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A state-space model for stock assessment of cod (*Gadus morhua*) stock in NAFO Subdivision 3Ps

D.A. Varkey[1], J. Babyn[1], P. Regular[1], D.W. Ings[1], R. Kumar[2], B. Rogers[1], J. Champagnat[3], and M.J. Morgan[1]

[1]Science Branch
Fisheries and Oceans Canada
PO Box 5667
St. John's, NL A1C 5X1

[2]Marine Institute
Memorial University
St John's, NL

[3]IFREMER
Av. du Général de Gaulle, 14520
Port en Bessin, France

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Foreword

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

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ABSTRACT

The paper describes the development of a state-space model (HYBRID) for the stock assessment of Northwest Atlantic Fisheries Organization (NAFO) Subdivision 3Ps cod stock. The HYBRID model fits to the DFO RV survey (1983–2005, 2007–19) as well as the following additional survey time series: the IFREMER (Institut Français de Recherche pour l'Exploitation de la Mer, English: French Research Institute for Exploitation of the Sea) ERHAPS (Evaluation des Ressources Halieutiques de la région 3PS) survey (1978–91), the Groundfish Enterprise Allocation Committee (GEAC) survey (1998–2005), and the sentinel gillnet and line-trawl surveys (1995–2018).

The HYBRID model also fits to fisheries data with the expectation that the model can separate fishing mortality from natural mortality. Fisheries catch-at-age is fit using continuation ratio logits, and the fisheries landings are fit via censored likelihood. The use of censored likelihood for fitting landings allows the inclusion of expert opinion on reliability of landings throughout the model time series. The HYBRID model presented here starts in 1959, which is the first year for which landings data are available.

The HYBRID model allows exploration of different forms for parameterization of time-varying fisheries selectivity, natural mortality, and approaches for estimation of catch-at-age data. The model formulations also differ depending on the survey series used in fitting the model. Seventeen model formulations are presented. Alternate formulations based on fishing mortality included:

1. a logistic flat topped or dome selectivity with time-blocks
2. SAM (State-space Assessment Model, Nielsen and Berg, 2014) style Multivariate Normal random walk
3. a separable age-year correlated process for fishing mortality rate (F) similar to NCAM (Cadigan 2016), and
4. option to break the processes for F in years where important events (like a moratorium) have impacted the fishery.

Alternate formulation based on natural mortality included:

1. invariant natural mortality across age and years, and
2. time-varying natural mortality related to fish condition.

The different model formulations are compared and evaluated on the basis of AIC (Akaike Information Criterion) values and their performance in retrospective analyses.

The meeting concluded that time-varying natural mortality is an important consideration for modelling the dynamics of 3Ps cod and selecting a population model for this stock. Following the evaluations of the alternate model formulations, model formulations 11 which includes fit to sentinel data series, has F modelled using an MVN Random walk with year break for the moratorium, and has time-varying natural mortality rate (M) was considered to have utility as an assessment model for 3Ps cod stock assessment.

INTRODUCTION

The goal of this report is to describe the methodology for developing a new population model for assessment and for providing advice for cod in NAFO Subdivision 3Ps. The new methodology is expected to provide estimates of population size fishing and natural mortality and provide information about the status of the stock. The assessment framework for 3Ps cod timeline began in May 2019 with a data review meeting. Scientists from DFO, IFREMER, academia, industry and Non-Governmental Organizations (NGOs) conducted a thorough review of available survey and fisheries data for the stock to determine data to be used in new model development (Table 1). Model development was conducted throughout May-September of 2019 with the goals to incorporate catch data and other survey data, including exploration of ecosystem influences on the stock and methods for explicit inclusion of these effects in the model. This report describes the development of this methodology for presentation at the assessment framework meeting (October 2019). The expectation is that the model will be able to characterize the effect of fishing pressure on the stock and be able to provide better advice to the management in terms of stock status and catch projections.

BRIEF DESCRIPTION OF AREA AND STOCK

The NAFO subdivision 3Ps includes the Canadian EEZ (Exclusive Economic Zone) south of Newfoundland and French EEZ surrounding the islands on St. Pierre and Miquelon (SPM). The 3Ps management area extends from Cape St. Mary's on the south-western tip of Avalon peninsula to Burgeo Bank in the west, and offshore it includes St. Pierre Bank and part of Green Bank (Figure 1). The distribution of 3Ps cod does not conform well to management boundaries, and the stock is considered a mixture of inshore and offshore sub-components. These may include fish that move seasonally between adjacent areas as well as between the inshore and offshore (Brattey and Healey 2007; Campana et al. 1998).

A survey-based model (SURBA; Ings et al. 2019a) was used in the previous assessments of the stock (2009–18). The SURBA model estimates of total mortality, relative recruitment strength, and relative estimates of total and spawning biomass using the DFO multi-species RV survey indices of abundance for cod (Cadigan 2010). Detailed model specification, sensitivities of results to modeling assumptions, and estimation procedures applied in developing this model are documented in Cadigan (2010). The 2017 assessment indicated an increase in spawning stock biomass from 2016–17 after a steep decline from the 2015–16 assessment (Rideout et al. 2017). In 2018, the stock was estimated to be in the Cautious Zone (49% above the limit reference point B_{lim}) as defined by the DFO Precautionary Approach (PA) Framework (Figure 2). In 2018, 71% of the spawning stock biomass (SSB) is comprised of ages 6 and 7. This conclusion was based on reliance on two cohorts that might experience high mortality rates over the next two to three years.

The SURBA model is an age-disaggregated cohort model that assumes total mortality experienced by the population can be separated into vectors of age effects (s_a) and year effects (f_y) (such that $Z_{a,y}= s_a \times f_y$). Total mortality rates reflect mortality from all sources, including fishing. Estimated total mortality increased gradually from 1997 to the time-series maximum in 2015 (Figure 3). Over 2015–17, total mortality averaged 0.61 (54% survival per year). Mortality rates are high considering that landings have been between one half to three quarters of the Total Allowable Catch (TAC) over this time period.

The SURBA model fits to the indices from DFO RV survey data for ages 1 to 12. Since the SURBA model does not include fisheries data in the estimation process, the model is unable to separate fisheries and natural mortality rates on the stock. As a result, there are limitations in providing advice on sustainable levels of total allowable catch on absolute scale (Shelton and Morgan 2013). The estimates of spawning stock biomass and stock status from SURBA model assessment of 2016 showed a "strong directional retrospective pattern" (Rideout et al. 2017) and retrospective patterns in model estimates have remained a point of discussion for the stock (Rideout et al. 2016a, Rideout et al. 2016b, Ings et al. 2019a, Ings et al. 2019b). Previous scientific assessments of the stock have documented the need to improve the assessment methodology for providing advice on stock and fisheries status (DFO 2017). In addition to DFO RV survey data used in fitting the SURBA model, more information is available that could be utilized to inform the assessment method. These include the commercial landings information, commercial catch-at-age data, and other scientific data from fisheries independent surveys that could potentially be incorporated into a new population model for 3Ps cod. Indices are available from bottom trawl surveys led by the French (ERHAPS survey from 1978–92) and a Canadian industry led survey (1997–2007), referred to as the GEAC survey in this document. The catch rate data from both the sentinel surveys conducted by inshore fishers using line-trawls and gillnets are also available. The sentinel catch-rates are standardized to remove site selection and seasonal effects (Stansbury et al. 2000, Mello et al. 2018). Finally, biological data on fish condition, and the results from tagging experiments are also potential sources of useful information.

SUMMARY FROM DATA-REVIEW MEETING

A scoping meeting in October 2017 (Varkey *et al*. in press[1]) and a data review meeting in May 2019 (Varkey *et al*. in press[2]) were held in preparation for the assessment framework. Following is a summary of the data review from these meetings.

RESEARCH SURVEY DATA

Canadian RV Survey

Stratified-random surveys have been conducted in the offshore areas of Subdiv. 3Ps during the winter-spring period by Canada since 1972. Canadian surveys were conducted using the research vessels *A.T. Cameron* (1972–82), *Alfred Needler* (1983–84; 2009–present), and *Wilfred Templeman* (1985–2008). Tows are conducted during day and night. The stratification scheme used in the DFO RV bottom-trawl survey in 3Ps is shown in Figure 4. DFO RV surveys have covered strata ranging down to 300 fathoms (ftm) in depth (1 fathom = 1.83 meters) since 1980. Five new inshore strata were added to the survey in 1994 (strata numbered 779–783) and a further eight inshore strata were added in 1997 (numbered 293–300) resulting in a combined 18% increase in the surveyed area (Figure 4).

Gear changes divide the survey into three time periods: the Yankee trawl (30-minute tow) was used from 1972 to 1982, the Engel 145 high-rise bottom trawl (30-minute tow) from 1983 to 1995, and the Campelen 1800 shrimp trawl (15-minute tow) from 1996 to present. The Engel trawl catches for 1983–95 were converted to Campelen 1800 shrimp trawl-equivalent catches

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[1] Varkey, D.A., Wheeland, L.J., Ings, D.W., Healey, B.P. In press. Determining the scope for an assessment framework for 3Ps cod. Can. Tech. Rep. Fish. Aquat. Sci. Fs97-6/3203E-PDF: vi + 19 p.

[2] Varkey, D.A., Ings, D.W., Champagnat, J., Penney, H., Rogers, B., Robertson, G., Regular, P., Novaczek, E. In press. Report on data-review meeting in preparation for the assessment framework of 3Ps Cod stock in southern Newfoundland. Can. Data. Rep. Fish. Aquat. Sci. Fs97-13E-PDF: vi + 67 p.

using a length-based conversion formulation derived from comparative fishing experiments (Warren 1996; Warren et al. 1997; Stansbury 1996, 1997). The Yankee data were not converted to Engel or Campelen equivalents.

The timing of the survey has varied considerably. In 1983 and 1984 the mean date of sampling was in April, in 1985 to 1987 it was in March, and from 1988–92 it was in February. Both a February and an April survey were carried out in 1993; subsequently, the survey has generally been carried out in April. The change to April was aimed at reducing the possibility of stock mixing with cod from the adjacent northern Gulf (3Pn4RS) stock which may be in the 3Ps area during early winter (DFO 1994).

Due to extensive mechanical problems with the research vessel, the survey in 2006 was not completed: only 48 of 178 planned sets were completed. Therefore, results for 2006 for the full survey area are not considered comparable to the remainder of the time-series. All subsequent surveys were considered complete. The 2018 survey completed 167 of the intended 178 fishing sets. It is common for 1 or 2 strata to dominate the catch in any given year. Examples include year 1995, when a single large tow accounted for >80% of the total index. Similarly in 2013 and in 2016, a single large tow in Burgeo Bank accounted for >50% of the total index.

Standardized Proportions by Age across Years (SPAY) plots (Kumar 2020) for the entire DFO RV series (1983–2018) and for the inshore-offshore combined index (1997–2018) show cohorts tracking through time (Figure 5). The age composition of the survey catch has become more contracted through time. Cod up to 20 years old were not uncommon in survey catches during the 1980s; however, few cod aged 15 or older have been sampled during surveys in the past two decades and none have been sampled in the last three years. Recently, stronger cohorts have been observed in 2006 and 2011.

Consistency plots were produced to explore how well each survey tracks cohorts, by calculating the correlation between different ages from the same cohorts based on numbers observed in the survey time series. The consistency plot of log-index from the DFO RV survey shows that cohorts track fairly well from ages 2 to 5 (Figure 6a). Moderate correlations are also observed among the high age groups from ages 9 to 13. When the time-series was truncated to include only the years before 1997 (DFO-RV offshore survey), the correlations between younger ages decreases, but overall the patterns remain the same (Figure 6b).

Decisions about usage of data:

- The research survey by A.T. Cameron (1972–82) is not used in the proposed stock-assessment model. The strata coverage prior to 1983 is very poor, with the exception of the last three years (1980–82) and, furthermore, these data are not converted to Campelen equivalents.
- Addition of the inshore strata in 1997 effectively creates two series of DFO RV survey data:
    - an offshore survey 1983 to 1996, and
    - a combined inshore-offshore survey 1997–2018.
- The spatial distribution of fish in the survey area was discussed and there was interest in exploring this further through approaches like post-stratification, habitat associations, and spatial age-length keys.

IFREMER ERHAPS Survey

French ERHAPS surveys were conducted by IFREMER from 1978 to 1992 using the same stratification scheme as the offshore DFO RV survey (Figure 4, strata in blue). There was a change in vessel in 1992 and there was no comparative fishing to compare the catchabilities of the two vessels. In the proposed model, we use the data series from 1978 to1991. The ERHAPS survey was conducted in February-March using a Lofoten trawl in daylight hours only. When some deep strata were missed during the survey, adjustments to the results of the survey were made using a multiplicative model. More detail about this survey is available in Champagnat and Vigneau (*in press*)[3].

The consistency plot for the ERHAPS survey data (Figure 6c) shows good correlations between the younger ages (2 to 5) and between the older ages (9 to 14). However, there is no correlation between ages 5 to 7.

Decisions about usage of data:

- The ERHAPS survey provides from 1978–82 provides additional five years of survey data for the proposed model. Strata coverage was evaluated and cohort strength models were developed using the ERHAPS survey and the DFO Offshore survey. The cohort strengths estimated using the two data sets showed the same trends and therefore suggested the tracking of the same year-classes (Varkey *et al. in press*, Champagnat and Vigneau, *in press*[1]). Given the consistency between the two surveys, and the time coverage, ERHAPS survey is included in the proposed stock-assessment model. More detail about the cohort strength models is available in a technical report presented by Champagnat and Vigneau (in press)[1].

Groundfish Enterprise Allocation Council (GEAC) Survey

A Canadian industry survey was conducted by GEAC (presently Atlantic Groundfish Council) in the fall (Nov-Dec) in 3Ps from 1997–2007 using the same stratification scheme as the offshore DFO RV survey (Figure 4, strata in blue). Twenty four strata were sampled annually. An Engels 96 high lift trawl was used to conduct 30 minute tows. In the eleven year survey period, coverage was incomplete in 1997, the survey was not conducted in 2006, and in 2007 a different vessel was used and several additional strata were included (McClintock 2010).

The consistency plot for the GEAC survey data from 1998–2005 shows correlation between ages 2 to 6 and between some higher ages (Figure 6d). Because of the short duration of the survey, it is not possible to explore correlations between fish ages more than five years apart.

Decisions about usage of data:

- The GEAC survey provides a short time series and it is not clear if this survey will provide useful information for the stock assessment model. The data-review meeting in May 2019 decided to try out the inclusion of eight years of data from this series (1998–2005).

Sentinel Survey

The sentinel survey includes gillnet and line-trawl sets in the inshore regions of Newfoundland. This ongoing survey began in 1995 and is conducted annually between June and November. The survey is accomplished through the participation of 16 to 32 fishing enterprises across the southern coast of Newfoundland. Mello et al. (2018) perform a age-disaggregated standardized of mean catch rates for both the gillnet and line trawl gears to account for seasonal and spatial effects. The standardised catch rates are available for use in the assessment model development.

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[3] Champagnat, J., and J. Vigneau. In press. ERHAPS: a French survey for cod in 3Ps (NAFO subdiv) IFREMER REPORT.

The consistency plot for the sentinel gillnet survey shows good correlation between ages 4 to 10 (Figure 6e). The sentinel line trawls show strong correlation between ages 3 to 5 and between ages 6 to 9 (Figure 6f).

Decisions about usage of data:

- At the data-review meeting in May 2019, some concerns were raised with regards to change in survey coverage over time. The decision at the meeting was to evaluate model outcomes with and without the inclusion of this survey.

COMMERCIAL DATA

Landings

Commercial and recreational fishery landings data are available from 1959–2018. Foreign fleets were active in the area in the 1960s and early-1970s with landings exceeding 60,000 tonnes (t) in several years (Figure 9). After the implementation of the Canadian EEZ, landings averaged near 30,000 to 40,000 t. Landings increased and TAC was exceeded in several years in the 1980s at the time of quota negotiations between Canada and France. Till 1993, when the moratorium was imposed, catches used in assessments under the purview of NAFO continued to be adjusted for French reported landings. The stock was under moratorium from September 1993–96 and the landings are predominantly bycatch. After the fishery reopened in 1997, the Canadian inshore fisheries, particularly gillnet fisheries, have become an important component of the fishery. Since 2010, the allocated TAC has not been taken and the landings have been below 10,000 t. Greater detail on the landings time series is available in Ings et al. 2019. In summary, the catch history of the fishery has seen many changes and during this history the accuracy of the data has varied with a combination of factors that could have led to both over and/or under-reporting (Shelton et al. 1996, Carruthers and Ings *pers. comm*., October 08, 2019).

Decisions about usage of data:

- Landings data were used to establish a timeline for the proposed stock-assessment model. The survey data begin in 1978, which provides a potential start date for the stock-assessment model. However, landings were higher pre-1978, and these data may help the model determine the magnitude of the historical stock and support the estimation of other model parameters.
- A fisher interview based study is undertaken to improve the understanding on the level of uncertainty in the fisheries landings throughout the history of the fisheries, wherein interviews are conducted with offshore and inshore fishers. This information thus gathered (Carruthers and Ings *pers. comm*., October 08, 2019) will potentially be used to develop lower and upper bounds for the variability in the landings. These bounds can be used for informing censored likelihood in the proposed model for fitting landings, similar to the approach adopted for fitting landings information for the northern cod assessment (Cadigan 2016).

Catch-at-age

Fisheries catch-at-age data are available from 1959–2017. Catch-at-age data existed prior to the commencement of this work but there was lack of clarity if the methodology adopted for generating the catch-at-age was consistent between years. Extensive effort was put into reconstructing the catch-at-age matrices so that commercial age-length sampling between gears and spatial locations could be accounted for correctly. In this process of reconstruction of the catch-at-age, it was difficult to reconstruct the catch-at-age data for year 1993, the year when the moratorium was implemented. The catch-at-age data used in the assessment model includes the 1993 catch-at-age developed in the older series.

A comparison of the spay plots of catch-at-age data pre and post reconstruction (Figure 7) shows both the plots tracking similar cohorts. The consistency plots for the old versus the updated catch-at-age data (Figure 8) show very similar correlation between age-groups. The updated catch-at-age improved upon the representation of age 2 fish in the catch.

Decisions about usage of data:

- Catch-at-age data were not reconstructed for the years 1959–70. Most of the decisions about assigning age-length keys to commercial samples pre-1970 are only retained in hard copies of historical documents that were not accessible. However, existing catch-at-age data were updated to include age 14+ fish based on a data table presented in International Commission for the Northwest Atlantic Fisheries (ICNAF) document (Pinhorn 1972).
- We were unable to reconstruct the catch at age for the years 1971–73 and 1993 due limited sampling and difficulty in assigning age-length keys to commercial data. We decided to use the existing data for these years.
- Commercial sampling data were recalculated to improve the consistency in the catch-at-age results for the years 1974–92 and 1994–2018.

HYBRID MODEL

Several aspects of the 3Ps cod stock make it a challenging stock to assess:

1. changes to the protocol in the historical surveys,
2. year-effects in the survey,
3. retrospective patterns in recent assessments,
4. previous assessments pointing to increase in mortality,
5. uncertainties in fisheries landings, and
6. mixing within the stock area between inshore and offshore components and with adjacent stocks.

In such a situation, multiple models need to be developed to facilitate exploration of different hypotheses. The method of multiple working models can be traced back to Chamberlain (1890). This idea was translated in the book *Ecological Detective* as ‘confrontation between more than one model arbitrated by data underlies science’ (Hilborn and Mangel 1997, Preface). In recent years, several papers authors have presented and compared alternate models for the assessment of a stock with different, for example:

1. parameterizations of selectivity, natural mortality, and catchability (Rossi et al. 2019);
2. approaches to model natural mortality (Miller and Hyun 2017);
3. likelihood choices (Albertsen et al. 2016) and others.

Often in these comparisons, the structure of the base model remains unchanged (Rossi et al. 2019). Miller and Hyun (2017) are a notable exception; this paper compares Statistical-catch-at-age (SCAA) and state-space models.

The goal of a stock assessment model is to be able to provide management advice. Two main components governing management advice are the spawning stock biomass and fishing mortality. The key variable of interest in fisheries stock assessments models is F, i.e., our description of the current and historical impact of fisheries on the stock. Hence, we have focused on developing alternative approaches to structure F in the model. Alternate formulations based on fishing mortality included:

1. a logistic flat topped or dome selectivity with time-blocks
2. SAM (State-space Assessment Model, Nielsen and Berg, 2014) style Multivariate Normal random walk
3. a separable age-year correlated process for fishing mortality rate (F) similar to NCAM (Cadigan 2016), and
4. option to break the processes for F in years where important events (like a moratorium) have impacted the fishery.

The data for 3Ps cod stock present several challenges which led us to develop additional options:

1. alternate parameterization of M,
   a. invariant natural mortality across age and years, and
   b. time-varying natural mortality related to a covariate (fish condition).
2. option to use censored likelihoods for missing data points,
3. option to fit results to catch numbers at age or to catch proportions and landings,
4. censored fitting of landings data when there is uncertainty about landings in different time periods,
5. year effects in survey where needed, and
6. use of correlated likelihoods in fitting catch-at-age or index-at-age.

The HYBRID model is named as such because it uses a variety of features from SAM—mainly the use of random-effects for modelling N and F matrices—and the NCAM (Northern Cod Assessment Model Cadigan 2016)—mainly the inclusion of expert opinion on reliability of landings time series through the use of censored likelihood. In summary, the HYBRID model allows exploration of different forms for parameterization of time-varying fisheries selectivity, natural mortality, and approaches for estimation of catch-at-age data. The 'HYBRID', a state space modelling framework therefore can incorporate multiple underlying model structures, wherein differently structured models are realizations within the same modelling platform. Features can be turned on or off depending on user choice. This provides opportunity to evaluate structural uncertainty stemming from model structure and parameterization.

A flexdashboard mechanism (Regular et al. 2020) allows comparison of residual patterns and stock status between models. The 'HYBRID' modelling platform incorporates this flexdashboard mechanism and allows the user to compare the influence of constraints and flexibilities built into alternate model structures and parameterizations on residual patterns and model output. Below, we elaborate on model formulation and some of the adaptations we have developed in the proposed model to address data related concerns.

STATE EQUATION

The state equation follows the parameterization in the State-space Assessment Model (SAM) (Nielsen and Berg 2014). The matrices of *logN* (log abundance) are treated as random variables and represent the underlying unobserved state. Age in the model spans from 2 to 14+ and the plus group is represented by "*A*". Years (*y*) in the model span from 1959–2018. First year abundances (for ages 3 to *A*) are estimated as part of the random variable matrix for *logN*. Recruitment (age 2) is modelled to follow a random walk with standard deviation *σR*. The process error is normally distributed with standard deviation *σP*. Fishing mortality (*F*) and natural mortality (*M*) are used to model exponential decay of the cohort.

$$log\ N_{2,y} = log\ N_{2,y-1} + \eta_{2,y};\ \eta_{2,y} \sim N(0, \sigma R) \tag{1}$$

$$log\ N_{a,y} = log\ N_{a-1,y-1} - F_{a-1,y-1} - M_{a-1,y-1} + \eta_{a,y}; 3 \leq a < A-1;\ \eta_{3:A-1,y} \sim N(0, \sigma P) \tag{2}$$

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

PARAMETERIZATION OF FISHING MORTALITY (F)

We explore five different approaches to model F in the 'HYBRID' modelling platform referred to as F-cases. Each F-case allows to explore different levels of flexibility in the time-varying fisheries selectivity estimation., Time varying selectivity is incorporated into the model to account for some of the temporal dynamics in the fishery. The primary gears used in the fishery for 3Ps cod has varied considerably over time. In the 1960s and early-1970s, the fishery was dominated by non-Canadian fleets fishing in the offshore (Figure 9). Recently, most of the TAC has been landed by Canadian inshore fixed gear fishermen with the remaining catch taken mainly by the mobile gear sector fishing the offshore. Line trawl (i.e. longline) catches dominated the fixed gear landings over the period 1977–93 and typically accounted for 40–50% of the annual total for fixed gear. In the post moratorium period, line trawls have accounted for 16–26% of the fixed gear landings. Gillnet landings increased steadily from about 2,300 t in 1978 to a peak of over 9,000 t in 1987, and remained relatively stable until the moratorium. Gillnets have been the dominant gear used for the inshore catch since the fishery reopened in 1997, accounting for 70–80% of the fixed gear landings since 1998. Gillnets accounted for a lower percentage of the fixed gear landings in 2001 (60%), partly due to a temporary management restriction in their use. Cod trap landings from 1975 up until the moratorium varied considerably, ranging from approximately 1,000–7,000 t. Since 1998, trap landings have been reduced to negligible amounts (<120 t). Hand line catches were a small component of the inshore fixed gear fishery prior to the moratorium (about 10–20%) and accounted for about 5% of landings on average for the post moratorium period. However, hand line catch for 2001 showed a substantial increase (to 17% of total fixed gear), and this might reflect the temporary restriction in use of gillnets described above. Increases in the proportion of hand-line catch in some years (e.g. 2009, 2013) were likely due to buyers paying a higher price for hook-caught fish than for gillnet landings. While there were changes in the gears used by the fishery over much of the time-series, the switch to a predominant gillnet fishery in 1998 represented a marked change in selectivity on the stock.

Five possible F-cases are described below.

1. Separable age (s_a) and year (f_y) effects. F experienced by the population can be separated into vectors of age effects s_a and year effects f_y.

$$F_{a,y} = s_a * f_y \quad (4)$$

$$\log(s_a) = \log(s_{a-1}) + \omega_a; \omega_a \sim N(0, \sigma_{sel1}) \quad (5)$$

2. Logistic selectivity. The second case allows for a flat-topped logistic or a double logistic domed selectivity. Selectivity is estimated in two blocks for the pre and post moratorium period by estimating two fixed effects for the age at 50% selectivity (a_{50}) parameter.

   Logistic

$$F_{a,y} = s_a * f_y \quad (6)$$

$$s_a = \frac{1}{1 + \exp(-b_1(a - a_{50}))} \quad (7)$$

   Double logistic

$$s_a = \frac{1}{1 + \exp(-b1(a - a_{50}))} \cdot \frac{1}{1 + \exp(b2(a - 14))} \quad (8)$$

   Random deviations in a_{50} parameter. Between year variation in selectivity is allowed through random variations on the a_{50} parameter. However, here the $sdev_y$ could be confounded with f_y.

$$\log(a_{50\,y}) = \log(a_{50}) + sdev_y;\ sdev_y \sim N(0, \sigma_{sel2}) \quad (9)$$

3. SAM Style F structure. The third case for F parameterization is drawn from SAM (Nielsen and Berg 2014) where the F matrix is a random walk over years. Correlation in the random walks between ages is enabled through multivariate normal (MVN) deviations. For the covariance matrix of MVN deviations, we adopt a autoregressive (AR1) process for the correlation such that similar age groups develop similar trends in the fishing mortality.

$$\log(F_{2:A,y}) = \log(F_{2:A,y-1}) + e_{2:A,y};\ e_{2:A,y} \sim MVN_{2:A}(0, \Sigma) \quad (10)$$

$$\Sigma_{a,\bar{a}} = \rho^{|a-\bar{a}|}\sigma_a^2 \quad (11)$$

Each element in Σ is a function of the standard deviation of the random walk and the evaluated correlation coefficient.

4. Correlated separable AR1 pattern in age and year. This fourth case for F parameterization is similar to the structure for F in Northern cod (Cadigan 2016) and American plaice state space models (Kumar et al. 2020). In this case, F in a given age and year is the product of a mean F and correlated age-year deviations. The deviations in *logF* is a two-way AR process correlated over ages and years. The correlation coefficient between two points in the deviation matrix is governed by the autocorrelation in age φ_{Fa} and in year φ_{Fy}. The auto-correlated F deviations are implemented in Template Model Builder (TMB) using "SEPARABLE" function which computes the separable extension of two MVN densities. The covariance of the density object is equal to the Kronecker product of the covariance matrices of the two MVN densities.

$$log\ F_{a,y} = \mu\ F_{a,y} + \Delta_{a,y} \quad (12)$$

$$Corr[\Delta_{a,y}, \Delta_{a-m,y-n}] = \varphi_{Fa}^{|m|}\varphi_{Fy}^{|n|} \quad (13)$$

5. SAM Style F structure with breaks. This parameterization is similar to case 3, with the addition of breaks to the MVN random walk at the beginning of the fishing moratorium. The moratorium was a big change in the fishing history and the break allows the F matrices for the two periods to be estimated independent of each other. Further, younger ages are de-coupled from the MVN random walk; we explore two options for decoupling:

   1) de-couple age 2 from older fish; and,
   2) de-couple both age 2 and 3 from older fish.

   These younger ages are not targeted in the fishery and fishing pressure on these ages may not be correlated with the fishing pressure on the older ages.

