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Atlantic mackerel (*Scomber scombrus* L.) in NAFO Subareas 3 and 4 in 2018

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Foreword

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

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ABSTRACT

The status of the northern contingent of Northwest Atlantic (NWA) mackerel (*Scomber scombrus* L.) is assessed every two years using an age-structured stock assessment model that explicitly accounts for missing catch statistics from Canadian and American fleets. This document presents the data and methods used to calculate the main stock status indicators that inform Fisheries Management in the setting of quotas (i.e. Total Allowable Catch; TAC), potentially as part of Harvest Control Rules (HCR). This document also provides a review of research pertaining to mackerel distribution and how changing environmental conditions influenced mackerel recruitment, condition and distribution of landings throughout the fishing season. This stock assessment indicates that in 2018, mackerel were still within the Critical Zone as per Canada's Precautionary Approach (PA) framework and have been since 2011. While there was a slight increase in SSB from 2016 to 2018 due to the arrival of the 2015 year class into the fishery, mackerel numbers have actually decreased. Low biomass is accompanied by overexploitation, the loss of older individuals from the population, and in the last two years, historical low recruitment. Short term projections over three years indicate that there is a 48% chance of leaving the Critical Zone by 2021 under a TAC of 10 000 t. Even under the most restrictive exploitation scenarios (e.g. TAC = 0 t), there is only a 68% chance of leaving the Critical Zone by 2021.

INTRODUCTION

This research document provides a description of the data, methods, and supporting analyses contributing to the stock assessment of the northern contingent of the Northwest Atlantic mackerel stock (*Scomber scombrus L.;* henceforth mackerel). This assessment is performed every two years by Fisheries and Oceans Canada (DFO) at the Maurice Lamontagne Institute in Mont-Joli Québec. To move towards an ecosystem approach to stock assessments, a review of the research pertaining to mackerel ecology was carried out to support new analyses linking mackerel condition and distribution to changes in their physical and biological environment.

Beginning with the previous assessment (DFO 2017, Doniol-Valcroze et al. 2019), stock status has been evaluated via a censored-catch-at-age stock assessment model (CCAM; Van Beveren et al. 2017a). The model uses both fisheries-independent (biomass index) and fisheries-dependent data (landings and catch-at-age) as input and can estimate both current and future stock status indices such as spawning stock biomass (SSB) and age-1 recruitment. The biomass index is derived from an annual egg survey (1979-2018) that covers the main mackerel spawning site, i.e.. the southern Gulf of Saint-Lawrence (GSL). Fisheries-dependent data includes catch statistics and biological samples acquired from the commercial mackerel fishery. Environmental data and biological samples are also obtained through DFO’s annual research vessel surveys in conjunction with the Atlantic Zonal Monitoring Program (AZMP; DFO 2019a). Additional sources of data and knowledge have come through peer reviewed literature as well as through consultation with and surveys carried out in collaboration with the industry, First Nations, and members of the mackerel Rebuilding Plan Working Group (RPWG).

All results herein were peer reviewed and the main results were incorporated into the Science Advisory Report (DFO 2019b). The results also served as basis for a Management Strategy Evaluation (MSE) framework that has been developed (Van Beveren et al. DFO, Mont-Joli, Qc, pers. comm.) to assist Fisheries Management and other stakeholders to evaluate the optimal trade-offs of different HCRs under a variety of uncertainties.

METHODS

LANDINGS

Commercial fisheries data for mackerel caught in Canada’s Exclusive Economic Zone (EEZ; NAFO Subareas 2-4) were acquired from the most recent ZIFF (Zonal Interchange File Format) files produced by DFO’s regional statistics bureaus for the years 1995-2018. Inconsistencies in landings data exist prior to 1995 due to the historic presence of foreign fishing vessels targeting mackerel, undocumented ship to ship sales, the allocation of quota to foreign vessels, and the chartering of foreign vessels by local stakeholders. To resolve these issues, we used commercial fisheries data for mackerel landings within Canada’s EEZ from the Northwest Atlantic Fisheries Organisation landings database for the years 1960-1994 (Grégoire et al. 2000, 2014). At the time of this assessment, landings data for the 2017 and 2018 fishing seasons were still preliminary as landings data were still being compiled by the various DFO regions exploiting mackerel (i.e. Québec, Gulf, Maritimes, and Newfoundland regions; Figures 1 and S1).

Data from the U.S. commercial and recreational fisheries (1960-2017) were provided by the Northeast Fisheries Science Center (NEFSC). Due to the 2018-2019 U.S. government shutdowns, leading to the temporary closure of the National Oceanic and Atmospheric Administration (NOAA), U.S. catch statistics were also preliminary for 2017 and 2018.

COMMERCIAL SAMPLING

Mackerel are monitored annually through DFO's commercial port sampling program. Length measurements and biological samples are collected throughout Eastern Canada covering the entire fishing season to ensure adequate spatio-temporal coverage (Tables S5-6). Port samplers provide length frequency data (measured to the nearest 5 mm) and a subsample (two fish per length-class) are sent to the Maurice Lamontagne Institute in Mont-Joli Québec for further analyses. The measurements taken of these subsamples include: fork-length (± 1 mm), mass (± 0.1 g), sex, gonad mass, stage of development, and age via extraction and examination of otolith structure. The latter measure has been the subject of a comparison with NOAA's stock assessment biologists (Grégoire et al. 2009b).

CATCH-AT-AGE

Catch-at-age was formerly calculated using a Visual Basic program developed at the Maurice Lamontagne Institute in 2011-2012 based on methods and equations detailed in Gavaris and Gavaris (1983). This procedure was rewritten in the R programming language (R Core Team 2019) using the same equations, as well as procedures described by Ogle (2015). Briefly, to estimate catch-at-age and the corresponding weight-at-age, biological samples were grouped by year, quarter (aggregated in 3 month blocks), NAFO Division, and gear type to produce age-length-keys. Ages were then assigned to the corresponding unaged length frequency data as per methods described in Kimura (1977), Isermann and Knight (2005), and Ogle (2015). Individual weights were assigned to the length frequency data based on predicted weight-length relationships for each year and quarter. The merged biological sample and length frequency data were then weighted by the regional (NAFO division) and quarterly landings, as well as by gear type (grouped by selectivity category). Time, space, and gear specific information was then averaged to obtain the annual catch-at-age (numbers of individuals) and their corresponding mean lengths and weights. Annual catch weight-at-age (biomass), the product of catch-at-age and weight-at-age, was then compared to commercial landings to detect possible grouping or weighting errors. In the event that no length frequency data and/or biological data was available for a given region, quarter, or gear type, age-length-keys corresponding to data from adjacent regions, quarters, or similar gear types were used instead.

MATURITY-AT-AGE

Maturity-at-age, that is the proportion of mature females at a given age, was calculated from commercial samples collected during spawning (June-July). Maturity ogives were also used to estimate maturity-at-length (L_{50}) were formerly calculated using the *Logistic* and *Probit* functions in SAS (v. 9.3; SAS Institute Inc. 2011). These procedures were rewritten in R whereby logistic regressions using a logit link family function were subsequently calculated. L_{50} were then extracted from the fitted models and were bootstrapped over 999 iterations using the 'modelr' package in R to produce 95% confidence intervals (Wickham et al. 2019).

BIOMASS INDEX

A relative index of mackerel SSB is calculated from data collected during an annual survey targeting mackerel eggs (1979-2018), from commercial mackerel samples from the southern GSL (4T), in June and July, from derived equations describing mackerel fecundity and egg incubation time, and from oceanographic data collected in conjunction with the AZMP (Girard 2000). Briefly, stage 1 egg counts are converted to density of eggs per squared metre for each of 65 fixed stations (occasionally fewer or additional stations covered due to weather, mechanical issues or special projects) covering the southern GSL by accounting for the depth of the sampled water column and volume of filtered water. Egg density is estimated for the back calculated spawning date by way of derived egg incubation equation (Lockwood et al. 2017). Ordinary kriging is used to interpolate a mean egg density for the entire area. A fitted logistic curve describing the evolution of a gonado-somatic index by day, and thus the duration of the spawning period, is then used to calculate the proportion of eggs spawned daily. The SSB index is subsequently calculated as a function of the mean daily egg production, the sampled area, the mean weight of a mature female during spawning for a given year, the proportion of eggs spawned at the median date of the egg survey, and the derived fecundity of females. From 2015 to 2018, the survey was carried out on board the CCGS Teleost (June 12th – June 20th), the Coriolis II (June 11th – June 23rd), the CCGS Teleost (June 10th – June 17th), and the Coriolis II (June 16th – June 24th). Methods for the sampling protocol and subsequent analyses to calculate various aspects of mackerel egg production and the resulting biomass index are described in detail in Doniol-Valcroze et al. (2019).

STOCK ASSESSMENT MODEL

The previous mackerel assessment (NAFO subareas 3 and 4) took place in March, 2017. A new statistical catch-at-age population dynamics model was developed to assess stock status and to fully integrate the various sources of uncertainty, including the estimation of missing catches.

