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Extending the Northern Cod (*Gadus morhua*) Assessment Model - Part I: Bridging Gaps with Additional Data and Model Variations

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Foreword

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

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ABSTRACT

Since 2016, the Northwest Atlantic Fisheries Organization (NAFO) Division (Divs.) 2J3KL (or Northern) cod stock has been assessed with a complex integrated state-space population model called NCAM (Northern Cod Assessment Model). While the time series in base-case NCAM begins in 1983 – when the Research Vessel (RV) survey started covering NAFO Divs. 2J, 3K, and 3L. Older data used in previous assessment models for Northern cod, such as reported landings and catch-at-age, have gone unused. Though limited to selected years, there is also considerable historical data from the tagging program that has yet to be utilized in a formal assessment model. Finally, data from two juvenile cod monitoring programs have yet to be utilized in an assessment model for Northern cod. Here we document the process and assumptions behind the inclusion of additional reported landings, catch-at-age, tagging data, and juvenile survey data into NCAM. Much of these data extend back to 1954. Additionally stock-recruitment (S-R) relationships are explored as are alternate approaches to estimating baseline rates of natural mortality (M; e.g., allometric M). The application of additional data and model variations not only extends the temporal perspective on Northern cod stock trends, but also enhances our understanding of critical aspects such as recruitment, the S-R relationship, and the estimation of M. These extensions bridge gaps in our knowledge, enable the reassessment of reference points, and offer a more robust foundation for informed fisheries management decisions.

1. INTRODUCTION

The Northern cod assessment is based on a state-space population dynamics model (Northern Cod Assessment Model, NCAM; [Cadigan 2015, 2016a]) that integrates much of the existing information about the stock. The model includes information from the Fisheries and Oceans Canada (DFO) Research Vessel (RV) autumn trawl survey (1983–2020), Sentinel fishery survey (1995–2020), Smith Sound acoustic survey (1995–2009), tagging program (1983–2020), and the fishery (reported landings and catch-at-age; 1983–2020). By integrating all of these data into one model, Cadigan (2015, 2016a) addressed problems that are difficult to solve using each series in isolation, such as estimating annual natural and fishing mortality (M and F, respectively). The model also censors the landings to account for bias introduced by partial reporting. Overall, the purpose of developing this model was to improve the projections of the stock and assess the impacts of proposed fishery catches on its recovery. With this objective, it was not necessary to include data from years prior to the DFO RV survey, which started covering the entire stock area (NAFO Divs. 2J3KL) in 1983. What is missing, however, is a longer-term perspective on the history and dynamics of the stock, in particular the relative magnitude of the fishery, the stock and its productivity.

Here we document the steps that were taken to extend the model back to 1954, providing a deeper historical perspective on the Northern cod stock's dynamics. Two key data sources enabled this backwards extension: existing time series of reported landings and catch-at-age, which had been used in previous assessments of Northern cod but were excluded when the assessment transitioned to a survey-based model and then to NCAM (Brattey et al. 2018). In addition, we incorporated data from the tagging program spanning multiple years, including 1954–55, 1962–66, and 1978–96 (Taggart et al. 1995). Furthermore, the integration of data from two juvenile cod monitoring programs, the Fleming and Newman Sound programs (Gregory et al. 2019, Lewis et al. 2022), brings valuable insights into the juvenile stages of Northern cod. These programs contribute data covering age 0 and 1 cod and extend our assessment model to incorporate juvenile dynamics.

The availability of these extended data sources opens doors to a more comprehensive exploration of the Northern cod stock's dynamics. We explore the relationship between stock size and recruitment with this extended series. Additionally, we revisit the estimation of baseline M, examining variations such as allometric M (i.e., the expectation that M should decrease as body size increases). The integration of these data sources and modeling variations enhances our ability to understand and project the dynamics of this iconic stock.

2. METHODS

We document a series of changes to NCAM (Cadigan 2015, 2016a), which broadly aim to:

1. improve the fit of the model to catch composition data,
2. minimize conflicts between survey indices,
3. extend the time series back to 1954,
4. integrate data from juvenile cod monitoring programs,
5. utilize a stock-recruitment (S-R) relationship and calculate per-recruit reference points, and
6. estimate baseline levels of M.

A series of stepwise changes were made to NCAM to achieve these goals. Much of the core structure of NCAM was retained and, as such, we first provide a brief overview of the base-case

structure of NCAM (see Cadigan 2015, 2016a for more details). We then document a series of stepwise changes. Note that we label different model formulations with M followed by a number, starting with base-case NCAM as model **M0**. Models that include additional data from the tagging program involved the extension of the time series back to 1954; these models are referred to as xteNCAM. Several sensitivity tests are also presented throughout, and these are labeled with an **S** followed by a number. Brief descriptions of each model are included in Table 2.1, and model notation is described in the text and summarized in Table 2.2. The proposed stepwise changes are outlined in Figure 2.1.

Data inputs being considered for use in xteNCAM are outlined in Tables A1 to A11 in Appendix I - Data inputs. The data used in NCAM are a subset of these inputs (Figure 2.2).

Table 2.1: Labels and descriptions of model formulations and sensitivity tests.

Label	Description
M0	Base-case NCAM
M1	Estimates catch composition variance parameter separately for age groups ≤2, 3–4, and ≥5 as an alternative to fixed multipliers
M2	Random walk process for Sentinel survey catchability across both years and ages
M3	Autoregressive process for Sentinel survey catchability across both years and ages
M4	Base-case xteNCAM including data back to 1954
M5	xteNCAM including data from the Fleming and Newman Sound juvenile surveys
M6	xteNCAM including data from the Fleming and Newman Sound juvenile surveys, allowing differences in catchability by survey
M7	xteNCAM including data from the Fleming and Newman Sound juvenile surveys, allowing differences in catchability by seine type (cotton or nylon)
M8	xteNCAM including juveniles and a linear stock-recruitment relationship
M9	xteNCAM including juveniles and a Beverton-Holt stock-recruitment relationship
M10	xteNCAM including juveniles and a sigmoidal stock-recruitment relationship
M11	xteNCAM including juveniles, Beverton-Holt S-R relationship, and a constant baseline level of natural mortality
M12	xteNCAM including juveniles, Beverton-Holt S-R relationship, and allometric baseline levels of natural mortality (i.e., Lorenzen M)
M13	xteNCAM including juveniles, Beverton-Holt S-R relationship, and shifts in baseline levels of natural mortality
S1	Model **M1** excluding the Sentinel survey index

Label	Description
S4	Model **M4** excluding disc tag releases (1954–1991)
S5	Model **M5** excluding the juvenile survey data
S8	Model **M8** excluding the juvenile survey data
S9	Model **M9** excluding the juvenile survey data

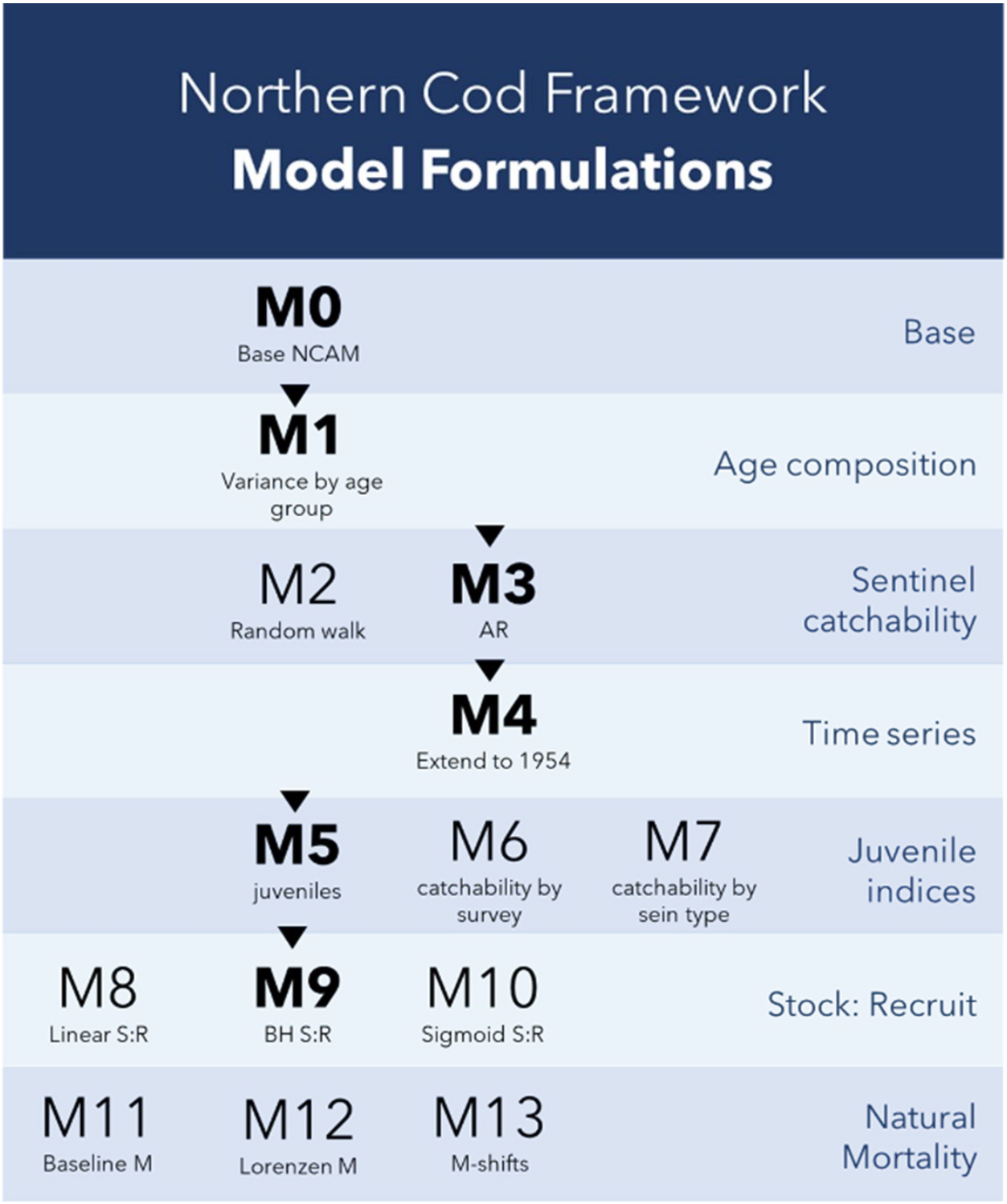

Figure 2.1: Depiction of proposed step-wise changes.

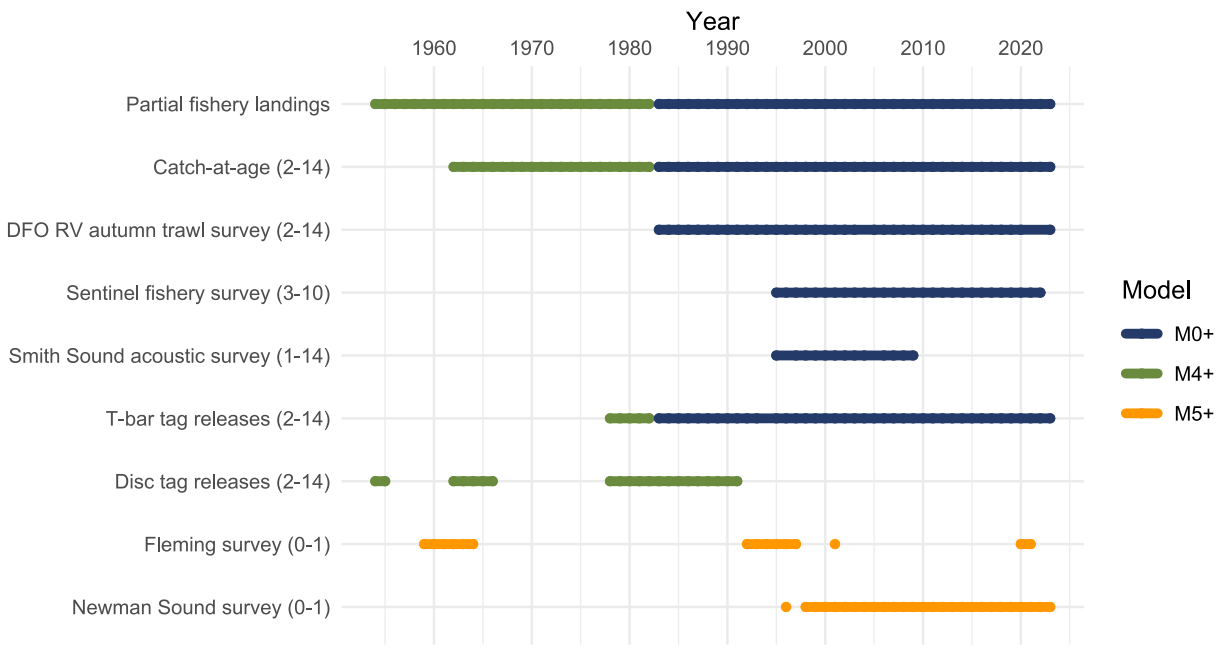

*Figure 2.2: Years from each data series integrated into NCAM (**M0-M3**) and xteNCAM (**M4-M13**). Ages informed by each data source are indicated in parentheses.*

Table 2.2: Model parameters, notation, and definitions.

Symbol	**Description**
$N_{a,y}$	Abundance in year y and age a
r_1, r_2	Initial recruitment for first year in the time series and 1992 random walk processes
α, β, γ	Parameters for stock-recruitment relationships
σ_r	Standard deviation of recruitment process
$Z_{a,y}, F_{a,y}, M_{a,y}$	Total, fishing, and natural mortality rate in year y and age a
$m_{a,y}$	Baseline natural mortality rate
$\delta_{a,y}$	Process deviations in natural mortality
σ_δ	Standard deviation of natural mortality process deviations
$\varphi_{\delta,\text{age}}$	Autocorrelation in natural mortality process deviations across ages
$\varphi_{\delta,\text{year}}$	Autocorrelation in natural mortality process deviations across years
$\varphi_{F,\text{age}}$	Autocorrelation in fishing mortality across ages
$\varphi_{F,\text{year}}$	Autocorrelation in fishing mortality across years
$C_{a,y}$	Predicted catch in year y and age a
L_y, U_y	Lower and upper bound for censored bounds around reported catch

Symbol	Description
σ_C	Standard deviation for censored bounds
$P_{a,y}$	Proportions of each age in the catch (catch-at-age composition)
$X_{oa,y}$	Continuation-ratio logit values of the catch-at-age composition
σ_{Pa}	Standard deviation for age composition log-likelihood
$I_{s,a,y}$	Age-based abundance estimates for each survey
$\sigma_{s,I}$	Standard deviation of the survey
$q_{s,a,y}$	Catchability parameters for surveys
$\hat{B}_{S,y}$	Biomass estimate from the Smith Sound survey
$J_{S,a,y}$	Observed age-samples from the Smith sound survey
$D_{a,y}$	Portion of the stock in Smith Sound
$C_{x,a,y}$	Predicted catch of tagged fish from each experiment x
s_x	Immediate post-tagging survival rate for tagged fish
$F_{x,a,y}, U_X$	Random variations in fishing mortality experienced by tagged fish
$R_{x,a,y}$	Number of reported tags
λ_x, λ_y	Reporting rate parameters for tagging data before and after 1997
k_1, k_2	Over-dispersion parameter for tagging data before and after 1997
b_1, b_2	Kirkwood parameters for tag loss model

2.1. OVERVIEW OF BASE-CASE NCAM

2.1.1. Process equations

Like most age-structured assessment models, NCAM utilizes a cohort equation to estimate abundance, $N_{a,y}$, in a given year, y, and age, a, using the previous year's abundance, incorporating a survival rate expressed by the total mortality rate, Z:

$$N_{a,y} = N_{a-1,y-1} \cdot \exp\left(-Z_{a-1,y-1}\right) \qquad (\mathbf{2.1})$$

As of the last assessment of Northern cod (DFO 2022a), the model included ages $a = 2,\ldots,14$, and years $y = 1983,\ldots,2020$. Initial abundances, $N_{1983,a}$, of ages $a = 3,\ldots,14$ are freely estimated, and recruits, $N_{y,2}$, are modeled using two random walks:

$$\log\left(N_{2,y}\right) = \begin{cases} r_1 + \varepsilon_y & \text{if } y = 1983 \\ \log\left(N_{2,y-1}\right) + \varepsilon_y & \text{if } y > 1983 \\ r_2 + \varepsilon_y & \text{if } y = 1992 \\ \log\left(N_{2,y-1}\right) + \varepsilon_y & \text{if } y > 1992 \end{cases}, \text{ where } \varepsilon_y \sim N(0, \sigma_r) \qquad (\mathbf{2.2})$$

Two recruitment parameters (r_1 and r_2) were chosen to capture the significant changes in stock size pre- and post-1992 (e.g., Lilly 2008).

The total mortality rate, Z, combines fishing, F, and natural mortality, M,

$$Z_{a,y} = F_{a,y} + M_{a,y}, \qquad (\mathbf{2.3})$$

and both components are estimated using random effects. Specifically, M is modeled as autocorrelated random variables,

$$\log(M_{a,y}) = \log(m_{a,y}) + \delta_{a,y}, \qquad (\mathbf{2.4})$$

where baseline levels of natural mortality, m, were fixed to values ranging from 0.36–0.43, depending on age, through 1983–90 and 1995-present and a large spike with values exceeding 2.0 for most ages through 1991–94 (Table 2.3). This baseline M assumption, called M-shift, was implemented to reduce the process error variance around baseline M and, consequently, reduced uncertainty around the projections of the stock (Brattey et al. 2018). The errors in the natural mortality process, $\delta_{a,y}$, are assumed to follow a stationary process with autocorrelation across ages and years:

$$\begin{aligned} Cov(\delta_{a,y}, \delta_{a-j,y-k}) &= \frac{\sigma_\delta^2 \varphi_{\delta,\text{age}}^j \varphi_{\delta,\text{year}}^k}{(1-\varphi_{\delta,\text{age}}^2)(1-\varphi_{\delta,\text{year}}^2)}, \\ Corr(\delta_{a,y}, \delta_{a-j,y-k}) &= \varphi_{\delta,\text{age}}^j \varphi_{\delta,\text{year}}^k. \end{aligned} \qquad (\mathbf{2.5})$$

This autocorrelation was introduced as M is expected to be more alike for fish that are close in age and over time. The level of correlation across ages and years is controlled by $\varphi_{\delta,\text{age}}$ and $\varphi_{\delta,\text{year}}$, respectively, and the scale of inter-annual deviations is controlled by σ_δ.

Table 2.3: Baseline levels of natural mortality assumed in "M-shift" formulations of NCAM.

Age	<1991	1991–1994	>1994
2	0.43	1.0225	0.43
3	0.38	1.1550	0.38
4	0.38	1.2275	0.38
5	0.40	1.8375	0.40
6	0.38	2.1500	0.38
7	0.42	2.5350	0.42
8+	0.36	2.0475	0.36

F is also modeled with an autoregressive process, with

$$Cov[\log(F_{a,y}), \log(F_{a-j,y-k})] = \frac{\sigma_F^2 \varphi_{F,\text{age}}^j \varphi_{F,\text{year}}^k}{(1-\varphi_{F,\text{age}}^2)(1-\varphi_{F,\text{year}}^2)}. \qquad (\mathbf{2.6})$$

The within-year correlation of F, $\varphi_{F,\text{age}}$, was estimated for stock ages 5–12, but it was fixed at zero for ages <5 as younger cod (≲1kg) are not targeted by the fishery. Finally, catch, $C_{a,y}$, is modeled using the Baranov catch equation:

$$C_{a,y} = N_{a,y} \cdot \left(1 - \exp\left(-Z_{a,y}\right)\right) \cdot \frac{F_{a,y}}{Z_{a,y}}. \qquad (\mathbf{2.7})$$

2.1.2. Observation equations

2.1.2.1. Catch

Due to concerns regarding the accuracy of reported landings (Table A1), a censored bounds approach was used to bound the model predicted catch within a pre-defined range. This range was informed by expert judgement of the scale of unreported landings throughout the history of the fishery. The censored log-likelihood for the observed catch time series is calculated using the normal cumulative density function $\Phi_N(\,)$,

$$l\left(\{C_{oy}\}|\boldsymbol{\theta}\right) = \sum_{y=1}^{Y} \log\left\{\Phi_N\left[\frac{\log\left(U_y/C_y\right)}{\sigma_C}\right] - \Phi_N\left[\frac{\log\left(L_y/C_y\right)}{\sigma_C}\right]\right\} \qquad (\mathbf{2.8})$$

where C_y represents the total predicted catch, which is calculated by summing Equation (2.7) over ages, C_oy is the observed catch, L_y is the lower catch limit, and U_y is the upper catch limit. The parameter σ_C cannot be estimated and, as such, it is fixed to a small value of 0.075 to ensure that $C_y \in \left(L_y, U_y\right)$ more often than not (i.e., a large penalty is applied when predicted values land outside the catch bounds). Bounds were defined as follows:

1. a pre-moratorium period (1983–91) where the upper catch bound was set to 1.5 times the reported landings;
2. an early post-moratorium period (1992–2005) where the upper bound was set to 2.0; and
3. a recent period (2006–present) where the upper bound was allowed to vary if information on the recreational fishery was available (Brattey et al. 2018). The lower bound for all periods was fixed at 1.1.

In addition to tracking landings from commercial fisheries, DFO also conducts extensive sampling of fisheries landings. These data are used to construct catch numbers-at-age (Table A2), which provide useful information on cohorts moving through the fishery. Observed, $C_{oa,y}$, and predicted, $C_{a,y}$, catch numbers-at-age are converted to proportions-at-age (e.g., $P_{a,y} = C_{a,y}/C_y$), which are converted to continuation-ratio logit values, $X_{oa,y}$ and $X_{a,y}$. The catch age composition log-likelihood is

$$l\left(\{X_{oa,y}\}|\boldsymbol{\theta}\right) = \Sigma_{a=1}^{A-1}\Sigma_{y=1}^{Y}\log\left[\varphi_N\left(\frac{X_{oa,y} - X_{a,y}}{\sigma_{Pa}}\right)\right] \qquad (\mathbf{2.9})$$

where φ_N is the probability distribution function (pdf) for a N(0,1) random variable and σ_{Pa} is an estimated parameter with the following ad hoc adjustment:

$$\sigma_{Pa} = \begin{cases} 3\sigma_P, & a \leq 2 \\ \sigma_P, & 3 \leq a \leq 7 \\ 2\sigma_P, & a \geq 8 \end{cases} \qquad (\mathbf{2.10})$$

2.1.2.2. Surveys

The combined use of landings and fisheries-independent survey data provide information on the scale of the population. Surveys also inform trends in Z. Age-based abundance estimates, $I_{s,a,y}$, for each survey s are assumed to be log-normally distributed,

$$E\left(I_{s,a,y}\right) = q_{s,a,y}N_{a,y}\exp\left(-t_{s,y}Z_{a,y}\right), \qquad (\mathbf{2.11})$$

where the term $\exp\left(-t_{s,y}Z_{a,y}\right)$ adjusts the beginning-of-year abundance, $N_{a,y}$, to the levels expected at the time of the survey, and the catchability parameters, $q_{s,a,y}$, adjust stock abundance to the scale of the survey. The likelihood term for survey indices is

$$l\left(\left\{I_{s,a,y}\right\}|\boldsymbol{\theta}\right) = \sum_{a}\sum_{y}\log\left(\varphi_N\left\{\frac{\log\left(I_{s,a,y}\right) - E\left[\log\left(I_{s,a,y}\right)\right]}{\sigma_{s,I}}\right\}\right) \qquad (\mathbf{2.12})$$

where $\sigma_{s,I}$ is the standard deviation of the survey, which is estimated by the model.

The main survey index used for assessing Northern cod comes from the DFO fall offshore RV survey of 2J3KL (Tables A3 to A6). The inshore gillnet catch-rate index provided by the Sentinel fishery program is also used (Table A7). The catchability, $q_{s,a,y}$, of the RV survey was assumed to be constant over time and for ages 6+. A shift in catchability was assumed for the inshore Sentinel survey by estimating year effects that follow a random walk,

$$\log\left(q_{s,a,y}\right) = \log\left(q_{s,a}\right) + \log\left(q_{s,y}\right). \qquad (\mathbf{2.13})$$

This was implemented to account for the possibility that the portion of the stock available to the inshore survey changed over time.

The portion of the stock available to the fall offshore RV survey likely also changed over time. Indeed, following the collapse of cod, a relatively large overwintering aggregation of cod was observed in Smith Sound, Trinity Bay, on the Northeast coast of Newfoundland (Rose et al. 2011). The size of this aggregation was assessed using an acoustic survey in 1995 and the aggregation, and the survey, persisted until 2009 (Table A8). The biomass estimate, $\hat{B}_{S,y}$, from this survey was used to estimate the size of the Smith Sound component,

$$\log\left(\hat{B}_{S,y}\right) \sim N\left\{\log\left[\sum_{a=1}^{A} q_{S,a}\, N_{S,a,y}\exp\left(-t_y Z_{a,y}\right)w_{a,y}\right], \hat{\sigma}_{Sy}^2\right\}, \qquad (\mathbf{2.14})$$

where $q_{S,a}$ are catchability parameters for the acoustic survey ($max_a q_{S,a} = 1$), $w_{a,y}$ are stock body mass-at-age, and $\hat{\sigma}_{Sy}^2$ is the estimated coefficient of variation (CV) of the biomass index. The age-composition of the Smith Sound component was informed by trawl samples collected during the acoustic survey (Table A9). Age-samples, $J_{S,a,y}$, were modeled using the negative binomial distribution,

$$J_{S,a,y} \sim NB\left\{q_{S,y}q_{S,a}N_{S,a,y}, k\right\}, \qquad (\mathbf{2.15})$$

where $q_{S,y}$ is the fully selected sampling rate in year y. The portion of the stock in Smith Sound, $D_{a,y} = N_{S,a,y}/N_{a,y}$, was then modeled using an age and year autoregressive process [AR(1)] for the logit of D (same structure as used for M process errors; Equation 2.5), and this was used to impose a year dependent adjustment of the portion of the stock available to the RV survey,

$$E\left(I_{\mathrm{RV},a,y}\right) = \begin{cases} q_a N_{a,y}\exp\left(-tZ_{a,y}\right), & y \neq 1995,\ldots,2009 \\ q_a\left(1 - D_{a,y}\right)N_{a,y}\exp\left(-tZ_{a,y}\right), & y = 1995,\ldots,2009 \end{cases} \qquad (\mathbf{2.16})$$

2.1.2.3. Tagging

Data from an extensive tagging program (Table A10) have been integrated into NCAM. These data provide useful information on mortality rates estimated in the model. First, the length of tagged fish are converted to age using a Von Bertalanffy growth model (Cadigan and Konrad 2016). The size of the tagged population from each experiment x can be modeled as

$$N_{x,a+1,y+1} = \begin{cases} s_{x,y} N_{0\ x,a,y} \exp\left(-F_{x,a,y} - M_{a,y} - \tau_{x,y}\right) & \text{if } y = y_x \\ N_{x,a,y} \exp\left(-F_{a,y} - M_{a,y} - \tau_{x,y}\right) & \text{if } y > y_x, \end{cases} \qquad (\mathbf{2.17})$$

where $N_{0\ x,a,y}$ is the number of cod tagged and released in a given experiment, $F_{x,a,y}$ is the fishing mortality rates experienced by the tagged fish in each experiment, $M_{a,y}$ is the rate of natural mortality for the whole stock (Equation 2.3), s_x represents the portion of tagged cod that survive the process of being captured and tagged, and $\tau_{x,y}$ is the tag loss rate which depends on the time-at-liberty of a tagged fish. Tag loss is modeled using a Kirkwood model where the time-at-liberty of a fish, Δt, affects the probability that the fish retains its tag. Specifically,

$$\tau_{x,y}(\Delta t) = \left(\frac{b_1}{b_1 + b_2 \Delta t}\right)^{b_1}, \qquad (\mathbf{2.18})$$

which imposes a monotone decreasing function of Δt. Kirkwood b parameters (b_1 = 0.07386 and b_2 = 0.04433) from Cadigan and Brattey (2006) and estimates of short-term tagging survival (s_x = 97% between November–June and s_x = 78% between July–October) from Brattey and Cadigan (2004) were used.