F-cases 1 and 2 allow for flexibility between years in the magnitude of F, but limit variation in estimated age patterns. In case 1, the age-effect is not parametric and therefore allows flexibility between ages but this pattern is not allowed to vary over time. The single and double logistic selectivity patterns in case 2 impose constraints on the shape of the selectivity function through the logistic function but allow variation in magnitude over time. Cases 3 and 4 allow for more flexibility; the MVN random walk in case 3 and the separable correlated age-year deviations in case 4 allow for flexibility for the shape of the selectivity function over the two-dimensional space of ages and years. However, the AR processes in case 4 impose a smoother shift over ages and years than the MVN random walk in case 3. We created a case 5 for F where we allowed breaks in the MVN random walk (from case 3) at the beginning of the moratorium to allow for more flexibility over time. In F-cases 3 to 5, the selectivity is derived as:

$$s_{a,y} = \frac{F_{a,y}}{\sum_a F_{a,y}} \quad (14)$$

PARAMETERIZATION OF NATURAL MORTALITY (M)

When much information on natural mortality is not available, the base assumption in fisheries stock assessments has been that natural mortality is invariant over age and year and equals 0.2 (M=0.2). Since previous assessments indicated an increase in total mortality (Ings et al. 2019a; Ings et al. 2019b), we develop models with time-invariant and time-varying M.

1. Time Invariant M. We choose M=0.3 as the base level because M estimates for neighbouring Northern cod 2J3KL (DFO 2019) and Flemish cap 3M cod stocks (Gonzalez-Costas and Gonzalez-Troncoso 2018) point towards M estimates higher than 0.2. Analysis of tagging data for 3Ps cod (Appendix B) also suggest M levels to be higher than 0.2; however, the coverage of tagging data is limited to the post -moratorium time period. Further, condition-based M estimates (*Mc*, explained in the following section) also indicate M levels to be higher than 0.2. A value of 0.3 allows similar base levels of M in both time-invariant and time-varying approaches.
2. Time-varying M. Several authors have approached time-varying M using model estimated random processes. The basic model is usually a variation with the M_{base} describing a necessary initialization for the first year and/or age and $\delta_{a,y}$ describing the structure of the random process.

$$M_{a,y} = M_{base} \exp\left(\delta_{a,y}\right) \quad (15)$$

   Examples are a random walk approach for Pacific herring (Martell et al. 2011) and for southern Gulf of St. Lawrence Atlantic cod (Swain et al. 2019) where the $\delta_{a,y}$ process is sampled from a normal distribution. Another example is a correlated process for $\delta_{a,y}$ over age and year for Northern cod mortality (Cadigan 2016). Considering the inclusion of process error in our state equations, model formulation here is not able to estimate additional random processes. Hence, we experimented with the following two approaches for time-varying M:

   a. The trend in M is forced in the model from data.

$$M_y = X_y \quad (16)$$

      In the 3Ps cod model here, X_y represents M as a function of fish condition. We hypothesize that low ‘energetic condition’ especially following the spring spawning season could make the fish more vulnerable to stressors in the environment. The main reason for interest in fish condition is that the previous assessment of neighbouring Northern cod stock found ‘good correspondence’ between the M estimates from the assessment model and fish condition based estimate of M (DFO 2019). Lab experiments have reported fish mortality when fish condition falls below a critical threshold (Dutil and Lambert 2000, Byström et al. 2006). Casini et al. (2016) presented a methodology for calculating M for wild fish based on the proportion of fish observed to be in poor condition referred to as the ‘condition corrected natural mortality’. We use a similar approach here to develop a condition-based index of M.

      Data and analysis of fish weights available to calculate fish condition for the 3Ps cod stock begins with the 1978 DFO RV surveys. Pre-1993, these surveys and recorded weights are from winter and starting 1993, the survey timing changed to spring. From 1993, the sentinel surveys also provide weight information through summer and fall. Fish growth and condition vary seasonally being low in spring and high towards the end of summer (Lilly 1996); therefore, the weight data collected in the above surveys cannot be applied directly to create a time series of fish condition. Hence, we develop a time series model, including the data from the DFO RV survey and the sentinel surveys to describe the monthly fish condition from 1978 to present. The analysis shows that condition of fish recorded in the DFO RV surveys declined over the time-period. Condition estimates from the time-series model is used, in an approach similar to Casini et al. (2016), to produce a condition-based index of M from 1978–2018 (Figure 10a, Appendix C for details on the time-series analysis and calculation of the condition-based index of M). The 'HYBRID' model timeline is from 1959–2018 and for the years 1959–77, we use 0.3 which is the average of the M estimates over the first five years (1978–1982). This estimate of condition-based index of M (*Mc*, Figure 10a) is input directly as M for the 'HYBRID' model.

b. The trend in M is obtained based on a covariate and associated parameter estimate. The parameterization follows a similar form as the applications of random processes for M. As in equation 15, $M_{a,t} = M_{base}\exp\left(\delta_{a,y}\right)$; however, the $\delta_{a,y}$ term is not a random process, but a covariate associated estimation.

$$\delta_{a,y} = mpar_a * X_y \quad (17)$$

Here, M follows the trend in the covariate and parameter *mpar* describes the strength of the relationship with the covariate. Estimates of *mpar* close to zero suggest none/little influence of covariate on M, a positive *mpar* indicates that M follows the trend in the covariate and a negative *mpar* indicates an M trend opposite to the trend in the covariate (Figure 15b). In our case, the covariate X_t is a normalized index of *Mc* described above in 'a'.

$$X_y = \frac{Mc_y - \mu_{Mc}}{\sigma_{Mc}} \quad (18)$$

This scaling allows the treatment of the covariate as an anomaly resulting in estimates above or below the baseline M_{base} provided, similar to the scaling for temperature anomaly for time-varying carrying capacity (Kumar et al. 2013). The mean (μ_{Mc}) and standard deviation (σ_{Mc}) are calculated for the reference period 1978 to 2012, the first 35 years of data; therefore, the normalization of *Mc* is based on a reference period from 1978 to 2012. The *mpar* parameter was estimated by two age groups (immature and mature) to allow different age groups to respond differently to the trends in fish condition. A similar implementation of time-varying M is for Kootenay Lake Kokanee population by Kurota et al. (2016). Hence the final equation for M is:

$$M_{a,y} = M_{base}\exp\left(mpar_a * \left(\frac{Mc_y - \mu_{Mc}}{\sigma_{Mc}}\right)\right) \quad (19)$$

SURVEY DATA LIKELIHOOD

The model was fit to four surveys:

1. the DFO RV survey (ages 2 to 14+),
2. the IFREMER ERHAPS survey (ages 2 to 14+),

3. the GEAC survey (ages 2 to 14+), and
4. the Sentinel gillnet (ages 4 to 10) and linetrawl surveys (ages 3 to 10). $\hat{I}_{a,y,s}$ represents the expected index-at-age in survey *s, ts*Z* represents an adjustment to total mortality to account for the timing of survey in the year (ex. *ts*=0.5 for a survey conducted in June).

The observation error standard deviation σ_s is estimated separately for survey '*s*'.

$$\log \hat{I}_{a,y,s} = \log q_{a,s} + \log N_{a,y} - ts_{y,s} * Z_{a,y} + e_{a,y,s};\ e_{a,y,s} \sim N(0, \sigma_s) \quad (20)$$

When the observed index is 'zero', we adopt the censored likelihood approach used in the northern cod assessment model (Cadigan 2016). The assumption is that the survey recorded zero fish in a given age and year because the stock density was lower than a minimum threshold (λ) for detection by the survey. When censoring is applied, the log-likelihood will be very small if the predicted index is lower than the threshold value or the 'detection limit'

$$l(I_{a,y,s} = 0|\theta) = log\left\{\Phi_N\left[log[\lambda/\hat{I}_{a,y,s}]\right]/\sigma_s\right\};\ \lambda = \begin{cases} 0.02, & if\ a = 2 \\ 0.004, & if\ a > 2 \end{cases} \quad (21)$$

(Cadigan 2016).

In equation 21, Φ_N is the cumulative distribution function (CDF) for a standard normal random variable.

Catchability Model for DFO RV Survey

The DFO RV survey provides continuous (except missing year 2006) records of mean numbers-per-tow (MNPT) throughout the time series. A major change to survey protocol was the addition of inshore strata leading to an 18% increase in total survey area for 3Ps cod at the same time as the fishery reopened in 1997 (Figure 4). Therefore the survey series does not represent a strictly single time series. We explored the following different approaches to model survey catchability.

1. Treating the offshore and inshore-offshore surveys as separate time series:
   a. separate offshore series from 1983-96, and
   b. inshore-offshore series from 1997-2018.

   The separate estimation of catchability for the two surveys led to poor performance in 10-year retrospective analysis. This is likely because the changes to the surveys and the fisheries, including the 1994-96 moratorium, occurred over the same time-period in mid-1990s. A timeline of the events in the surveys and the fisheries (Figure 11) shows that none of the surveys span this critical time-period in the fishery: the ERHAPS ended in 1992, GEAC started in 1997, the sentinel started in 1995, and inshore strata were added to the DFO RV survey in 1997. Only the commercial fisheries data span the entire time series. We discard the idea of estimating separate catchabilities and explore alternate options.
2. Split the DFO RV survey into two series according to survey area covered: This approach divides the DFO RV survey into:
   a. an offshore time series from 1983-2018, and
   b. an inshore time series from 1997-2018 (see Figure 11).

The assumption associated with this approach is that both the offshore and the inshore surveys can represent the stock. Similar to option (1) above, this treatment of the survey data also led to poor performance in 10-year retrospective analysis.

3. Adjusting catchabilities: The SURBA model (Cadigan 2010) uses the combined survey indices from 1983–2017 and applied a catchability adjustment between the offshore series and the inshore-offshore series to address the addition of survey area in 1997. SURBA assumes q to be constant (q=1 for the inshore-offshore combined survey index 1997–2018) for ages 4 and above (i.e. selectivity is "flat-topped"). For the DFO RV offshore series (1983–96), an adjustment is applied to the fixed q values. Year 1997 and onwards, inshore and offshore strata data are available. The adjustment is equal to the log ratio of the average index-at-age for the offshore region versus the same for the combined inshore-offshore region.

   In 'HYBRID', q is estimated for all ages. The catchability adjustment applied is similar to SURBA with the difference that q is estimated for all ages. Similar to the adjustment (in SURBA) noted above the catchability of the offshore index series is calculated as the catchability of the combined inshore-offshore series plus an adjustment ($log\ q_{offset}$). The adjustment for each age is calculated as the log ratio of the average index-at-age in the offshore versus combined inshore-offshore region. In equation 21, A^* represents the maximum age for which q is freely estimated (Note: this is not the same as A used to represent the plus group age in the model). For all ages>A^*, q is equal to q at A^* and represents the older ages for which the $log\ q_{offset}$ values calculated are similar.

$$log\ q_{a:A,DFO\ RV1983:1996} = log\ q_{a:A*,DFO\ RV1997:2018} + \log q_{offset\ a:A} \quad (22)$$

   There are, however, some concerns associated with making such an adjustment based on the average indices-at-age between the two areas from the 1997–2018 survey period:

   a. in the pre-1993 phase, the offshore survey was conducted in winter, and the distribution of fish between inshore and offshore areas could be different from that observed in the spring surveys from 1997–2018;
   b. survey coverage in the offshore DFO RV survey (1983–96) was not as consistent (ex. strata 319 was missed in 1990) as in the period post 1997;
   c. previous studies have indicated that DFO RV survey catchability inside the 100 m depth contour is influenced by bottom temperatures (Colbourne and Murphy 2005) and there is evidence for change in bottom temperature in spring in the inshore regions (Colbourne et al. 2016);
   d. analysis of habitat available and occupied by 3Ps cod in DFO RV surveys show differences in habitat occupied before and after 1998 (see Appendix A).

   Further investigation into the habitat associations by size-classes of cod, small (less than 37 cm), medium (37 to 55 cm) and large (greater than 55 cm), showed that the changes in habitat association is most prominent for the small fish (see Appendix A). An average adjustment of inshore-offshore catchability based on post 1997 period assumes a similar environmental mean and variability and habitat association in the earlier (pre-1997) time period.

4. Use the total swept area abundance instead of the MNPT data. Comparison of the total survey abundances shows that older fish (7–8+) are predominantly recorded in the offshore and only a small fraction of older fish are recorded in the inshore (Figure 12). This finding can

be used to provide an anchor between the two surveys by estimating a common catchability for ages 8 and older fish in both the surveys. Catchability for all ages <8 are estimated freely for both the surveys. This approach removes the subjectivity associated with the assumptions of similarity in *q* patterns across all ages (except age 8 and older) between the two time-periods. There are however two caveats associated with this approach:

a. swept area abundances are likely to be influenced more by changes in strata coverage in the survey,

b. there is a small fraction of fish age 8 and older that are caught in the inshore strata (Figure 12) and this approach assumes that fish older than 8 are not caught in the inshore strata.

$$\log q_{\mathrm{OFF}\ 1983:1996,8+} = \log q_{IO\ 1997:2018,8+} \quad (23)$$

5. Catchability adjustment is applied only for older ages. This approach evolved out of exploration of options (3) and (4). The ratio of average index-at-age for fish in the offshore versus combined inshore-offshore is less variable for the older ages than for the younger ages, since older ages are predominantly caught in the offshore strata. The average fraction of fish age 8 and older in the inshore area was less than 5% in the DFO-RV combined inshore-offshore index (Figure 12). We adopt a catchability adjustment similar to option (3) with the difference that the catchability adjustment is made only to ages 8 and older (i.e. $log\ q_{offset}$ is applied only to ages 8 and older). The offset for *q* at age is calculated as the median of the log ratio of the index-at-age for the combined inshore-offshore region versus the same for the offshore region (equation 24). Catchability parameters for the younger ages are allowed to be estimated freely.

$$log\ q_{offset\ 8:A} = median\left[-log\left(\frac{I_{DFO\ RV\_IO\ 8:A}}{I_{DFO\ RV\_OFF\ 8:A}}\right)\right] \quad (24)$$

Following these comparisons, we came to the conclusion that options 1 and 2 which split the DFO RV survey into two independent series were not a viable approach because of poor performance in retrospective analyses. The model needs an anchoring between the data from the two time-periods. The options that remained are options 3, 4, and 5. With option 3, we had concerns related to the habitat use of young fish. In using totals indices instead of MNPT (option 4), we got the least retrospective patterns among the different comparisons tested, but we were making the assumption that older fish are not caught in the inshore strata. We chose option 5 (with catchability adjustment for ages 8 and above) for the model because:

a. the retrospective were better than when treating the surveys separately,

b. this approach avoided assumptions about the ratio of fish in the offshore versus combined inshore-offshore for all ages <8,

c. the fits to survey index for younger ages were better than all comparisons, and

d. we avoid the assumptions related to the use of total swept area abundances.

Survey year-effects

Survey indices of cod in 3Ps are influenced by “year-effects”, primarily caused by occasional sets with large catch usually in the Halibut Channel or Burgeo Bank strata. These large catches are likely unrelated to absolute stock size and are a result of a number of factors such as environmental conditions, movement, degree of aggregation. A clear sign of a year-effect is the observation that the 2013 DFO RV survey (Figure 13) estimated that the abundance of multiple cohorts increased compared to observations of these same cohorts at one age younger in 2012. The number of fish in a cohort cannot increase as the age increases (without immigration) and when analyses suggest that such an increase has occurred for multiple ages, it is considered to be evidence for a year-effect. In the 2013 survey, the 2011 year-class (age 2 fish) was estimated to be by far the strongest in the times series. Similar to the DFO surveys in spring, the ERHAPS and GEAC surveys (McClintock 2003) also recorded occasional sets with large catch.

We estimate year-effects in catchability. When there is a year-effect in the survey owing to a large tow, it is expected that the indices of multiple ages would be affected similarly although not necessarily to the same extent. Considering this, we estimate correlated (AR1) year-effects. The correlation between ages for the year-effects for survey *s* is represented using φ_{ye_s}.

$$YE_{2,y,s} \sim N\left(0, \sqrt{\frac{\sigma_{ye_s}^2}{\left(1-{\varphi_{ye_s}}^2\right)}}\right) \quad (25)$$

$$YE_{3:A,y,s} \sim N\left(\varphi_{ye_s} * YE_{a-1,y,s}, \sigma_{ye_s}\right) \quad (26)$$

When applied, the survey-year effects are added to the observation equation.

$$\log \hat{I}_{a,y,s} = \log q_{a,s} + \log N_{a,y} - sf * Z_{a,y} + YE_{a,y,s} + e_{a,y,s} \quad (27)$$

Including year-effects could perhaps assist in separating some of the issues caused by mixing with 3Pn4RS cod in western part of the stock especially in the winter survey.

CATCH DATA LIKELIHOOD

The age-composition information in the catch-at-age and the magnitude of the catch (i.e. landings) data are fitted separately. The age composition is fit using continuation ratio logits (CRLs) and the landings using censored likelihood.

Fisheries catch-at-age

Fisheries catch is predicted using the Baranov catch equation:

$$\hat{C}_{a,y} = N_{a,y}\left(1-\exp\left(-Z_{a,y}\right)\right)^{F_{a,y}}/_{Z_{a,y}} \quad (28)$$

CRLs ($X_{a,y}$) are the logit transformation of the conditional probability $\pi_{a,y}$ of proportions-at-age $P_{a,y}$ in a given year (Cadigan 2016).

$$\hat{P}_{a,y} = \frac{\hat{C}_{a,y}}{\sum_2^A \hat{C}_{a,y}} \quad (29)$$

$$\pi_{a,y} = Prob(age = a | age \geq a) = \frac{\hat{P}_{a,y}}{\sum_a^A \hat{P}_{a,y}}, 2 \leq a \leq A \quad (30)$$

$$\hat{X}_{a,y} = \log\left(\frac{\pi_{a,y}}{1 - \pi_{a,y}}\right), 2 \leq a \leq A - 1 \quad (31)$$

The observed CRLs $X_{a,y}$ are calculated similarly from the proportions at age in the observed catch-at-age data. When the observed catch-at-age was equal to zero, it was replaced by the minimum value in the observed catch-at-age. The likelihood is described using a MVN likelihood. The Σ describes the covariance between age-groups within years (Berg and Nielsen 2016). We explored model configurations with and without correlation between the age groups.

$$X_{a,y} = \hat{X}_{a,y} + \epsilon_{a,y}, \epsilon_{1:A-1,y} \sim MVN(0, \Sigma) \quad (32)$$

Fisheries Landings

As noted earlier, the accuracy of landings information has varied over time. Specific periods of high uncertainty include:

1. 1960s to early-1970s when foreign fleets were present in the stock area,
2. the period of jurisdiction change following EEZ implementation from 1976–77,
3. years of quota negotiations between Canada and France from 1987 to 1989,
4. period up to 1993 when the landings data used in NAFO assessments were adjusted for French reported landings, and
5. 1997 to early-2000s due to a number of factors such as high-grading for price differential, net loss, and discarding and depredation.

To address this uncertainty, we apply a censored-likelihood approach for landings time series (equation 33), similar to the method used in the assessment of northern cod by Cadigan (2016). This approach requires the specification of lower (LB_y) and upper (UB_y) bounds information for each year of the landings time series. These bounds (lower and upper) for the landings are based on the information gathered from fisher interviews (Carruthers and Ings *pers. comm.*, 8 October 2019) plus a literature review on stock assessment. Let L_{obs} be the observed landings, L be the predicted landings in year y, then the censored-likelihood (l) is defined as:

$$l\left(L_{obs\,y}\middle|\theta\right) = \sum_{y=1}^{Y} log\left\{\Phi_N\left[\frac{\log\left({UB_y}/{L_y}\right)}{\sigma_L}\right] - \Phi_N\left[\frac{\log\left({LB_y}/{L_y}\right)}{\sigma_L}\right]\right\}, 1 \le y \le Y \qquad (33)$$

where, Φ_N is the CDF for a standard normal random variable, and σ_L is fixed at 0.02, which is a small value to ensure that predicted landings are unlikely to be estimated outside the given bounds (Cadigan 2016).

MULTIPLE MODEL FORMULATION, COMPARISON, AND EVALUATION

We perform a model building and evaluation process in four steps, which contain a total of 17 alternate models developed for the stock (Table 2). The most relevant results from these steps are presented in this document; however, the full details of the model runs of all four steps are available in the form of four dashboards, which were presented at the assessment framework meeting in October 2019 and can be provided upon request.

Step A mainly focusses on different options for modelling fishing mortality rate. Step B focuses on approaches to fit the fisheries catch-at-age. Models in Step A and Step B fit to the survey data from three trawl surveys, DFO RV, EHRAPS, and GEAC. At the data-review meeting, which was held in May 2019, it was decided that the new assessment model would include the DFO RV, IFREMER ERHAPS, the GEAC, and possibly the sentinel surveys. Beginning Step C, the models fit to the data from the sentinel surveys as well. Step C also introduces models with time-varying natural mortality. Step D tries to address the issues related to year-effects in the surveys by including year-effects in the observation model.

Step A: Evaluation of F Structure

Step A evaluates the different approaches for fitting F (Table 2). In all the models, the age composition of the commercial catch is fit using CRLs of the catch numbers-at-age, and the magnitude is fit using censored likelihood for landings. Model 1 fits a logistic selectivity model with two blocks in selectivity for the pre and post-moratorium period (equations 6–7). Model 2 fits an MVN random walk for F (equation 10–11) where the F for ages 9+ in a given year are mapped to be the same. Model 3 fits an AR structure over ages and years in F, the AR deviations are allowed to vary freely over ages and years (equations 12–13). The two-way correlation structure in F is allowed to break at the moratorium so that correlation structure is separate for the pre-moratorium period. Model 4 is similar to model 2, with the addition of a break in the MVN random walk at the moratorium.

A comparison of estimated F-at-age shows that these F values are small for ages 2 and 3 and do not necessarily correlate with the pattern in F for older ages. We decouple the correlation for the younger ages from the older ages in MVN random walk in models 5 and 6. Model 5 is similar to model 4 and decouples age 2 from MVN random walk for F. In model 6, we decouple both ages 2 and 3 from MVN random walk; therefore, model 6 has an MVN random walk applied on ages 4 and older. We estimate common standard deviations for all ages for catch-at-age CRLs and for all the survey indices.

In all the models, the F levels peaked in 1992, prior to the moratorium. Models 3 and 4 have better AIC estimates and have lower peaks in F prior to the moratorium (Table 2). The fits to the catch-at-age CRLs are similar in Models 2 to 6. The fits to the survey data are similar in models 2 to 6. In all the cases, there is an indication of year effects in the residual plots of indices. We find that Model 5, with the MVN random walk with a year break in the random walk at moratorium and an age break for the first age (age 2), has the best AIC among the alternate models. At the end of the first step, we choose to move forward with Model 5 for further development and evaluation.

Step B: Evaluation of Fitting to Catch-at-age

We evaluate different options for fitting the catch-at-age CRLs. For the catch-at-age data, there is an associated estimate of variance that is derived from the amounts of length and age sampling done from the fisheries (Gavaris and Gavaris 1983). The coefficient of variation is usually smaller for the dominant ages and higher for the younger and the older ages.

As mentioned before, model 5 is the base model for all evaluations in step B. In step B, the mapping of CRL standard deviation parameters for the catch-at-age are relaxed. All CRL standard deviations are allowed to be estimated freely in model 7. Several of the standard deviations estimated in model 7 are similar and accordingly, in model 8, these parameters are mapped by age groups (2, 3–4, 5–8, 9+). Model 9 allowed correlation in the CRL standard deviations using an AR1 process across ages. Model 7 and model 9 have comparable low AIC values. In a similar testing using SAM model for the same stock, the estimation of correlations in observation errors for catch-at-age resulted in the model fitting the landings data poorly (Champagnat and Vigneau, in press[4]). Here, the impact of estimating correlations in catch-at-age CRLs on the other estimated parameters is unclear and therefore, model 9 is not continued further. Though model 7 has the lowest AIC in this step, we discard this model because it did not converge in several additional runs in step C. Finally, model 8 is carried forward to Step C. Standardized CRL residual analysis suggests that fitting is good in general, except with some issues in age 2. Hence, it might be worthwhile to consider for future model update to eliminate the fitting of age 2 for F and catch-at-age especially, because this age forms a very small proportion of the landed catches.

Step C: Sentinel Data Inclusion and Additional Hypotheses for M

In step C, we bring sentinel gillnet and line-trawl data in the model fitting, and we make changes to the baseline assumptions about M. As noted earlier, time-varying M is based on the hypothesis that fish condition is a reflection of fish health and the capacity to survive stressful conditions. Due to the addition of new data to the model, the AIC estimates presented in the table for step C are not all directly comparable with the AIC values presented for models 1 to 9.

In model 10, model 8 is updated to include the fitting to sentinel gillnet and sentinel line-trawl data. Model 12 includes time-varying M based on condition-based index of M provided as data to the model (equation 16). Models 11 to 13 include time-varying M with estimation of parameter *mpar* (equations 15–17). Model 13 is similar to model 11 in the application of M but does not fit to sentinel data and hence, the AIC for this model is comparable to models presented in step A and step B.

Step D: Inclusion of Year Effects

The residuals for the DFO RV survey continue to show year-effects in step C (Figure 14). In step D we include year-effects (equations 25–26) in models 8, 10, 11, and 13 from the previous steps. Model 14 (model 8 with year-effects) estimates year-effects for all ages; however, this model over-fits the survey data (Figure 15). To overcome the over-fitting problem, we estimate

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[4] Champagnat, J., and J. Vigneau. In press. Development of a state space assessment model for cod (*Gadus morhua*) stock in NAFO subdivision 3Ps.

year-effects in two age groups in models 15–17; for example, we provide the results from model 16 in Figure 16.

Model Evaluation for Step C and Step D

Among the models with sentinel data (models 10–12, 14–16), model 14, which includes estimation of parameters for time-varying M and includes year-effects, yields lowest AIC, but owing to the over-fitting issues, we discard this model and proceed to the model 16 with next lowest AIC. Model 16 presents better residual patterns and retrospective outcomes among all the models (models 1–17) compared. However, at the assessment framework meeting, the model 16 is not judged suitable for assessing the stock for several reasons:

1. it is unclear how the year-effects can be used for short term projections of the stock and
2. it is unclear if estimated year-effects are explaining away other patterns in the stock behaviour.

The meeting concludes that models in step D are useful only for exploratory purposes.

The model choices remaining for the further consideration are model 8 from step B and all the models in step C. For all these models, we perform 5 year retrospective runs on SSB , recruitment, and total mortality Z (Figure 17 to Figure 19). Including the sentinel data in the fitting gets rid of the negative retrospective patterns in the SSB. Model 13 (model with time-varying M but no sentinel data) also reduces the retrospective pattern, but not as much as model 11 (model with both time-varying M and sentinel data).

The DFO RV and the sentinel surveys are the surveys that are presently monitoring the 3Ps cod stock. As mentioned before the DFO RV survey extends from 1983 to present and sentinel surveys extend from 1995-present. Now, model 11 has the lowest AIC among all the models with sentinel data; on the other hand, model 13 has lowest AIC among all the models without sentinel data. Since both model 11 and model 13 estimate time-varying M, we compare M estimates from different models (model 11, 13, 16, 17) estimating time-varying M for checking their robustness. We find that the estimates of M for ages 6+ are consistent between the models (Figure 20). For the age group 2 to 5, the M estimation is found to vary between whether sentinel data is fitted in the model or not (model 13 and 17), or whether year-effects are being estimated for the survey predictions (model 16 and 17). Various suggestions were provided at the meeting for performing additional exploration on estimation of time-varying M. These include:

1. sensitivity analyses based on a different threshold for the calculation of condition-based index of M (see Appendix C),
2. comparison with estimates of M from tagging analysis,
3. further analysis into better approaches to calculate condition-based index for M an
4. exploration of alternate covariates for M.

These models (11 and 13) show considerable differences in fit to DFO RV survey (Figure 21), model 13 produces better fit to the survey. Model 11 fits to both the surveys and beginning around 2010, it starts under-estimating recent DFO RV indices for ages 2 to 4 and also age 5 to some degree (Figure 21). The fits of model 11 to sentinel data are good, except in the early phase during the period of moratorium on fishing (Figure 22 and Figure 23). The reason for the model 11 underestimating DFO RV indices for younger ages is that this model is influenced more by the declining trends in sentinel data. Fits of model 11 and model 13 fits to other surveys are similar, both ERHAPS and GEAC surveys also show the evidence of year-effects (Figure 24 and Figure 25). Model 11 fit to catch-at-age data is good especially for the main ages (ages 5 to 8) caught in the fishery. The data for age 2 is sparse and the fits to the very small proportions of this age group in the catch are not good (Figure 26).