This censored statistical catch-at-age model was described in detail by Van Beveren et al. (2017b) and was developed using the Template Model Builder (TMB; Kristensen et al. 2016) package in R (R Core Team 2019). Model equations are provided in Tables S7-S8 and input data is plotted in Figures 1-3 and S4-S5. The model was denoted "censored" as it uses a new approach in which reported catches are explicitly considered biased, and are thus estimated to occur between a lower limit, corresponding to reported catches, and an upper limit. This upper limit for unreported catches have been informed, as far as possible, by the available information on the bait and recreational fishing industry, the order of magnitude of which has been confirmed by results from an online survey distributed among active mackerel harvesters in Eastern Canada (Van Beveren et al. 2017a). The survey was undertaken again in 2018 and the preliminary results concord with the previous survey. In correspondence with the Precautionary Approach (PA) (DFO 2009), the Limit Reference Point (LRP) and Upper Stock Reference (USR) are calculated from this model as 40% and 80% of $SSB_{F40\%}$, respectively (Spawners-Per-Recruit at $F_{40\%}$ multiplied by the average recruitment over 1969-2018). All data, model code, and scripts are available online.

Short-term projections were also performed as a basis for 2019 TAC advice. A Management Strategy Evaluation (MSE) was also developed, which provided both medium-term and long-term projections under various uncertainty scenarios (DFO 2018). The statistical framework of the MSE and the assessment is the same (with the exception of eq. 4.1 in Table S7 and the proportion mature data, see Van Beveren et al., DFO, Mont-Joli, Qc, pers. comm.), and the forecasting procedure is detailed within the former. For the projections presented within this document and the SAR, recruitment was projected towards the mean value (1969-2018) with a temporal autocorrelation of 0.9 (as in Core model 1 of the MSE, Van Beveren et al., DFO, Mont-Joli, Qc, pers. comm.).

ENVIRONMENTAL DRIVERS OF RECRUITMENT, CONDITION, AND CATCH DISTRIBUTION

To test how mackerel recruitment, body condition, and catch distribution were influenced by the environment, we used several environmental variables and mackerel stock characteristics obtained from commercial landings and samples, CCAM model output, and from the AZMP (DFO 2019a). We hypothesized that mackerel recruitment and condition depend on food availability in their habitat. We used a number of biological and physical environmental variables (Table S12) to test whether they could explain the variability in mackerel recruitment and condition. Specifically, we used physical environmental variables related to food availability in space (*St. Lawrence Runoffs* - a proxy for primary productivity) and in time (*Last Ice* and *Spring Timing* – proxies for the beginning of the spring bloom; and finally, sea surface temperature (*SST*)). More direct biological data were also used as explanatory variables such as the timing, duration, and amplitude of the phytoplankton bloom, as well as abundance indices for zooplankton prey known to be important for various mackerel life stages (*Calanus glacialis, C. finmarchicus, C. hyperboreus, Pseudocalanus, Temora spp.*). Time series for the variables were obtained from the AZMP oceanographic surveys (DFO 2019a). To test these relationships, we used Generalized Additive Models (mgcv::gam; Wood 2008) to allow for nonlinear relationships.

Depending on the availability of data in the time series, we considered different time periods using different combinations of the above mentioned variables in our analyses (1985-2016 only the physical variables, 2001-2016 only physical variables and, 2001-2016 with both physical and biological variables). In the later time series, we hypothesized that food availability and abundance would be the main drivers of mackerel recruitment and condition.

Following this, we also investigated how mackerel distribution could change as a function of the environment and mackerel stock characteristics. Mackerel distribution had to be estimated indirectly through the commercial fisheries' landings data. The availability of georeferenced landings data in this fishery is limited so we used the relative proportion of landings by NAFO Division as a proxy for mackerel distribution, provided we also had sufficient biological sample data to calculate condition (i.e.4T, 4R, 3K, and 3L). We assumed that harvesters that prosecute this fishery do so every year and that the percentage of landings data in each NAFO subarea represented the relative mackerel occurrence in that area. Licences issued for mackerel in Newfoundland increased substantially in the mid-1990s, all the while purse and tuck seiners, which dominate catches in that region, increased their efficiency (e.g. dual frequency echo sounders (mackerel have no swim bladder), hold capacity, horse-power, GPS, and telecommunications). To account for this change in fishing efficiency, a variable for fishing period was included in the analyses (1982-1999 and 2000-2017). We hypothesized that mackerel's distribution around Newfoundland is constrained by SSB, water temperature, and mackerel energy reserves. We assumed that when taken together, these variables would describe the physical and biological conditions experienced by mackerel and explain the observed changes in mackerel seasonal migrations and distribution (% landings).

Ringuette et al. (2002) found evidence of a negative relationship between density-dependence and growth for mackerel. Density-dependence would imply that when SSB is large, there would be greater dispersal to locate food and avoid competition. Historic accounts and the primary literature associate the arrival of mackerel around Newfoundland with warmer water temperatures along its coast (Moores et al. 1975; Pinhorn 1976). Mackerel generally avoid water temperatures lower than 7°C (Olla and Bejda 1976) and as such much of the waters surrounding Newfoundland are only occasionally available as mackerel habitat, due to the influence of the cold Labrador current. We used body condition and zooplankton abundance to describe how available food was and how well mackerel acquired energy reserves in a given region. Biological variables for NAFO Divisions 4R3KL (Newfoundland) were only available from 2000-2016 via the AZMP. As before, GAMs were used to allow for non-linear relationships (P. Brosset 2018*,* DFO Mont-Joli, pers. Comm.).

RESULTS AND DISCUSSION

The key indicators used as model inputs for this stock are total catch statistics, catch-at-age data, and the biomass index. Maturity-at-length, $L_{50,}$ is also used as advice as to the minimum size at which fish could be caught to ensure that 50% of the fish are given the opportunity to spawn at least once.

LANDINGS

During the 1980s and 1990s, declared landings by Canadian vessels were relatively stable and averaged around 22 000 t per year. The number of mackerel fishing permits increased in the early 1990s as part of a second mackerel development plan (DFO 1990, 1993). From 2000 to 2010, landings averaged 40 498 t. Canadian landings reached a record high of 55 726 t in 2005 due to the marked increase in fishing effort by small and large seiners on both the East and West coasts of Newfoundland, and the presence of a very large 1999 year class (Patterson 2014). This was followed by a severe drop in landings, reaching a low of 4 272 t in 2015. From 2016 to 2018, preliminary landings were 8 050 t (TAC 8 000 t), 9 430 t (TAC 10 000 t), and 10 499 t (TAC 10 000 t), respectively. Values for missing catch due to discards, fish caught through bait licences, fish caught recreationally, and the proportion of Canadian spawned mackerel caught in the U.S. winter mackerel fishery are not currently known. True total removals of northern contingent fish are hence presumed to fall somewhere between two bounds (i.e., they are ‘censored’), established as 110% of the declared Canadian landings (lower bound, grey line in Figure 1) to which an unknown fraction of Canadian are added (see Doniol-Valcroze et al. 2019) as well as 25-50% of the US catch statistics. Catch data since 1960 for the entire NWA stock are presented in Figure S1. Landings occurring solely within Canada’s EEZ and split by country of origin, Canadian province, DFO region, and NAFO Division are presented in Tables S1-S4 and Figures 1, S1, and S2.

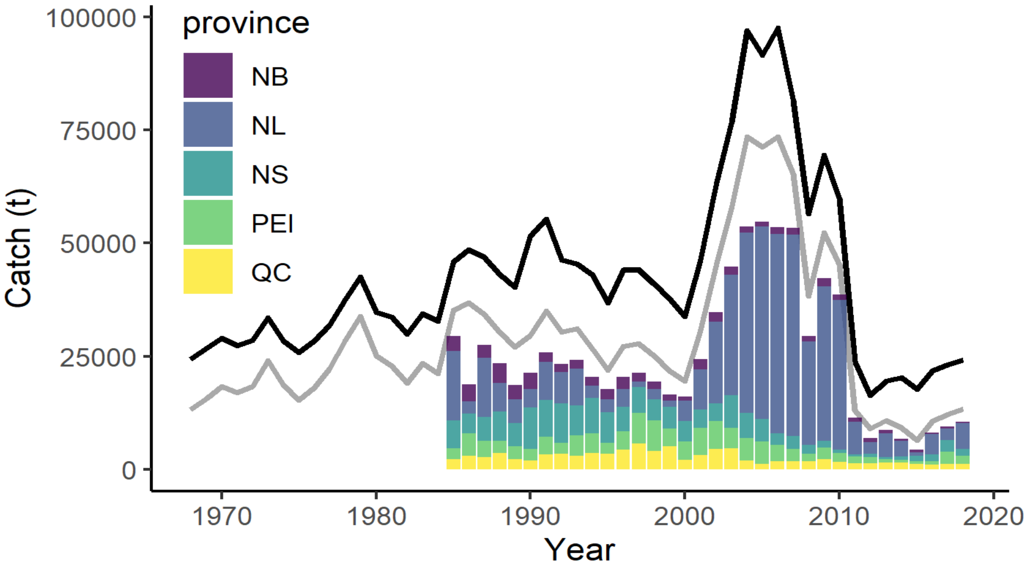

Figure 1. Canadian landings by province (barplot) with indication of the lower (grey) and upper (black) bound of the estimated total removals (including unaccounted-for catches of Canada and the US).