Rates of $M_{a,y}$, were assumed to be the same for all fish across all experiments, however, rates of $F_{x,a,y}$, were allowed to be random across experiments in the first year of the experiment. That is,

$$F_{x,a,y} = p_x F_{a,y} \exp(U_x) \quad \text{if } y = y_x, \qquad (\mathbf{2.19})$$

where $F_{a,y}$ is the rate of fishing mortality for the whole stock (Equation 2.3), and p_x represents an adjustment for partial exposure to the fishery, which is estimated using monthly landing statistics, and $U_x \sim N\left(0, \sigma_{fx}^2\right)$ adds random variations around $F_{a,y}$. These random variations were implemented to account for incomplete mixing of cod tagged and released at discrete experiment locations (e.g., Trinity Bay in 3L) throughout the rest of the 2J3KL stock. It is assumed that after a year has passed, the fish tagged in each experiment have sufficiently mixed with the rest of the stock.

The catch of tagged fish, $C_{x,a,y}$ is then predicted using the Baranov catch equation,

$$C_{x,a,y} = N_{x,a,y} 1 - \exp\left(-Z_{x,a,y} - \tau_{x,y}\right) \frac{F_{x,a,y}}{Z_{x,a,y} + \tau_{x,y}}, \qquad (\mathbf{2.20})$$

where $Z_{x,a,y}$ is the total mortality rate ($Z_{x,a,y} = F_{x,a,y} + M_{a,y}$). Finally, the number of reported tags are modeled using a negative binomial distribution,

$$R_{x,a,y} \sim \begin{cases} NB\left\{\lambda_x C_{x,a,y}, k_1\right\} & \text{if } y < 1997 \\ NB\left\{\lambda_y C_{x,a,y}, k_2\right\} & \text{if } y \geq 1997, \end{cases} \qquad (\mathbf{2.21})$$

where λ_x is a catch-all parameter for variable tag reporting rates, additional initial tagging mortality and additional tag loss for each experiment (sensu θ in Myers et al. 1996), and λ_y are annual reporting rates informed by the model described in Konrad et al. (2016). The distinction in how the tagging data are handled arises from modifications in the tagging program,

specifically the introduction of high- and low-reward tags in 1997. Reporting rates of the low reward tags could then be estimated by assuming a 100% return rate for high-reward tags. Also note that separate over-dispersion parameters, k_1 and k_2, were estimated for the pre and post 1997 tagging periods.

2.2. ESTIMATION AND MODEL SELECTION

Base-case NCAM and all subsequent models presented in this document were fit using the same estimation approach. Fixed effects parameters, denoted as $\boldsymbol{\theta}$, were estimated using maximum likelihood estimation (MLE) based on the marginal likelihood ($L(\boldsymbol{\theta})$). This approach involves "integrating out" random effects, represented by $\boldsymbol{\Psi}$. Letting S denote the data, the marginal likelihood is expressed as

$$L(\boldsymbol{\theta}) = \iiint_{\boldsymbol{\Psi}} f_{\boldsymbol{\theta}}(S|\boldsymbol{\Psi}) g_{\boldsymbol{\theta}}(\boldsymbol{\Psi})\, \partial\boldsymbol{\Psi}. \qquad (\mathbf{2.22})$$

Here, $f_{\boldsymbol{\theta}}(S|\boldsymbol{\Psi})$ represents the joint probability density function of the data, while $g_{\boldsymbol{\theta}}(\boldsymbol{\Psi})$ is the joint probability density function for the random effects. The Template Model Builder (TMB; Kristensen et al. 2016) package in R (R Core Team 2021) is utilized for model implementation. The MLEs for $\boldsymbol{\theta}$ are derived by maximizing $L(\boldsymbol{\theta})$. The high-dimensional integral represented by Equation (2.22) is numerically evaluated within TMB using Laplace approximation. TMB also employs automatic differentiation to calculate the gradient function of Equation (2.22). The gradient function is automatically generated from $f_{\boldsymbol{\theta}}(S|\boldsymbol{\Psi})$ and $g_{\boldsymbol{\theta}}(\boldsymbol{\Psi})$, enhancing parameter estimation using derivative-based optimization methods. The nlminb function within R is used to find the MLE for $\boldsymbol{\theta}$.

Step-wise model selection was informed by model diagnostics, information criteria, and expert judgement (i.e., we ask whether a specific model formulation is statistically and ecologically defensible). Specifically, we use marginal Akaike Information Criterion, $AIC = -2\log\big(L(\boldsymbol{\theta})\big) + 2k$, where k represents the number of fixed parameters (Akaike 1974). Marginal AIC is known to have poor behaviour under state-space models (Greven and Kneib 2010), so it is treated as a coarse indicator of model fit. Pearson residuals are used to assess model fit though they are also known to have poor behaviour for state-space models. Information criteria and diagnostics were used as the primary guides for step-wise changes; however, biological realism was considered in parallel. Marginal AIC and Pearson residuals were used as better metrics were technically intractable when NCAM was developed. Future efforts should consider using marginal AIC and one-step-ahead residuals, if possible.

2.3. STEP-WISE CHANGES

2.3.1. Catch composition

A potential alternate approach to the ad-hoc adjustments of the variance of the catch composition data (see Equation 2.10) is to estimate σ_{Pa} in age blocks instead of applying fixed multipliers. This change will still allow differences in the variability of composition data across age groups, however it will not constrain the scale of the differences. For comparison to the base-case NCAM approach, we present results from a version of NCAM where σ_{Pa} is estimated for ages $\leq$ 2, 3–4, and $\geq$ 5. This model is labeled **M1** and base-case NCAM is labeled **M0**. Model **M1** resulted in a minor improvement in the diagnostics and AIC (see Results and Discussion section); this modification was therefore retained in subsequent models.

2.3.2. Survey conflicts

Interpreting trends from the Sentinel index has been a challenge, especially since it suggests a very different trajectory for the stock compared to the RV survey (Cadigan 2016a). To improve fits to the Sentinel index and avoid conflicts with the RV survey, a random walk on catchability was implemented (Equation (2.13); Cadigan 2016a). This resulted in reasonable diagnostics in 2016; however, conflicting patterns began to emerge in the stock assessment of Northern cod in 2019 (DFO 2019a). Since the model can account for changes in catchability across years, the conflicts appear to be arising from diverging trends in the age composition of the Sentinel index. The specific cause, or causes, of diverging trends are currently unknown.

While it would be preferable to utilize parametric equations to explain the diverging trends, extending the random walk formulation offers a potential solution to the conflicting patterns. Allowing catchability to vary across both years and ages as follows:

$$\log\left(q_{s,a,y}\right) = \log\left(q_{s,a}\right) + \Delta_{s,a,y}. \qquad (\mathbf{2.23})$$

should enable sufficient flexibility to capture the diverging trends. Here, $\Delta_{s,a,y}$ is assumed to follow an autoregressive process like that used to model M (Equation (2.4)). Two formulations are presented for comparison with the default temporal random walk approach, which was used in model **M1**: 1) a 2D random walk where the correlation parameters $\varphi_{q,\text{age}}$ and $\varphi_{q,\text{year}}$ are fixed to 1 (**M2**), and 2) a 2D autoregressive process where both correlation parameters are estimated (**M3**). Finally, to compare diagnostics and assess the influence of the Sentinel index on model estimates, a model run excluding the Sentinel data is also presented (**S1**).

Model diagnostics and AIC values were improved under both **M2** and **M3** (see Results and Discussion section). The more flexible approach, **M3**, was used in subsequent models.

2.3.3. Extending the time series

While NCAM integrates most of the available data from the tagging program, and all of the data from the modern (1997 onward) high- and low-reward T-bar tagging program, thousands of releases from nearly 100 tagging experiments are not included. This is largely because NCAM was constructed to start in 1983, when the fall RV survey of 2J3KL began; however, the tagging program extends back to 1954 (Figure 2.2). Landings have also been reconstructed back to 1508 (Schijns et al. 2021) and catch-at-age estimates are available back to 1962 (Brattey et al. 2018). We therefore extended the model back to 1954 to leverage these data. Versions of the model that extend back to 1954 are generally referred to as xteNCAM. The base-case version is labeled **M4** and it follows the core structure of NCAM, specifically model **M3**, with modifications described below.

2.3.3.1. Additional catch data

We used estimates of landings presented in Schijns et al. (2021) for 1954–58 and the remainder were values reported in the last stock assessment of Northern cod (DFO 2022a; Table A1). Likewise, catch-at-age estimates back to 1962 reported in the last assessment were utilized (Table A2).

Total catch bounds used to censor the landings in NCAM were based on expert opinion solicited during the 2016 assessment of Northern cod. At that meeting, the constant catch bounds initially described in Cadigan (2016a) were modified to include three periods:

1. a pre-moratorium period (1983–91) where the upper catch bound was set to 1.5 times the reported landings;
2. an early post-moratorium period (1992–2005) where the upper bound was set to 2.0; and

3. a recent period (2006–present) where the upper bound was allowed to vary if information on the recreational fishery was available (Brattey et al. 2018).

The lower bound for all periods was fixed at 1.1. For xteNCAM, we retained the 1.1 lower bound and extended the 1.5 upper bound for the pre-moratorium period back to 1978. The scale of the landings prior to 1977 are more uncertain as catches may have been relatively unconstrained prior to the establishment of the 200-mile limit. Alternatively, there may have been little motivation for under-reporting through this period, so reported landings may be relatively accurate. Given the wide range of possibilities, including extensive foreign fishing pressure on the stock through this period, we opted to increase the upper bound to 2.0 for 1954–77.

2.3.3.2. Additional tagging data

The only difference in the data supplied to NCAM and xteNCAM between 1983–2020 is the addition of data based on the disc tagging program. Disc tags were the main tag type used in the tagging program between 1962–66 and they continued to be used extensively between 1978–91, after which they were phased out and T-bar tags became the main type [Table A10; Taggart et al. (1995)]. Disc tag deployments and recaptures therefore represent an important source of information through this earlier period. Data from disc tags, however, require a different set of tag loss assumptions. Tag loss rates for T-bar tags are based on Kirkwood model parameter estimates in Cadigan and Brattey (2006) and these estimates were derived from double tagging experiments. The shape of the T-bar tag loss curve is unlikely to be the same for disc tags and, because double tagging experiments were not conducted for disc tags, coarser estimates of tag loss from Barrowman and Myers (1996) were utilized. Specifically, an instantaneous rate of shedding disc tags of 0.1 and 0.02 was assumed for the first year and subsequent years-at-liberty, respectively. Previous assumptions of mortality directly attributed to tagging ($s_{x,y}$ in Equation (2.17) was set to 97% in winter, and 78% in summer; Brattey and Cadigan 2004) were maintained for the disc tag data, and the same corrections for incomplete mixing and partial exposure to the fishery and other sources of mortality were applied (Equation (2.19)). Like all experiments prior to 1997, the additive effects of tag reporting rate plus additional initial tagging mortality plus additional short-term tag loss were estimated using experiment-specific fixed parameters (Equation (2.21)).

For the tagging data to be used in an age-based assessment model such as NCAM, the length-based information recorded for each tagged fish upon release has to be converted to age. A cohort time-series Von Bertalanffy growth model for Northern cod was constructed for this purpose (Cadigan and Konrad 2016); however, this model is based on data from the DFO RV survey of 2J3KL which only goes back to 1983. Cohort-specific growth parameters were used to generate deterministic hind-casts estimates of mean length-at-age. Hind-cast estimate from this model tend to transition from means informed by cohort-specific growth towards means based on overall growth rates (i.e., towards time-invariant mean lengths-at-age). These hind-casts were used to fill in the mean lengths-at-age matrix which is used to assign ages to fish tagged between 1954–82.

Given a large number of assumptions were required to utilize the disc tag data, we decided to assess the sensitivity of the model to these data. We therefore excluded the disc tag data from model **M4** to evaluate whether the disc tag data were providing useful information back to 1954 (sensitivity test **S4**).

2.3.3.3. Weight-at-age

Beginning-of-year and mid-year weights-at-age used in NCAM are based on a cohort-based Von Bertalanffy growth model for Northern cod and this model utilizes data from the DFO RV survey of 2J3KL (Cadigan 2016b). These estimates are used in NCAM to estimate

beginning-of-year spawning stock biomass (SSB) and to estimate landings from the fishery using mid-year weights-at-age. Like the length-based model used in the processing of the tagging data (see previous section), hind-casts from this model were used to estimate beginning-of-year and mid-year weights-at-age for the years that pre-date the RV survey of 2J3KL (1954–82; Table A4, A5). Again, estimates eventually converge on time-invariant mean weights-at-age. While these estimates are not ideal, they should suffice for a coarse reconstruction of biomass back to 1954.

2.3.3.4. Initial abundance

The lack of catch-at-age data between 1954–61 did challenge the estimation of initial abundance, $N_{1954,a}$, of ages $a = 3, \ldots, 14$. Rather than estimating initial abundances freely, we applied exponential decay such that abundances for ages $a = 3, \ldots, 14$ are populated using estimates of recruits, $N_{2,1954}$, in the first year as well as estimates of Z. Initial abundance for the remaining ages are calculated as follows:

$$N_{a,1954} = N_{a-1,1954} \cdot \exp\left(-Z_{a-1,1954}\right). \qquad (\mathbf{2.24})$$

This modification avoided convergence issues and generated more stable results. The trade-off is that this approach is less flexible and potentially less realistic than freely estimating initial abundance. In base-case NCAM, the process errors on M (Equation (2.4)) were forced to zero for the first year to avoid confounding with initial abundance estimates. Since we are using a less flexible approach, we have relaxed this constraint and, rather than forcing the process errors to zero, we couple the process errors such that $\delta_{a,1954} = \delta_{a,1955}$. This change introduces a little more flexibility while avoiding issues with estimation.

2.3.3.5. Natural mortality

The accepted version of NCAM in the 2016 assessment included a baseline M assumption which imposed a large spike in M between 1991–94 (labeled M-shift; Brattey et al. 2018). This spike helped reduce the process error variance around baseline M and, consequently, reduced uncertainty around the projections of the stock. Baseline M values exceed 2.0 for most ages through 1991–94 and average approximately 0.4 through 1983–90 and 1995–present (Table 2.3). For xteNCAM, baseline M values for 1962–82 were set to the same values as those used between 1983–90. However, pre-collapse levels of M may have been lower than post-collapse levels. Different M assumptions were therefore considered and are described in the Baseline natural mortality section.

2.3.4. Juvenile survey indices

There are two long-term surveys designed to monitor the abundance of juvenile cod:

1. the Fleming survey (see Lewis et al. 2022 for details), and
2. the Newman Sound survey (see Gregory et al. 2019 for details) (Table A11).

The Fleming survey was conducted along the Northeast Coast of Newfoundland from 1959–64, 1992–97, and 2020 (Figure 2.2). The survey methods remained consistent over time, sampling the same season (October–September) and sites using a beach seine. Note however that the seine material changed from cotton to nylon in 1992. Though the time series is fragmented, consistent methods permit direct comparisons of catch rates of cod aged 0-2. The Newman Sound survey uses similar methods as the Fleming survey, except it is isolated to Newman Sound, Bonavista Bay. The area is, however, sampled more intensely; sampling is conducted from July to November, and an index has been produced for nearly every year since 1995 (Figure 2.2).

Both indices are potentially useful for informing trends in recruitment in the model. The Fleming survey offers an historic perspective on the relative abundance of recruits while the Newman Sound survey provides more recent trends. Indeed, the latter appears to be a promising indicator of year-class strength (Lunzmann-Cooke et al. 2021). To utilize this information, xteNCAM (model **M4**) had to be extended further to include ages 0 and 1. Like the extension of the time series, this required extra assumptions to be made.

Though rates of M are expected to be significantly greater for smaller age 0 and 1 cod compared to the larger components of the stock (Lorenzen 2022), for simplicity we first utilize the baseline levels of M for age 2 in Table 2.3 for ages 0 and 1. Different M assumptions are described in the Baseline natural mortality section. Weights-at-age are also significantly smaller and, like the hind-cast for the time series extension, weights for ages 0 and 1 are extrapolated using the Von Bertalanffy growth model described by Cadigan (2016b). Finally, F and catch-at-age for ages 0 and 1 are assumed to be zero.

With process and biological inputs addressed, the next step is to relate the juvenile survey indices to the modeled estimates of abundance. To do so, we followed Equation (2.11), assuming that the indices are log-normally distributed and that the catchability, q_a, is time-invariant and the same for both surveys (model **M5**). We also utilize a design matrix, X, to evaluate potential differences in catchability across the Fleming and Newman Sound surveys, as well as seine type (cotton or nylon). That is, $q_i = \Delta_q X_i$, where Δ_q represents the parameter estimates associated with the main covariate, age, and survey or seine type covariates. Model **M6** estimates the difference in catchability of the Fleming survey from the Newman Sound survey, and model **M7** estimates the difference in catchability of the cotton from the nylon seine. The difference in catchability of ages 0 and 1 is kept constant in both models as an interactive effect could not be estimated. AIC values indicate that the time- and survey-invariant catchability is the most parsimonious; the **M5** formulation was therefore retained in subsequent models.

2.3.5. Stock-recruitment (S-R) relationships

Recruitment in base-case NCAM and all previously mentioned variations (models **M1**-**M7**) all assume that recruitment follows a random walk with a break point at 1992 (Equation (2.2)). Though this is a flexible approach that captures the dramatic shift in recruitment following the collapse, it does have a tendency to shrink recent estimates of recruitment towards the post-collapse mean, r_2 (Cadigan 2016a). Though a S-R relationship would limit this issue, the large and rapid reduction in SSB in the early-1990s leaves a gap in the S-R scatter at intermediate SSB values and, as such, the fitting of curves would invariably be connecting two clouds of points (DFO 2019b). Earlier versions of xteNCAM did indicate that this space may be filled by estimates of SSB and recruitment from the 1970s. We therefore attempt to internally predict recruitment as a function of SSB.

A simple hypothesis for the S-R relationship is to assume that the number of recruits linearly increase as a function of SSB,

$$N_{0,y} = \beta S_y, \qquad (\mathbf{2.25})$$

where β represents the time-invariant average number of recruits per unit of SSB, and S_y is the sum product of numbers-at-age $N_{a,y}$, weights-at-age $w_{a,y}$, and maturity-at-age $p_{a,y}$. The model using this relationship is labeled **M8**. Previous analyses indicate that the S-R relationship follows this form (Rose and Rowe 2022). This is, however, an atypical S-R relationship as it is commonly assumed, on first principles, that density-dependent effects will impose an asymptotic relationship with SSB. However, it is possible that the bio-geographic expansion of the stock

with stock size helps buffer density-dependent effects and, as such, we have yet to observe the asymptote (Rose and Rowe 2022).

Alternatively, it is possible that previous analyses have failed to find evidence of density-dependence as S-R relationships have been estimated outside the model. This practice likely suffers from inconsistent estimates due to conflicting assumptions between how recruitment is estimated and how it is modeled externally (Punt 2023). So as not to discount possible density-dependence, we implement a Beverton-Holt equation (Beverton and Holt 1957), where

$$N_{0,y} = \frac{\alpha S_y}{1 + \beta S_y}. \qquad (\mathbf{2.26})$$

In this equation, α accounts for the fraction surviving the pre-recruit stage from density-independent mortality and β captures mortality from both density-independent and density-dependent mortality. The version of xteNCAM assuming a Beverton-Holt relationship is labeled **M9**.

A common criticism of the Beverton-Holt relationship is that it assumes compensation. This assumption may lead to less conservative advice if depensation is at play as the stock would be much less resilient to perturbations than assumed. To check for evidence of depensation, we implement the sigmoidal Beverton-Holt relationship described by Myers et al. (1995), which adds a γ parameter to control depensation in the recruitment curve:

$$N_{0,y} = \frac{\alpha S_y^{\gamma}}{1 + \beta S_y^{\gamma}}. \qquad (\mathbf{2.27})$$

Specifically, if γ equals 1, there is no depensation, while γ estimates greater than 1 are indicative of depensatory dynamics (Myers et al. 1995). If depensation is present, this relationship can be used to identify an Alle-effect zone (Perälä et al. 2022) and, consequently, inform the setting of a Limit Reference Point (LRP) as it represents a formal quantification of a point below which recruitment is impaired. The model that assumes a sigmoidal Beverton-Holt relationship is labeled **M10**.

Both the Beverton-Holt and sigmoidal Beverton-Holt relationships provide evidence of density-dependence. To ensure that support of the Beverton-Holt curve is not driven primarily by the juvenile survey data, we also ran two sensitivity tests where xteNCAM was fit without the juvenile survey data but with a linear (model) and Beverton-Holt (model) S-R relationships. For comparison, a version of model **M5** was also run excluding the juvenile survey data (model **S5**). Overall, the Beverton-Holt relationship appears to be the most defensible option (see Results and Discussion for more details). We therefore proceed with using the Beverton-Holt equation in subsequent models.

2.3.5.1. Per-recruit reference points

The use of S-R relationships enable the calculation of per-recruit reference points (e.g., Albertsen and Trijoulet 2020). Per-recruit reference points may serve as an alternate proxy for the current LRP for this stock, which was defined as the average SSB from the 1980s as this was the last time good recruitment was observed (DFO 2019b). Per-recruit calculations specifically enable the estimation of Maximum Sustainable Yield (MSY), F_{MSY}, and B_{MSY}. The commonly used $40\%B_{\text{MSY}}$ proxy of a LRP (DFO 2009) can therefore be considered. Likewise, $80\%B_{\text{MSY}}$ may serve as a proxy for the Upper Stock Reference point (USR) for the stock, which is currently undefined.

We follow methods described in Albertsen et al. (2020) to internally calculate per-recruit reference points. In short, the method begins by projecting the size of a cohort of fish, starting from a single recruit ($N_0 = 1$), by applying fully selected fishing mortality ($\tilde{F}$), average fishing selectivity ($\bar{s}_a$), and average natural mortality ($\bar{M}_a$):

$$N_a = N_{a-1}\exp\left(-\tilde{F}\bar{s}_a + \bar{M}_a\right). \qquad (\mathbf{2.28})$$

Spawning biomass-per-recruit (SPR) is then calculated by

$$S_R\left(\tilde{F}\right) = \sum_a N_a\, \bar{w}_a^{(s)} \bar{p}_a, \qquad (\mathbf{2.29})$$

where $\bar{w}_a^{(s)}$ and $\bar{p}_a$ are average stock weights and maturities-at-age, respectively. Similarly, yield-per-recruit (YPR) is calculated by

$$Y_R\left(\tilde{F}\right) = \sum_a N_a\, \bar{w}_a^{(c)} \frac{\tilde{F}\bar{s}_a}{\tilde{F}\bar{s}_a + \bar{M}_a}\left(1 - \exp\left(-\tilde{F}\bar{s}_a - \bar{M}_a\right)\right), \qquad (\mathbf{2.30})$$

where $\bar{w}_a^{(c)}$ are average catch weights-at-age. Finally, equilibrium spawning biomass (S_e), recruitment (R_e), and yield can be obtained by solving these equations:

$$S_e\left(\tilde{F}\right) = S_R\left(\tilde{F}\right) \cdot R\left(S_e\left(\tilde{F}\right)\right), \qquad (\mathbf{2.31})$$

$$R_e\left(\tilde{F}\right) = R\left(S_e\left(\tilde{F}\right)\right) = \frac{S_e\left(\tilde{F}\right)}{S_R\left(\tilde{F}\right)}, \text{ and} \qquad (\mathbf{2.32})$$

$$Y_e\left(\tilde{F}\right) = Y_R\left(\tilde{F}\right) \cdot R_e\left(\tilde{F}\right) = \frac{Y_R\left(\tilde{F}\right) \cdot S_e\left(\tilde{F}\right)}{S_R\left(\tilde{F}\right)}. \qquad (\mathbf{2.33})$$

An optimization routine is then applied to solve for the F at which the equilibrium yield is maximized (F_{MSY}), from which corresponding levels of SSB are derived (B_{MSY}). We used a Newton-Raphson method to solve for the optimal yield for models fitting a Beverton-Holt S-R relationship (**M9**+). See Albertsen et al. (2020) for a more detailed description of the calculations behind per-recruit reference points.

Notice, however, that this method requires the averaging of metrics such as $\bar{s}_a$ and $\bar{M}_a$. These processes change through time and, as such, optimal yields will not be time-invariant, as is commonly assumed. DFO's Precautionary Approach Policy indicates that "in general, as long as a time series as possible should be used in establishing reference points for a stock" (DFO 2009). This implies that averages should be based on the whole time series; however, averaging across non-stationary temporal processes can be problematic. DFO's guidelines on writing rebuilding plans per the Fish Stock Provisions is more specific with regards to MSY, defining it as "the maximum average annual catch, or yield, that can be removed from a stock over an indefinite period under prevailing environmental conditions" (DFO 2022b). Unfortunately, these guidelines lack a definition of prevailing environmental conditions. We therefore implemented a flexible approach where the years across which to calculate averages can be adjusted. We utilize geometric means to minimize the influence of relatively extreme values.

2.3.6. Baseline natural mortality

Natural mortality is a critical but notoriously difficult population parameter to estimate. Though all previously mentioned NCAM and xteNCAM models estimate time-varying rates of natural

mortality ($M_{a,y}$), baseline levels are assumed. That is, values for $m_{a,y}$ in Equation (2.4) are supplied (Table 2.3). These "M-shift" values were constructed from estimates of $M_{a,y}$ from a previous version of NCAM that applied time-invariant values for m_a. The main idea was to introduce a large spike in M through 1991–94 to account for the collapse using the baseline process and, in doing so, reduce the level of process error variance required for the process errors ($\delta_{a,y}$) to account for this spike (Brattey et al. 2018). This was justified as the 1991–94 period was associated with a collapse of the cod stock and the demersal fish community as a whole. There is also uncertainty with regard to the portion of this spike that can be attributed to unreported fisheries landings. Regardless of the cause, the M-shift values effectively assumes that the spike was an isolated event and the variance associated with it should not be included in the projections from the model.

In this document, we revisit the estimation of baseline rates of M. Rather than supplying fixed values, we attempt to estimate $m_{a,y}$ using three approaches: 1) constant m (model **M11**), 2) allometric m_a (model **M12**), and 3) m_y blocks (model **M13**). Attempting to estimate both m and δ represents another step toward current best practices, which advise against using pre-specified rates of M (Punt 2023).

The constant option can be looked at as a straightforward NULL hypothesis under which the M process is assumed to be stationary, where the process errors ($\delta_{a,y}$) cause estimates of $M_{a,y}$ to varying above and below a long term mean (m) with correlation over time and age:

$$\log(M_{a,y}) = \log(m) + \delta_{a,y}. \qquad (\mathbf{2.34})$$

In the allometric approach, we aim to apply the generalized concept that mortality decreases as body length increases, a pattern believed to be applicable during various stages of a fishes lifecycle, particularly juveniles (Lorenzen 2022). We extend Equation (2.34) to include a standard model for allometric scaling by length l:

$$\log(M_{a,y}) = \log(m_{a,y}) + \delta_{a,y}, \text{ where } m_{a,y} = m_r\left(\frac{l_{a,y}}{l_r}\right)^b. \qquad (\mathbf{2.35})$$

In this equation, b is the allometric exponent, m_r is the average mortality rate at reference length l_r, and $l_{a,y}$ is the average length-at-age. Average length-at-age was produced using the Von Bertalanffy growth model used to convert the lengths of tagged cod to age (Cadigan and Konrad 2016), except the estimates are stock-level, like mean weights-at-age (Cadigan 2016b), rather than division and quarter specific. The reference length was set to the maximum average length-at-age, which was 99 cm.

Finally, the m_y blocks option is analogous to M-shift, and it is therefore called M-shift2, except separate baseline levels of M are estimated for the pre-collapse (<1991), collapse (1991–94), and post-collapse (>1994) periods:

$$\log(M_{a,y}) = \log(m_y) + \delta_{a,y}, \text{ where } m_y = \begin{cases} m_1 & \text{if } y < 1991 \\ m_2 & \text{if } 1991 \le y \le 1994 \\ m_3 & \text{if } y > 1994. \end{cases} \qquad (\mathbf{2.36})$$

Like the original M-shift formulation, this model attempts to capture substantive shifts in baseline levels of M to reduce magnitude of the δ values required to explain the shifts. These breakpoints are informed by hindsight as shifts in productivity have been noted in previous analyses of this stock (e.g., Lilly 2008, Brattey et al. 2018) and the broader demersal fish community (e.g., Pedersen et al. 2017, Dempsey et al. 2018).