There is debate on whether (or not) to include sentinel survey along with DFO RV and other surveys in the modelling exercises. We feel both the choices have their merits and demerits. DFO RV survey covers the larger stock area and is expected to better represent the stock. There are some concerns about this survey and these include year-effects, and some evidence of changes in cod-habitat associations (Appendix A of this document) both of which affect the representativeness of the survey. The annual sentinel surveys monitor the inshore areas from June to November. Fish move inshore in the summer months and a large proportion of the commercial catch is also taken from the inshore regions. There are concerns about this survey as well: (i) the number of sites where the survey has been active has changed over time, (ii) the mean length-at-age of fish has decreased over time, and (iii) the changes to inshore environment, all of which may potentially affect the representativeness of the sentinel surveys.

The SURBA model used in previous assessments (2010–18) used only the DFO RV survey data and concerns about high retrospective patterns in the assessment is one of the important reasons for questioning the validity of the SURBA model for this stock. For the current assessment framework, we explore several state-space model formulations and we find that including the sentinel data reduces the retrospective patterns considerably. Further, the meeting agreed that a generally accepted norm in integrated state-space modelling is to use all data available to the extent possible. Model 11 under-estimates the fits to younger ages in the recent years, but provides a better performance in retrospective analysis than the other models. For this reason, the meeting judged model 11 to be the best representing the stock dynamics among all the 'HYBRID' models evaluated (models 1 to 17) for the assessment of 3Ps cod stock. In summary, model 11 has the following main features:

1. fits to all the available surveys,
2. MVN random walk for F with age 2 decoupled from the MVN correlation and with a discontinuity in the random walk at the moratorium,
3. incorporates uncertainty in fisheries landings, and
4. incorporates time-varying M.

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TABLES

Table 1. Comparison of data used in 2018 assessment (SURBA) and the new methodology (HYRBID).

Type	Model	2018 assessment (SURBA)	HYBRID
DATA	Surveys	DFO RV 1983–2018	ERHAPS 1978–91 DFO RV 1983–2018 GEAC 1998–2005 Sentinel 1995–2018
	Fisheries	-	Fisheries Landings Fisheries Catch-at-Age Commercial weights
	Age span	Ages 1 to 12. Age 12 is not a plus group. (Ages 1 and 2 years for 1983 to 1995 not part of likelihood)	Ages 2 to 14+
	Stock weights	Rivard adjustment of commercial weights. Stock-weights 0 for age 1 and age 2	Estimation from Cadigan 2019
MODELLING	Treatment of 'zero' indices	Removed	Censored likelihood
	Catchability	Fixed q (Fully selected q from age 4+ equals 1) Correction for inshore strata is through adjustment of catchability.	Estimated q for all surveys
	Total mortality Z	Separable Z=log_s (age effect) + log_f (year effect) Penalties applied for log_s and log_f Correlation in log_f broken in 1994 and 1997 to correspond with the moratorium. In the last year log_f is the average of the previous three years	Z=F+M Alternate parameterizations for F and M

Table 2. Summary of model comparison and evaluation

Step	Model	Model description	Converge	Comment	AIC	Mohn's rho (SSB)	Mohn's rho (Recruits)	Mohn's rho (Z)
Step A: F structure	1	Logistic/flat-topped F	Yes	-	4,557	-0.23	2.08	0.28
	2	F MVN Random walk (SAM)	Yes	-	4,005	0.56	0.3	-0.17
	3	F Correlated AR deviations in year and age with year break	Yes	-	3,823	0.71	0.76	-0.18
	4	F MVN Random walk with year break	Yes	-	3,825	0.53	0.2	-0.16
	5	F MVN Random walk with year break and splitting age 2 from the multivariate normal random walk (MVN-RW)	Yes	Model taken to Step B because of better AIC	3,796	0.54	0.26	-0.16
	6	F MVN Random walk with year break and splitting age 2 and 3 from the MVN-RW	No	-	3,818	-	-	-
Step B: Fitting catch-at-age	7	Model 5 (F MVN-RW with year break and decoupling age 2 from the MVN-RW)	Yes	Low AIC, of the 13 CRLs, several are similar. Failed	3,657	0.56	0.39	-0.16

Step	Model	Model description	Converge	Comment	AIC	Mohn's rho (SSB)	Mohn's rho (Recruits)	Mohn's rho (Z)
		with freely estimated standard deviations for catch-at-age		convergence in Step C				
	8	**Model 5 with standard deviations for the catch-age-CRL grouped for ages 2,3-4,5-8,9+ age groups**	Yes	Model taken to Step C because of very little correlation in CRL residuals	3,686	0.52	0.33	-0.15
	9	Model 8 with correlation in CRL standard deviations	Yes	CRL residuals correlated	3,656	0.54	0.39	-0.16
Step C: Sentinel + M	10	**Model 8** (F is MVN-RW with year break and decoupling age 2 from MVN-RW standard deviations for the catch-age-CRL grouped for ages 2, 3–4, 5–8, 9+ age groups) **sentinel data fit**	Yes	Good alternative to consider sentinel	4,286	0.19	0.11	-0.07
	11	**Model 10 + time varying M** estimated as a correlate of fish condition based M	Yes	Good alternative to consider sentinel and M	4,273	0.07	0.05	0.09

Step	Model	Model description	Converge	Comment	AIC	Mohn's rho (SSB)	Mohn's rho (Recruits)	Mohn's rho (Z)
	12	Model 10 + time varying M provided as data	Yes	Comparatively poor AIC	4,323	-0.11	-0.28	0.03
	13	**Model 8 + time varying M** estimated as a correlate of fish condition based M **(no sentinel data)**	Yes	Good alternative in Step D if not using sentinel data	3,640	0.16	0.11	0.37
Step D: Year effects (YE)	14	Model 11 + sentinel data fit + YE	Yes	-	3,850	0.04	0.28	0.3
	15	Model 10 + YE (age-groups)	Yes	Could be an alternative with sentinel data.	4,031	0.19	0.08	-0.08
	16	Model 11 + YE (age-groups)	Yes	Model presented at meeting. But some issues with M estimation.	4,015	0.01	0.11	0.18
	17	Model 15 with no sentinel fit	Yes	-	3,356	0.25	0.15	0.54

FIGURES

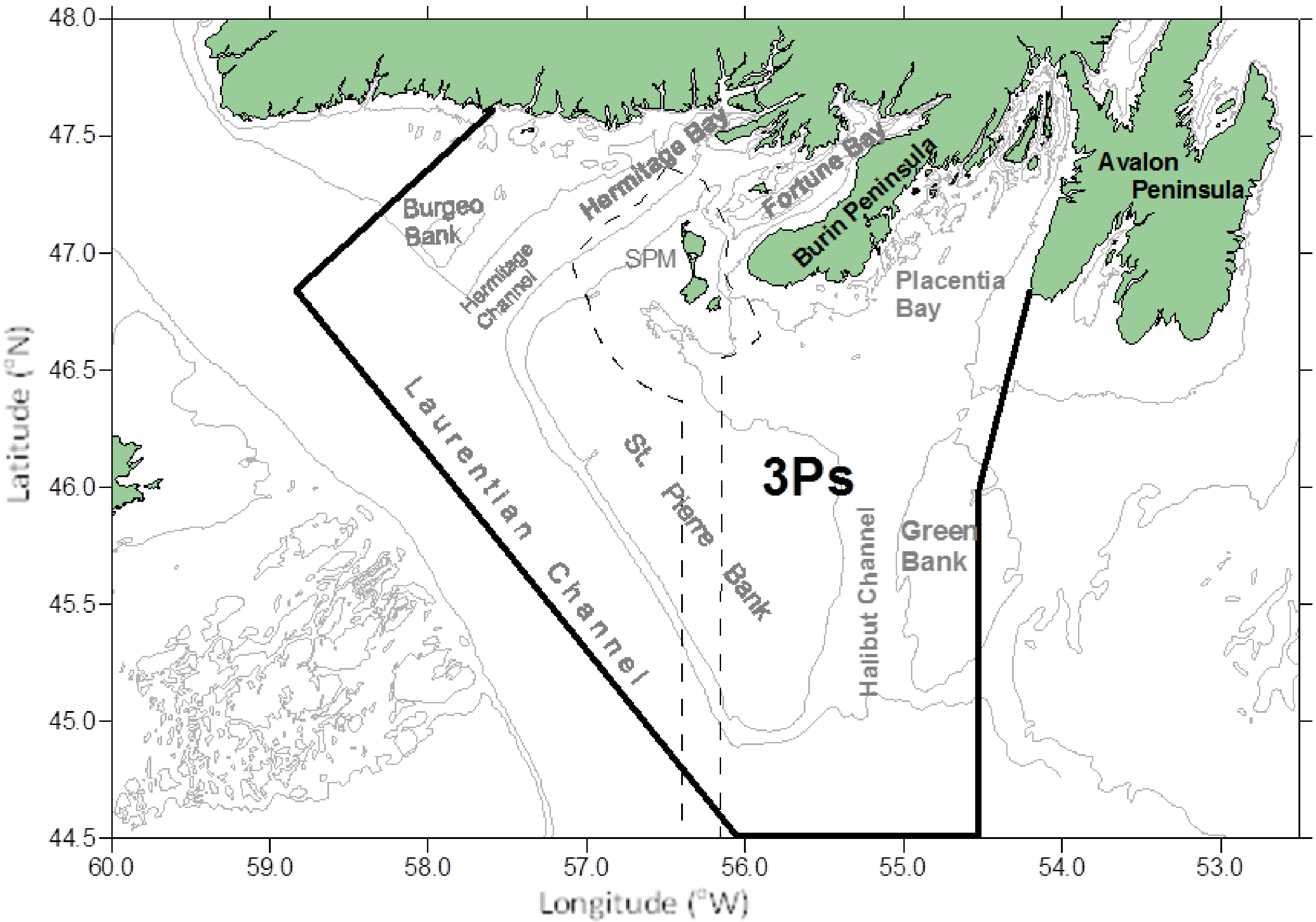


Figure 1. NAFO Subdiv. 3Ps management zone showing the economic zone around the French islands of St. Pierre and Miquelon (SPM, dashed line), the 100 m and 250 m depth contours (grey lines) and the main fishing areas.

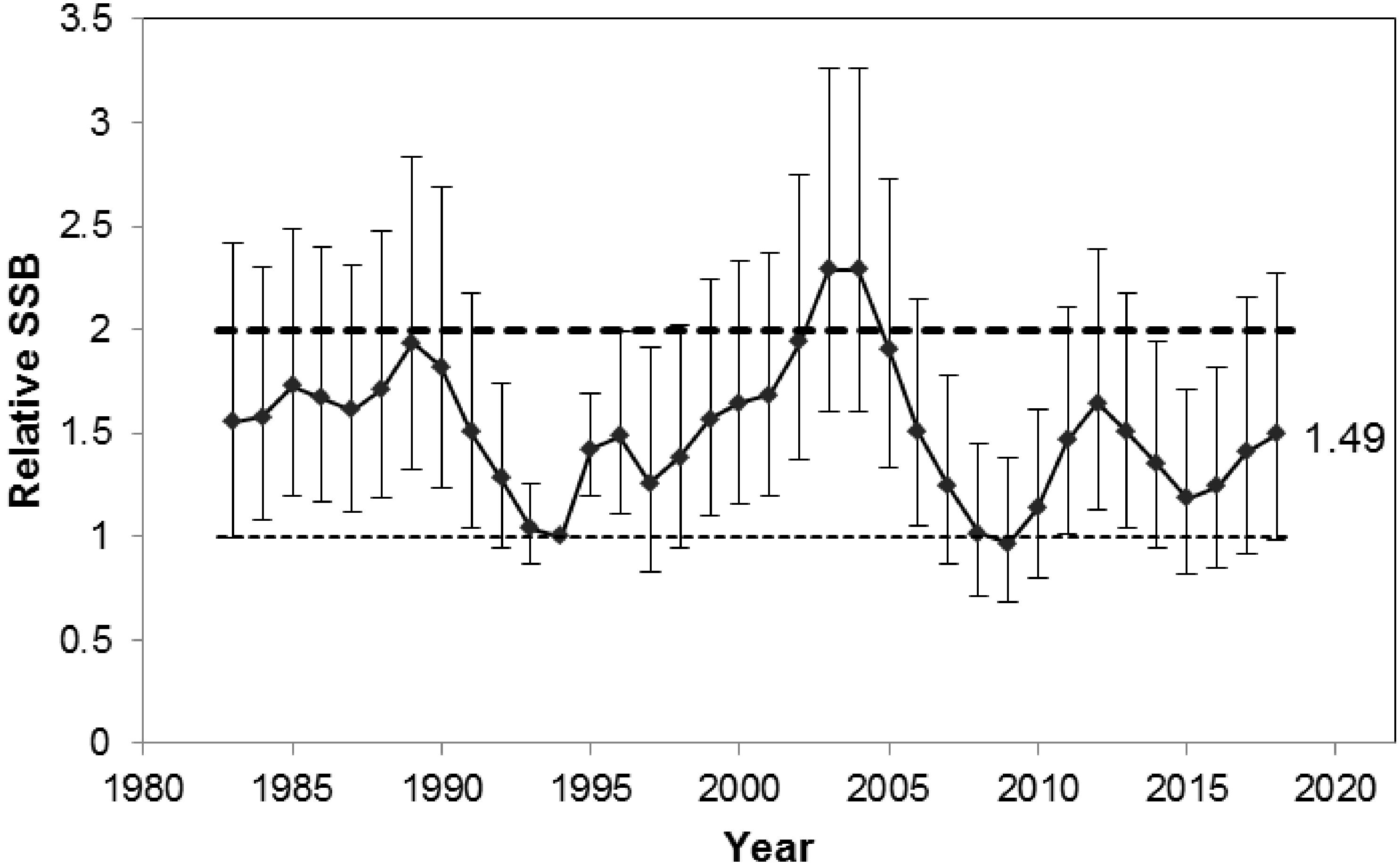


Figure 2. Cohort analysis estimates of SSB, relative to the 1994 value (median estimate with 95% confidence interval) from the 2018 assessment with SURBA. The lower dashed line at one (reference level) represents the SSB Limit Reference Point and the upper horizontal dashed line at two represents the Upper Stock Reference (i.e., 2 x LRP). These reference points represent the boundaries between the zones of DFO's precautionary approach framework, as indicated on the right axis. Text label indicates the current SSB relative to the LRP.

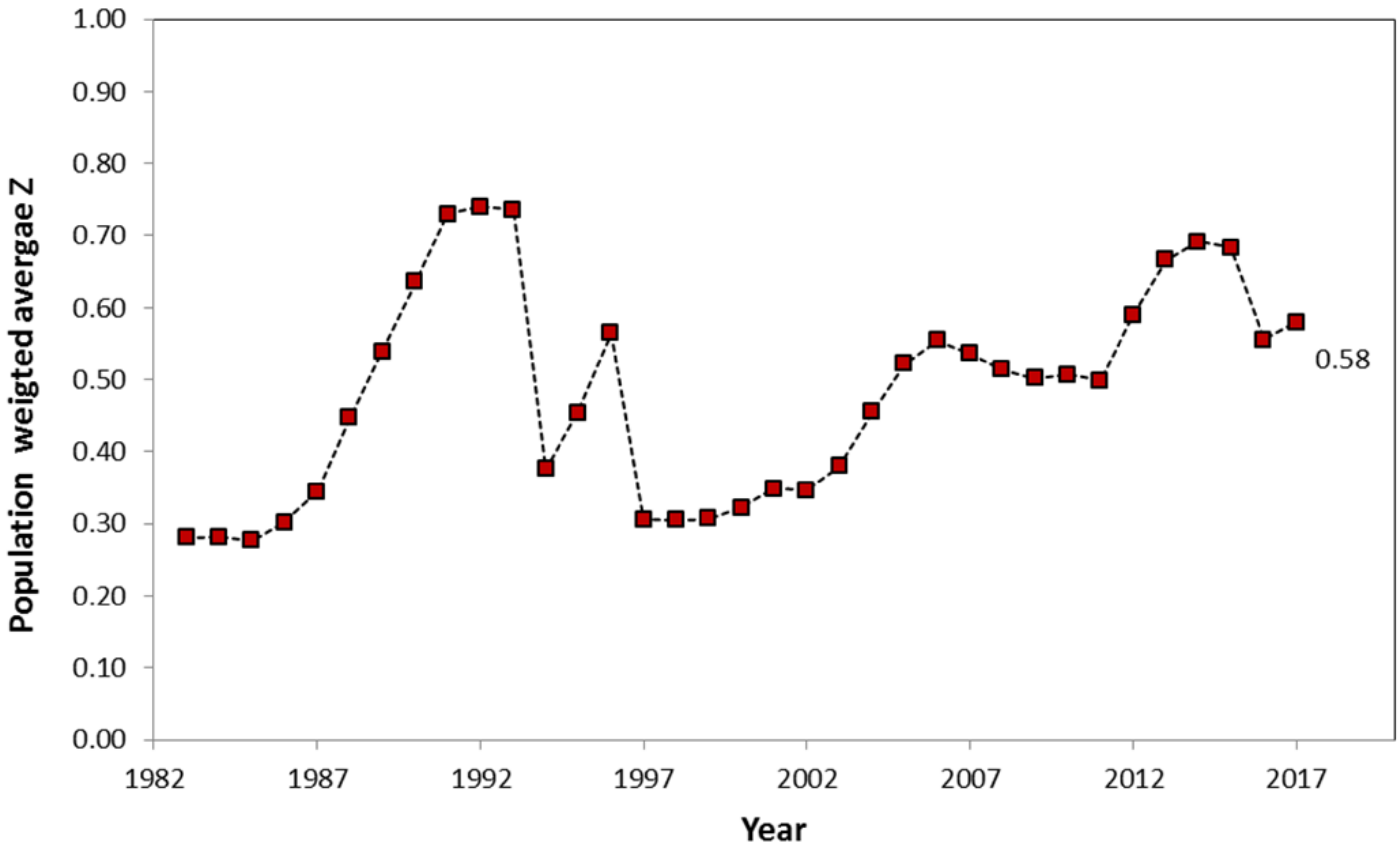


Figure 3. Cohort analysis estimates of population weighted average annual mortality (ages 5–10). Text label indicates the estimated total mortality for 2017.

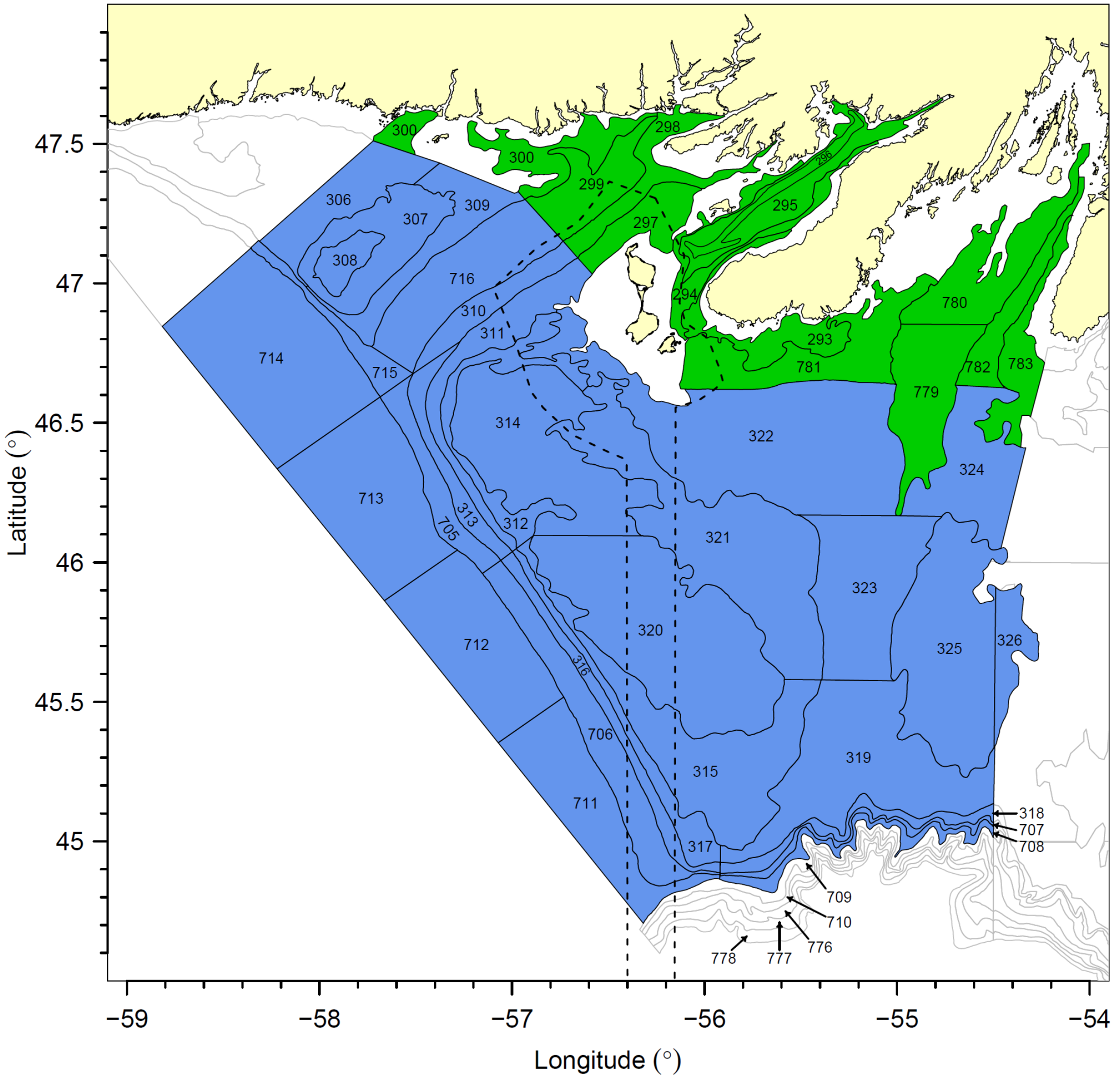


Figure 4. Stratum area boundaries and area surveyed during the DFO research vessel bottom-trawl survey of NAFO Subdiv. 3Ps. Offshore strata are shaded blue. Inshore strata were added in 1994 (strata 779–783) and 1997 (strata 293–300) and are shaded green. The dashed line represents the boundary of the French economic zone.

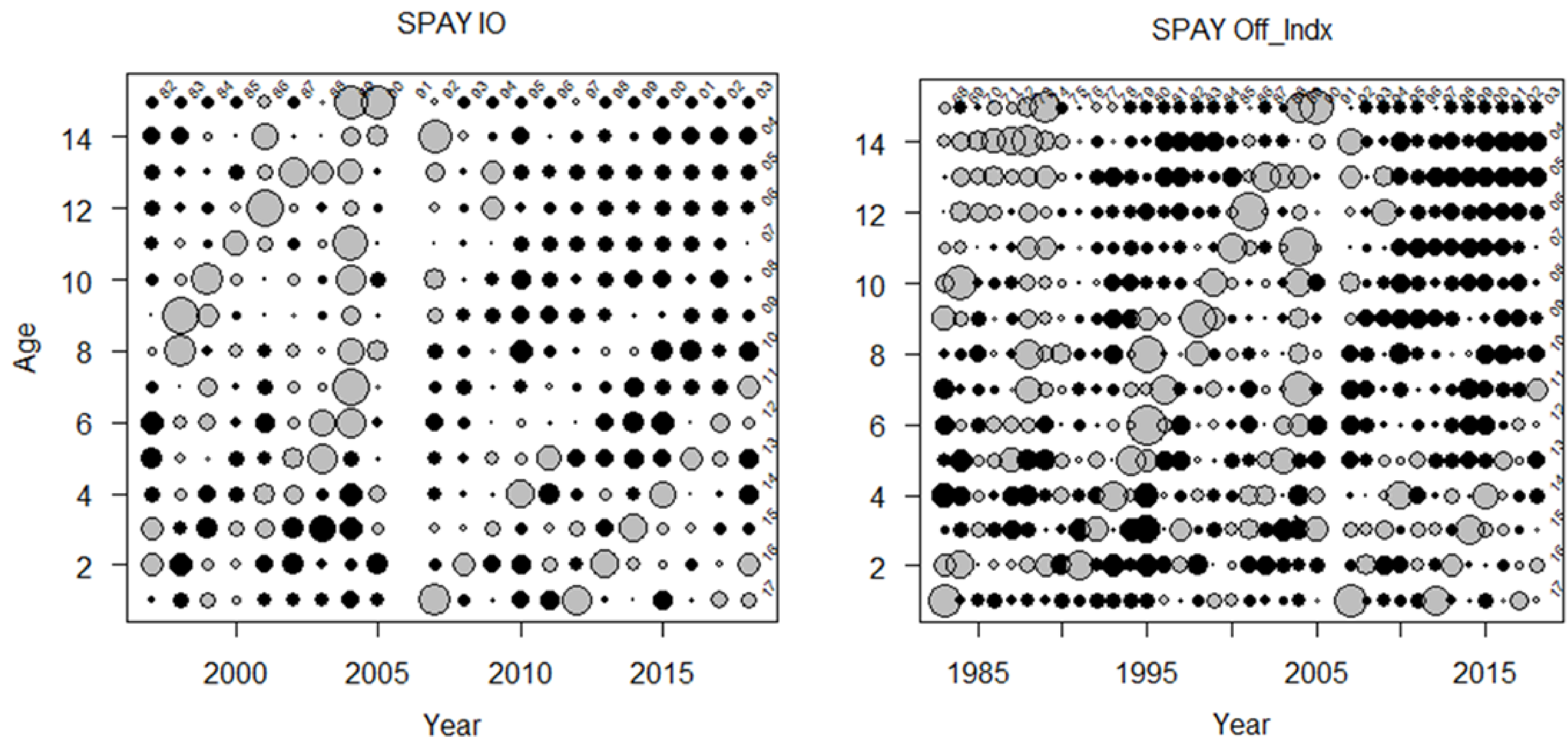


Figure 5. Standardized age-disaggregated catch rates from the spring bottom trawl survey of Subdiv. 3Ps. Catch rates (mean nos per tow) were converted to proportions within each year. Values were standardized by subtracting the mean proportion and dividing by the standard deviation of the proportions computed across years. Symbol sizes are scaled and values greater than average are shown as grey circles, average values are shown as small dots, and less than average values are shown as black circles. Labels in the upper and right margins identify cohorts. Left panel includes the 1997–2018 "All Strata <300 fm" data, and panel at right includes data which comprise the "Offshore" index (1983–2018).

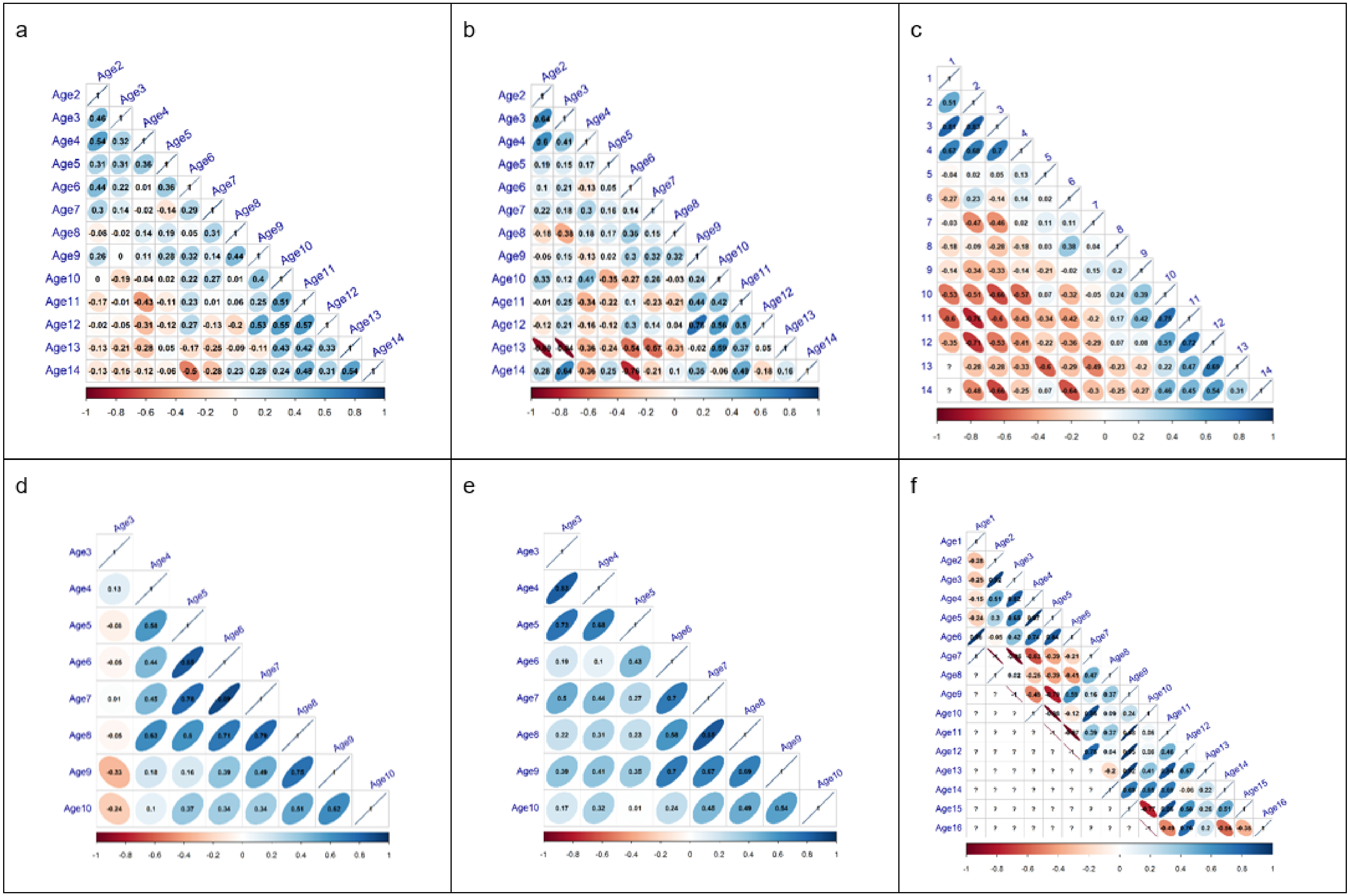


Figure 6. Consistency plots for Surveys. a) DFO RV survey 1983–2018, b) DFO RV survey 1997–2018, c) ERHAPS survey 1978–92, d) Sentinel gillnet 1995-2017, e) Sentinel line trawl 1995-2017, f) GEAC survey 1998–2005.

