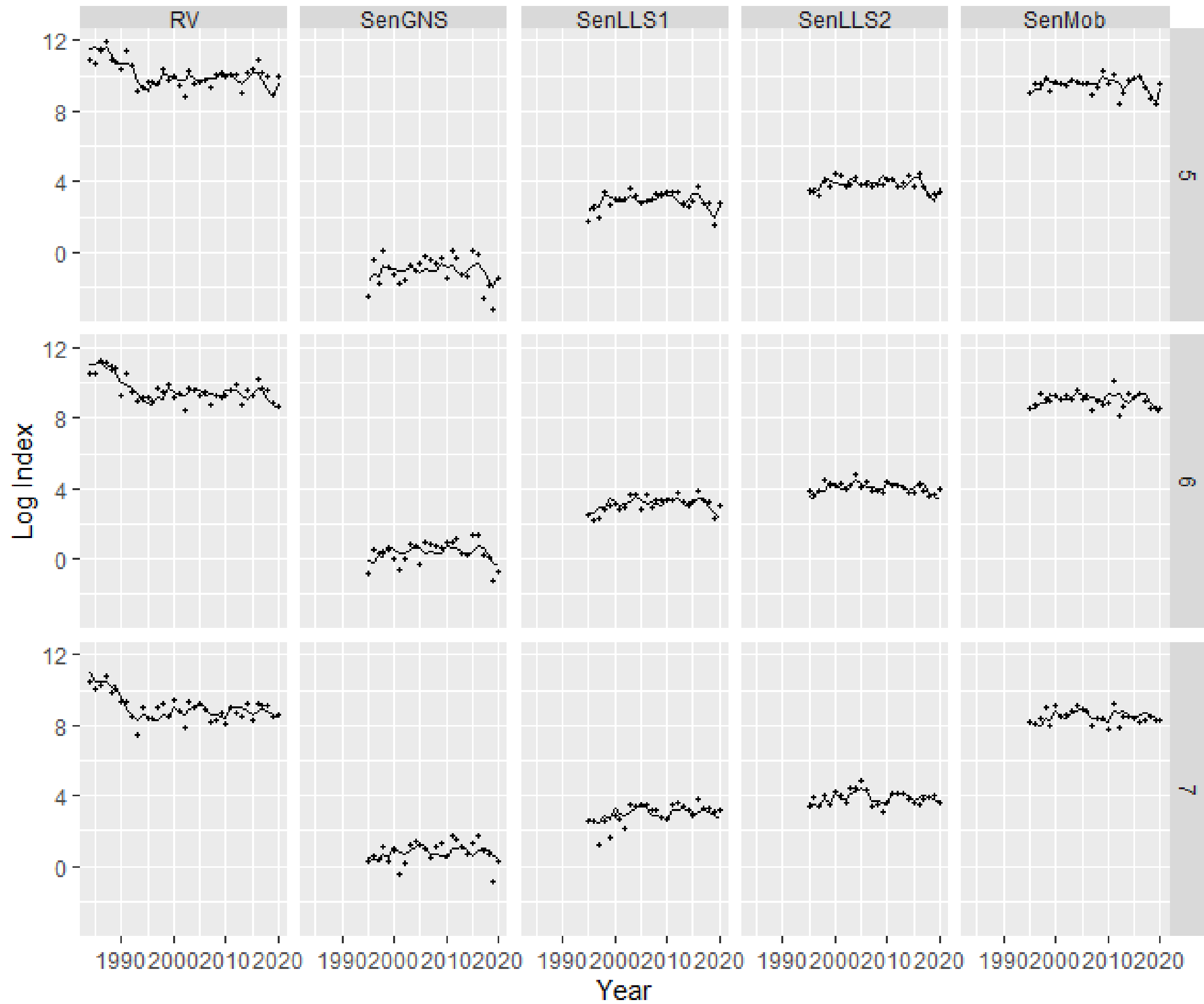


Figure 17. con't.

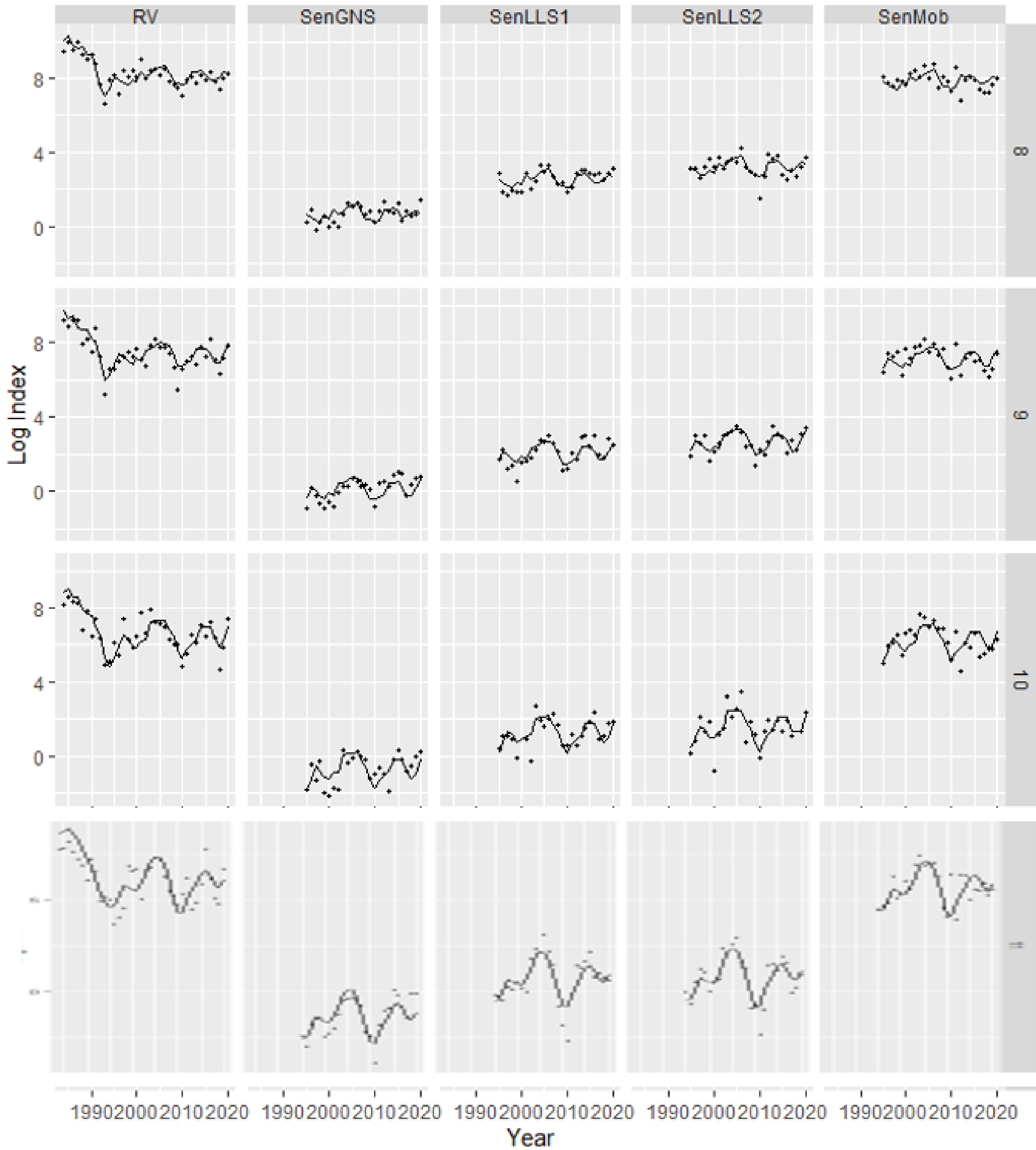


Figure 17. con't.

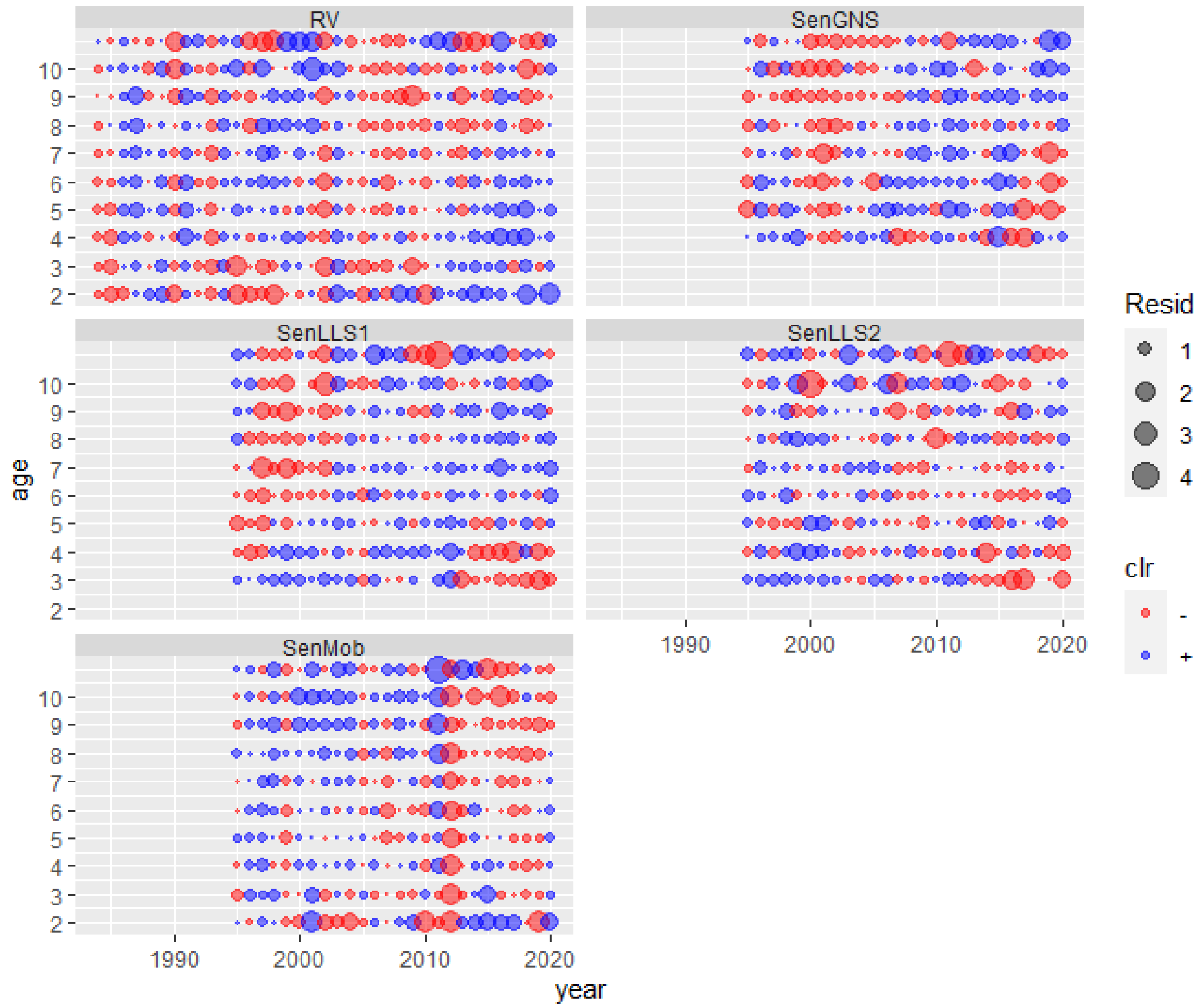


Figure 18. Baseline model residuals for the age-specific abundance indices for each survey (panels). The surface area of a bubble is proportional to the absolute value. Red is negative and blue is positive.

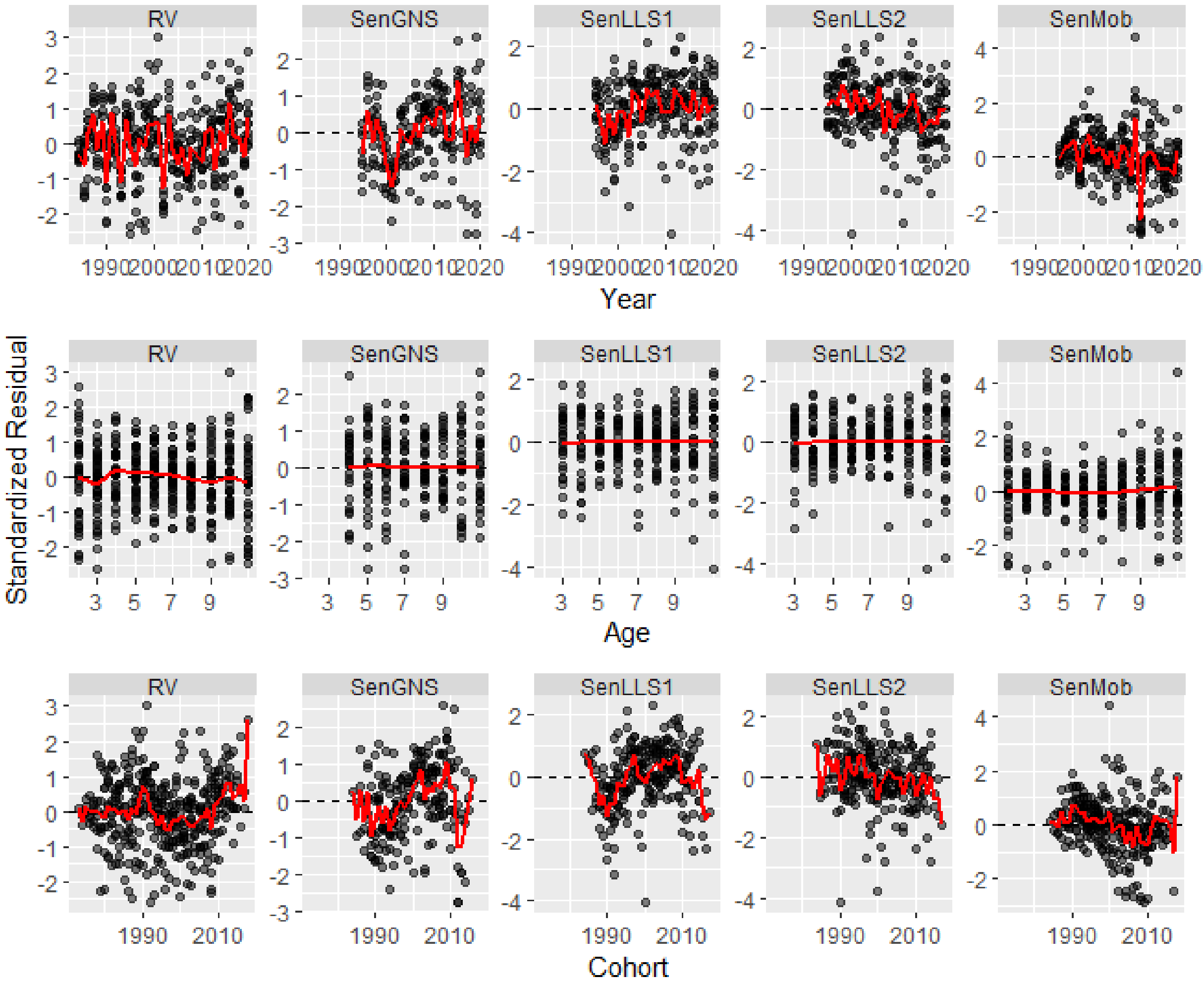


Figure 19. Baseline model residuals for the age-specific abundance indices for each survey (columns) versus year (top row), age (middle row), and cohort (bottom row). Red lines connect the means for age year/age/cohort.

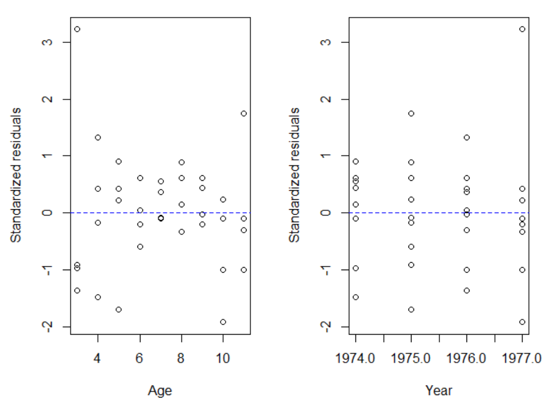


Figure 20. Baseline model residuals for the Minet survey abundance indices as a function of age (left) and year (right).

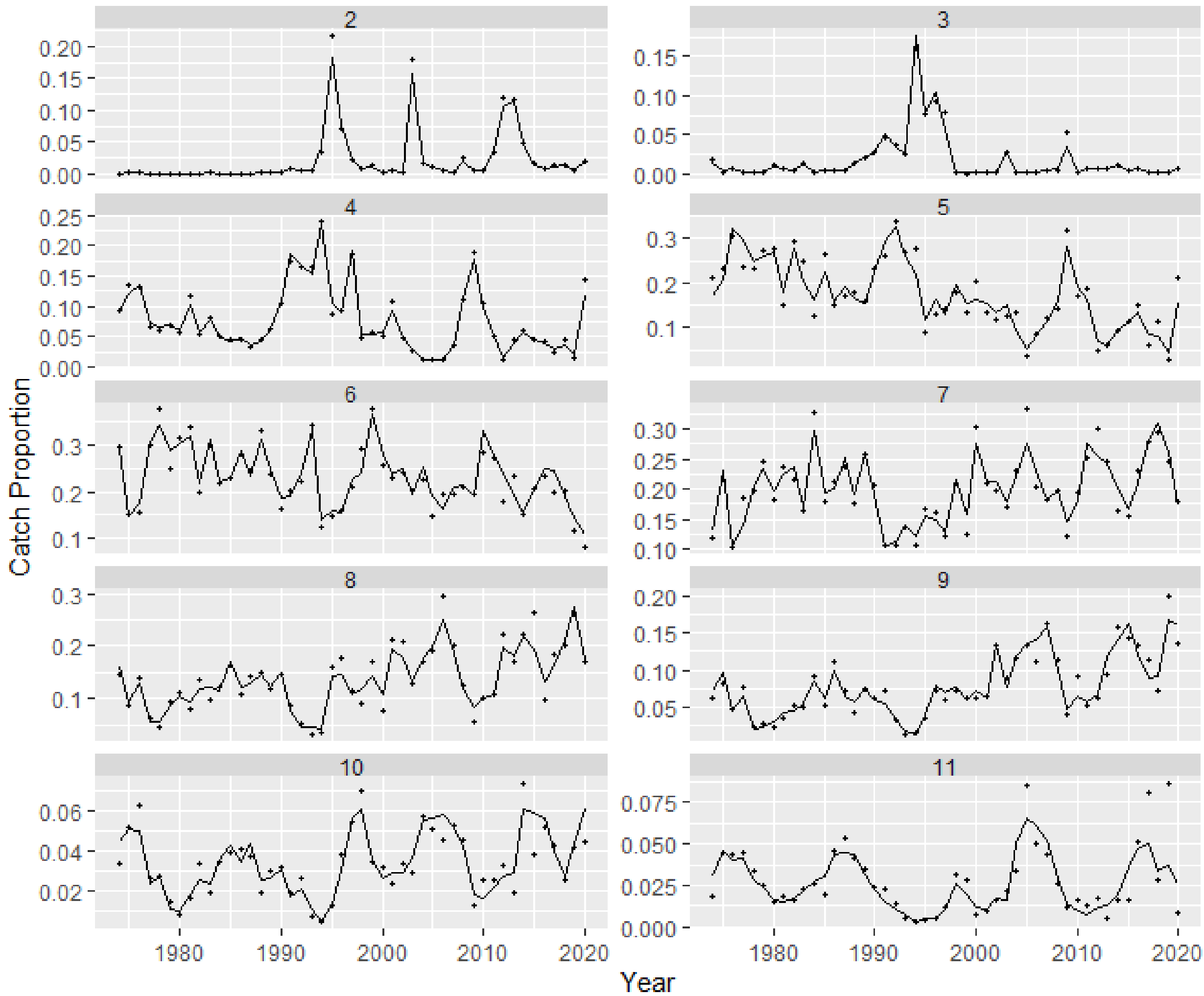


Figure 21. Observed (points) and baseline model predicted (lines) catch proportion-at-age.

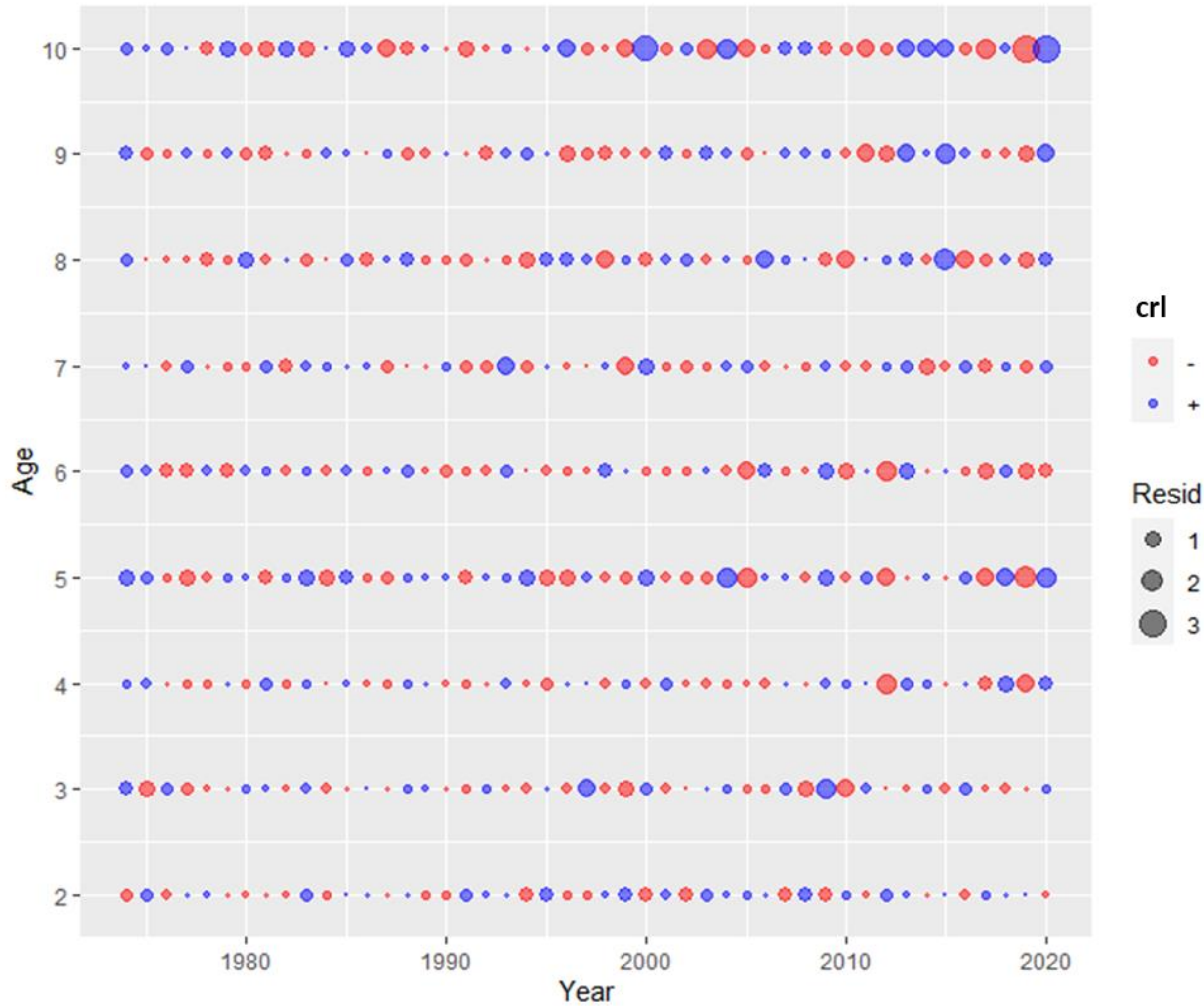


Figure 22. Baseline model catch-at-age composition continuation ratio logit (crl) residuals. The surface area of a bubble is proportional to the absolute value. Red is negative and blue is positive.

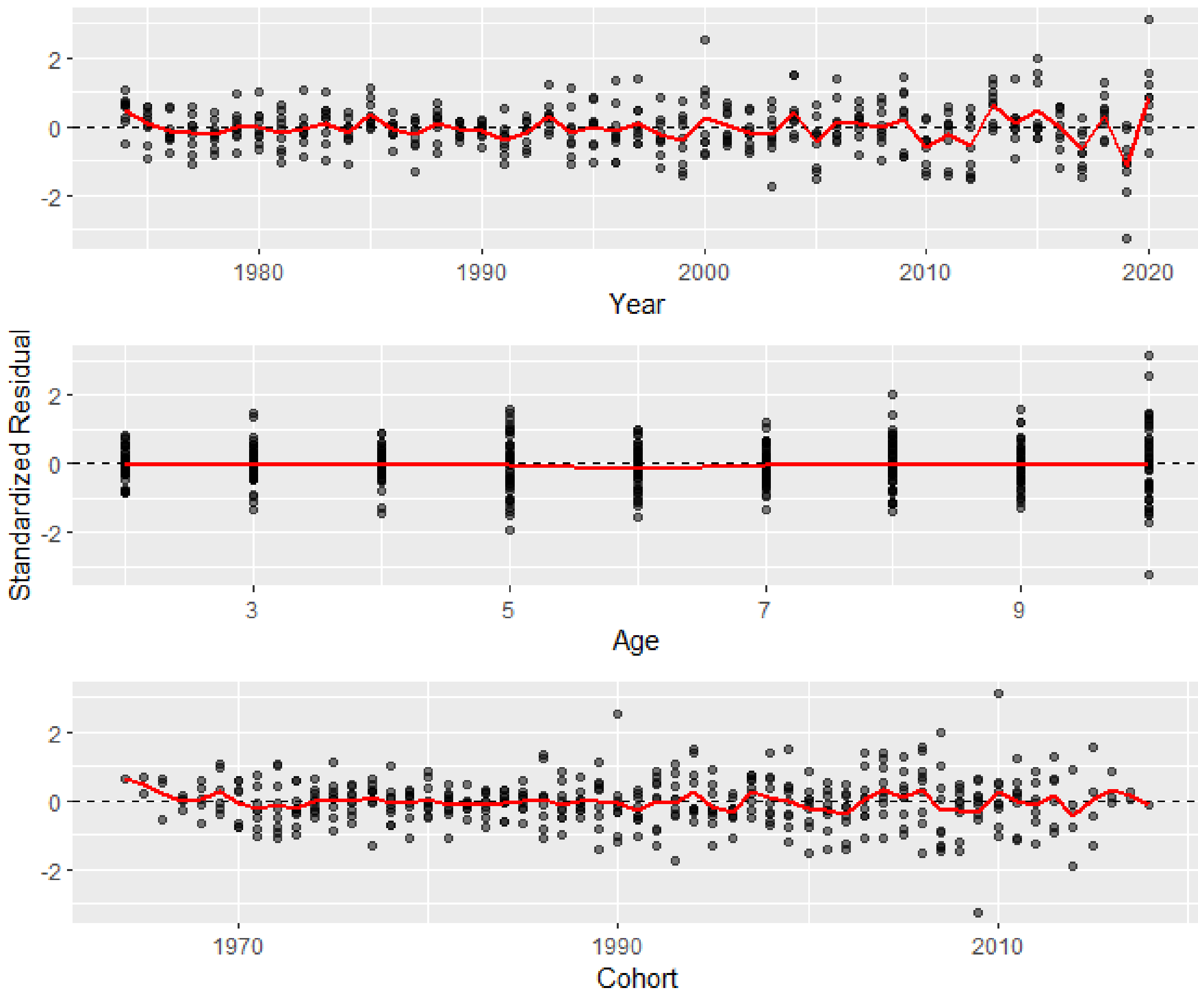


Figure 23. Baseline model catch-at-age composition continuation ratio logit (crl) residuals versus year (top panel), age (middle panel), and cohort (bottom panel). Red lines connect the means for year/age/cohort.

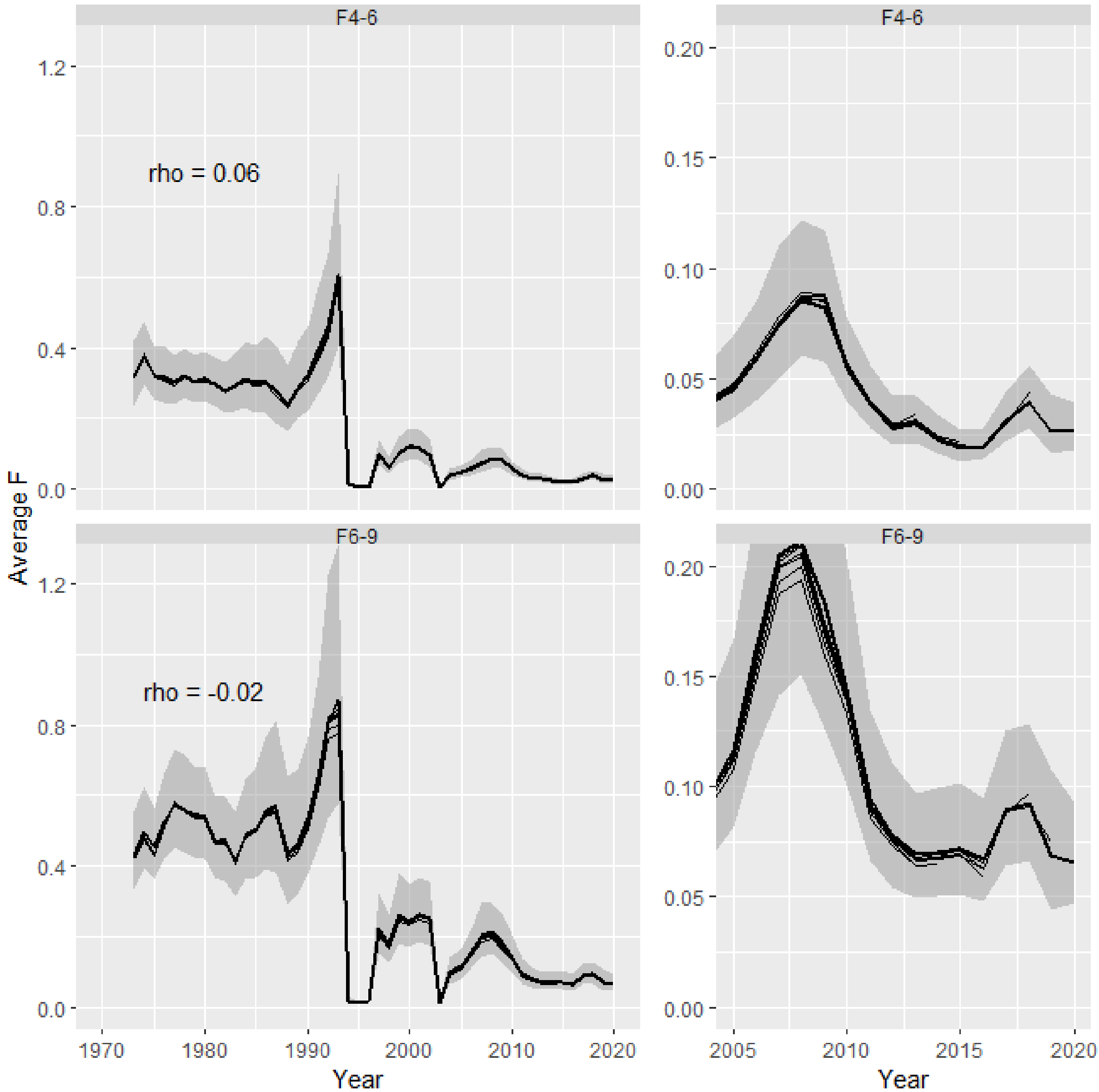


Figure 24. Retrospective estimates of average F at ages 4-6 (top panels) and 6-9 (bottom panels). Shaded regions indicate 95% confidence intervals based on the full time-series of data. The value of Mohn's rho is indicated in the panels. Rightmost panels show trends since 2005.

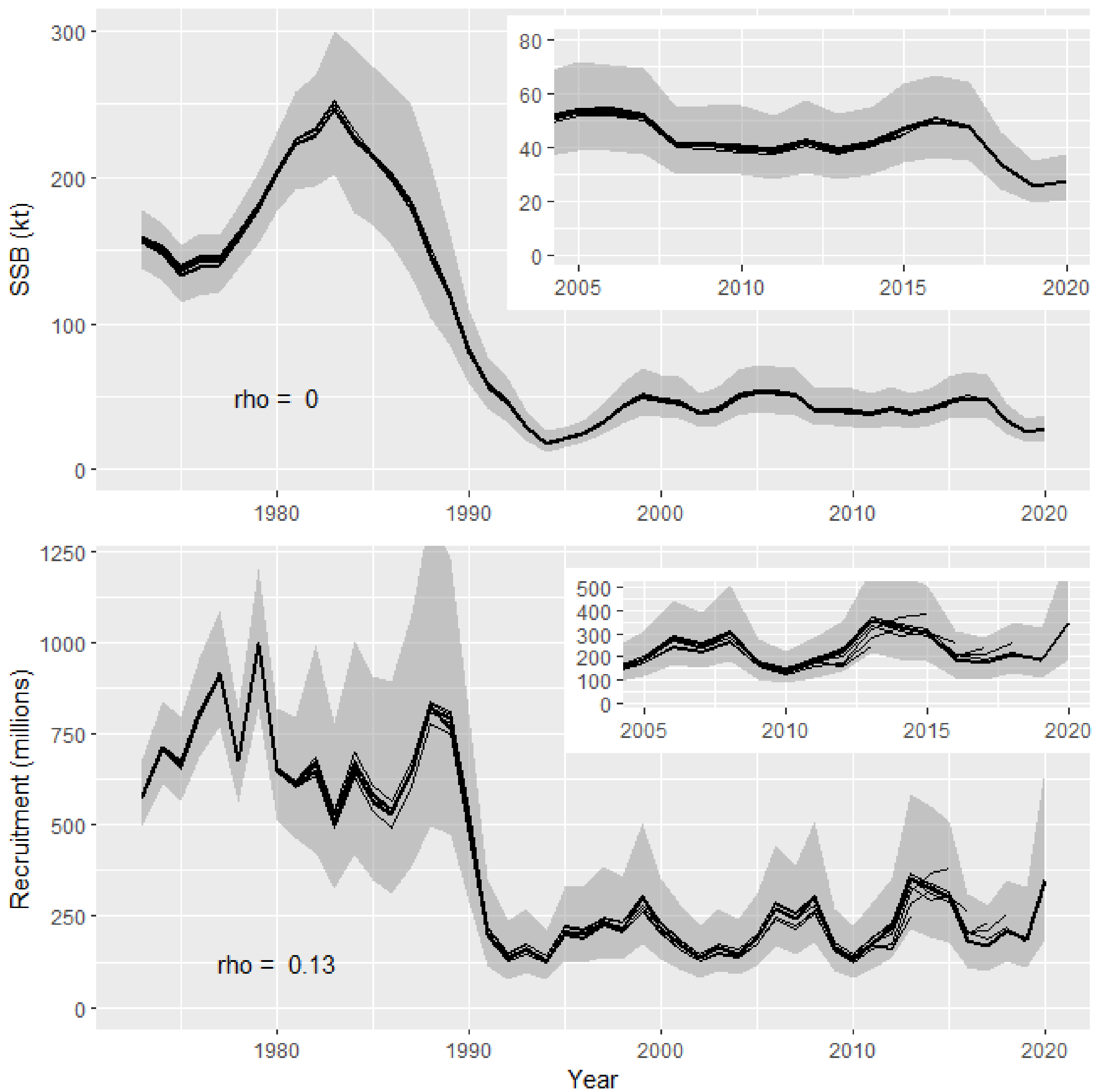


Figure 25. Retrospective estimates of spawning stock biomass (top panel) and recruitment (bottom panel) for the baseline model. Shaded regions indicate 95% confidence intervals based on the full time-series of data. The value of Mohn's rho is indicated in the panels. The inset panels show trends since 2005.