3. RESULTS AND DISCUSSION

3.1. GENERAL OBSERVATIONS

In our effort to improve and expand NCAM (Cadigan 2015, 2016a), we have discovered that, despite several changes to the underlying data and structure of the model, resultant estimates of key metrics like spawning stock biomass (SSB) are very consistent across model variations (Figure 3.1). This suggests that the model is primarily driven by data rather than assumptions. That said, we have managed to make incremental improvements that generally improve the fit of the model to data, and our efforts to include more data have refined our understanding of trends in productivity in the stock. The combined use of past tagging data, a longer series of reported landings, and juvenile survey data have enabled the first quantification of uncertainty in vital rates, stock size, and recruitment levels back to 1954 using modern methods. With regards to recruitment, its scale does show some sensitivity to model choices, with older estimates being most affected. The most notable outlier with regards to recruitment is model **M8**, which assumes a linear S-R relationship (Figure 3.1). Differences in rates of M were imposed by the allometric model **M12**; however, those effects are largely isolated to ages <5 and therefore not visible in Figure 3.1. Such results will be discussed in detail below.

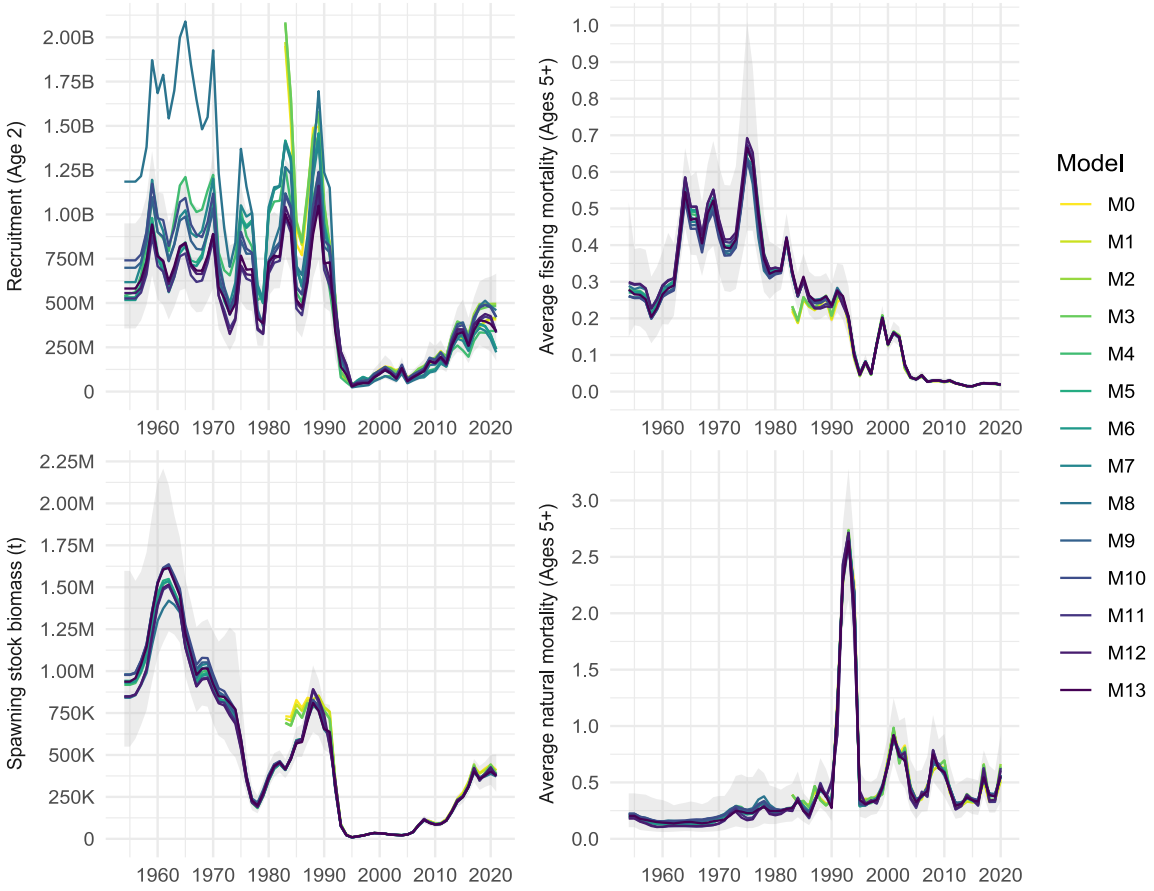

*Figure 3.1: Trends in recruitment to age 2, spawning stock biomass, fishing mortality, and natural mortality across all NCAM and xteNCAM models. Shaded area represents the 95% confidence interval from model **M13** (xteNCAM including juveniles, Beverton-Holt S-R relationship, and shifts in baseline levels of natural mortality).*

3.2. CATCH COMPOSITION

Our replacement of the ad-hoc adjustments of the variance of the catch composition data used in base-case NCAM, **M0**, resulted in relatively subtle changes to the catch composition diagnostics (Figure 3.2). Though standardized residuals showed little difference, a drop in AIC values does indicate improved model performance, which may stem from the reduction in the F process variation (Table 3.1). This change to the estimation of variance for the catch composition data was retained in subsequent models as it is less ad-hoc and more data driven.

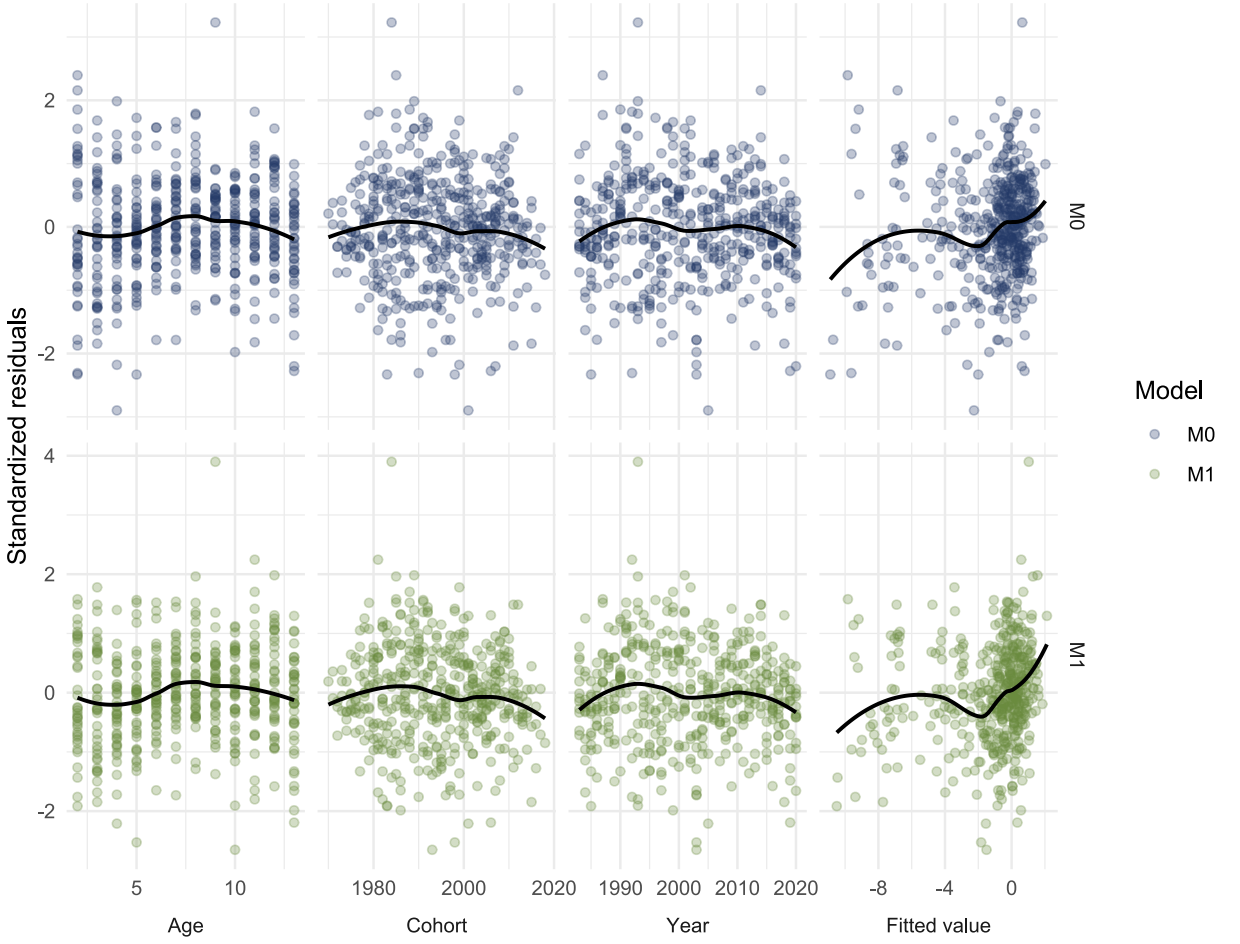

*Figure 3.2: Standardized residuals from catch composition continuation ratio logits faceted by age, cohort, year, and fitted value for model **M0** (base-case NCAM), and **M1** (estimates catch composition variance parameter separately for age groups ≤2, 3–4, and ≥5 as an alternative to fixed multipliers). Black lines are lowess curves.*

*Table 3.1: Comparison of the number of parameters, k, log-likelihood, $ln(L)$, Akaike information criterion, AIC, and select parameter estimates for models **M0** (base-case NCAM), and **M1** (estimates catch composition variance parameter separately for age groups ≤2, 3–4, and ≥5 as an alternative to fixed multipliers).*

Model	k	$ln(L)$	AIC	ΔAIC
M1	**147**	**10182.31**	**20658.62**	**0.000**
M0	**145**	**10195.96**	**20681.92**	**23.301**

Quantity	**Symbol**	**M0**	**M1**
Age composition error	σ_P	0.231	NA
Age composition error (age 2)	σ_{P_a}	NA	1.047
Age composition error (ages 3-4)	-	NA	0.627
Age composition error (ages 5-14)	-	NA	0.282
RV survey observation error	σ_{RV}	0.416	0.419
SN survey observation error	σ_{SN}	0.590	0.587
SN q random walk error	$\sigma_{\text{SN}_{RW}}$	0.270	0.268
Age correlation in process errors	$\varphi_{\delta,\text{age}}$	0.802	0.786
Year correlation in process errors	$\varphi_{\delta,\text{year}}$	0.577	0.583
Process error variance	σ_δ	0.227	0.228
Age correlation in F	$\varphi_{F,\text{age}}$	0.865	0.875
Year correlation in F	$\varphi_{F,\text{year}}$	0.996	0.996
F variance parameter	σ_F	0.284	0.278
Mean recruitment (pre 1992; billion)	r_1	1.926	1.943
Mean recruitment (post 1992; billion)	r_2	0.092	0.096
Variance of log-recruitment	σ_r	0.355	0.322
Variance of tagging F deviations (pre 1997)	$\sigma_{f_{x,1}}$	0.750	0.755
Variance of tagging F deviations (post 1997)	$\sigma_{f_{x,2}}$	1.065	1.059
NB overdispersion parameter for pre 1997 tag experiments	κ_1	59.565	62.264
NB overdispersion parameter for post 1997 tag experiments	κ_2	7.974	8.076

3.3. SURVEY CONFLICTS

Conflicting patterns in recent indices from the RV and Sentinel surveys have contributed to poor residual patterns, which are especially noticeable in the Sentinel survey residuals versus cohort plot from model **M1** (Figure 3.3). These patterns are resolved when a random walk or autoregressive process for catchability is applied over years and ages (models **M2**, and **M3**; Figure 3.3). This additional flexibility is further supported by reductions in AIC values for models **M2**, and **M3** (Table 3.2). Though this resolved the conflicting trends, the underlying cause of the differences remains unknown. Conflicting trends may be related to shifting portions of specific age or size groups residing in the offshore through the summer and fall, and therefore inaccessible to the inshore Sentinel survey. It may also be related to shifts in the ages captured by the gillnets used in the Sentinel survey as a consequence of shifts in the lengths-at-age of the stock.

Poor residual patterns in the RV survey are resolved by the more flexible catchability models for the Sentinel index (models **M2**, and **M3**), and they are also resolved if the Sentinel index is removed from the model (test **S1**; Figure 3.4). All of these models, including the sensitivity test where the Sentinel index is removed, have very little effect on the estimates of stock size or vital rates (Figure 3.5). It therefore appears that either discarding the Sentinel index from the model or retaining it using a more flexible catchability structure are viable options. We have opted to retain the Sentinel series here and, given its comparable diagnostics and relatively low AIC score, we utilize the structure of **M3** in all subsequent models.

Though we have retained the index in subsequent analyses, it is still important to consider the pros and cons of these data. On the positive side, our analysis suggests that the impact of the Sentinel index on the overall assessment is relatively minimal, indicating that its inclusion or exclusion may not significantly affect key estimates. However, its utility in enhancing our comprehension of cod dynamics remains uncertain (DFO 2022a). Additionally, the lack of clarity regarding factors influencing the Sentinel series presents a challenge in structuring catchability parameters. Removing the Sentinel series would, however, leave a spatial gap in the monitoring of this stock as the inshore is not covered by the RV survey. Further research is therefore required to gain a better understanding of how these data relate to the overall stock.

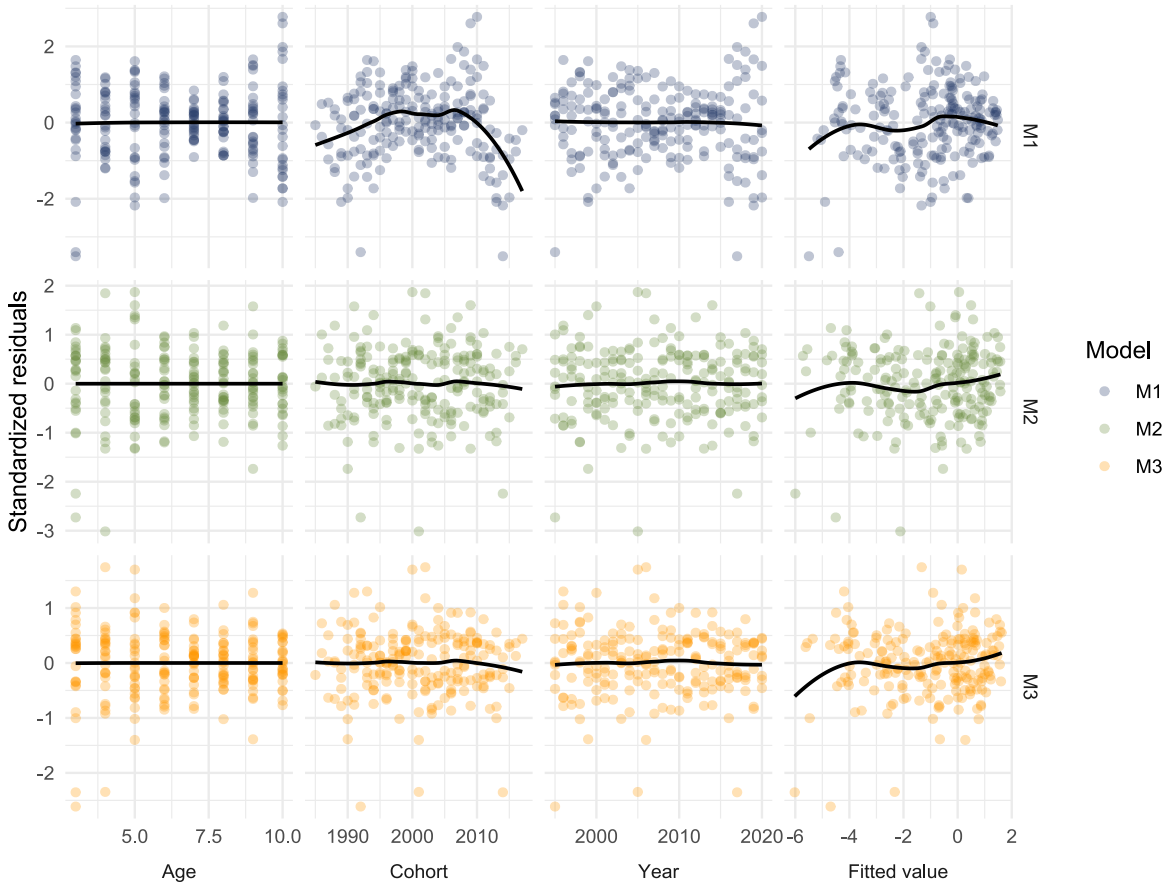

*Figure 3.3: Standardized residuals from the Sentinel survey index faceted by age, cohort, year, and fitted value for model **M1** (estimates catch composition variance parameter separately for age groups ≤2, 3–4, and ≥5 as an alternative to fixed multipliers), **M2** (random walk process for Sentinel survey catchability across both years and ages), and **M3** (autoregressive process for Sentinel survey catchability across both years and ages). Black lines are lowess curves.*

*Table 3.2: Comparison of the number of parameters, k, log-likelihood, $ln(L)$, Akaike information criterion, AIC, for models **M1**, **M2**, and **M3** and select parameter estimates from models **M1** (estimates catch composition variance parameter separately for age groups ≤2, 3-4, and ≥5 as an alternative to fixed multipliers), **M2** (random walk process for Sentinel survey catchability across both years and ages), **M3** (autoregressive process for Sentinel survey catchability across both years and ages), and **S1** (model **M1** excluding the Sentinel survey index). Sensitivity test **S1** was excluded from the AIC table as it does not use the same data.*

Model	$\boldsymbol{k}$	$\boldsymbol{ln(L)}$	$\boldsymbol{AIC}$	$\boldsymbol{\Delta AIC}$
M3	150	10052.64	20405.28	0.000
M2	148	10083.27	20462.54	57.267
M1	147	10182.31	20658.62	253.343

Quantity	**Symbol**	**M1**	**M2**	**M3**	**S1**
SN survey observation error	σ_{SN}	0.587	NA	NA	NA
SN q random walk error	$\sigma_{\text{SN}_{RW}}$	0.268	NA	NA	NA
Age correlation in SN q	$\varphi_{\text{SN}_q,\text{age}}$	NA	NA	0.867	NA
Year correlation in SN q	$\varphi_{\text{SN}_q,\text{year}}$	NA	NA	0.886	NA
SN survey observation error (age 3)	σ_{SN_a}	NA	0.694	0.652	NA
SN survey observation error (ages 4-14)	-	NA	0.163	0.121	NA
SN q variance parameter	σ_{SN_q}	NA	6.133	0.835	NA
RV survey observation error	σ_{RV}	0.419	0.394	0.390	0.390
Age composition error (age 2)	σ_{P_a}	1.047	1.046	1.043	1.053
Age composition error (ages 3-4)	-	0.627	0.607	0.612	0.643
Age composition error (ages 5-14)	-	0.282	0.275	0.277	0.285
Age correlation in process errors	$\varphi_{\delta,\text{age}}$	0.786	0.789	0.783	0.826
Year correlation in process errors	$\varphi_{\delta,\text{year}}$	0.583	0.413	0.392	0.546
Process error variance	σ_{δ}	0.228	0.280	0.284	0.233
Age correlation in F	$\varphi_{F,\text{age}}$	0.875	0.871	0.872	0.871
Year correlation in F	$\varphi_{F,\text{year}}$	0.996	0.996	0.996	0.996
F variance parameter	σ_F	0.278	0.284	0.284	0.283
Mean recruitment (pre 1992; billion)	r_1	1.943	2.040	2.048	2.027
Mean recruitment (post 1992; billion)	r_2	0.096	0.105	0.105	0.107
Variance of log-recruitment	σ_r	0.322	0.343	0.350	0.324
Variance of tagging F deviations (pre 1997)	$\sigma_{f_{x,1}}$	0.755	0.748	0.749	0.750
Variance of tagging F deviations (post 1997)	$\sigma_{f_{x,2}}$	1.059	1.053	1.053	1.055
NB overdispersion parameter for pre 1997 tag experiments	κ_1	62.264	60.558	60.950	61.656
NB overdispersion parameter for post 1997 tag experiments	κ_2	8.076	8.054	8.033	8.104

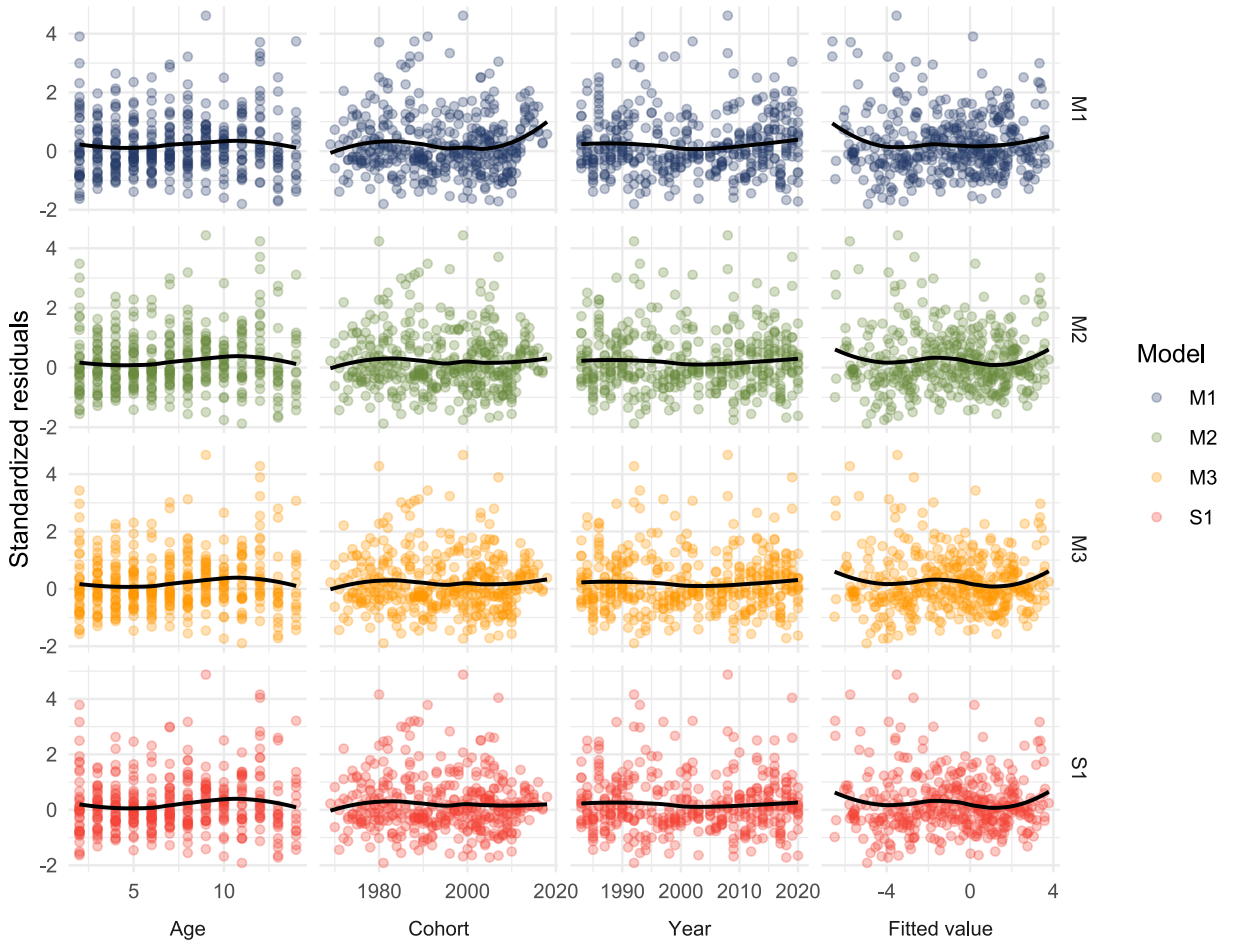

*Figure 3.4: Standardized residuals from the RV survey index faceted by age, cohort, year, and fitted value for model **M1** (estimates catch composition variance parameter separately for age groups ≤2, 3–4, and ≥5 as an alternative to fixed multipliers), **M2** (random walk process for Sentinel survey catchability across both years and ages), **M3** (autoregressive process for Sentinel survey catchability across both years and ages), and **S1** (model **M1** excluding the Sentinel survey index). Black lines are lowess curves.*

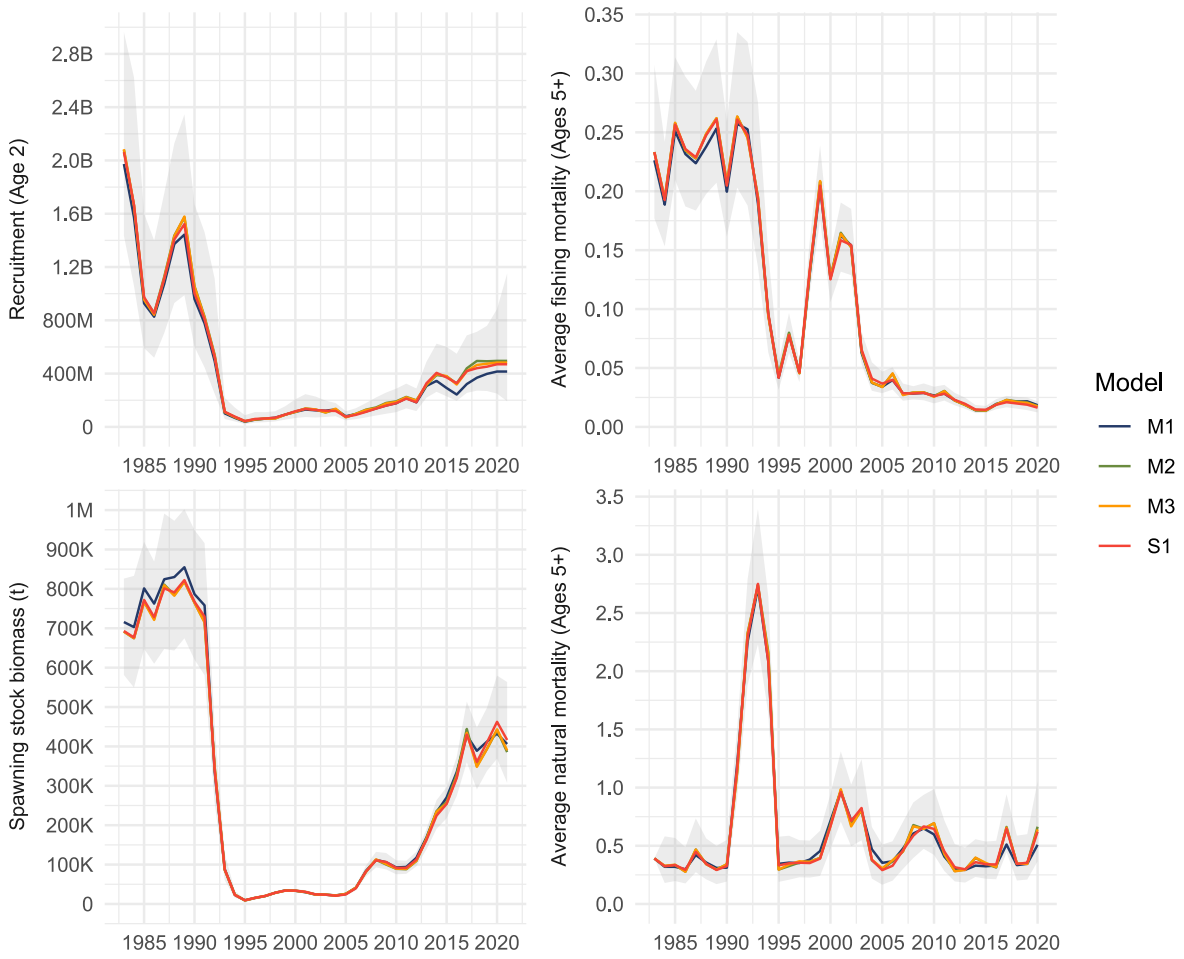

*Figure 3.5: Trends in recruitment to age 2, spawning stock biomass, fishing mortality, and natural mortality across models **M1** (estimates catch composition variance parameter separately for age groups ≤2, 3–4, and ≥5 as an alternative to fixed multipliers), **M2** (random walk process for Sentinel survey catchability across both years and ages), **M3** (autoregressive process for Sentinel survey catchability across both years and ages), and **S1** (model **M1** excluding the Sentinel survey index). Shaded area represents the 95% confidence interval from model **S1**.*

3.4. EXTENDING THE TIME SERIES

Diagnostics from the model utilizing data back to 1954, model **M4** (xteNCAM), were not drastically different from diagnostics of model **M3** (NCAM). There appears to be little issue with the fit to the catch-at-age data (Figure 3.6) or the RV survey index (Figure 3.7). Despite using additional disc tag data which required their own assumptions about tag loss, fits to observed T-bar recaptures appear comparable between NCAM and xteNCAM for experiments where both tag types were used (Figure 3.8). For other data sources that remained the same through the 1983–2020 time period, xteNCAM and NCAM predictions are virtually indistinguishable (not shown). Likewise, there are no substantive differences in estimates of SSB or vital rates (Figure 3.9). The most obvious difference between estimates from both models is the higher recruitment estimated by NCAM (Figure 3.9). This is likely related to the extension of the first recruitment random walk back to 1954, which seems to have caused a reduction in the pre-1992 mean recruitment parameter estimate (Table 3.3). Some parameter estimates relating to tagging were also affected (Table 3.3), such as the NB overdispersion parameter for the per

1997 tag experiments, where a lower value indicates more noise. However, increases in variances are expected given the addition of more data and a new tag type.