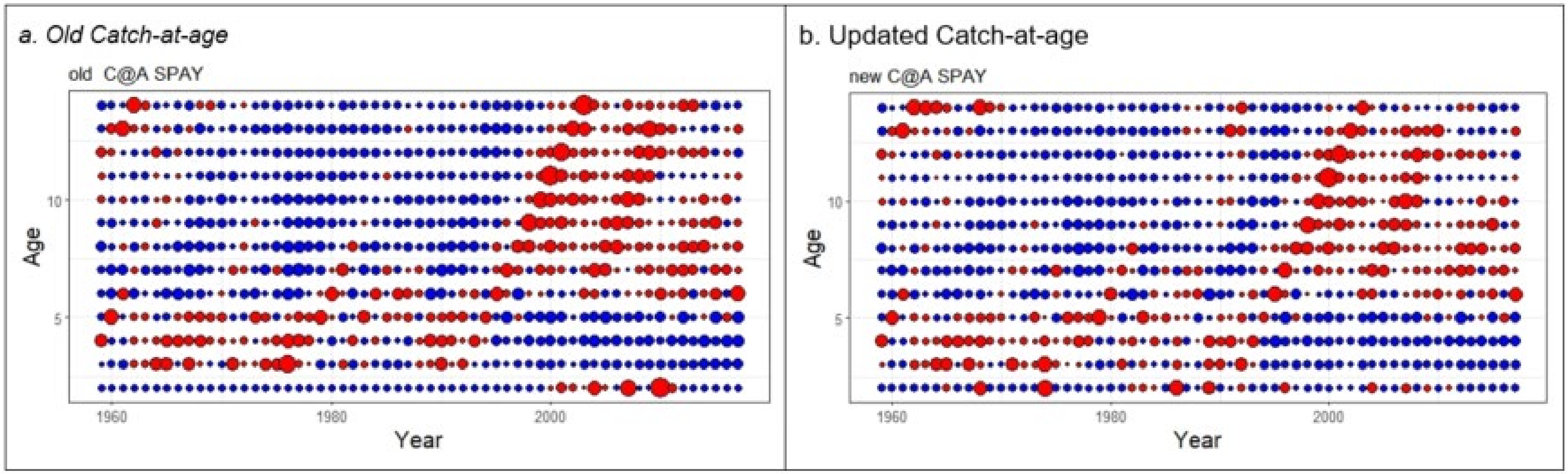


Figure 7. Standardized age-disaggregated catch rates from the catch-at-age of Subdiv. 3Ps cod. a. Older version of catch-at-age; b. Reconstructed/improved catch-at-age

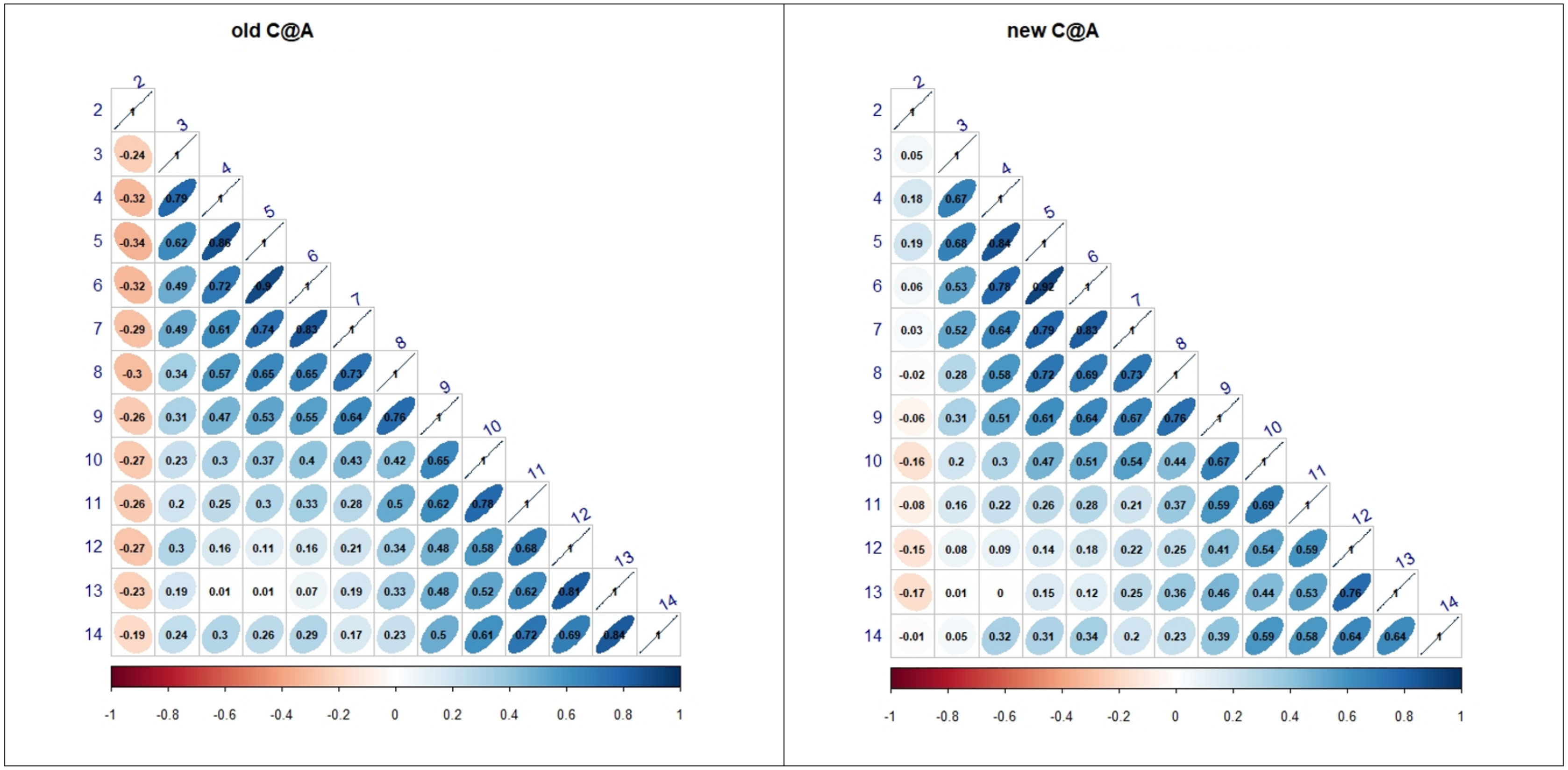


Figure 8. Consistency plots for Catch-at-age. a) Old catch-at-age. b) Updated catch-at-age.

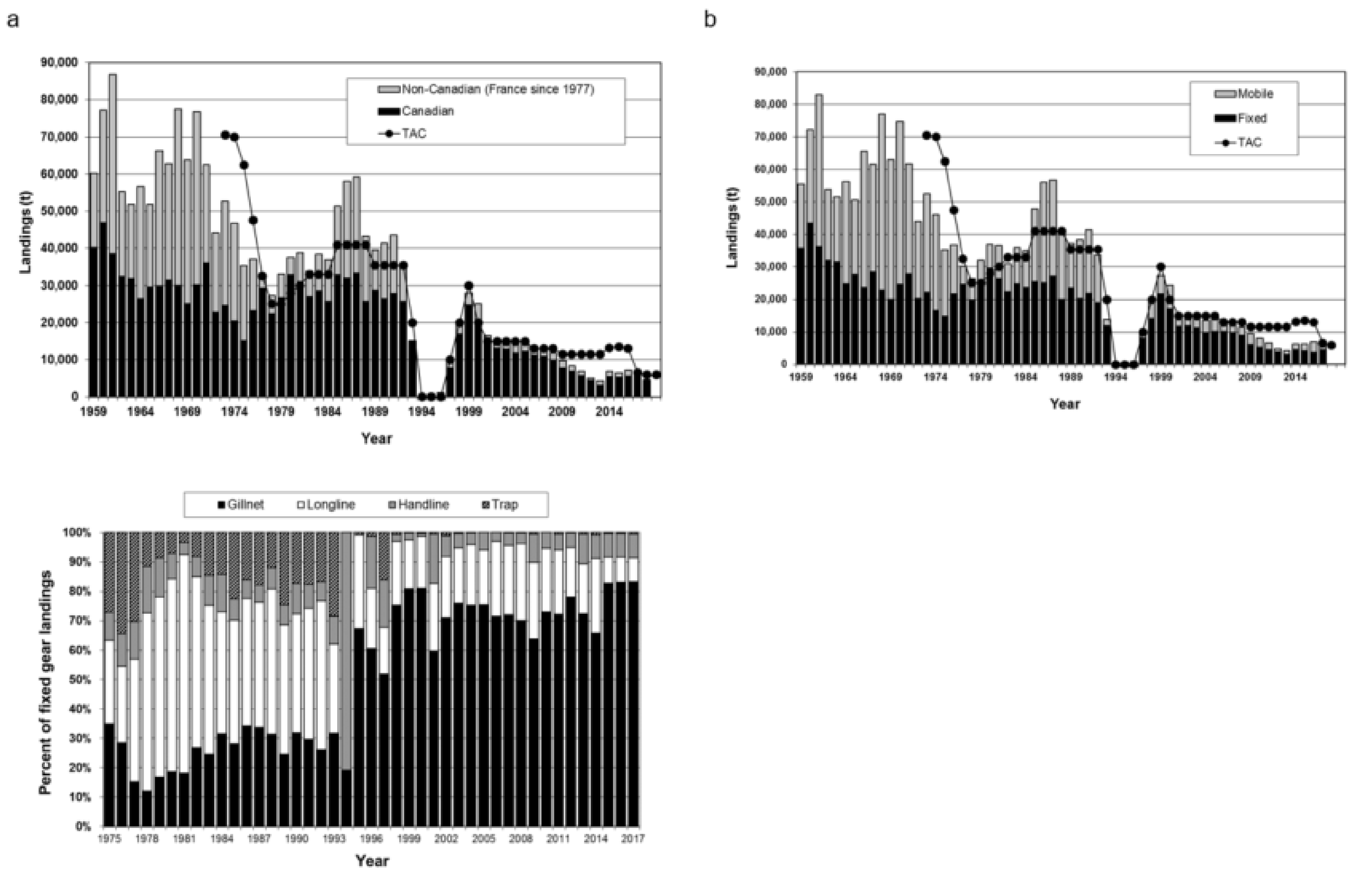


Figure 9. a) Reported landings of cod by Canadian and non-Canadian vessels in NAFO Subdiv. 3Ps. Note that the 2019 fishery was still in progress at the time of the current assessment. b) Reported landings of cod by fixed and mobile gears in NAFO Subdiv. 3Ps. Note that the 2019 fishery was still in progress at the time of the current assessment. c) Percent of total fixed gear landings by the four main fixed gears used in the cod fishery in NAFO Subdiv. 3Ps. The fishery was under a moratorium during 1994–96 and values for those years are based on sentinel and by-catch landings of <800 t.

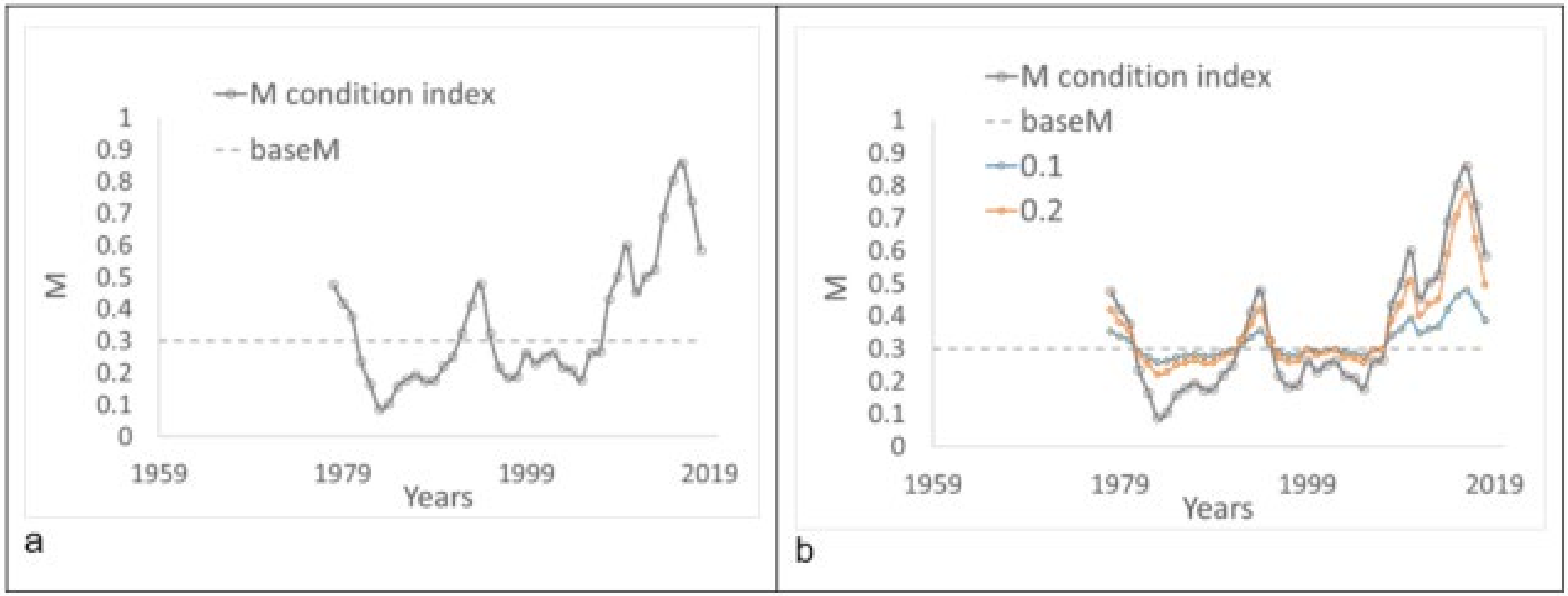


Figure 10. Implementation of M in 'HYBRID' model. a) Index for M derived from fish condition, base M shows the time-invariant M. b) Shows application of M based on equations 14 and 15. Orange and blue lines show values 0.1 and 0.2 assigned to mpar parameter in equation 17.

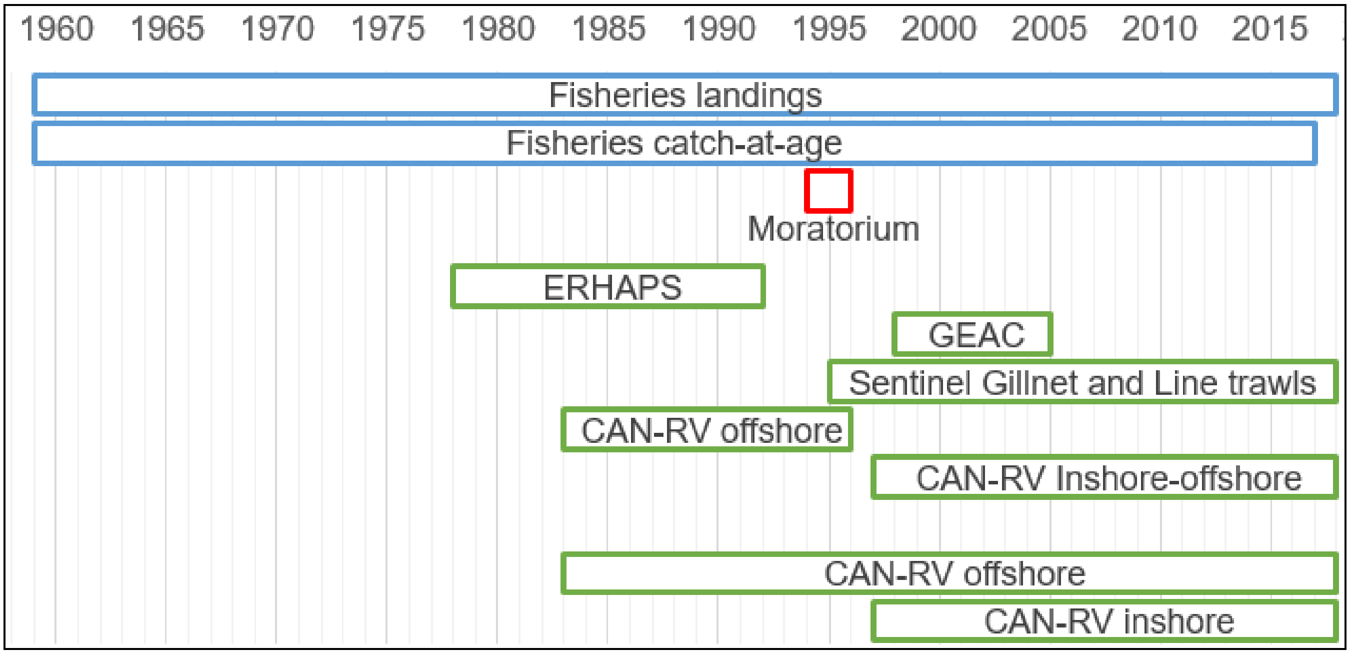


Figure 11. Timeline of fisheries (blue) and survey (green) data.

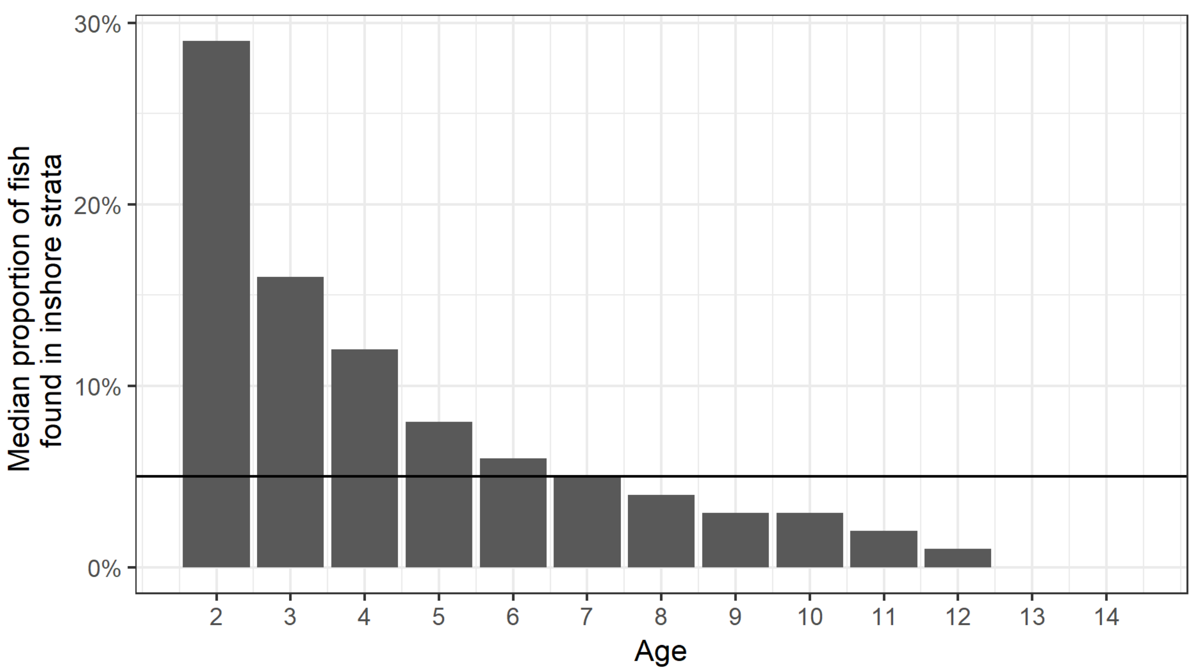


Figure 12. Proportion of fish by age in the inshore versus combined inshore-offshore area in the Canadian-RV surveys from 1997-2018. The offset for q was applied to ages 8 and older. The horizontal line indicates 5% which was used as a cut-off for ages to apply the offset.

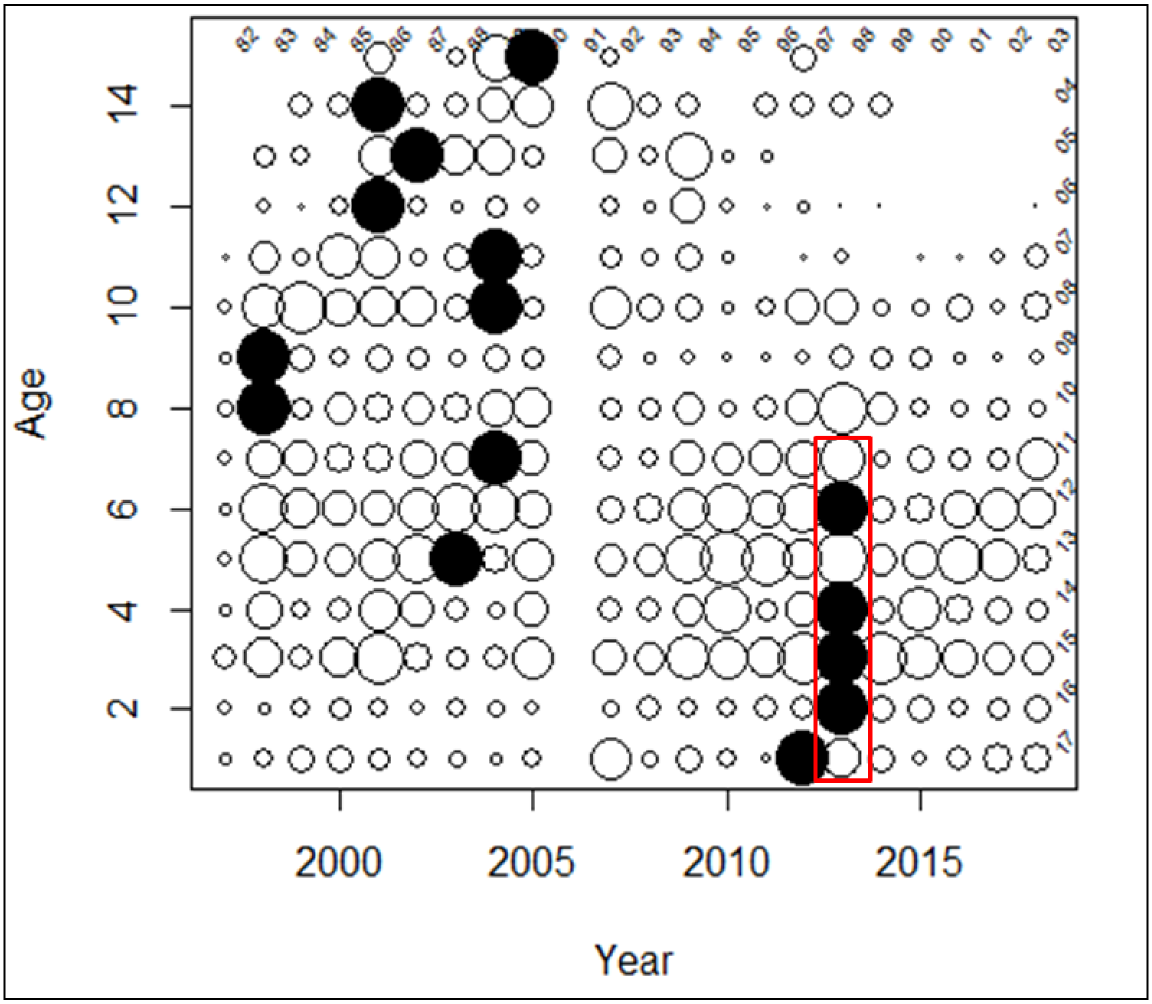


Figure 13. Age-Standardized catch rates from the spring bottom trawl survey of Subdiv. 3Ps. Catch rates (mean nos per tow) were converted to proportions within each age. Values were standardized by subtracting the mean proportion and dividing by the standard deviation of the proportions computed across ages.

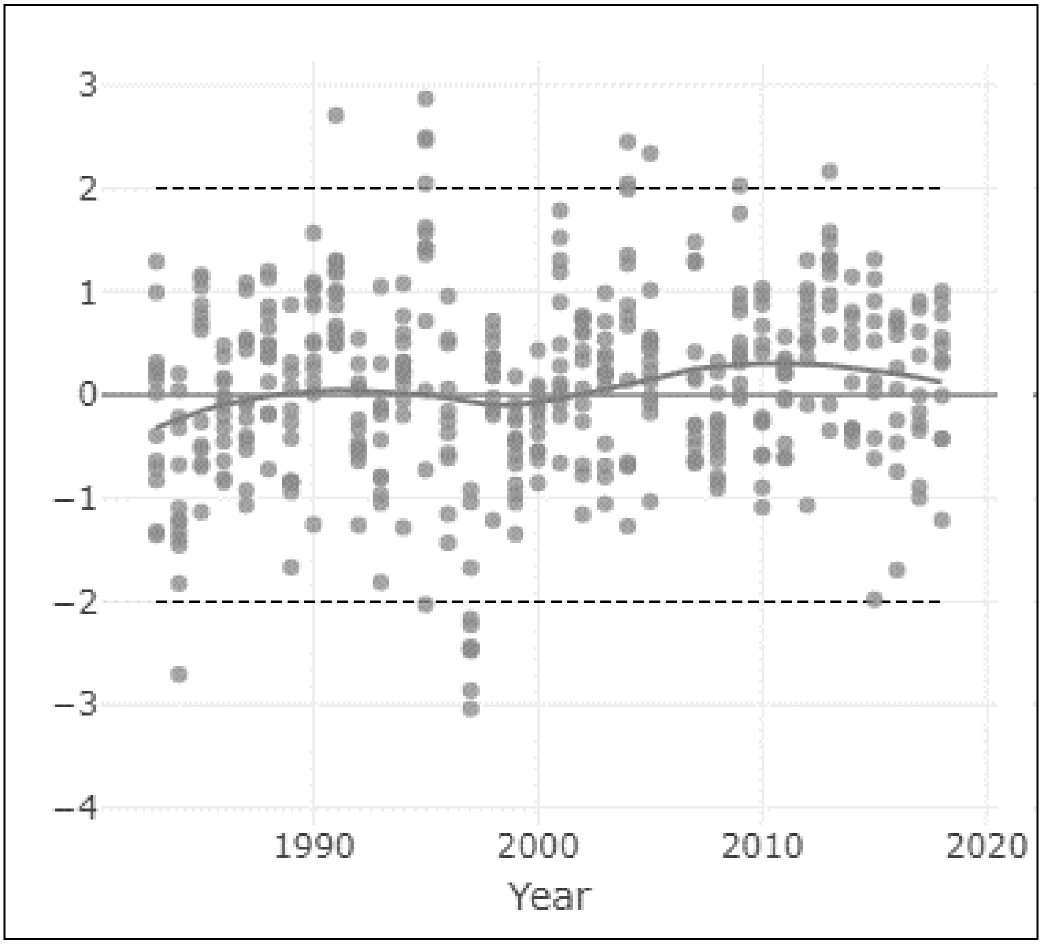


Figure 14. Standardized log residual plot for DFO RV survey for Model 10.