CATCH-AT-AGE

The oldest mackerel on record from biological samples was 18 years old, but individuals over the age of 9 have been rare since the early 2000s, and individuals over the age of 6 have become increasingly rare since 2012, suggesting a collapse in the age structure of the stock.

Fish under 3 years old dominated the fishery for the past 4 years, reflecting the entry of the 2015 cohort into the fishery (Figure 2). Similar trends in catch-at-age are observed in the southern contingent (NEFSC 2017).

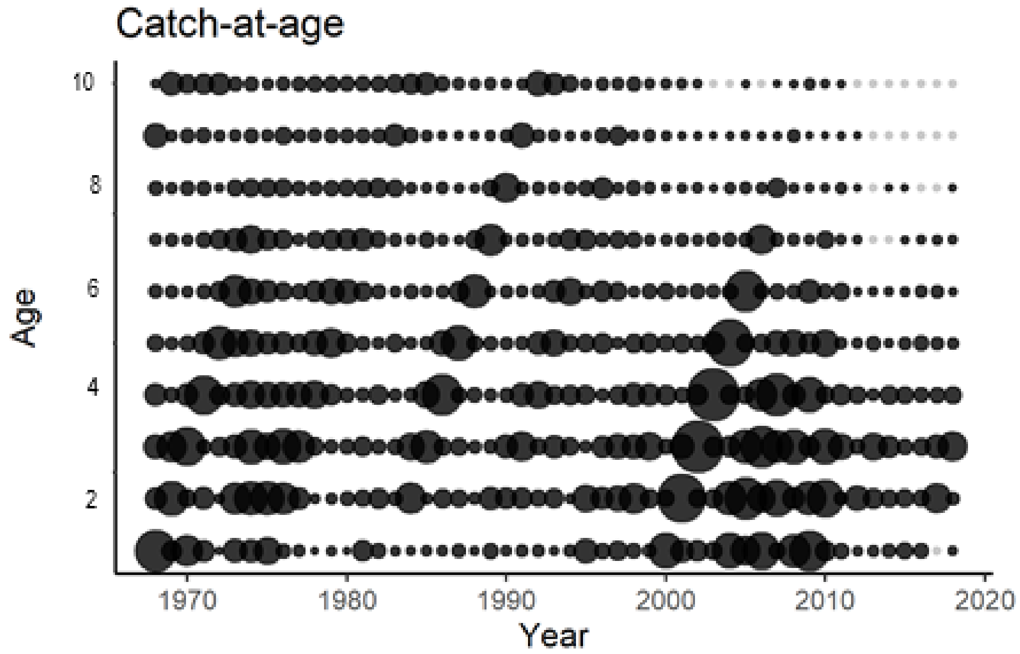

Figure 2. Catch-at-age (numbers). Grey dots indicate 0.

BIOMASS INDEX

The biomass index calculated from the annual egg survey and from commercial samples in the southern GSL shows a variable yet clearly declining trend, reaching historic lows in recent years. The mean biomass index value since 1995 is approximately 12% of those from 1979-1994 (Figure 3). Furthermore, the area in which mackerel eggs are distributed has decreased (Grégoire et al. 2014) .

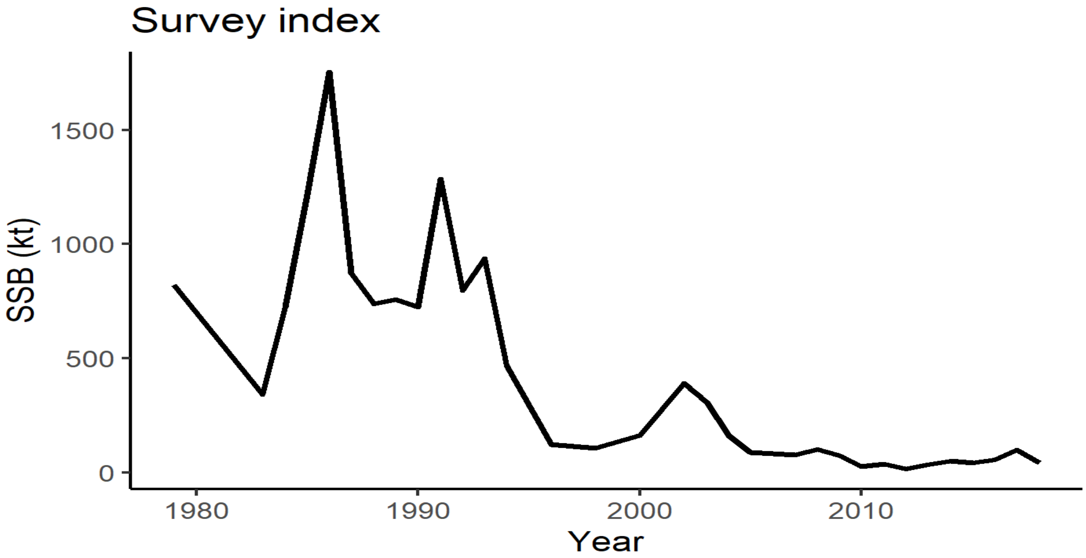

Figure 3. Relative biomass index derived from the egg survey.

The southern GSL has long been acknowledged as the main spawning site for northern contingent mackerel (Sette 1943; Arnold 1970). Ichthyoplankton surveys covering this area began at the beginning of the 20th century (Dannevig 1919) and have been repeated and improved over time (Maguire 1981; Ouellet 1987, Grégoire and Lafleur 2006; Grégoire and Faucher 2006). Many other ichthyoplankton surveys have also been carried out throughout mackerel's distribution in the NWA. For example, surveys have been carried out in the Estuary and Gulf of Saint Lawrence (Kohler et al. 1974a, 1974b, 1975, 1976, 1977; Grégoire et al. 2008, 2009a), the Labrador and Newfoundland shelves as well as the inner bays of Newfoundland (Carter-Lynn 2000), and the Scotian Shelf (Sparks 1929; Grégoire et al. 2012; Bernier and Levesque 2000; Shackell and Frank 2000). These surveys suggested very limited spawning on the West coast of Newfoundland and the Scotian Shelf. The results also suggest that the low egg production measured in the Southern Gulf of Saint Lawrence since 2005 reflects a real decline in mackerel abundance.

The most recent exploratory mackerel egg survey took place on the northeast coast of Newfoundland following continued observations of juvenile mackerel in the area (Parsons and Hodder 1970). Three consecutive surveys in White Bay and Notre Dame Bay took place from June to August in 2015, followed by two more surveys in the same bays in July and August the following year. Two consecutive surveys in Trinity Bay, NL, were also undertaken in 2015 and 2016 during August and September as part of the annual DFO ichthyoplankton surveys targeting capelin but following nearly the same sampling protocols (however sampling over a greater portion of the water column up to depths of ~250 m; Shikon et al. 2019; Nakashima and Mowbray 2014). There were no mackerel eggs or larvae detected in either 2015 or 2016 across all three survey sites. These results are consistent with previous ichthyoplankton surveys describing species compositions in the region (Conception Bay, Bonavista Bay, Placentia Bay, and Trinity Bay; Carter-Lynn 2009), as well as known and predicted optimal spawning habitat preferences of mackerel (Mbaye et al. 2019*)*.

MODEL OUTPUT

Residual plots and retrospective patterns are shown in Figures S5 and S6. Although there are no major issues, residuals for the egg survey index showed a linear tendency towards recent overestimation, possibly due to non-stationary processes that have not been considered in the current model formulation. Attempts to correct the bias by allowing for changes in fishery or survey selectivity (2 blocks reflecting pre- and post-2000) or natural mortality (Van Beveren et al., DFO, Mont-Joli, Qc, pers. comm.) did not significantly improve the pattern of survey residuals. Other causes could include temporal changes in fecundity, for which, however, no up to date data are available (Pelletier 1986).

The stock was estimated to have dropped below the USR in 2010 and below the LRP the year after (Figure 4A). In 2018, the SSB was estimated to be at 77% of the LRP, up from 59% in 2016 because of a relatively strong 2015 year class. The strength of this year class was important relative to more recent recruitment levels, but was however estimated to be significantly smaller relative to historically observed peaks (Figure 4C,D). For instance, the 2015 cohort (number of Age 1 fish) was estimated to be only 32% and 38% of the size of the 1982 and 1999 cohorts, respectively. Nonetheless, the 2015 cohort now dominates the landings as the population age structure is truncated (Figure 4B). Subsequent recruitment was estimated to be at all-time lows. A stock-recruitment relationship became clearly apparent, even when the model did not force such a relationship. Specifically, since biomass dropped below the USR in 2010, recruitment has on average been on the lower end (Figure 4D).