In the context of previous analyses, it is reassuring that our extended model show trends consistent with past assessments of this stock (Lilly 2008), which indicate that the stock declined severely in the 1960s and 1970s and partially recovered in the 1980s. Stock size prior to the 1960s has, however, always been assumed to be, or estimated to be, on the same scale or larger than levels in the 1970s (Rose 2004, Schijns et al. 2021). Our extended model contrasts previous results by indicating that the stock increased from the mid-1950s to the 1960s, revealing historic dynamics that have previously gone unobserved. Interestingly, our sensitivity test where we removed the disc tag data from the model suggests that this pattern would have remained unobserved if we were not using these data. This test (**S4**) resulted in an increase in the uncertainty of model predicted landings through the 1950s, 1960s, and 1970s (Figure 3.10). There were also notable differences in the estimates of SSB and vital rates in the early part of the time series (Figure 3.11). Uncertainty around recruitment and SSB increased considerably, and estimates of average F decreased and M increased. This indicates that the disc tagging program provides valuable information for reconstructing the vital rates of the stock back to 1954. This information paired with reported landings also contributes to the reconstruction of landings and stock trends. Given this result, and the minimal differences in diagnostics and population estimates in the post 1983 era, we utilize variants of xteNCAM (model **M4**) for all subsequent models.

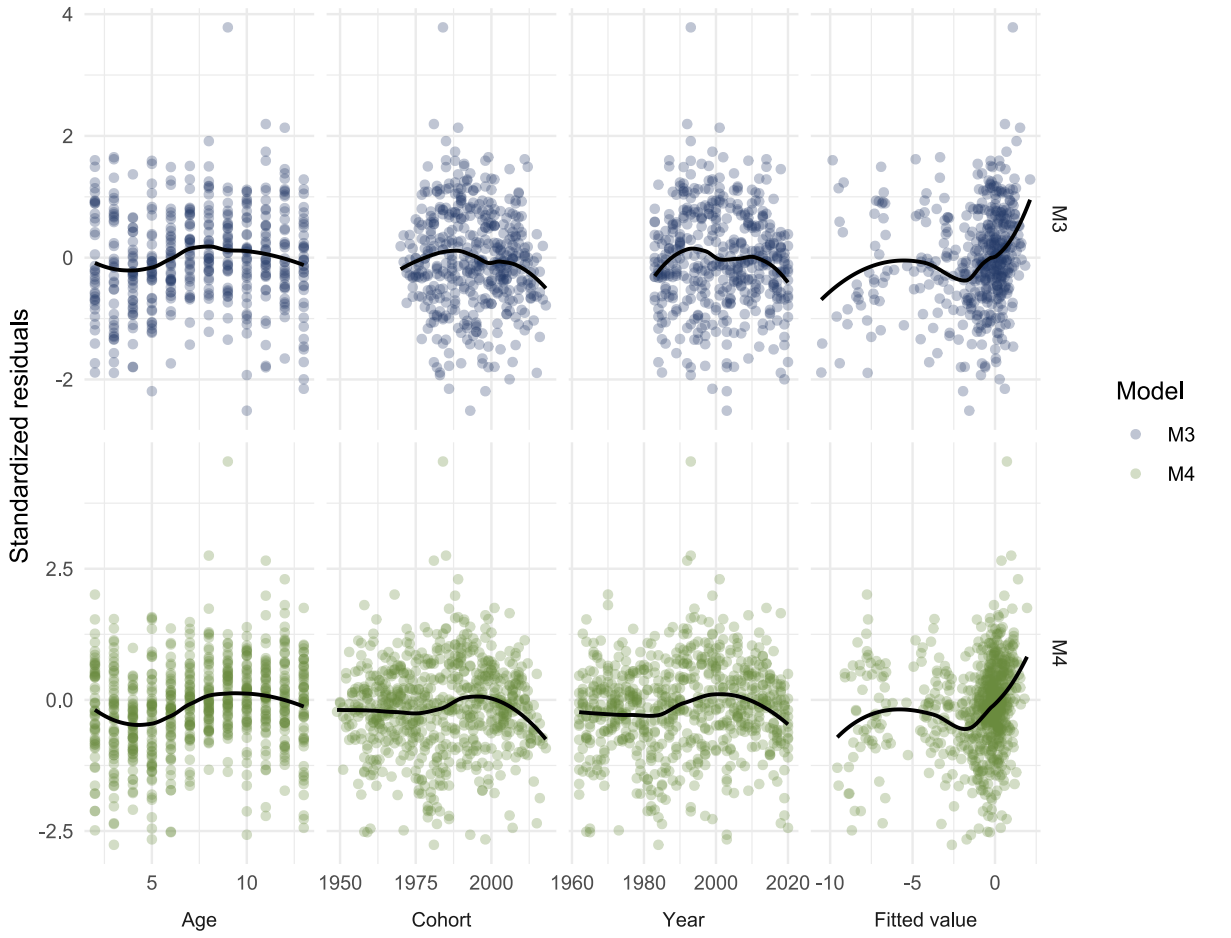

*Figure 3.6: Standardized residuals from catch composition continuation ratio logits faceted by age, cohort, year, and fitted value for model **M3** (autoregressive process for Sentinel survey catchability across both years and ages), and **M4** (base-case xteNCAM including data back to 1954). Black lines are lowess curves.*

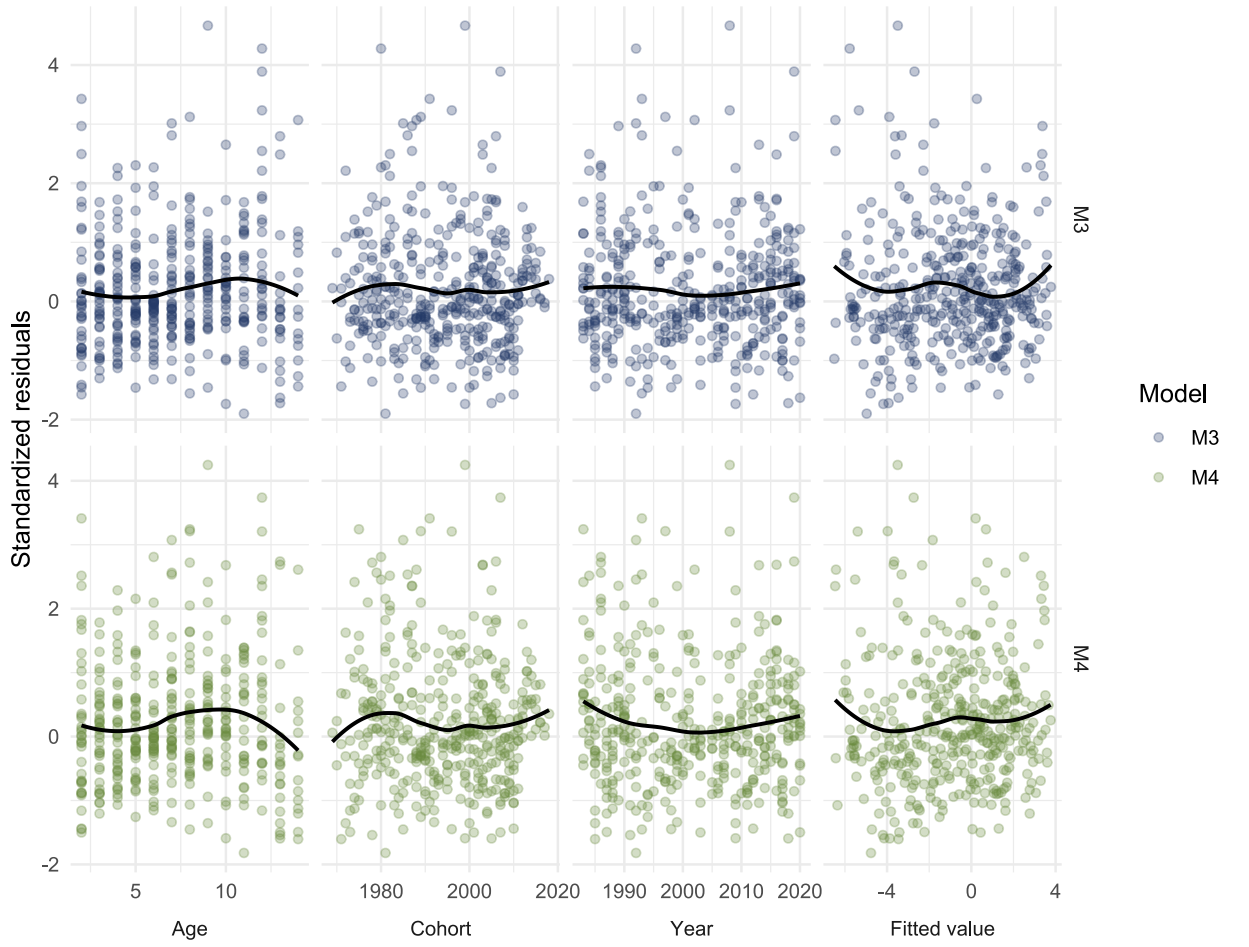

*Figure 3.7: Standardized residuals from the RV survey index faceted by age, cohort, year, and fitted value for model **M3** (autoregressive process for Sentinel survey catchability across both years and ages), and **M4** (base-case xteNCAM including data back to 1954). Black lines are lowess curves.*

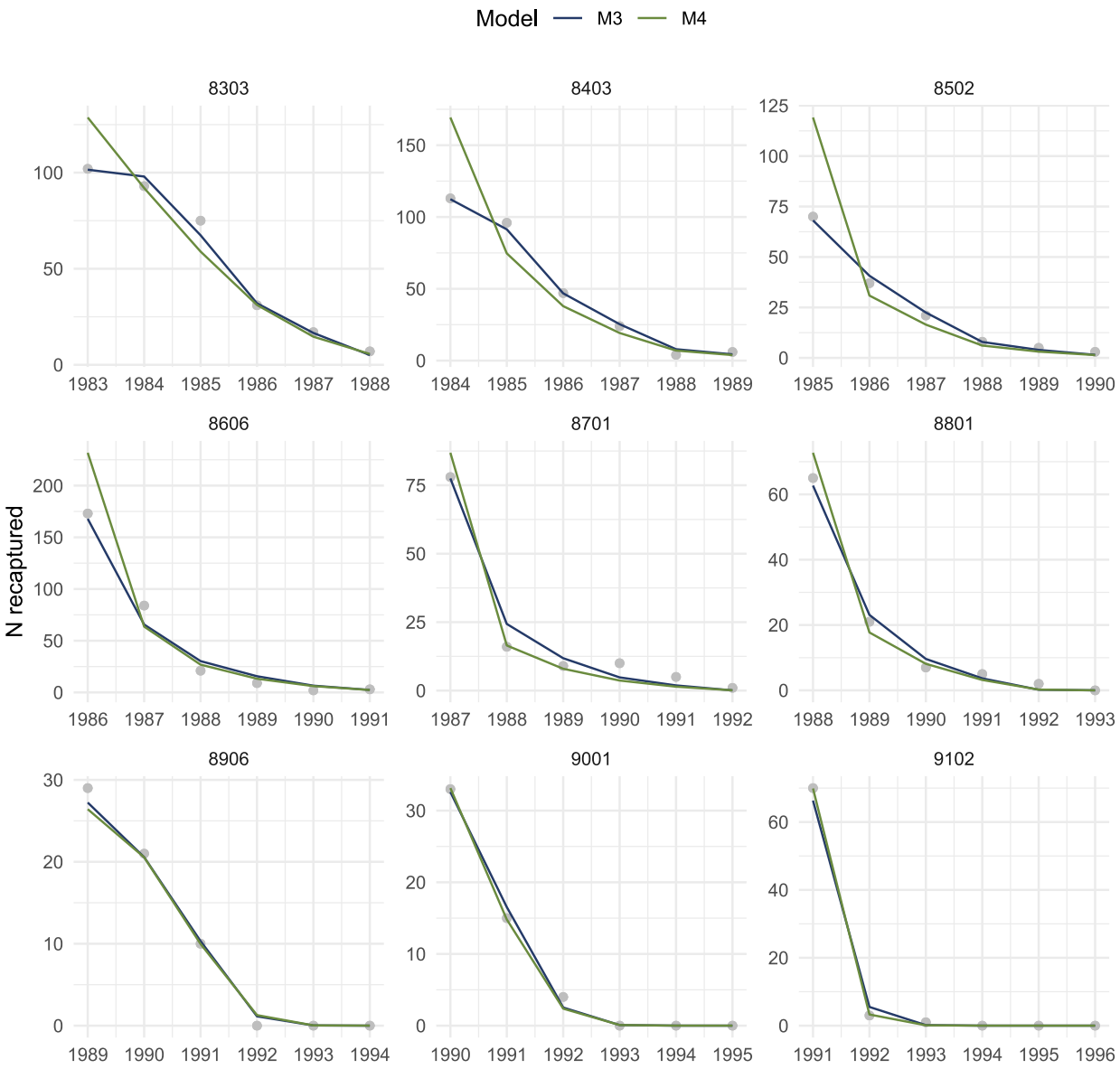

*Figure 3.8: Aggregate (all ages) observed versus (grey dots) **M3** (autoregressive process for Sentinel survey catchability across both years and ages), and **M4** (base-case xteNCAM including data back to 1954) predicted (lines) numbers of recaptures of cod tagged using T-bar type tags for select experiments between 1983 and 1991, when both T-bar and disc type tags were being deployed. Model **M3** does not utilize the disc tag data while model **M4** does. Experiment number (two digit year and number) is shown at the top of each plot.*

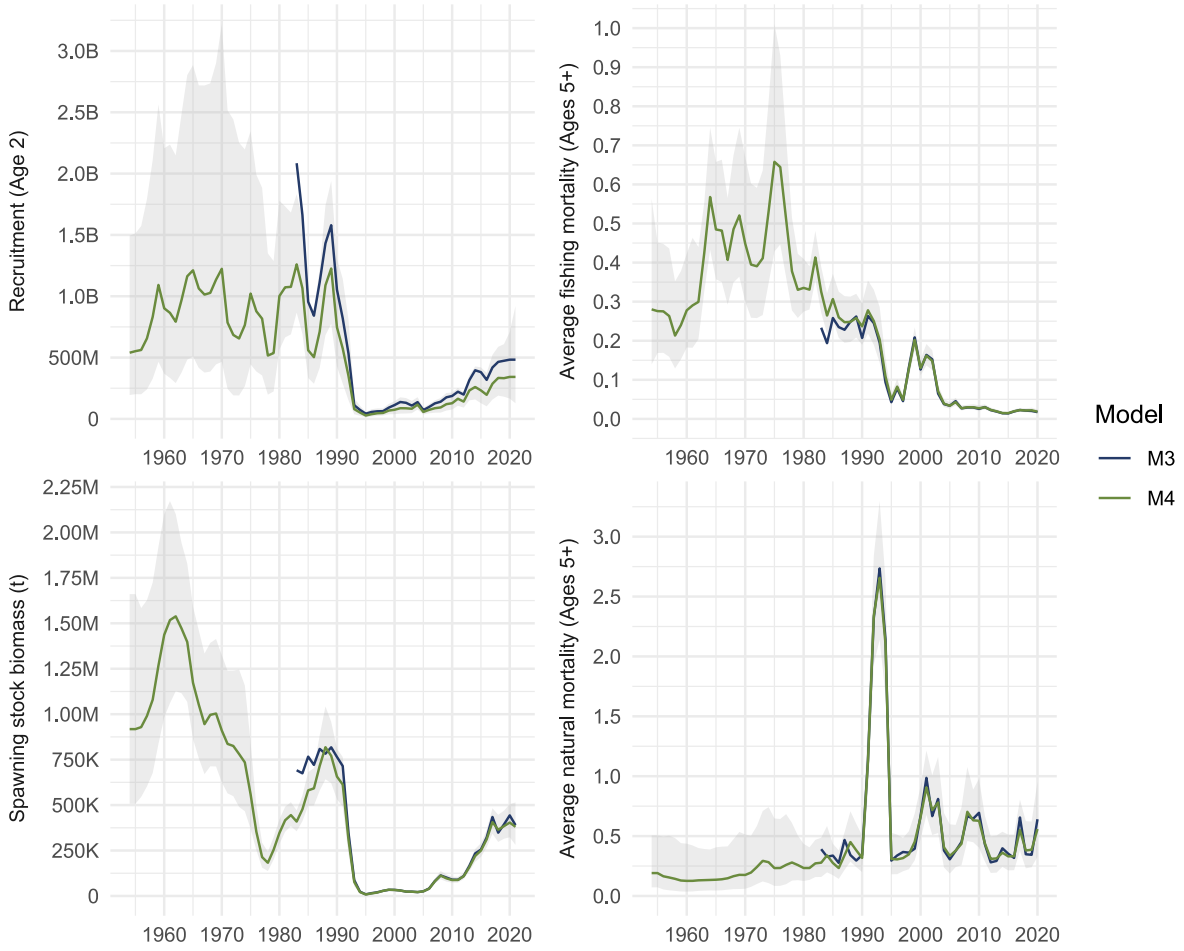

*Figure 3.9: Trends in recruitment to age 2, spawning stock biomass, fishing mortality, and natural mortality across models **M3** (autoregressive process for Sentinel survey catchability across both years and ages), and **M4** (base-case xteNCAM including data back to 1954). Shaded area represents the 95% confidence interval from model **M4**.*

*Table 3.3: Comparison of parameter estimates for models **M3** (autoregressive process for Sentinel survey catchability across both years and ages), and **M4** (base-case xteNCAM including data back to 1954). AIC values are not shown given difference in data inputs.*

Quantity	Symbol	M3	M4
RV survey observation error	σ_{RV}	0.390	0.433
SN survey observation error (age 3)	σ_{SN_a}	0.652	0.674
SN survey observation error (ages 4-14)	-	0.121	0.136
Age correlation in SN q	$\varphi_{\text{SN}_q,\text{age}}$	0.867	0.863
Year correlation in SN q	$\varphi_{\text{SN}_q,\text{year}}$	0.886	0.887
SN q variance parameter	σ_{SN_q}	0.835	0.827
Age composition error (age 2)	σ_{P_a}	1.043	1.846
Age composition error (ages 3-4)	-	0.612	0.878
Age composition error (ages 5-14)	-	0.277	0.309
Age correlation in process errors	$\varphi_{\delta,\text{age}}$	0.783	0.817
Year correlation in process errors	$\varphi_{\delta,\text{year}}$	0.392	0.833
Process error variance	σ_{δ}	0.284	0.234
Age correlation in F	$\varphi_{F,\text{age}}$	0.872	0.909
Year correlation in F	$\varphi_{F,\text{year}}$	0.996	0.998
F variance parameter	σ_F	0.284	0.201
Mean recruitment (pre 1992; billion)	r_1	2.048	0.465
Mean recruitment (post 1992; billion)	r_2	0.105	0.073
Variance of log-recruitment	σ_r	0.350	0.342
Variance of tagging F deviations (pre 1997)	$\sigma_{f_{x,1}}$	0.749	0.938
Variance of tagging F deviations (post 1997)	$\sigma_{f_{x,2}}$	1.053	1.050
NB overdispersion parameter for pre 1997 tag experiments	κ_1	60.950	16.314
NB overdispersion parameter for post 1997 tag experiments	κ_2	8.033	8.094

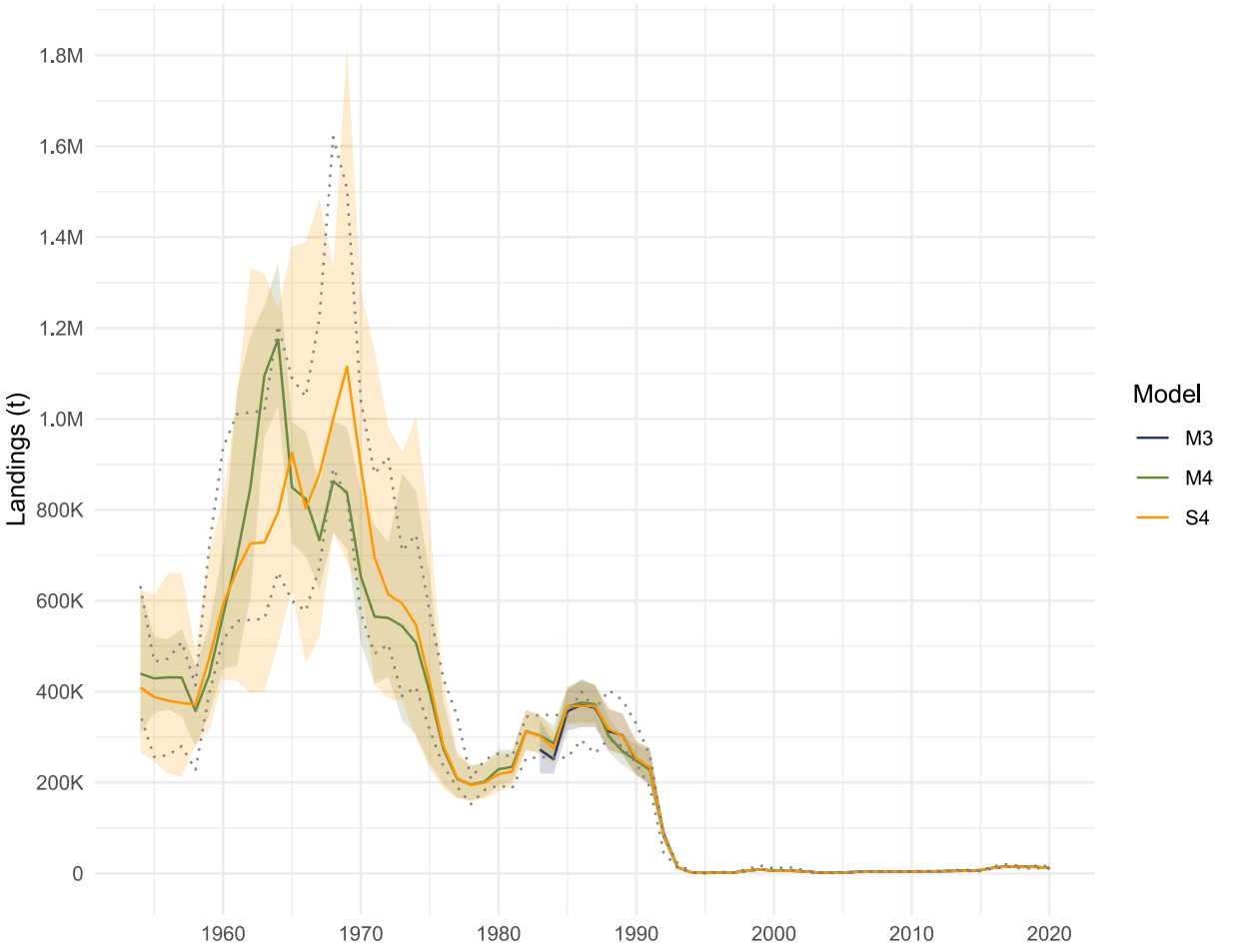

*Figure 3.10: Trends in predicted landings from models **M3** (autoregressive process for Sentinel survey catchability across both years and ages), **M4** (base-case xteNCAM including data back to 1954), and **S4** (model **M4** excluding disc tag releases [1954–91]). Shaded areas represent 95% confidence intervals around predicted landings and dotted grey lines are the lower and upper catch bounds.*

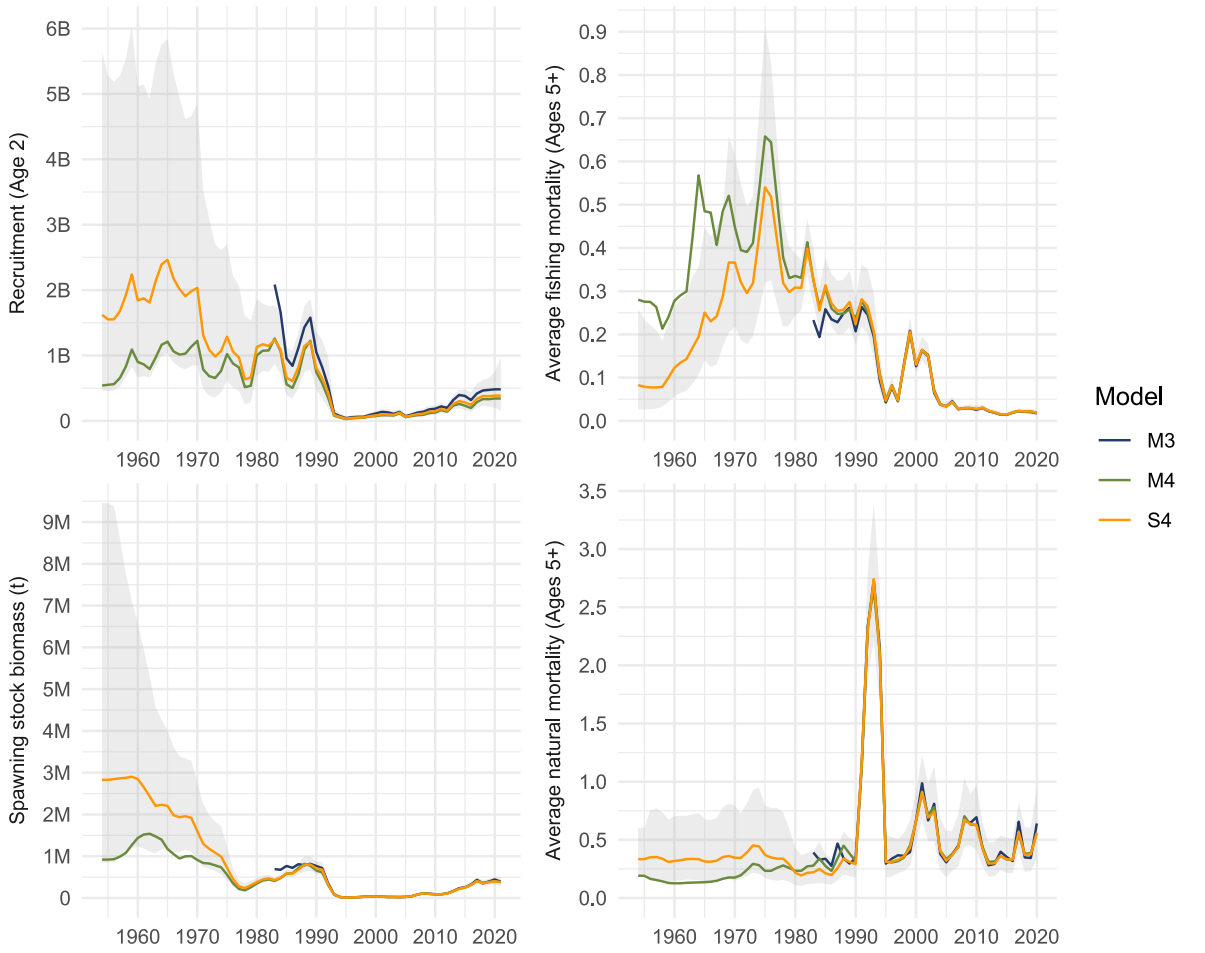

*Figure 3.11: Trends in recruitment to age 2, spawning stock biomass, fishing mortality, and natural mortality across models **M3** (autoregressive process for Sentinel survey catchability across both years and ages), **M4** (base-case xteNCAM including data back to 1954), and **S4** (model **M4** excluding disc tag releases [1954–91]). Shaded area represents the 95% confidence interval from model **S4**.*

3.5. JUVENILE SURVEY INDICES

The addition of juvenile survey data from the Fleming and Newman Sound monitoring programs enabled the inclusion of age 0 and 1 to the model. Recall that we implemented three variations where different catchability assumptions were applied. The simplest model (**M5**) assumed catchability was constant across time and surveys, while the others assumed that the survey (**M6**) or seine type (**M7**) caused a difference in catchability. Diagnostics were comparable across these models (**M4**, **M5**, **M6**, and **M7**; Figure 3.12). AIC values were similar across these models (Table 3.4), and parameter estimates from models **M6** and **M7** indicated no clear difference in catchability between the surveys (difference in $\log(q)$ [95% CI] = -0.1 [-0.71, 0.51]) or seine type (0.65 [-0.27, 1.57]), respectively. Relative to model **M4**, all models reduced the uncertainty around estimates of age 2 cod, especially through the 1960s and 1970s (Figure 3.13). Uncertainty around estimates of age 0 and 1 cod increased when catchability was allowed to differ by seine type (Figure 3.13). While it is difficult to be confident there is no difference by survey catchability or seine type, we opted to follow the principle of parsimony and utilize the simplest model formulation, **M5**, assuming constant juvenile survey catchability for

subsequent formulations of xteNCAM. The inclusion of these data in the model represented an important advancement as it added information on ages 0 and 1, filling a gap in NCAM. These data are expected to be a useful indicator of year-class strength (Lunzmann-Cooke et al. 2021), which should aid forecasts of future stock production.