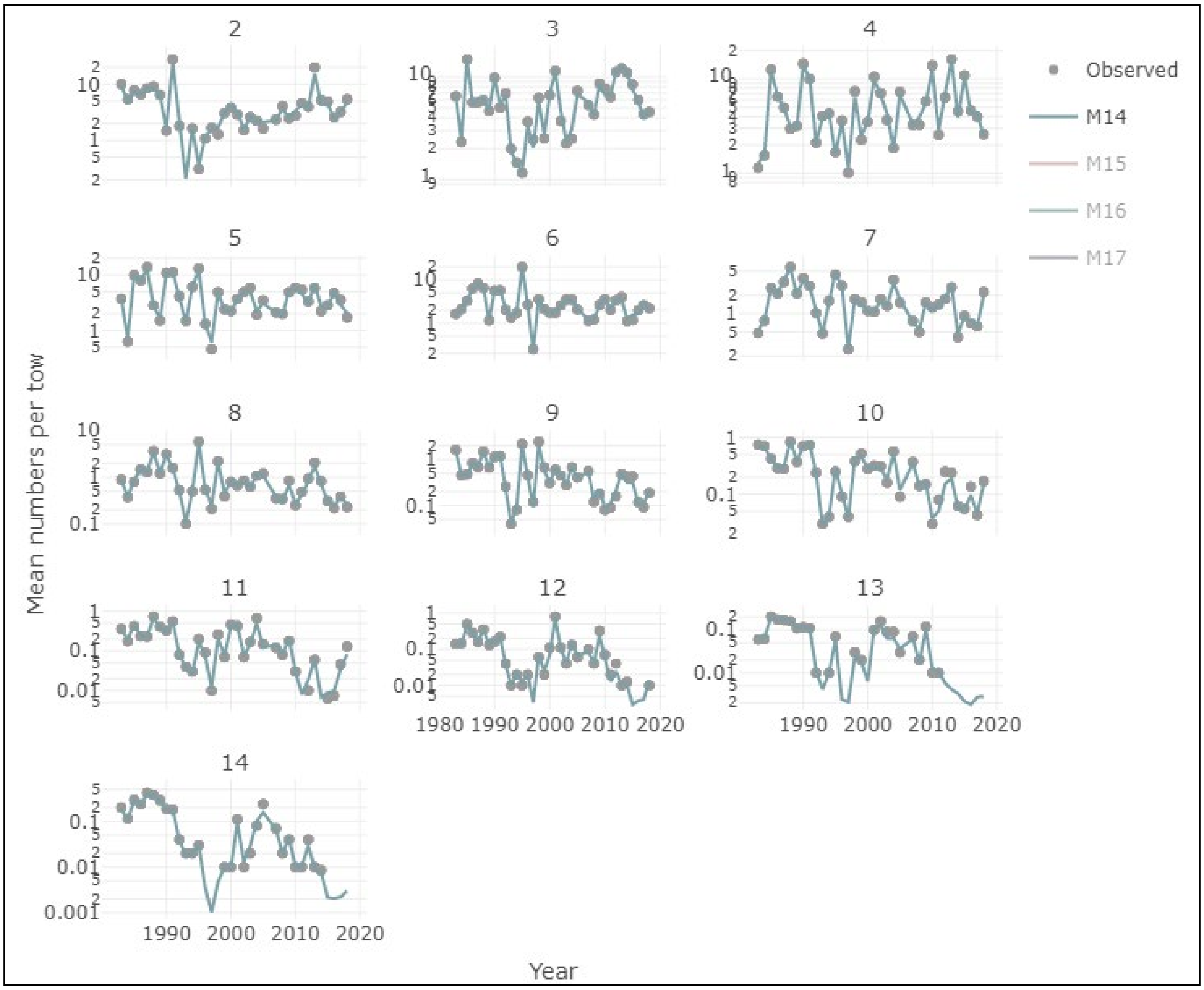


Figure 15. Model fit to DFO RV survey index-at-age for model 14.

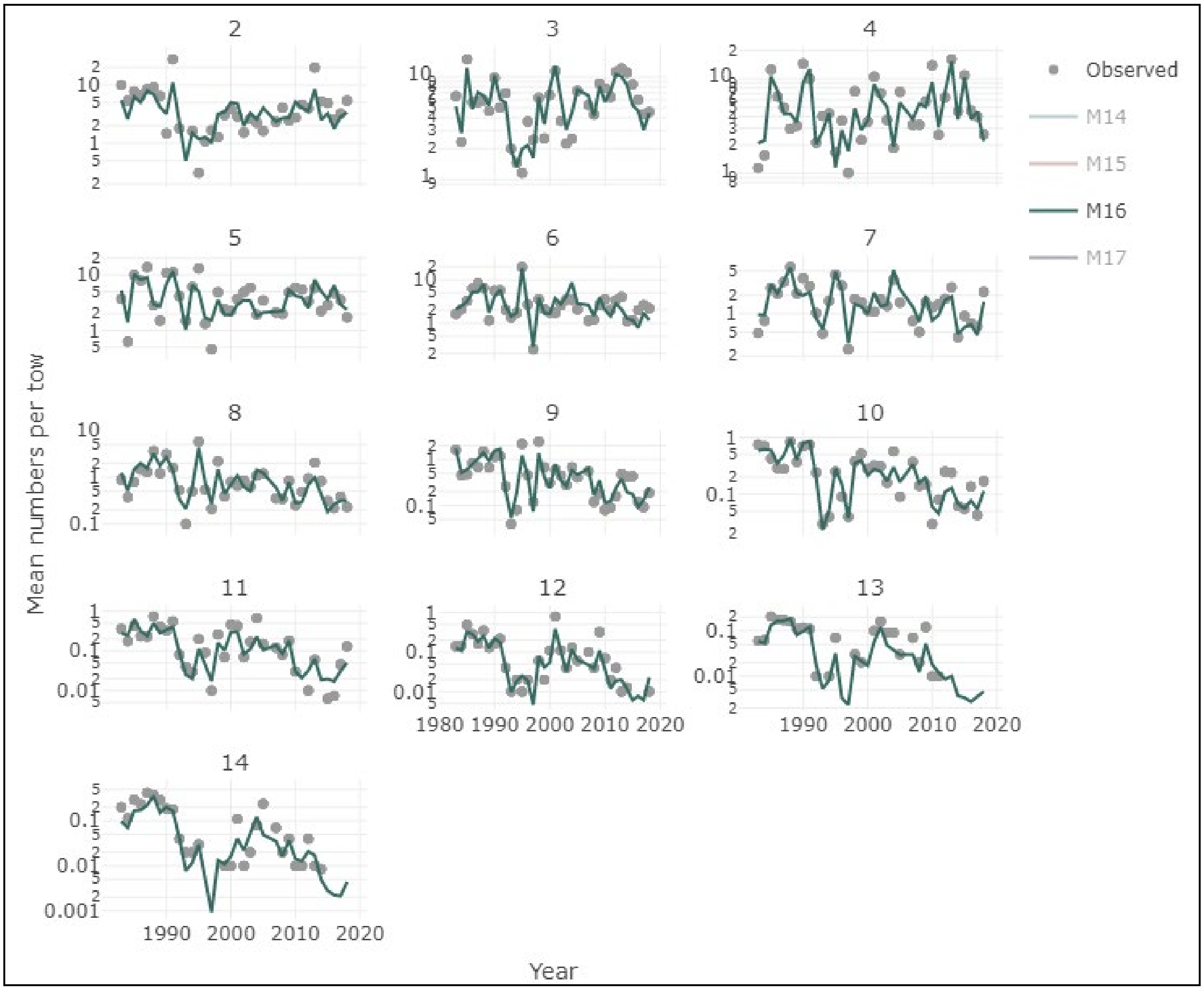


Figure 16. Model fit to DFO RV survey index-at-age for model 16.

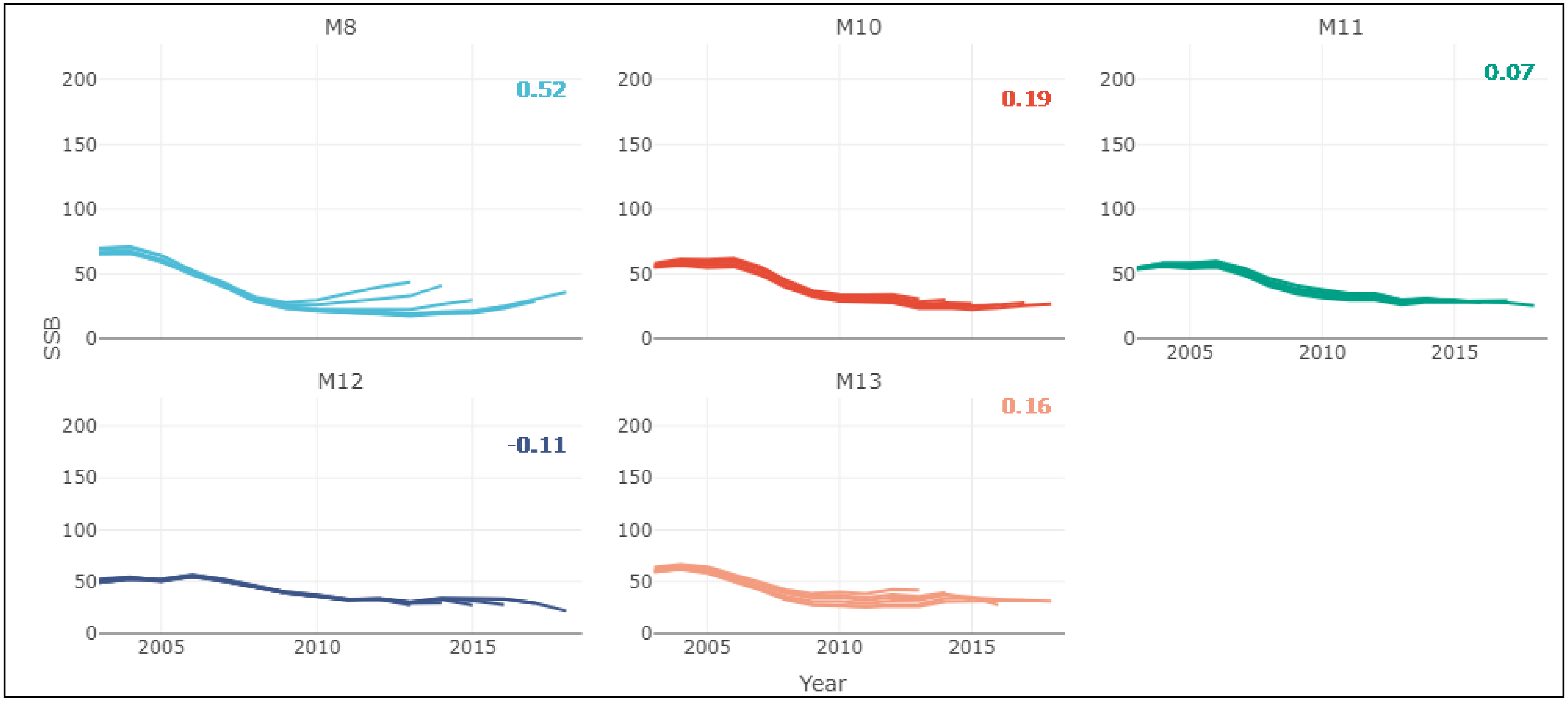


Figure 17. Five year retrospective patterns in spawning stock biomass.

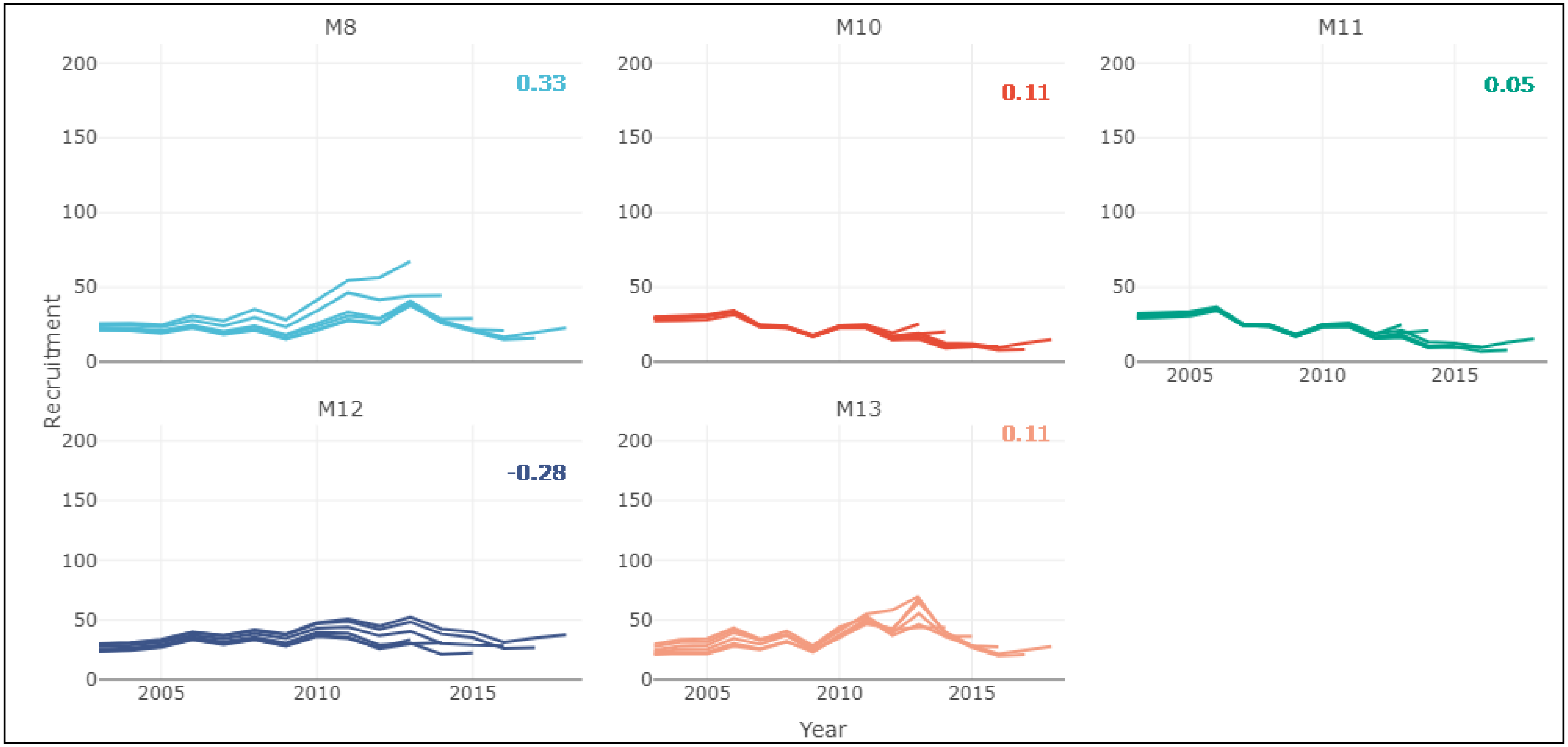


Figure 18. Five year retrospective patterns in recruitment.

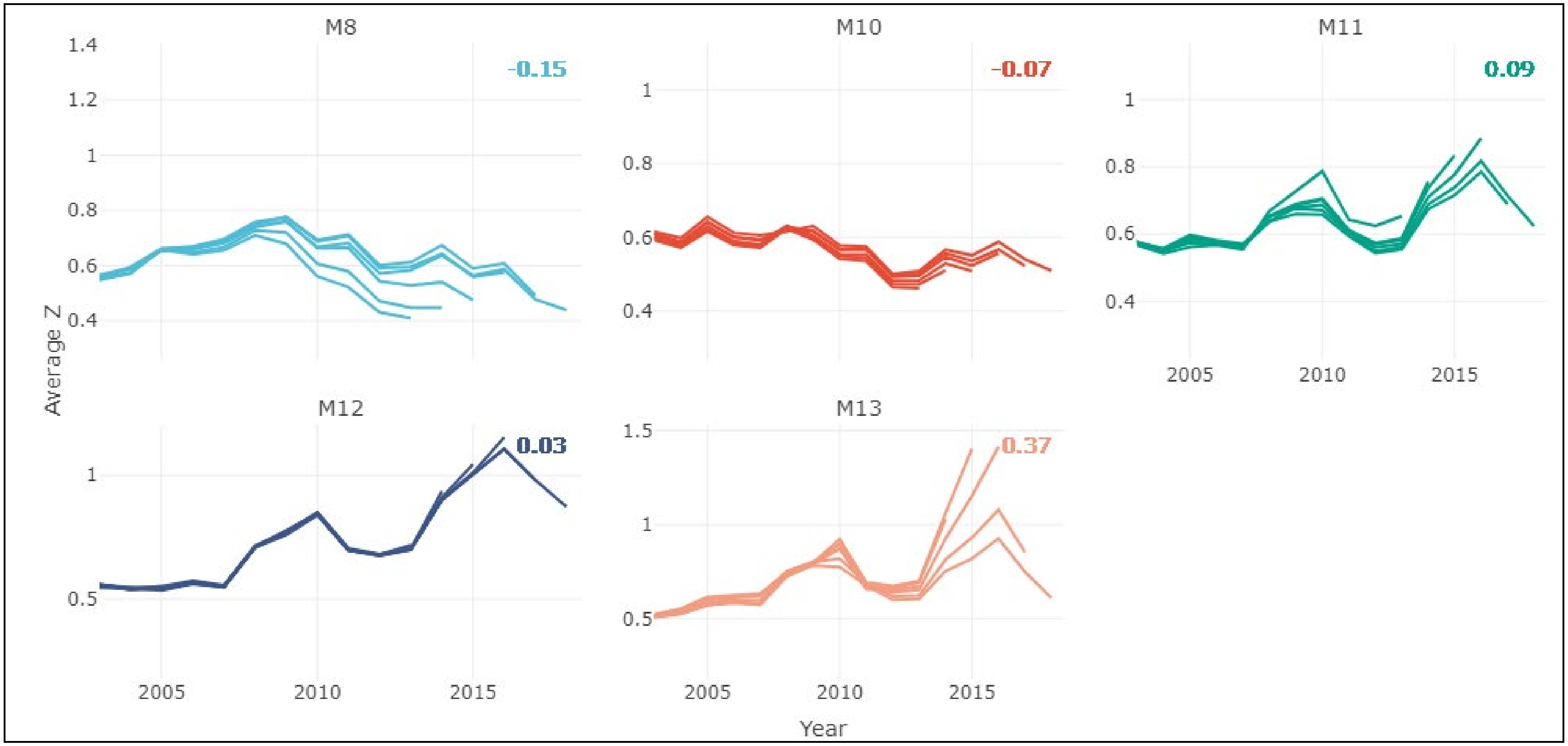


Figure 19. Five year retrospective patterns in average total mortality (Z).

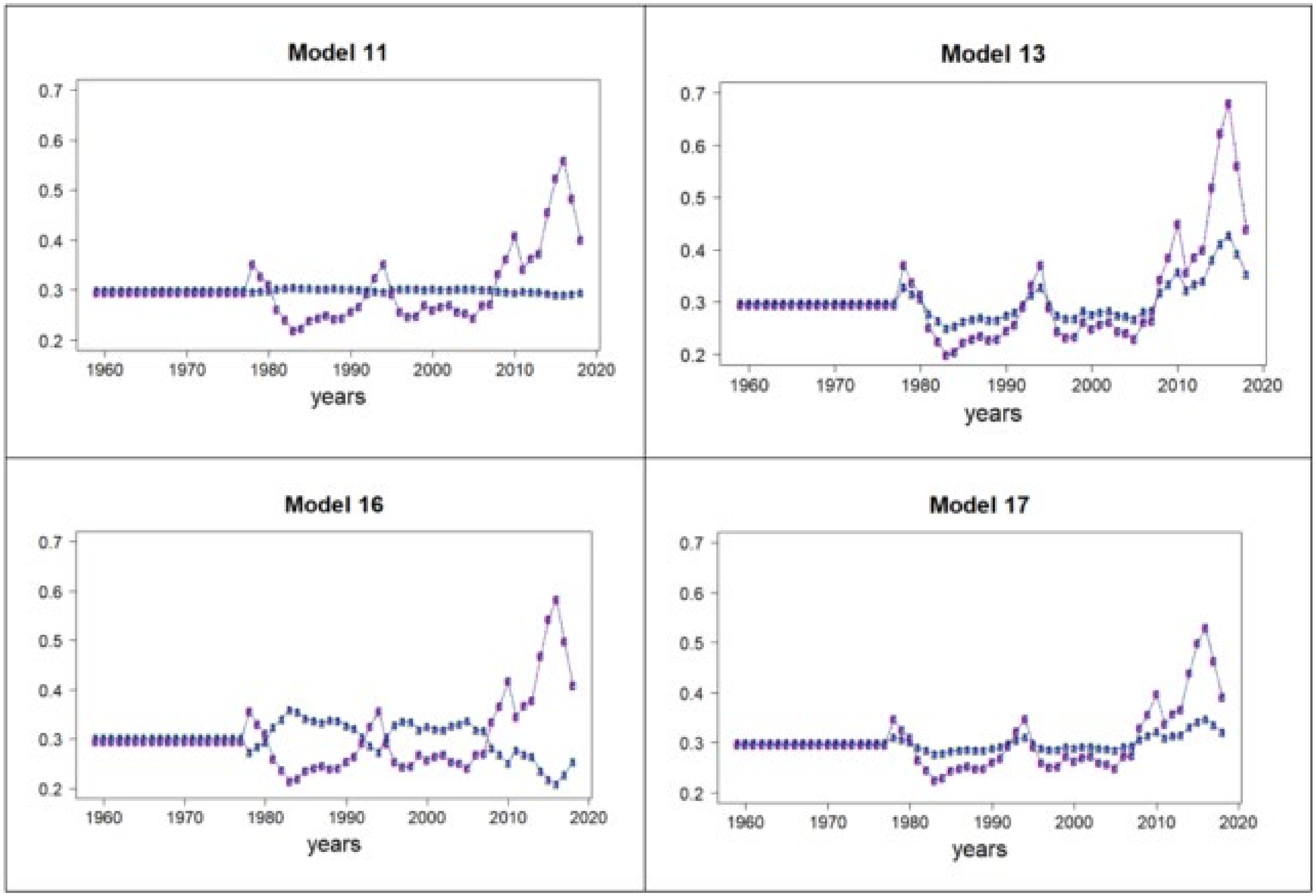


Figure 20. Comparison of estimates of time-varying M in different models where this feature was applied. Blue lines shows the estimates for age group 2 to 5 and the purple line shows the estimation for ages 6+.

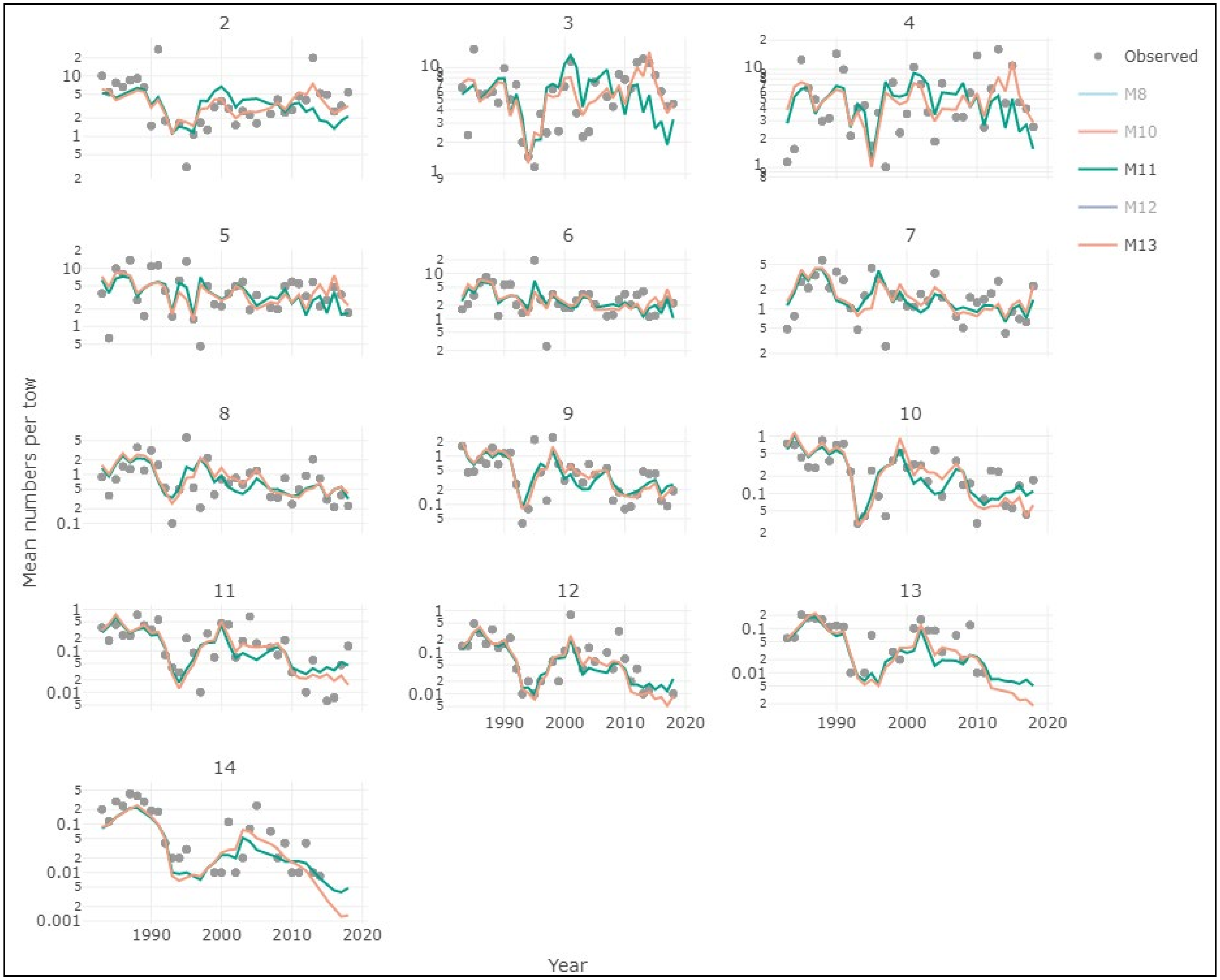


Figure 21. Comparison of fits to DFO RV survey index-at-age for model 11 (model fits to sentinel surveys) and model 13 (model does not fit sentinel surveys).

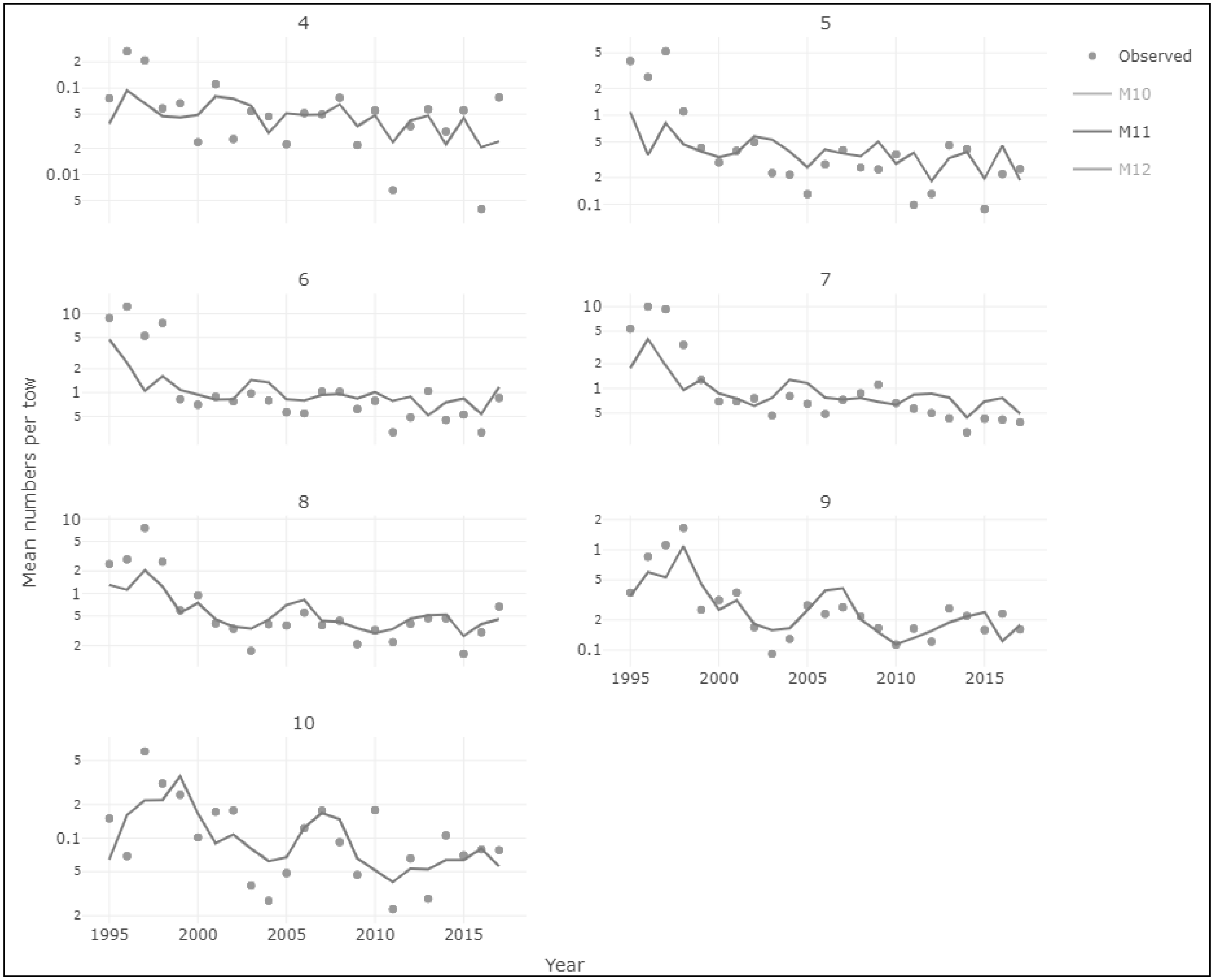


Figure 22. Fit to Sentinel Gillnet data from model 11.