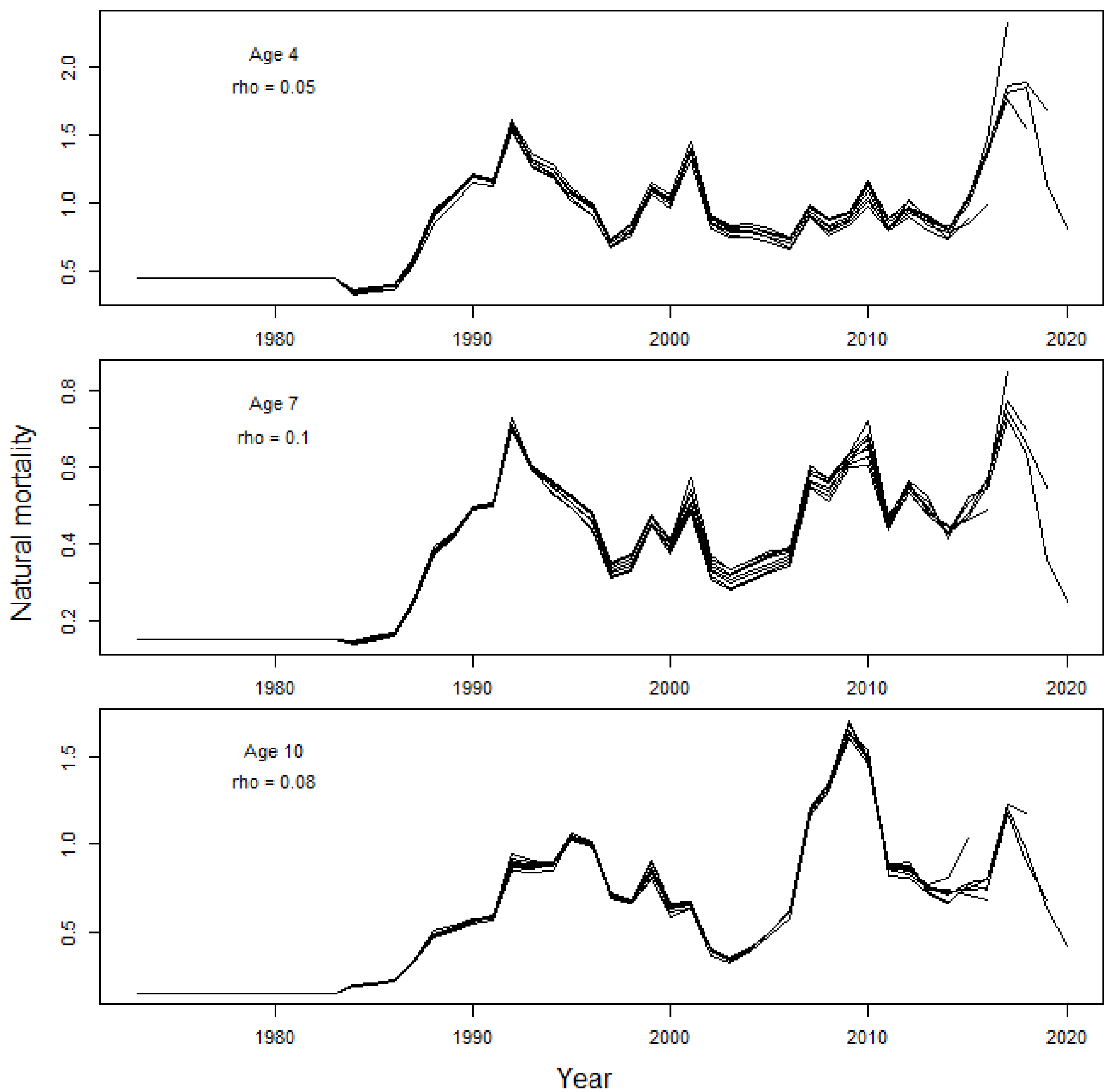


Figure 26. Retrospective estimates of natural mortality for three ages in the baseline model. The value of Mohn's rho is indicated in the panels.

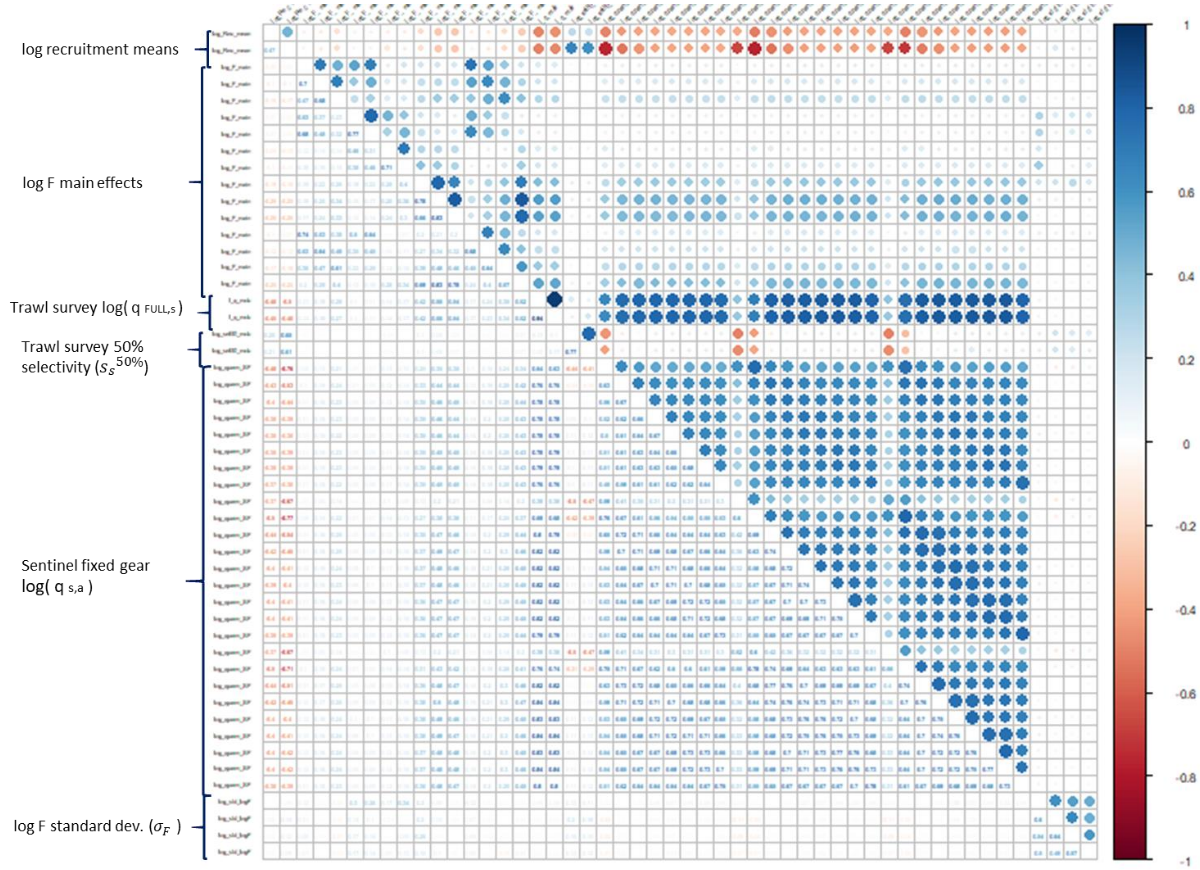


Figure 27. Correlation matrix for model parameters with absolute correlations >0.15.

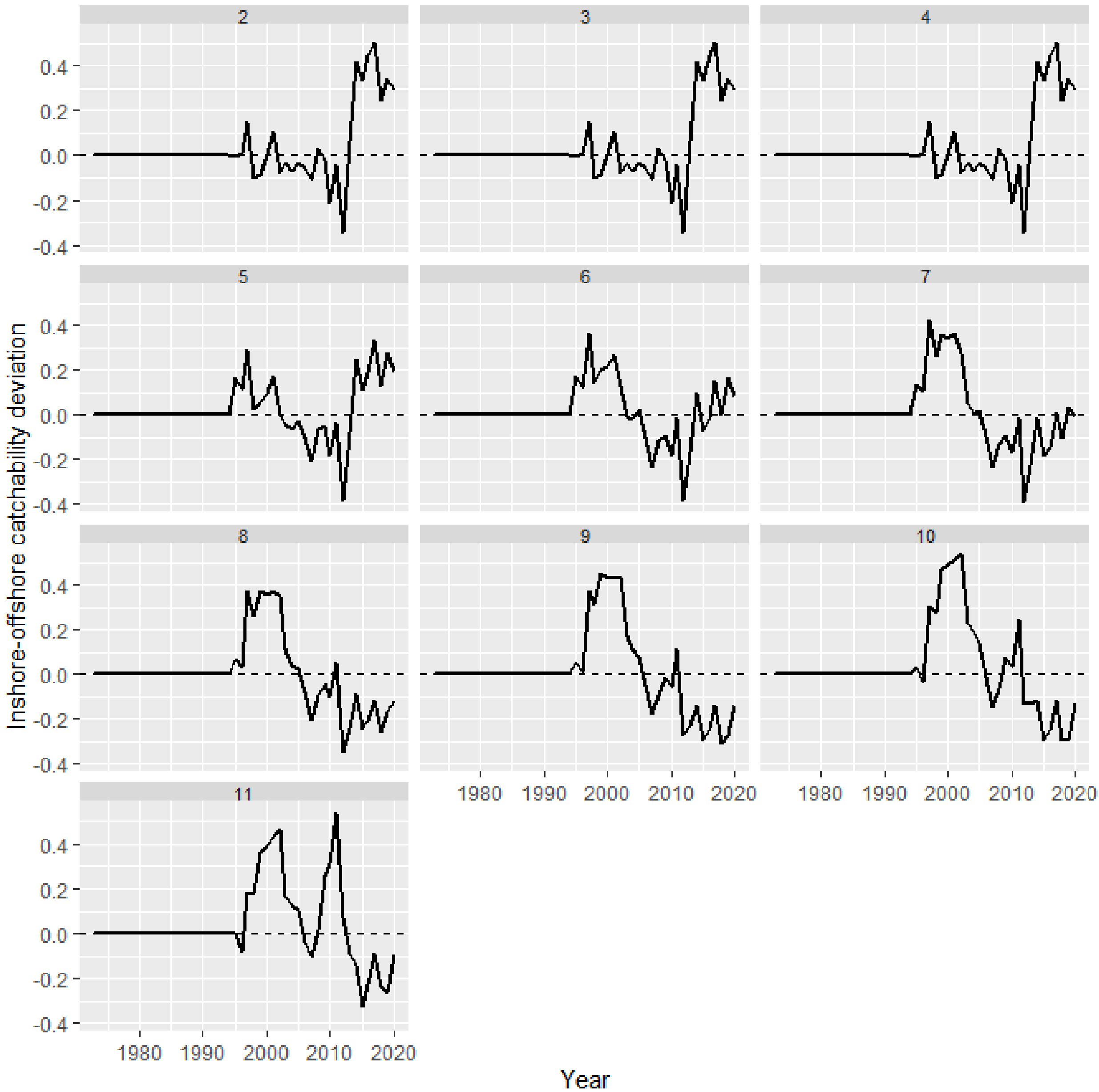


Figure 28. Age-specific (panels) catchability deviations; proportion of cod available to the offshore and unavailable to the nearshore for positive values, reverse for negative values.

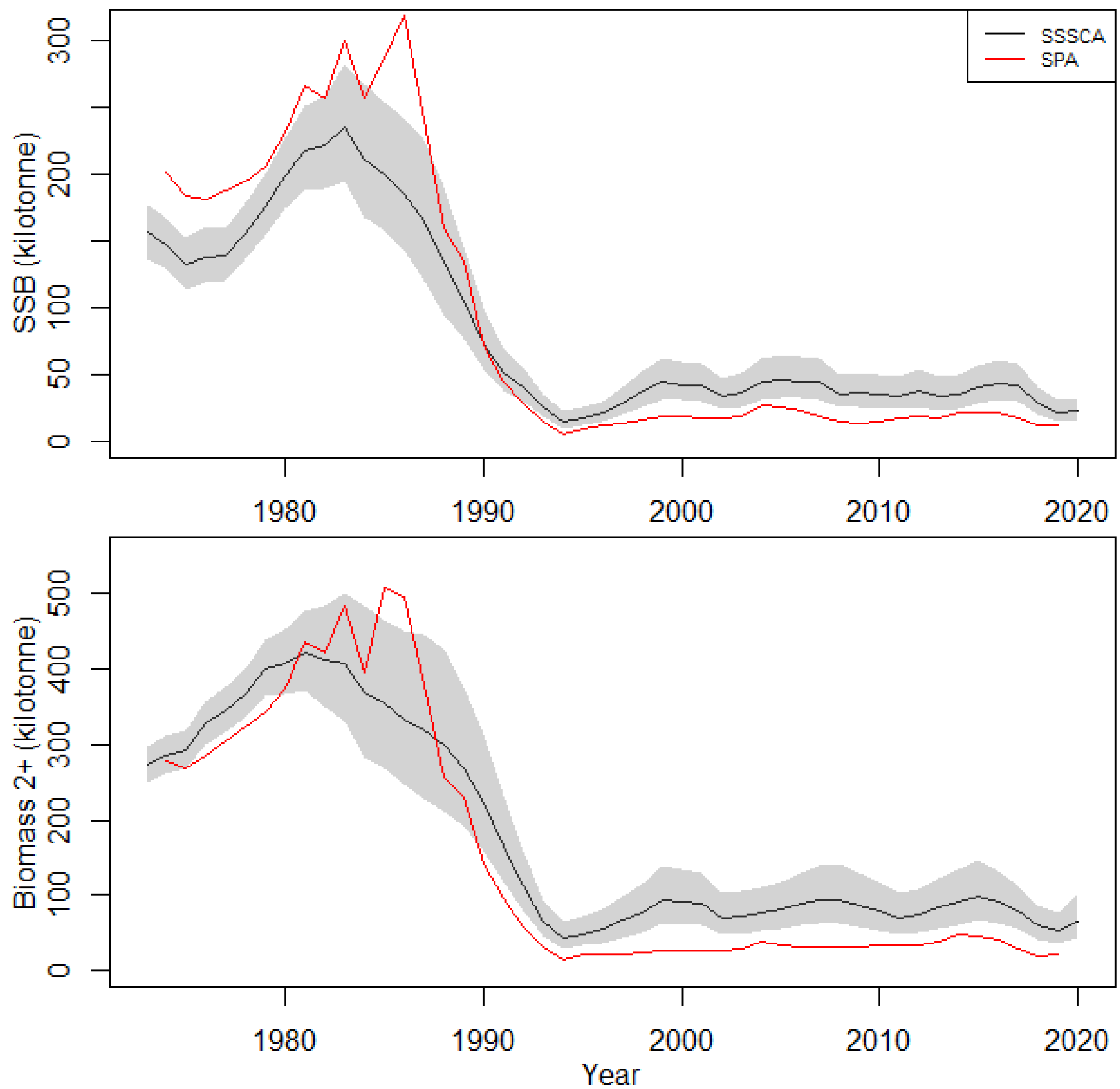


Figure 29. Distribution shift model estimates of spawning stock biomass (SSB) and age 2+ biomass, with 95% confidence interval (shaded region), compared to values from the 2019 assessment using the SPA.

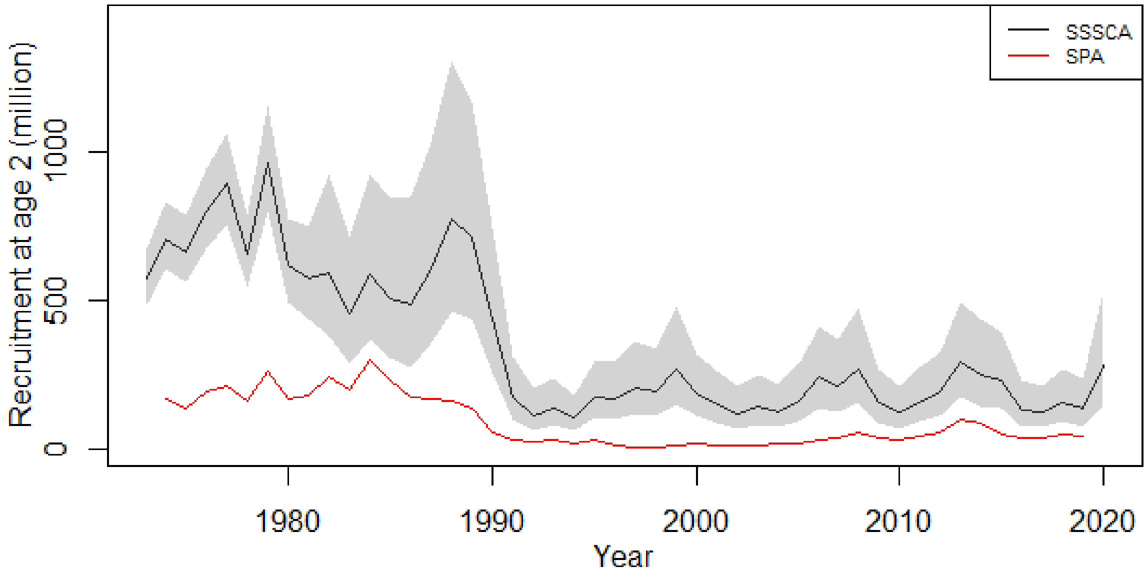


Figure 30. Distribution shift model estimates recruitment (numbers at age 2), with 95% confidence interval (shaded region), compared to values from the 2019 assessment using the SPA.

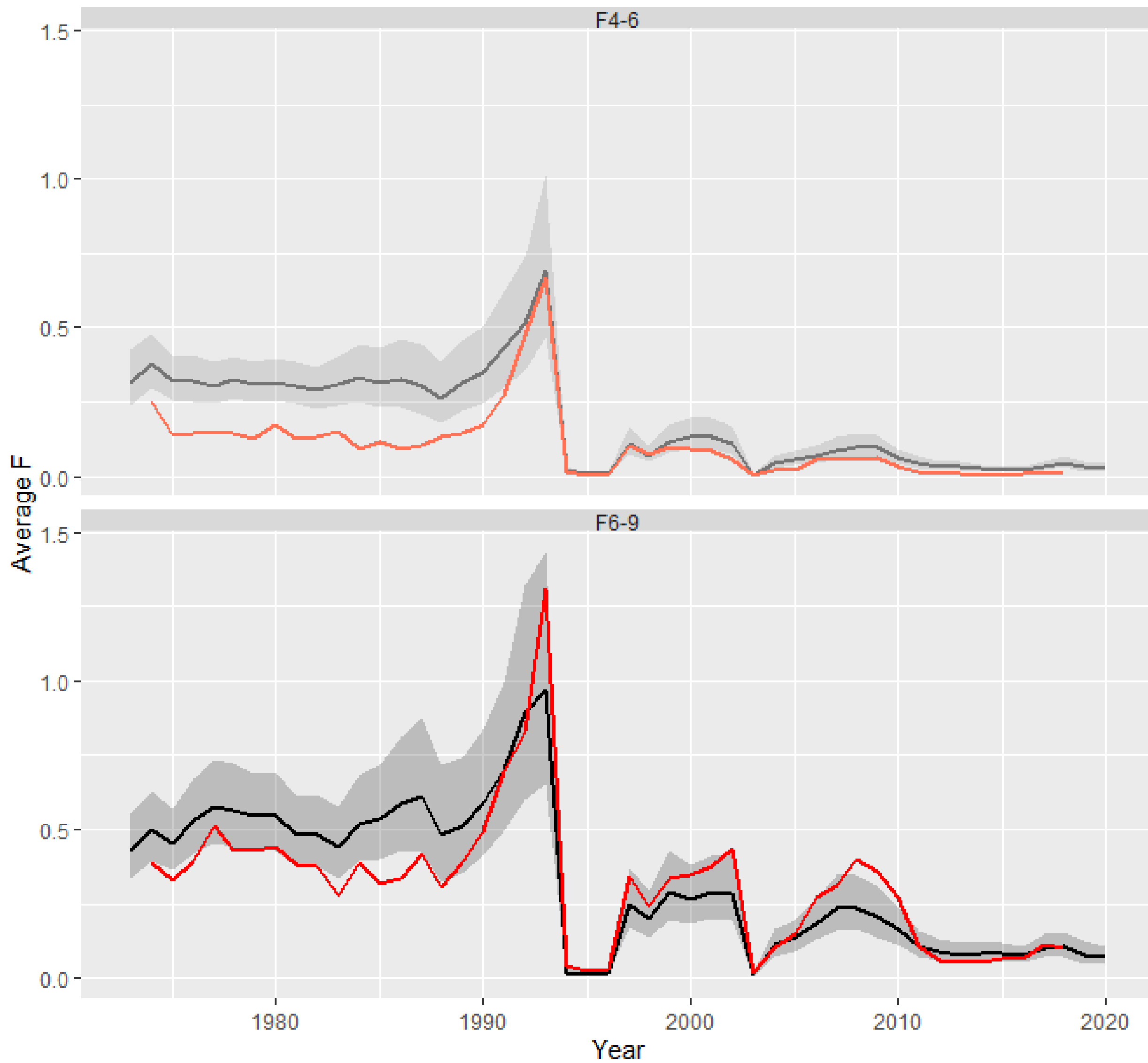


Figure 31. Distribution shift model estimates of average fishing mortality F at ages 4-6 and 6-9 (panels), with 95% confidence interval (dark line and shaded region), compared to values from the 2019 assessment using the SPA (red line).

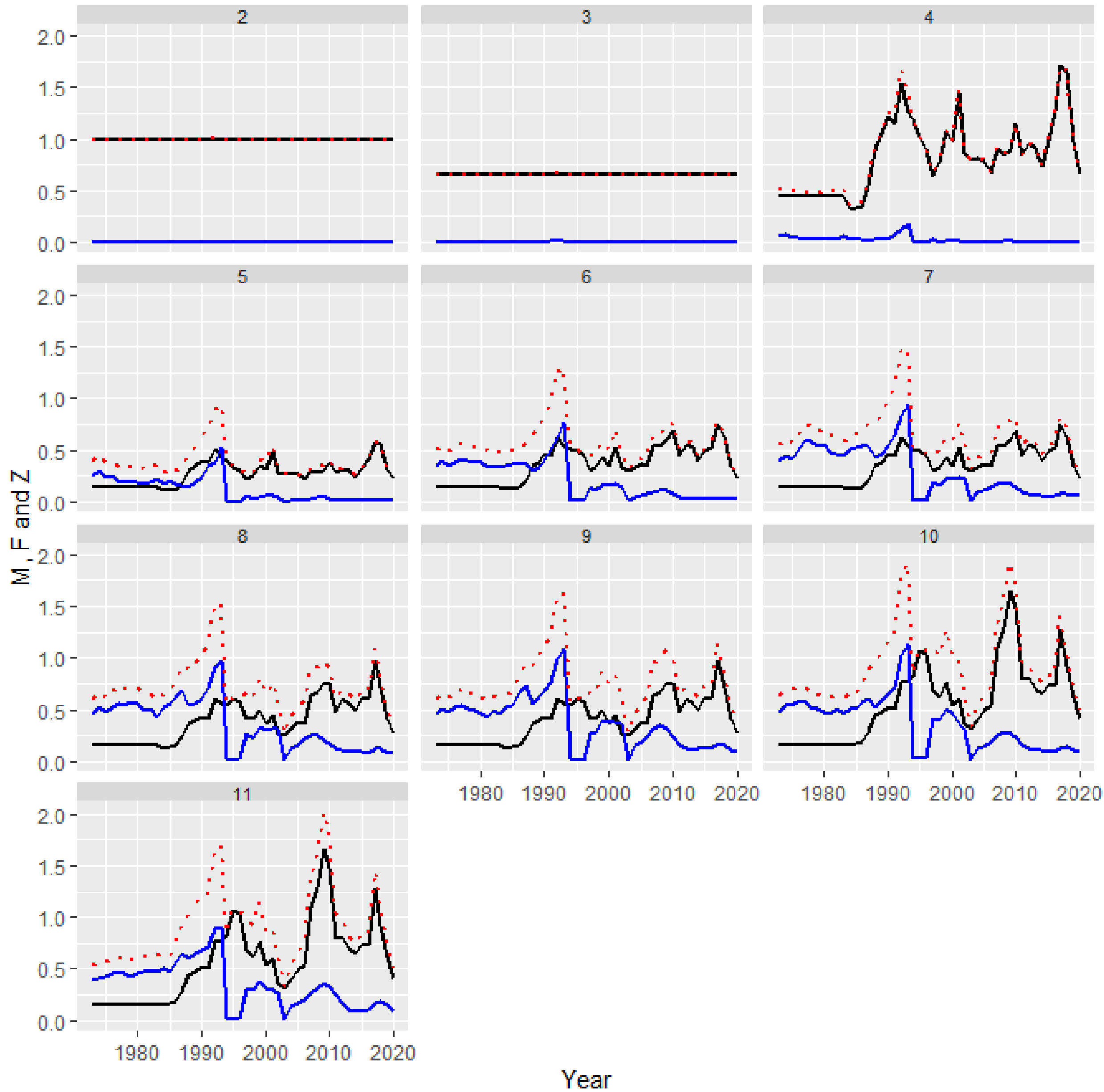


Figure 32. Distribution shift model estimates of age-specific fishing mortality (F, blue lines), natural mortality (M, black lines) and total mortality (Z= M+F; dotted red lines).

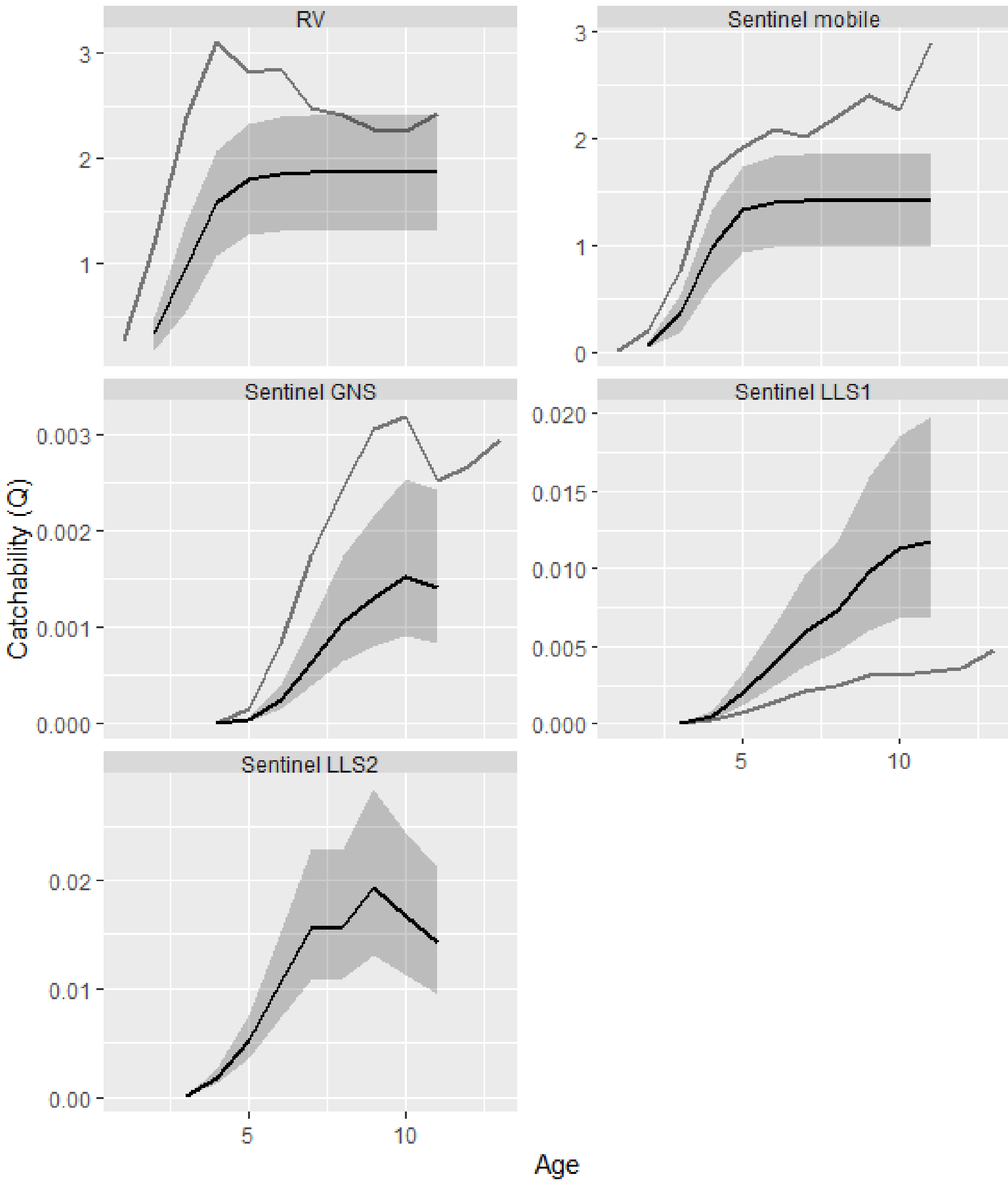


Figure 33. Distribution shift model estimates of age-specific catchability to the five main surveys, with 95% confidence interval (black line and shaded region), compared to values from the 2019 assessment using the SPA (grey line). The Sentinel Longline 1 (LLS1) index in the present model is most similar to the SPA Sentinel longline index and the two are therefore plotted together. Note that for the Sentinel Gillnet (GNS) and LLS1 the values from the SPA model were divided by 100 for plotting. Note also that the SPA uses a 13+ group.

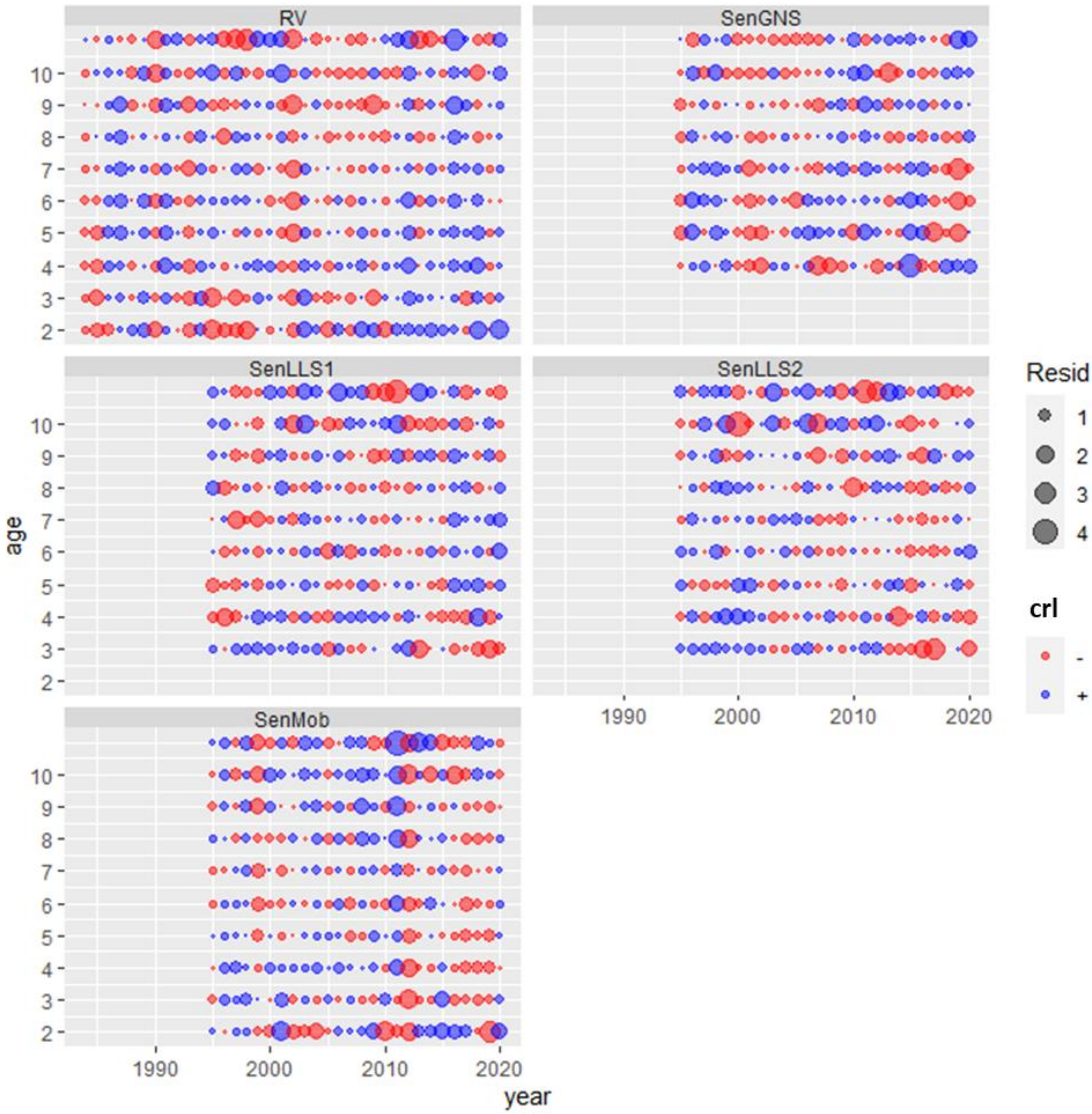


Figure 34. Distribution shift model residuals for the age-specific abundance indices for each survey (panels). The surface area of a bubble is proportional to the absolute value. Red is negative and blue is positive.