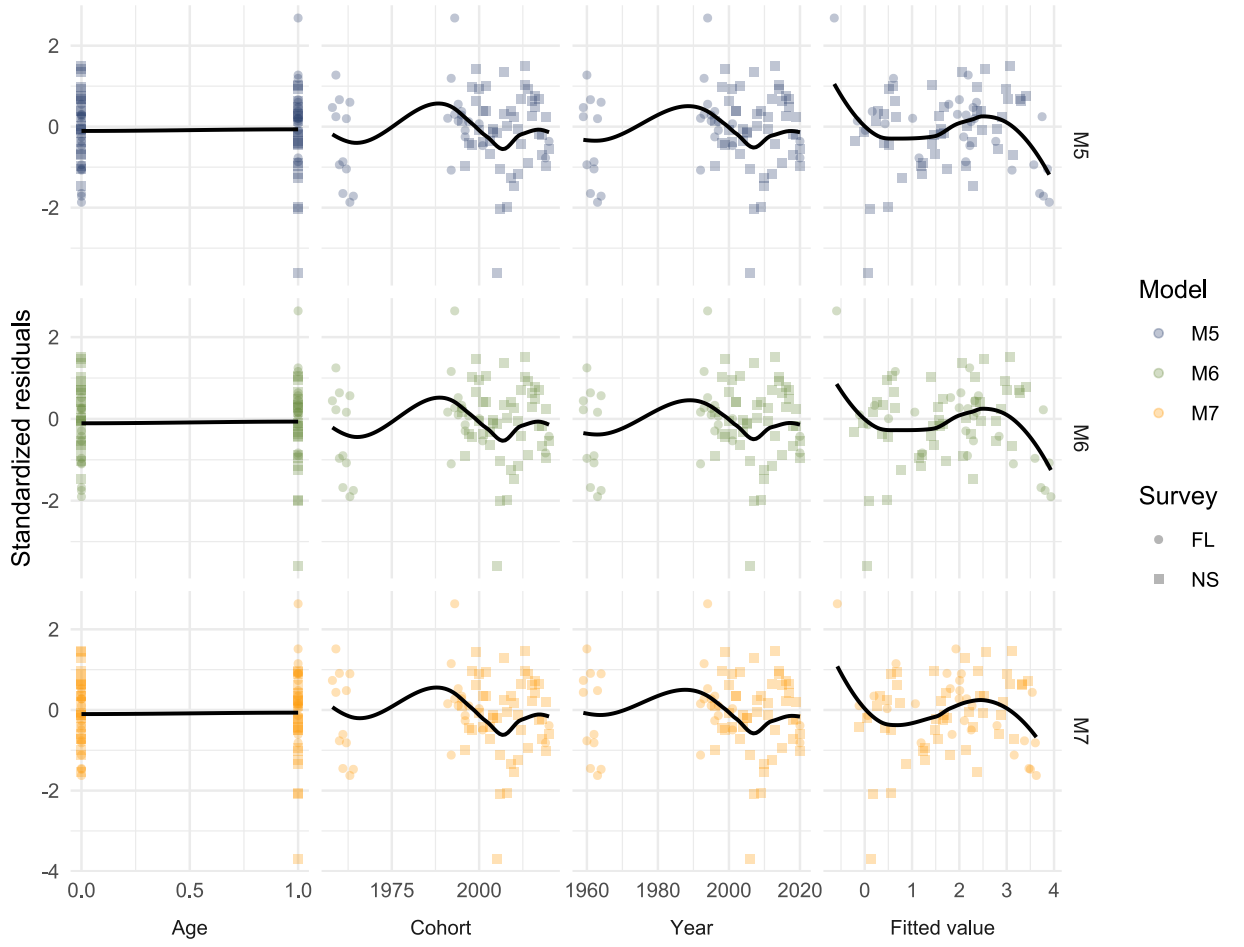

*Figure 3.12: Standardized residuals from the Fleming (FL) and Newman Sound (NS) juvenile surveys faceted by age, cohort, year, and fitted value for model **M4** (base-case xteNCAM including data back to 1954), **M5** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys), **M6** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys, allowing differences in catchability by survey), and **M7** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys, allowing differences in catchability by seine type (cotton or nylon)). Black lines are lowess curves.*

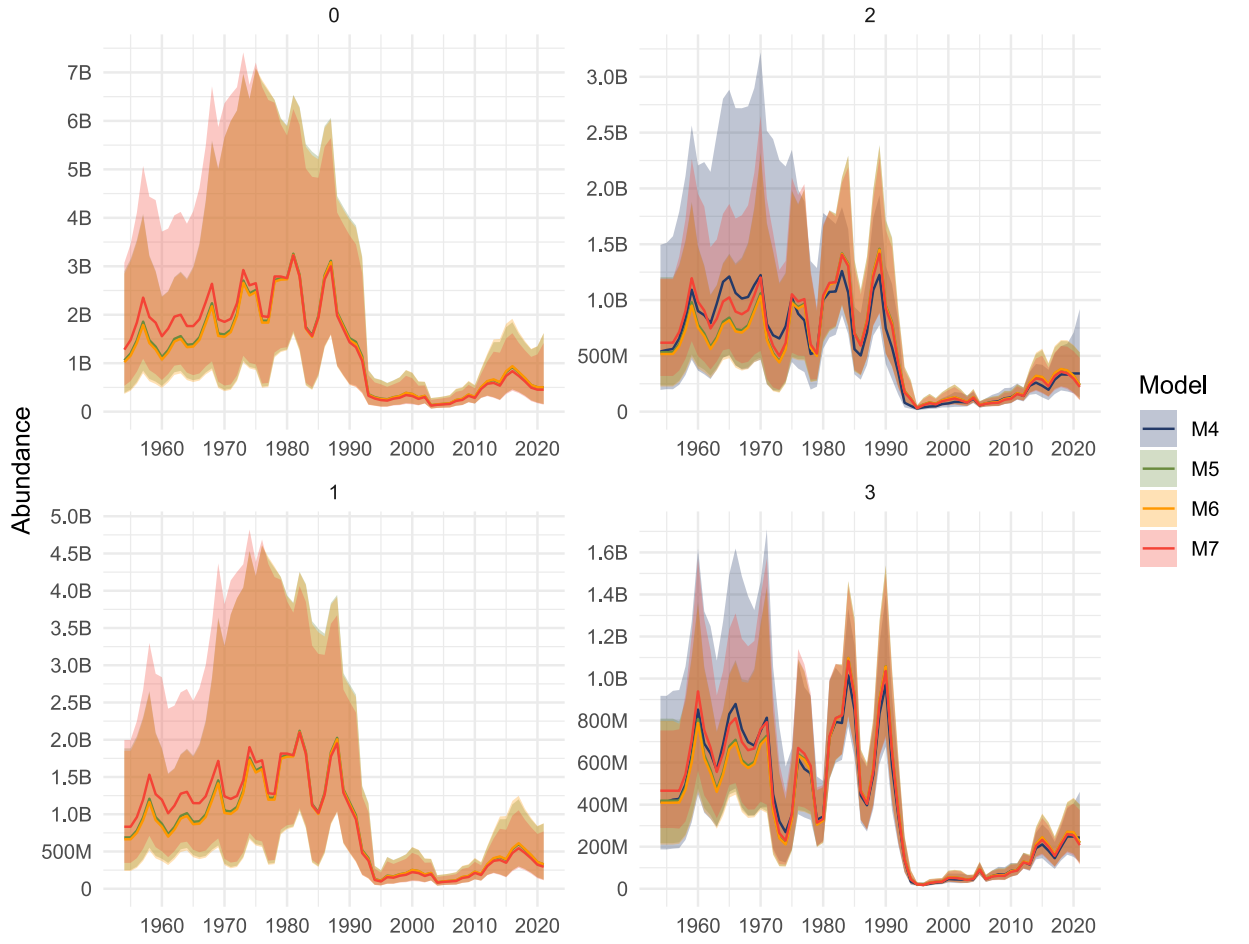

*Figure 3.13: Estimates of abundance for ages 0-3 from models **M4** (base-case xteNCAM including data back to 1954), **M5** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys), **M6** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys, allowing differences in catchability by survey), and **M7** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys, allowing differences in catchability by seine type (cotton or nylon)). Shaded areas represent 95% confidence intervals.*

*Table 3.4: Comparison of the number of parameters, k, log-likelihood, $ln(L)$, Akaike information criterion, AIC, for models **M5**, **M6**, and **M7**; and select parameter estimates from models **M4** (base-case xteNCAM including data back to 1954), **M5** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys), **M6** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys, allowing differences in catchability by survey), and **M7** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys, allowing differences in catchability by seine type (cotton or nylon)). Model **M4** was excluded from AIC comparison given differences in data inputs.*

Model	$\boldsymbol{k}$	$\boldsymbol{ln(L)}$	$\boldsymbol{AIC}$	$\boldsymbol{\Delta AIC}$
M5	201	17946.04	36294.07	0.000
M7	202	17945.05	36294.10	0.026
M6	202	17945.98	36295.97	1.895

Quantity	**Symbol**	**M4**	**M5**	**M6**	**M7**
Age composition error (age 2)	σ_{P_a}	1.846	NA	NA	NA
Age composition error (ages 0-2)	σ_{P_a}	NA	1.839	1.840	1.832
Juvenile survey observation error	σ_{juv}	NA	1.102	1.101	1.098
RV survey observation error	σ_{RV}	0.433	0.429	0.429	0.429
SN survey observation error (age 3)	σ_{SN_a}	0.674	0.679	0.679	0.680
SN survey observation error (ages 4-14)	-	0.136	0.134	0.134	0.134
Age correlation in SN q	$\varphi_{\text{SN}_q,\text{age}}$	0.863	0.862	0.862	0.861
Year correlation in SN q	$\varphi_{\text{SN}_q,\text{year}}$	0.887	0.886	0.886	0.886
SN q variance parameter	σ_{SN_q}	0.827	0.830	0.830	0.828
Age composition error (ages 3-4)	-	0.878	0.882	0.881	0.883
Age composition error (ages 5-14)	-	0.309	0.308	0.308	0.309
Age correlation in process errors	$\varphi_{\delta,\text{age}}$	0.817	0.827	0.831	0.806
Year correlation in process errors	$\varphi_{\delta,\text{year}}$	0.833	0.815	0.819	0.801
Process error variance	σ_{δ}	0.234	0.226	0.225	0.230
Age correlation in F	$\varphi_{F,\text{age}}$	0.909	0.909	0.909	0.909
Year correlation in F	$\varphi_{F,\text{year}}$	0.998	0.998	0.998	0.998
F variance parameter	σ_F	0.201	0.202	0.202	0.202
Mean recruitment (pre 1992; billion)	r_1	0.465	0.951	0.918	1.136
Mean recruitment (post 1992; billion)	r_2	0.073	0.320	0.309	0.293
Variance of log-recruitment	σ_r	0.342	0.319	0.322	0.314
Variance of tagging F deviations (pre 1997)	$\sigma_{fx,1}$	0.938	0.938	0.938	0.940
Variance of tagging F deviations (post 1997)	$\sigma_{fx,2}$	1.050	1.050	1.050	1.050
NB overdispersion parameter for pre 1997 tag experiments	κ_1	16.314	16.317	16.318	16.301
NB overdispersion parameter for post 1997 tag experiments	κ_2	8.094	8.117	8.117	8.115

3.6. STOCK-RECRUITMENT (S-R) RELATIONSHIPS

The shift from two random walks for predicting recruitment (model **M5**) to a linear (model **M8**), Beverton-Holt (model **M9**), or sigmoidal Beverton-Holt (model **M10**) S-R relationship produced different stock-recruit scatters (Figure 3.14). Among the options, the Beverton-Holt and sigmoidal Beverton-Holt were similar. The linear model resulted in the largest estimates of recruitment, especially through the 1960s (Figure 3.15). These results indicate that the model has some flexibility to estimate different functional forms of the S-R relationship, and an uncertainty around the recruitment process (σ_r) may provide scope for the fitting of different functional forms. That said, the different functional forms are not supported equally by the data. The linear model proved to be a poor fit to the juvenile survey data (Figure 3.16), and it received a relatively high AIC score (Table 3.5). Diagnostics and AIC scores were very similar for both the Beverton-Holt and sigmoidal Beverton-Holt models (Figure 3.16, Table 3.5). The original random walk formulation appears to provide the best description of the data as it receives the lowest AIC score, however, it lacks biological realism since it is not mechanistically linked to SSB. We therefore consider the Beverton-Holt relationships more defensible.

The similar shape and performance of the two Beverton-Holt relationship stems from the fact that the depensation parameter estimate from the sigmoidal version is close to 1 (γ = 0.72 [0.45, 1.16]), which is what is assumed in a standard Beverton-Holt relationship. This also means that, despite the large range of modeled SSB levels, there is little evidence for depensatory dynamics ($P(\gamma < 1)$ = 0.09). This contrasts with the neighboring stock of Atlantic Cod in NAFO sub-division 3Ps, where recruitment analyses indicate week depensatory dynamics (Perälä et al. 2022). This difference in inference may be related to the different approaches in that we present an internal S-R analysis while the 3Ps analysis was done with model output, or there may actually be differences in the functional relationship between SSB and recruitment for the two stocks. For Northern cod, there appears to be more support for compensatory dynamics. Given the choice between these two forms, we followed the principle of parsimony and chose to retain the more simplistic Beverton-Holt form for subsequent models.

To further assess evidence for a density-dependent effect, we ran a series of sensitivity tests where the juvenile survey data were excluded (tests **S5**, **S8**, and **S9**). The recruitment levels are higher when the juvenile data are excluded, however the shape of the Beverton-Holt curve is similar (Figure 3.17). The relatively high estimates of recruitment is likely related to the absence of the early Fleming survey data. Though that influence is lost under these tests, the data still lend more support to the Beverton-Holt S-R relationship (Table 3.6), which implies that density-dependence limits recruitment as SSB increases.

Both this sensitivity test and the model variations noted above contrast with expectations based on previous analyses, which indicated that the relationship between SSB and recruitment was linear (Rose and Rowe 2022). A key distinction in our results is that stock-recruitment (S-R) relationships were internally fitted within the assessment model, rather than derived from post-hoc analyses conducted externally. The differing conclusions may stem from differences in analytical approach, as recruitment assumptions within the assessment model can influence the shape of externally estimated stock-recruitment relationships(Punt 2023). Our current analysis is fully integrated and the data offer the most support to the asymptotic Beverton-Holt relationship. The shape is further supported by the 1959 to 1964 Fleming survey campaign, which fail to indicate levels of recruitment that would be expected under a linear relationship.

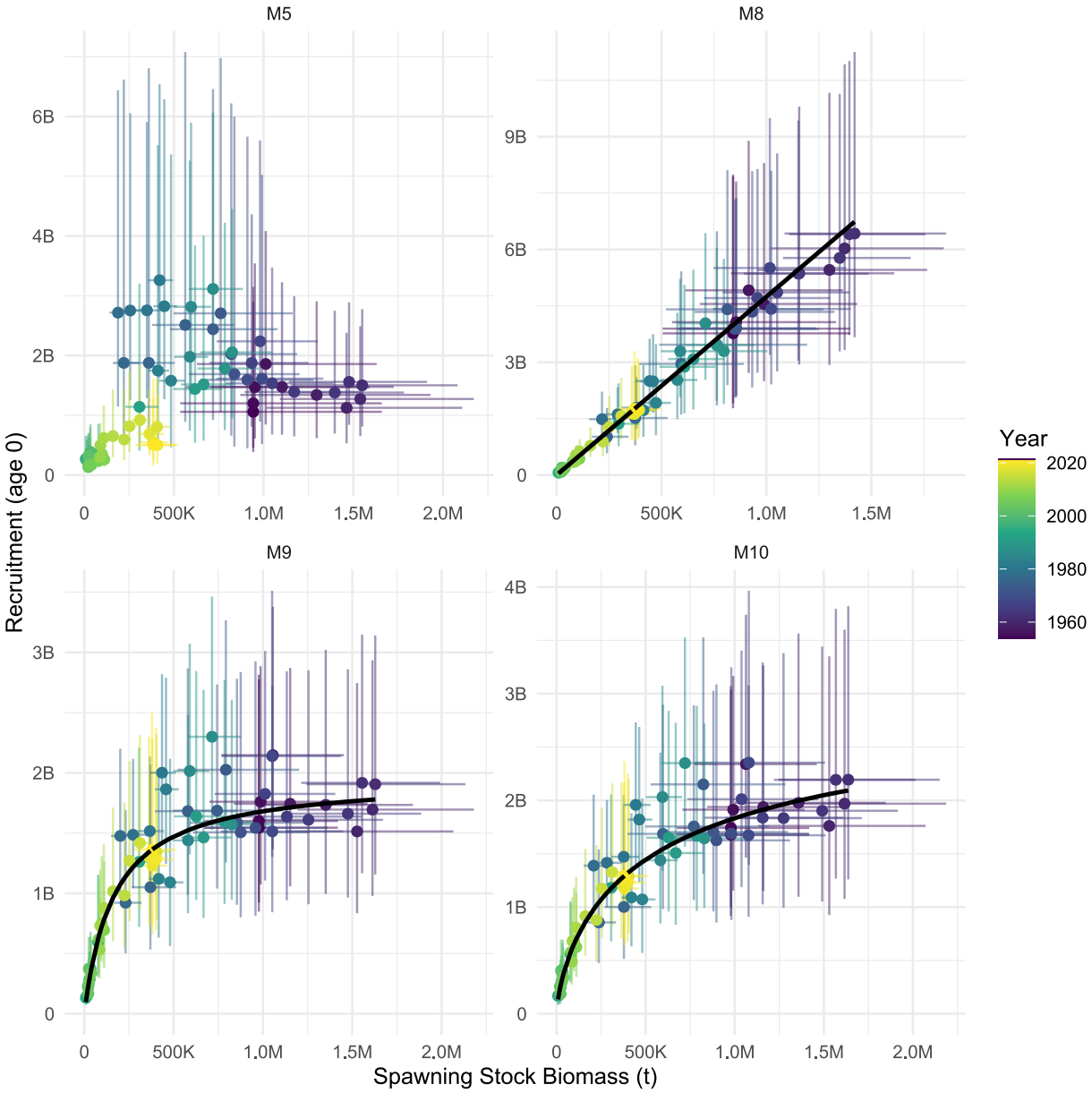

*Figure 3.14: Predictions from a model fit using two random walks (**M5**) compared to models fit using a linear (**M8**), Beverton-Holt (**M9**) and sigmoidal Beverton-Holt (**M10**) stock-recruitment relationship. Horizontal and vertical whiskers represent 95% confidence intervals around estimates of recruitment (dots), and black lines are predicted levels of recruitment.*

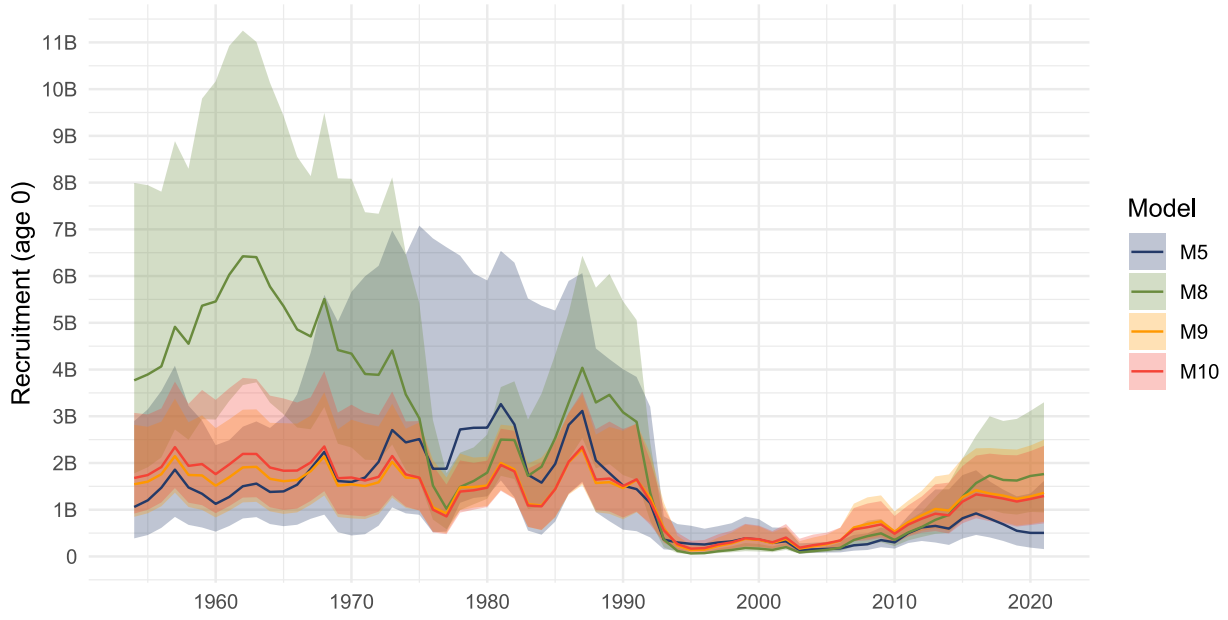

*Figure 3.15: Estimates of recruitment (age 0 abundance) from models **M5** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys), **M8** (xteNCAM including juveniles and a linear stock-recruitment relationship), **M9** (xteNCAM including juveniles and a Beverton-Holt stock-recruitment relationship), and **M10** (xteNCAM including juveniles and a sigmoidal stock-recruitment relationship). Shaded areas represent 95% confidence intervals.*

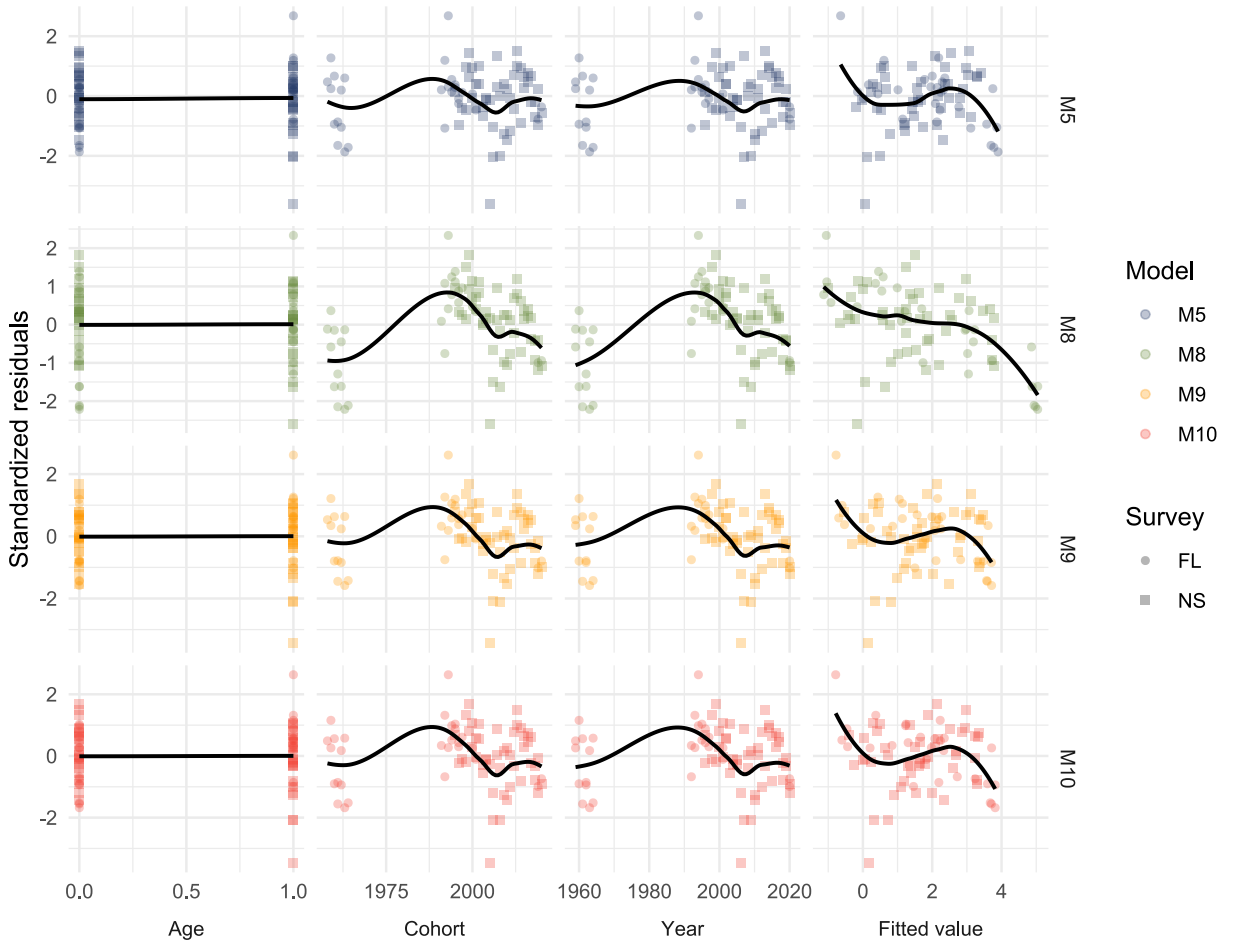

*Figure 3.16: Standardized residuals from the Fleming (FL) and Newman Sound (NS) juvenile surveys faceted by age, cohort, year, and fitted value for model **M5** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys), **M8** (xteNCAM including juveniles and a linear stock-recruitment relationship), **M9** (xteNCAM including juveniles and a Beverton-Holt stock-recruitment relationship), and **M10** (xteNCAM including juveniles and a sigmoidal stock-recruitment relationship). Black lines are lowess curves.*

*Table 3.5: Comparison of the number of parameters, k, log-likelihood, $ln(L)$, Akaike information criterion, AIC, and select parameter estimates from models **M5** (xteNCAM including data from the Fleming and Newman Sound juvenile surveys), **M8** (xteNCAM including juveniles and a linear stock-recruitment relationship), **M9** (xteNCAM including juveniles and a Beverton-Holt stock-recruitment relationship), and **M10** (xteNCAM including juveniles and a sigmoidal stock-recruitment relationship).*

Model	$\boldsymbol{k}$	$\boldsymbol{ln(L)}$	$\boldsymbol{AIC}$	$\boldsymbol{\Delta AIC}$
M5	201	17946.04	36294.07	0.000
M10	202	17947.38	36298.75	4.678
M9	201	17948.52	36299.05	4.975
M8	200	17972.42	36344.84	50.769