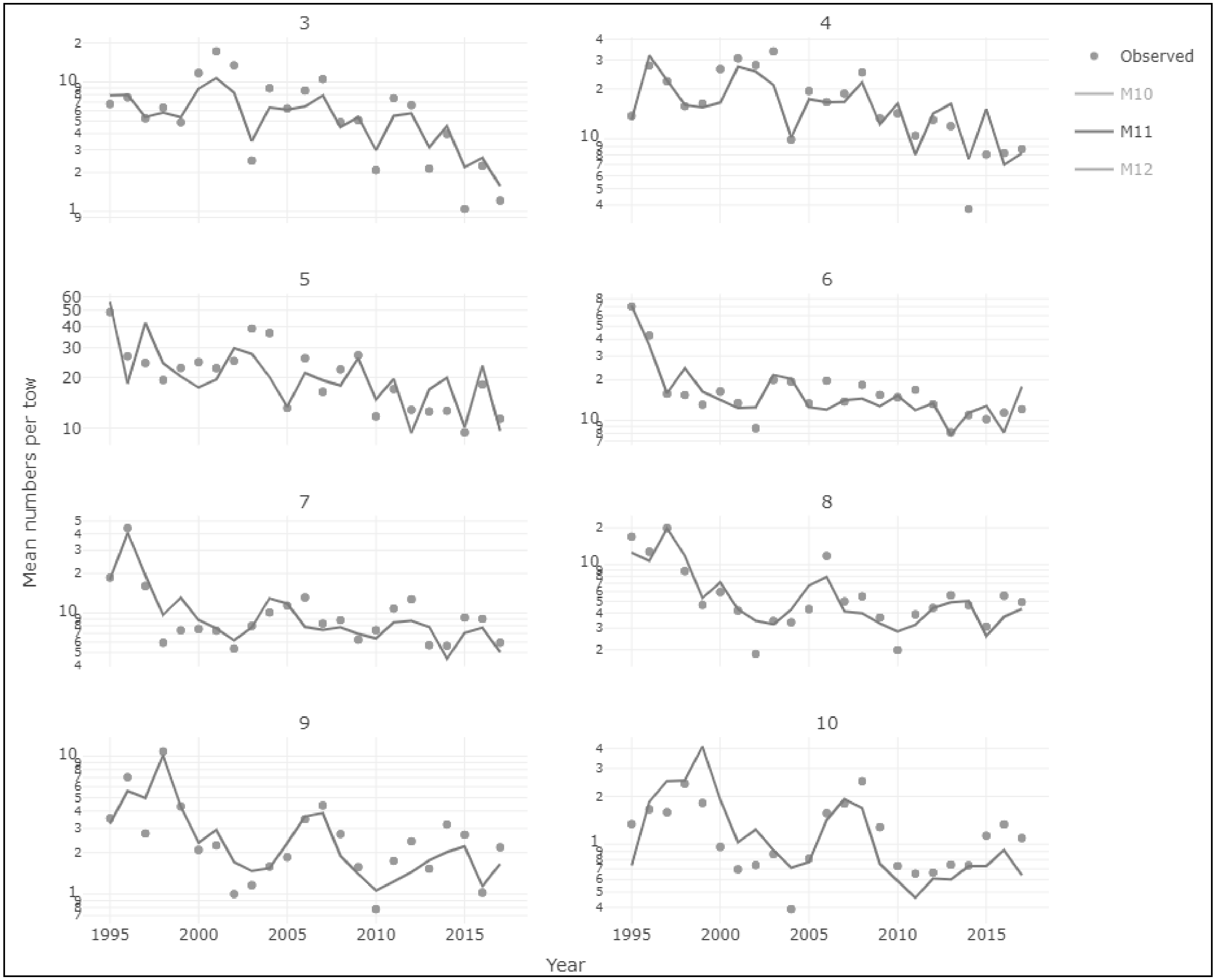


Figure 23. Fit to sentinel line trawl data from model 11.

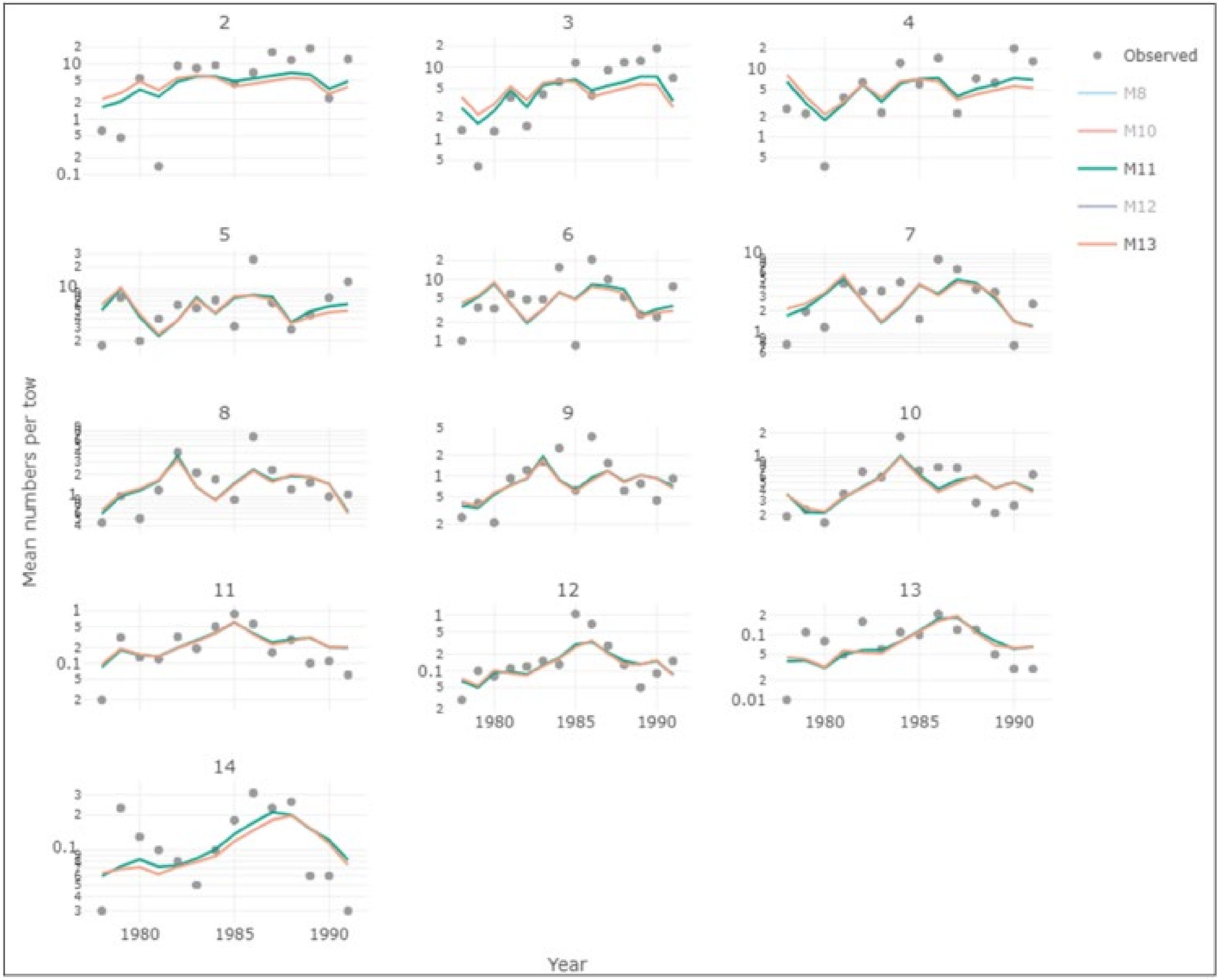


Figure 24. Fit to ERHAPS survey from model 11.

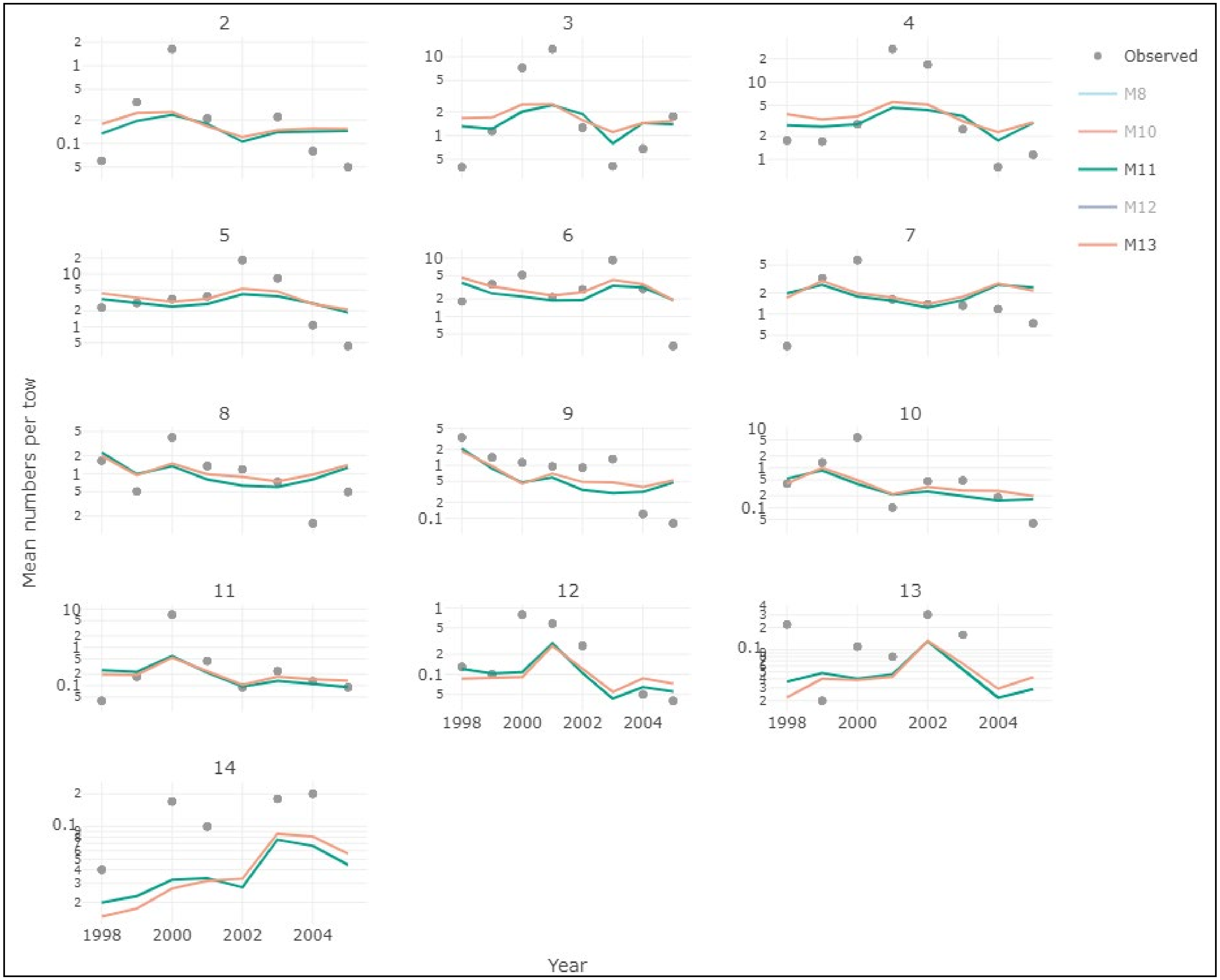


Figure 25. Fit to GEAC survey from model 11.

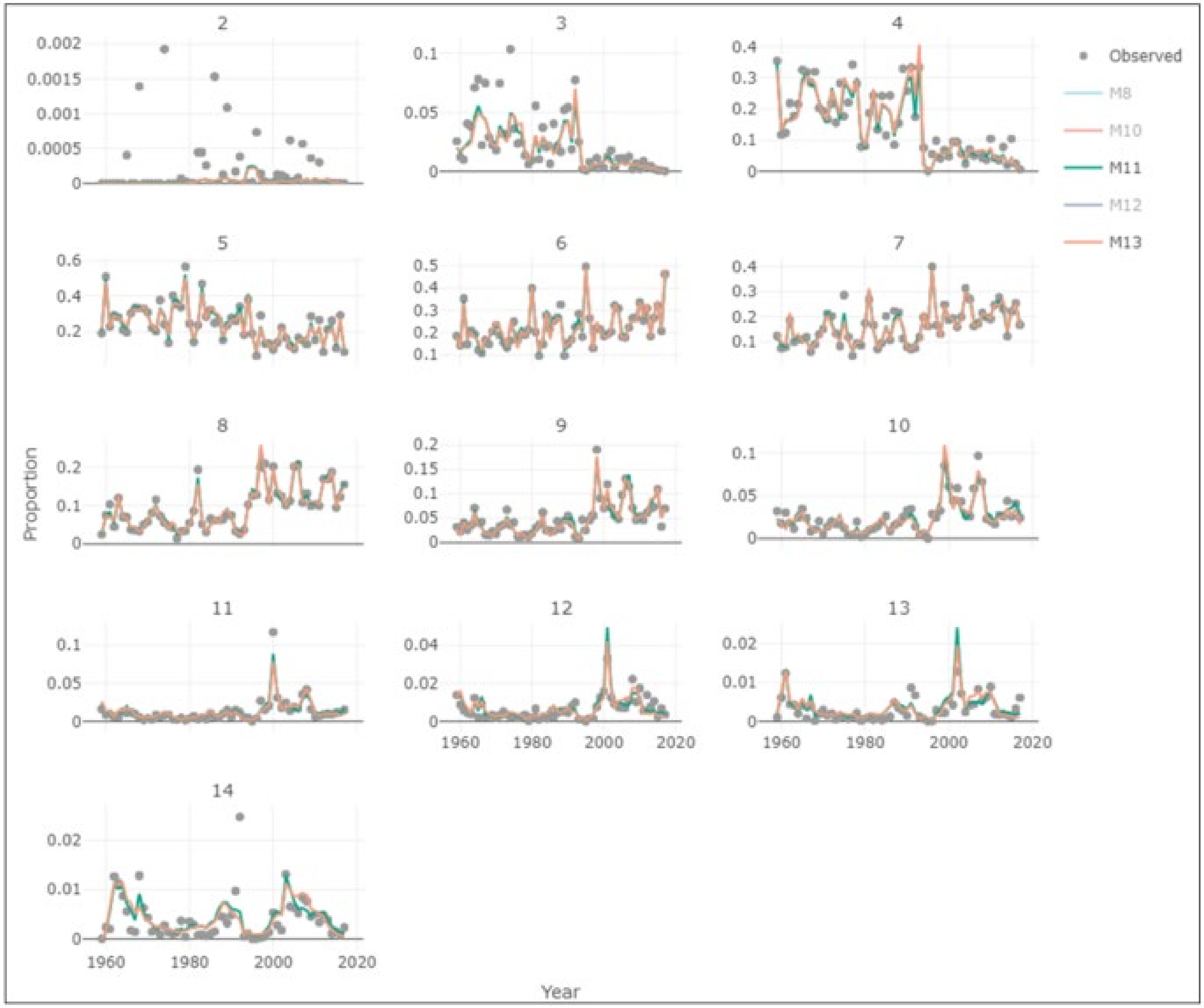


Figure 26. Fisheries catch-at-age fit for model 11.

APPENDIX A: COD HABITAT ASSOCIATIONS IN SOUTHERN NEWFOUNDLAND

Bob Rogers

Quantifying associations between cod catch and environmental data was a multi-step process. The basic premise behind this methodology is to test the differences between two CDFs, one for hydrographic variable (temperature and depth) and one for species catch. First, the hydrographic CDF is constructed (while incorporating the survey design) as:

$$f(t) = \sum_h \sum_i \frac{W_h}{n_h} I(x_{hi})$$

with the indicator function:

$$I(x_{hi}) = \begin{cases} 1, \text{if } x_{hi} \le t; \\ 0, \text{otherwise.} \end{cases}$$

where W_h = proportion of the survey area in stratum h, n_h = number of sets in stratum h, x_{hi} = measurement of hydrographic variable in set i of stratum h, and t = index ranging from the lowest to the highest value of the hydrographic variable at a step size appropriate for the desired resolution (i.e. 0.1°C or 1m). Inclusion of terms (W_h/n_h) to describe the stratification scheme ensured that the estimate of the frequency distribution for the hydrographic variable was unbiased (Perry and Smith 1994). Without the inclusion of the W_h/n_h term, the number of sets allocated per stratum would not be included. This means that analyses would assume that the number of sets allocated to each stratum is proportional to the size of that stratum, which is untrue in this case. While the set allocation in the DFO RV survey is theoretically assumed to be proportional this is not the case in practice due to the minimum sampling requirements of two sets per stratum, which leads to oversampling of small strata relative to large strata. Next, catch-weighted CDF is calculated to associate the number of fish in each set with the hydrographic conditions at that set.

$$g(t) = \sum_h \sum_i \frac{W_h}{n_h} \frac{y_{hi}}{y_{st}} I(x_{hi})$$

Where y_{hi} = number of fish caught in set i and stratum h and y_{st} = estimated stratified mean abundance of fish calculated using:

$$y_{st} = \sum_{h=1}^{L} W_h \, y_h$$

where y_h = estimated mean abundance of fish in stratum h ($y_h = \sum_{i=1}^{n_h} y_{hi} / n_h$; Smith 1990; 1997).

The maximum vertical distance between the hydrographic CDF and the catch-weighted CDF can then be calculated using:

$$D = \max|g(t) - f(t)|$$

$$= \max\left|\sum_h \sum_i \frac{W_h}{n_h}\left(\frac{y_{hi} - y_{st}}{y_{st}}\right) I(x_{hi})\right|$$

where *D* is the test statistic used to determine whether or not the association between hydrographic variables and fish catch is significant (modified Kolmogorov-Smirnov test statistic; Conover, 1980). To test the significance of *D*, Monte-Carlo simulation using randomized pairings of $(W_h/n_h)[(y_{hi} - y_{st})/y_{st}]$ and x_{hi} for all h and i within the survey and then calculating the test statistic for those pairs (Perry and Smith 1994; Rogers et al. 2016). The procedure was repeated K times (generally K>1000) to establish a pseudo-population (*D'*; includes the original test statistic; Rogers et al. 2016) of test statistics. Significance levels were assessed using the formula for Kolmogorov-Smirnov tests:

$$p = \frac{\sum D' \geq D}{K + 1}$$

where *D'* = maximum vertical difference between the randomized curves and *K* = number of times resampling occurred (*K+1* was used to account for the original *D*).

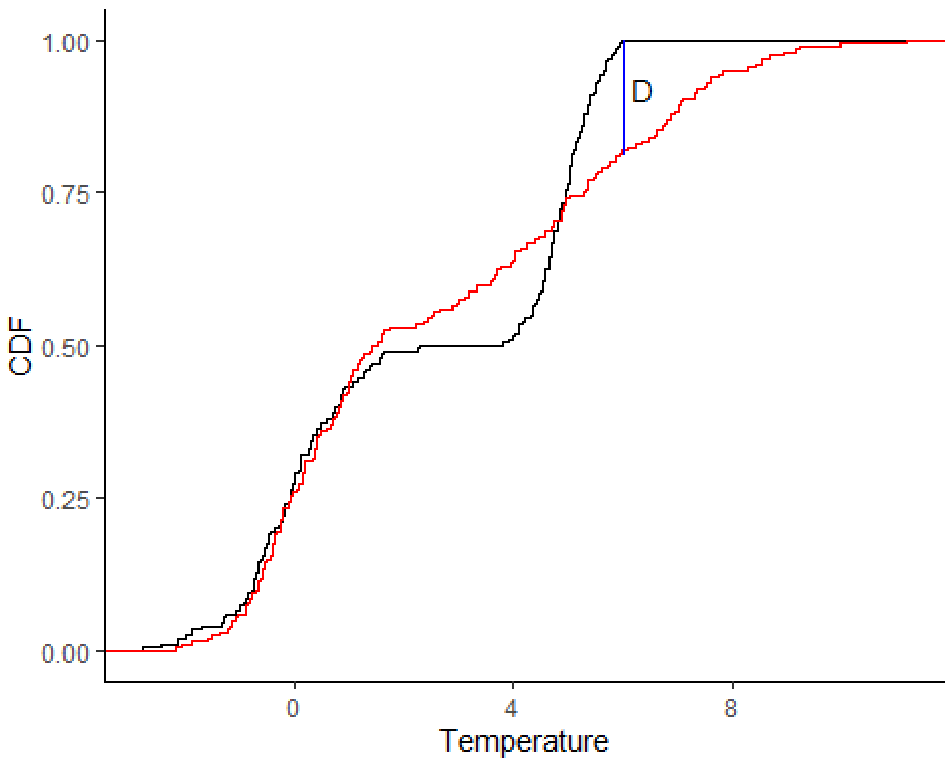


Figure A1. Cumulative distributions of theoretical used (black) and available (red) habitat. Maximum distance between both curves (D) is denoted by blue line.

Using these habitat associations, we can examine annual trends in habitat preference. The preferred temperature occupied shifted considerably in the late-1990s and early-2000s. In ~1998, the median temperature occupied decreased from ~5°C to ~2°C (Fig. A2). This shift occurred nearly simultaneously with a shift in survey design to cover more inshore areas as well as a change in the size-structure of the stock towards smaller fish.

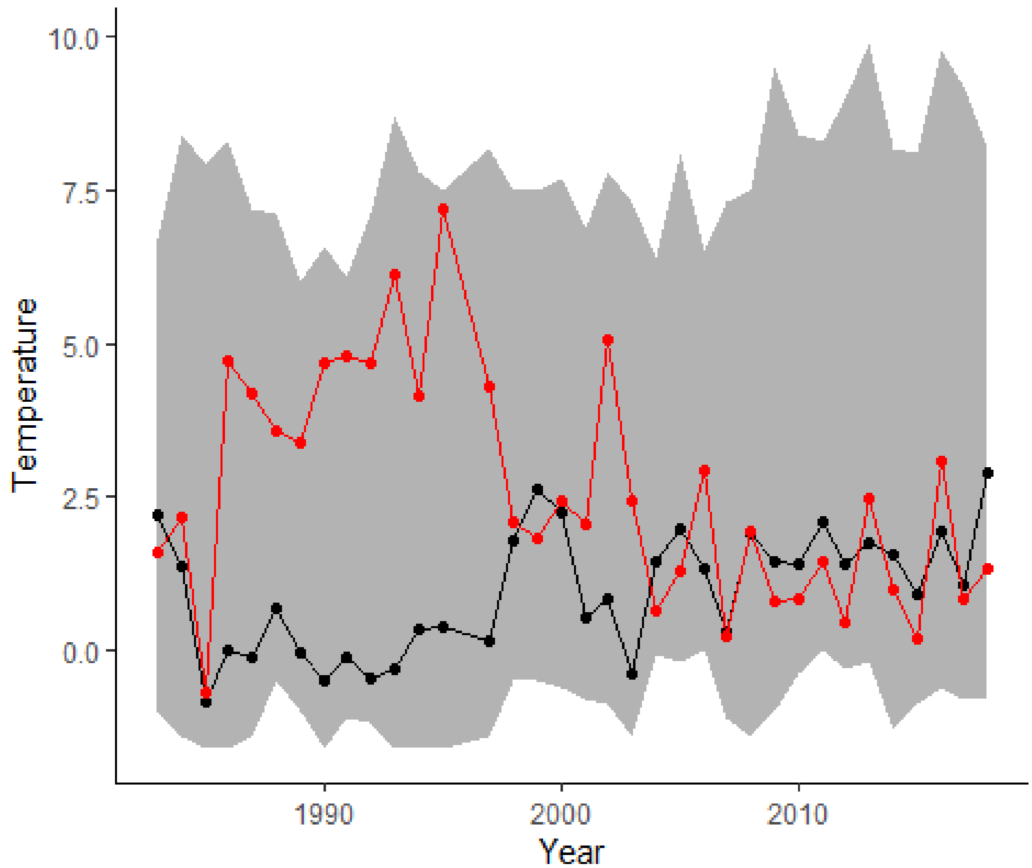
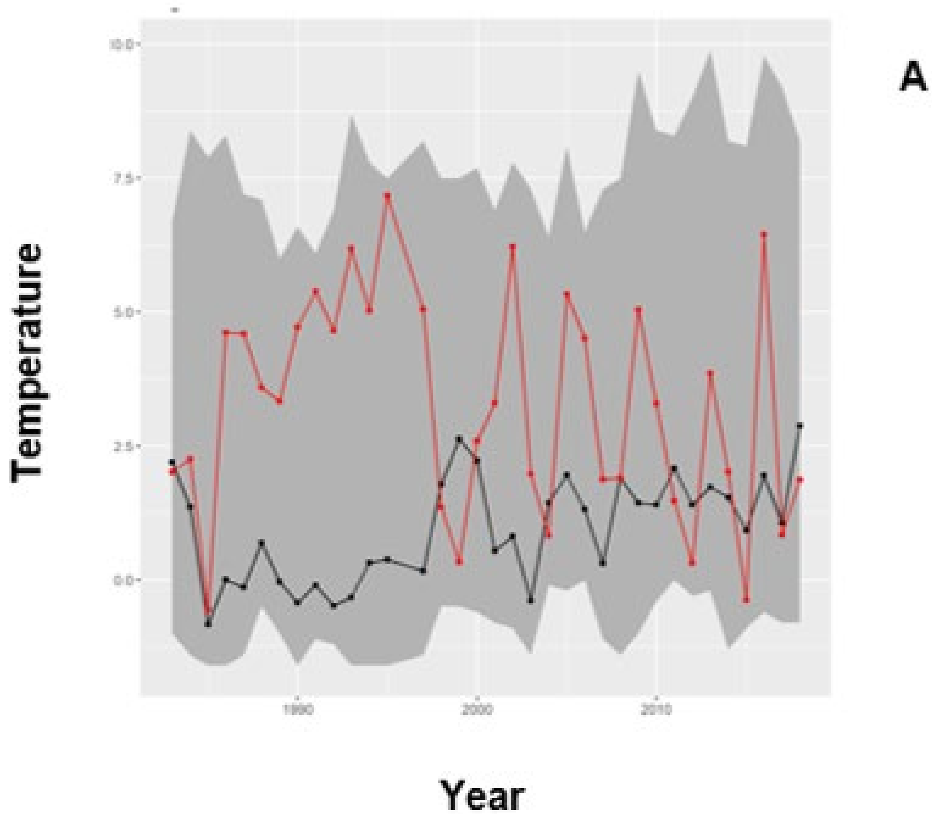
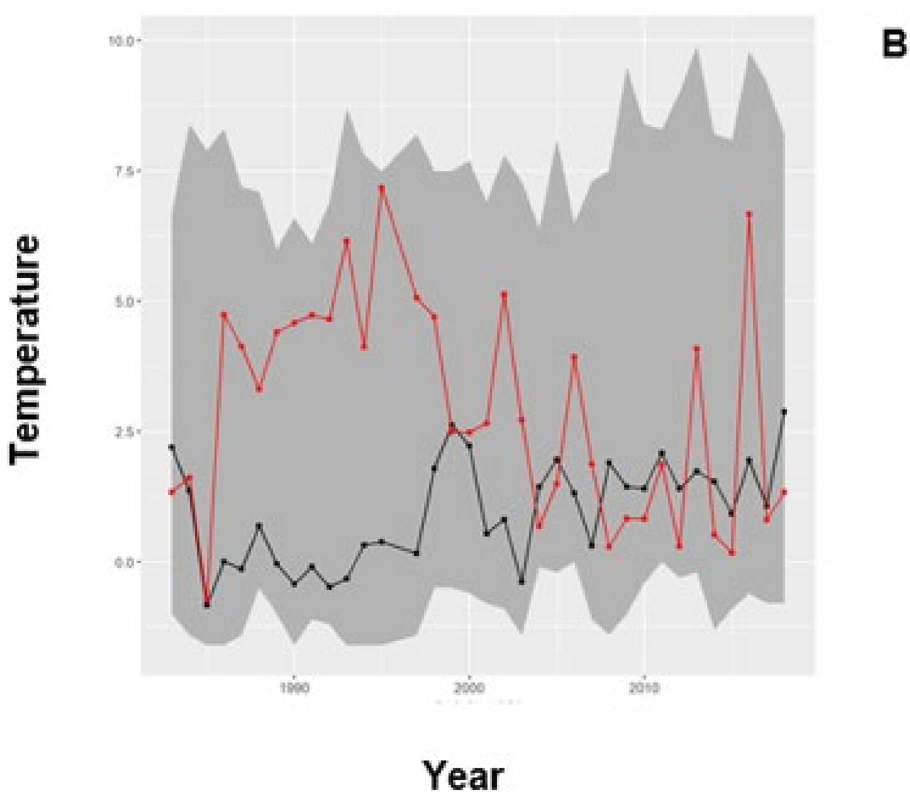


Figure A2. Median temperature used (red) and available (black) for 3Ps cod. Grey polygon illustrates the ranges of temperatures available. Closed circles denote significant habitat associations.