Fishing mortality rates (including estimated missing catch values) were estimated to remain above the reference level (Figure 4E,F). According to the consensus model, the estimated 2018 fishing mortality rate on fully exploited mackerel (ages 5 to 10) was 1.13 (exploitation rate of 68%). Although exploitation rate is usually given for fish that are fully recruited to the fishery, these mackerel do not compose a large fraction of the population anymore. The exploitation rate over all ages weighted by their numbers ($F_{overall} = \sum_{a=1}^{A} F_a * N_a / \sum_{a=1}^{A} N_a$) was F = 0.44 (exploitation rate of 36%). Note that this exploitation rate is still relatively high, especially given that most fish are not fully targeted by the fishery yet. The 2018 exploitation rate on the dominant 2015 cohort was estimated to be 45%.

Projections were made over a three-year period to estimate the impact of different HCRs on the SSB. These HCRs were developed within the MSE framework by the RPWG. Although these rules determine a TAC dynamically (i.e., a TAC is applied annually according to the stock status, approximated by the egg survey index), they mostly result in a constant TAC within the short-term. The only exception is HCR 3, which allows the TAC to change up to 25% from one year to the next, depending on the relative change in the egg survey index. As such, testing these HCRs is currently similar to the use of traditional constant TACs in projections (e.g., previous mackerel assessment, Doniol-Valcroze et al. 2019), but parallels the ongoing MSE process.

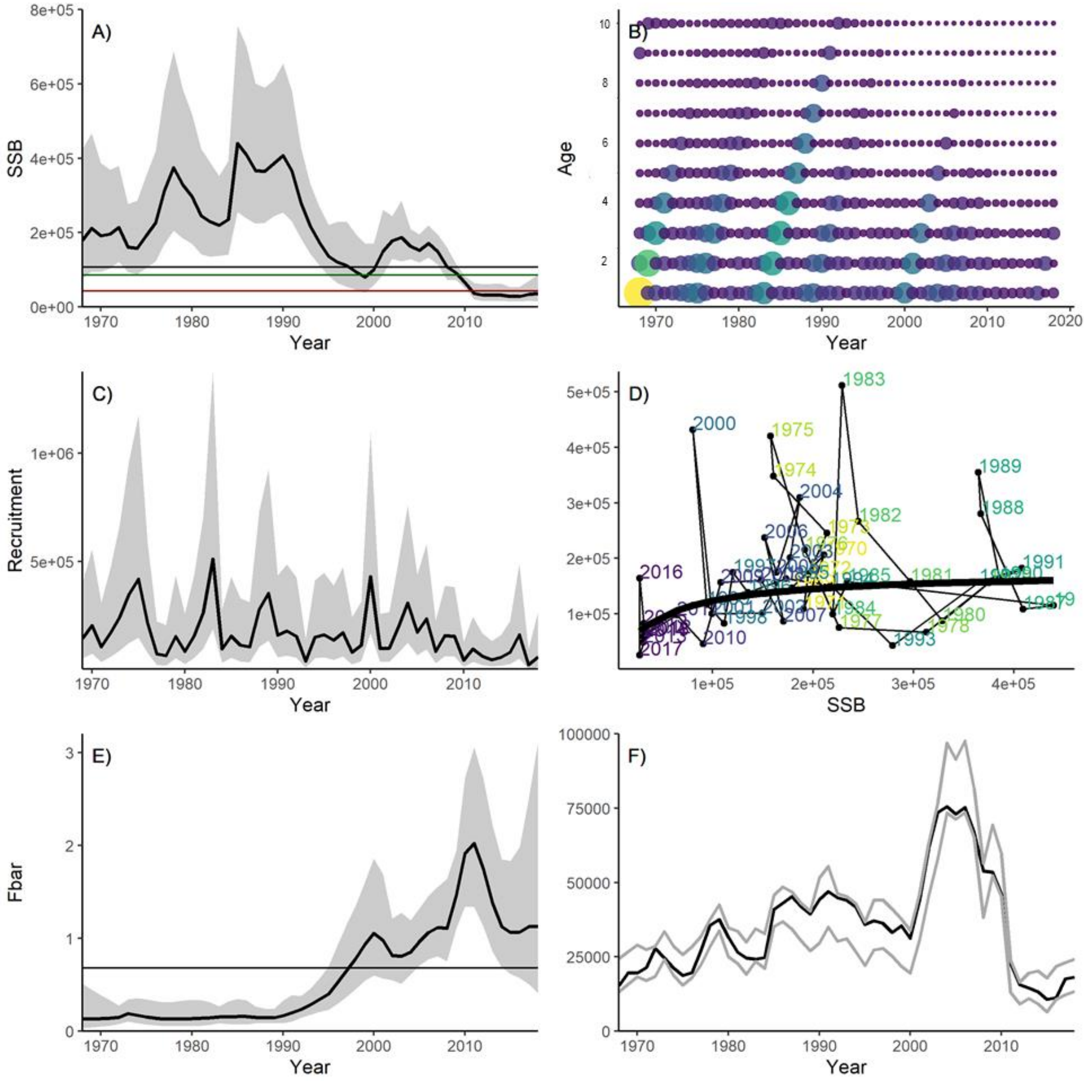

Figure 4. Model output: (A) Spawning Stock Biomass (t) with horizontal lines indicating $SSB_{F40\%}$ (black), USR (green) and LRP (red), (B) abundance at age, (C) recruitment (numbers), (D) stock-recruitment, (E) fishing mortality (averaged over the fully selected age classes 5-10), (F) estimated catch (black) between the pre-determined bounds (grey).

In 2016, projections were made based on total removals, which included deterministic levels of unaccounted-for catches. We improved this projection approach by stochastically projecting unaccounted-for catches of both Canada and the US separately. The TAC generated by the HCR is added to these estimated catches to calculate total removals and the resulting next years' stock biomass. During the assessment there was agreement that the Canadian missing catches had likely decreased due to the imposition of recent management measures, whereas the direction of possible US catches of northern contingent fish was unknown (although it was presumed the fraction remained at 25-50%). At the time, the US planned to increase their quota but it was unclear whether this would also materialise and if it would result in increased landings. The presumed missing catch patterns and their uncertainty for each missing catch component are plotted in Figure 5 and modelling details are provided in the MSE research document (Van Beveren et al., DFO, Mont-Joli, Qc, pers. comm.).

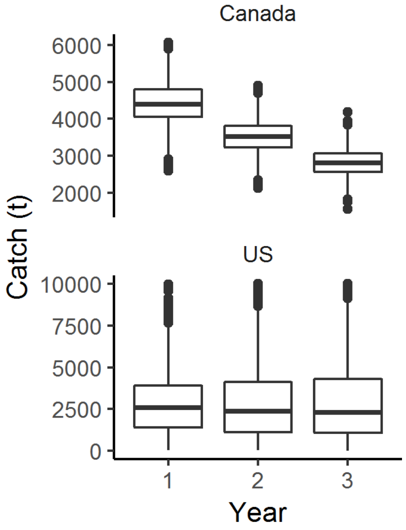

Figure 5. Boxplots of the assumed unaccounted-for catch over the next 3 years (2019-2021), for Canada (upper panel) and the US (lower panel) (generated with functions IEindep2019 and IEdep2550, CCAM package).

The projection table below was provided within the Stock Advisory Report. With increasing TACs from 0 to 10 000 t, the probability of exceeding the LRP by 2021 decreased from 68% to 48%, and the probability of stock growth from 2019 to 2021 decreased from 78% to 49%. Note that under the 2018 quota (10 000 t), the stock has a 51% chance to decline. Percentages of stock rebuilding (out of the Critical Zone) and growth do not extremely differ between the HCRs (despite a difference in floor TAC of 10 000 t) because of the large influence of unaccounted-for catch (e.g., the decrease in catches produced by lowering the TAC is not as large relative to the total landings) and the significant probability of not attaining the TAC during the next 3 years when fishing at the highest exploitation rates (e.g., HCR 10 and 11 are similar because 10 000 t might not be landed each year; Table 1).

Table 1. Three-year projections under different TACs (as determined by the Harvest Control Rules or HCRs, described in Van Beveren et al., DFO, Mont-Joli, Qc, unpublished data. Some HCRs (e.g. HCR 2, 4, 5 and 6) would result in (quasi-) identical TACs (median values) over the next three years and were therefore removed. The projections indicate the probability of reaching the Limit Reference Point (LRP) in 2020 and 2021 "Prob(SSB > LRP)" and the probability of growth occurring between 2019 and 2021 "Prob(SSB2021 > SSB2019)". The beginning of year SSB is given relative to the LRP (median value) for 2020 and 2021. Projections were performed under the assumption that mackerel will also be caught outside of the TAC, by both the Canadian and US fleets (uncertainties represented by the 5th and 95th quantile taken over the three years). Figure 9 shows the assumed annual unaccounted-for catch distributions in detail.