Quantity	**Symbol**	**M5**	**M8**	**M9**	**M10**
Mean recruitment (pre 1992; billion)	r_1	0.951	NA	NA	NA
Mean recruitment (post 1992; billion)	r_2	0.320	NA	NA	NA
S-R relationship parameter	γ_{SSB}	NA	NA	NA	0.721
S-R relationship parameter	$\log(\beta_{\text{SSB}})$	NA	NA	-12.023	-9.618
S-R relationship parameter	α_{SSB}	NA	4.744	11.772	208.459
RV survey observation error	σ_{RV}	0.429	0.432	0.431	0.432
SN survey observation error (age 3)	σ_{SN_a}	0.679	0.676	0.671	0.670
SN survey observation error (ages 4-14)	-	0.134	0.130	0.130	0.130
Age correlation in SN q	$\varphi_{\text{SN}_q,\text{age}}$	0.862	0.865	0.865	0.865
Year correlation in SN q	$\varphi_{\text{SN}_q,\text{year}}$	0.886	0.886	0.887	0.887
SN q variance parameter	σ_{SN_q}	0.830	0.821	0.826	0.828
Age composition error (ages 0-2)	σ_{P_a}	1.839	1.802	1.817	1.804
Age composition error (ages 3-4)	-	0.882	0.865	0.859	0.859
Age composition error (ages 5-14)	-	0.308	0.311	0.308	0.308
Age correlation in process errors	$\varphi_{\delta,\text{age}}$	0.827	0.742	0.787	0.782
Year correlation in process errors	$\varphi_{\delta,\text{year}}$	0.815	0.821	0.787	0.785
Process error variance	σ_{δ}	0.226	0.263	0.248	0.244
Age correlation in F	$\varphi_{F,\text{age}}$	0.909	0.908	0.908	0.908
Year correlation in F	$\varphi_{F,\text{year}}$	0.998	0.998	0.998	0.998
F variance parameter	σ_F	0.202	0.201	0.203	0.203
Variance of log-recruitment	σ_r	0.319	0.215	0.227	0.223
Variance of tagging F deviations (pre 1997)	$\sigma_{f_{x,1}}$	0.938	0.948	0.944	0.946
Variance of tagging F deviations (post 1997)	$\sigma_{f_{x,2}}$	1.050	1.049	1.050	1.050
NB overdispersion parameter for pre 1997 tag experiments	κ_1	16.317	16.209	16.128	16.085
NB overdispersion parameter for post 1997 tag experiments	κ_2	8.117	8.021	8.063	8.071
Juvenile survey observation error	σ_{juv}	1.102	1.444	1.182	1.176

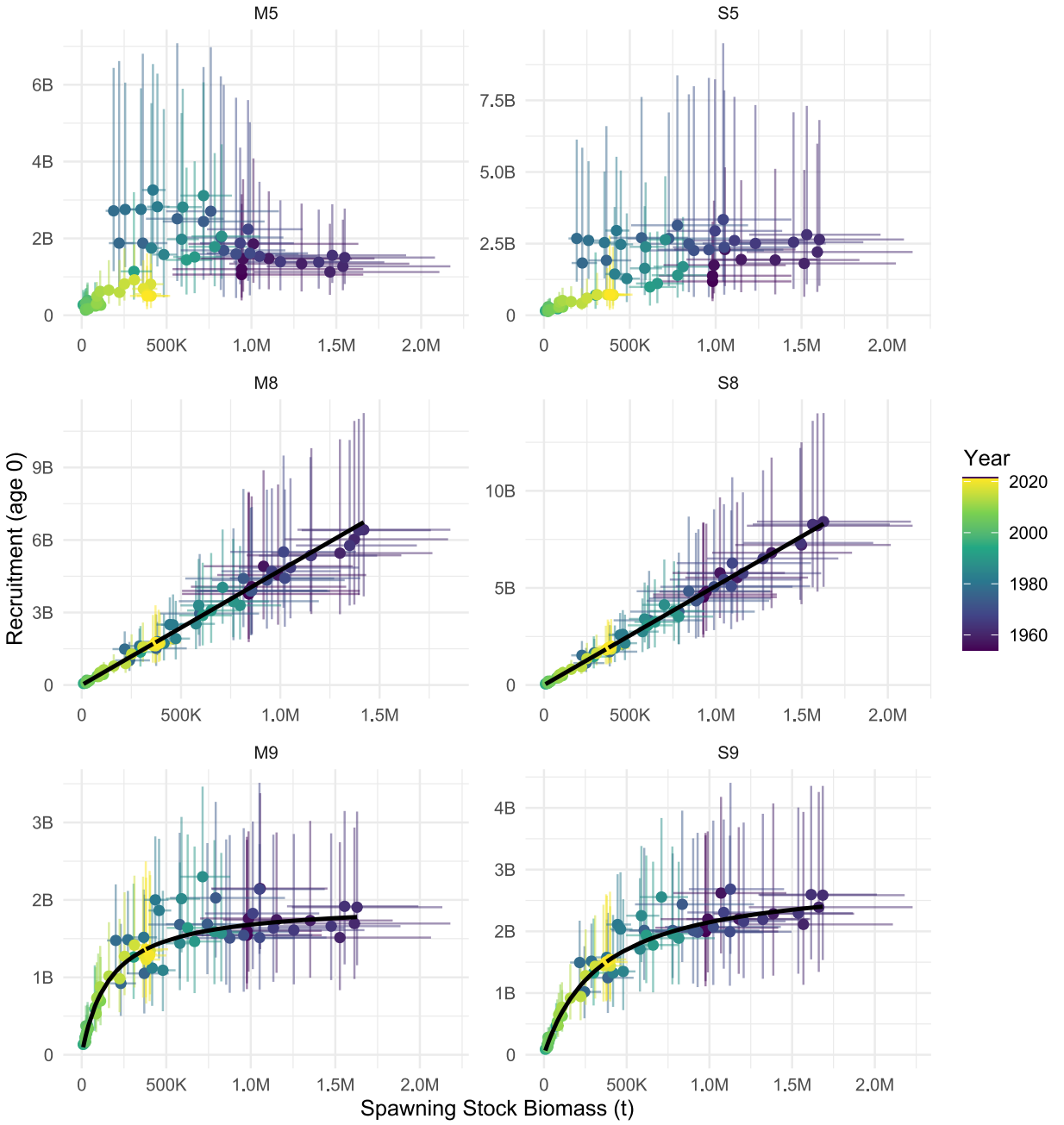

*Figure 3.17: Stock-recruitment scatter plots from models that include or exclude juvenile survey data. Specifically, predictions following two random walks (**M5** and **S5**) compared to models fit using a linear (**M8** and **S8**), and Beverton-Holt (**M9** and **S9**) stock-recruitment relationship. Horizontal and vertical whiskers represent 95% confidence intervals around estimates of recruitment (dots), and black lines are predicted levels of recruitment.*

*Table 3.6: Comparison of the number of parameters, k, log-likelihood, $ln(L)$, Akaike information criterion, AIC, and select parameter estimates from sensitivity tests **S5** (model **M5** excluding the juvenile survey data), **S8** (model **M8** excluding the juvenile survey data), and **S9** (model **M9** excluding the juvenile survey data).*

Model	$\boldsymbol{k}$	$\boldsymbol{ln(L)}$	$\boldsymbol{AIC}$	$\boldsymbol{\Delta AIC}$
S9	198	17824.81	36045.62	0.000
S5	198	17826.47	36048.93	3.314
S8	197	17833.75	36061.49	15.874

Quantity	**Symbol**	**S5**	**S8**	**S9**
Mean recruitment (pre 1992; billion)	r_1	1.002	NA	NA
Mean recruitment (post 1992; billion)	r_2	0.198	NA	NA
S-R relationship parameter	$\log(\beta_{\text{SSB}})$	NA	NA	-12.763
S-R relationship parameter	α_{SSB}	NA	5.106	8.295
RV survey observation error	σ_{RV}	0.434	0.431	0.430
SN survey observation error (age 3)	σ_{SN_a}	0.679	0.679	0.674
SN survey observation error (ages 4-14)	-	0.137	0.132	0.131
Age correlation in SN q	$\varphi_{\text{SN}_q,\text{age}}$	0.862	0.867	0.867
Year correlation in SN q	$\varphi_{\text{SN}_q,\text{year}}$	0.887	0.888	0.888
SN q variance parameter	σ_{SN_q}	0.826	0.826	0.829
Age composition error (ages 0-2)	σ_{P_a}	1.840	1.805	1.825
Age composition error (ages 3-4)	-	0.877	0.861	0.857
Age composition error (ages 5-14)	-	0.309	0.309	0.308
Age correlation in process errors	$\varphi_{\delta,\text{age}}$	0.805	0.719	0.765
Year correlation in process errors	$\varphi_{\delta,\text{year}}$	0.813	0.804	0.747
Process error variance	σ_δ	0.227	0.271	0.261
Age correlation in F	$\varphi_{F,\text{age}}$	0.910	0.908	0.908
Year correlation in F	$\varphi_{F,\text{year}}$	0.998	0.998	0.998
F variance parameter	σ_F	0.201	0.202	0.203
Variance of log-recruitment	σ_r	0.315	0.185	0.201
Variance of tagging F deviations (pre 1997)	$\sigma_{f_{x,1}}$	0.940	0.947	0.946
Variance of tagging F deviations (post 1997)	$\sigma_{f_{x,2}}$	1.050	1.049	1.050
NB overdispersion parameter for pre 1997 tag experiments	κ_1	16.289	16.165	16.095
NB overdispersion parameter for post 1997 tag experiments	κ_2	8.110	7.999	8.049

3.7. BASELINE NATURAL MORTALITY

Changes to our underlying assumptions with regards to baseline levels of M had a minimal impact on the estimates of average M and F for ages 5+ (Figure 3.18). The greatest differences are apparent in the juvenile component of the stock, where rates of M were higher when assuming M-shift baseline levels (model **M9**) or when estimating an allometric effect (model **M12**; Figure 3.19). Consequently, estimates of recruitment were higher for these models (Figure 3.18). Note, however, that with an allometric exponent of 0.31 [0.11, 0.86], estimates of M for the youngest ages are lower than would be expected under the commonly estimated value of approximately -1 (Lorenzen et al. 2022).

Estimates of M tended to be lower when constant (age-invariant) levels of mortality were assumed (models **M11** and **M13**; Figure 3.19). Both the M-shift (model **M9**) and M-shift2 (model **M13**) options better captured temporal shifts in the rates of M and both received the lowest AIC scores (Table 3.7). However, the performance of these models is likely driven by the explanation of the shifts in mortality rates which were informed by hindsight. While using such a formulation does account for a large observed change in the system, we lack the ability to predict the next change. Though the allometric model, **M12**, does not capture these temporal shifts and receives a higher AIC score than the other models (except the constant model, **M11**), estimates of juvenile mortality are likely more biologically realistic under this model. These results leave a difficult decision between the most statistically defensible option (model **M13**) versus the most biologically defensible option (model **M12**).

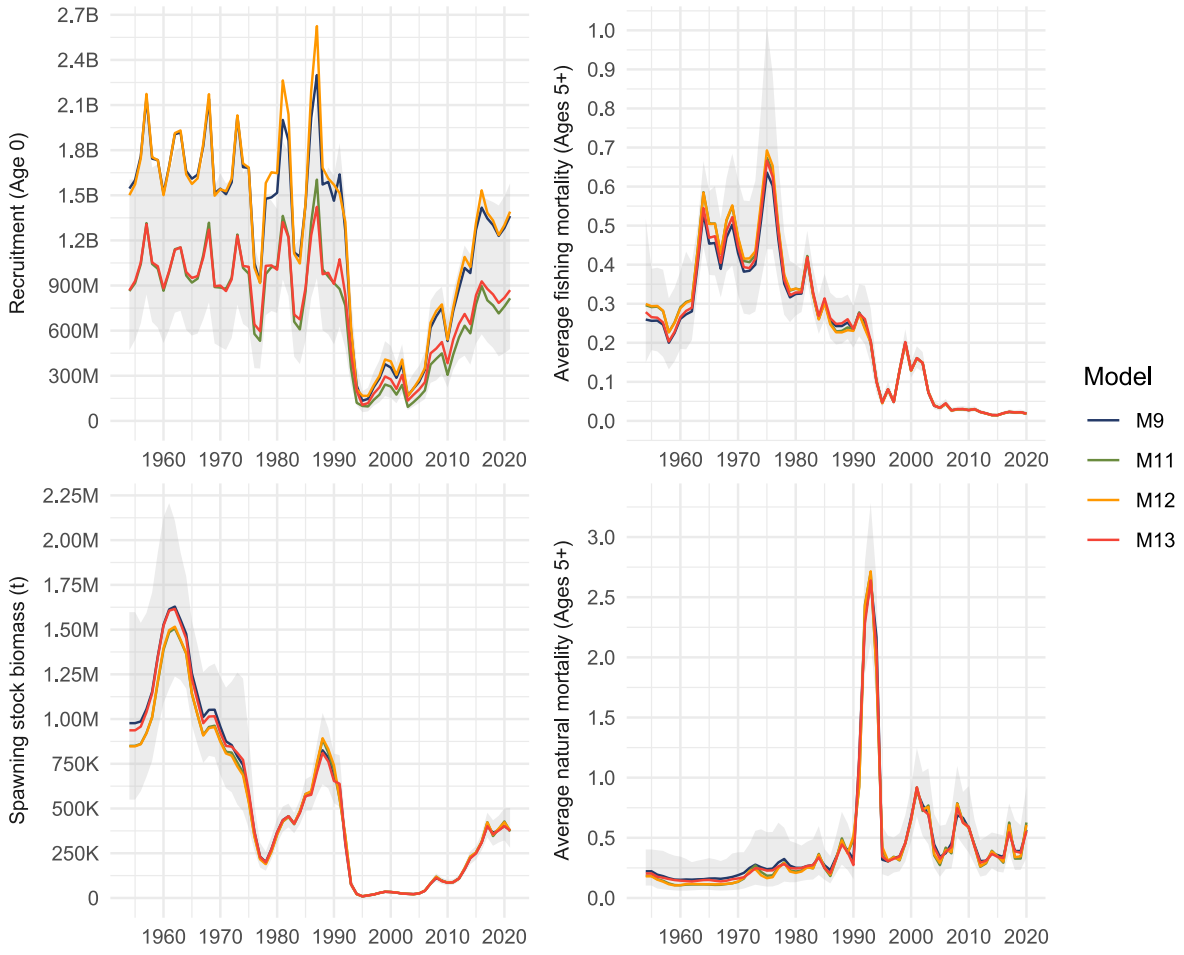

*Figure 3.18: Trends in recruitment to age 0, spawning stock biomass, fishing mortality, and natural mortality across models **M9** (xteNCAM including juveniles and a Beverton-Holt stock-recruitment relationship), **M11** (xteNCAM including juveniles, Beverton-Holt S-R relationship, and a constant baseline level of natural mortality), **M12** (xteNCAM including juveniles, Beverton-Holt S-R relationship, and allometric baseline levels of natural mortality (i.e., Lorenzen M)), and **M13** (xteNCAM including juveniles, Beverton-Holt S-R relationship, and shifts in baseline levels of natural mortality). Shaded area represents the 95% confidence interval from model **M13**.*

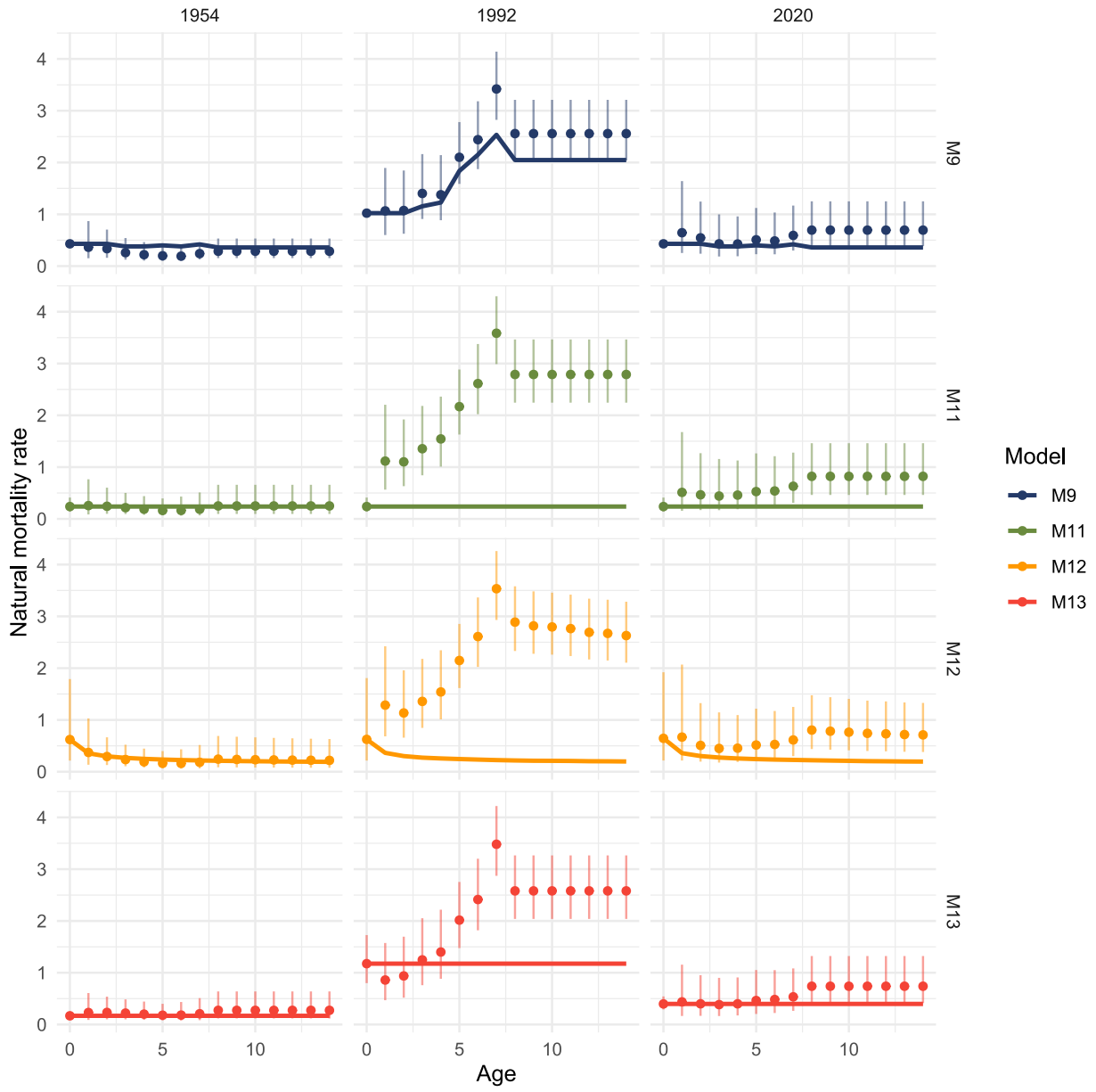

*Figure 3.19: Rates of natural mortality by age for select years estimated by models **M9** (xteNCAM including juveniles and a Beverton-Holt stock-recruitment relationship), **M11** (xteNCAM including juveniles, Beverton-Holt S-R relationship, and a constant baseline level of natural mortality), **M12** (xteNCAM including juveniles, Beverton-Holt S-R relationship, and allometric baseline levels of natural mortality (i.e., Lorenzen M)), and **M13** (xteNCAM including juveniles, Beverton-Holt S-R relationship, and shifts in baseline levels of natural mortality). Thick lines represent assumed (**M9** [M-shift]) or estimated baseline rates (**M11** [constant], **M12** [allometric], and **M13** [M-shift2]).*

*Table 3.7: Comparison of the number of parameters, k, log-likelihood, $ln(L)$, Akaike information criterion, AIC, and select parameter estimates from models **M9** (xteNCAM including juveniles and a Beverton-Holt stock-recruitment relationship), **M11** (xteNCAM including juveniles, Beverton-Holt S-R relationship, and a constant baseline level of natural mortality), **M12** (xteNCAM including juveniles, Beverton-Holt S-R relationship, and allometric baseline levels of natural mortality (i.e., Lorenzen M)), and **M13** (xteNCAM including juveniles, Beverton-Holt S-R relationship, and shifts in baseline levels of natural mortality).*

Model	k	$ln(L)$	AIC	ΔAIC
M13	204	17939.66	36287.32	0.000
M9	201	17948.52	36299.05	11.732
M12	203	17955.75	36317.50	30.185
M11	202	17957.47	36318.95	31.632

Quantity	**Symbol**	**M9**	**M11**	**M12**	**M13**
Baseline level of natural mortality (1954–90)	m_y	NA	NA	NA	0.168
Baseline level of natural mortality (1991–94)	-	NA	NA	NA	1.175
Baseline level of natural mortality (1995-2020)	-	NA	NA	NA	0.398
Baseline level of natural mortality	m	NA	0.239	0.189	NA
RV survey observation error	σ_{RV}	0.431	0.431	0.435	0.428
SN survey observation error (age 3)	σ_{SN_a}	0.671	0.668	0.669	0.663
SN survey observation error (ages 4-14)	-	0.130	0.128	0.130	0.120
Age correlation in SN q	$\varphi_{\text{SN}_q,\text{age}}$	0.865	0.868	0.868	0.865
Year correlation in SN q	$\varphi_{\text{SN}_q,\text{year}}$	0.887	0.886	0.886	0.886
SN q variance parameter	σ_{SN_q}	0.826	0.830	0.829	0.824
Age composition error (ages 0-2)	σ_{P_a}	1.817	1.831	1.826	1.818
Age composition error (ages 3-4)	-	0.859	0.844	0.851	0.851
Age composition error (ages 5-14)	-	0.308	0.306	0.306	0.306
Age correlation in process errors	$\varphi_{\delta,\text{age}}$	0.787	0.862	0.860	0.689
Year correlation in process errors	$\varphi_{\delta,\text{year}}$	0.787	0.766	0.772	0.641
Process error variance	σ_δ	0.248	0.281	0.267	0.305
Age correlation in F	$\varphi_{F,\text{age}}$	0.908	0.908	0.911	0.907
Year correlation in F	$\varphi_{F,\text{year}}$	0.998	0.998	0.998	0.998
F variance parameter	σ_F	0.203	0.203	0.202	0.203
S-R relationship parameter	α_{SSB}	11.772	7.233	12.484	9.986
S-R relationship parameter	$\log(\beta_{\text{SSB}})$	-12.023	-11.994	-11.971	-11.638
Variance of log-recruitment	σ_r	0.227	0.271	0.260	0.236
Variance of tagging F deviations (pre 1997)	$\sigma_{f_{x,1}}$	0.944	0.942	0.942	0.944
Variance of tagging F deviations (post 1997)	$\sigma_{f_{x,2}}$	1.050	1.051	1.052	1.050
NB overdispersion parameter for pre 1997 tag experiments	κ_1	16.128	16.112	16.157	16.032
NB overdispersion parameter for post 1997 tag experiments	κ_2	8.063	8.081	8.092	8.018
Juvenile survey observation error	σ_{juv}	1.182	1.158	1.156	1.177

3.8. CONCLUSION

Our enhancements to NCAM have yielded consistent estimates of key metrics, such as SSB, across various model variations. This robustness indicates that the model is predominantly data-driven, showcasing its reliability in capturing the dynamics of the Northern cod stock. Incremental improvements, including the incorporation of past tagging data, an extended series of reported landings, and juvenile survey data, have refined our understanding of historical trends dating back to 1954.

Noteworthy improvements include the adoption of a more data-driven approach for estimating catch composition variance, enhancing the model's overall performance. Conflicting patterns in recent survey indices were addressed through the implementation of a flexible catchability structure for the Sentinel survey. The extension of the time series to 1954 using the xteNCAM model revealed consistent trends with past assessments (compare Lilly 2008), with disc tag data proving crucial for reconstructing historical vital rates.

The addition of juvenile survey data represents a significant advancement, allowing for the inclusion of age 0 and 1 in the model. Despite variations in catchability assumptions, the chosen simple model formulation with constant juvenile survey catchability appears to be a reasonable assumption. These data are expected to be a useful indicator of year-class strength (Lunzmann-Cooke et al. 2021), which should aid forecasts of future stock production.

Exploring S-R relationships highlighted the superiority of Beverton-Holt and sigmoidal Beverton-Holt models over the linear model. Sensitivity tests excluding juvenile survey data supported the density-dependent nature of recruitment, challenging previous inferences regarding a linear relationship (Rose and Rowe 2022). These findings emphasize the importance of integrated analyses and suggest that density-dependent dynamics play a role in Northern cod recruitment.

Explorations of baseline M assumptions emphasizes a trade-off between statistical defensibility and biological realism. While models incorporating temporal shifts perform well statistically, the allometric model aligns more closely with biological expectations, particularly in estimating juvenile mortality (Lorenzen et al. 2022). Identifying the most defensible option requires further discussion.

In conclusion, xteNCAM appears to be a reliable and robust tool for assessing the Northern cod stock, providing valuable insights into historical dynamics that were not easily assessed using base-case NCAM. The extended model we propose bridges gaps in our knowledge and offers a robust foundation for informed fisheries management decisions.

4. ACKNOWLEDGEMENTS

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6. APPENDIX I - DATA INPUTS

Table A1: Reported landings (t) of cod from NAFO Divs. 2J+3KL from 1954 onward.

Year	Landings
1954	315,843.0
1955	232,858.0
1956	236,210.0
1957	254,456.0
1958	206,710.0
1959	359,572.0
1960	467,802.0
1961	505,105.0
1962	507,026.0
1963	509,209.0
1964	602,651.0
1965	545,035.0
1966	524,505.0
1967	611,764.0
1968	810,014.0
1969	753,690.0
1970	520,226.0
1971	439,518.0
1972	458,295.0
1973	354,509.0
1974	372,650.0
1975	287,508.0
1976	214,220.0
1977	172,720.0
1978	138,559.0
1979	166,899.0
1980	175,788.0
1981	170,748.0
1982	229,774.0
1983	232,345.0
1984	232,471.0
1985	231,293.0
1986	266,713.0
1987	239,924.0
1988	268,677.0
1989	253,990.0
1990	219,452.0
1991	172,012.0
1992	40,956.0
1993	11,392.0
1994	1,314.0
1995	413.0

Year	Landings
1996	1,875.0
1997	877.0
1998	4,507.0
1999	8,526.0
2000	5,430.0
2001	6,969.0
2002	4,249.0
2003	994.0
2004	649.0
2005	1,331.0
2006	2,701.0
2007	2,931.0
2008	3,385.0
2009	3,116.0
2010	2,962.0
2011	3,770.0
2012	3,871.0
2013	4,506.0
2014	4,870.0
2015	4,436.0
2016	10,105.0
2017	12,881.0
2018	9,456.0
2019	10,503.0
2020	10,260.0
2021	10,977.0
2022	12,475.0
2023	12,998.0

Table A2: Catch numbers-at-age (thousands) for the commercial cod fishery in NAFO Divs. 2J+3KL from 1965 onward.