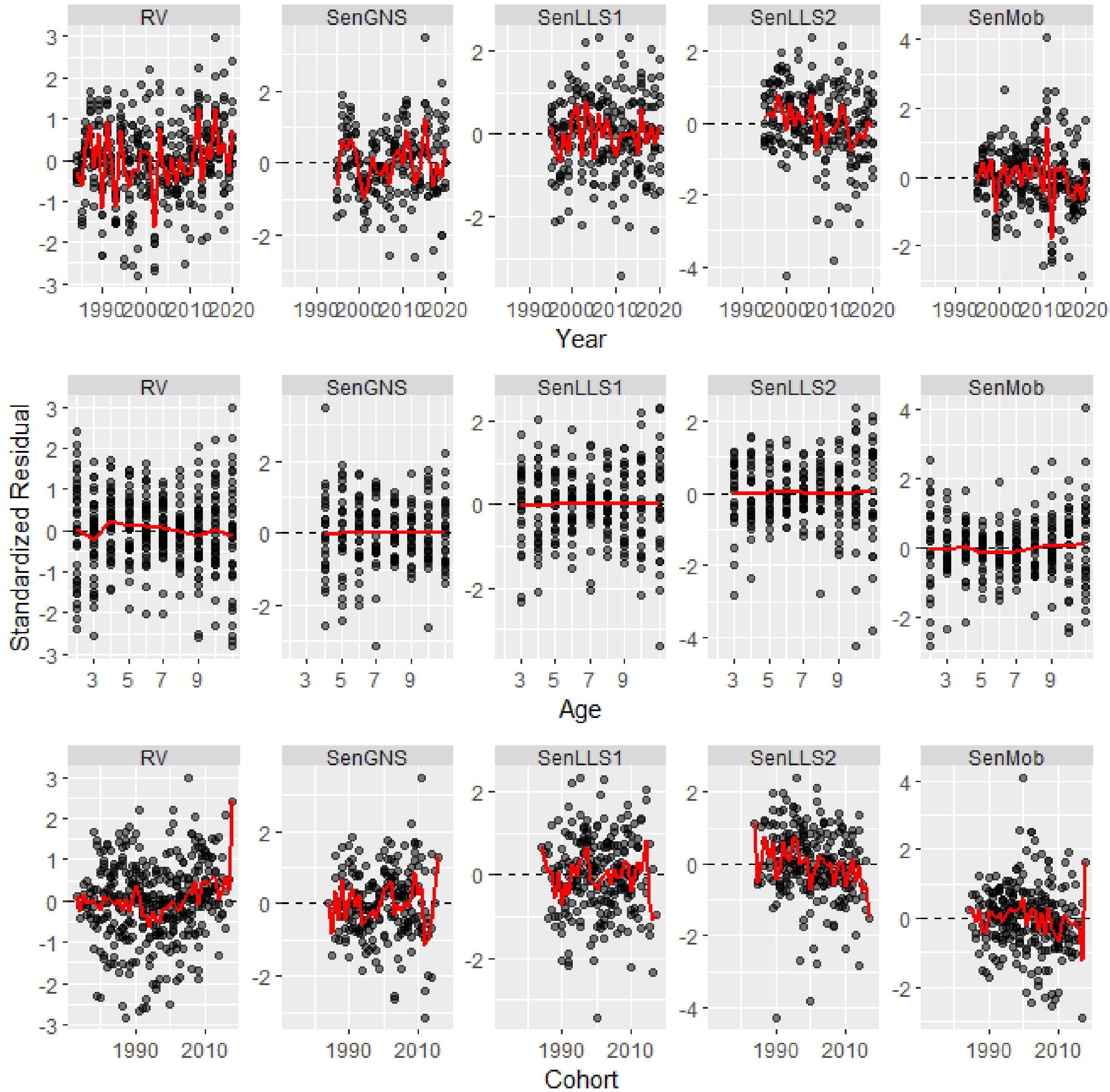


Figure 35. Distribution shift model index residuals for each survey (columns) versus year (top row), age (middle row), and cohort (bottom row). Red lines connect the means for age year/age/cohort.

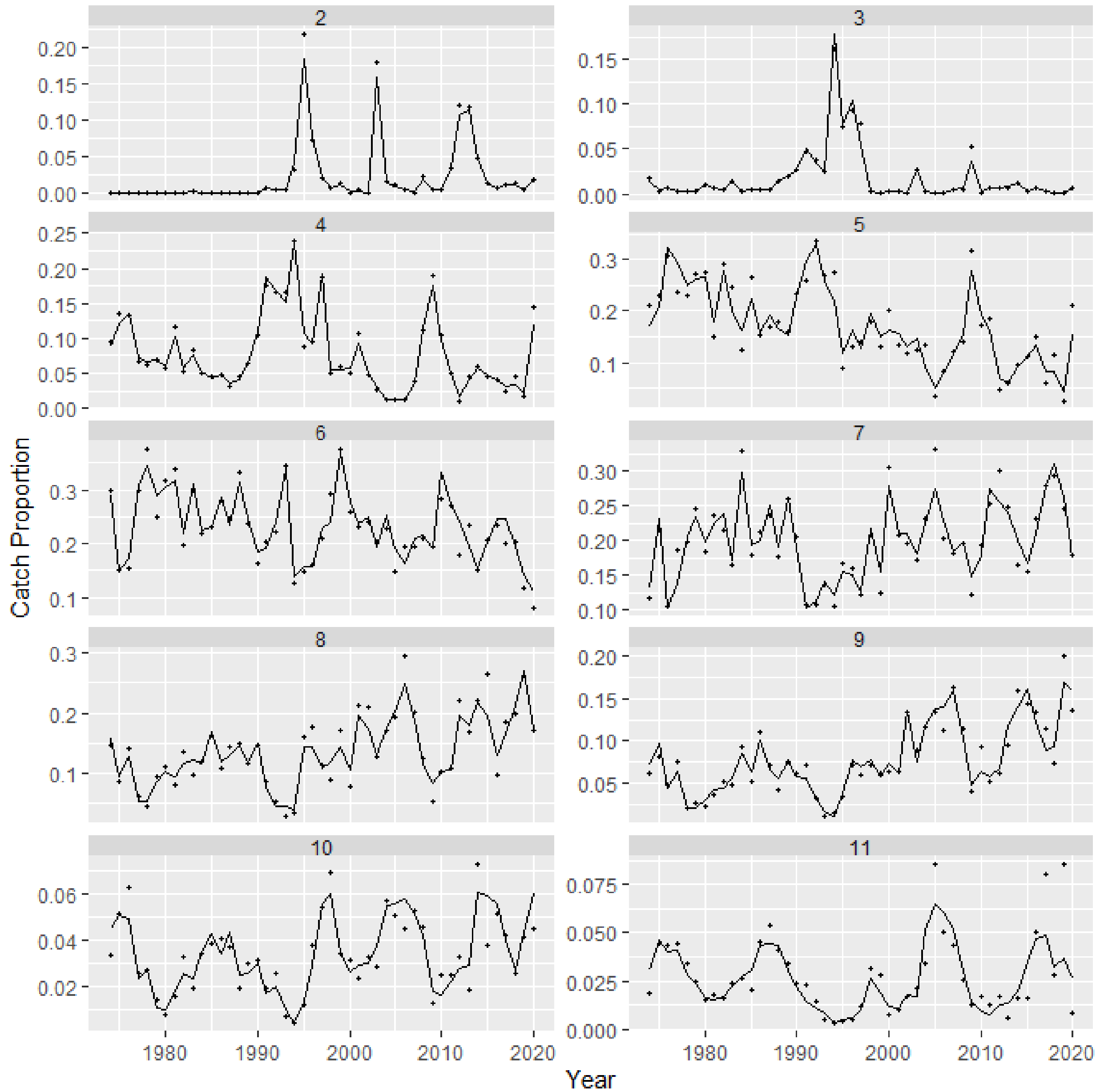


Figure 36. Observed (points) and distribution shift model predicted (lines) catch proportion-at-age.

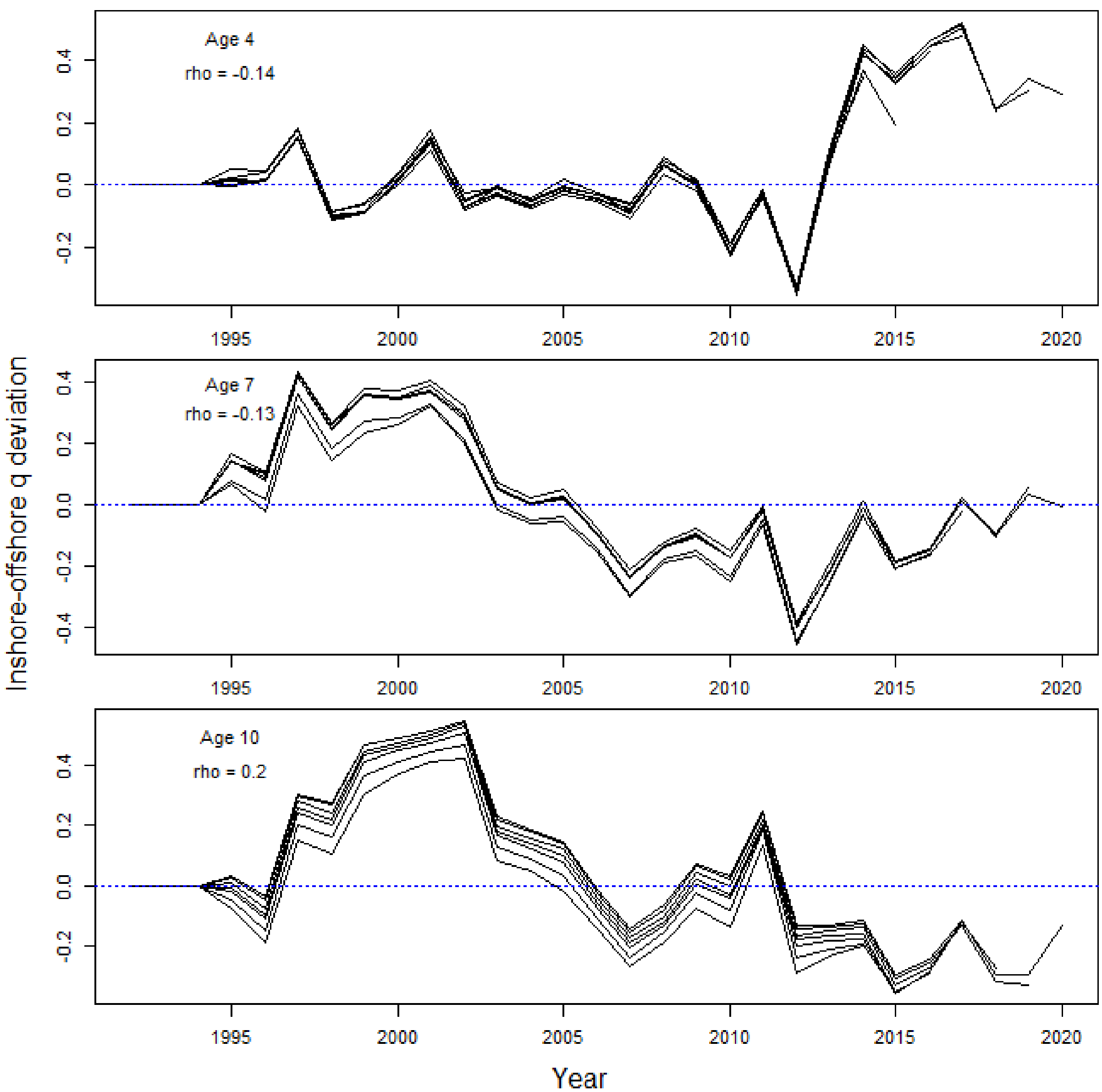


Figure 37. Retrospective estimates of the catchability deviations for nearshore vs offshore distribution for example ages (panels). The value of Mohn's rho is indicated in the panels.

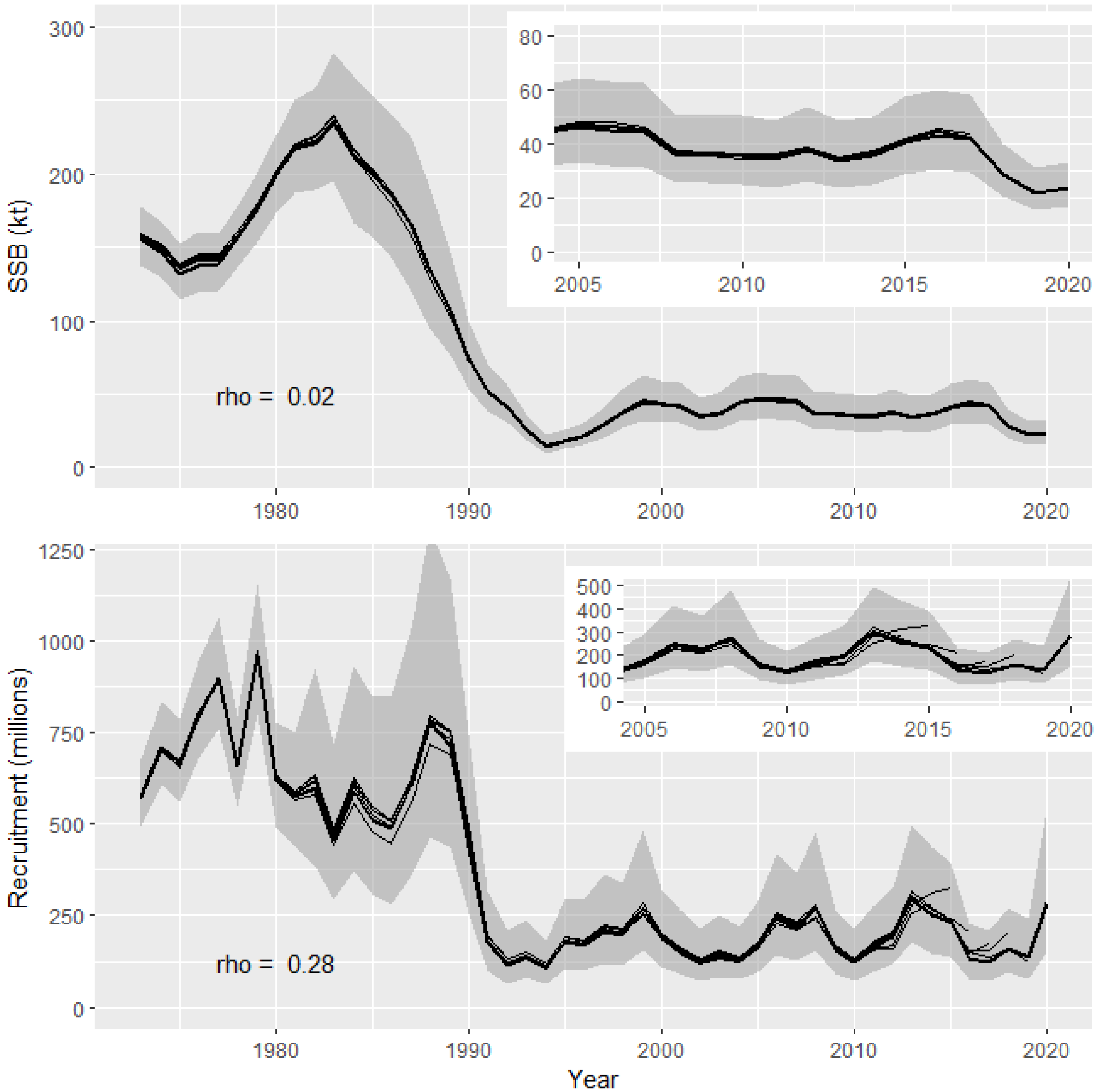


Figure 38. Retrospective estimates of spawning stock biomass (top panel) and recruitment (bottom panel) for the distribution shift model. Shaded regions indicate 95% confidence intervals based on the full time-series of data. The value of Mohn's rho is indicated in the panels. The inset panels show trends since 2005.

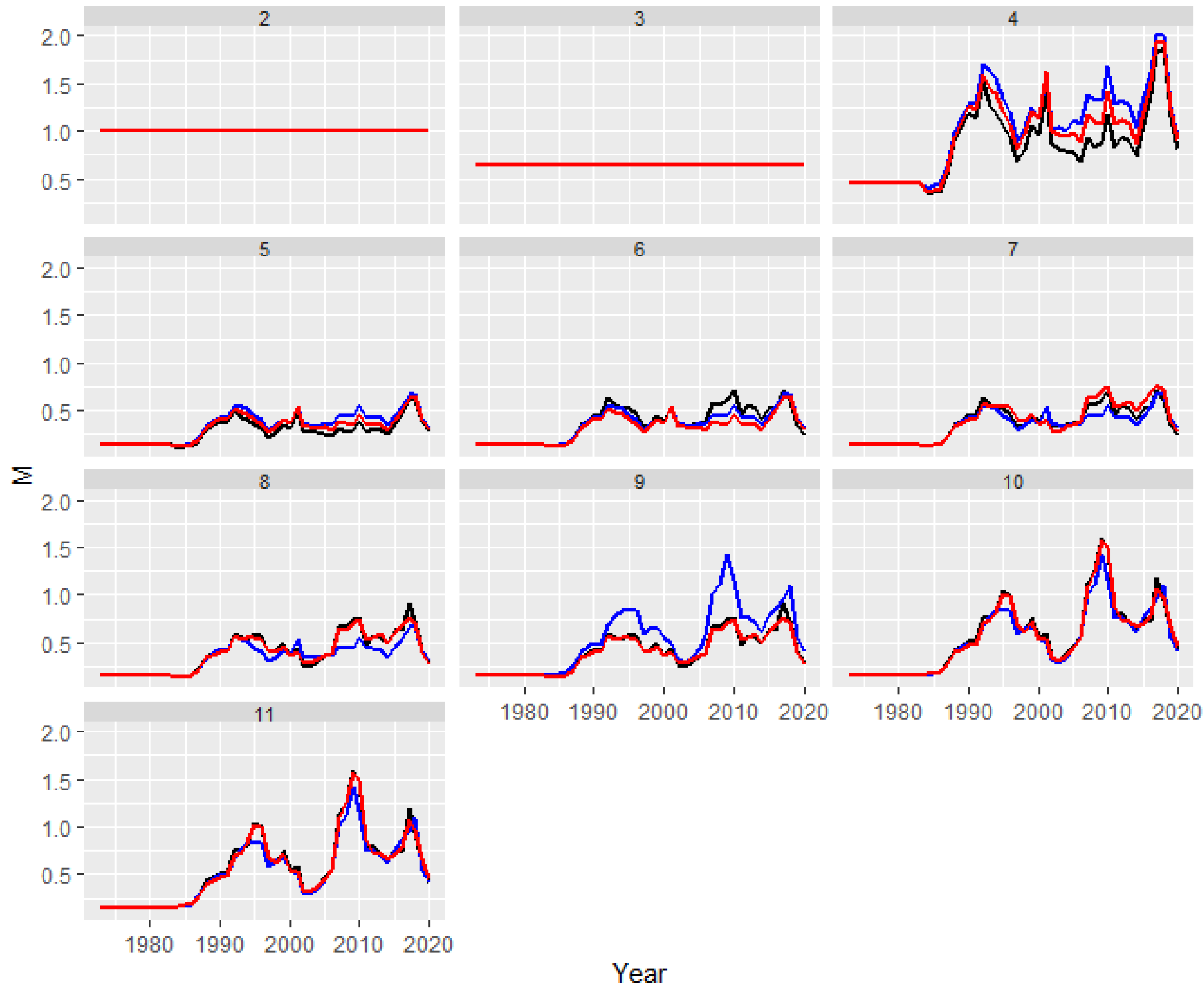


Figure 39. Comparison of estimated M trends for the baseline model (black lines), model with two (blue lines) or three (red lines) M categories for ages 2-11+ (panels). Note that the three lines are almost perfectly superimposed in many of the plots.

Figure 40. Comparison of estimated F trends for the baseline model (black lines), model with two (blue lines) or three (red lines) M categories for ages 2-11+ (panels). Note that the three lines are almost perfectly superimposed in the plots.

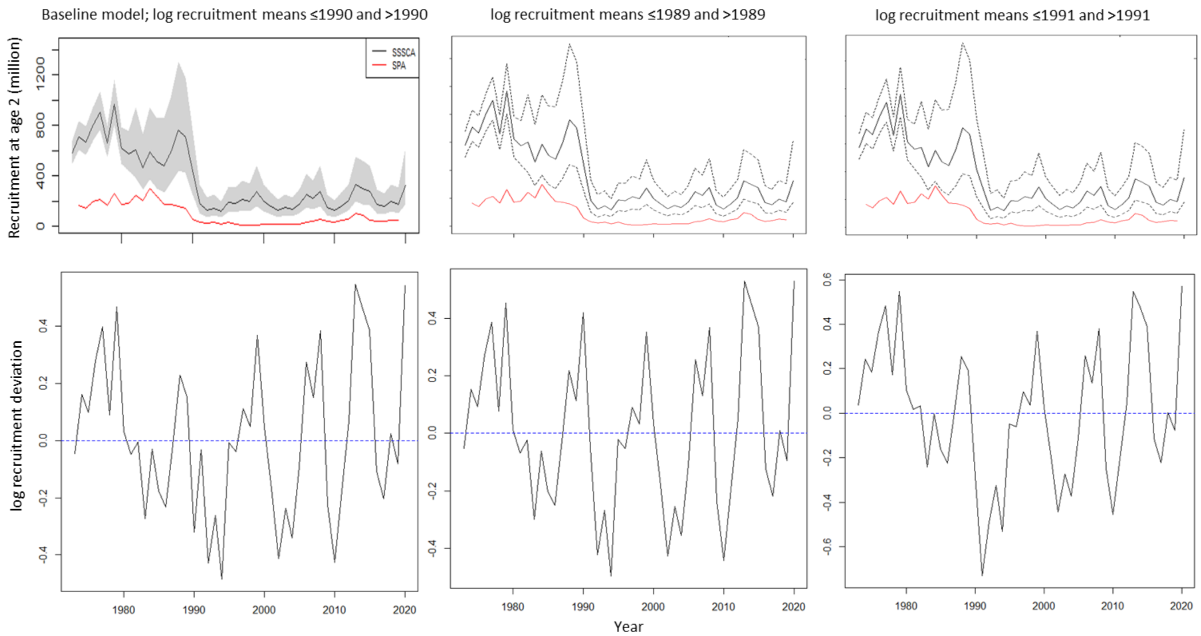


Figure 41. Estimates of recruitment (numbers at age 2) with 95% confidence interval (top row) and estimates of log recruitment deviations (bottom row), for the baseline model and the two mean recruitment time-block sensitivity runs (columns). Recruitment estimates from the 2019 assessment using the SPA are shown for reference using a red line.

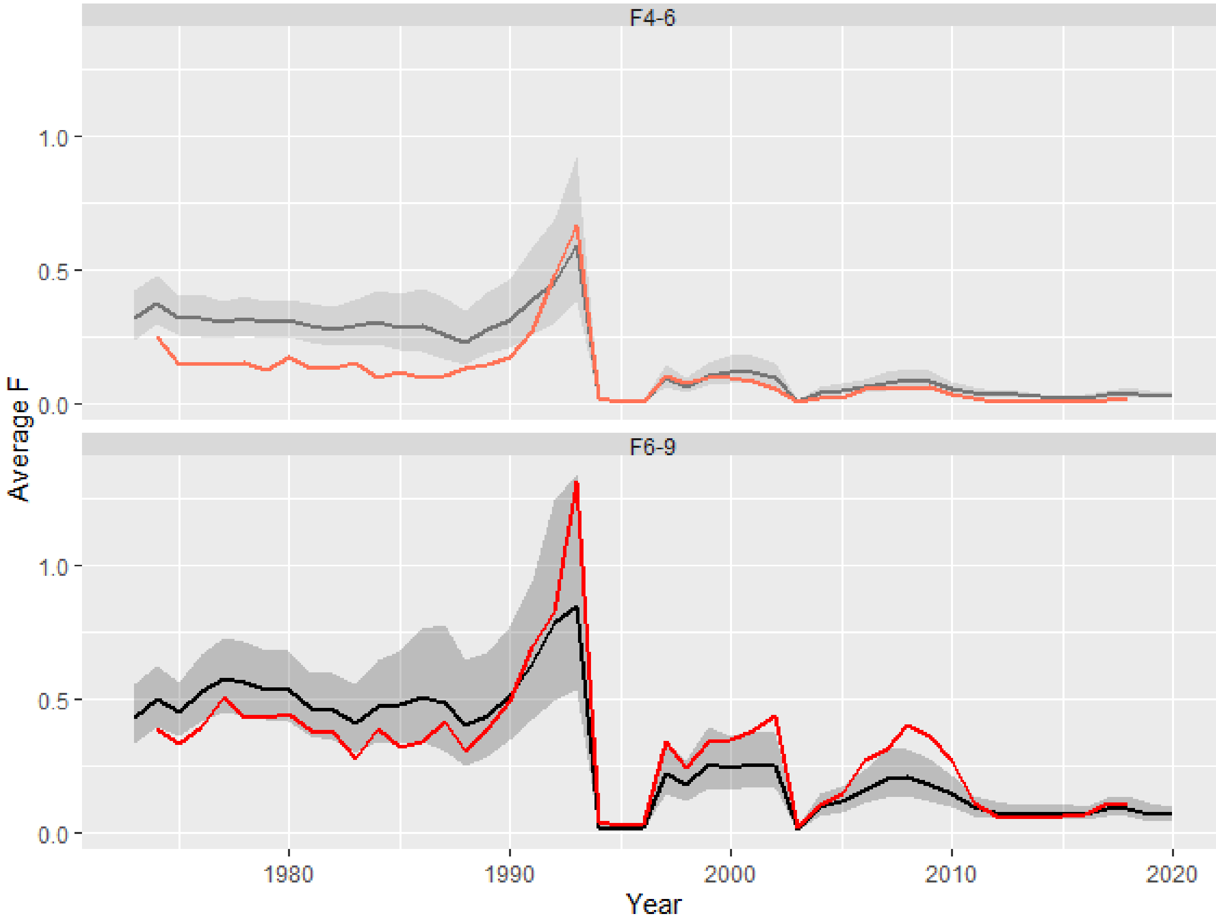


Figure 42. Model estimates of average fishing mortality F at ages 4-6 and 6-9, with 95% confidence interval (dark line and shaded region) when the Myers F priors are excluded, compared to values from the 2019 assessment using the SPA (red line).

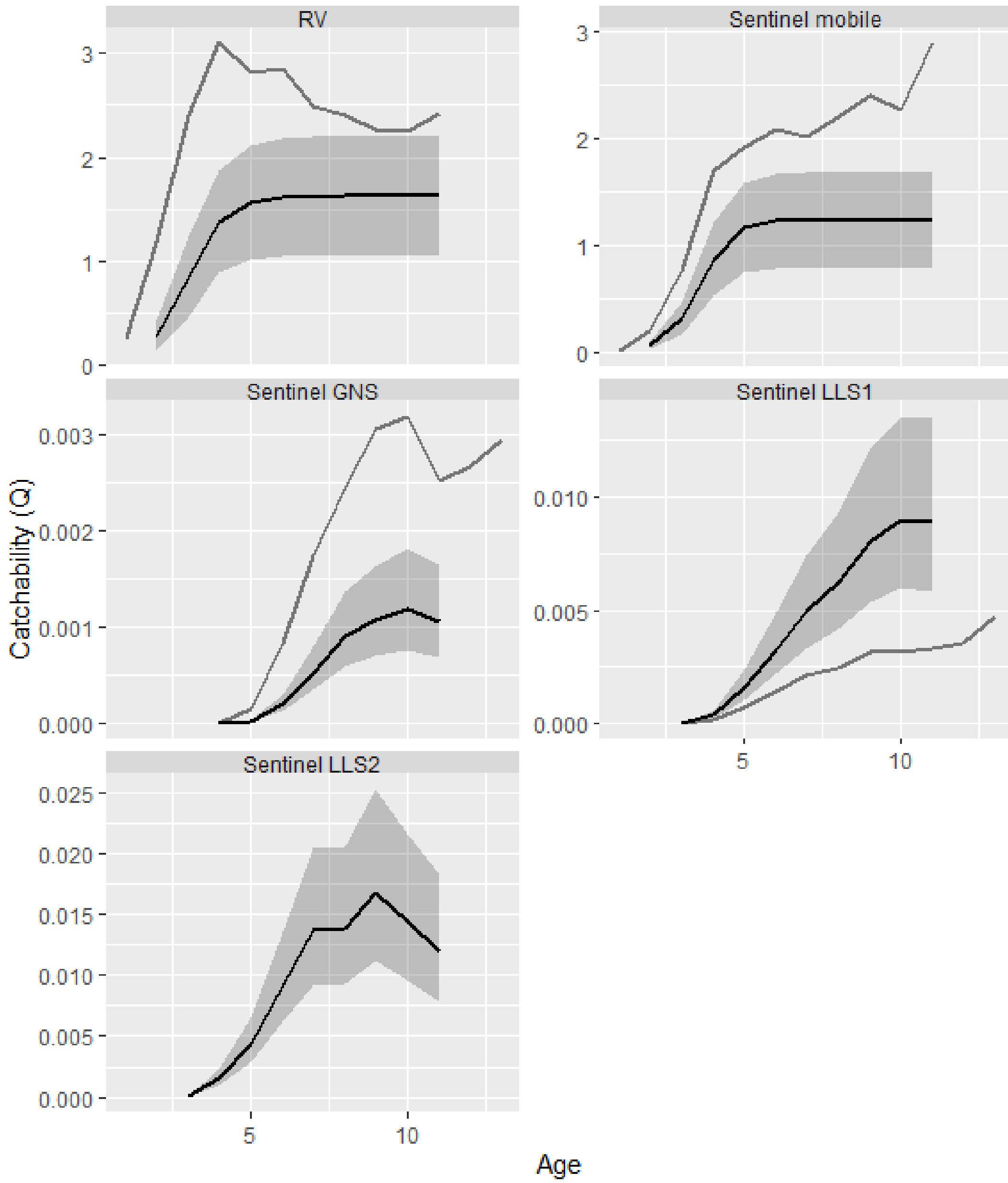


Figure 43. Model estimates of age-specific catchability to the five main surveys, with 95% confidence interval (dark line and shaded region) when the Myers priors on F are excluded from the model, compared to values from the 2019 assessment using the SPA. The Sentinel Longline 1 (LLS1) index in the present model is most similar to the SPA Sentinel longline index and the two are therefore plotted together. Note that for the Sentinel Gillnet (GNS) and LLS1 the values from the SPA model were divided by 100 for plotting. Note also that the SPA uses a 13+ group.

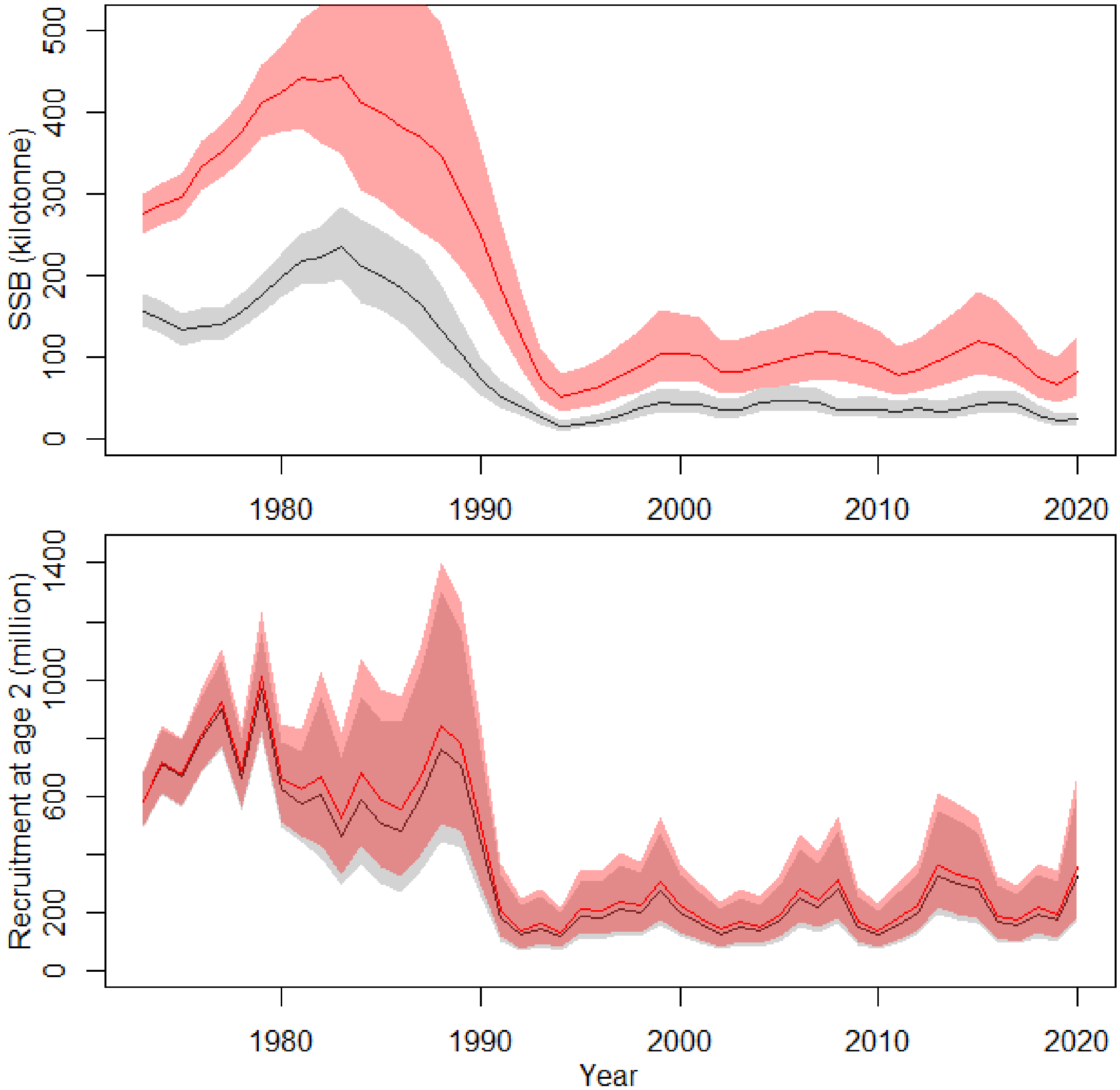


Figure 44. Comparison of estimates of SSB (top) and recruitment (bottom) for the baseline model (greys) and for that model but with the Myers priors on F omitted (reds). The lines are the estimates and the shaded areas are the 95% confidence intervals.