HCR	**TAC**			**Prob(SSB>LRP)**		**Prob(SSB_{2021}>SSB_{2019})**	**SSB/LRP**		**Unaccounted-for catch**			
									Canada		US	
	2019	2020	2021	2020	2021	2019→2021	2020	2021	5%	95%	5%	95%
3	9640	9334	8614	0.49	0.49	0.51	0.69	0.71	2425	4986	420	7282
4	0	0	0	0.60	0.68	0.78	0.98	1.16	2425	4986	420	7282
7	2000	2000	2000	0.58	0.65	0.72	0.92	1.06	2425	4986	420	7282
8	4000	4000	4000	0.55	0.60	0.65	0.86	0.96	2425	4986	420	7282
9	6000	6000	6000	0.53	0.56	0.59	0.79	0.86	2425	4986	420	7282
10	8000	8000	8000	0.51	0.52	0.53	0.74	0.76	2425	4986	420	7282
11	10000	10000	10000	0.49	0.48	0.49	0.67	0.68	2425	4986	420	7282

MATURITY-AT-LENGTH

L_{50} has varied between 221-301 mm from 1974 to 2018 (Figure 6). In 2018, the time series mean was 267 mm while the five year mean (2013-2018) was 268 mm. The commercial samples used to calculate these values are primarily from the mackerel gillnet fishery in the southern GSL which coincides with mackerel spawning timing. Increasing the minimum commercial size should permit larger fish to spawn, however due to the large relative abundance of only a single year class in the population, the current effectiveness of this strategy is unknown.

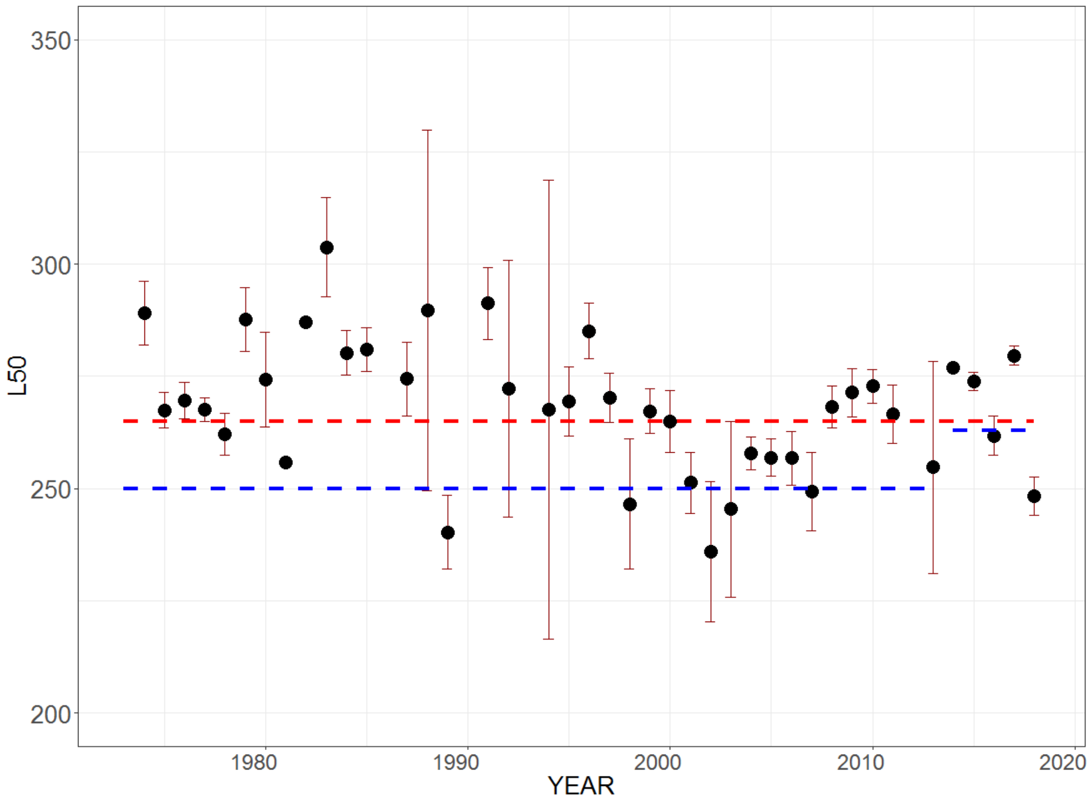

Figure 6. L_{50} with bootstrapped 95% confidence intervals (1968-2018).

ENVIRONMENTAL DRIVERS OF RECRUITMENT, CONDITION, AND LANDINGS DISTRIBUTION

The Northwest Atlantic ecosystem is changing (DFO 2019a; Galbraith et al. 2019; Blais et al. 2019) and mackerel have strict habitat requirements and prey preferences. Mackerel recruitment, body condition, and other life history traits are not surprisingly also influenced by environmental conditions (Runge et al. 2001; Castonguay et al. 2008; Plourde et al. 2015). These results are further corroborated by observations made by mackerel researchers and harvesters alike who have attributed the variability in this species' seasonal migrations and distribution to changes in water temperature (Templeman and Fleming 1953; Pinhorn 1976). Together, these observations and analyses suggest that the environment is a key driver in many aspects of mackerel life history (Trenkel et al. 2014).

We found that variation in mackerel recruitment and condition could be explained by environmental variables related to the availability and quality of food resources. The explicative power of all the models improved substantially when biological variables were included as independent variables. Taken together, these results show that when recruitment is low, as has been observed recently, it may be due, in part, to a mismatch between the temporal overlap of the emergence of mackerel larvae and the availability and quality of their food. Similarly, when the gain in adult condition is lower in a given area over the summer, it may be because they are feeding in a relatively poor feeding area.

Model fit for mackerel recruitment (deviance explained), improved from 57% to 82% when considering the biological variables. Specifically, recruitment was greater when mean SST was lower (May-August), when spring timing was early, when *C. finmarchicus* abundance was high, and when *Pseudocalanus sp.* phenology was early. Together these results indicate that recent low mackerel recruitment may be due to a mismatch between mackerel spawning and the availability of their prey (Figure S7, Tables S13-S14).

In the absence of biological variables, mackerel gain in condition was difficult to explain regardless of the time period or the area analysed. When biological variables were included, model fit for gain in condition in 4R went from non-significant to 80% deviance explained. Similarly, model fit for mackerel gain in condition in 4T improved from 62% to 83% with the inclusion of biological variables. The results suggest that when phytoplankton and zooplankton abundances in 4R were larger and synchronised with mackerel spawning, then mackerel had a greater gain in condition between June and September. As with 4R, mackerel caught in 4T had a greater gain in condition with the earlier development of phytoplankton and *C. finmarchicus*. Thus, when phytoplankton and zooplankton blooms occurred at the beginning of summer, coinciding with the end of mackerel migration to and spawning within the southern GSL, food may have been more available and resulted in a greater gain in condition over the summer in 4T (Figure S7, Tables S13-S14).

Our results show that the proportion of landings in the GSL (4T and 4R) relative to northeastern Newfoundland (3K and 3L) depends on stock size (SSB), relative gain in condition, as well as environmental variables related to food availability. When SSB was large and condition in 4T was poor, a greater proportion of landings were observed in 4R relative to 4T. A greater proportion of landings in 3K and 3L relative to 4R was also observed when SSB was large (i.e. greater competition for resources) and there was poor body condition in 4R. Increased landings in 3K and 3L also coincided with years when there were greater abundances of *C. finmarchicus* in those areas. While the effect of SST on mackerel landings was not detected, *C. finmarchicus* is associated with warmer waters and thus water temperature might limit food availability in 3KL in colder years as well as mackerel’s access to that resource due to their strict thermal tolerances. These results are similar to analyses relating the Northeast Atlantic mackerel distribution and their recent occurrences around Iceland to changes in SSB, SST, and food availability (Nikolioudakis et al. 2019). Together, these results tell us that increased landings of mackerel in a given area following spawning (mid-July to early November) can be explained by greater food availability (abundance of food and mackerel condition) in that region relative to another (Figure S7, Tables S13-S14).

QUALITY OF THE ASSESSMENT

Many of the key uncertainties within the data highlighted in previous assessments, as well as our knowledge of stock dynamics, have in large part been accounted for through the use of the current stock assessment model. Although uncertainties remain, stock status trends across different data sources are consistent and large enough to lend confidence as to stock status. The trends and derived conclusions are also consistent when different stock assessment models and sensitivity analyses are performed. However, the proportion of northern contingent mackerel caught in the U.S. mackerel fishery is not known but is yet likely to be high. The lack of catch data from the bait and recreational fisheries, missing or incomplete logbooks, the use of less detailed purchase slips as opposed to logbooks, the different levels of dockside monitoring among regions, and the lack of observer-at-sea coverage for this species are all important issues that should be addressed to improve advice.