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1965	0	0	85	5,177	28,709	46,800	66,946	64,360	68,176	33,819	14,913	6,945	3,729	3,948	3,730
1966	0	0	819	14,057	65,992	93,687	62,812	59,312	30,423	23,844	8,762	4,528	2,280	1,825	1,186
1967	0	0	790	15,262	77,873	100,339	96,759	54,996	38,691	17,146	16,084	5,949	3,367	2,108	1,529
1968	0	0	288	6,142	94,291	205,805	150,541	83,808	39,443	23,171	10,984	5,591	5,249	1,939	1,334
1969	0	0	59	4,330	39,626	100,858	163,228	107,509	52,661	19,651	12,370	6,389	4,479	3,004	1,557
1970	0	0	6,819	18,104	60,102	82,357	101,249	85,696	29,218	10,857	3,825	2,000	1,200	507	224
1971	0	0	33	12,876	71,557	95,384	98,111	57,865	25,055	11,732	4,470	2,223	1,287	1,140	720
1972	0	0	236	6,737	79,809	116,562	76,196	55,984	29,553	11,750	6,393	2,987	1,660	1,388	725
1973	0	0	0	3,963	40,785	94,844	59,503	35,464	27,351	14,153	7,566	3,815	2,153	1,173	450
1974	0	0	473	3,231	13,201	34,927	74,403	60,539	35,687	18,854	10,492	5,818	2,934	1,078	652
1975	0	0	420	3,968	14,101	25,370	34,426	39,105	36,485	13,421	7,514	2,315	1,179	808	372
1976	0	0	15	13,767	33,727	28,049	20,898	16,811	16,022	10,931	4,637	1,462	631	292	251
1977	0	0	108	7,128	65,510	40,462	12,107	5,397	3,396	2,730	1,381	532	296	149	75
1978	0	0	0	1,323	17,556	39,206	20,319	7,711	3,078	1,530	1,083	437	219	105	62
1979	0	0	0	1,152	12,361	37,493	29,202	10,982	3,460	1,300	757	560	183	116	51
1980	0	0	92	2,554	12,025	28,814	30,016	18,017	4,830	1,217	520	232	229	56	65
1981	0	0	0	2,185	7,172	13,191	24,800	22,014	11,848	3,175	779	309	195	125	48
1982	0	0	0	1,702	31,286	19,003	14,397	25,435	16,930	11,936	1,923	338	156	90	153
1983	0	0	18	2,585	13,616	42,602	19,028	12,044	14,701	8,934	6,341	1,018	248	90	41
1984	0	0	3	782	14,871	31,760	38,624	12,503	7,246	8,910	4,227	2,536	451	146	48
1985	0	0	0	650	14,824	36,614	33,922	28,006	7,050	3,836	5,162	2,905	1,681	254	107
1986	0	0	1	831	15,219	44,168	45,869	26,025	14,722	3,104	2,000	1,977	1,101	574	116
1987	0	0	42	2,329	9,217	32,340	49,061	28,469	19,505	5,818	1,346	676	873	391	200

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1988	0	0	25	2,779	14,651	20,184	47,917	45,725	18,608	9,026	4,337	774	422	366	223
1989	0	0	8	1,696	17,639	21,150	25,212	38,708	28,499	8,696	3,640	1,695	572	244	180
1990	0	0	58	7,693	40,557	36,410	22,695	16,390	17,940	9,156	2,865	1,084	478	103	98
1991	0	0	35	3,111	31,654	53,805	29,553	9,064	6,164	4,745	1,696	641	250	88	39
1992	0	0	0	430	3,860	14,535	12,211	4,526	1,372	376	199	104	18	9	4
1993	0	0	0	940	4,993	3,343	1,940	700	147	21	0	0	0	0	0
1994	0	0	0	105	379	575	177	74	22	2	0	0	0	0	0
1995	0	0	0	12	41	93	76	25	10	2	0	0	0	0	0
1996	0	0	1	35	157	304	401	131	24	7	2	0	0	0	0
1997	0	0	0	12	39	92	95	148	35	5	2	0	0	0	0
1998	0	0	3	96	229	395	689	384	236	74	10	5	2	1	0
1999	0	0	7	70	238	638	795	1,157	370	253	52	13	3	0	0
2000	0	0	5	141	258	419	437	328	294	151	136	33	5	3	1
2001	0	0	10	249	778	710	611	365	190	272	80	117	33	3	1
2002	0	0	6	166	296	399	335	235	124	77	113	50	52	10	2
2003	0	0	0	9	11	19	53	44	28	22	9	32	20	27	7
2004	0	0	1	10	24	33	47	59	32	14	7	3	5	2	2
2005	0	0	0	16	27	137	182	101	51	19	7	4	2	2	1
2006	0	0	0	12	159	307	381	168	79	30	13	5	2	1	2
2007	0	0	0	12	44	357	423	178	69	21	8	5	2	1	1
2008	0	0	0	11	84	172	649	422	147	37	12	6	2	1	1
2009	0	0	0	25	96	124	170	410	248	68	15	5	1	1	0
2010	0	0	3	18	72	122	202	200	329	143	34	6	1	1	0
2011	0	0	4	27	74	92	186	247	188	202	78	17	2	1	0

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2012	0	0	3	38	63	165	248	271	228	117	131	43	7	1	0
2013	0	0	0	22	137	287	432	357	231	153	75	55	24	6	1
2014	0	0	8	36	42	232	438	461	211	115	69	34	38	12	1
2015	0	0	0	3	26	87	450	397	266	115	52	49	21	21	4
2016	0	0	0	3	48	259	520	1,221	720	384	188	70	32	14	21
2017	0	0	0	1	34	224	836	706	1,318	689	354	123	59	41	20
2018	0	0	0	0	23	101	596	1,072	824	545	274	117	42	9	6
2019	0	0	0	1	46	104	384	859	1,364	568	418	165	88	19	25
2020	0	0	0	3	58	202	273	530	1,194	910	354	212	60	20	30
2021	0	0	0	3	50	203	512	471	917	968	808	290	126	44	20
2022	0	0	0	1	22	127	438	646	744	861	970	416	146	142	104
2023	0	0	0	0	17	159	617	1,353	1,140	665	405	288	257	80	63

Table A3: Mean number of cod per tow-at-age in the index strata for the autumn DFO RV bottom-trawl surveys of NAFO Divs. 2J+3KL from 1983 onward.

Year	2	3	4	5	6	7	8	9	10	11	12	13	14
1983	58.000	42.954	20.918	16.086	4.202	2.540	4.812	2.585	1.084	0.221	0.075	0.025	0.027
1984	56.924	47.820	33.362	16.569	10.657	2.369	1.255	2.015	1.103	0.424	0.191	0.040	0.027
1985	10.632	32.232	30.342	17.065	8.460	4.159	0.864	0.756	0.672	0.374	0.128	0.032	0.010
1986	14.801	20.783	63.369	57.562	29.380	11.526	5.087	1.246	0.505	0.601	0.354	0.104	0.047
1987	11.960	7.646	10.218	23.054	15.594	4.726	3.133	1.512	0.333	0.139	0.163	0.085	0.038
1988	18.859	13.237	7.677	10.338	13.925	10.209	2.446	1.342	0.675	0.137	0.087	0.072	0.042
1989	62.961	35.266	21.412	12.117	10.183	10.143	5.447	1.392	0.719	0.337	0.106	0.034	0.032
1990	15.555	47.277	28.508	12.951	7.104	4.136	5.278	2.398	0.716	0.329	0.143	0.037	0.026
1991	11.283	15.132	39.039	18.536	4.714	1.472	0.697	0.423	0.188	0.041	0.027	0.005	0.000
1992	2.514	5.118	3.441	5.911	2.103	0.372	0.043	0.018	0.011	0.002	0.008	0.000	0.000
1993	3.034	2.013	1.670	0.477	0.410	0.077	0.003	0.000	0.001	0.000	0.000	0.000	0.000
1994	0.467	0.694	0.342	0.101	0.028	0.020	0.009	0.000	0.000	0.000	0.000	0.000	0.000
1995	0.969	0.727	0.295	0.090	0.058	0.010	0.001	0.000	0.000	0.000	0.000	0.000	0.000
1996	1.392	0.855	0.393	0.150	0.047	0.032	0.003	0.003	0.000	0.000	0.000	0.000	0.000
1997	0.678	0.890	0.255	0.115	0.010	0.035	0.045	0.003	0.000	0.000	0.000	0.000	0.000
1998	0.393	0.614	0.488	0.159	0.043	0.024	0.022	0.009	0.000	0.003	0.000	0.000	0.000
1999	1.722	1.543	0.507	0.232	0.044	0.011	0.008	0.013	0.007	0.003	0.003	0.000	0.000
2000	1.608	1.529	0.974	0.209	0.072	0.015	0.008	0.004	0.000	0.000	0.000	0.000	0.000
2001	1.535	1.776	0.691	0.316	0.053	0.013	0.010	0.013	0.000	0.024	0.007	0.000	0.000
2002	2.271	1.063	0.628	0.150	0.030	0.006	0.000	0.000	0.000	0.000	0.003	0.003	0.003
2003	0.544	0.630	0.251	0.073	0.019	0.004	0.000	0.004	0.000	0.003	0.000	0.003	0.003
2005	1.012	2.018	0.764	0.212	0.036	0.003	0.004	0.000	0.000	0.000	0.000	0.000	0.000

Year	2	3	4	5	6	7	8	9	10	11	12	13	14
2006	1.178	1.435	1.874	1.240	0.312	0.029	0.036	0.010	0.007	0.000	0.004	0.000	0.000
2007	2.272	1.884	1.350	1.786	0.714	0.173	0.037	0.014	0.011	0.000	0.004	0.000	0.000
2008	2.091	2.850	1.918	1.144	1.447	0.618	0.124	0.086	0.000	0.012	0.011	0.004	0.000
2009	2.590	4.379	3.748	1.815	0.606	0.548	0.135	0.026	0.005	0.004	0.004	0.000	0.000
2010	1.803	2.832	2.154	1.255	0.827	0.436	0.360	0.151	0.036	0.014	0.000	0.000	0.000
2011	2.559	2.233	1.395	0.794	0.660	0.393	0.255	0.253	0.088	0.014	0.000	0.000	0.000
2012	1.383	3.773	2.972	1.517	0.701	0.533	0.328	0.194	0.218	0.075	0.012	0.000	0.000
2013	5.949	2.748	4.014	2.860	1.697	0.918	0.541	0.223	0.208	0.157	0.072	0.012	0.000
2014	11.846	8.697	3.630	4.137	1.977	0.893	0.457	0.234	0.108	0.039	0.110	0.020	0.000
2015	8.395	11.372	8.402	3.722	3.657	1.453	0.736	0.364	0.141	0.117	0.053	0.039	0.021
2016	5.899	11.409	9.650	5.423	2.084	2.157	1.355	0.576	0.293	0.123	0.086	0.054	0.049
2017	6.849	6.593	7.850	6.419	3.024	0.942	0.774	0.253	0.107	0.061	0.030	0.011	0.008
2018	10.925	9.850	6.805	5.450	4.421	2.921	1.013	0.721	0.313	0.148	0.044	0.006	0.006
2019	8.096	10.837	9.021	4.925	4.263	3.495	2.123	0.749	0.389	0.214	0.169	0.056	0.008
2020	9.173	10.017	8.739	5.687	2.524	2.864	1.626	0.982	0.245	0.157	0.050	0.011	0.000
2023	5.311	7.606	6.204	5.840	3.026	1.916	1.101	0.473	0.392	0.184	0.116	0.049	0.009

Table A4: Beginning of year weight-at-age estimates (kg) from a generalized Von Bertalanffy (VonB2) growth model described in Cadigan (2016b), fitted by cohort to average weight-at-age data for cod from autumn bottom-trawl surveys in Division 2J+3KL.

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1954	0.000	0.014	0.076	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1955	0.000	0.014	0.076	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1956	0.000	0.014	0.076	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1957	0.000	0.014	0.076	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1958	0.000	0.014	0.076	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1959	0.000	0.014	0.076	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1960	0.000	0.014	0.076	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1961	0.000	0.014	0.076	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1962	0.000	0.014	0.076	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1963	0.000	0.014	0.076	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1964	0.000	0.013	0.076	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1965	0.000	0.013	0.075	0.231	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1966	0.000	0.013	0.072	0.228	0.520	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1967	0.000	0.013	0.070	0.217	0.514	0.978	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1968	0.000	0.013	0.068	0.207	0.483	0.966	1.629	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1969	0.000	0.013	0.068	0.200	0.456	0.901	1.611	2.485	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1970	0.000	0.013	0.068	0.200	0.440	0.844	1.492	2.457	3.540	4.776	6.165	7.669	9.245	10.852	12.448
1971	0.000	0.013	0.069	0.200	0.440	0.811	1.390	2.266	3.501	4.776	6.165	7.669	9.245	10.852	12.448
1972	0.000	0.012	0.071	0.208	0.441	0.812	1.331	2.102	3.221	4.726	6.165	7.669	9.245	10.852	12.448
1973	0.000	0.012	0.067	0.216	0.462	0.817	1.335	2.009	2.980	4.343	6.103	7.669	9.245	10.852	12.448
1974	0.000	0.012	0.062	0.197	0.486	0.864	1.346	2.016	2.843	4.012	5.610	7.596	9.245	10.852	12.448
1975	0.000	0.012	0.062	0.178	0.436	0.916	1.434	2.037	2.856	3.824	5.181	6.991	9.163	10.852	12.448

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1976	0.000	0.012	0.064	0.177	0.382	0.809	1.531	2.182	2.889	3.844	4.936	6.460	8.452	10.762	12.448
1977	0.000	0.013	0.065	0.182	0.379	0.694	1.336	2.343	3.108	3.893	4.965	6.156	7.822	9.957	12.353
1978	0.000	0.013	0.068	0.185	0.392	0.685	1.124	2.025	3.349	4.200	5.032	6.196	7.460	9.235	11.470
1979	0.000	0.013	0.068	0.193	0.394	0.709	1.106	1.679	2.877	4.535	5.436	6.283	7.510	8.818	10.670
1980	0.000	0.014	0.068	0.190	0.411	0.711	1.148	1.648	2.360	3.882	5.875	6.788	7.617	8.879	10.204
1981	0.000	0.014	0.070	0.187	0.400	0.741	1.146	1.712	2.310	3.159	5.024	7.334	8.225	9.006	10.275
1982	0.000	0.014	0.072	0.193	0.389	0.710	1.191	1.703	2.402	3.087	4.068	6.278	8.873	9.709	10.420
1983	0.000	0.014	0.069	0.199	0.400	0.682	1.128	1.767	2.381	3.211	3.969	5.072	7.618	10.451	11.208
1984	0.000	0.014	0.070	0.191	0.412	0.699	1.072	1.656	2.465	3.174	4.129	4.944	6.154	9.014	12.029
1985	0.000	0.014	0.073	0.195	0.394	0.721	1.094	1.557	2.289	3.280	4.072	5.141	5.994	7.297	10.435
1986	0.000	0.013	0.071	0.204	0.405	0.689	1.129	1.585	2.134	3.022	4.199	5.060	6.231	7.103	8.481
1987	0.000	0.013	0.070	0.198	0.427	0.710	1.078	1.635	2.166	2.797	3.844	5.208	6.122	7.379	8.254
1988	0.000	0.013	0.067	0.195	0.416	0.754	1.114	1.561	2.234	2.830	3.535	4.743	6.289	7.241	8.566
1989	0.000	0.013	0.067	0.189	0.411	0.737	1.194	1.617	2.132	2.918	3.567	4.339	5.706	7.425	8.399
1990	0.000	0.014	0.070	0.191	0.398	0.729	1.167	1.744	2.214	2.785	3.677	4.368	5.198	6.718	8.597
1991	0.000	0.014	0.075	0.203	0.408	0.707	1.156	1.709	2.403	2.898	3.511	4.500	5.221	6.100	7.766
1992	0.000	0.014	0.076	0.223	0.442	0.734	1.124	1.694	2.358	3.160	3.659	4.299	5.375	6.115	7.033
1993	0.000	0.014	0.074	0.226	0.496	0.808	1.180	1.650	2.339	3.106	4.005	4.485	5.138	6.290	7.037
1994	0.000	0.015	0.077	0.218	0.502	0.923	1.317	1.750	2.284	3.084	3.943	4.926	5.366	6.017	7.235
1995	0.000	0.015	0.078	0.222	0.475	0.934	1.524	1.975	2.442	3.017	3.919	4.856	5.907	6.289	6.926
1996	0.000	0.016	0.079	0.223	0.481	0.870	1.542	2.310	2.780	3.249	3.841	4.830	5.831	6.933	7.243
1997	0.000	0.016	0.084	0.223	0.475	0.876	1.420	2.335	3.276	3.724	4.160	4.742	5.805	6.853	7.992
1998	0.000	0.016	0.087	0.239	0.469	0.852	1.419	2.129	3.310	4.408	4.790	5.160	5.708	6.827	7.908
1999	0.000	0.017	0.089	0.247	0.506	0.832	1.365	2.115	2.996	4.451	5.682	5.959	6.234	6.724	7.883

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2000	0.000	0.017	0.091	0.255	0.526	0.902	1.318	2.015	2.961	4.008	5.734	7.069	7.207	7.362	7.776
2001	0.000	0.017	0.091	0.260	0.543	0.940	1.434	1.927	2.798	3.945	5.148	7.129	8.532	8.509	8.527
2002	0.000	0.018	0.091	0.255	0.554	0.971	1.497	2.102	2.653	3.702	5.050	6.391	8.599	10.037	9.841
2003	0.000	0.019	0.095	0.253	0.534	0.990	1.549	2.199	2.900	3.486	4.713	6.252	7.711	10.110	11.549
2004	0.000	0.019	0.099	0.263	0.521	0.939	1.578	2.277	3.037	3.816	4.413	5.813	7.528	9.079	11.625
2005	0.000	0.019	0.099	0.273	0.541	0.906	1.477	2.316	3.146	3.999	4.833	5.418	6.980	8.851	10.468
2006	0.000	0.018	0.098	0.273	0.561	0.936	1.409	2.143	3.197	4.142	5.066	5.933	6.483	8.194	10.196
2007	0.000	0.019	0.096	0.270	0.559	0.972	1.448	2.026	2.929	4.204	5.245	6.217	7.094	7.592	9.433
2008	0.000	0.019	0.100	0.265	0.552	0.966	1.504	2.072	2.746	3.822	5.319	6.433	7.429	8.297	8.728
2009	0.000	0.019	0.102	0.273	0.541	0.954	1.493	2.152	2.797	3.558	4.806	6.517	7.682	8.681	9.520
2010	0.000	0.019	0.101	0.279	0.557	0.933	1.473	2.133	2.904	3.610	4.447	5.862	7.775	8.969	9.950
2011	0.000	0.018	0.101	0.275	0.568	0.959	1.438	2.103	2.874	3.747	4.496	5.398	6.971	9.069	10.268
2012	0.000	0.017	0.093	0.274	0.560	0.974	1.475	2.052	2.832	3.703	4.663	5.439	6.396	8.116	10.374
2013	0.000	0.016	0.088	0.254	0.557	0.959	1.495	2.098	2.761	3.648	4.604	5.638	6.425	7.425	9.278
2014	0.000	0.016	0.083	0.240	0.516	0.953	1.470	2.122	2.817	3.554	4.536	5.561	6.655	7.439	8.472
2015	0.000	0.016	0.080	0.226	0.486	0.883	1.459	2.084	2.844	3.618	4.417	5.479	6.559	7.699	8.467
2016	0.000	0.016	0.080	0.217	0.459	0.833	1.354	2.067	2.790	3.646	4.486	5.333	6.462	7.584	8.756
2017	0.000	0.016	0.079	0.216	0.440	0.787	1.278	1.921	2.765	3.575	4.513	5.407	6.290	7.472	8.621
2018	0.000	0.016	0.079	0.216	0.439	0.755	1.209	1.816	2.574	3.539	4.422	5.431	6.365	7.272	8.495
2019	0.000	0.015	0.079	0.215	0.438	0.753	1.161	1.720	2.437	3.300	4.376	5.319	6.384	7.347	8.268
2020	0.000	0.015	0.079	0.214	0.437	0.752	1.157	1.654	2.311	3.129	4.088	5.260	6.250	7.360	8.341
2021	0.000	0.015	0.078	0.213	0.435	0.750	1.156	1.648	2.225	2.972	3.882	4.923	6.178	7.204	8.345
2022	0.000	0.015	0.076	0.212	0.433	0.747	1.153	1.646	2.217	2.864	3.692	4.682	5.794	7.117	8.167
2023	0.000	0.014	0.074	0.207	0.431	0.743	1.149	1.642	2.214	2.854	3.562	4.460	5.518	6.688	8.067

Table A5: Mid-year weight-at-age estimates (kg) from a generalized Von Bertalanffy (VonB2) growth model described in Cadigan (2016b) fitted by cohort to average weight-at-age data for cod from autumn bottom-trawl surveys in Division 2J+3KL.

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1954	0.003	0.036	0.139	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1955	0.003	0.036	0.139	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1956	0.003	0.036	0.139	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1957	0.003	0.036	0.139	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1958	0.003	0.036	0.139	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1959	0.003	0.036	0.139	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1960	0.003	0.036	0.139	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1961	0.003	0.036	0.139	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1962	0.003	0.036	0.139	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1963	0.003	0.036	0.139	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1964	0.003	0.036	0.139	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1965	0.003	0.035	0.138	0.356	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1966	0.003	0.034	0.132	0.352	0.726	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1967	0.003	0.033	0.126	0.332	0.717	1.278	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1968	0.003	0.033	0.123	0.315	0.671	1.264	2.031	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1969	0.003	0.033	0.122	0.305	0.631	1.174	2.008	2.988	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1970	0.003	0.033	0.122	0.305	0.608	1.097	1.856	2.955	4.137	5.454	6.905	8.451	10.048	11.654	13.230
1971	0.003	0.034	0.126	0.305	0.608	1.052	1.725	2.721	4.093	5.454	6.905	8.451	10.048	11.654	13.230
1972	0.003	0.032	0.130	0.318	0.611	1.054	1.650	2.521	3.762	5.398	6.905	8.451	10.048	11.654	13.230
1973	0.003	0.030	0.121	0.333	0.643	1.062	1.655	2.407	3.478	4.960	6.838	8.451	10.048	11.654	13.230
1974	0.003	0.030	0.110	0.301	0.679	1.127	1.671	2.416	3.316	4.581	6.288	8.373	10.048	11.654	13.230
1975	0.003	0.031	0.110	0.268	0.605	1.200	1.785	2.443	3.332	4.365	5.808	7.714	9.961	11.654	13.230

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1976	0.003	0.032	0.113	0.266	0.524	1.052	1.912	2.623	3.373	4.390	5.534	7.133	9.201	11.561	13.230
1977	0.003	0.033	0.115	0.274	0.518	0.893	1.660	2.822	3.634	4.447	5.569	6.799	8.524	10.715	13.133
1978	0.003	0.034	0.120	0.277	0.536	0.881	1.386	2.431	3.921	4.801	5.645	6.844	8.134	9.952	12.220
1979	0.003	0.034	0.119	0.289	0.539	0.913	1.362	2.004	3.361	5.188	6.100	6.941	8.190	9.509	11.385
1980	0.003	0.035	0.118	0.283	0.562	0.913	1.414	1.964	2.745	4.437	6.592	7.498	8.307	9.576	10.898
1981	0.003	0.036	0.122	0.277	0.542	0.951	1.409	2.042	2.685	3.601	5.638	8.096	8.963	9.712	10.974
1982	0.003	0.034	0.126	0.285	0.524	0.906	1.463	2.027	2.792	3.516	4.559	6.939	9.660	10.459	11.128
1983	0.003	0.035	0.121	0.294	0.537	0.865	1.378	2.101	2.764	3.657	4.446	5.604	8.311	11.243	11.953
1984	0.003	0.036	0.123	0.282	0.554	0.884	1.302	1.959	2.859	3.611	4.624	5.460	6.719	9.723	12.807
1985	0.003	0.035	0.128	0.289	0.530	0.913	1.328	1.834	2.644	3.727	4.556	5.677	6.542	7.885	11.146
1986	0.003	0.034	0.124	0.303	0.545	0.872	1.370	1.864	2.455	3.422	4.693	5.583	6.799	7.675	9.082
1987	0.003	0.033	0.123	0.295	0.577	0.899	1.308	1.923	2.488	3.157	4.285	5.740	6.676	7.969	8.840
1988	0.003	0.033	0.118	0.291	0.563	0.960	1.353	1.836	2.566	3.190	3.930	5.218	6.851	7.817	9.169
1989	0.003	0.034	0.119	0.281	0.556	0.938	1.455	1.904	2.449	3.288	3.961	4.763	6.207	8.007	8.987
1990	0.003	0.036	0.125	0.286	0.539	0.928	1.424	2.061	2.546	3.140	4.081	4.789	5.644	7.239	9.190
1991	0.003	0.036	0.136	0.308	0.556	0.902	1.411	2.020	2.769	3.269	3.898	4.931	5.663	6.563	8.298
1992	0.003	0.036	0.137	0.342	0.608	0.941	1.373	2.004	2.720	3.572	4.065	4.712	5.828	6.573	7.509
1993	0.004	0.037	0.134	0.346	0.688	1.044	1.449	1.954	2.700	3.514	4.457	4.920	5.573	6.760	7.507
1994	0.004	0.038	0.137	0.330	0.697	1.201	1.627	2.081	2.639	3.491	4.390	5.409	5.823	6.469	7.714
1995	0.004	0.039	0.138	0.336	0.654	1.215	1.894	2.360	2.831	3.418	4.366	5.336	6.415	6.763	7.388
1996	0.004	0.041	0.140	0.334	0.660	1.125	1.916	2.771	3.236	3.692	4.283	5.311	6.337	7.459	7.727
1997	0.004	0.042	0.149	0.332	0.647	1.128	1.755	2.801	3.822	4.243	4.650	5.218	6.311	7.377	8.528
1998	0.004	0.043	0.154	0.357	0.636	1.091	1.748	2.544	3.861	5.029	5.363	5.689	6.211	7.352	8.443
1999	0.004	0.044	0.158	0.371	0.687	1.059	1.673	2.520	3.485	5.077	6.364	6.575	6.792	7.247	8.419

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2000	0.004	0.044	0.162	0.382	0.715	1.150	1.607	2.390	3.437	4.564	6.420	7.793	7.853	7.941	8.311
2001	0.004	0.045	0.160	0.390	0.739	1.200	1.751	2.276	3.235	4.484	5.758	7.857	9.282	9.173	9.117
2002	0.004	0.047	0.159	0.379	0.753	1.241	1.830	2.486	3.057	4.195	5.640	7.043	9.352	10.794	10.509
2003	0.004	0.049	0.167	0.373	0.720	1.265	1.895	2.602	3.345	3.939	5.253	6.883	8.391	10.869	12.297
2004	0.004	0.049	0.173	0.388	0.699	1.192	1.929	2.695	3.504	4.313	4.907	6.389	8.185	9.773	12.374
2005	0.004	0.048	0.173	0.402	0.724	1.143	1.794	2.740	3.629	4.520	5.374	5.944	7.582	9.523	11.162
2006	0.004	0.048	0.171	0.401	0.751	1.178	1.704	2.522	3.686	4.681	5.632	6.507	7.033	8.811	10.869
2007	0.005	0.049	0.168	0.396	0.748	1.223	1.747	2.374	3.364	4.750	5.830	6.817	7.692	8.158	10.056
2008	0.005	0.050	0.173	0.389	0.738	1.215	1.815	2.423	3.141	4.304	5.909	7.052	8.052	8.907	9.300
2009	0.005	0.050	0.177	0.401	0.722	1.199	1.800	2.516	3.193	3.994	5.326	7.140	8.322	9.315	10.134
2010	0.004	0.050	0.175	0.409	0.743	1.172	1.774	2.491	3.315	4.045	4.916	6.411	8.419	9.618	10.585
2011	0.004	0.046	0.175	0.403	0.756	1.203	1.732	2.456	3.278	4.197	4.961	5.892	7.540	9.721	10.917
2012	0.004	0.044	0.162	0.402	0.745	1.220	1.773	2.395	3.231	4.145	5.145	5.927	6.907	8.696	11.024
2013	0.004	0.041	0.153	0.372	0.741	1.201	1.796	2.446	3.148	4.084	5.076	6.143	6.929	7.947	9.860
2014	0.004	0.040	0.144	0.350	0.686	1.192	1.765	2.472	3.208	3.978	5.001	6.056	7.175	7.952	8.998
2015	0.004	0.040	0.138	0.331	0.647	1.106	1.751	2.427	3.236	4.045	4.869	5.966	7.069	8.227	8.983
2016	0.004	0.040	0.138	0.317	0.611	1.044	1.626	2.406	3.174	4.073	4.941	5.807	6.965	8.101	9.285
2017	0.004	0.040	0.137	0.316	0.586	0.986	1.536	2.237	3.144	3.992	4.967	5.882	6.779	7.983	9.140
2018	0.004	0.039	0.137	0.316	0.584	0.947	1.454	2.117	2.929	3.951	4.866	5.904	6.854	7.769	9.008
2019	0.004	0.039	0.137	0.315	0.583	0.944	1.397	2.006	2.775	3.687	4.813	5.781	6.870	7.843	8.768
2020	0.004	0.039	0.136	0.314	0.582	0.943	1.392	1.930	2.633	3.499	4.500	5.715	6.725	7.852	8.839
2021	0.004	0.038	0.135	0.312	0.580	0.940	1.390	1.923	2.536	3.325	4.276	5.355	6.646	7.685	8.839
2022	0.004	0.037	0.132	0.311	0.577	0.937	1.387	1.920	2.527	3.207	4.071	5.096	6.238	7.591	8.650
2023	0.004	0.036	0.129	0.304	0.574	0.932	1.383	1.916	2.524	3.195	3.930	4.859	5.946	7.140	8.542

Table A6: Estimated proportions-at-age of mature female cod from NAFO Div. 2J+3KL, from DFO RV autumn bottom trawl surveys. Estimates were obtained from a cohort-specific binomial logistic regression model fitted to observed proportions mature-at-age.