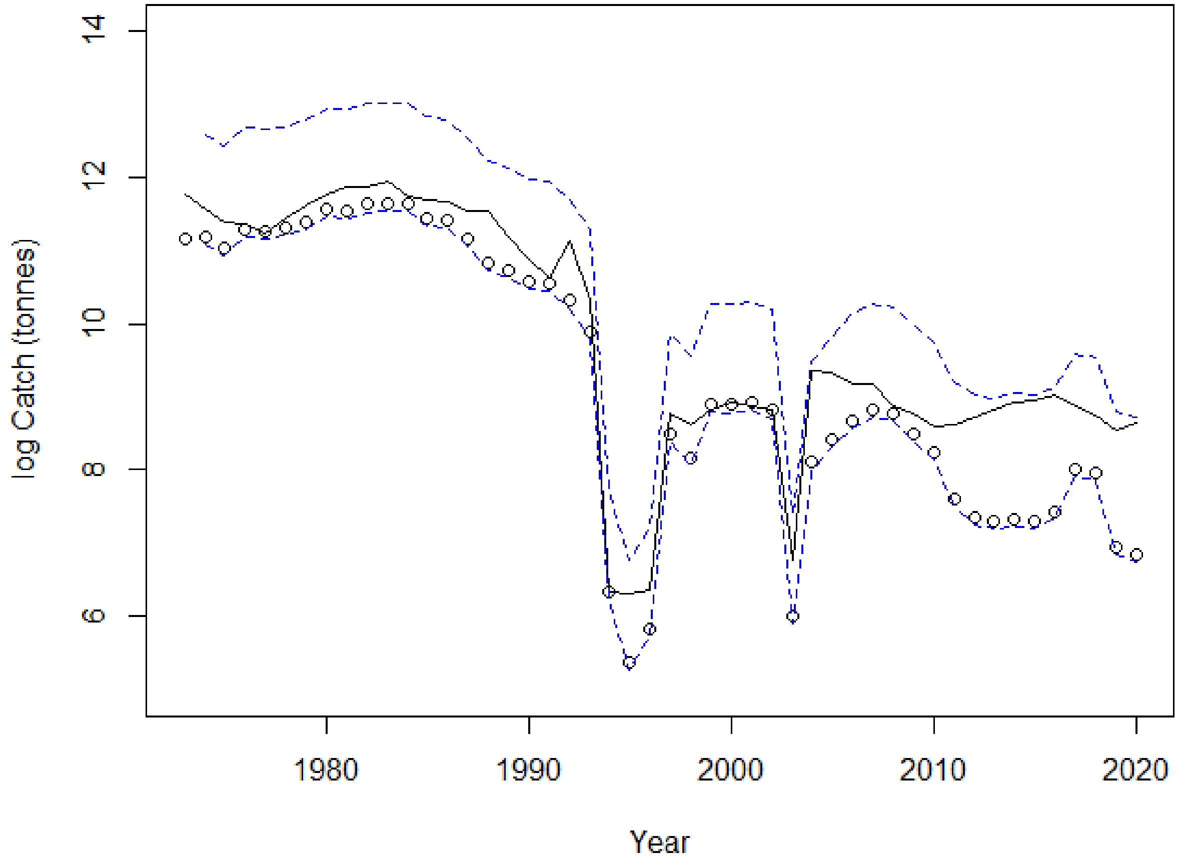


Figure 45. Predicted log-catch (black line), compared to input log-catch (points) and catch bounds (dashed blue lines) for 1973-2020 in the first catch error runs, involving the censored likelihood and wide upper bounds.

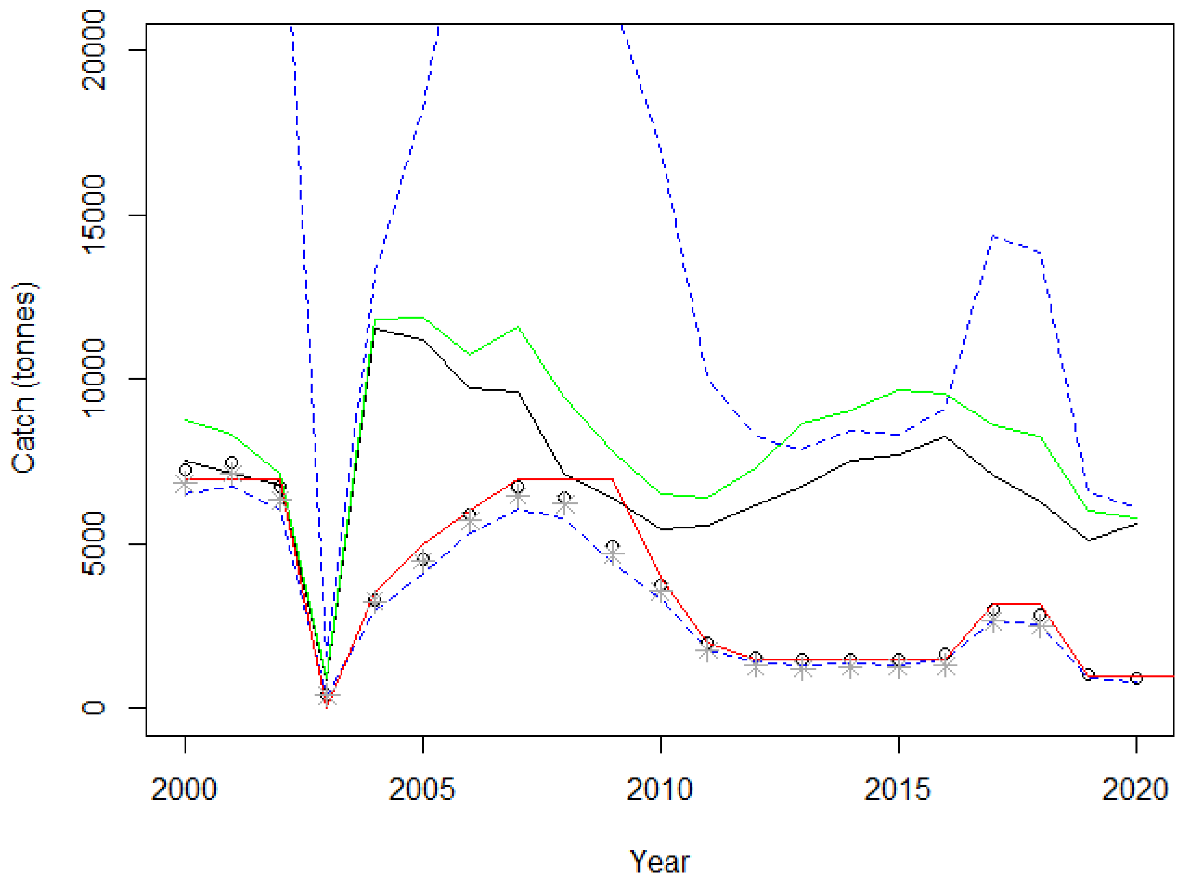


Figure 46. Input (black circles, predicted catch (black line), total allowable catch (red line) and catch bounds (dashed blue lines) for 2000-2020, with the addition of the landings (grey asterisk) and the sum of model predicted catch and surplus unaccounted catch inferred from M (green line) in the first catch error runs, involving the censored likelihood and wide upper bounds.

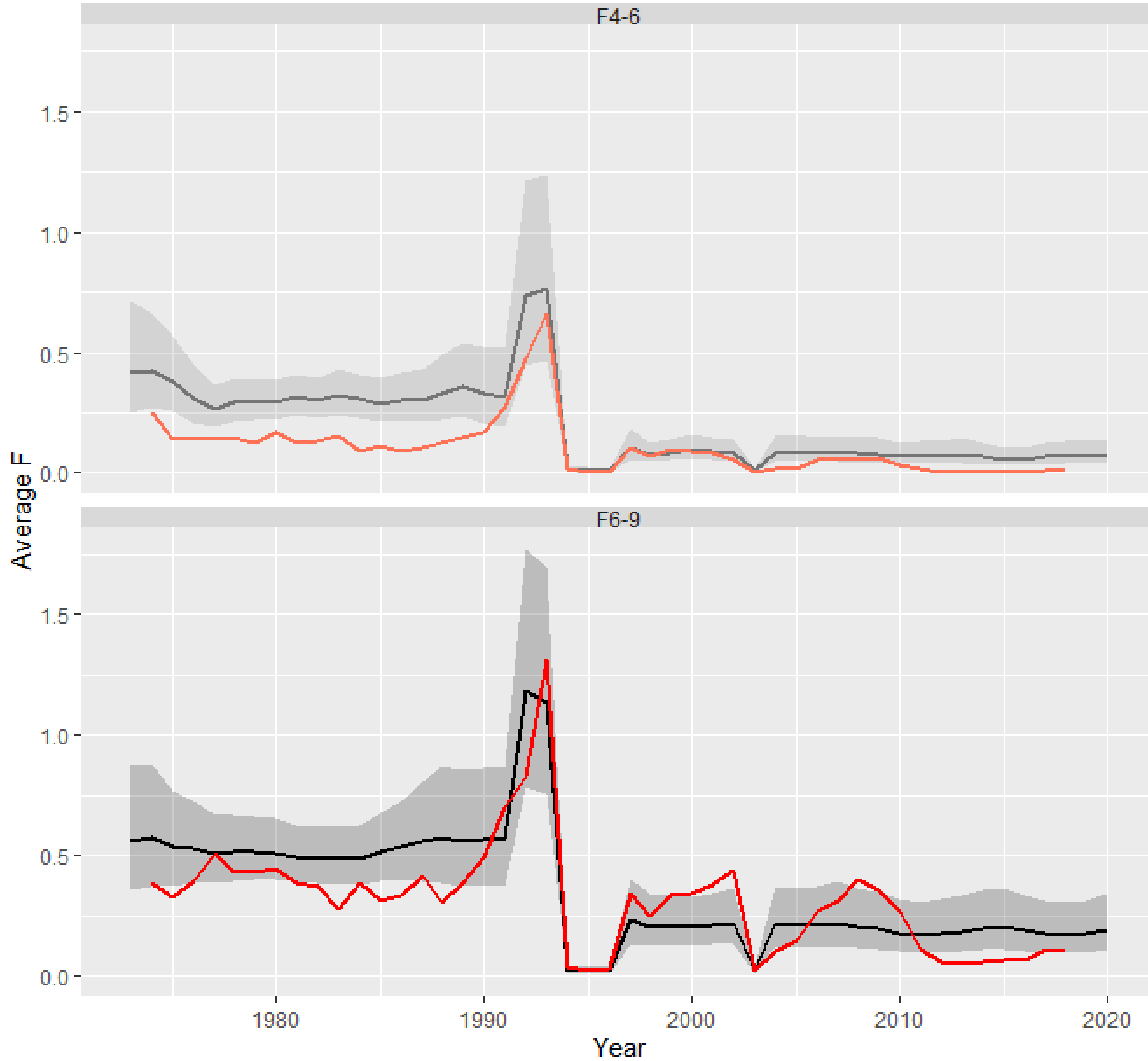


Figure 47. Estimates of average fishing mortality F at ages 4-6 and 6-9 (panels), with 95% confidence interval (dark line and shaded region), compared to values from the 2019 assessment using the SPA (red line), in the first catch error runs, involving the censored likelihood and wide upper bounds.

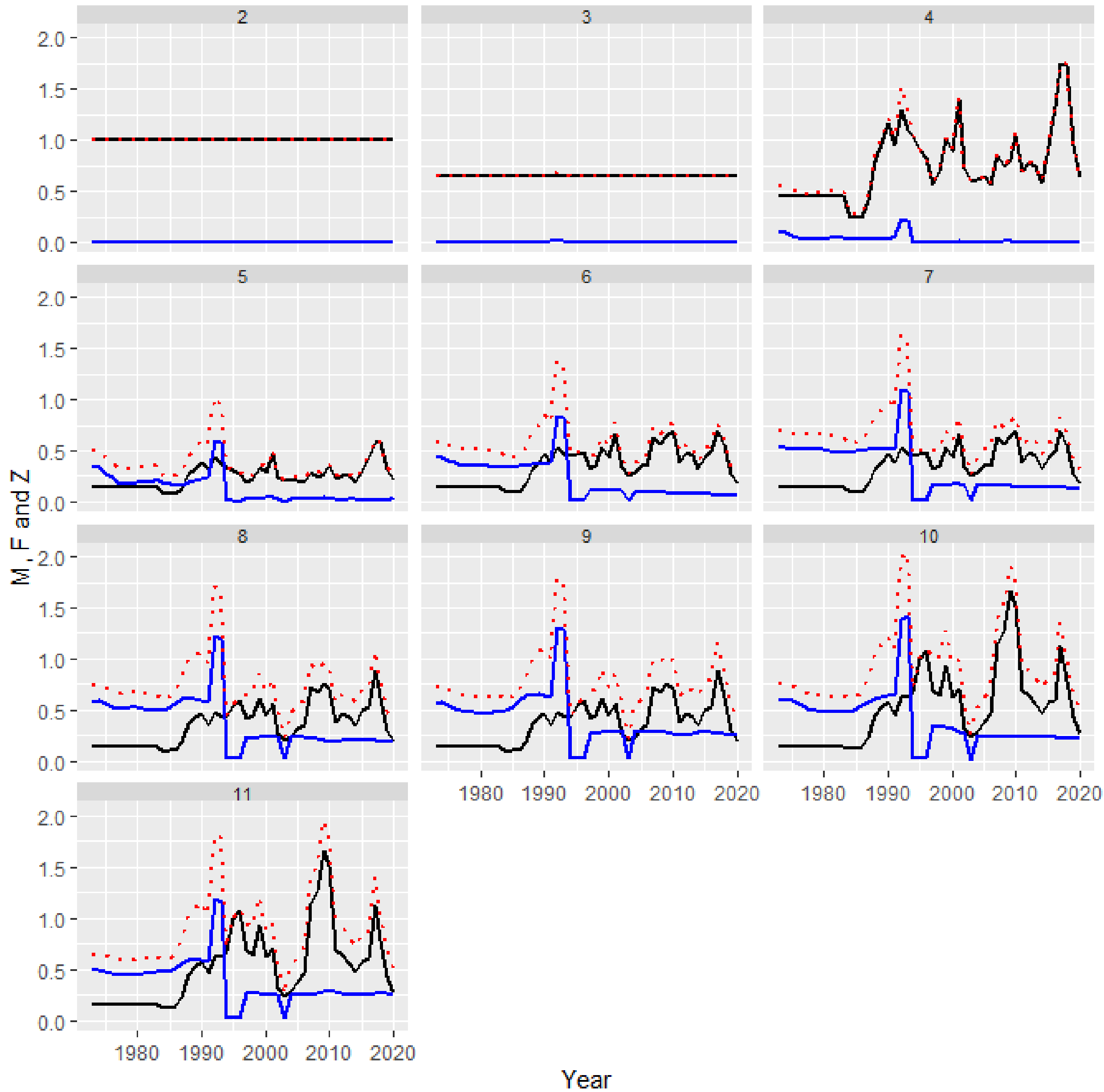


Figure 48. Estimates of age-specific fishing mortality (F, blue lines), natural mortality (M, black lines) and total mortality (Z= M+F; dotted red lines) in the first catch error runs, involving the censored likelihood and wide upper bounds.

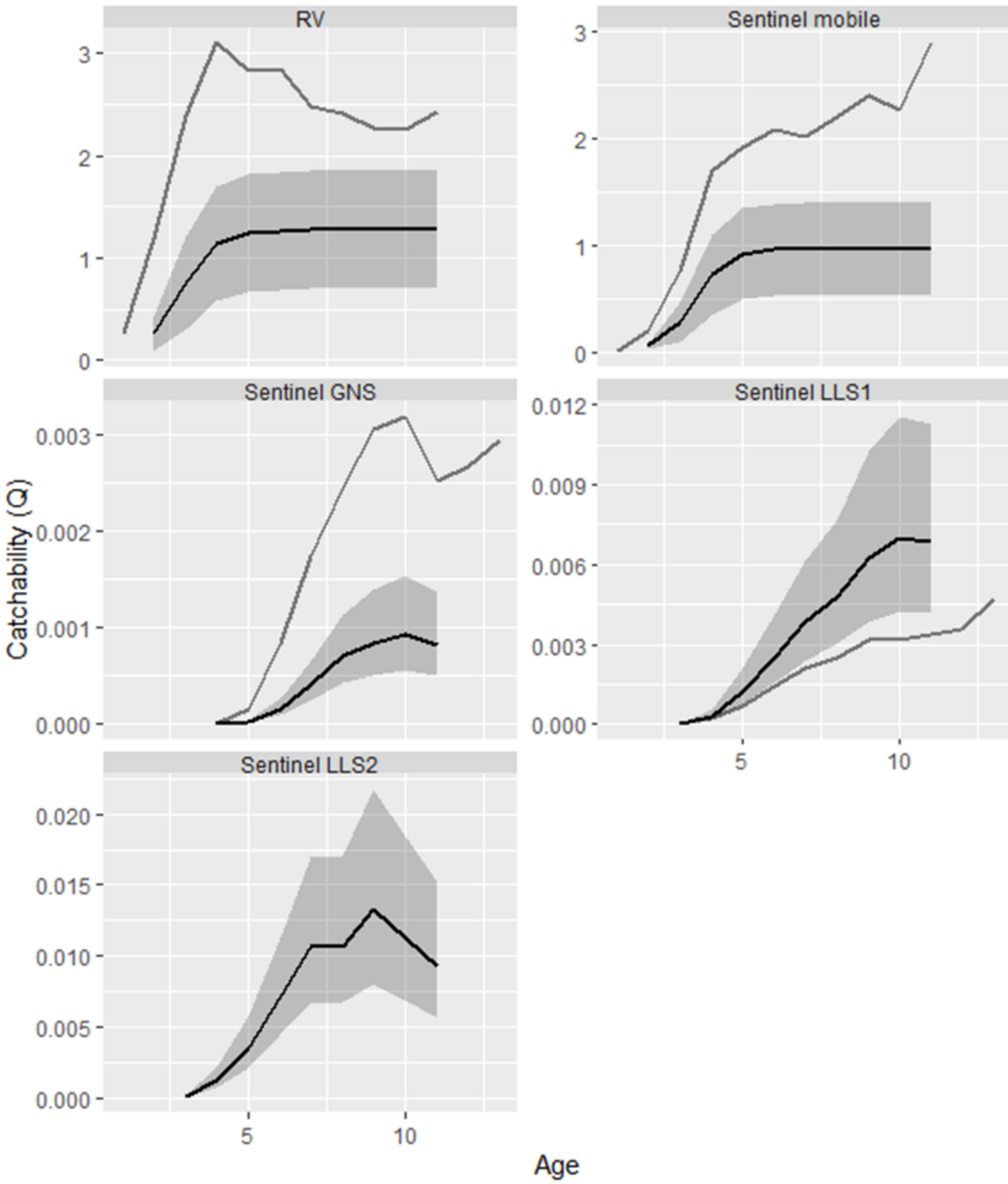


Figure 49. Estimates of age-specific catchability to the five main surveys, with 95% confidence interval (black line and shaded region) in the first catch error runs, involving the censored likelihood and wide upper bounds, compared to values from the 2019 assessment using the SPA (grey line). The Sentinel Longline 1 (LLS1) index in the present model is most similar to the SPA Sentinel longline index and the two are therefore plotted together. Note that for the Sentinel Gillnet (GNS) and LLS1 the values from the SPA model were divided by 100 for plotting. Note also that the SPA uses a 13+ group.

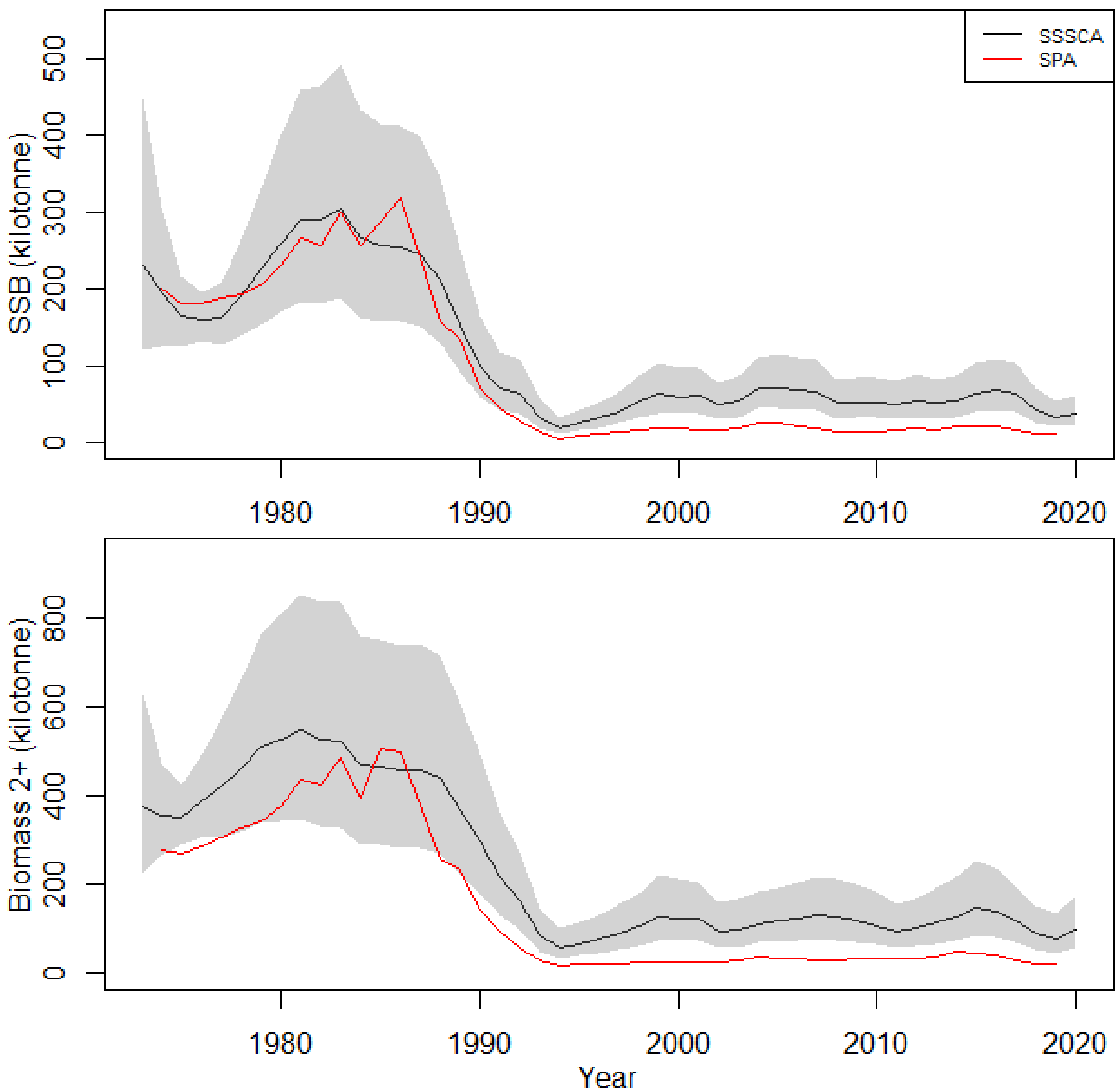


Figure 50. Estimates of spawning stock biomass (SSB) and age 2+ biomass, with 95% confidence interval (black line and shaded region), in the first catch error runs, involving the censored likelihood and wide upper bounds, compared to values from the 2019 assessment using the SPA (red line).

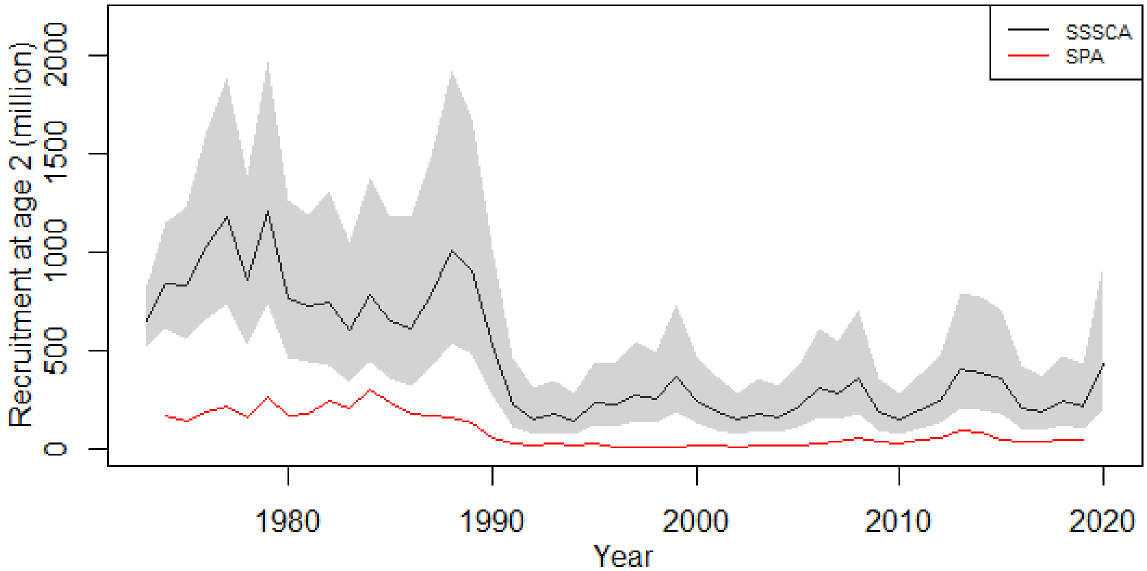


Figure 51. Estimates of recruitment (numbers at age 2), with 95% confidence interval (black line and shaded region), in the first catch error runs, involving the censored likelihood and wide upper bounds, compared to values from the 2019 assessment using the SPA (red line).

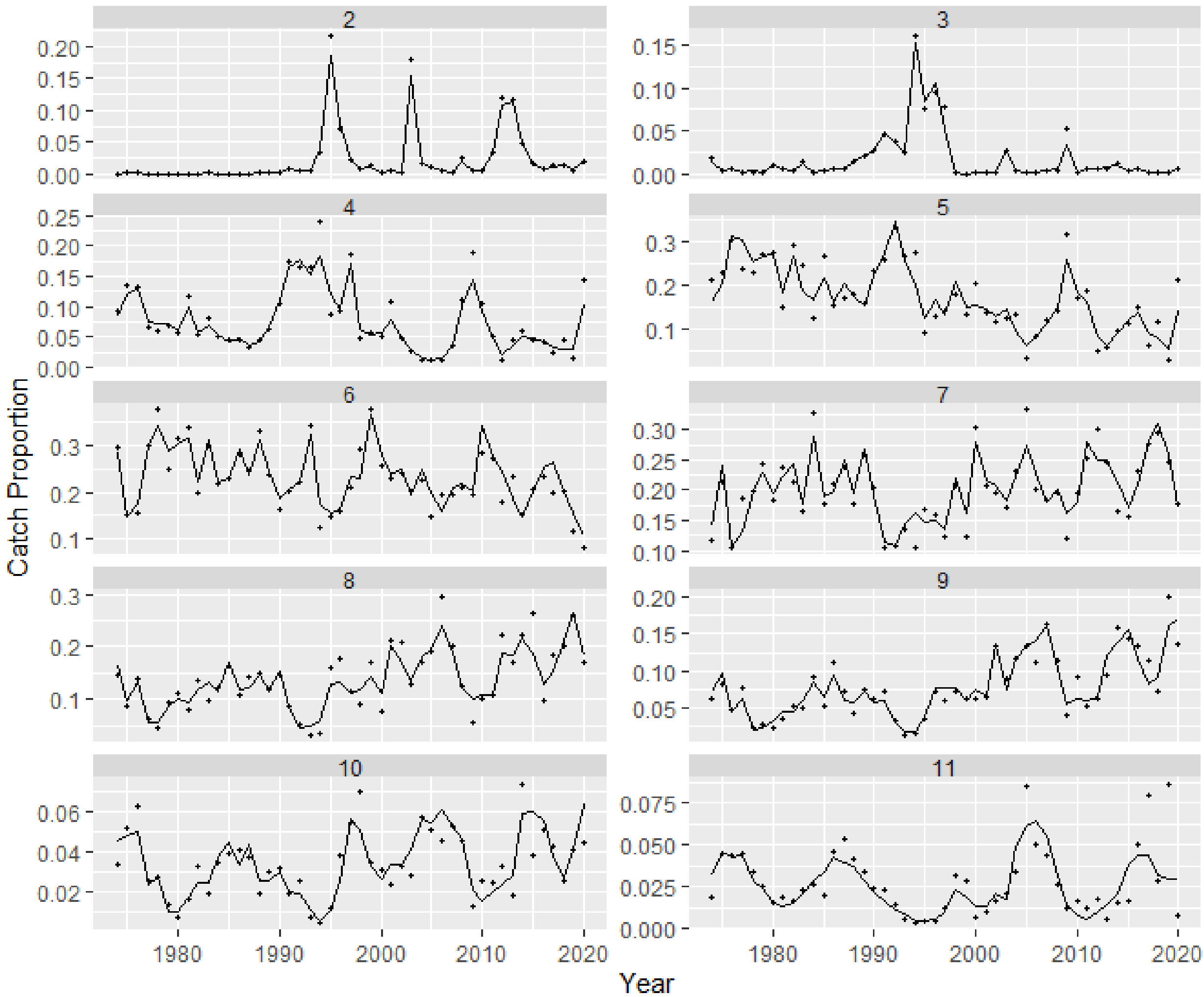


Figure 52. Observed (points) and model predicted (lines) catch proportion-at-age in the first catch error runs, involving the censored likelihood and wide upper bounds. Each panel corresponds to an age.

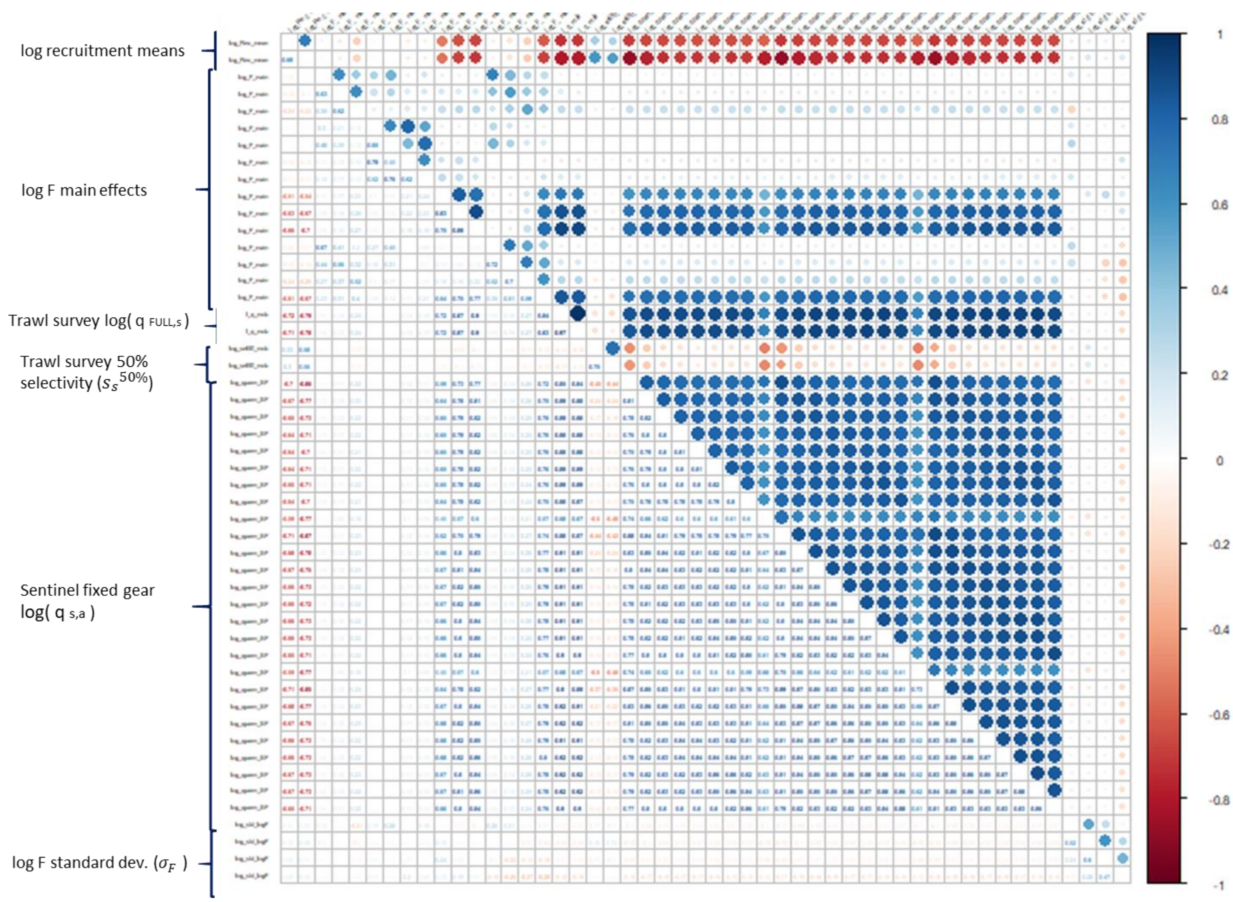


Figure 53. Correlation matrix for model parameters with absolute correlations >0.15 in the in the first catch error runs, involving the censored likelihood and wide upper bounds.