CONCLUSIONS AND ADVICE

The northern contingent of Northwest Atlantic mackerel is currently in the Critical Zone as defined by DFO’s PA framework (DFO 2009) and has been since 2011. According to the PA framework, while a stock is in the Critical Zone, management actions must “*promote stock growth out of the Critical Zone (i.e. grow the stock beyond the LRP) by ensuring removals from all fishing sources are kept to the lowest possible level until the stock has cleared this zone. There should be no tolerance for preventable decline. This objective remains the same* *whether the stock is declining, stable or increasing".* Stock projections provided in Table 1 will allow decision makers to weight the trade-offs between stock size and different HCRs over a period of three years. The quality of advice could be improved by ensuring that all mackerel fisheries accurately account for all removals (Van Beveren et al., DFO, Mont-Joli, Qc, pers. comm.*)*.

These stock projections must also be considered within the context of the species' biology and the ecosystem in which it lives. Stock productivity is currently low due to changes in the environment and the collapsed age structure of the population. It should be kept in mind that the collapse in age structure is due solely to overfishing. As there is a stock-recruit relationship, the currently high fishing mortality and low recruitment may impede the stock's ability to renew itself and grow under current HCRs. Variation in mackerel recruitment, how well individuals grow during the summer season, and their distributions, are likely to continue to vary with respect to the relative availability of food in a given region and other environmental features such as water temperature.

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APPENDIX I –SUPPLEMENTARY TABLES

*Table S1: Annual landings (t) within Canada's Exclusive Economic Zone from 1960 to 2018**.*

Year	Canadian	Foreign	Total
1960	5888	0	5888
1961	5458	11	5469
1962	6901	64	6965
1963	6363	99	6462
1964	10786	174	10960
1965	11185	405	11590
1966	11577	1244	12821
1967	11181	62	11243
1968	11118	9720	20838
1969	13257	5379	18636
1970	15710	5296	21006
1971	14942	9554	24496
1972	16253	6107	22360
1973	21566	16984	38550
1974	16701	27954	44655
1975	13540	22718	36258
1976	15746	17319	33065
1977	19852	2913	22765
1978	25429	470	25899
1979	30244	368	30612
1980	22135	161	22296
1981	19294	61	19355
1982	16380	3	16383
1983	19797	9	19806
1984	17320	913	18233
1985	29855	1051	30906
1986	30325	772	31097
1987	27488	71	27559
1988	24060	956	25016
1989	20795	346	21141
1990	19190	3796	22986
1991	24914	597	25511
1992	24307	2255	26562
1993	26158	690	26848
1994	20564	49	20613
1995	17706	62	17768
1996	20394	76	20470
1997	21309	116	21425
1998	19334	10	19344
1999	16561	12	16573
2000	16080	26	16106
2001	24336	11	24347
2002	34755	7	34762
2003	44736	12	44748
2004	53650	15	53665
2005	54726	-	54726
2006	53554	3	53557
2007	53275	-	53275
2008	29511	4	29515
2009	42206	42	42248
2010	38650	1	38651
2011	11485	-	11485
2012	6844	2	6846
2013	8674	1	8675
2014	6679	-	6679
2015	4272	1	4273
2016	8050	2	8052
2017*	9430	3	9433
2018*	10499	-	10499

* 2017 and 2018 values are preliminary

** NAFO Subareas 2-4 and small portions of Subarea 5

Table S2. Annual landings (t) by province from 1985-2018.

Year	*New Brunswick*	*Newfoundland & Labrador*	*Nova Scotia*	*Prince Edward Island*	*Québec*
1985	3269	15339	6175	2489	2179
1986	3723	2700	4351	4943	3004
1987	2789	13154	5237	3566	2753
1988	4308	6399	6450	2611	3662
1989	3185	5233	5218	2775	2252
1990	3614	4087	9182	2458	1971
1991	2137	8380	8115	3922	3256
1992	1748	6915	8831	2299	3480
1993	1916	8177	6512	4562	2971
1994	1879	2775	7792	4441	3529
1995	2206	2919	6681	2518	3382
1996	2684	3857	5517	4018	4317
1997	1990	1188	5669	6693	5769
1998	1682	2240	4562	6784	4066
1999	1373	1445	4797	3842	5104
2000	972	4406	4547	4134	2022
2001	2199	8981	4058	5886	3212
2002	2182	17982	3989	6181	4421
2003	1734	26675	7187	4543	4597
2004	1419	39732	5642	4878	1979
2005	1044	42589	4926	4946	1221
2006	1489	44121	2586	3540	1818
2007	1419	44486	2837	2782	1750
2008	1202	22885	1955	1606	1863
2009	1762	34218	1453	2457	2316
2010	1256	33114	668	1903	1709
2011	903	7317	416	1505	1345
2012	780	2618	683	1485	1278
2013	766	5169	450	836	1453
2014	449	3432	769	527	1502
2015	571	701	1183	635	1182
2016	199	4631	1434	821	966
2017*	408	2648	2461	2702	1211
2018*	362	5625	1464	1808	1239

* 2017 and 2018 values are preliminary.

Table S3. Annual landings (t) by DFO region from 1985-2018.

						Proportion (%)			
Year	*Gulf*	*Newfoundland*	*Quebec*	*Maritimes*	*Total*	*Gulf*	*Newfoundland*	*Quebec*	*Maritimes*
1985	6125	14883	2179	6265	29452	21	51	7	21
1986	8518	2400	3004	4799	18721	45	13	16	26
1987	9611	9902	2753	5233	27499	35	36	10	19
1988	9469	4234	3662	6065	23431	40	18	16	26
1989	9686	1911	2252	4814	18663	52	10	12	26
1990	9634	1208	1971	8499	21312	45	6	9	40
1991	14451	834	3256	7270	25810	56	3	13	28
1992	9888	1283	3480	8622	23273	42	6	15	37
1993	6932	8177	2971	6058	24138	29	34	12	25
1994	6765	2775	3529	7347	20417	33	14	17	36
1995	4831	2919	3382	6574	17706	27	16	19	37
1996	7049	3857	4317	5170	20394	35	19	21	25
1997	9590	1188	5769	4762	21309	45	6	27	22
1998	8676	2240	4066	4353	19334	45	12	21	23
1999	5462	1445	5104	4550	16561	33	9	31	27
2000	5294	4406	2022	4359	16080	33	27	13	27
2001	9030	8981	3212	3113	24336	37	37	13	13
2002	10162	17982	4421	2190	34755	29	52	13	6
2003	9727	26675	4597	3737	44736	22	60	10	8
2004	7725	39732	1979	4214	53650	14	74	4	8
2005	8233	42589	1221	2683	54726	15	78	2	5
2006	6013	44121	1818	1603	53554	11	82	3	3
2007	4681	44486	1750	2357	53275	9	84	3	4
2008	3593	22885	1863	1170	29511	12	78	6	4
2009	4556	34218	2316	1116	42206	11	81	5	3
2010	3273	33114	1709	554	38650	8	86	4	1
2011	2415	7317	1345	409	11485	21	64	12	4
2012	2256	2618	1278	692	6844	33	38	19	10
2013	1648	5169	1453	403	8674	19	60	17	5
2014	1042	3432	1502	702	6679	16	51	22	11
2015	1218	701	1182	1171	4272	29	16	28	27
2016	1241	4631	966	1213	8050	15	58	12	15
2017*	3560	2648	1211	2012	9430	38	28	13	21
2018*	2260	5625	1239	1375	10499	22	54	12	13

** Values for 2017-2018 are preliminary. Values may not add due to rounding errors.*

Time period	Mean proportion			
	Gulf	*Newfoundland*	*Quebec*	*Maritimes*
Pre-1999	39	17	16	28
Post-1999	20	59	11	10

Table S4. Annual landings (t) by NAFO Division from 1985-2018.