The analysis was repeated by size classes of cod in the survey, small (less than 37 cm), medium (37 to 55 cm) and large (greater than 55 cm), and we found that the results were predominantly driven by the small cod.



A
Temperature
10.0
7.5
5.0
2.5
0.0
1990
2000
2010
Year



B
Temperature
10.0
7.5
5.0
2.5
0.0
1990
2000
2010
Year

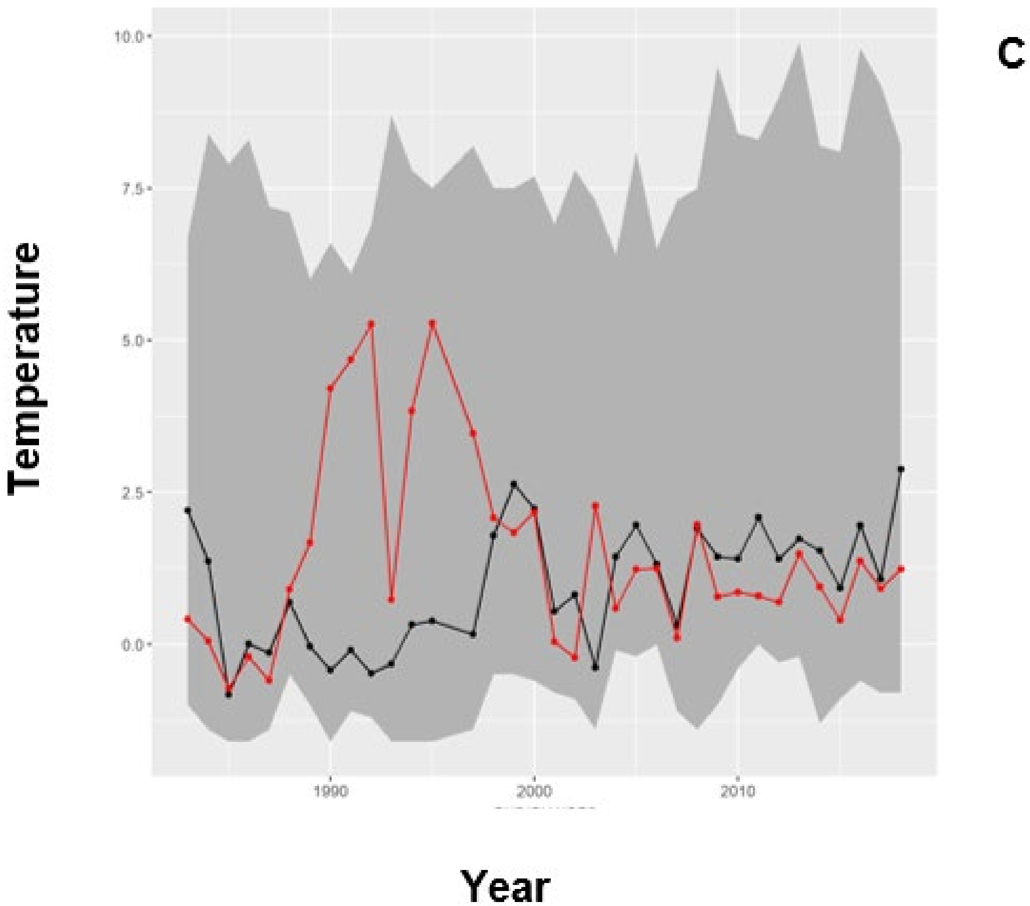


Figure A3. Median temperature used (red) and available (black) for 3Ps cod by size classes. Grey polygon illustrates the ranges of temperatures available. Closed circles denote significant habitat associations. a. Large sized cod, b. medium sized cod, c. small sized cod.

Analysis of the thermal habitat available over time (i.e. the bottom area covered by varying range of temperature) showed warming across all areas in recent years (Figure A4). Prior to 1998, cod seemed to prefer temperature ~3–5°C (yellow band) whereas after 1998, cod seemed to prefer ~1.5–3.5°C (green band).

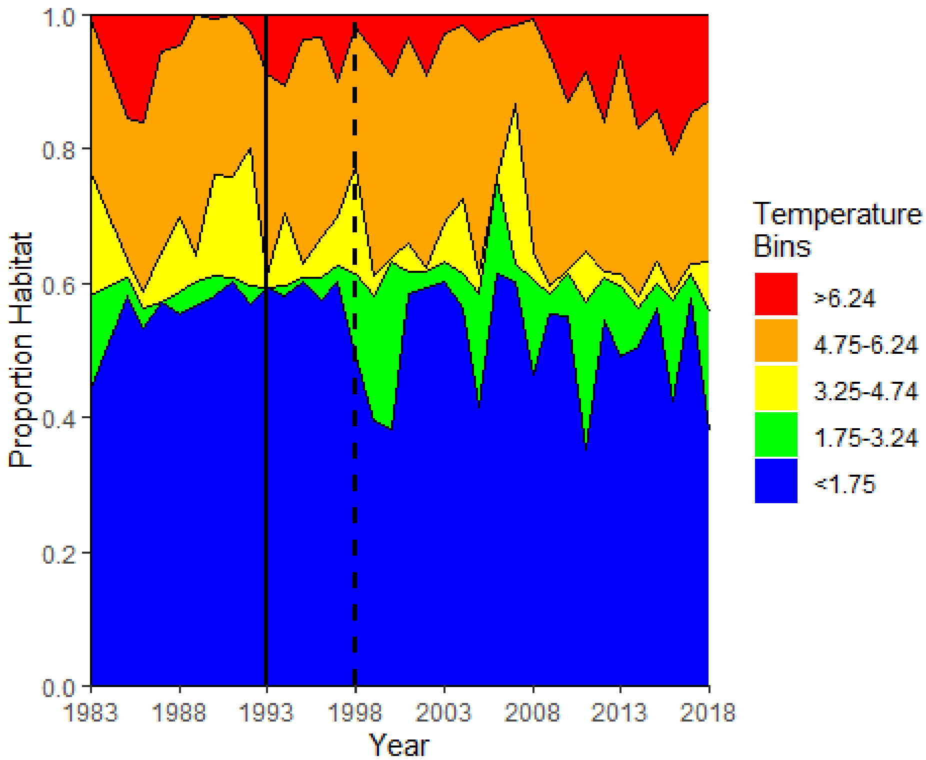


Figure A4. Proportion of available thermal habitat bins. Solid line represents a change from 'winter' surveys to 'spring' surveys and dashed line represents shift in thermal habitat preferences.

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APPENDIX B: TAGGING BASED ANALYSIS OF NATURAL MORTALITY

Greg Robertson

TAGGING DATA FOR 3Ps COD

Tagging has occurred extensively in 3Ps, starting in 1954 (Taggart et al. 1995). Various methods and tag types were used during the period 1954-1996, in 1997 a program involving t-bar Floy tags was established and continues to 2019. Summaries of the current tagging program are available in (Brattey and Healey 2006, Brattey et al. 2008, Brattey 2013, Ings et al. 2019), but in brief it involves tagging cod in batches (experiments), captured generally with handlines (although some offshore tagging was done with modified trawls (Brattey and Healey 2006), with each fish over 45 cm FL receiving a yellow ($10 reward/low reward) or a pink ($100/high reward) tag under the dorsal fin. Tags are deployed in a ratio of 4 yellow for every 1 pink tag deployed. Between 1997 and 2017, 86,638 tags have been deployed in 3Ps, ranging from 395 to 11,211 annually.

To date tagging data has not been directly used in assessments of 3Ps cod, but with the tagging analysis approach developed for Northern cod assessment model NCAM (Cadigan 2016ab), estimates of F and M from the tagging data alone are now possible. Tagging data is able to provide information on F and M when other information is available on various nuisance parameters that can bias estimates of M and especially F. All of these nuisance parameters have been estimated to varying degrees for the Newfoundland cod tagging programs, and methods for incorporating these nuisance parameters into a tagging analysis is described below, largely based on Cadigan (2016ab), and reflects the current approach used in NCAM (Dwyer et al. in press[5]).

APPROACHES BASED ON THE NCAM TAGGING MODULE

Tagged fish are subjected to initial tagging mortality due to the stress of capture and handling in the year of release. In addition, depending on the time of year fish were released and the timing of the fishery only a fraction of *F* and *M* were applied in the year of release; the fraction of fishing that occurred was estimated from a table of monthly landings (Table B1). The population of tagged cod from an experiment diminishes over time due to a combination of initial tagging mortality, tag loss, as well as fishing and natural mortality. For all experiments, irrespective of capture gear type, short-term tagging survival was assumed to be 97% for tag releases in November-June, and 78% for those during July-October (Brattey and Cadigan 2004).Tag loss was estimated using double tagging and applied using Kirkwood's model (Kirkwood 1981) with parameter estimates as described in Brattey and Healey (2007). Harvesters do not return the tags from all they fish that are captured, consequently reporting rates have to be estimated and this was achieved using a high-reward tagging scheme initiated in 1997. Tag reporting rates for Northern cod have been extensively studied (Cadigan and Brattey 2006; Konrad et al. 2016) and for the 1997 experiments onwards, annual reporting rates are estimated using the approach in Konrad et al. (2016). Reporting rates and uncertainties were estimated directly within the NCAM tagging module. This was achieved by considering reporting rates as random effects,

[5] Dwyer, K.S., Healey, B.P., Ings, D.W., Mello, L., Morgan, M.J., Regular, P., Rideout, R.M., Robertson, G., Rogers, R., and L. Wheeland. In press. Assessment of the Northern Cod (*Gadus morhua*) stock in NAFO Divisions 2J3KL in 2019.

and adding a likelihood component for these reporting rates (Cadigan 2016b). The likelihood was based on the externally derived estimates and their estimated covariance matrix using Konrad's et al. (2016) random walk model.

With tag return data, estimates of tag returns in the year of release often differ substantially from the numbers observed and this can be due to a combination of non-mixing of tagged fish and local changes in *F* which is a well-known problem in tagging analyses (Hoenig et al. 1998). The *F* in the release year for each tagging experiment was allowed to vary from the overall stock *F* to account for possible under- or over-exploitation of tagged fish due to incomplete mixing (Cadigan 2016b), this was achieved by including an experiment specific random effect on F in the year of release.

The estimation of the age of tagged fish is described in Cadigan and Konrad (2016), which uses estimates of age-at-length to assign tagged fish of a known length to an age. Similar to NCAM, only experiments with >70 fish tagged in total and only experiments and ages with ≥10 fish tagged were used.

ADDITIONAL MODIFICATIONS FOR 3Ps DATA

NCAM is an integrated population model (IPM) written in TMB (Kristensen et al. 2016). As an IPM, the tagging data is integrated with other data inputs (such as survey indices and catch data), and *Fs* and *Ms* obtained in NCAM use all data sources. To use the tagging data without other data sources for 3Ps, the relevant portions of the script related to the tagging data and the treatments of *F* and *M* were extracted from the NCAM script and repackaged into a stand-alone TMB script (*TagEst*) that accepts only tagging data. To ensure proper functionality of the script, two approaches were used to check that *TagEst* was performing as expected and returning estimates that reflected the input tagging data. The first approach was to run the 2J3KL tagging through *TagEst*, the same data set used in the latest run of NCAM (Dwyer et al. in press[5]). This analysis returned similar estimates of *F* and *M* as the overall NCAM run, especially in terms of patterns of year and age-specific estimates. Identical estimates would not be expected, as NCAM includes other data sources, but overall patterns should be similar due to the tagging data's influence on *F* and *M* (Dwyer et al. in press[5]). The second approach was to simulate tagging data sets with known rates and run those through *TagEst*. *TagEst* generally returned rates similar to the rates used to simulate the data, indicating *TagEst* was functioning as expected. As a further check, a simple Brownie et al. (1985) model was fit to the 3Ps tagging data. This approach was not expected to return similar estimates as *TagEst*, given that the various nuisance parameters are not included in the Brownie models. However, the general patterns in *F* and *M* were similar with both approaches.

One challenge with the 3Ps tagging is the complex stock structure within the division, and linkages with other divisions (notably 3L, 3Pn and 4R) that leads to different fishing pressures across 3Ps (Brattey and Healey 2006, Ings et al. 2019). To address this issue, a fixed effect on *F* was introduced in *TagEst*, with tagging subdivision as the factor (3Psa, 3Psb, 3Psc, 3Psd and 3Psg and 3Psh pooled). The reference level was selected to be 3Psb (Fortune Bay), this subdivision is in the centre of 3Ps, and tags returns from fish released in Fortune Bay appear to well distributed across 3Ps, especially when compared to returns from other sub-subdivisions. Including these fixed effects in *F* for subdivisions appeared to have a number of desirable consequences, including returning realistic values of *M* during periods of limited or exclusively offshore tagging (2004-2006). The choice of subdivision reference level for *F* influenced the overall magnitude of *F*, but generally did not change the annual variation in *F*, and had no appreciable effect on the magnitude and variation in *M*.

Ages were assigned using the same approach used in Cadigan and Konrad (2016), but a suitable fitted age-at-length relationship was not available for 3Ps cod, so data from the adjacent division 3L was used in the interim.

Ages considered in *TagEst* ranged from 4 to 14 (only fish >45 cm FL are tagged, so younger cohorts are not tracked with the tagging data) for F_a, and 4 to 8+ for M_a (similar to NCAM). Age- and year-specific estimates of $F_{a,y}$ and $M_{a,y}$ are calculated, following the same autocorrelation (AR(1) in both years and ages) structure in NCAM. *M* in first year of the time series (1997 in this case) is not estimated but provided as a prior. Since *TagEst* has no information on total population size, weighted annual estimates of F_y and M_y were calculated as means weighted by the numbers of fish of each age captured in that year.

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TABLES

Table B1. Monthly landings of 3Ps cod, 1997-2017, used to assign the remaining amount of fishing pressure experienced by fish first tagged in that year.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1997	25	605	34	9	12	1,666	923	30	2,271	199	1,531	111
1998	15	20	76	228	136	118	3,833	655	3,550	2,523	4,189	514
1999	38	112	119	289	1,859	1,218	3,174	471	3,475	2,408	9,492	1,506
2000	1,573	2,452	1,403	87	86	3,214	1,667	390	2,037	1,204	4,660	922
2001	1,126	572	467	15	89	1,309	1,937	1,117	1,157	1,129	2,879	1,150
2002	805	585	133	33	357	931	2,225	1,384	1,662	1,195	1,697	729
2003	1,003	774	49	19	360	1,127	1,837	814	2,585	816	2,299	625
2004	1,090	510	166	4	352	1,796	1,858	649	613	1,345	1,988	604
2005	514	1,382	330	5	220	1,465	1,647	1,578	877	816	1,928	600
2006	621	755	41	22	486	1,485	1,882	994	912	1,038	1,839	463
2007	525	1,088	22	1	236	2,017	1,968	1,071	906	1,089	1,071	623
2008	834	573	2	15	303	1,702	1,767	410	1,006	1,294	1,334	372
2009	861	1,044	172	25	102	778	1,559	181	569	657	1,276	361
2010	774	782	180	9	62	1,211	1,151	207	328	612	960	370
2011	747	402	160	0	145	778	583	230	778	546	636	421
2012	294	451	41	0	110	801	559	110	345	311	900	332
2013	175	193	44	18	111	591	583	107	143	344	617	133
2014	248	284	217	43	252	877	532	231	348	525	464	792
2015	677	261	475	11	135	368	571	354	435	562	710	562
2016	775	1,008	232	3	127	466	573	258	282	340	827	382
2017	962	637	123	3	129	614	1,061	245	350	601	443	632

FIGURES

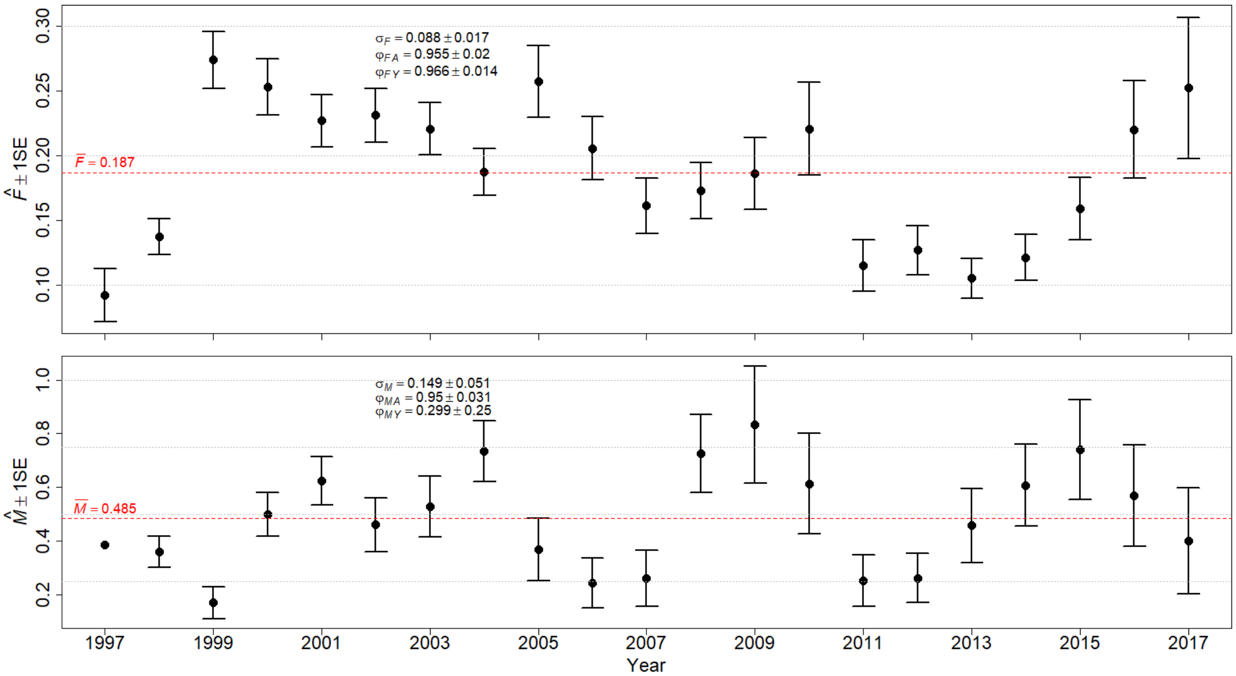

Figure B1. Annual estimates of F and M based on tagging of cod (>45 cm FL) in 3Ps through the period 1997-2017. Methods of estimation are based on the approach used in NCAM (Cadigan 2016ab), and include an AR1 autocorrelation structure on F and M across ages (ϕ_A) and years (ϕ_y). Note that M is not estimated in 1997 (and is not included in the overall mean). Annual estimates are calculated using a weighted mean of annual age-specific estimates, with each age weighted by the number of fish of that age returned that year.

APPENDIX C: FISH CONDITION BASED NATURAL MORTALITY

Paul Regular

BACKGROUND

The ubiquity of starvation and its role in regulating populations has long been recognized, and it remains a central theme in ecology (McCue 2010). For instance, one of the key assumptions behind carrying capacity based models is that individuals die of starvation when the number of individuals in a certain area exceeds the maximum number that area can support (Van Gils et al. 2004). On an individual scale, limited access to food leads to starvation which leads to mass loss as the body utilizes energy sources. Fat is generally oxidized first and once fat reserves are essentially depleted, the body shifts to protein mobilization as the primary source of energy (Bar 2014). For many fish species, protein mobilization cannot be sustained for long periods and laboratory experiments have shown that fish are very likely to die of starvation when their body condition falls below a critical threshold (Bilton and Robins 1973, Dutil and Lambert 2000, Byström et al. 2006). Assessing trends in body condition may therefore provide useful information on starvation based mortality. This was exemplified by experimental work conducted on cod which indicated that fish with Fulton's K values between 0.42–0.67 were very likely to die of starvation (Dutil and Lambert 2000). This result was extended to wild fish to estimate condition-corrected natural mortality by calculating the proportion of fish below a Fulton's K value of 0.65 (Casini et al. 2016). The goal of this work was to extend this concept to 3Ps cod using the extensive sampling data.

SAMPLES

Fisheries and Oceans Canada, NL region, has been collecting an extensive amount of information on the body condition of cod from 3Ps. Specifically, >20 thousand length, weight, gutted weight, gonad weight, age, etc. samples have been collected across a range of months in the DFO RV (1978–2018) and Sentinel (1995–2016) surveys. To explore trends in body condition, the data were restrict to fish with lengths ≥20 cm and length and gutted weight values were used to calculate both Fulton's K ($\mathrm{K} = (\mathrm{W}/\mathrm{L}^3) * 100$) and relative condition ($\mathrm{Kr} = \mathrm{W}/\mathrm{W}'$, where *W'* is predicted gutted weight from a regression of log gutted weight as a function of log length; Le Cren 1951). The length cut-off was used to limit issues associated with the weights of fish smaller than 20 cm and condition was based on gutted weight to obtain a less variable assessment of the condition of an individual's protein reserves (Dutil and Lambert 2000). See Table C1 and C2 for details on the sample sizes by year and month from the DFO RV and Sentinel surveys, respectively.

Table C1. Number of length and gutted weight samples, by year and month, from the DFO RV survey of 3Ps.

-	1	2	3	4	5	6	8
1978	0	108	0	0	0	0	0
1979	0	127	16	0	0	0	0
1980	0	0	162	1	0	0	0
1981	0	0	148	0	0	0	0
1982	0	0	0	0	93	61	0
1983	0	0	0	175	14	0	0
1984	0	0	0	140	0	0	0
1985	0	0	84	0	0	0	0

-	1	2	3	4	5	6	8
1986	0	0	139	0	0	0	0
1987	0	231	1	0	0	0	0
1988	2	233	0	0	0	0	0
1989	0	335	0	0	0	0	0
1990	0	582	0	0	0	0	0
1991	0	759	0	0	0	0	0
1992	0	552	0	0	0	0	0
1993	0	370	0	996	0	0	0
1994	0	0	0	572	0	0	24
1995	0	40	134	586	0	0	9
1996	0	84	0	805	4	0	7
1997	0	0	0	479	0	0	0
1998	0	0	0	623	91	0	0
1999	0	0	0	407	384	0	0
2000	0	0	0	857	119	0	27
2001	0	0	0	971	0	0	0
2002	0	0	0	581	0	0	0
2003	0	0	0	961	0	0	0
2004	0	0	0	367	193	0	0
2005	0	0	0	440	127	0	0
2006	0	0	0	237	0	0	0
2007	0	0	0	477	67	0	0
2008	0	0	0	220	363	0	0
2009	0	0	0	447	186	0	0
2010	0	0	0	317	127	0	0
2011	0	0	0	316	200	0	0
2012	0	0	2	1,284	0	0	0
2013	0	0	255	244	0	0	0
2014	0	0	0	315	162	0	0
2015	0	0	0	247	197	0	0
2016	0	0	0	384	0	0	0
2017	0	0	0	287	179	0	0
2018	0	0	0	64	406	0	0

Table C2. Number of length and gutted weight samples, by year and month, from the Sentinel survey of 3Ps.

-	1	2	3	4	5	6	7	8	9	10	11	12
1995	0	70	243	360	641	398	119	0	66	356	448	199
1996	161	47	0	0	0	0	109	15	105	195	121	109
1997	33	21	9	0	19	0	56	0	89	71	195	170
1998	74	31	0	0	0	232	123	194	81	19	29	209
1999	165	9	0	0	0	0	0	0	0	0	0	0
2000	108	63	29	0	38	20	70	51	18	57	98	80
2001	33	43	2	48	9	10	79	105	20	30	153	94
2002	53	33	0	0	0	21	84	93	88	45	120	98
2003	34	0	0	0	0	0	28	23	15	18	79	72
2004	0	0	0	0	0	3	63	12	0	20	92	67
2005	62	0	0	0	0	5	25	24	0	20	193	57
2006	42	0	0	0	0	0	52	16	20	15	178	71
2007	45	0	0	0	0	0	36	16	7	45	87	70

-	1	2	3	4	5	6	7	8	9	10	11	12
2008	46	0	0	0	0	20	22	24	16	34	87	93
2009	30	0	0	0	0	15	18	23	23	37	77	66
2010	28	0	0	0	0	3	0	44	110	61	102	71
2011	28	0	0	0	83	62	20	32	0	117	78	22
2013	26	0	0	0	0	41	23	15	60	58	93	48
2015	0	0	0	0	13	29	0	0	21	59	59	69
2016	0	0	0	0	10	31	11	0	11	67	93	28

MODELLING CONDITION

One of the key challenges with applying the method described in Casini et al. (2016) is that it requires survey data with consistent temporal coverage as there are seasonal trends in the growth of cod. Unfortunately, the timing of the 3Ps survey has shifted, precluding the use of the whole time series. A seasonal model was therefore developed to utilize all data spread across months. The model estimates seasonal trends in condition using an AR1 process across time and length group:

$$k_{t,l} = \phi_1 k_{t-1,l} + \phi_2 k_{t-12,l} + \xi_{t,l}; \text{ where } \xi_{t,l} \sim N(0, \Sigma_{l,l})$$

where the covariance matrix, $\Sigma_{l,l}$, is defined via the standard deviation for the process, σ_k, and the correlation coefficient, ρ, as a function of difference in length groups, specifically $\Sigma_{l,l} = \rho^{|l-l|}\sigma_k\sigma_k$. Note that if there is only one length group, ρ does not need to be estimated and the multivariate normal reduces to a standard normal distribution. In short, this formulation implies that last year's and last month's condition is a predictor of current condition. In addition to the seasonality estimated by this AR1 process, a harmonic effect can be applied to estimate a consistent seasonal pattern in condition through time:

$$h_t = \beta \cos\left(\frac{2\pi t}{12}\right) + \gamma \sin\left(\frac{2\pi t}{12}\right)$$

The AR1, $k_{t,l}$, and harmonic, h_t, components are added to a baseline level of condition, α_μ, to estimate the underlying mean condition, $\mu_{t,l}$:

$$\mu_{t,l} = \alpha_\mu + k_{t,l} + h_t$$

note that α_μ is fixed to 1 if modeling relative condition, Kr. Observed condition values, K or Kr, are a modeled as a function of $\mu_{t,l}$ with a random effect for set:

$$K_i = \mu_{t,l} + \delta_s + \varepsilon_i; \text{ where } \delta_s \sim N(0, \sigma_s^2) \text{ and } \epsilon_i \sim N(0, \sigma_K^2)$$

where *s* represents a set identifier and *i* represents each observation.

In addition to changes in mean condition, there may be natural variation in the variation around the mean (i.e. a wider range of condition values may be observed in some years while in other years observed condition values may be more tightly clustered around the mean). A stochastic volatility component was also added to the model to address potential changes in the variance:

$$v_t = \alpha_v + \varphi(v_{t-1} - \alpha_v) + \varepsilon_t \quad \text{where} \quad \varepsilon_t \sim N(0, \sigma_v^2)$$

this models changes in variance over time in log space and v_t values are exponentiated to obtain σ_K.

Overall this formulation provides a flexible framework for modeling seasonal changes in condition. This model was written using TMB (Kristensen et al. 2016). A series of variations of this model was tested and model selection was conducted using a combination of marginal AIC (Akaike 1974) and BIC (Schwarz 1978).

ESTIMATING CONDITION-CORRECTED NATURAL MORTALITY

Given the model estimates of mean condition $\mu_{t,l}$ and the standard deviation σ_K around the mean, the probability of being below a critical threshold can be calculated for each month and length group. This proportion can be converted to instantaneous rates per month, which are subsequently summed within a year to obtain annual instantaneous rates of condition-based mortality. These estimates are added to a baseline of 0.2 for sources of mortality other than starvation to obtain estimates of condition-corrected mortality.

To avoid issues with bias in Fulton's K by length group, relative condition values were used in the model. This, of course, precluded the use of the 0.65 Fulton's K based threshold used in Casini et al. (2016), however, we used a relative condition based threshold of 0.85 which, on average, corresponds to the relative condition of fish with a Fulton's K value of less than 0.65.

RESULTS

Table C3. Information criteria for a range of models fit to cod condition data, where n represents the sample size, K is the number of fixed parameters, $log(L)$ is the negative log likelihood, AIC is the marginal Akaike information criterion, BIC is the marginal Bayesian information criterion, and ΔAIC and ΔBIC are differences from their lowest value.