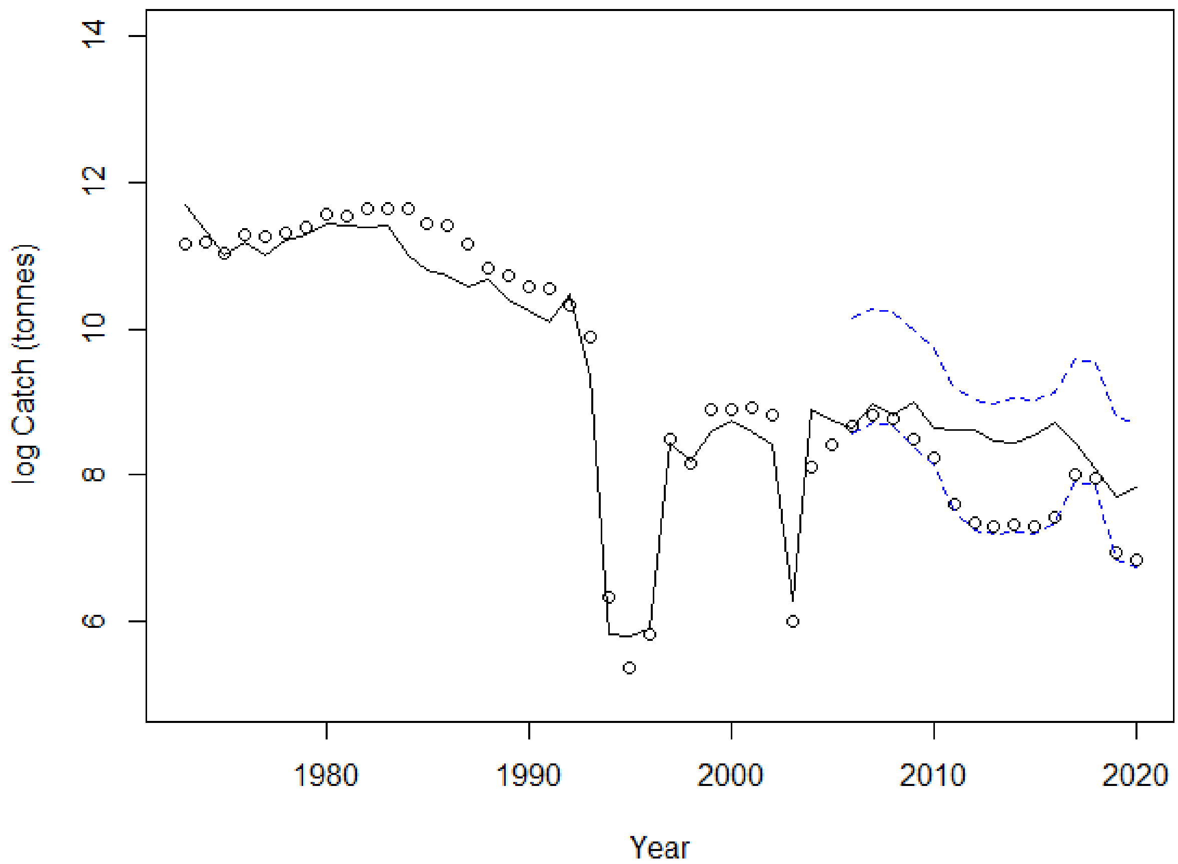


Figure 54. Predicted log-catch (black line), compared to input log-catch (points) and catch bounds (dashed blue lines) for 1973-2020 in the second set of catch-error runs involving the lognormal likelihood with wide variance.

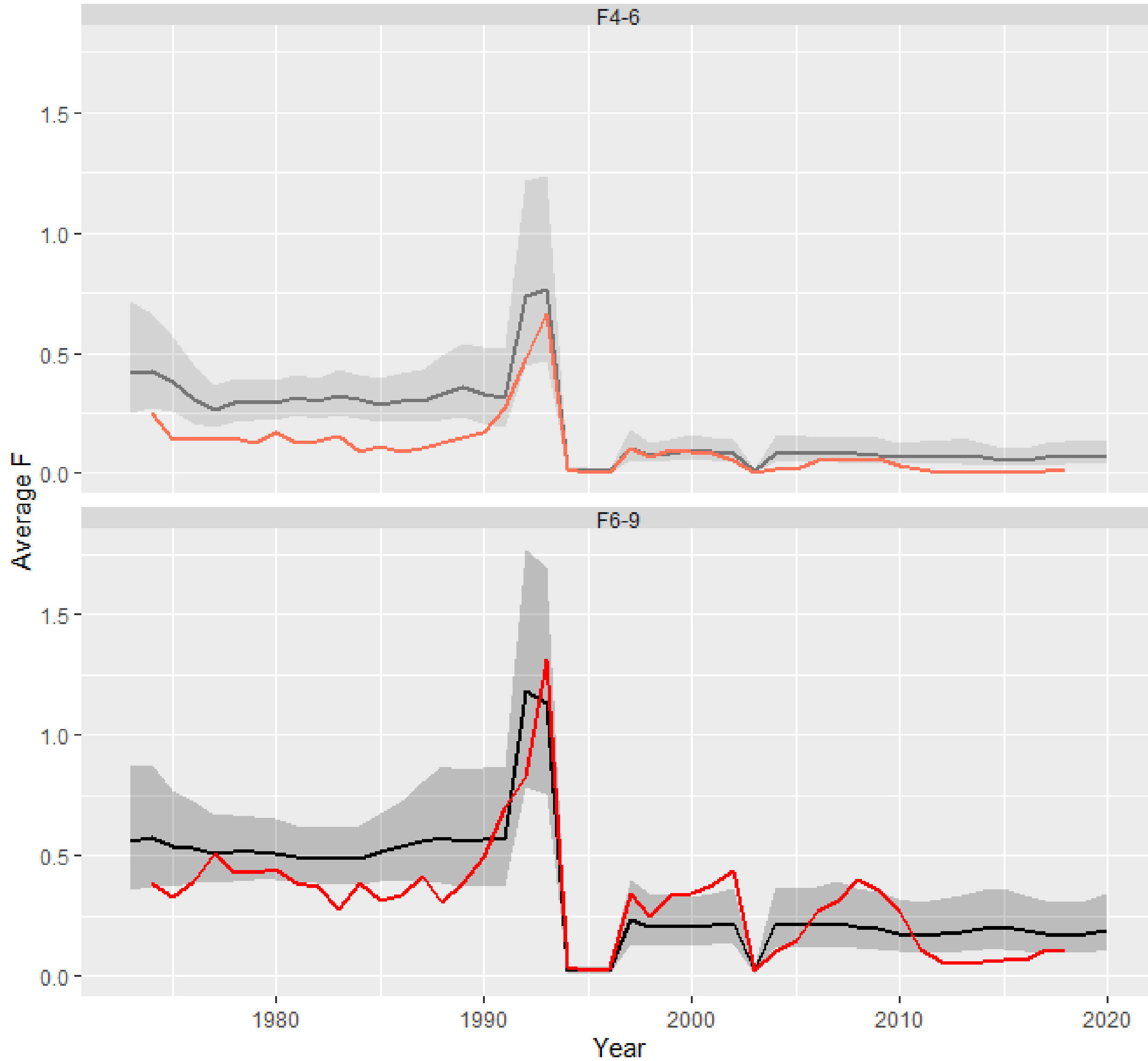


Figure 55. Estimates of average fishing mortality F at ages 4-6 and 6-9 (panels), with 95% confidence interval (dark line and shaded region), compared to values from the 2019 assessment using the SPA (red line), in the second set of catch-error runs involving the lognormal likelihood with wide variance.

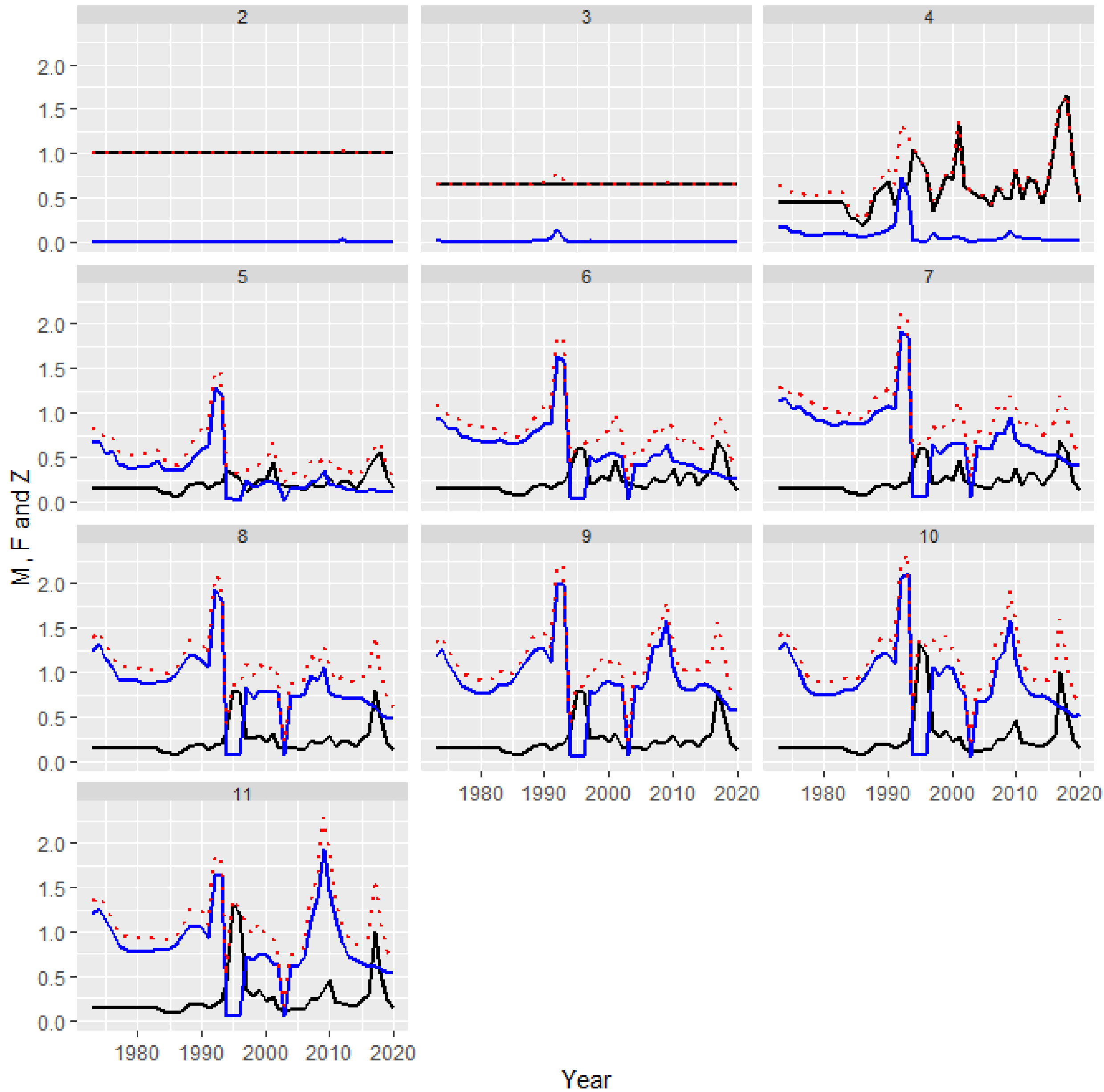


Figure 56. Estimates of age-specific fishing mortality (F, blue lines), natural mortality (M, black lines) and total mortality (Z= M+F; dotted red lines) in the second set of catch-error runs involving the lognormal likelihood with wide variance.

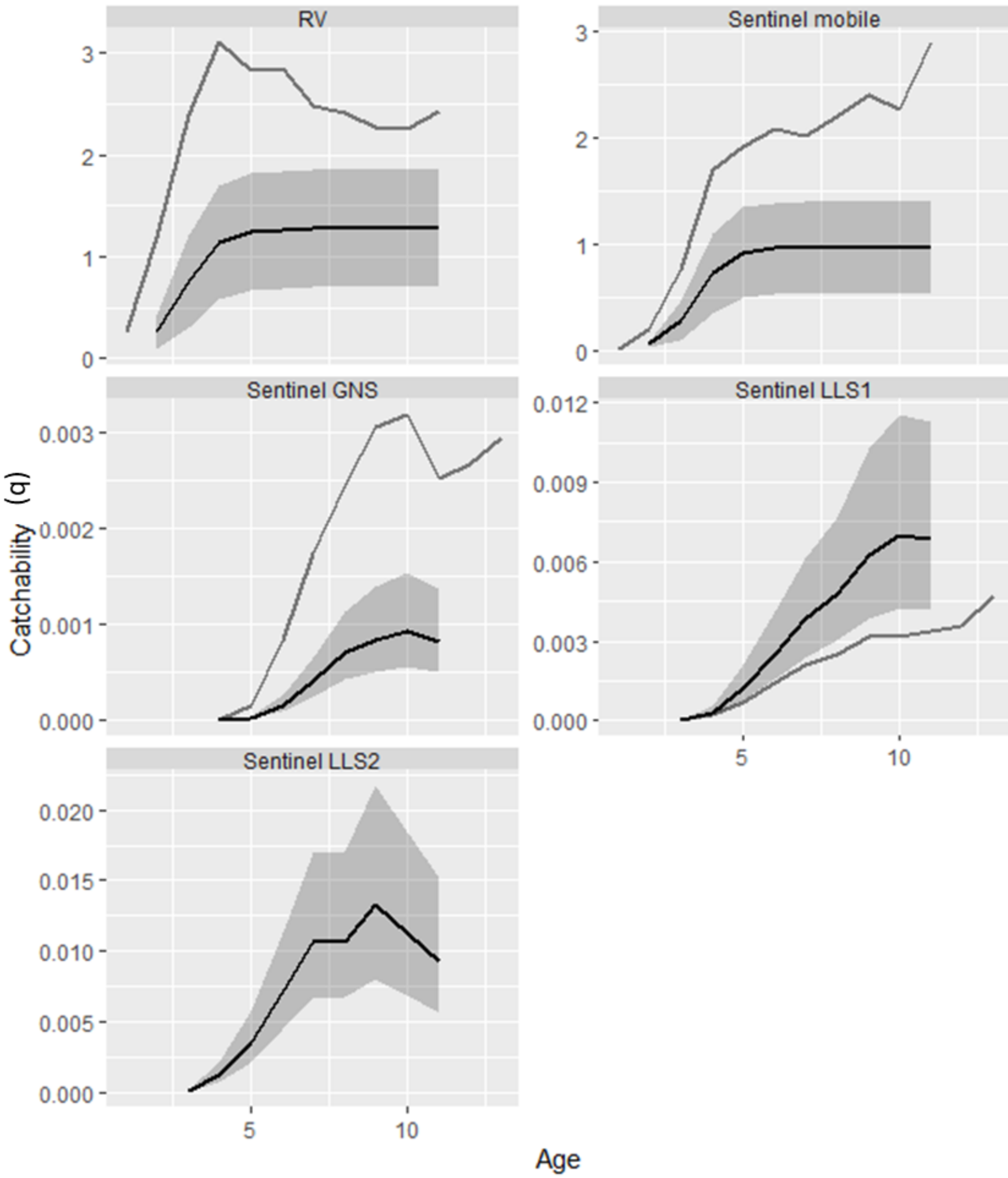


Figure 57. Estimates of age-specific catchability to the five main surveys, with 95% confidence interval (black line and shaded region) in the second set of catch-error runs involving the lognormal likelihood with wide variance, compared to values from the 2019 assessment using the SPA (grey line). The Sentinel Longline 1 (LLS1) index in the present model is most similar to the SPA Sentinel longline index and the two are therefore plotted together. Note that for the Sentinel Gillnet (GNS) and LLS1 the values from the SPA model were divided by 100 for plotting. Note also that the SPA uses a 13+ group.

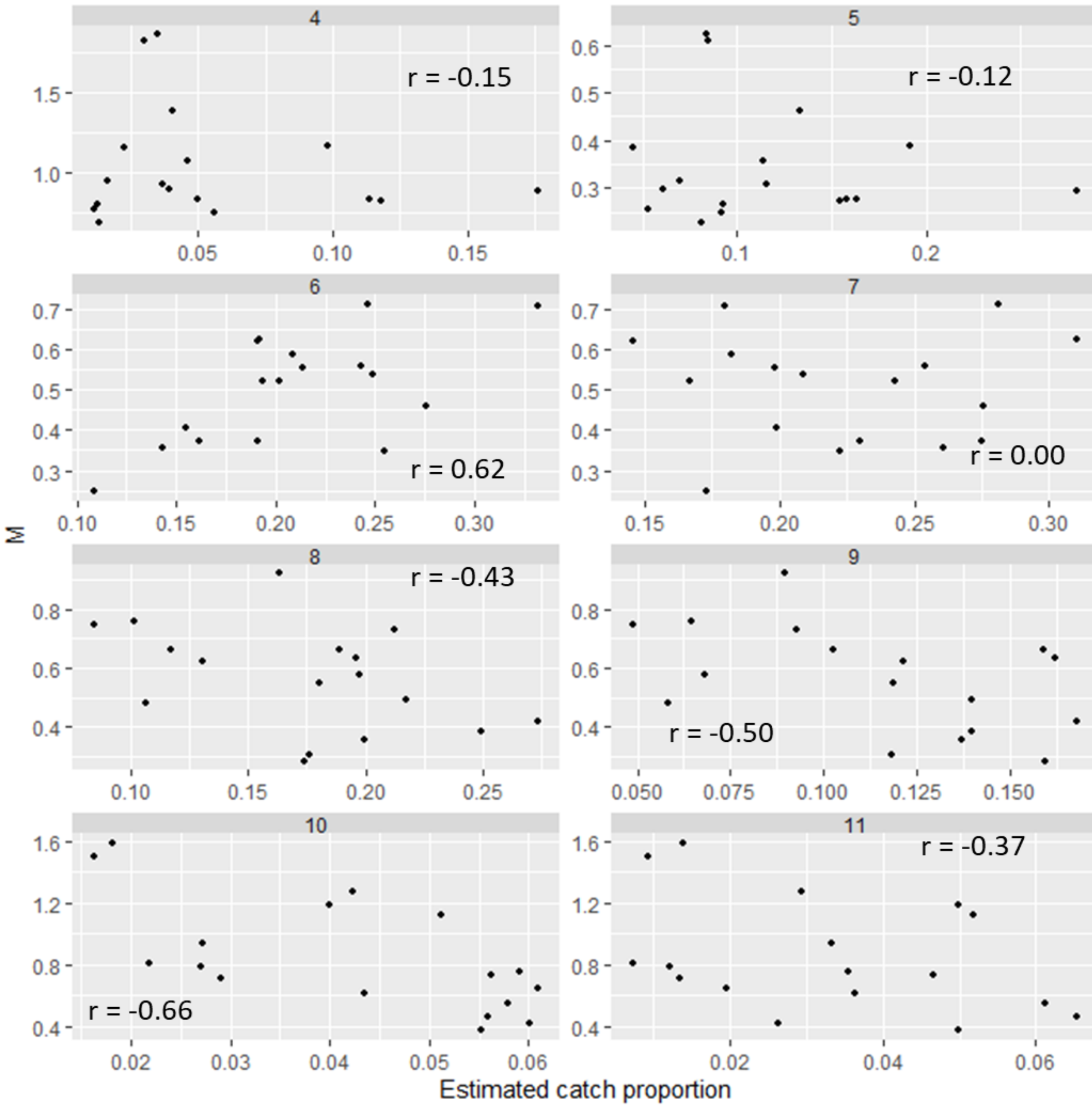


Figure 58. Estimated catch proportions of fishery catches versus natural mortality (M) by age (panels). The values within each panel are the age-specific correlation between these two series for 2004-2020.

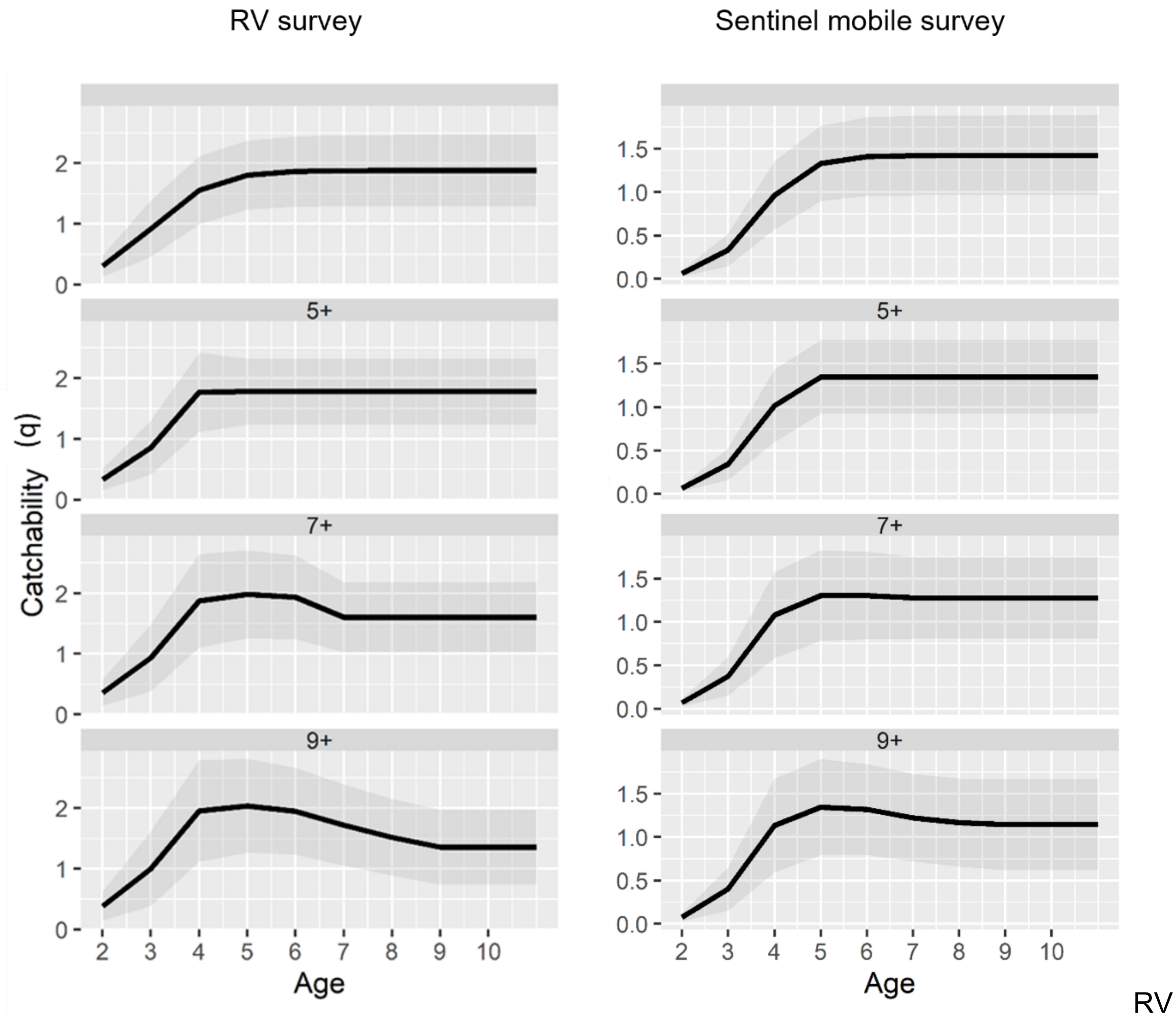


Figure 59. Estimated age specific survey catchabilities for the RV survey (left column) and Sentinel mobile survey (right column) for the baseline model (top row), and for three variants assuming constant catchability for ages 5+, 7+ and 9+ respectively (bottom three rows).

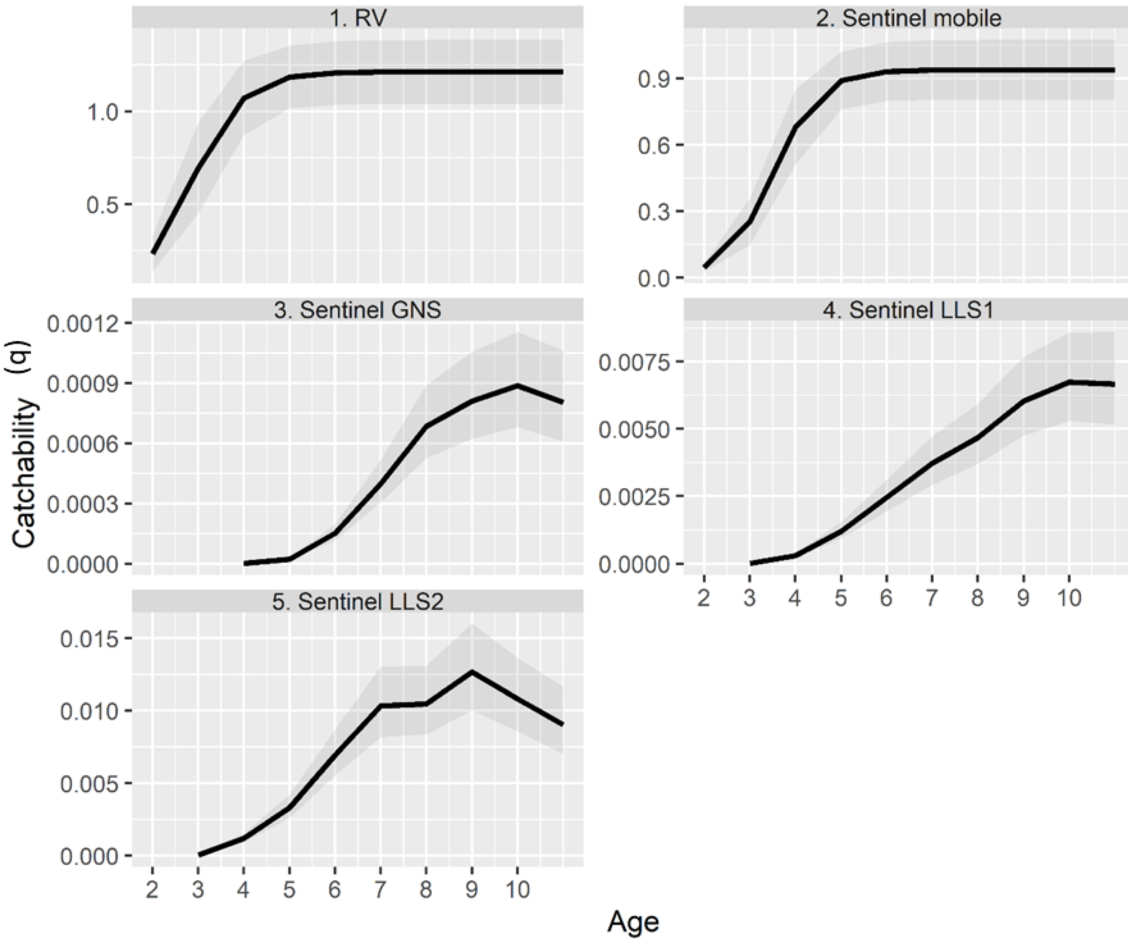


Figure 60. Estimates of age-specific catchability to the five main surveys, with 95% confidence intervals (black line and shaded region) in the sensitivity run for the standard deviation of the prior on the RV survey fully selected catchability.

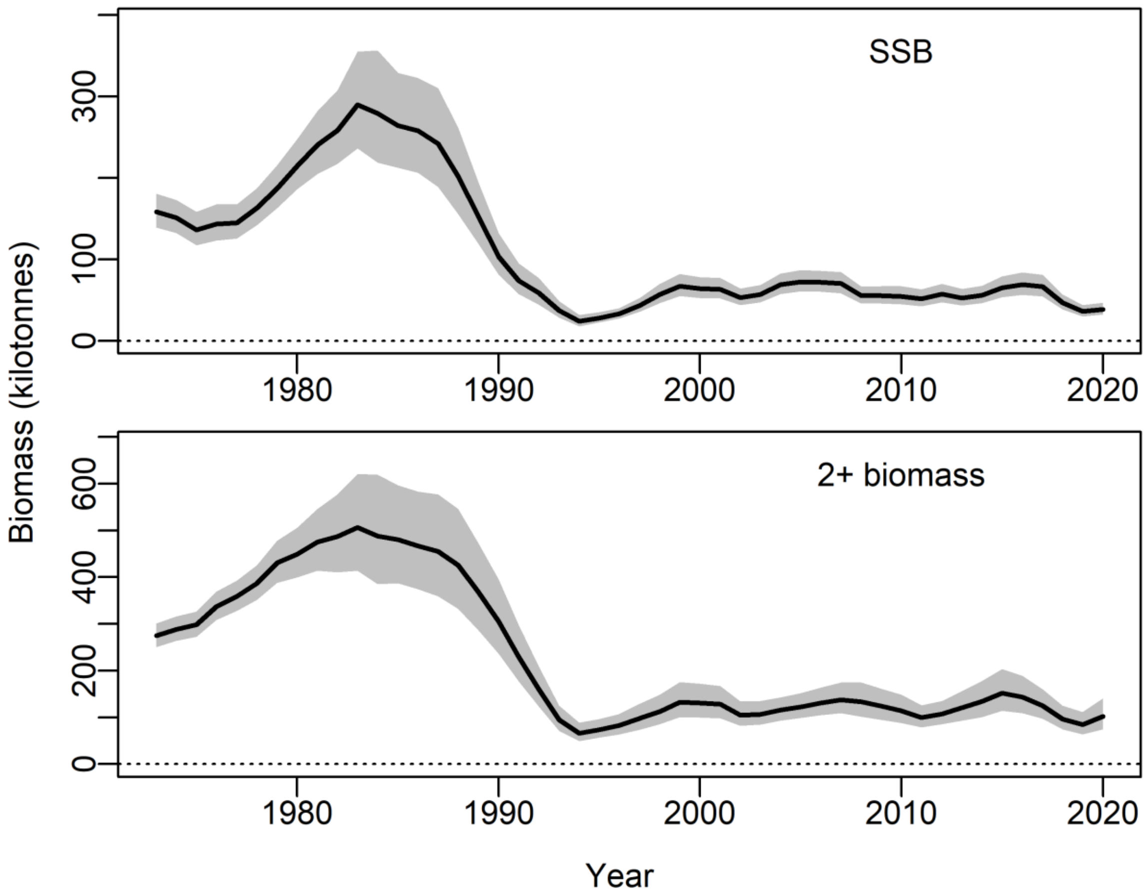


Figure 61. Estimates of spawning stock biomass (SSB) and age 2+ biomass, with 95% confidence interval (shaded region) in the sensitivity run for the standard deviation of the prior on the RV survey fully selected catchability.

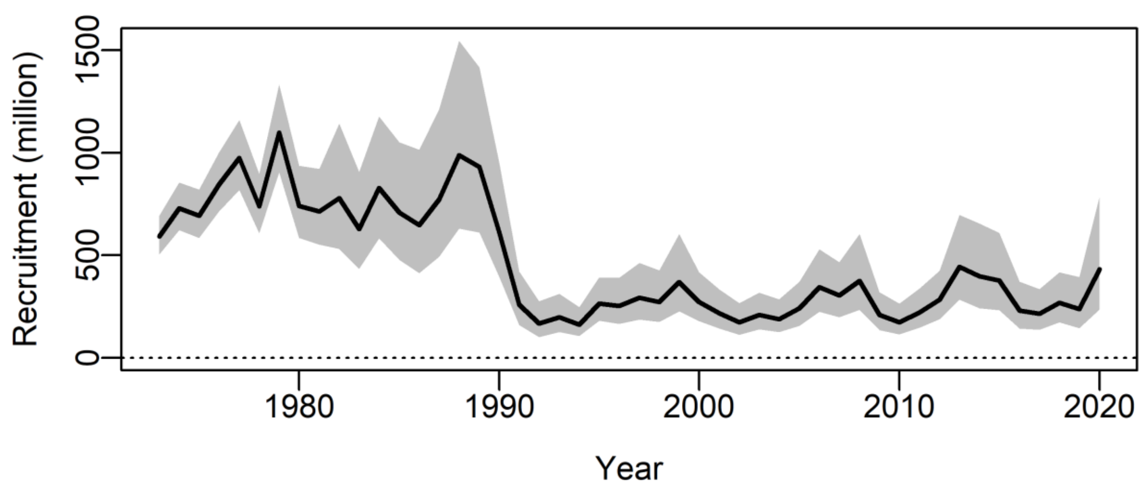


Figure 62. Estimates of recruitment (numbers at age 2), with 95% confidence interval (shaded region), in the sensitivity run for the standard deviation of the prior on the RV survey fully selected catchability.

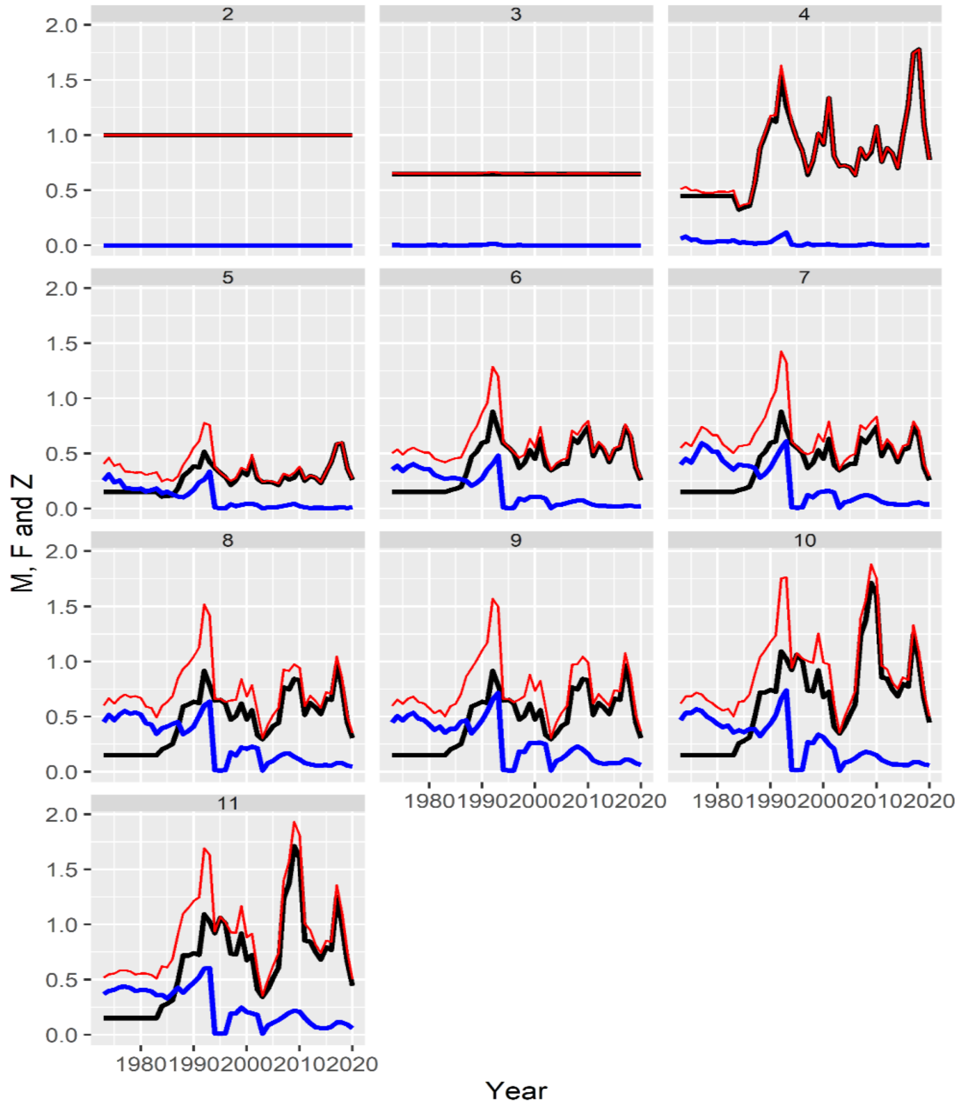


Figure 63. Estimates of age-specific fishing mortality (F, blue lines), natural mortality (M, black lines) and total mortality (Z= M+F; red lines) in the sensitivity run for the standard deviation of the prior on the RV survey fully selected catchability.