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1954	0.000	0.000	0.000	0.000	0.001	0.011	0.158	0.763	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1955	0.000	0.000	0.000	0.000	0.001	0.011	0.158	0.763	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1956	0.000	0.000	0.000	0.000	0.001	0.011	0.158	0.763	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1957	0.000	0.000	0.000	0.000	0.001	0.011	0.158	0.763	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1958	0.000	0.000	0.000	0.000	0.001	0.011	0.158	0.763	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1959	0.000	0.000	0.000	0.000	0.001	0.011	0.158	0.763	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1960	0.000	0.000	0.000	0.000	0.001	0.011	0.158	0.763	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1961	0.000	0.000	0.000	0.000	0.000	0.011	0.158	0.763	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1962	0.000	0.000	0.000	0.000	0.001	0.001	0.158	0.763	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1963	0.000	0.000	0.000	0.000	0.001	0.013	0.040	0.763	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1964	0.000	0.000	0.000	0.001	0.003	0.020	0.186	0.649	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1965	0.000	0.000	0.001	0.003	0.010	0.040	0.247	0.799	0.988	0.999	1.000	1.000	1.000	1.000	1.000
1966	0.000	0.000	0.002	0.005	0.016	0.066	0.335	0.842	0.986	1.000	1.000	1.000	1.000	1.000	1.000
1967	0.000	0.000	0.000	0.008	0.027	0.092	0.360	0.858	0.989	0.999	1.000	1.000	1.000	1.000	1.000
1968	0.000	0.000	0.000	0.001	0.039	0.129	0.385	0.826	0.986	0.999	1.000	1.000	1.000	1.000	1.000
1969	0.000	0.000	0.000	0.000	0.009	0.166	0.440	0.795	0.973	0.999	1.000	1.000	1.000	1.000	1.000
1970	0.000	0.000	0.001	0.000	0.004	0.066	0.496	0.812	0.960	0.996	1.000	1.000	1.000	1.000	1.000
1971	0.000	0.009	0.001	0.003	0.000	0.045	0.364	0.829	0.960	0.993	0.999	1.000	1.000	1.000	1.000
1972	0.000	0.017	0.022	0.007	0.019	0.008	0.368	0.823	0.960	0.992	0.999	1.000	1.000	1.000	1.000
1973	0.000	0.000	0.042	0.054	0.037	0.092	0.200	0.879	0.974	0.992	0.999	1.000	1.000	1.000	1.000
1974	0.000	0.000	0.000	0.101	0.130	0.176	0.372	0.880	0.989	0.997	0.998	1.000	1.000	1.000	1.000
1975	0.000	0.000	0.000	0.000	0.222	0.299	0.543	0.874	0.995	0.999	1.000	1.000	1.000	1.000	1.000

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1976	0.000	0.000	0.001	0.002	0.004	0.422	0.597	0.869	0.984	1.000	1.000	1.000	1.000	1.000	1.000
1977	0.000	0.000	0.001	0.005	0.015	0.043	0.650	0.847	0.973	0.997	1.000	1.000	1.000	1.000	1.000
1978	0.000	0.000	0.000	0.005	0.028	0.114	0.355	0.826	0.949	0.995	1.000	1.000	1.000	1.000	1.000
1979	0.000	0.000	0.000	0.002	0.031	0.140	0.519	0.871	0.924	0.982	0.999	1.000	1.000	1.000	1.000
1980	0.000	0.000	0.000	0.000	0.017	0.166	0.475	0.901	0.988	0.969	0.993	1.000	1.000	1.000	1.000
1981	0.000	0.000	0.000	0.000	0.003	0.113	0.553	0.834	0.987	0.999	0.987	0.997	1.000	1.000	1.000
1982	0.000	0.000	0.001	0.002	0.004	0.044	0.479	0.885	0.965	0.998	1.000	0.995	0.999	1.000	1.000
1983	0.000	0.000	0.000	0.005	0.019	0.059	0.398	0.869	0.980	0.994	1.000	1.000	0.998	1.000	1.000
1984	0.000	0.000	0.000	0.000	0.024	0.142	0.481	0.905	0.980	0.997	0.999	1.000	1.000	0.999	1.000
1985	0.000	0.000	0.000	0.000	0.005	0.111	0.590	0.932	0.993	0.997	0.999	1.000	1.000	1.000	1.000
1986	0.000	0.000	0.000	0.001	0.003	0.053	0.388	0.926	0.995	1.000	1.000	1.000	1.000	1.000	1.000
1987	0.000	0.000	0.000	0.001	0.014	0.039	0.411	0.763	0.991	1.000	1.000	1.000	1.000	1.000	1.000
1988	0.000	0.000	0.000	0.002	0.013	0.122	0.380	0.897	0.942	0.999	1.000	1.000	1.000	1.000	1.000
1989	0.000	0.000	0.000	0.002	0.015	0.115	0.580	0.901	0.991	0.988	1.000	1.000	1.000	1.000	1.000
1990	0.000	0.000	0.000	0.001	0.017	0.098	0.569	0.932	0.993	0.999	0.998	1.000	1.000	1.000	1.000
1991	0.000	0.000	0.000	0.000	0.018	0.130	0.434	0.931	0.993	1.000	1.000	1.000	1.000	1.000	1.000
1992	0.000	0.002	0.001	0.001	0.013	0.250	0.567	0.844	0.993	0.999	1.000	1.000	1.000	1.000	1.000
1993	0.000	0.000	0.008	0.009	0.037	0.276	0.859	0.920	0.975	0.999	1.000	1.000	1.000	1.000	1.000
1994	0.000	0.000	0.000	0.029	0.071	0.511	0.916	0.991	0.990	0.996	1.000	1.000	1.000	1.000	1.000
1995	0.000	0.000	0.000	0.003	0.098	0.405	0.966	0.997	1.000	0.999	0.999	1.000	1.000	1.000	1.000
1996	0.000	0.002	0.001	0.002	0.034	0.282	0.858	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1997	0.000	0.001	0.008	0.008	0.029	0.294	0.588	0.982	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1998	0.000	0.000	0.003	0.030	0.076	0.311	0.834	0.838	0.998	1.000	1.000	1.000	1.000	1.000	1.000
1999	0.000	0.000	0.000	0.014	0.109	0.464	0.872	0.984	0.949	1.000	1.000	1.000	1.000	1.000	1.000

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2000	0.000	0.000	0.000	0.004	0.067	0.325	0.900	0.990	0.999	0.985	1.000	1.000	1.000	1.000	1.000
2001	0.000	0.001	0.001	0.001	0.040	0.263	0.654	0.990	0.999	1.000	0.996	1.000	1.000	1.000	1.000
2002	0.000	0.000	0.005	0.010	0.028	0.325	0.640	0.881	0.999	1.000	1.000	0.999	1.000	1.000	1.000
2003	0.000	0.000	0.001	0.026	0.080	0.380	0.849	0.898	0.967	1.000	1.000	1.000	1.000	1.000	1.000
2004	0.000	0.000	0.001	0.008	0.112	0.425	0.928	0.985	0.978	0.991	1.000	1.000	1.000	1.000	1.000
2005	0.000	0.001	0.003	0.007	0.056	0.380	0.863	0.996	0.999	0.995	0.998	1.000	1.000	1.000	1.000
2006	0.000	0.000	0.004	0.019	0.089	0.315	0.748	0.982	1.000	1.000	0.999	0.999	1.000	1.000	1.000
2007	0.000	0.001	0.001	0.023	0.118	0.560	0.782	0.935	0.998	1.000	1.000	1.000	1.000	1.000	1.000
2008	0.000	0.000	0.003	0.006	0.109	0.487	0.943	0.965	0.986	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.000	0.000	0.002	0.015	0.045	0.389	0.871	0.995	0.995	0.997	1.000	1.000	1.000	1.000	1.000
2010	0.000	0.002	0.003	0.013	0.077	0.268	0.768	0.979	1.000	0.999	0.999	1.000	1.000	1.000	1.000
2011	0.000	0.000	0.009	0.017	0.086	0.314	0.739	0.945	0.997	1.000	1.000	1.000	1.000	1.000	1.000
2012	0.000	0.000	0.000	0.045	0.102	0.404	0.714	0.956	0.989	1.000	1.000	1.000	1.000	1.000	1.000
2013	0.000	0.000	0.001	0.004	0.199	0.425	0.830	0.932	0.994	0.998	1.000	1.000	1.000	1.000	1.000
2014	0.000	0.000	0.001	0.005	0.027	0.565	0.827	0.972	0.987	0.999	1.000	1.000	1.000	1.000	1.000
2015	0.000	0.000	0.001	0.010	0.047	0.176	0.872	0.969	0.996	0.998	1.000	1.000	1.000	1.000	1.000
2016	0.000	0.000	0.002	0.007	0.079	0.321	0.624	0.973	0.995	0.999	1.000	1.000	1.000	1.000	1.000
2017	0.000	0.000	0.000	0.011	0.050	0.429	0.819	0.928	0.995	0.999	1.000	1.000	1.000	1.000	1.000
2018	0.000	0.001	0.000	0.005	0.071	0.270	0.868	0.978	0.990	0.999	1.000	1.000	1.000	1.000	1.000
2019	0.000	0.001	0.004	0.002	0.049	0.347	0.722	0.983	0.998	0.999	1.000	1.000	1.000	1.000	1.000
2020	0.000	0.001	0.004	0.019	0.039	0.367	0.786	0.948	0.998	1.000	1.000	1.000	1.000	1.000	1.000
2021	0.000	0.001	0.003	0.019	0.083	0.489	0.866	0.962	0.992	1.000	1.000	1.000	1.000	1.000	1.000
2022	0.000	0.001	0.003	0.013	0.080	0.292	0.957	0.986	0.994	0.999	1.000	1.000	1.000	1.000	1.000
2023	0.000	0.001	0.003	0.013	0.067	0.281	0.654	0.998	0.999	0.999	1.000	1.000	1.000	1.000	1.000

Table A7: Standardized age-disaggregated Sentinel gill-net (5 1/2" mesh) catch rates (fish / net) of cod in NAFO Divs. 2J+3KL from 1995 onward.

Year	3	4	5	6	7	8	9	10
1995	0.002	0.045	1.048	1.376	0.560	0.320	0.081	0.017
1996	0.031	0.128	0.881	4.880	2.030	0.590	0.130	0.034
1997	0.017	0.082	1.368	2.045	3.679	0.914	0.120	0.049
1998	0.032	0.079	1.050	5.164	3.346	1.835	0.510	0.067
1999	0.013	0.094	1.093	1.926	2.649	0.777	0.409	0.101
2000	0.015	0.065	0.676	1.117	0.782	0.968	0.433	0.207
2001	0.009	0.049	0.293	0.725	0.486	0.226	0.285	0.102
2002	0.019	0.051	0.367	0.579	0.482	0.216	0.117	0.140
2003	0.028	0.073	0.321	1.255	0.765	0.285	0.126	0.050
2004	0.012	0.116	0.701	1.210	1.267	0.394	0.136	0.039
2005	0.023	0.071	1.339	2.006	1.078	0.515	0.188	0.052
2006	0.012	0.306	1.045	2.474	1.203	0.409	0.190	0.066
2007	0.025	0.061	2.021	2.838	1.358	0.438	0.134	0.063
2008	0.020	0.074	0.414	4.251	2.693	0.808	0.216	0.061
2009	0.018	0.047	0.286	0.841	2.750	1.693	0.414	0.101
2010	0.010	0.024	0.244	1.277	1.225	2.139	0.997	0.234
2011	0.013	0.045	0.283	1.030	1.785	1.261	1.393	0.563
2012	0.029	0.082	1.068	2.140	2.342	1.590	0.872	0.910
2013	0.007	0.080	0.945	3.613	2.579	1.879	1.102	0.589
2014	0.027	0.103	2.024	4.468	4.434	1.816	1.018	0.433
2015	0.011	0.077	0.878	5.159	4.670	2.234	0.913	0.434
2016	0.002	0.034	0.403	1.631	4.138	2.545	1.340	0.627
2017	0.001	0.020	0.232	1.589	2.324	3.638	1.708	0.823
2018	0.003	0.013	0.140	1.291	4.253	2.756	1.858	0.834
2019	0.004	0.017	0.093	0.515	2.082	4.109	2.067	1.896
2020	0.004	0.055	0.106	0.713	2.093	2.990	3.441	1.849
2021	0.000	0.027	0.320	1.201	1.707	2.216	2.676	1.743
2022	0.001	0.059	0.235	1.352	2.207	1.866	1.846	1.306

Table A8: Acoustic biomass estimates (t) for Smith Sound, Trinity Bay during 1995-2009 (Rose et al. 2010).

Year	Month	Biomass	SE^2
1995	5.5	11,000	4,000
1997	6.0	14,800	4,500
1998	6.0	15,000	4,500
1999	1.0	15,000	5,000
2000	1.0	17,558	7,000
2001	1.0	25,363	8,800
2002	1.0	22,733	6,800
2003	1.0	19,628	2,720
2004	1.0	17,800	2,000
2006	1.0	17,322	1,273
2007	2.0	14,024	3,222
2008	2.0	7,147	1,053
2009	4.0	600	350

Table A9: Age composition of cod sampled during acoustic surveys in Smith Sound during 1995-2003 (Rose et al. 2010).

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
1995	0	0	0	8	69	49	17	5	2	0	0	0	0
1998	0	6	15	13	42	168	66	236	63	2	2	0	0
1999	3	22	17	144	92	99	194	63	127	34	5	8	0
2000	2	10	153	366	251	137	100	259	92	153	32	8	0
2001	5	19	38	93	80	79	46	37	66	23	38	8	0
2002	0	5	18	68	198	70	53	25	25	59	11	42	4
2003	0	2	20	152	121	105	37	13	5	1	10	3	10

Table A10: Number of tagging experiments and tags released in 2J3KL and recaptured (up to December 2023) by tag type and year of release and recapture.

Year	Disc tags			T-bar tags		
	experiments	released	recaptured	experiments	released	recaptured
1954	6	6,936	213	0	0	0
1955	1	1,071	787	0	0	0
1956	0	0	547	0	0	0
1957	0	0	322	0	0	0
1958	0	0	119	0	0	0
1959	0	0	81	0	0	0
1960	0	0	48	0	0	0
1961	0	0	31	0	0	0
1962	6	4,893	185	0	0	0
1963	8	8,828	924	0	0	0
1964	9	8,064	2,704	0	0	0

Year	Disc tags			T-bar tags		
	experiments	released	recaptured	experiments	released	recaptured
1965	3	3,069	1,774	0	0	0
1966	1	1,120	1,625	0	0	0
1967	0	0	653	0	0	0
1968	0	0	328	0	0	0
1969	0	0	159	0	0	0
1970	0	0	55	0	0	0
1971	0	0	35	0	0	0
1972	0	0	16	0	0	0
1973	0	0	4	0	0	0
1974	0	0	0	0	0	0
1975	0	0	0	0	0	0
1976	0	0	0	0	0	0
1977	0	0	0	0	0	0
1978	1	3,522	285	1	928	27
1979	3	2,441	418	3	2,547	186
1980	3	3,926	521	5	4,312	456
1981	6	3,907	504	9	4,537	386
1982	8	3,931	883	10	5,409	882
1983	6	3,882	620	7	5,360	670
1984	7	3,796	608	7	3,802	543
1985	6	2,897	769	6	2,661	699
1986	4	2,784	681	6	2,920	583
1987	5	3,200	768	5	3,067	603

Year	Disc tags			T-bar tags		
	experiments	released	recaptured	experiments	released	recaptured
1988	7	3,944	619	7	4,271	566
1989	6	3,084	389	7	4,456	434
1990	5	3,502	499	5	3,407	399
1991	9	7,296	917	8	8,057	869
1992	0	0	71	3	8,603	198
1993	0	0	4	2	1,089	37
1994	0	0	3	0	0	7
1995	0	0	3	3	2,769	17
1996	0	0	1	35	6,475	141
1997	0	0	3	8	3,450	110
1998	0	0	6	1	118	320
1999	0	0	2	35	8,267	1,173
2000	0	0	0	23	3,511	698
2001	0	0	1	14	5,961	1,073
2002	0	0	0	15	5,093	1,037
2003	0	0	0	1	472	534
2004	0	0	0	1	923	88
2005	0	0	0	5	1,026	77
2006	0	0	1	12	6,628	356
2007	0	0	1	9	3,792	210
2008	0	0	0	12	5,443	257
2009	0	0	0	11	3,245	213
2010	0	0	0	12	2,046	139

Year	Disc tags			T-bar tags		
	experiments	released	recaptured	experiments	released	recaptured
2011	0	0	0	8	2,012	118
2012	0	0	0	8	1,655	91
2013	0	0	0	7	2,308	99
2014	0	0	0	14	5,297	87
2015	0	0	0	19	5,864	140
2016	0	0	0	17	6,540	256
2017	0	0	0	12	1,562	203
2018	0	0	0	5	2,525	116
2019	0	0	0	7	2,614	124
2020	0	0	0	8	1,219	75
2021	0	0	0	10	4,143	84
2022	0	0	0	8	3,164	81
2023	0	0	0	9	3,972	69

Table A11: Number of cod per tow-at-age in the Fleming and Newman Sound juvenile cod surveys from 1959 onward. Net material was changed from cotton to nylon in 1991.

Year	Fleming		Newman Sound	
	0	1	0	1
1959	55.667	16.619	-	-
1960	12.613	36.242	-	-
1961	6.532	15.404	-	-
1962	15.036	3.255	-	-
1963	6.302	12.632	-	-
1964	6.588	20.632	-	-
1992	6.882	3.456	-	-
1993	9.922	6.844	-	-
1994	10.885	10.115	-	-
1995	11.686	1.000	-	-
1996	6.129	1.774	2.910	1.460
1997	10.809	0.915	-	-
1998	-	-	31.380	0.950
1999	-	-	62.070	1.010
2000	-	-	11.090	3.880
2001	5.509	1.667	6.270	4.630
2002	-	-	16.530	2.040
2003	-	-	2.120	5.610
2004	-	-	4.660	0.550
2005	-	-	4.510	0.850
2006	-	-	1.780	0.020
2007	-	-	34.800	0.120
2008	-	-	8.680	2.150
2009	-	-	17.870	0.180
2010	-	-	1.960	0.550
2011	-	-	15.300	2.520
2012	-	-	44.080	0.930
2013	-	-	112.330	2.560
2014	-	-	54.470	12.630
2015	-	-	54.290	1.270
2016	-	-	70.180	6.440

Year	Fleming		Newman Sound	
	0	1	0	1
2017	-	-	56.830	8.920
2018	-	-	10.660	4.020
2019	-	-	23.270	3.470
2020	10.691	1.345	8.970	1.120

7. COLOPHON

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 language (EN)
 collate  English_United States.utf8
 ctype    English_United States.utf8
 tz       America/St_Johns
 date     2024-03-11
 pandoc   3.1.1 @ C:/Program Files/RStudio/resources/app/bin/quarto/bin/tools/ (via rmarkdown)

─ Packages ─────────────────────────────────────────────────────────────────────────────────────────────────
! package          * version    date (UTC) lib source
  askpass            1.1        2019-01-13 [1] CRAN (R 4.3.1)
  bookdown           0.35       2023-08-09 [1] CRAN (R 4.3.1)
  cachem             1.0.8      2023-05-01 [1] CRAN (R 4.3.1)
  callr              3.7.3      2022-11-02 [1] CRAN (R 4.3.1)
  cli                3.6.1      2023-03-23 [1] CRAN (R 4.3.1)
  colorspace         2.1-0      2023-01-23 [1] CRAN (R 4.3.1)
  crayon             1.5.2      2022-09-29 [1] CRAN (R 4.3.1)
  crul               1.4.0      2023-05-17 [1] CRAN (R 4.3.1)
  csasdown           0.1.3      2024-03-11 [1] local
  curl               5.0.1      2023-06-07 [1] CRAN (R 4.3.1)
  data.table         1.14.8     2023-02-17 [1] CRAN (R 4.3.1)
  devtools           2.4.5      2022-10-11 [1] CRAN (R 4.3.1)
  digest             0.6.33     2023-07-07 [1] CRAN (R 4.3.1)
  dplyr              1.1.2      2023-04-20 [1] CRAN (R 4.3.1)
  ellipsis           0.3.2      2021-04-29 [1] CRAN (R 4.3.1)
  equatags           0.2.0      2022-06-13 [1] CRAN (R 4.3.1)
```

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evaluate            0.21       2023-05-05 [1] CRAN (R 4.3.1)
fansi               1.0.4      2023-01-22 [1] CRAN (R 4.3.1)
farver              2.1.1      2022-07-06 [1] CRAN (R 4.3.1)
fastmap             1.1.1      2023-02-24 [1] CRAN (R 4.3.1)
flextable         * 0.9.4      2023-10-22 [1] CRAN (R 4.3.2)
fontBitstreamVera   0.1.1      2017-02-01 [1] CRAN (R 4.3.0)
fontLiberation      0.1.0      2016-10-15 [1] CRAN (R 4.3.0)
fontquiver          0.2.1      2017-02-01 [1] CRAN (R 4.3.1)
fs                  1.6.3      2023-07-20 [1] CRAN (R 4.3.1)
ftExtra           * 0.6.0      2023-05-29 [1] CRAN (R 4.3.1)
gdtools             0.3.3      2023-03-27 [1] CRAN (R 4.3.1)
generics            0.1.3      2022-07-05 [1] CRAN (R 4.3.1)
gfonts              0.2.0      2023-01-08 [1] CRAN (R 4.3.1)
ggplot2           * 3.4.4      2023-10-12 [1] CRAN (R 4.3.2)
glue                1.6.2      2022-02-24 [1] CRAN (R 4.3.1)
gridExtra           2.3        2017-09-09 [1] CRAN (R 4.3.1)
gtable              0.3.3      2023-03-21 [1] CRAN (R 4.3.1)
here              * 1.0.1      2020-12-13 [1] CRAN (R 4.3.1)
htmltools           0.5.5      2023-03-23 [1] CRAN (R 4.3.1)
htmlwidgets         1.6.2      2023-03-17 [1] CRAN (R 4.3.1)
httpcode            0.3.0      2020-04-10 [1] CRAN (R 4.3.1)
httpuv              1.6.11     2023-05-11 [1] CRAN (R 4.3.1)
httr                1.4.6      2023-05-08 [1] CRAN (R 4.3.1)
jsonlite            1.8.7      2023-06-29 [1] CRAN (R 4.3.1)
kableExtra          1.3.4      2021-02-20 [1] CRAN (R 4.3.1)
katex               1.4.1      2022-11-28 [1] CRAN (R 4.3.1)
knitr             * 1.43       2023-05-25 [1] CRAN (R 4.3.1)
labeling            0.4.2      2020-10-20 [1] CRAN (R 4.3.0)
later               1.3.1      2023-05-02 [1] CRAN (R 4.3.1)
lattice             0.21-8     2023-04-05 [2] CRAN (R 4.3.0)
lazyeval            0.2.2      2019-03-15 [1] CRAN (R 4.3.1)
lifecycle           1.0.3      2022-10-07 [1] CRAN (R 4.3.1)
magrittr            2.0.3      2022-03-30 [1] CRAN (R 4.3.1)
Matrix              1.6-5      2024-01-11 [1] CRAN (R 4.3.2)
memoise             2.0.1      2021-11-26 [1] CRAN (R 4.3.1)
mgcv                1.8-42     2023-03-02 [2] CRAN (R 4.3.0)
```

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mime             0.12       2021-09-28 [1] CRAN (R 4.3.0)
miniUI           0.1.1.1    2018-05-18 [1] CRAN (R 4.3.1)
munsell          0.5.0      2018-06-12 [1] CRAN (R 4.3.1)
NCAM           * 0.1.0.9000 2024-03-11 [1] local
nlme             3.1-162    2023-01-31 [2] CRAN (R 4.3.0)
officer          0.6.2      2023-03-28 [1] CRAN (R 4.3.1)
openssl          2.1.0      2023-07-15 [1] CRAN (R 4.3.1)
patchwork      * 1.1.2      2022-08-19 [1] CRAN (R 4.3.1)
pillar           1.9.0      2023-03-22 [1] CRAN (R 4.3.1)
pkgbuild         1.4.2      2023-06-26 [1] CRAN (R 4.3.1)
pkgconfig        2.0.3      2019-09-22 [1] CRAN (R 4.3.1)
pkgload          1.3.2.1    2023-07-08 [1] CRAN (R 4.3.1)
plotly         * 4.10.2     2023-06-03 [1] CRAN (R 4.3.1)
png              0.1-8      2022-11-29 [1] CRAN (R 4.3.0)
prettyunits      1.1.1      2020-01-24 [1] CRAN (R 4.3.1)
processx         3.8.2      2023-06-30 [1] CRAN (R 4.3.1)
profvis          0.3.8      2023-05-02 [1] CRAN (R 4.3.1)
promises         1.2.0.1    2021-02-11 [1] CRAN (R 4.3.1)
ps               1.7.5      2023-04-18 [1] CRAN (R 4.3.1)
purrr            1.0.1      2023-01-10 [1] CRAN (R 4.3.1)
R6               2.5.1      2021-08-19 [1] CRAN (R 4.3.1)
ragg             1.2.5      2023-01-12 [1] CRAN (R 4.3.1)
Rcpp             1.0.11     2023-07-06 [1] CRAN (R 4.3.1)
RcppEigen      * 0.3.3.9.4  2023-11-02 [1] CRAN (R 4.3.2)
remotes          2.4.2.1    2023-07-18 [1] CRAN (R 4.3.2)
rlang            1.1.1      2023-04-28 [1] CRAN (R 4.3.1)
rmarkdown          2.23       2023-07-01 [1] CRAN (R 4.3.1)
rprojroot        2.0.3      2022-04-02 [1] CRAN (R 4.3.1)
rstudioapi       0.15.0     2023-07-07 [1] CRAN (R 4.3.1)
rvest            1.0.3      2022-08-19 [1] CRAN (R 4.3.1)
scales         * 1.2.1      2022-08-20 [1] CRAN (R 4.3.1)
sessioninfo      1.2.2      2021-12-06 [1] CRAN (R 4.3.1)
shiny            1.7.4.1    2023-07-06 [1] CRAN (R 4.3.1)
stringi          1.7.12     2023-01-11 [1] CRAN (R 4.3.0)
stringr          1.5.0      2022-12-02 [1] CRAN (R 4.3.1)
svglite          2.1.1      2023-01-10 [1] CRAN (R 4.3.1)
```

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  systemfonts         1.0.4      2022-02-11 [1] CRAN (R 4.3.1)
  textshaping         0.3.6      2021-10-13 [1] CRAN (R 4.3.1)
  tibble              3.2.1      2023-03-20 [1] CRAN (R 4.3.1)
  tidyr               1.3.0      2023-01-24 [1] CRAN (R 4.3.1)
  tidyselect          1.2.0      2022-10-10 [1] CRAN (R 4.3.1)
  tinytex             0.45       2023-04-18 [1] CRAN (R 4.3.1)
D TMB               * 1.9.10     2023-12-12 [1] CRAN (R 4.3.2)
  urlchecker          1.0.1      2021-11-30 [1] CRAN (R 4.3.1)
  usethis             2.2.2      2023-07-06 [1] CRAN (R 4.3.1)
  utf8                1.2.3      2023-01-31 [1] CRAN (R 4.3.1)
  uuid                1.1-0      2022-04-19 [1] CRAN (R 4.3.0)
  V8                  4.3.3      2023-07-18 [1] CRAN (R 4.3.1)
  vctrs               0.6.3      2023-06-14 [1] CRAN (R 4.3.1)
  viridis             0.6.4      2023-07-22 [1] CRAN (R 4.3.1)
  viridisLite         0.4.2      2023-05-02 [1] CRAN (R 4.3.1)
  webshot             0.5.5      2023-06-26 [1] CRAN (R 4.3.1)
  withr               2.5.0      2022-03-03 [1] CRAN (R 4.3.1)
  xfun                0.39       2023-04-20 [1] CRAN (R 4.3.1)
  xml2                1.3.5      2023-07-06 [1] CRAN (R 4.3.1)
  xslt                1.4.4      2023-02-21 [1] CRAN (R 4.3.1)
  xtable              1.8-4      2019-04-21 [1] CRAN (R 4.3.1)
  yaml                2.3.7      2023-01-23 [1] CRAN (R 4.3.0)
  zip                 2.3.0      2023-04-17 [1] CRAN (R 4.3.1)

[1] C:/Users/RegularP/AppData/Local/R/win-library/4.3
[2] C:/Program Files/R/R-4.3.0/library

D ── DLL MD5 mismatch, broken installation.
```