Year	*2GJ*	*3K*	*3L*	*3PO*	*4R*	*4S*	*4T*	*4V*	*4W*	*4X*	*5YZ***	*NA****	*Total*
1985	0	9559	4961	701	118	68	7780	1701	596	3968	0	0	29452
1986	1	1374	995	132	198	178	11039	972	500	3333	0	0	18721
1987	2	7044	2689	177	3242	101	9010	1347	836	3050	0	0	27499
1988	0	3384	812	51	2152	34	10939	1807	729	3523	0	0	23431
1989	0	1634	217	63	3319	50	8567	1685	264	2864	0	0	18663
1990	2	798	315	97	2875	19	8707	2402	3000	3098	0	0	21312
1991	0	690	52	97	7541	22	10138	2386	1756	3128	0	0	25810
1992	0	1259	20	56	5580	28	7708	1345	2535	4743	0	0	23273
1993	0	3725	380	0	4072	74	9837	1579	438	4032	0	0	24138
1994	0	16	6	20	2697	73	10258	1671	700	4976	0	0	20417
1995	0	11	11	90	2807	30	8184	1475	622	4477	0	0	17706
1996	0	3	0	60	3794	9	11358	1591	1182	2398	0	0	20394
1997	0	0	0	8	1181	1	15358	838	716	3208	0	0	21309
1998	0	0	0	65	2175	1	12739	554	138	3662	0	0	19334
1999	0	0	0	7	1438	2	10562	762	126	3663	0	0	16561
2000	13	2317	55	20	2001	0	7005	576	120	3663	1	311	16080
2001	0	322	10	273	8375	16	11915	125	248	2743	0	308	24336
2002	0	6566	3	162	11251	2	14251	308	115	1771	0	326	34755
2003	0	588	0	149	25938	0	14107	60	9	3669	0	217	44736
2004	0	15964	58	78	23631	0	9342	13	59	4143	0	362	53650
2005	0	24170	4105	238	14077	35	9234	126	36	2521	0	186	54726
2006	0	19050	7932	266	16872	76	7755	224	75	1304	0	0	53554
2007	0	8672	10659	381	24777	19	5759	370	59	1928	0	651	53275
2008	0	8974	4	166	13741	23	4884	111	63	997	0	549	29511
2009	0	6883	39	5387	21909	64	6652	55	65	980	16	157	42206
2010	0	12874	830	5541	13869	123	4702	7	129	418	0	158	38650
2011	0	426	61	1544	5286	107	3542	2	18	390	0	112	11485
2012	78	128	3	149	2261	304	3129	150	177	365	0	101	6844
2013	44	191	0	26	4909	245	2759	146	17	241	0	97	8674
2014	0	6	25	246	3155	20	2389	143	220	339	0	135	6679
2015	0	208	54	0	438	29	2234	58	186	682	245	137	4272
2016	0	2795	0	0	1836	62	1987	124	149	939	1	158	8050
2017*	1	1160	0	45	1443	139	4629	156	288	1435	133	3	9430
2018*	74	5336	3	0	211	467	3015	118	112	1143	2	14	10499

** Values for 2017-2018 are preliminary. Values may not add due to rounding errors.*

*** Small portions of Canada's EEZ occur in NAFO Divisions 5YZ.*

**** Geospatial data missing.*

Table S5: Number of fish measured from commercial samples by NAFO division. Note, this does not include fisheries-independent data.

Year	*3KL*	*3P*	*4R*	*4S*	*4T*	*4V*	*4W*	*4X5YZ*	*Total*
1973	-	-	-	-	1497	1544	148	756	3945
1974	-	-	-	-	385	388	329	898	2000
1975	-	-	-	-	740	333	195	1051	2319
1976	-	-	-	-	6056	2926	-	8400	17382
1977	-	-	-	-	4467	1443	441	9542	15893
1978	-	-	-	-	4854	2298	2084	4248	13484
1979	-	-	-	-	10322	1588	900	3984	16794
1980	-	-	-	-	7293	1827	718	4123	13961
1981	-	-	-	-	5828	679	244	5019	11770
1982	-	-	-	-	3651	503	204	6817	11175
1983	1919	192	862	-	788	296	615	1133	5805
1984	1547	81	2181	-	20524	155	67	178	24733
1985	1698	50	988	-	14986	-	-	289	18011
1986	1912	184	856	203	11322	-	-	-	14477
1987	903	101	5028	-	14255	50	716	68	21121
1988	919	158	2669	-	19086	551	167	2652	26202
1989	1110	109	2362	-	19250	767	205	522	24325
1990	515	56	2700	-	9179	158	23	-	12631
1991	263	145	4742	-	7849	251	-	1440	14690
1992	393	97	5508	-	7715	-	-	-	13713
1993	514	41	4384	-	8812	312	-	98	14161
1994	93	99	3019	-	8496	533	1103	318	13661
1995	-	-	3177	420	11397	2407	990	1088	19479
1996	-	50	3510	288	7823	2413	261	407	14752
1997	-	-	529	-	11944	1556	-	195	14224
1998	-	-	-	-	12322	2190	-	701	15213
1999	-	-	256	-	13444	1784	-	675	16159
2000	1762	-	588	-	10098	2338	-	590	15376
2001	-	-	4034	306	11725	3190	2354	221	21830
2002	729	-	3949	-	11918	1900	-	-	18496
2003	-	-	5830	-	11681	3750	102	181	21544
2004	2599	127	2951	-	9849	1808	-	5836	23170
2005	1921	199	2453	214	9784	1642	-	3061	19274
2006	4092	142	2968	201	11077	2185	-	-	20665
2007	2152	219	4467	-	9239	1680	-	452	18209
2008	342	113	1344	173	9415	283	-	1097	12767
2009	718	748	3372	447	8586	1664	849	-	16384
2010	4100	774	3556	802	9010	-	-	294	18536
2011	657	328	3279	597	5771	-	-	446	11078
2012	590	184	2782	585	5399	-	-	-	9540
2013	-	-	1195	554	5322	-	-	-	7071
2014	-	-	2000	-	6913	-	-	-	8913
2015	582	-	202	185	7513	-	-	-	8482
2016	1071	-	1548	423	9388	-	-	314	12744
2017	-	-	1374	640	11397	-	-	-	13411
2018	687	-	416	1205	8180	488	428	1096	12500

Table S6: Number of commercial samples received by NAFO division (generally one sample = 100 fish measured for length, and a subsample consisting of two fish per length class (5 mm) sent for measuring of biological traits. Note, this does not include fisheries-independent data.

Year	*3KL*	*3P*	*4R*	*4S*	*4T*	*4V*	*4W*	*4X5YZ*	*Total*
1973	0	-	-	-	29	21	6	20	76
1974	0	-	-	-	6	9	7	14	36
1975	0	-	-	-	15	5	7	19	46
1976	0	-	-	-	24	15	-	36	75
1977	0	-	-	-	23	8	1	26	58
1978	0	-	-	-	27	12	9	21	69
1979	0	-	-	-	44	8	5	21	78
1980	0	-	-	-	34	12	6	21	73
1981	0	-	-	-	33	5	2	15	55
1982	0	-	-	-	23	4	1	30	58
1983	32	5	12	-	19	3	5	8	84
1984	31	2	5	-	50	4	2	5	99
1985	32	1	4	-	38	-	-	8	83
1986	35	4	3	1	28	-	-	-	71
1987	16	2	18	-	46	1	7	1	91
1988	16	4	10	-	27	4	1	12	74
1989	22	4	8	-	39	4	2	5	84
1990	10	1	9	-	26	5	1	-	52
1991	6	4	14	-	20	4	-	7	55
1992	8	2	18	-	22	-	-	-	50
1993	12	2	12	-	23	7	-	2	58
1994	2	2	11	-	27	2	3	2	49
1995	0	-	11	2	33	8	4	5	63
1996	0	1	9	1	24	8	1	2	46
1997	0	-	2	-	33	6	-	1	42
1998	0	-	-	-	34	7	-	2	43
1999	0	-	2	-	40	9	-	3	54
2000	11	-	2	-	26	9	-	3	51
2001	0	-	12	2	29	13	8	1	65
2002	8	-	9	-	30	7	-	-	54
2003	0	-	15	-	35	14	1	1	66
2004	15	2	7	-	23	7	-	20	74
2005	16	3	7	1	37	7	-	17	88
2006	33	3	8	1	40	8	-	-	93
2007	38	3	14	-	37	5	-	2	99
2008	9	2	3	1	40	8	-	5	68
2009	13	3	9	2	30	8	3	-	68
2010	38	3	13	4	36	-	-	1	95
2011	13	5	10	3	22	-	-	2	55
2012	13	3	11	3	22	-	-	-	52
2013	0	-	4	3	26	-	-	-	33
2014	0	-	5	-	30	-	-	-	35
2015	2	-	1	1	25	-	-	-	29
2016	3	-	3	2	35	-	-	2	45
2017	0	-	4	4	41	-	-	-	49
2018	2	-	2	6	37	3	8	11	69

Table S7: Model equations and parameters (a = age, y = year). $F_y$is modelled as a random walk with deviance σ_{F_y}, $N_{a,y}$ as a multivariate normal distribution with deviance σ_N and the errors around the log transformed survey index and continuation-ratio logit transformed catch-at-age are assumed to be normal (with parameters σ_s^2 and $\sigma_{crl_a}^2$, respectively) whereas total annual catch has a censored loglikelihood (with $\sigma_C = 0.01$, eq. 3.3). Fishing selectivity (on a logit scale) is maximal at ages 5 and higher (only Sel_1 to Sel_4 are estimated). Three values of σ_{crl}^2 are estimated ($\sigma_{crl_1}^2$, $\sigma_{crl_{2,8,9}}^2$, $\sigma_{crl_{2,\dots,7}}^2$). $M_{a,y}$ = natural mortality, U_y= upper catch limit, L_y= lower catch limit, $\varepsilon_{a,y}^N$ = process error.