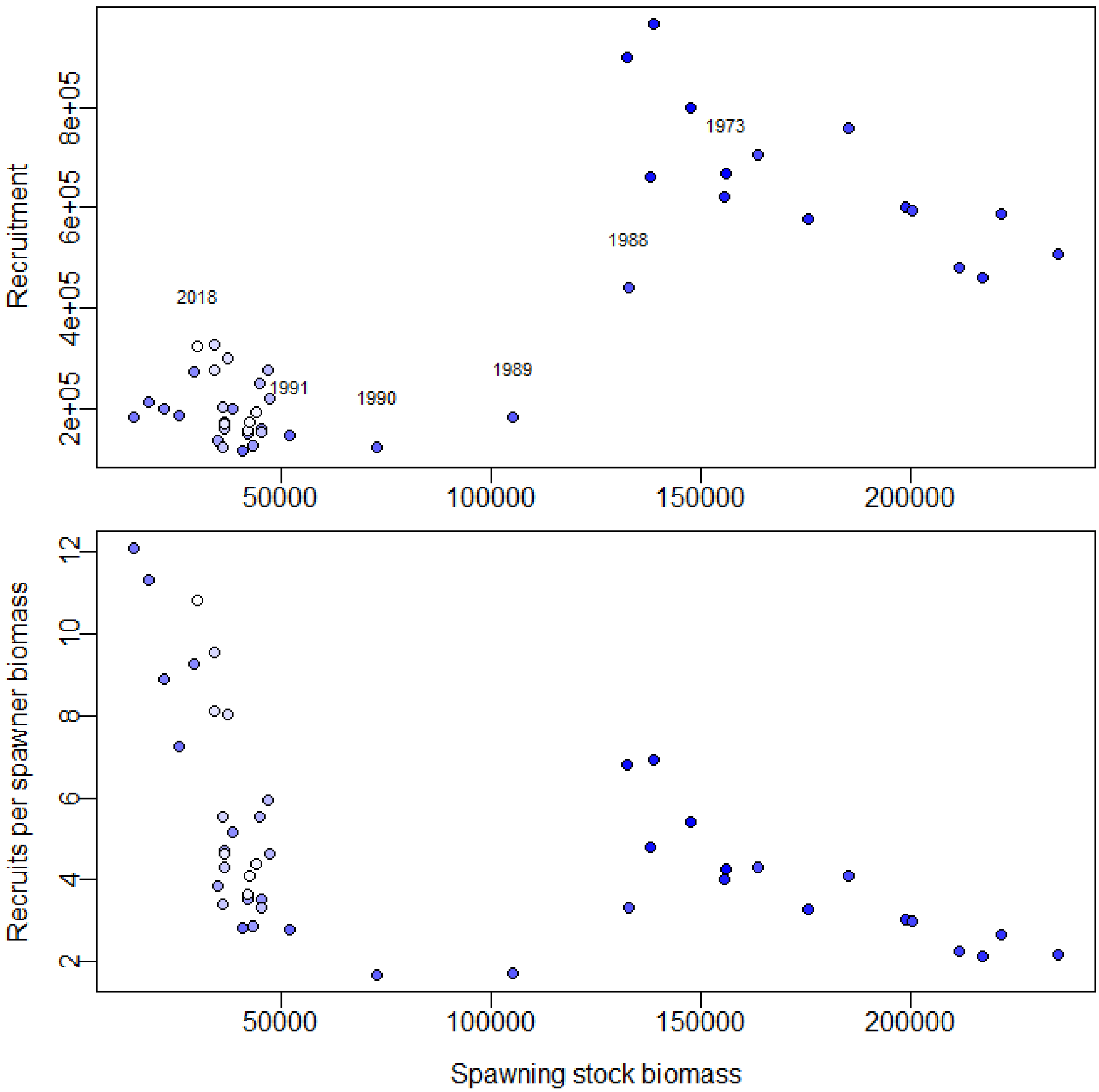


Figure 64. Top panel: Stock-recruitment relationship estimated in the baseline model, with older years plotted in dark blue, turning to white for the most recent years. First, last and certain transitory years are labelled, recalling that the 2020 of recruitment at age 2 is for the 2018 cohort. Bottom-panel: Plot of recruit numbers per spawner biomass for estimates from the baseline model, using the same colour coding as the top panel.

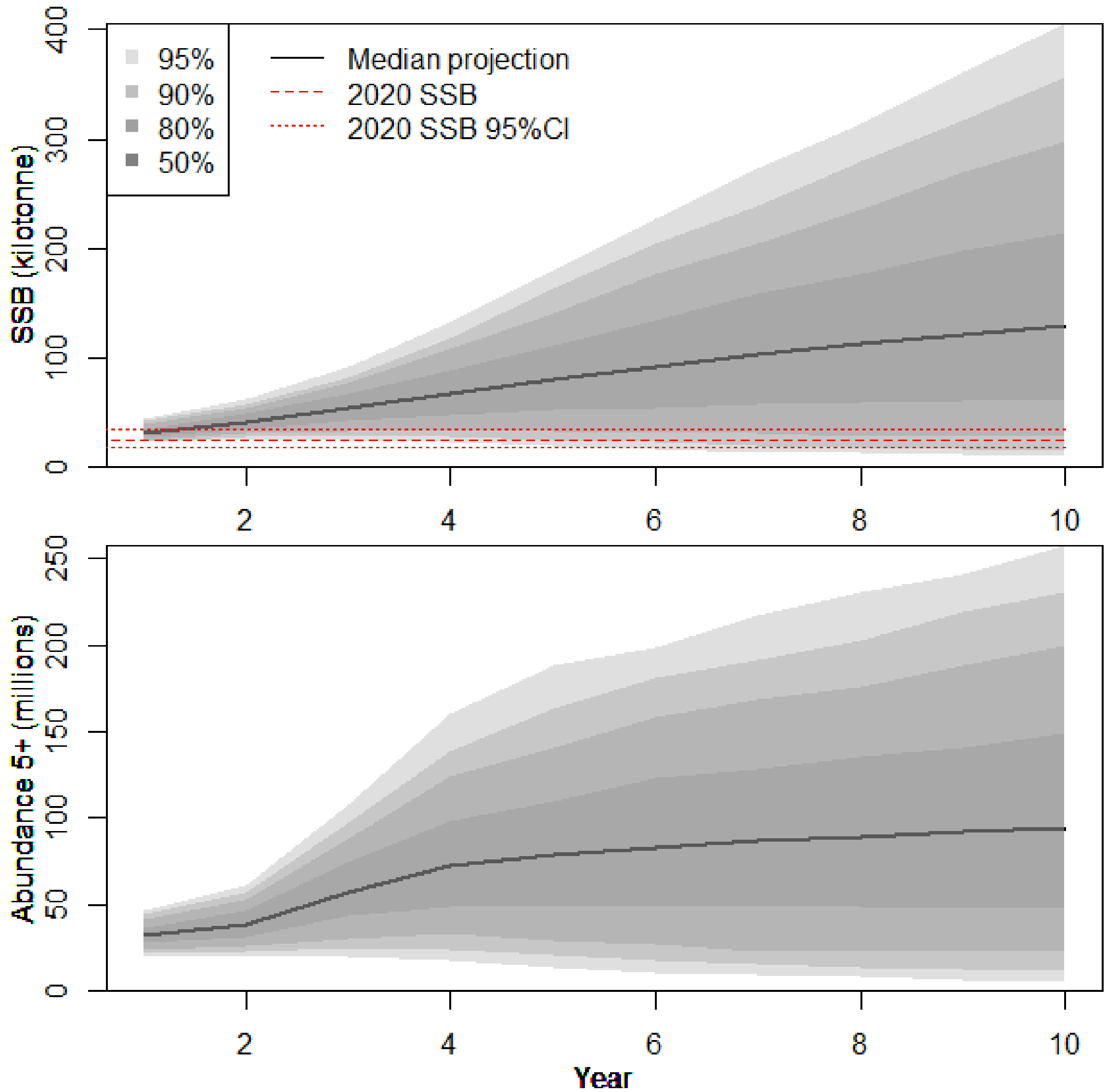


Figure 65. Results of projections from the baseline model assuming a status quo total catch of 2000 t annually for SSB (top) and age 5+ abundance (bottom). The shaded areas are the core probability envelope for the inner 50% of iterations (darkest) to the inner 95% (lightest). The median projection value is plotted with a black line, and the level of the 2020 estimated SSB and 95%CI is plotted in red in the top panel. Projection year 1 is 2021.

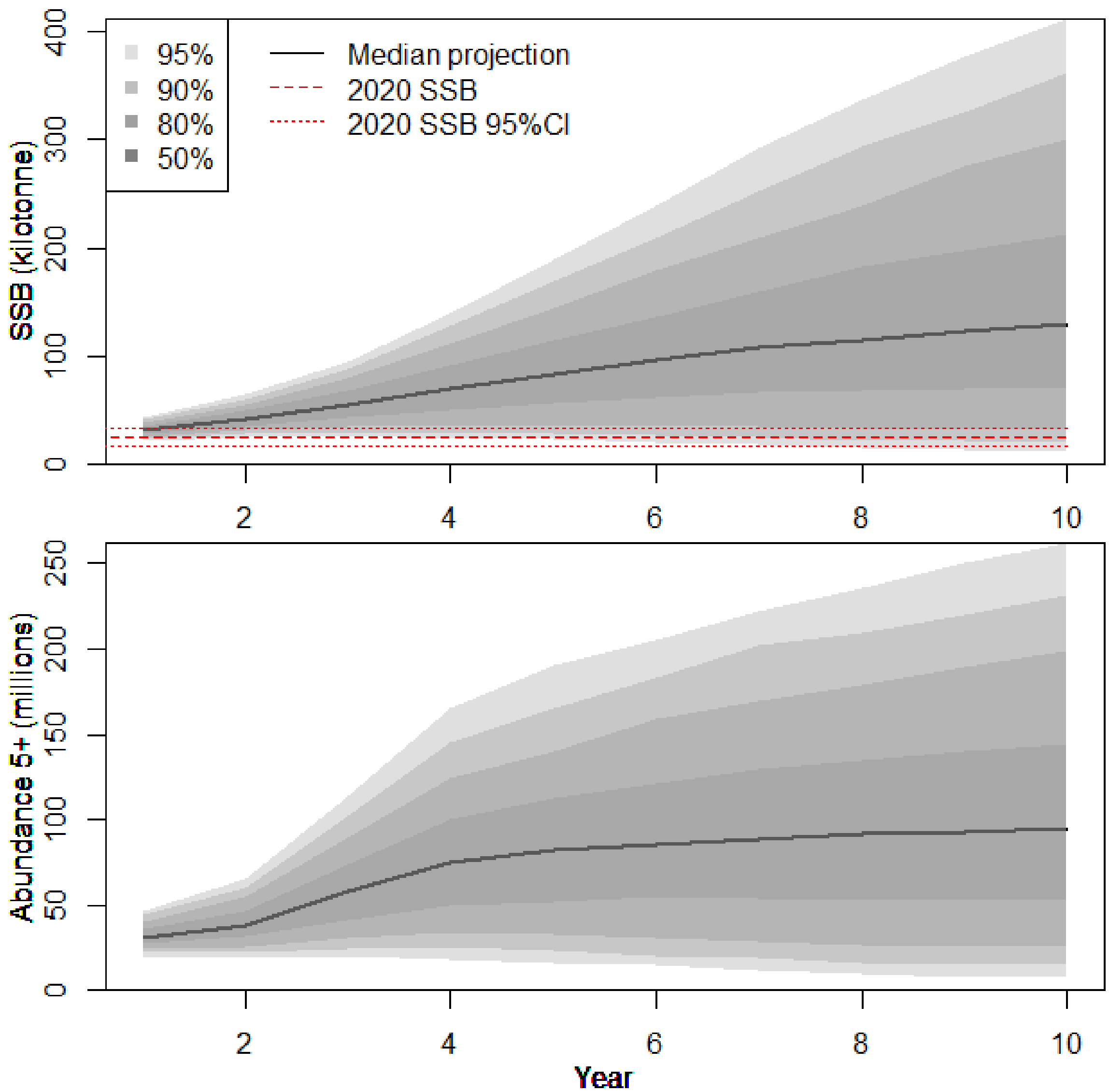


Figure 66. Results of projections from the baseline model assuming a catch of 100 t annually for SSB (top) and age 5+ abundance (bottom). The shaded areas are the core probability envelope for the inner 50% of iterations (darkest) to the inner 95% (lightest). The median projection value is plotted with a black line, and the level of the 2020 estimated SSB and 95%CI is plotted in red in the top panel. Projection year 1 is 2021.

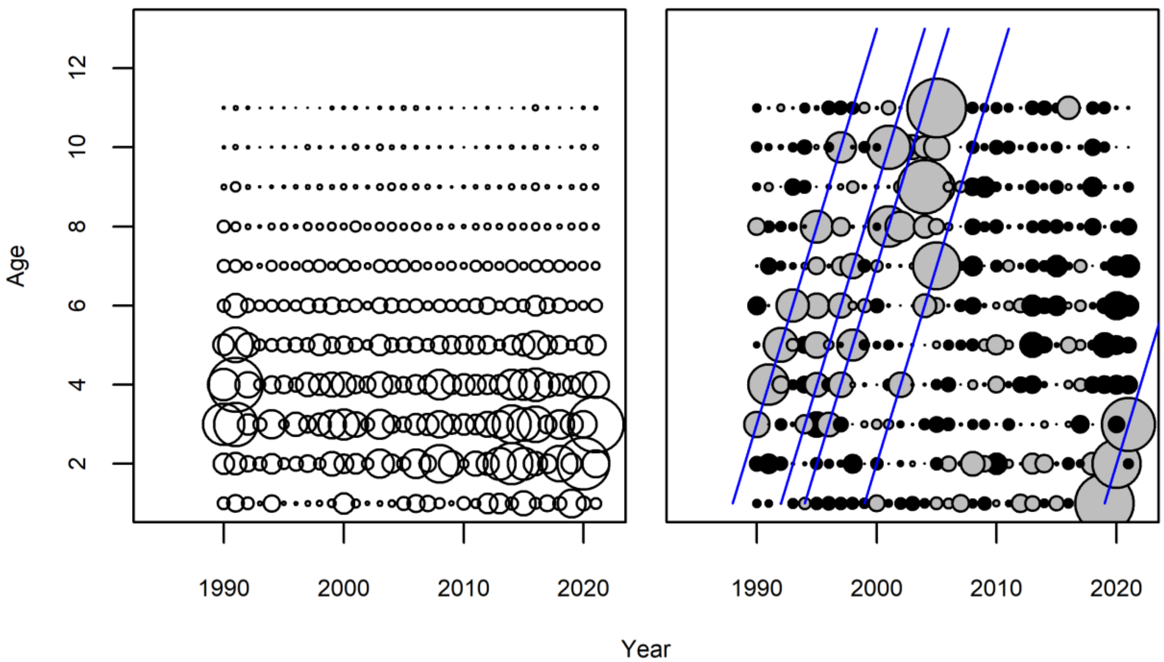


Figure 67. Catch-at-age in the DFO RV survey for beginning in 1990. The shortened series (i.e., excluding 1984-1989) was chosen for plotting to avoid having to make the model-estimated corrections for the catchability of age 2 and 3 cod for the change in vessel and gear that occurred in 1990. The left panels show catch proportional to circle size, while the right panel shows standardized proportions at age and year (SPAY) with grey circles indicating above average catch and black below average. The blue lines indicate some consistently tracked above average cohorts in the survey. See Benoît et al. (2022) for further details.

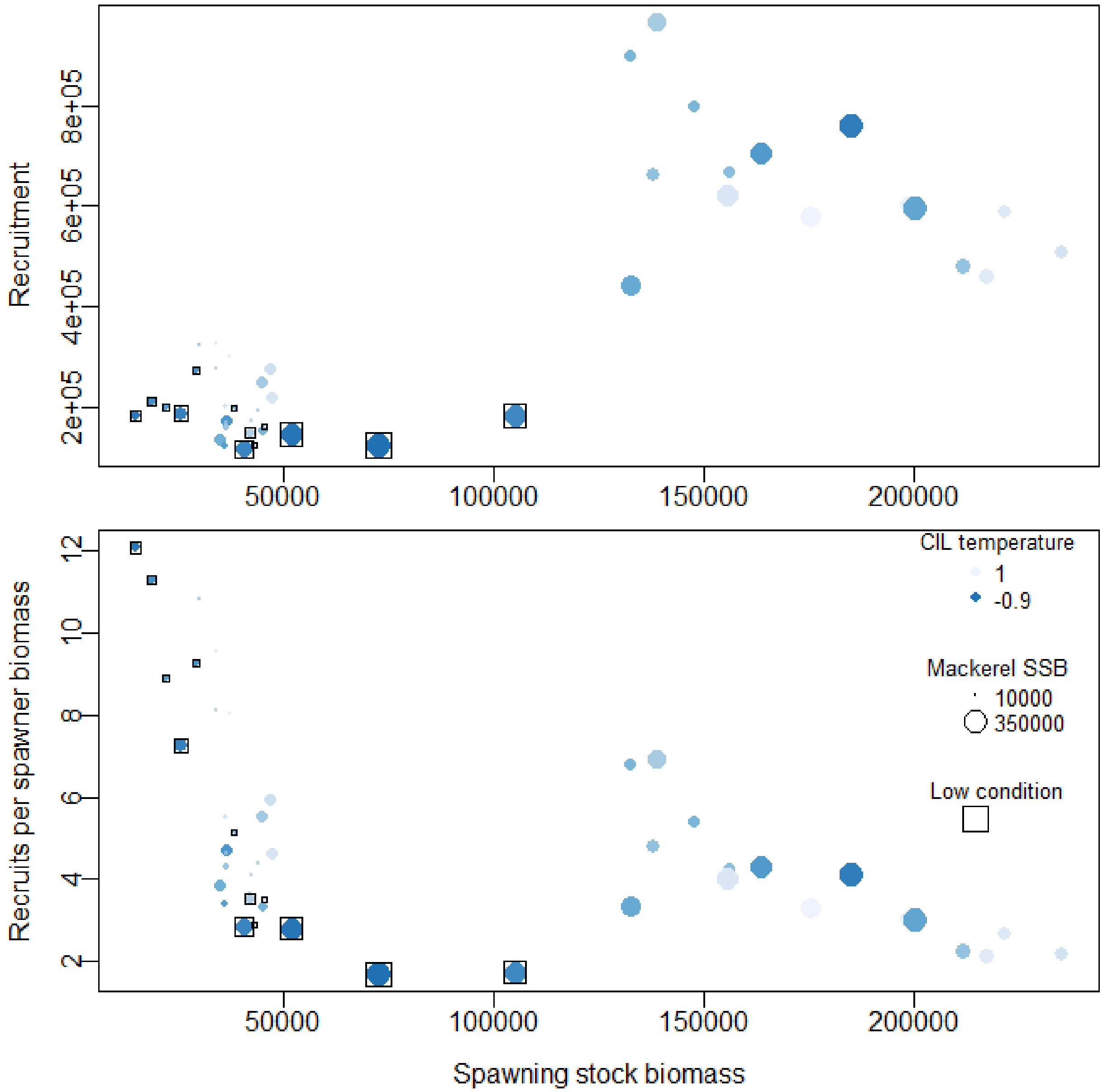


Figure 68. Top panel: Stock-recruitment relationship estimated in the baseline model with symbols defining the conditions in the year the stock originated: blue shading indicates the mean core temperature in the cold intermediate layer (CIL; from Galbraith et al 2021), symbol size corresponds to the SSB for mackerel (from DFO 2021b) and boxes indicate years associated with low physiological condition in adults (from Lambert 2011). Bottom-panel: Plot of recruit numbers per spawner biomass for estimates from the baseline model, using the same symbol coding as the top panel.

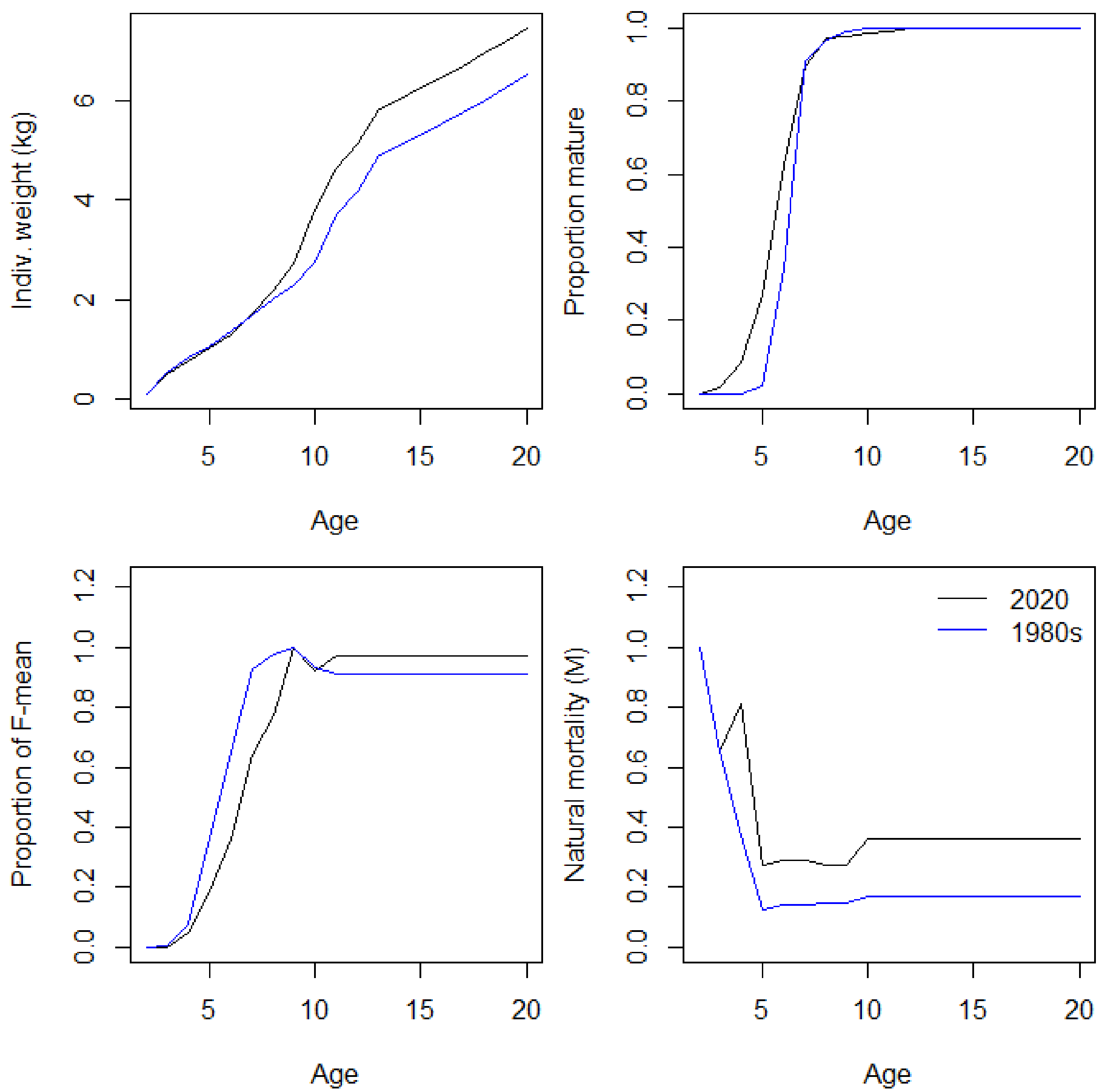


Figure 69. Age specific functions used as inputs to the YPR and SPR calculations for 2020 and for the 1980-1985 period. Values were projected to age 20 for the calculation based on the values at age 11+ in the model. Note that the individual weights presented are the population beginning of year weights (stock weights); fishery weights (catch weights) show similar patterns and are not shown.

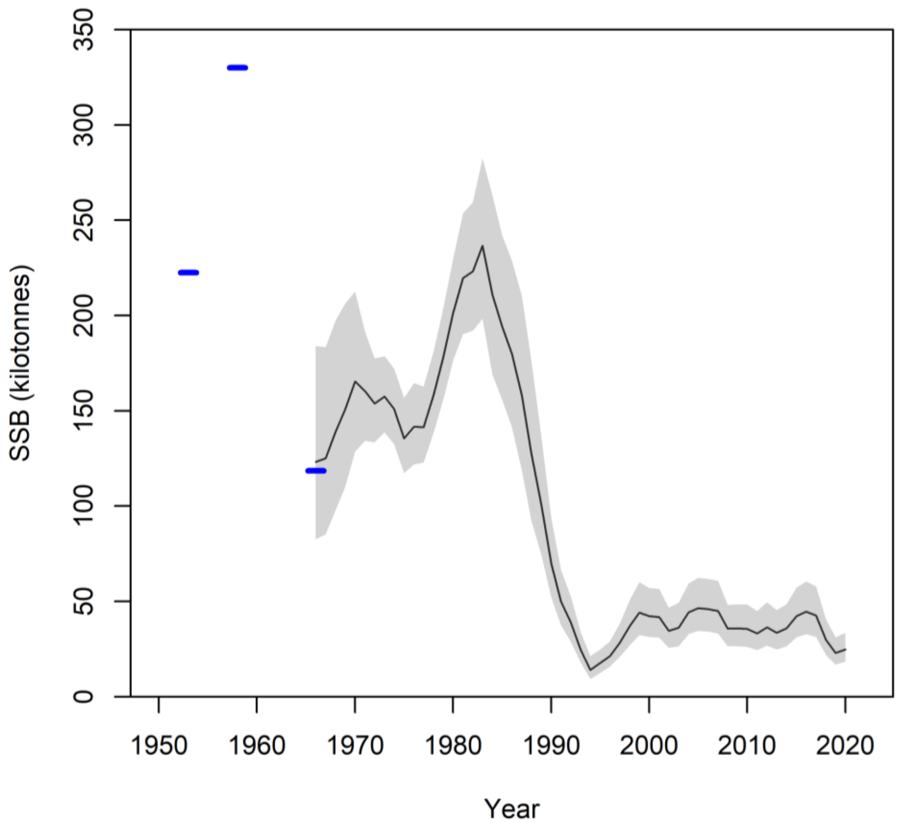


Figure 70. Estimates of spawning stock biomass from the extended model with 95% confidence intervals (solid line and grey shaded area respectively). The blue bars indicate the point estimates calculated for 1953 and 1958, and recalculated for 1966, using the stock weight and maturity information from Wiles and May (1968).

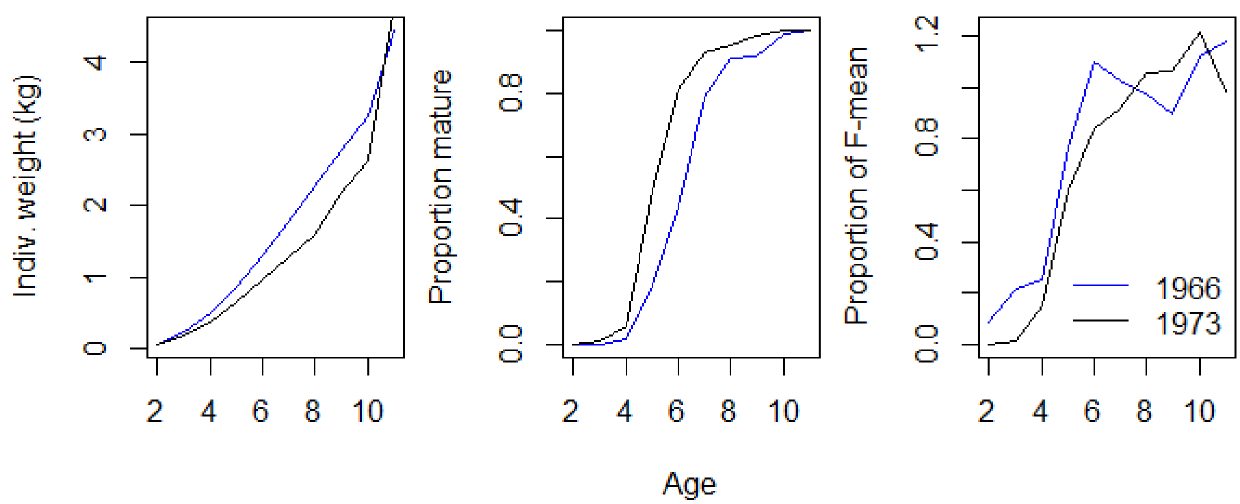


Figure 71. Individual weights, maturity ogive and relative fishery selectivity for 1966 and 1973 used in the extended model. Note that the individual weights presented are the population beginning of year weights (stock weights).

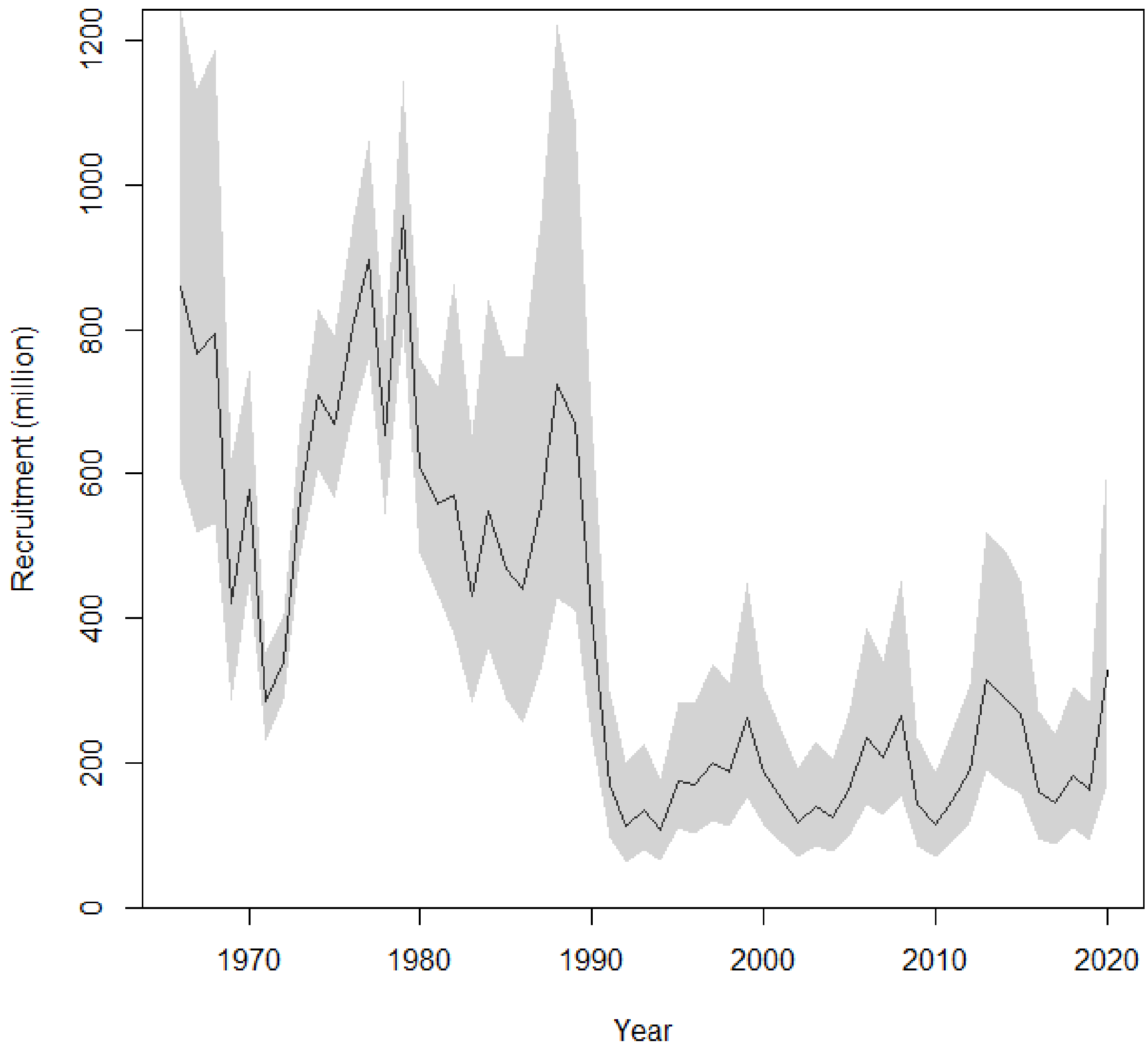


Figure 72. Estimates of recruitment (numbers at age 2) from the extended model with 95% confidence intervals (solid and dashed lines respectively).

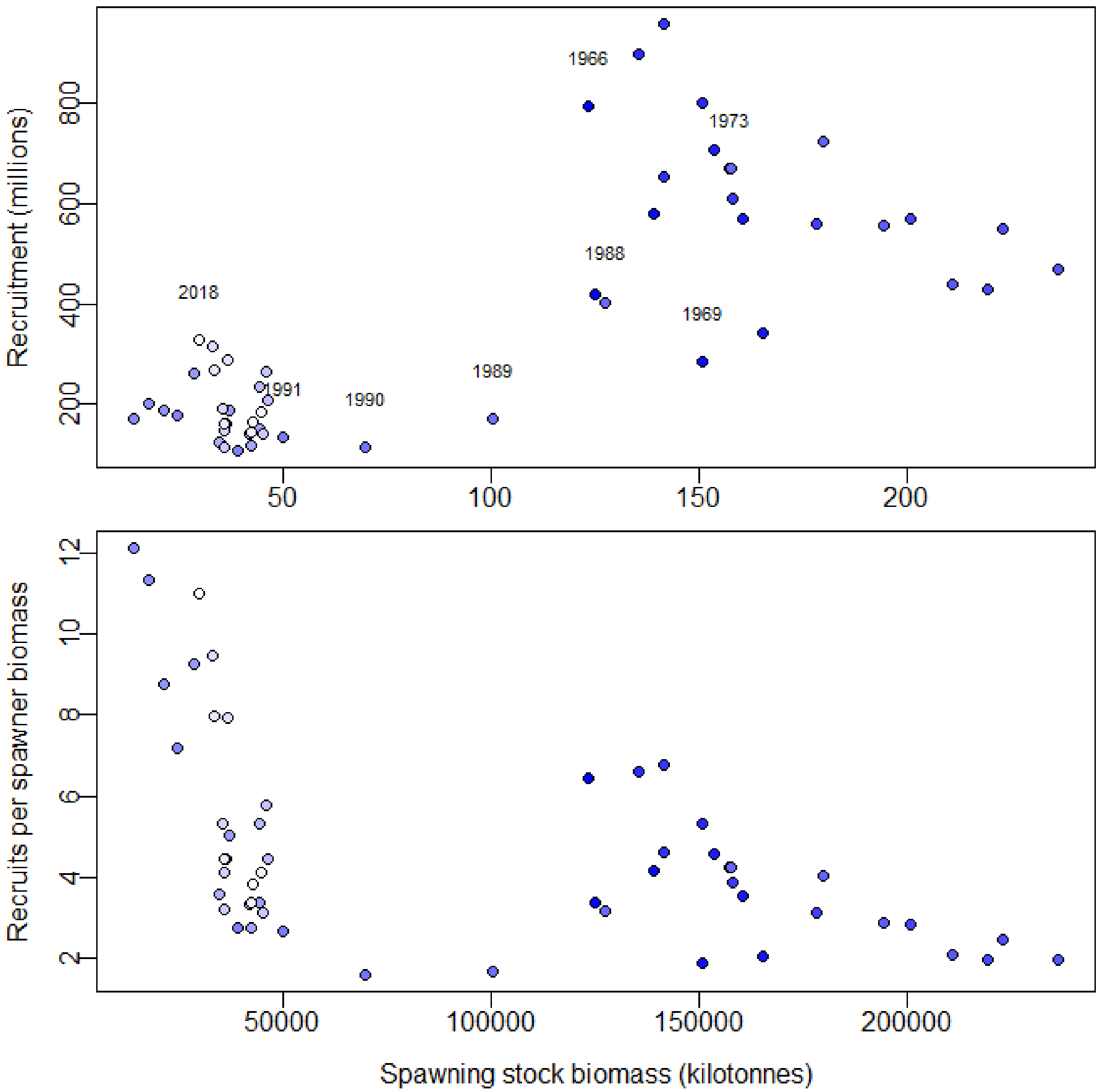


Figure 73. Stock and recruit plots from the extended model. Top panel: Stock-recruitment relationship, with older years plotted in dark blue, turning to white for the most recent years. Bottom-panel: Plot of recruit numbers per spawner biomass, using the same colour coding as the top panel.