Model	n	K	log(L)	AIC	BIC	ΔAIC	ΔBIC
No harmonic	31402	8	-33239.2	-66462.4	-66395.6	1.5	0.0
No stochastic volitility and no harmonic	31402	6	-33226.5	-66441.0	-66390.8	22.9	4.7
Full model	31402	10	-33242.0	-66463.9	-66380.4	0.0	15.2
No stochastic volitility	31402	8	-33229.2	-66442.3	-66375.5	21.6	20.1
No dependence on last month	31402	9	-33204.5	-66391.1	-66315.9	72.8	79.7
No stochastic volitility and no dependence on last month	31402	7	-33192.0	-66370.0	-66311.6	93.9	84.0
No dependence on last year	31402	9	-33119.7	-66221.3	-66146.1	242.6	249.4
No stochastic volitility and no dependence on last year	31402	7	-33101.2	-66188.4	-66130.0	275.5	265.6

The "No harmonic" model was considered the most parsimonious as it received the lowest BIC score and an AIC score that is essentially the same as the AIC score from the "Full model". Moreover, the harmonic may be a redundant effect that is addressed by the seasonal AR1 that assumes dependence on the previous month and year. Given the relative rankings, there appears to be strong support for the estimation of ϕ_2 (i.e. dependence on last year). Diagnostics from the “No harmonic” model are presented below.

Table C4. Fixed parameter estimates from the “No harmonic” model.

Description	**Symbol**	**Estimate**	**CV**
Correlation with previous month	ϕ_1	0.16	0.20
Correlation with previous year	ϕ_2	0.83	0.20
Correlation across length groups	ρ	0.74	0.23
Baseline standard deviation	$\exp(\alpha_v)$	0.08	0.01
Weight placed on previous residual from baseline standard deviation	φ	0.45	0.53
Standard deviation of the seasonal process	σ_k	0.02	0.07
Standard deviation of set deviations	σ_s	0.03	0.03
Standard deviation of stochastic volatility process	σ_v	0.05	0.17

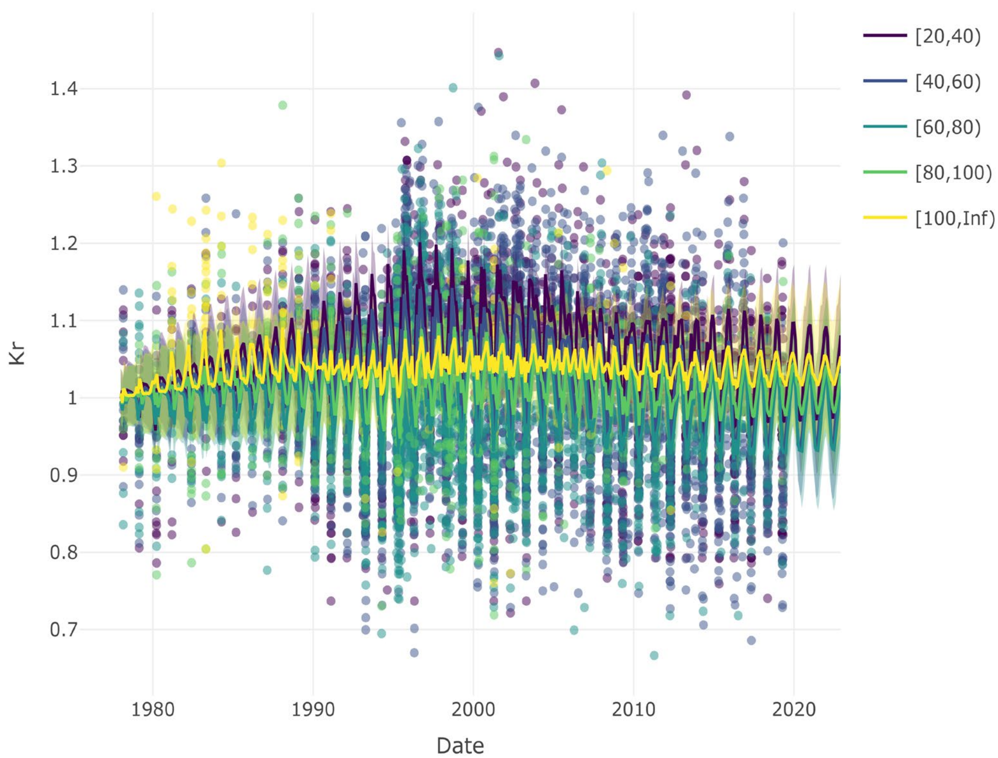

Figure C1. Observed and predicted values of relative condition.

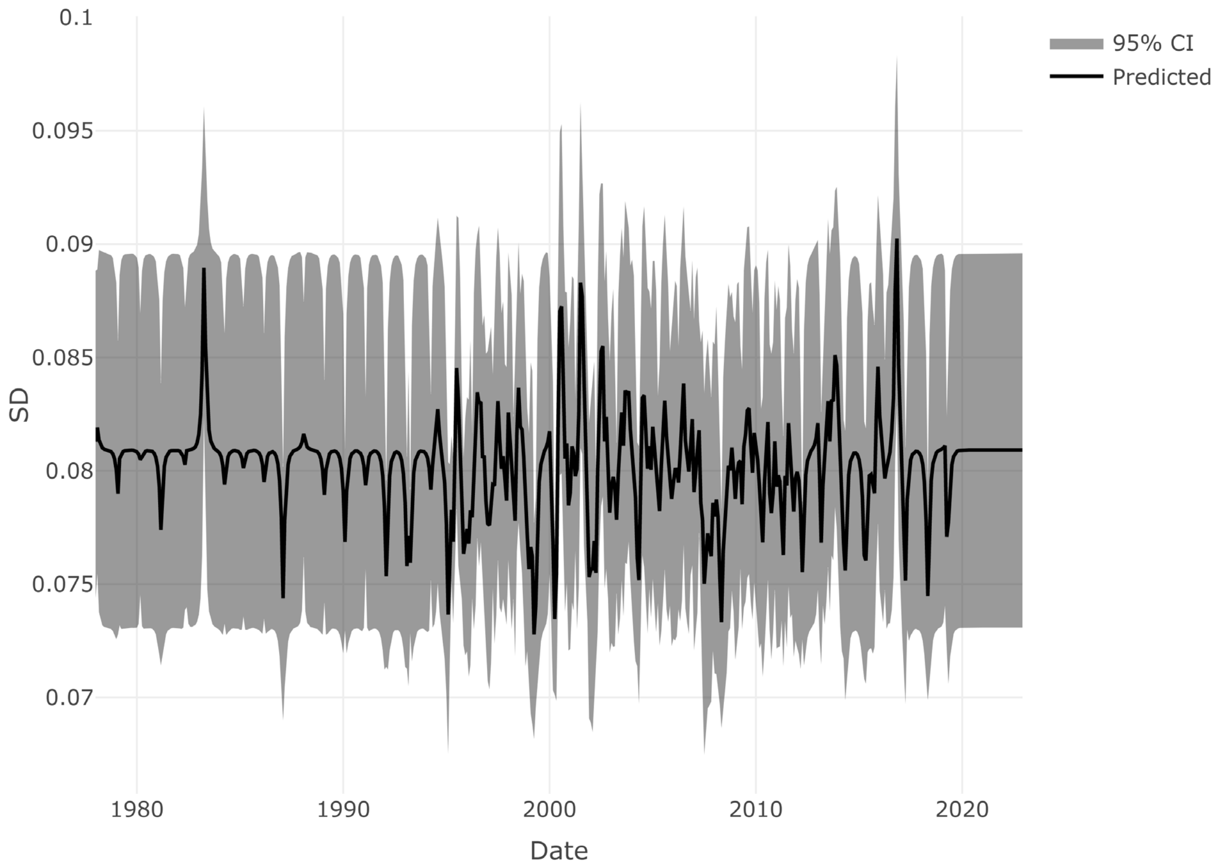

Figure C2. Stochastic volatility.

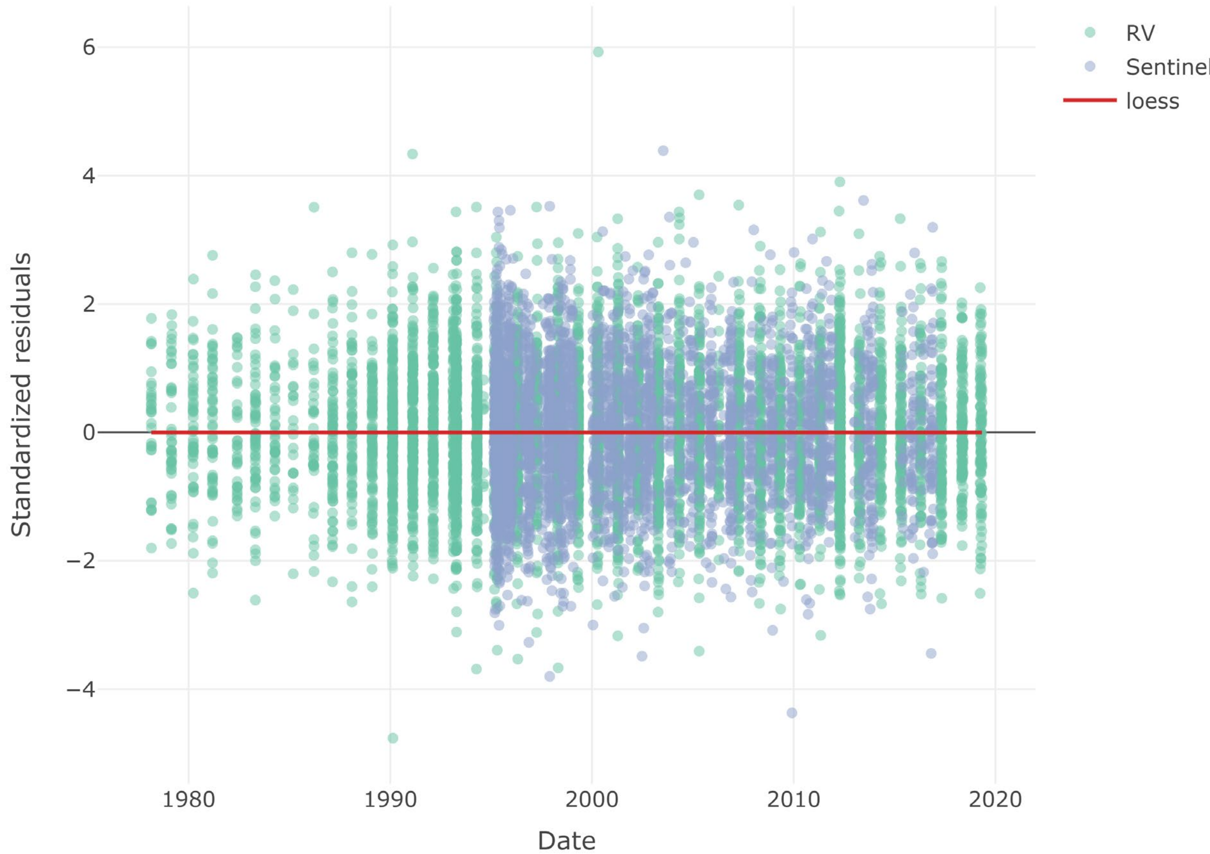

Figure C3. Residuals by date.

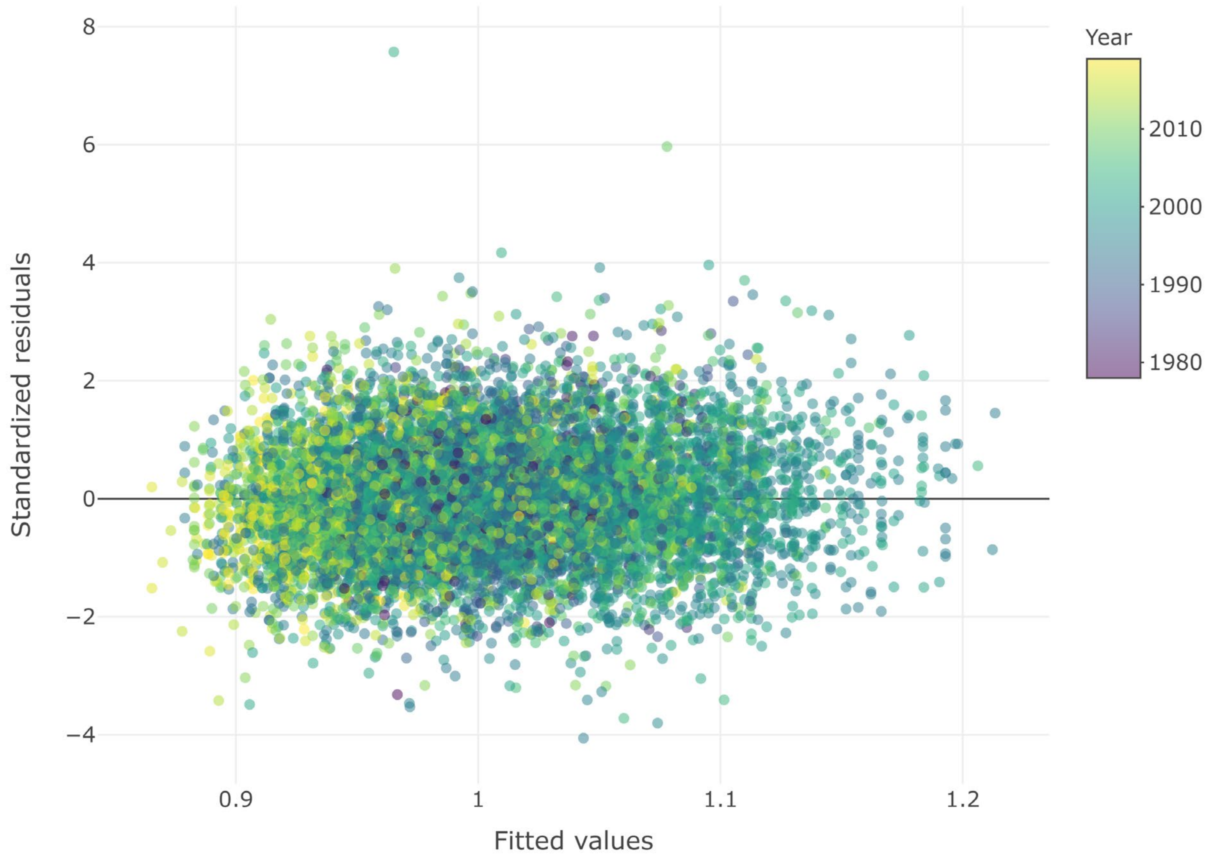

Figure C4. Residuals vs fitted values.

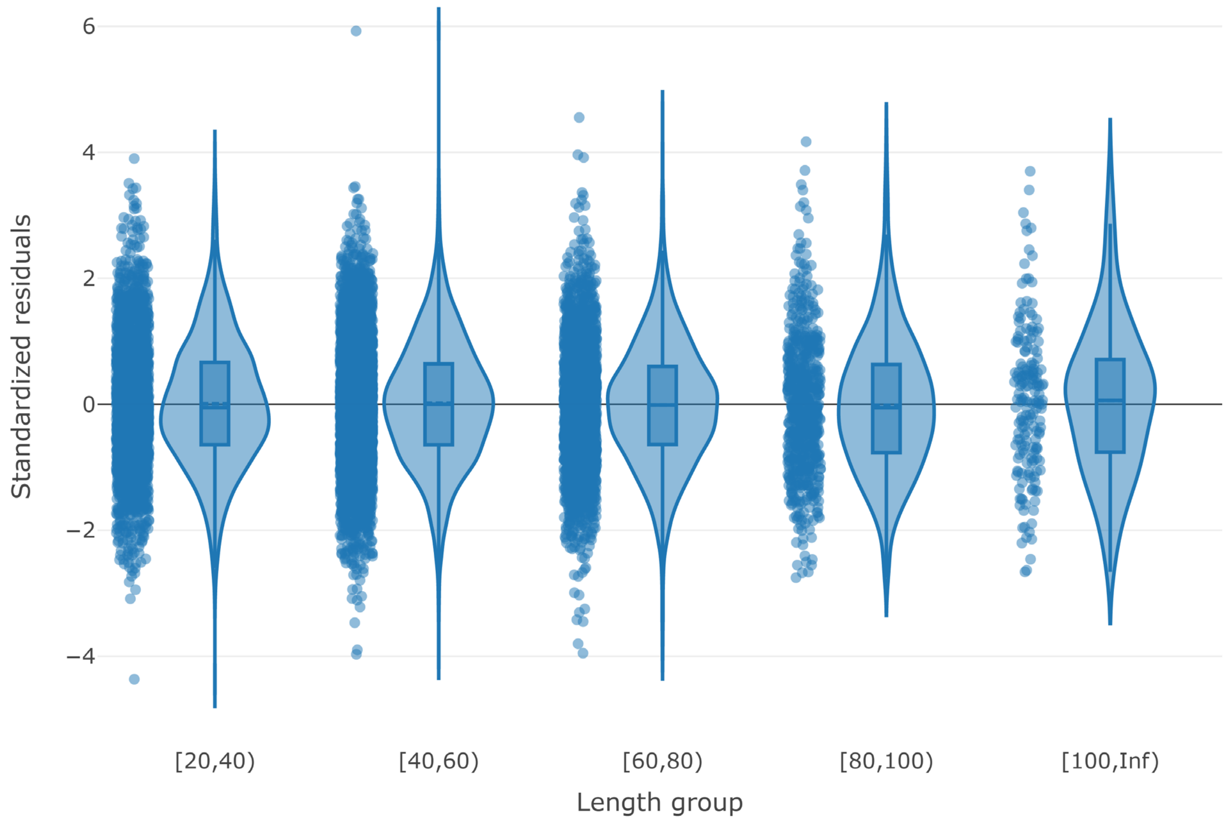

Figure C5. Residuals by length group.

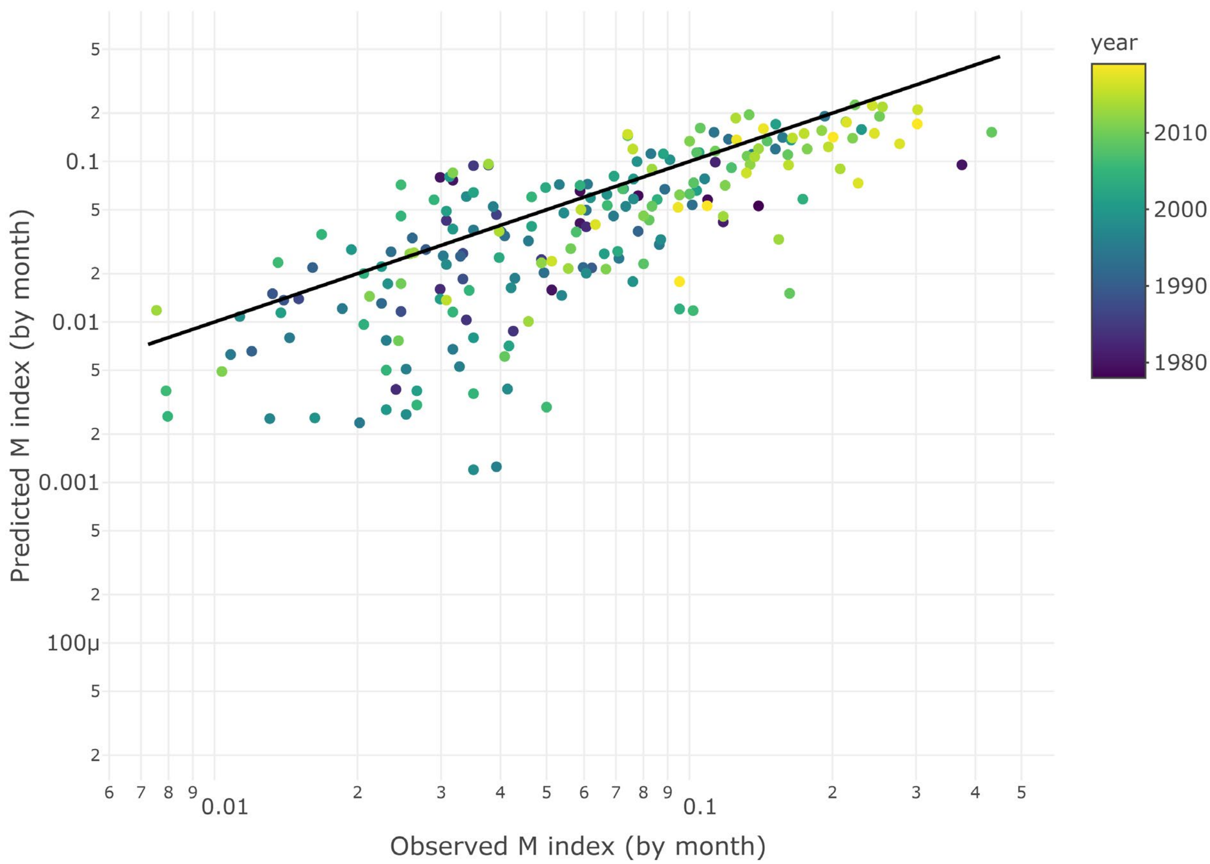

Figure C6. Observed and predicted M index by month. Observed values are generated from raw proportions below the threshold.

COMPARISON WITH TAGGING BASED ESTIMATES

Condition-corrected estimates of natural mortality, from a model run estimating an average trend across all lengths, were regressed against estimates of average natural mortality using data from the tagging program. As there is uncertainty in the estimates from both approaches, regressions were run using the best-fit straight line package (Sturm 2018).

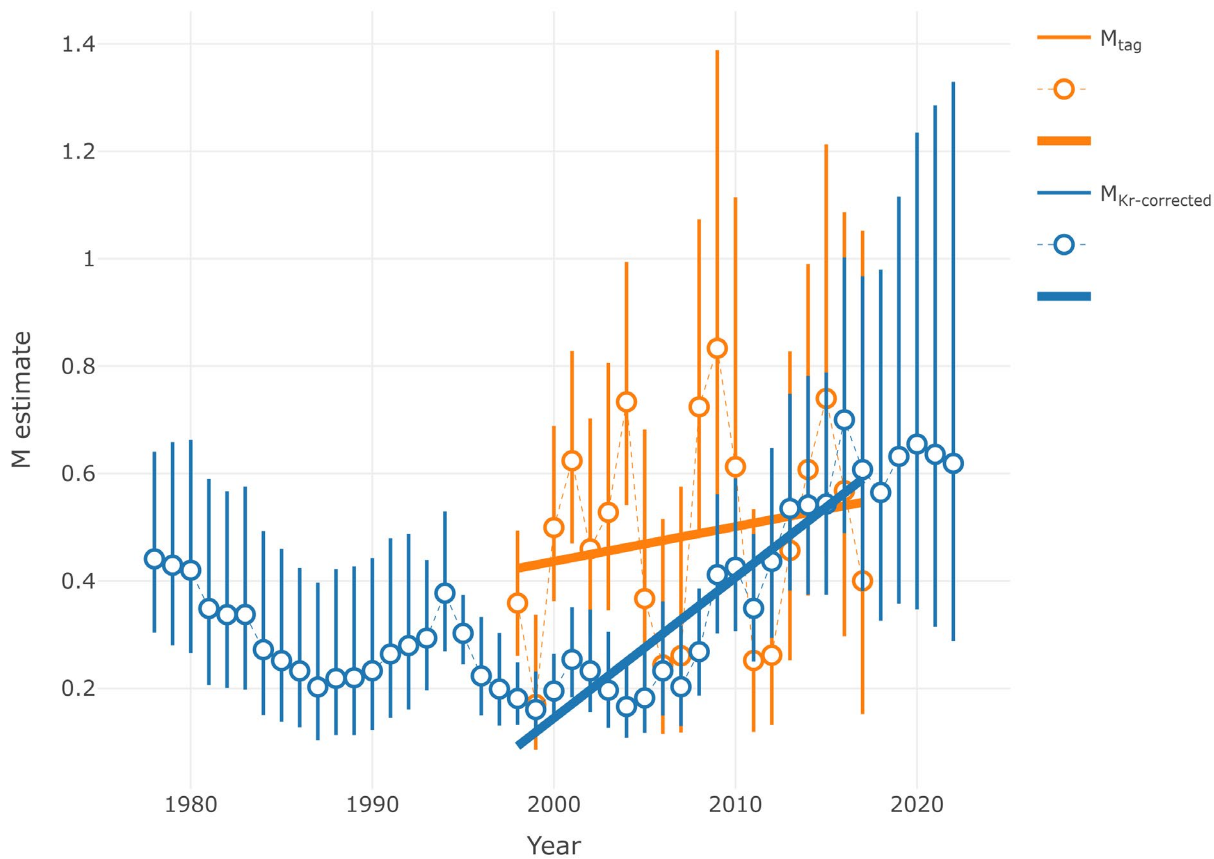

Figure C7. Trends in mean estimates of M from the tagging data and condition data.

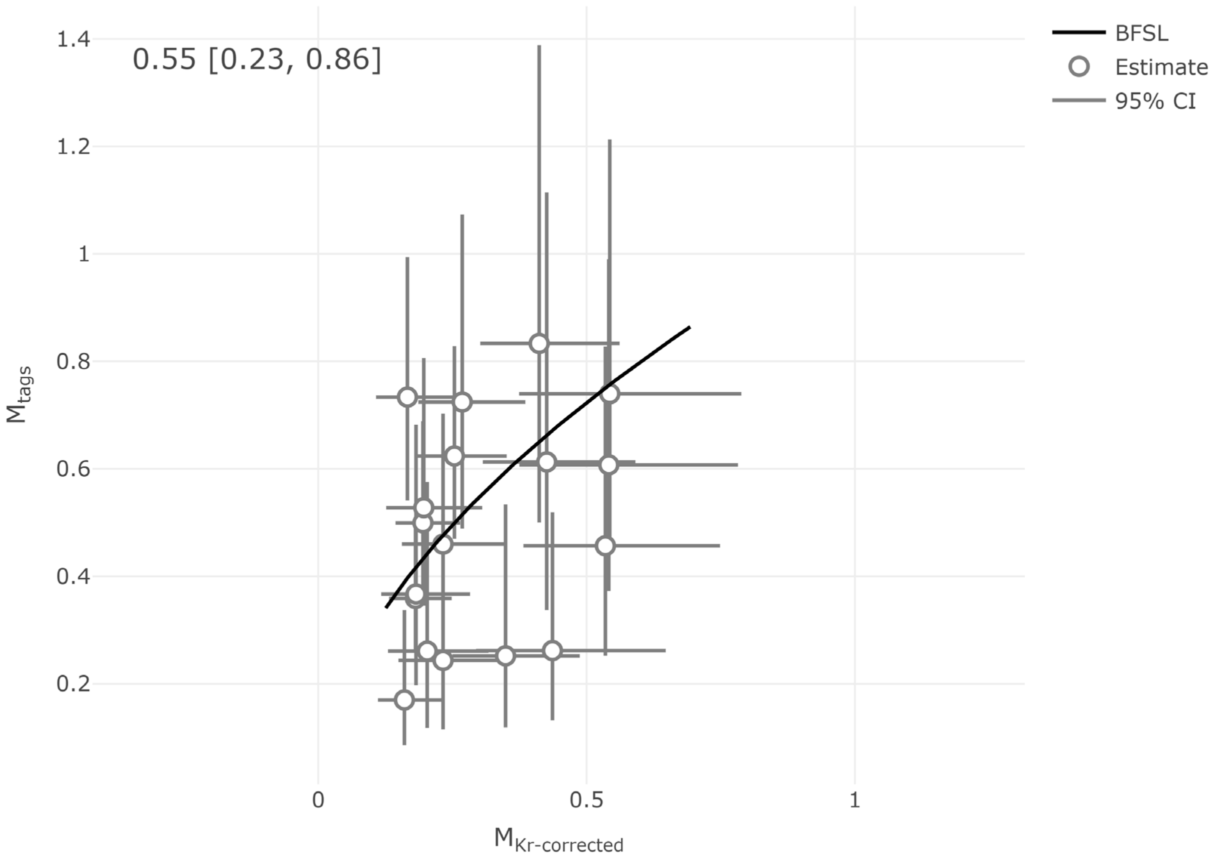

Figure C8. Comparison of mean estimates of M from the tagging data and condition data. Estimates from 2016 and 2017 were excluded as there is little data to inform tagging-based M in the most recent years. The slope estimate from the best-fit straight line regression is presented in the top left corner along with 95% confidence intervals in square brackets.

CONCLUSIONS

The number of cod in poor condition has been increasing in recent years (since ~2004) and many of these cod may have died of starvation. Assuming the critical threshold of Kr <0.85 is reasonable, the magnitude of natural mortality from starvation could be considerably higher than 0.2 in some years. An analysis of data from the tagging program indicate that natural mortality from all sources can be high and variable (~ 0.2–0.8), and correspondence between these estimates and condition-corrected natural mortality suggest that starvation may be a large component of death from natural causes. Overall these results imply that prey availability may be a factor limiting the productivity of cod in 3Ps.

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