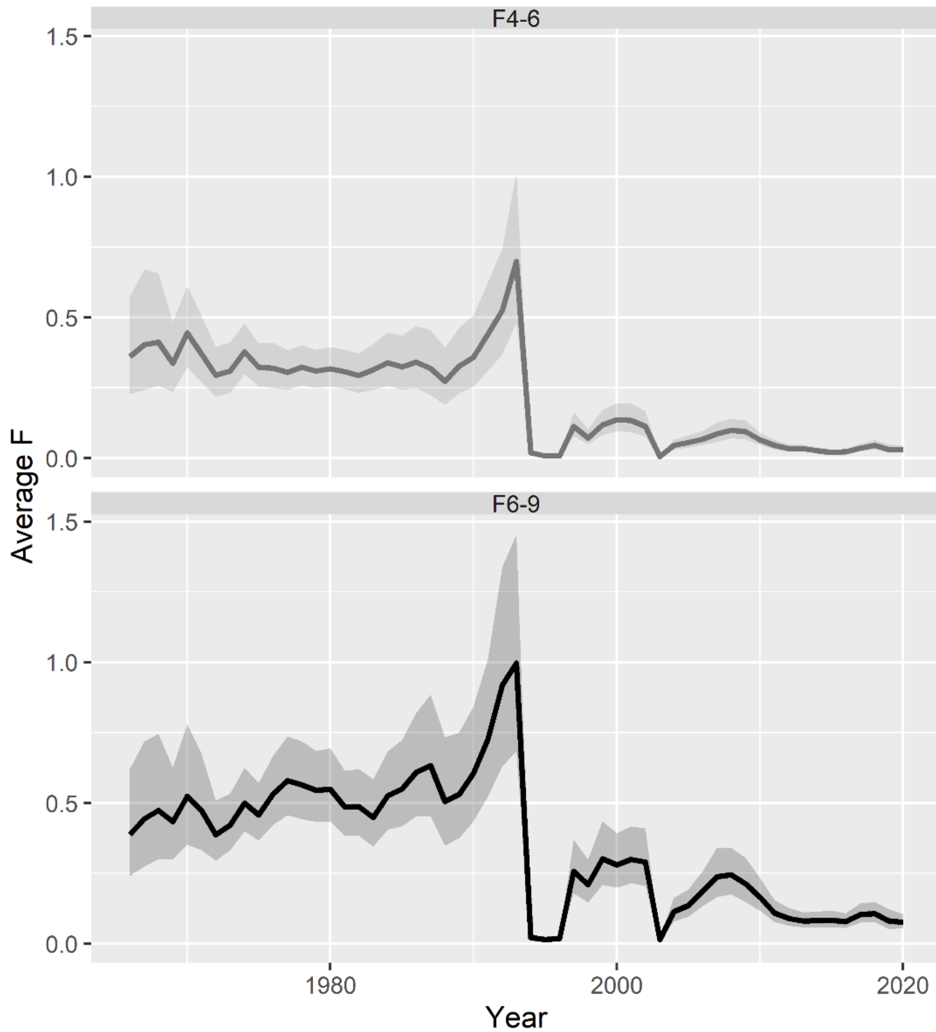


Figure 74. Estimates of average fishing mortality F at ages 4-6 and 6-9 (panels), with 95% confidence interval (shaded region) from the extended model.

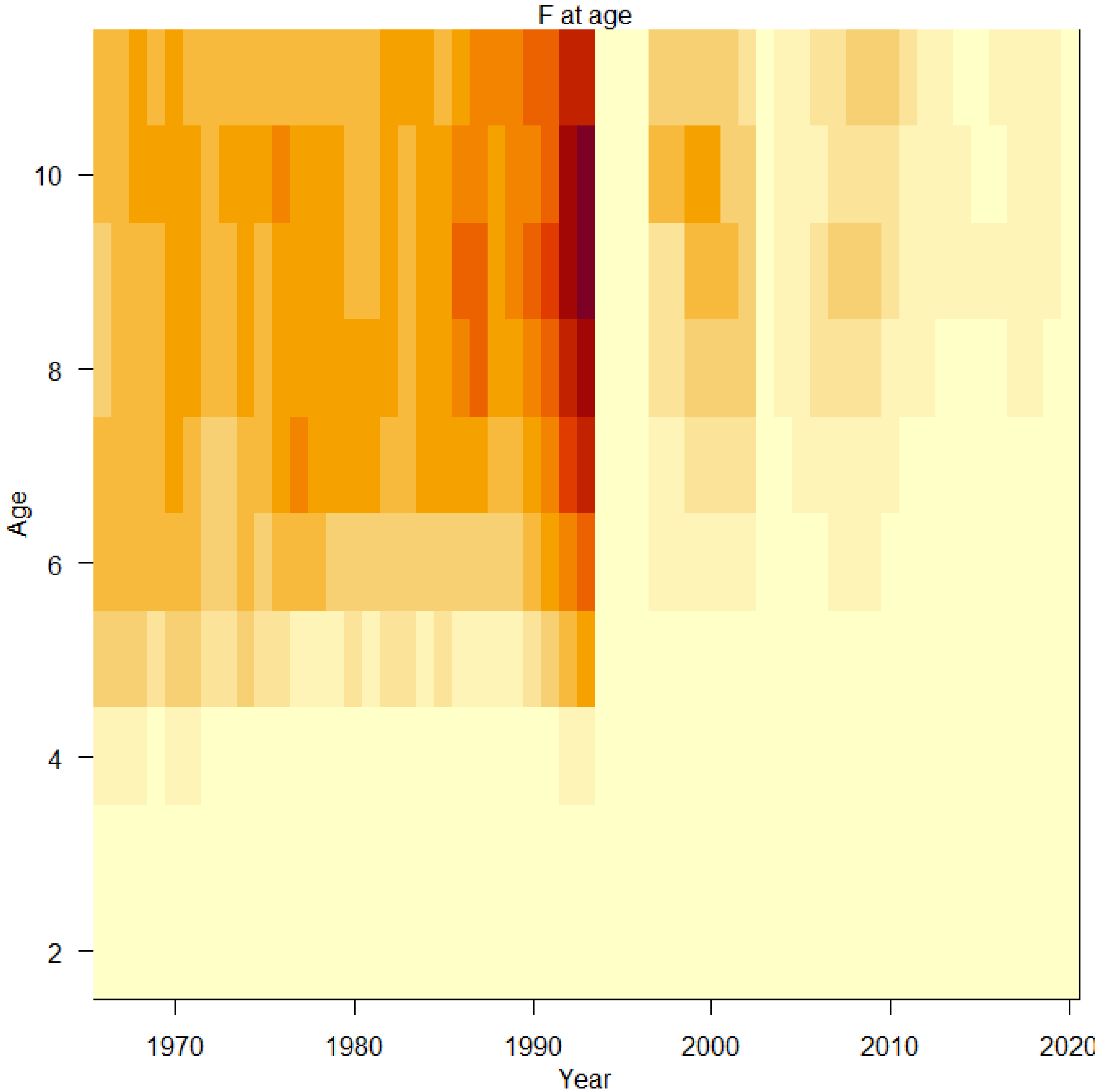


Figure 75. Illustration of the extended model estimates of fishing mortality at age, where darker colours indicate higher values.

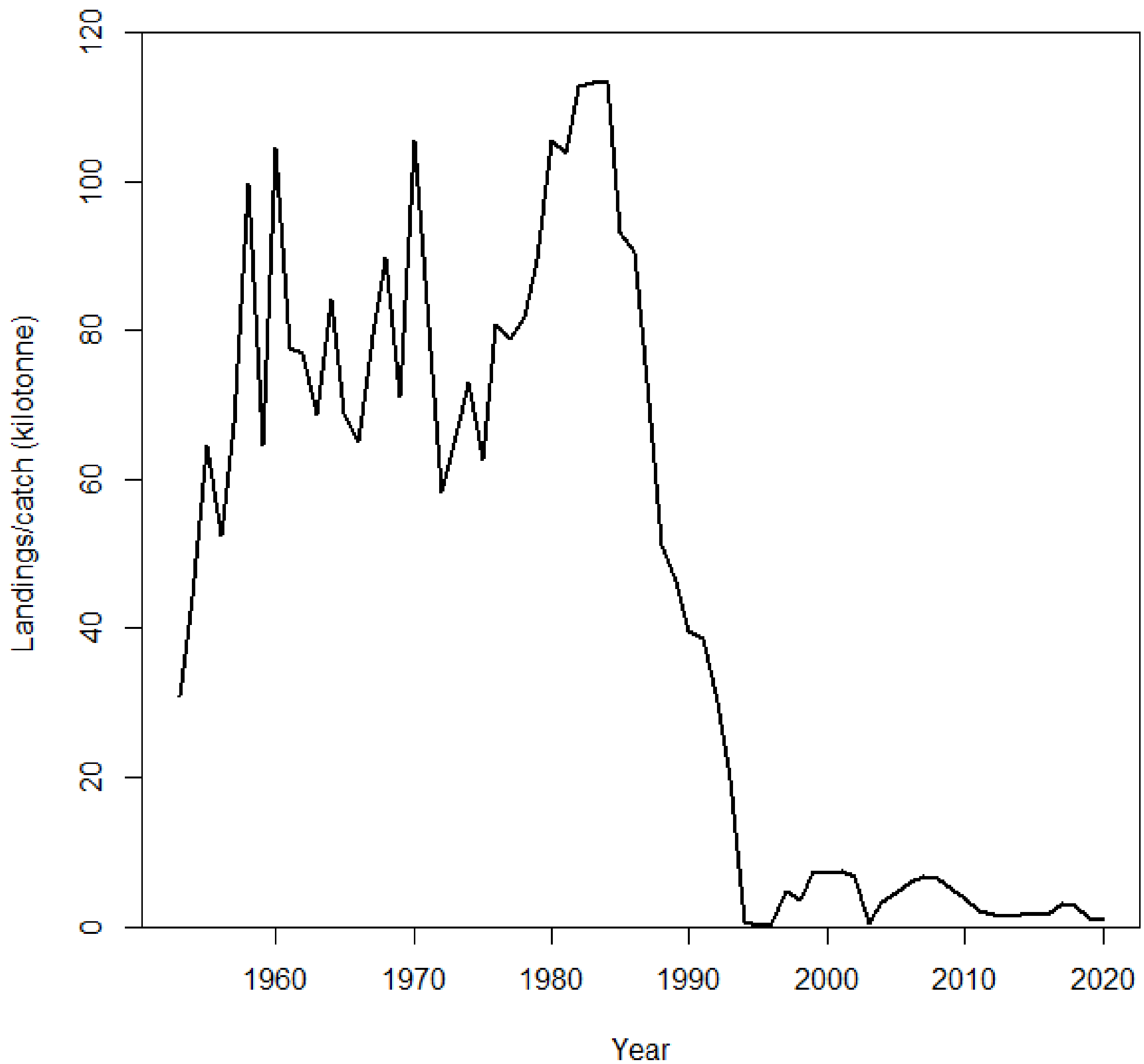


Figure 76. Time series of nGSL cod landings used in the extended model.

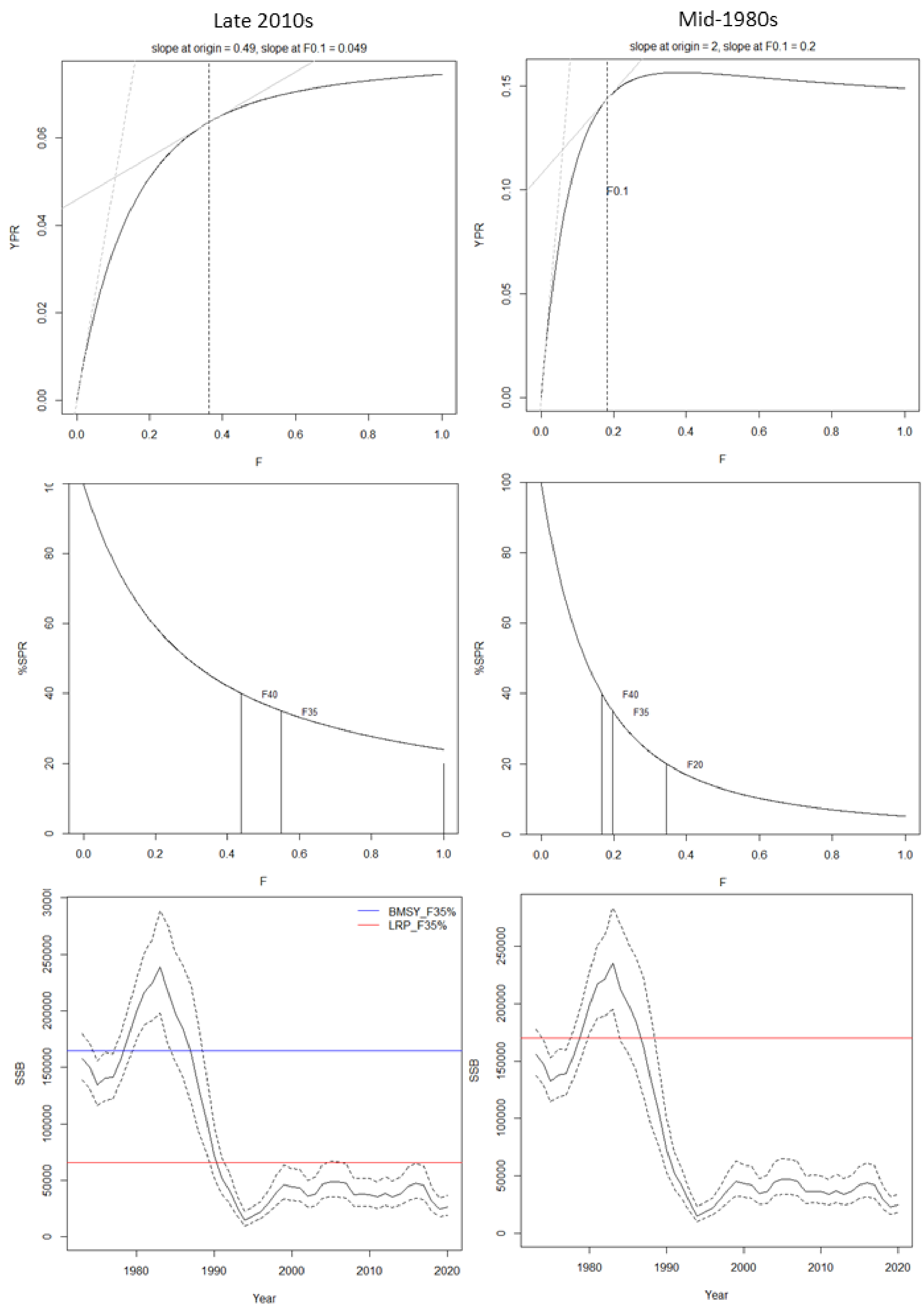


Figure 77. Results for proxy reference point calculations employing age-dependent functions for 2020, relevant to the late 2010 period (left column), and the 1980-1985 period (right column). Top row: Yield per recruit functions with function slopes and F0.1 indicated in the plots. Middle row: Spawner per recruit functions with $F_{SPR20\%}$, $F_{SPR35\%}$, and $F_{SPR40\%}$ indicated. Bottom row: Estimates of SSB and 95% confidence interval from the baseline model along with SPR based reference points (note that BMSY_F35% is beyond the y-axis range and therefore not plotted for the early to mid-1980s estimates).

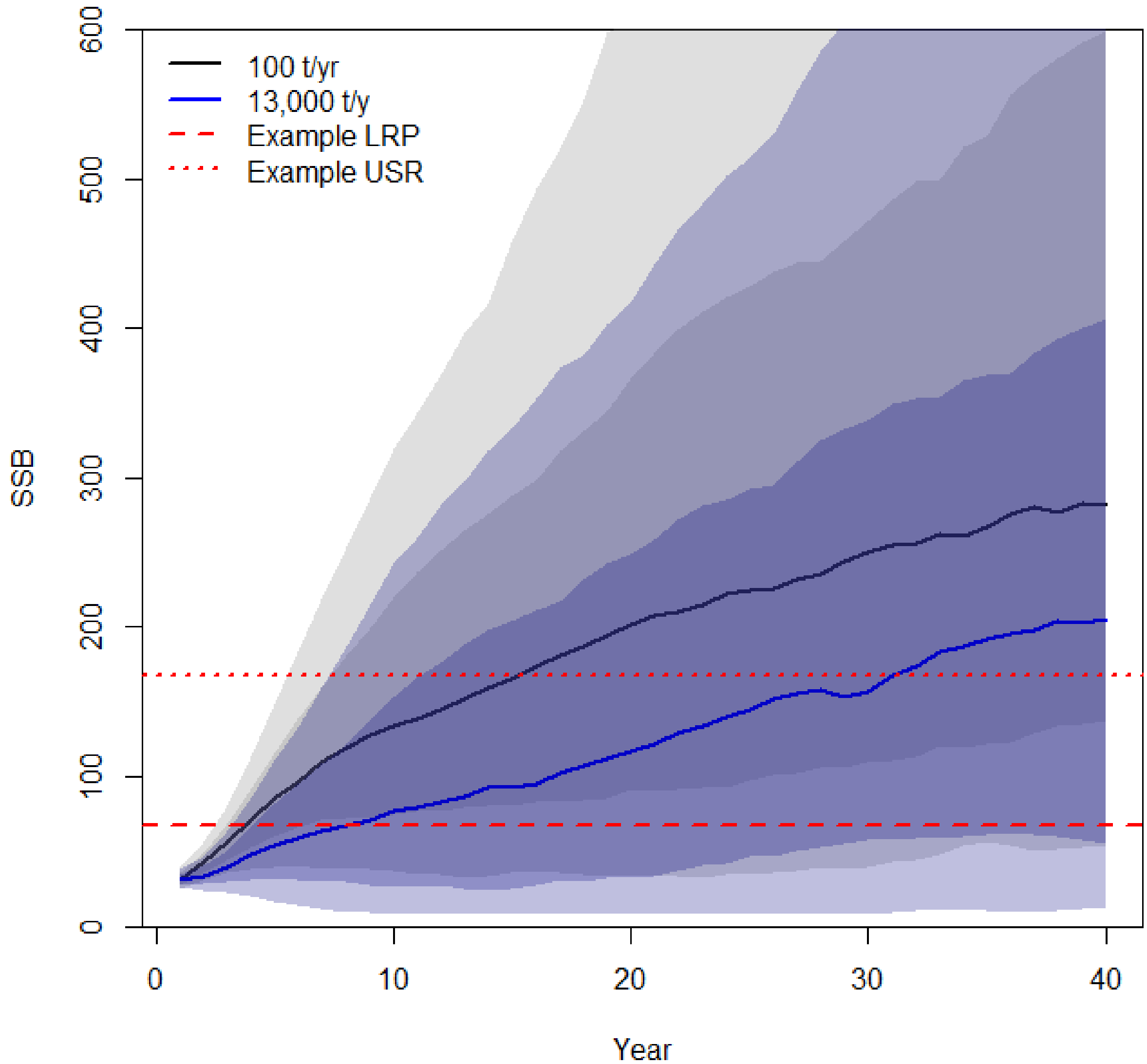


Figure 78. Forty-year projections for the nGSL cod stock under two fishing scenarios,100 t per year and 13,000 t per year, and with respect to example values for an LRP and for a USR, which is assumed as a rebuilding target. The darkest shaded area for each projection defines the interquartile range of probabilities, while the lighter shaded area defines probabilities ranging from 10-90%. Projection year 1 is 2021.

APPENDIX A – BASELINE MODEL SIMULATION RESULTS

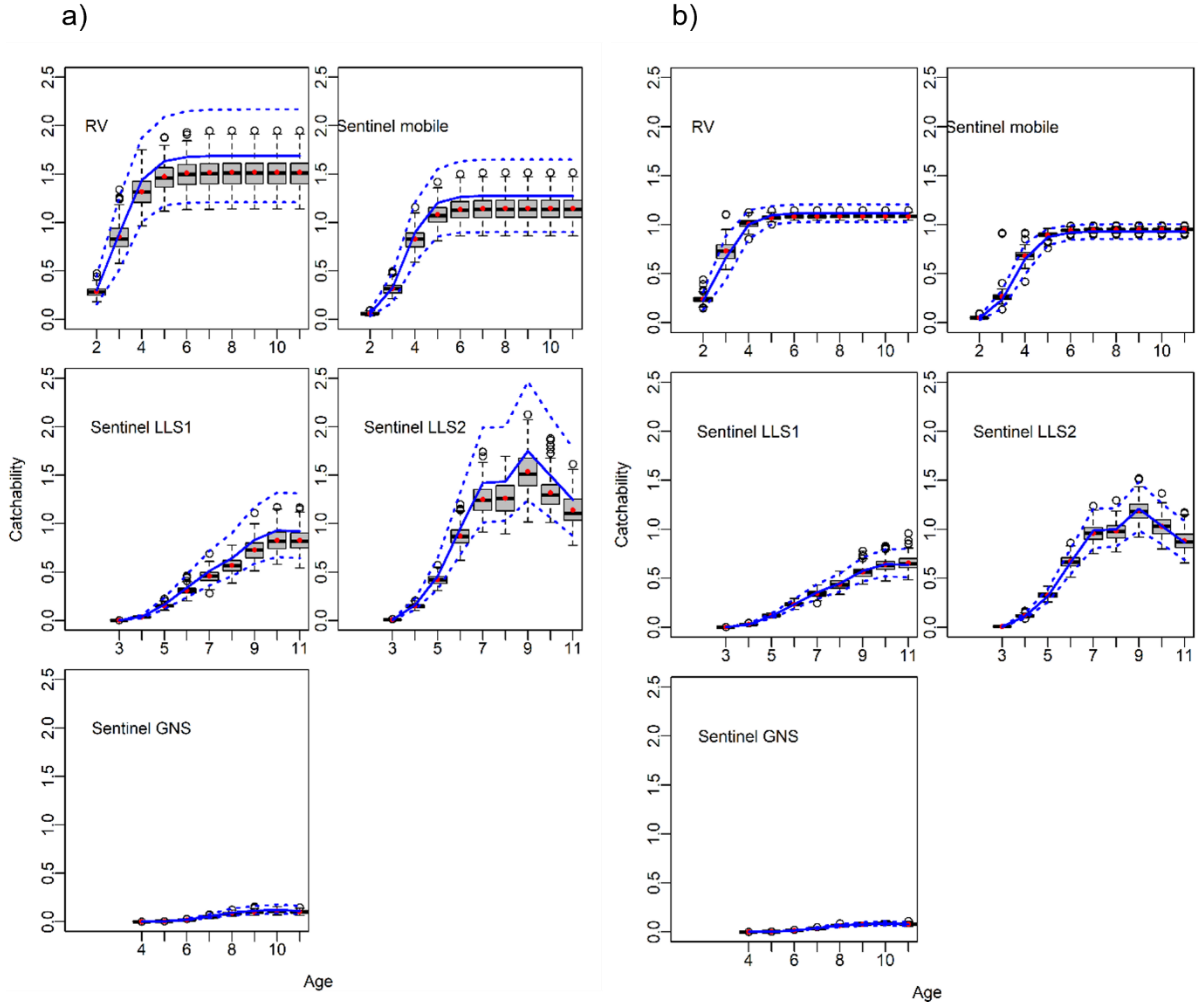


Figure A1.1. Results of self-simulations for survey catchability functions for a) the baseline model and b) the baseline model assuming a highly informative prior on DFO RV survey fully recruited catchability. The blue solid and dashed lines are the original model estimates and 95% confidence intervals, respectively. The boxplot summarize the estimates generated by 100 simulation iterations and the red dots indicate the mean of those iterations.

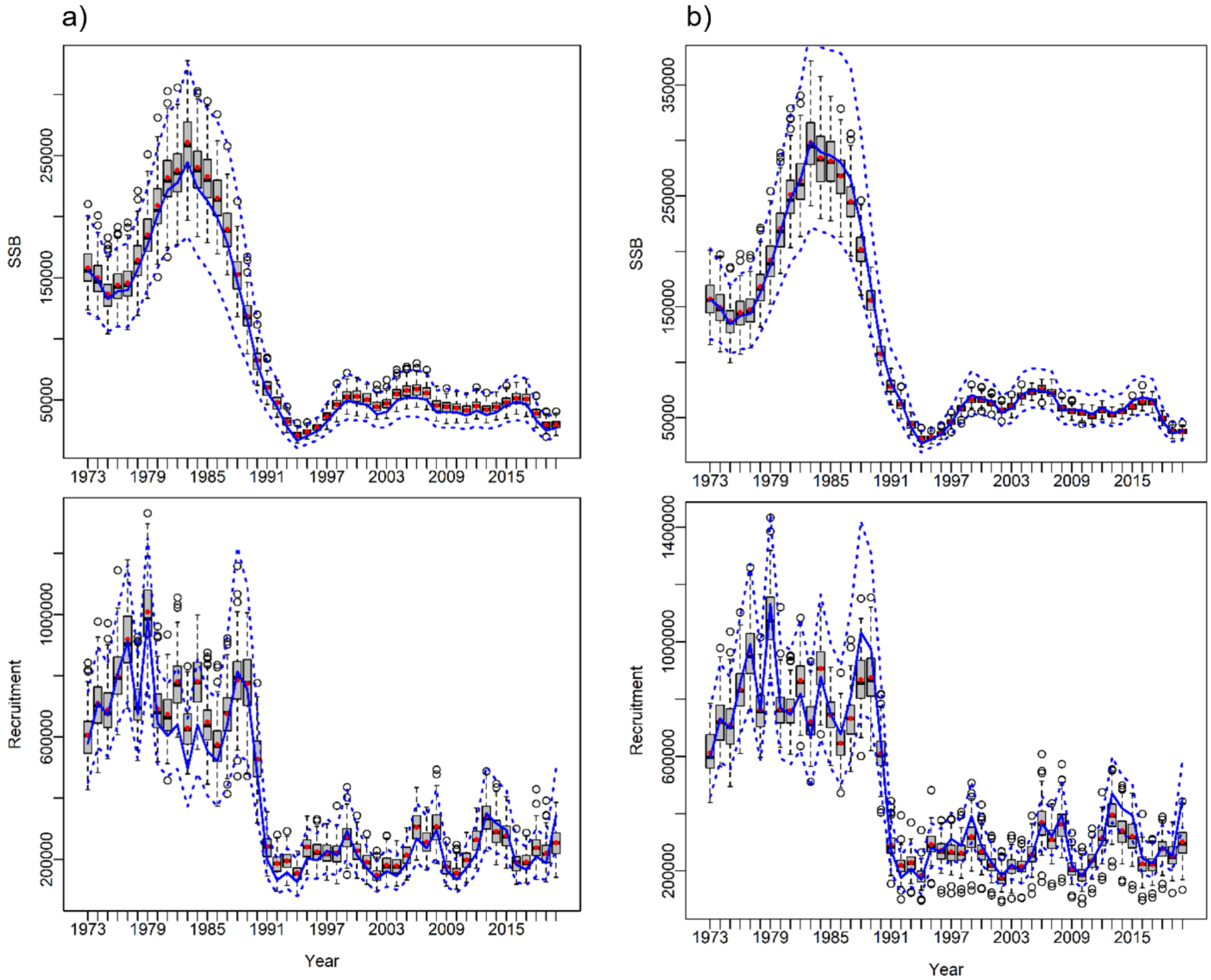


Figure A1.2. Results of self-simulations for spawning stock biomass (tonnes, top) and recruitment (millions, bottom) for a) the baseline model and b) the baseline model assuming a highly informative prior on DFO (RV) bottom-trawl survey fully recruited catchability. The blue solid and dashed lines are the original model estimates and 95% confidence intervals, respectively. The boxplot summarize the estimates generated by 100 simulation iterations and the red dots indicate the mean of those iterations.

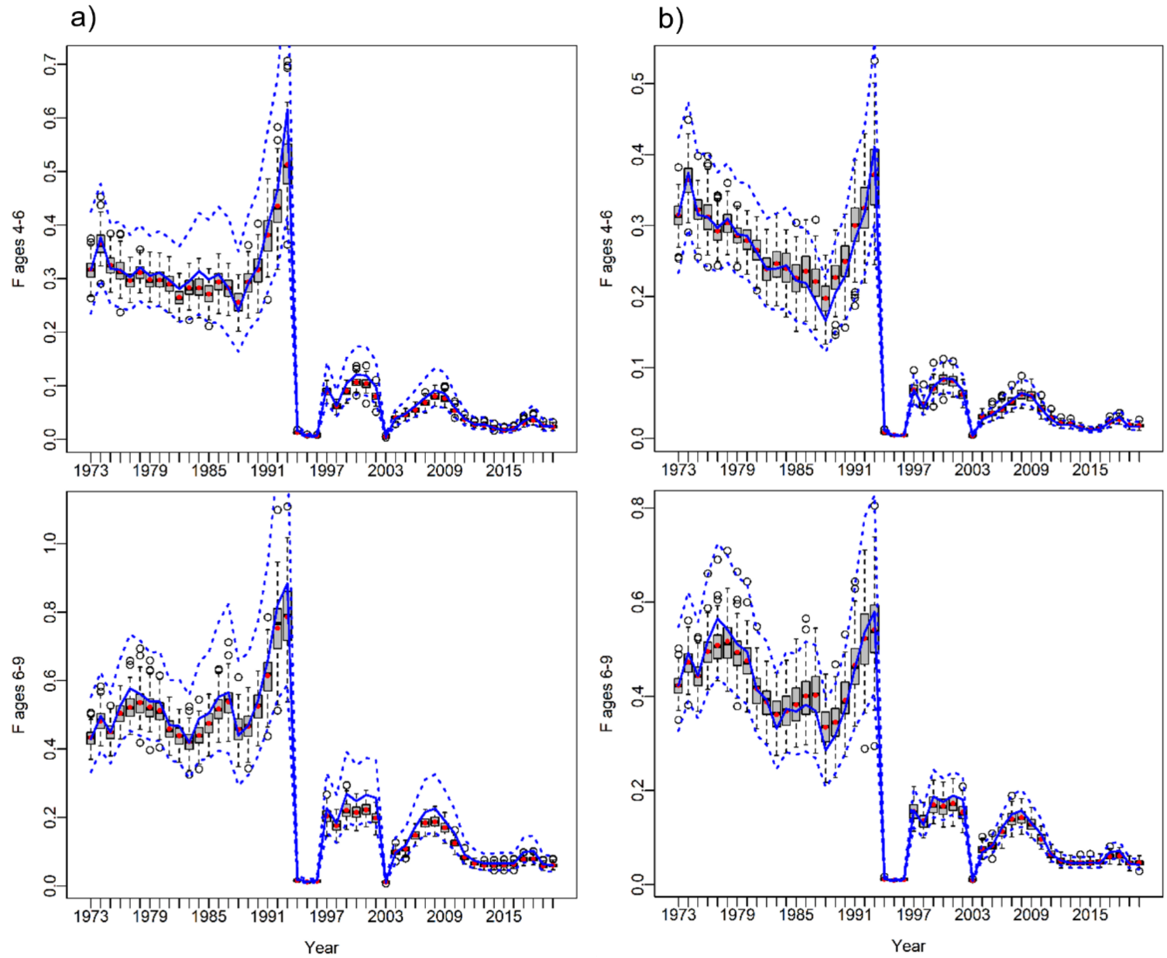


Figure A1.3. Results of self-simulations for average fishing mortality for ages 4-6 (top) and for ages 6-9 (bottom) for a) the baseline model and b) the baseline model assuming a highly informative prior on DFO RV survey fully recruited catchability. The blue solid and dashed lines are the original model estimates and 95% confidence intervals, respectively. The boxplot summarize the estimates generated by 100 simulation iterations and the red dots indicate the mean of those iterations.

APPENDIX B – FORMER REBUILDING PLAN FOR NGSL COD

Note that the references to figures, tables and appendices in the text that follows concern the rebuilding plan document and are therefore specific to Appendix II of the present research document.

Rebuilding Plan
Northern Gulf Cod (*Gadus morhua*)
NAFO Divisions 3Pn, 4RS

May 2013 – May 2018

Foreward:

1. Fisheries and Oceans Canada (DFO) has developed "*A Fisheries Decision-Making Framework Incorporating the Precautionary Approach*" (PA Framework) under the auspices of the Sustainable Fisheries Framework. It outlines the departmental methodology for applying the precautionary approach (PA) to Canadian fisheries. A key component of the PA Framework requires that when a stock has reached or fallen below a limit reference point (LRP), a rebuilding plan must be in place with the aim of having a high probability of the stock growing above the LRP within a reasonable timeframe.

2. The purpose of this rebuilding plan is to identify the main objectives and requirements for the 3Pn,4RS cod stock, as well as the management measures that will be used to achieve these objectives. This document also serves to communicate the basic information on the stock and its management primarily to DFO staff, fishing industry and legislated co-management boards and other fishery interests. This plan provides a common understanding of the basic "rules" for rebuilding the stock. The objectives and measures outlined in this plan are applicable as long as the stock is below the LRP. Once the stock grows and remains consistently above the LRP, the stock will be managed through the standard Integrated Fisheries Management Plan (IFMP) process. Management measures outlined in this rebuilding plan are mandatory, and may be modified to include additional catch restrictions if they fail to result in stock rebuilding.

3. This rebuilding plan is not a legally binding instrument which can form the basis of a legal challenge. The plan can be modified at any time and does not fetter the Minister's discretionary powers set out in the *Fisheries Act*. The Minister can, for reasons of conservation or for any other valid reasons, modify any provision of the rebuilding plan in accordance with the powers granted pursuant to the *Fisheries Act*.

4. Where DFO is responsible for implementing a rebuilding plan in an area under a land claim agreement, the rebuilding plan will be implemented in a manner consistent with that agreement.

Preamble:

5. International agreements such as the United Nations Fishing Agreement (UNFA) and the FAO Code of Conduct for Responsible Fisheries, and DFO's Precautionary Approach Framework call for the rebuilding of depleted stocks through application of the precautionary approach. Continued rebuilding and growth of this stock is desired, to ensure its long-term sustainability and to promote associated economic opportunities. Guidelines as defined in DFO's Precautionary Approach Framework apply consistently to all stocks. However, the TAC decision rules may vary from one stock to another. It is noted that this approach will be done using established fleet sector allocation shares.

6. The last scientific assessment for this stock was in 2012. The next assessment is scheduled for 2015 and again in 2017. Experience gained from the application of this plan will be reviewed in 2018 (i.e., after five years) to determine the extent to which changes in the plan might be made. Adjustments to the plan could occur earlier if there is a change in stock assessment methodology.

Recent Stock and Fishery History:

7. The recent (~20 year) history of this stock and the fishery is represented in Appendix 1. Prior to this period the stock experienced mature biomass levels as high as 450,000 t in the early 1980's. The number of adults in the population collapsed over the 1983 to 1994 period from 200 million to 7 million with 1994 having the lowest observed level of biomass.

8. The population collapse through the 1980's and early 1990's generally corresponded to a change from a period of low natural mortality (M=0.20) to a period of higher natural mortality (M=0.40). With the exception of a few years in the late 1990's, this higher natural mortality regime has persisted. Natural mortality estimates include all potential mortality sources different than catch statistics. It can represent natural mortality from predation, poor condition, disease as well as unreported, unaccounted and/or discards from recreational fishery, directed fishery and by-catch in other fisheries.

9. In the 1970's and 1980's fishing mortality was relatively high, ranging from 0.27 to 0.41. The increase in natural mortality going into the 1990's coincided with a period of even higher fishing mortality, with F's as high as 0.75 prior to the moratorium and as high as 0.39 since the fishery re-opening. However, the level of fishing mortality since 2011 has been below 0.10.

Reference points:

10. Reference points for this stock are as follows:

    (a) Limit reference point (LRP or Blim) for spawning stock biomass (SSB) = 116,000 t.
    (b) Upper Stock reference point for SSB (B*usr*) = 180,000 t
    (c) Target reference point for SSB (B*msy*) = 200,000 t

11. It is noted that most industry organizations do not agree with the adoption of these reference points. Productivity dynamics of the stock have rarely been observed at SSB levels between 60,000 t and 160,000 t. Therefore, addition of data points towards the middle part of this range is likely to bring important new information to stock productivity dynamics and would warrant a re-evaluation of reference points.

12. When SSB first reaches or exceeds 50% of Blim, a review of methods for the determination of Blim will be conducted, or every 5 years if there is significant SSB increase, to confirm whether 116,000 t remains the best determination of Blim or whether some other method may be more appropriate. This review will also consider the effect of changes in the productivity regime and potential impact of these changes on Bmsy and Fmsy.

Long Term Objectives of the Rebuilding Plan:

13. The long term objective is to achieve and maintain the 3Pn,4RS Cod Spawning Stock Biomass (SSB) at or above Bmsy for the primary benefit of harvesters, industry and the coastal communities which depend on the resource for their livelihood, and also to provide reasonable fishing opportunities during the rebuilding period. It is noted that this will be done using established fleet sector allocation shares.

Short Term Objectives:

14. The SSB for this stock has ranged between 5,300 t and 25,000 t since 1993 and as of January 1, 2012 was 18,740 t. The SSB was 28,000 t in 1992 and 46,000 t in 1991. The short term objective is to double the SSB in ten years (i.e., to ~40,000 t), commencing 2013, based on the SSB as of January 1, 2012. It is noted that use of a ten-year period for application of this short-term objective is selected for this stock, which may not be considered to be appropriate for other stocks.

15. Once SSB has doubled from the January 2012 level, the short term objective thereafter will be to increment SSB by 50% for each subsequent five-year period.

Summary Analysis:

16. Current F (2012) is estimated to be 0,075.

17. Three scenarios were considered in the development of Harvest Control Rules as outlined in Appendix 2 (Table 1). Hypothetical SSB trajectories for a 10 year period using the three scenarios of harvest control rules (HR1, HR2 and HR3) for low, medium and high productivity regimes were conducted with a starting SSB of either 18,740 t or 25,000 t (Fig. 3). A scenario with no directed fishery (Low-to-no fishing with TAC/catch=400 t) was also presented for the low productivity regime. Productivity regime is defined as the potential rate of population growth (i.e., % increase/year in Table 2) derived from population matrix models using age specific mortality and reproductive rates.

18. There were no substantive differences in outcome against the short term objective when using the two different starting SSB's. All three scenarios showed positive stock trajectory with the stock achieving the short term objective within the 10 year time frame in the medium and high productivity regime. In the low productivity regime the stock only achieves the short term objective under the scenario with no directed fishery (Low-NF, Fig. 4), reflecting the impact of high natural mortality on the potential for future stock growth.

19. Since the moratorium in 1993 this stock has experienced periods of natural mortality which have been low, medium and high (Fig. 1). The average productivity regime in place for the stock since the 1993 moratorium can be characterized as medium. The current productivity regime is low. Based on the assumption that the last 20 years productivity regime will apply for the life of this rebuilding plan the following Harvest Control Rules are considered

reasonable and balanced. The approach is most similar to the scenario presented by some industry (scenario 2 in appendix 2).

Harvest Control Rules:

When the SSB is in the Critical Zone (below B*lim*):

20. Starting in 2013 with SSB below Blim total catch, including all removals, will be limited to 1,500 t per annum for a 5-year period.

21. Notwithstanding paragraph 20 if growth in SSB is achieved, based on a rolling two-year average, then the harvest control rules in Table 1 for total removals, including a directed harvest shall be applied. If, subsequent to TAC increases, SSB again declines the harvest control rules in Table 1 will apply according to the level of SSB. It is noted that use of a two-year period to establish the rolling average, and providing for increases in catch prior to achievement of the short term objective, are provisions that are selected for this stock, which may not be considered to be appropriate for other stocks.

Table A2.1. Harvest Control Rules in Situations of Increasing or Decreasing SSB.

SSB (t)	Harvest Control Rule (TAC (t) or F)	Corresponding measure (TAC (t) or F or other measure)
<12,000	-	Moratorium
12,000 < 15,000	F[1]=.075	Stewardship/Bycatch
15,000 < 18,000	F[1]=.075	Variable (1200 < 1500)
18,000 < 25,000	TAC=1,500 t	1,500
25,000 < 30,000	1,800 t	~F[1]=.067
30,000 < 40,000	3,185 t	~F[1]=.101

[1] F for ages 7-9 based on 2012 stock assessment data.

22. Notwithstanding paragraphs 20 and 21 should the two year average of SSB decline below 15,000 t, directed commercial and recreational fishing will revert to a "Stewardship/Bycatch" fishery at F=0.075. It is noted that any Stewardship fishery will be implemented using established fleet sector allocation shares. At levels of SSB below 12,000, a moratorium shall be declared and removals will be limited to those required to meet (a) Food Social and Ceremonial requirements of First Nations based on Aboriginal Fisheries Strategy agreements, (b) by-catch requirements for other directed groundfish fisheries and (c) science/sentinel survey work. If subsequent trends in stock trajectory continue to be negative further measures will be considered.

23. Notwithstanding paragraphs 20 and 21 after five years should the stock appear to be on neither a positive or negative trajectory, based on averaging the two most recent annual 1 January SSB estimates of SSB, then the harvest controls contained in Table 1 will be re-

evaluated to include recruitment indices in a manner to encourage stock growth according to the short term goal.

REBUILDING PLAN APPENDIX 1

Biomass 3+, Natural Mortality, TAC, Catch and Exploitation Rate

3Pn,4RS Cod Stock

1991 – 2012 (as of March 2012)

Year	Biomass 3+ for mature SSB	M	TAC	Catch	F (Exploitable)
1991	45,760	0.40	35,000	32,017	0.46
1992	28,488	0.40	35,000	28,015	0.62
1993	18,087	0.40	18,000	18,440	0.75
1994	5,323	0.40	0	387	0.08
1995	12,483	0.40	0	148	0.04
1996	13,480	0.40	0	317	0.05
1997	15,811	0.19	6,000	4,792	0.31
1998	16,576	0.19	3,000	3,296	0.19
1999	21,469	0.19	7,500	7,136	0.39
2000	20,525	0.19	7,000	6,834	0.35
2001	21,142	0.19	7,000	7,150	0.34
2002	21,403	0.31	7,000	6,341	0.34
2003	20,431	0.31	0	4,069	0.02
2004	24,625	0.31	3,500	3,264	0.14
2005	25,048	0.31	5,000	4,491	0.20
2006	23,075	0.31	6,000	5,715	0.26
2007	21,091	0.40	7,000	6,470	0.30
2008	16,881	0.40	7,000	6,224	0.39
2009	18,131	0.40	7,000	4,695	0.30
2010	13,540	0.40	4,000	3,576	0.22
2011	19,156	0.40	2,000	1,742	0.08
2012	18,741	-	1,500	1,368	-
2013	No Assessment	-	1,500	1,022*	-

*Year To Date, November 7.

REBUILDING PLAN APPENDIX 2

Table A2.2. Harvest control rules for different levels of SSB (t) from different scenarios suggested by DFO (scenario 1), industry (scenario 2) and alternative (scenario 3). SSB range, TAC (t) and corresponding fishing mortality (F) are presented.

Scenario 1			Scenario 2			Scenario 3		
SSB (t)	Harvest Control Rules (TAC t)	Corresponding F	SSB (t)	Harvest Control Rules (TAC t)	Corresponding F	SSB (t)	Harvest Control Rules (TAC t)	Corresponding F
< 25,000	1,500	-	< 25,000	1,500	-	< 25,000	1,500	-
25,000 < 30,000	1,500	F[1]= ~ .055	25,000 < 30,000	1,800	F[1]= ~ .067	25,000 < 30,000	1,800	F[1]= ~ .067
30,000 < 40,000	1,800	F[1]= ~ .055	30,000 < 40,000	3,185	F[1]= ~ .101	30,000 < 40,000	2,156	F[1]= ~ .067
40,000 < 50,000	2,800	F[1]= ~ .065	40,000 < 50,000	4,365	F[1]= ~ .103	40,000 < 50,000	3,290	F[1]= ~ .077
50,000 < 58,000	4,000	F[1]= ~ .075	50,000 < 60,000	5,665	F[1]= ~ .107	50,000 < 60,000	4,628	F[1]= ~ .087
58,000 < 80,000	5,300	F[1]= ~ .085	60,000 < 70,000	7,085	F[1]= ~ .112	60,000 < 70,000	6,165	F[1]= ~ .097
80,000 < 116,000	9,300	F[1]= ~ .095	70,000 < 80,000	8,625	F[1]= ~ .117	70,000 < 80,000	7,900	F[1]= ~ .107
116,000 < 180,000	15,753	F[1]= ~ .13	80,000 < 90,000	10,285	F[1]= ~ .123	80,000 < 90,000	9,831	F[1]= ~ .117
-	-	-	90,000 < 100,000	12,065	F[1]= ~ .128	90,000 < 100,000	11,060	F[1]= ~ .117
-	-	-	100,000 < 110,000	13,965	F[1]= ~ .134	100,000 < 110,000	12,289	F[1]= ~ .117
-	-	-	110,000 < 120,000	15,985	F[1]= ~ .139	110,000 < 120,000	14,938	F[1]= ~ .13

[1] F for ages 7 to 9 based on 2012 stock assessment data

Table A2.3. Recruitment rate (i.e., mean instantaneous mortality rate /year between age 0 and 3; Z- 0-3), adult natural mortality (i.e., instantaneous rate for age 3+; M3+), percent increase per year and doubling time in SSB for low, medium and high productivity regimes estimated for 10-year block period following the 1994-1996 moratorium. Percent increase per year calculated from estimated potential rate of population growth using matrix population models (with no fishing, i.e., catch=0 t) is used as the indicator of productivity regime. Possible percent of increase in SSB over 10 years in the absence of directed fishing (i.e., catch of 400 t per year) is also presented for each productivity regime.

Productivity	High	Medium	Low
Years	1997-2006	1999-2008	2002-2011
Z0-3	4.31	4.35	4.35
M3+	0.25	0.29	0.36
%/year	19.1	12.7	6.1
% increase - 10 years	581	293	97

Table A2.4. Two and three year average SSB estimates and corresponding percent change in SSB between consecutive years for the 1997-2012 period.

Year	SSB (t)	2-year average	3-year average	% change 2-y avg	% change 3-y avg
1997	15811	-	-	-	-
1998	16576	16194	-	-	-
1999	21469	19023	17952	17.5%	-
2000	20525	20997	19523	10.4%	8.8%
2001	21142	20834	21045	-0.8%	7.8%
2002	21403	21273	21023	2.1%	-0.1%
2003	20431	20917	20992	-1.7%	-0.1%
2004	24625	22528	22153	7.7%	5.5%
2005	25048	24837	23368	10.2%	5.5%
2006	23075	24062	24249	-3.1%	3.8%
2007	21091	22083	23071	-8.2%	-4.9%
2008	16881	18986	20349	-14.0%	-11.8%
2009	18131	17506	18701	-7.8%	-8.1%
2010	13540	15836	16184	-9.5%	-13.5%
2011	19156	16348	16942	3.2%	4.7%
2012	18741	18949	17146	15.9%	1.2%

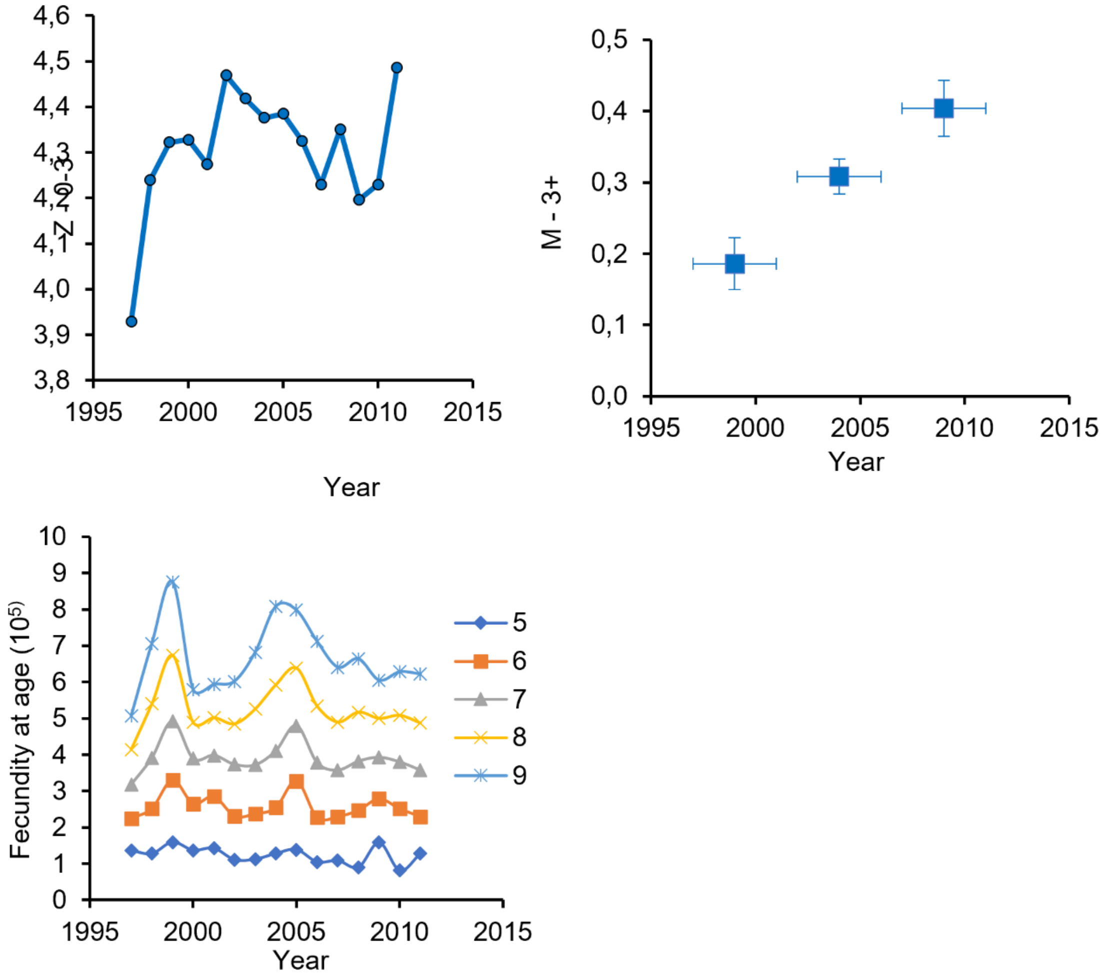


Figure 1. Estimates of mean instantaneous mortality rate per year between age 0 and 3 (i.e., Z -0-3: recruitment rate), instantaneous natural mortality rate of age 3+ fish (M-3+) and fecundity at age (estimated from size, maturity and fecundity-at-age) used to determine age-specific mortality and reproductive rate for the different years between 1997 and 2011. Data are taken from Lambert (2012).

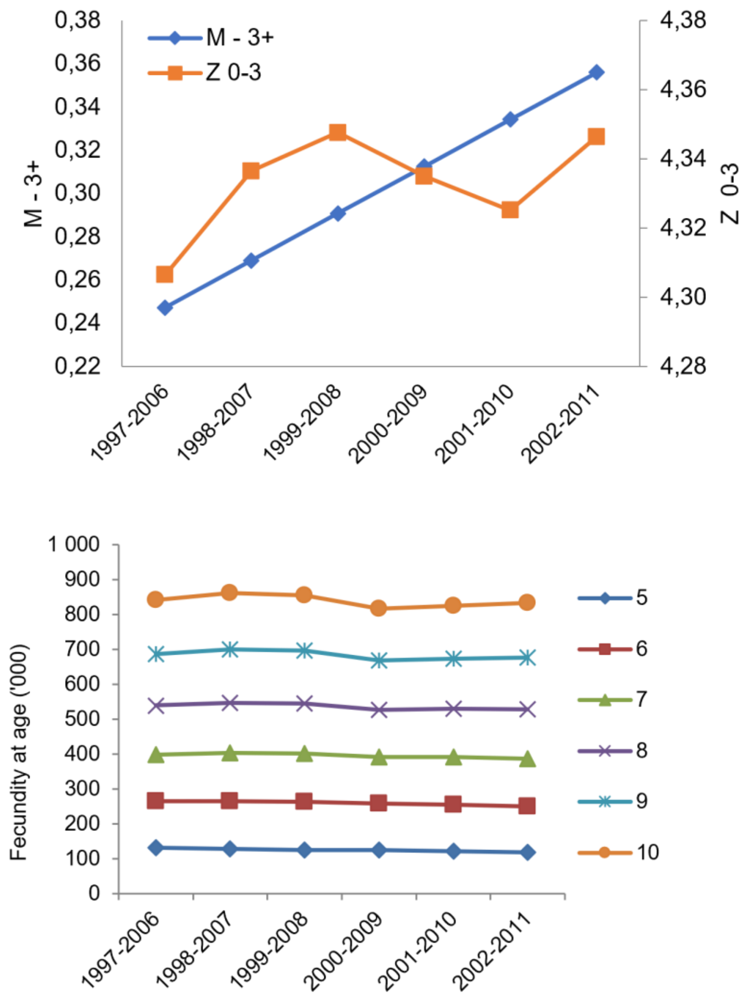
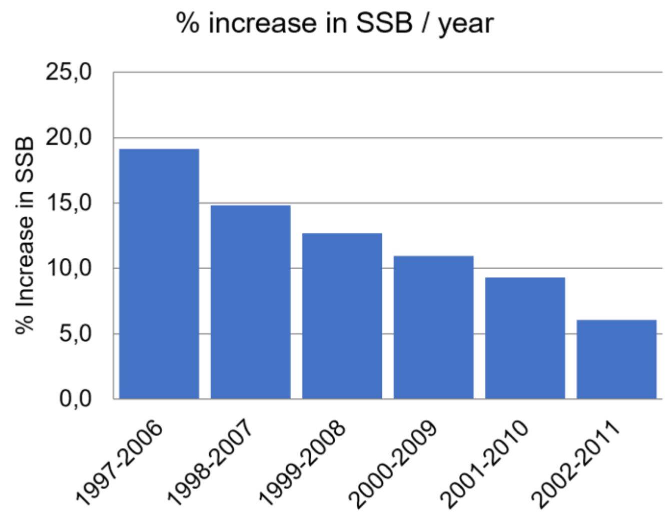


Figure 2. Mean recruitment rate (i.e., instantaneous mortality rate /year between age 0 and 3; Z- 0-3), instantaneous natural mortality rate of 3+ fish (3+) and reproductive rate at age (estimated from size, maturity and fecundity-at-age) estimated for 10-year blocks between 1997 and 2011.



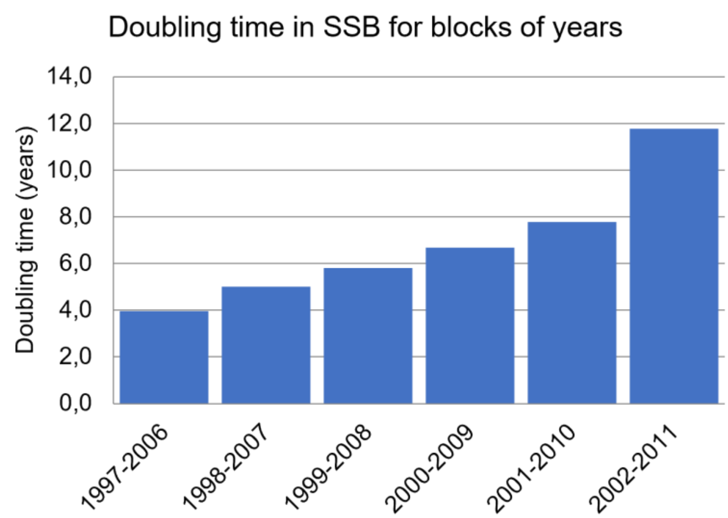
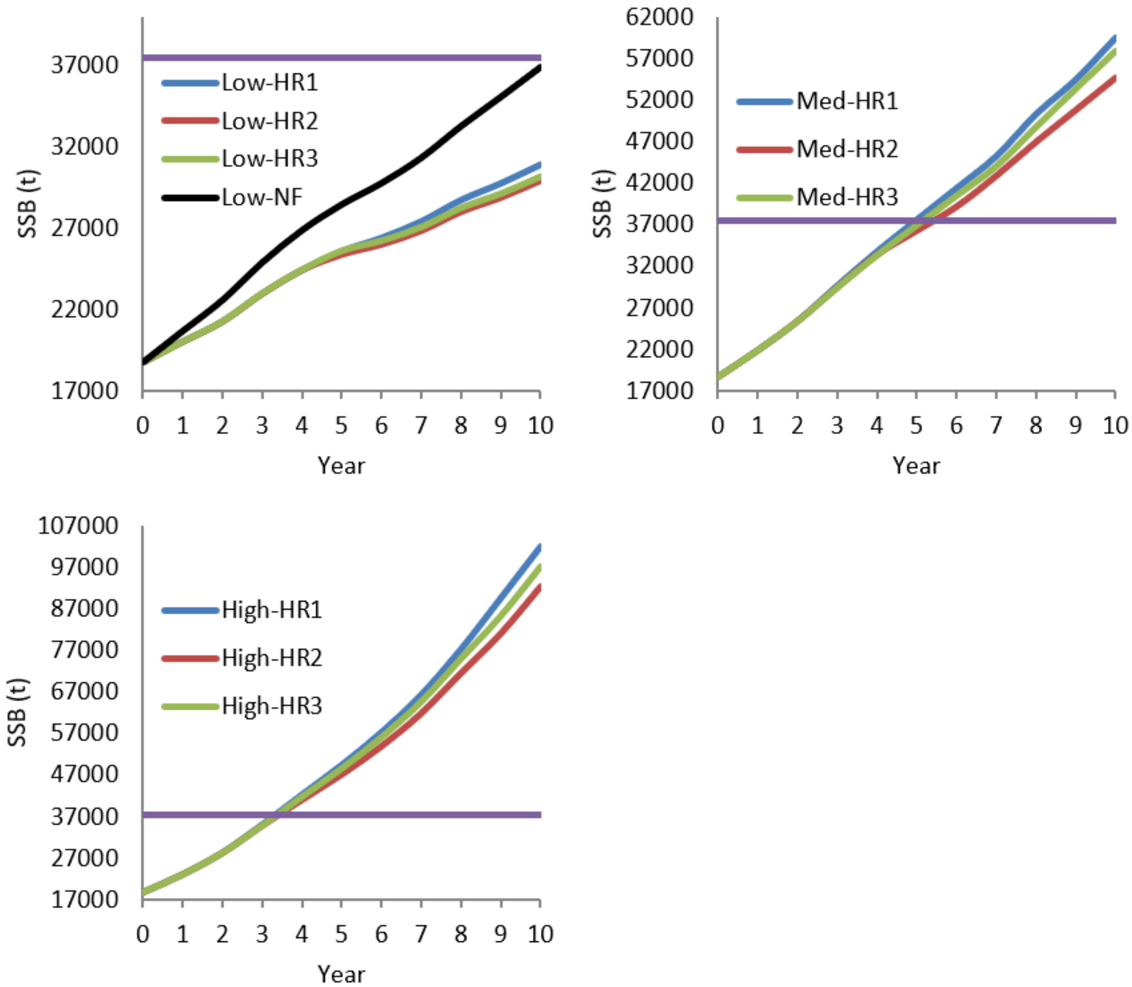


Figure 3. Percent increase in SSB per year and doubling time of SSB for 10-year block periods derived from population matrix models using age specific mortality and reproductive rates.


Low-HR1
Low-HR2
Low-HR3
Low-NF
SSB (t)
Year
Med-HR1
Med-HR2
Med-HR3
SSB (t)
Year
High-HR1
High-HR2
High-HR3
SSB (t)
Year

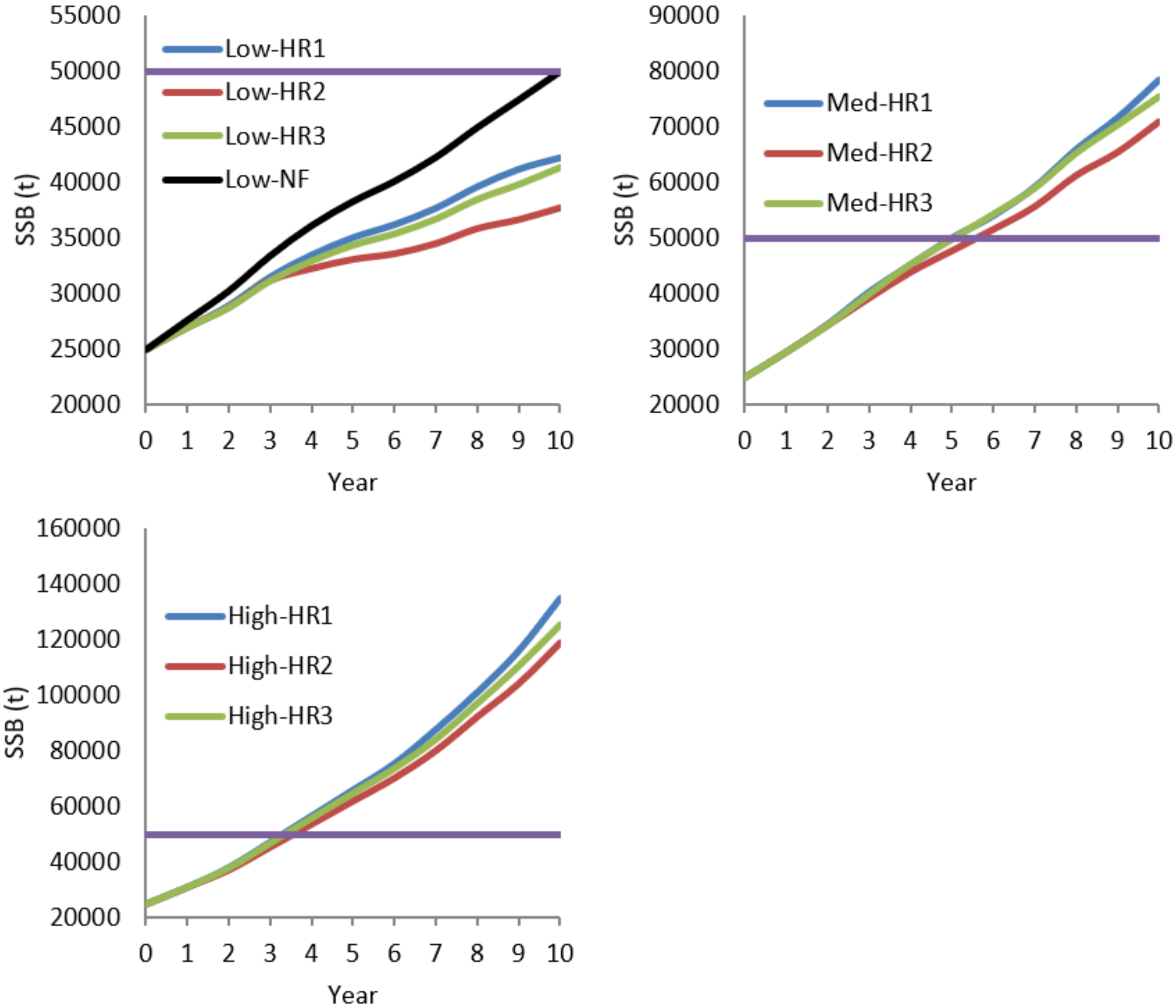


Figure 4. Hypothetical SSB trajectories for a 10 year period using the 3 scenarios of harvest control rules (HR1, HR2 and HR3) for low, medium and high productivity regimes (i.e., productivity defined as potential rate of population growth) estimated from age specific mortality and reproductive rates. A scenario with no directed fishery for the last 10-year period (Low-NF with TAC=400 t) is also presented. SSB trajectories are estimated with starting SSB of 18,740 and 25,000 t. The horizontal line indicates the SSB level corresponding to an increase of 100% in SSB.

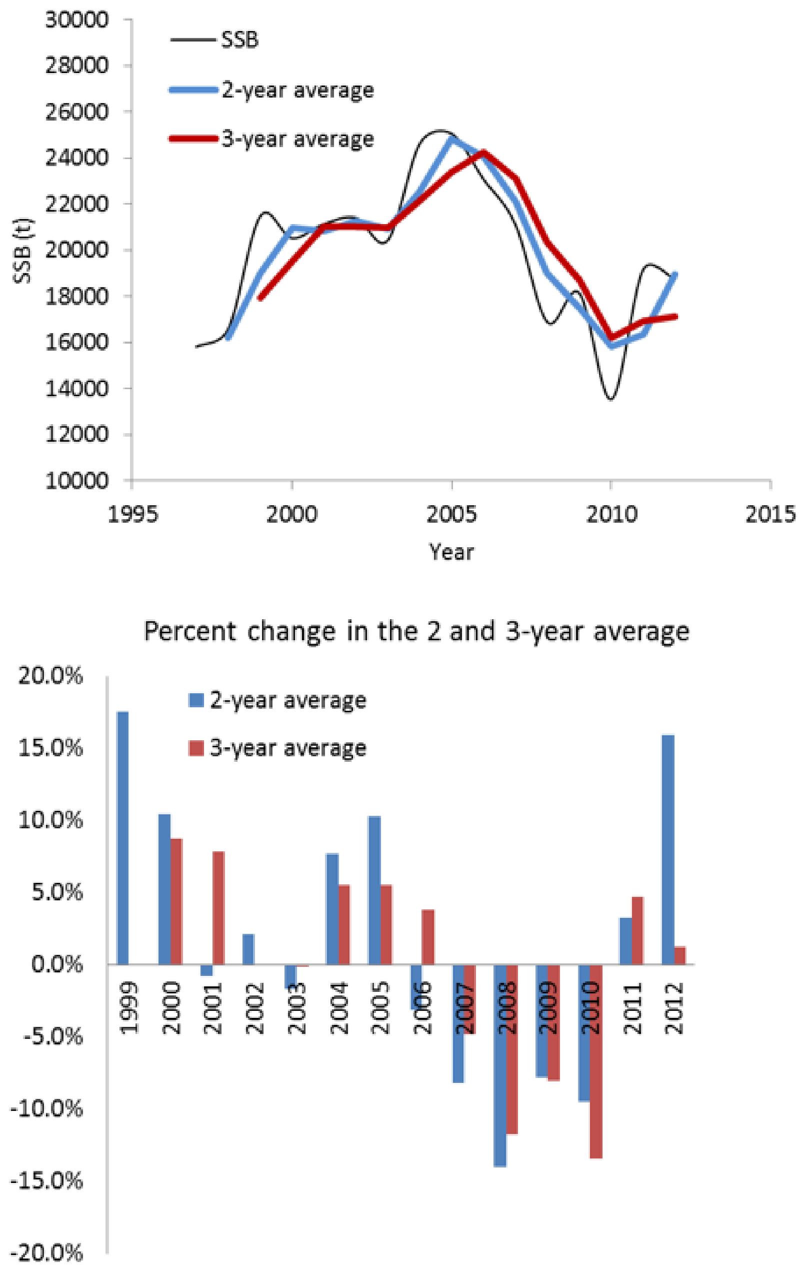


Figure 5. Interannual variations in observed SSB, in 2-, 3-year average SSB and percent change in SSB averaged over 2 and 3 years for the period between 1997 and 2012.

References

Lambert, Y. 2012. Updated life history parameters for northern Gulf of St. Lawrence (3Pn, 4RS) cod (*Gadus morhua*) and their impact on reproductive potential and projections of population growth. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/056. iii + 20 p.