Equations

Parameter	*Formula*	*No.*
Cohort abundance	$N_{1,y} = \dfrac{\alpha SSB_{y-1}}{1+\beta SSB_{y-1}}\exp\left(\varepsilon_{1,y}^N\right)$	1.1
	$N_{a,y} = N_{a-1,y-1}\exp\left(-Z_{a-1,y-1} + \varepsilon_{a,y}^N\right)$	1.2
	$N_{A,y} = \left[N_{A-1,y-1}\exp\left(-Z_{A-1,y-1}\right) + N_{A,y-1}\exp\left(-Z_{A,y-1}\right)\right]\exp\left(\varepsilon_{A,y}^N\right)$	1.3
Mortality rates	$F_y = F_{y-1}\exp\left(\varepsilon_y^F\right)$	2.1
	$F_{a,y} = F_a F_y$	2.2
	$Z_{a,y} = F_{a,y} + M_{a,y}$	2.3
Catch	$C_{a,y}=N_{a,y}\dfrac{F_{a,y}}{Z_{a,y}}\left[1-\exp\left(-Z_{a,y}\right)\right]\exp\left(\varepsilon_{a,y}^C\right)$	3.1
	$C_y = \sum_{a=1}^{A} C_{a,y}Weight_{a,y}$	3.2
	$l(L_1,\dots,L_Y;\theta) = \sum_{y=1}^{Y} log\left\{\phi_N\left[\dfrac{log\left(U_y/C_y\right)}{\sigma_C}\right] - \phi_N\left[\dfrac{log\left(L_y/C_y\right)}{\sigma_C}\right]\right\}$	3.3
Survey SSB	$SSB_y = q\sum_{a=1}^{A} N_{a,y}exp\left(-Z_{a,y}t_s\right)Weight_{a,y}PropMature_{a,y}$	4.1
Stock SSB	$SSB_y = \sum_{a=1}^{A} N_{a,y}Weight_{a,y}PropMature_{a,y}$	5.1

Parameters

Parameter	*Definition*	*Type*
$N_{a,y}$	Stock abundance	Random
F_y	Fishing mortality	Random
α	Stock-recruitment coefficient	Fixed
β	Stock-recruitment coefficient	Fixed
Sel_a	Fishing selectivity	Fixed
q	Survey index catchability	Fixed
σ_N^2	Process error	Fixed
σ_{F_y}	Annual fishing mortality variance	Fixed
$\sigma_{crl_a}^2$	Catch-at-age measurement error	Fixed
σ_s^2	Survey measurement error	Fixed

Table S8: Estimated model parameters.

Parameter	par	sd
$log q$	0.53	0.11
$log\sigma_{F_y}$	-1.12	0.11
$log\sigma^2_{N_1}$	-0.33	0.19
$log\sigma^2_{N_{2-10}}$	-0.89	0.09
$log\sigma^2_{crl_1}$	0.76	0.1
$log\sigma^2_{crl_{2,8,9}}$	-0.08	0.1
$log\sigma^2_{crl_{2,\ldots,7}}$	-0.5	0.07
$log\sigma^2_s$	-0.31	0.08
$log\alpha$	1.42	0.51
$log\beta$	-10.66	0.76
$logitSel_1$	-3.07	0.35
$logitSel_2$	-1.12	0.2
$logitSel_3$	0.12	0.23
$logitSel_4$	0.73	0.29

Table S9: Summary of CCAM model output.

Year	SSB (t)	Recruitment (000s of age-1 fish)	F_{5-10}	Catch (000s of fish)	Exploitation (%)	Mean age	SSB as % of LRP
1968	178914.1	1175678	0.13	15127.79	7.45	1.89	388.01
1969	211096.7	146755.6	0.13	19492.19	8.13	2.8	457.8
1970	190697.7	206534.2	0.13	19462.23	8.99	3.18	413.56
1971	195163.6	108821.8	0.14	21390.48	9.65	3.71	423.25
1972	213976.6	171203.8	0.15	27810.19	11.45	3.91	464.04
1973	160729.3	245404.9	0.19	24614.56	13.49	3.31	348.57
1974	157677.6	348003.4	0.17	21203.93	11.84	2.88	341.95
1975	192042.3	419898	0.15	18660.68	8.56	2.66	416.48
1976	225899.4	215059	0.14	19698.61	7.68	2.96	489.9
1977	313080.1	75035.52	0.13	27048.11	7.61	3.6	678.97
1978	374942.4	66762.32	0.13	35641.51	8.37	4.33	813.13
1979	328921.5	155915.9	0.13	37540.35	10.05	4.46	713.32
1980	296742.3	87163.41	0.13	31674.44	9.4	4.69	643.54
1981	245286.7	157788.5	0.14	26527.65	9.53	4.33	531.95
1982	229100.7	266270.9	0.14	24573.46	9.45	3.69	496.84
1983	219702.7	511683.9	0.15	24219.92	9.71	2.88	476.46
1984	234484.5	99097.57	0.15	24775.56	9.31	3.08	508.52
1985	439711.4	158273.8	0.16	40912.19	8.2	3.4	953.59
1986	409117.2	115192.5	0.15	42997.19	9.26	3.81	887.24
1987	367096.3	108662.7	0.15	45336.57	10.88	4.31	796.11
1988	364885.2	280489.2	0.14	41882.74	10.11	4.17	791.32
1989	385903.2	354918.5	0.14	39307.87	8.97	3.69	836.9
1990	407816.1	161710.5	0.17	44360.65	9.58	3.9	884.42
1991	365407.1	182170.1	0.2	46937.09	11.31	3.86	792.45
1992	279155.1	157009	0.23	44862.98	14.16	3.97	605.4
1993	217538.7	43139.56	0.28	44009.2	17.82	4.26	471.77
1994	173238.1	151716.5	0.34	41732.25	21.22	3.91	375.7
1995	135381.6	163349.2	0.4	35832.88	23.31	3.3	293.6
1996	120361.8	138413.8	0.52	37100.37	27.15	3.08	261.03
1997	111368	174385	0.65	36282.11	28.7	2.62	241.52
1998	94175.59	83017.68	0.78	33217.25	31.07	2.66	204.24
1999	80132.91	116760.2	0.94	35382.21	38.89	2.52	173.78
2000	99535.97	431647.4	1.05	31275.51	27.68	1.63	215.86
2001	149657	100103.8	0.98	43832.52	25.8	2.1	324.56
2002	177452.1	101957	0.82	61470.5	30.51	2.68	384.84
2003	186963.6	200881.8	0.81	73532.55	34.64	2.86	405.46
2004	163325.5	309526.3	0.85	75501.7	40.72	2.52	354.2
2005	152034.5	174744.5	0.96	72988.71	42.29	2.6	329.71
2006	170627.5	237481.6	1.06	75327.59	38.89	2.47	370.03
2007	148522.1	86610.5	1.12	66775.96	39.6	2.71	322.1
2008	108105.6	160259.2	1.11	53927.23	43.94	2.54	234.45
2009	90811.3	156424.7	1.46	53440.28	51.83	2.4	196.94
2010	64494.33	45966.18	1.91	46175.76	63.06	2.57	139.87
2011	35538.36	97881.18	2.02	22696	56.25	2	77.07
2012	31014.52	65484.74	1.75	15575.39	44.23	1.88	67.26
2013	30962.36	49285.45	1.38	14422.66	41.03	2.06	67.15
2014	31604.19	59251.92	1.12	13211.44	36.82	2.08	68.54
2015	27270.41	82838.06	1.06	10690.95	34.53	1.88	59.14
2016	27350.21	164390.6	1.06	11217.57	36.13	1.6	59.31
2017	33480.44	25246.35	1.13	17623.9	46.37	2.21	72.61
2018	35692.23	61377.4	1.13	18122.78	44.72	2.48	77.4

Table S10: Estimated N (numbers-at-age in 000s of fish) by CCAM.

Year	1	2	3	4	5	6	7	8	9	10
1968	1175.68	247	77.72	32.35	17.19	15.54	7.64	11.11	88.38	0.82
1969	146.76	840.14	201.04	43.86	14.59	10.59	13.23	5.96	6.93	89.49
1970	206.53	104.77	596.84	121	30.11	7.8	7.14	12.12	5.37	57.62
1971	108.82	156.95	68.89	435.02	72.85	21.43	5.29	6	8.9	40.15
1972	171.2	68.83	107.02	70.22	263.41	46.96	20.59	2.2	3.9	40.2
1973	245.4	176.48	71.51	78.55	64.37	131.87	33.67	13.67	1.86	15.23
1974	348	208.68	144.31	60.85	57.15	48.01	66.61	18.12	7.76	9.01
1975	419.9	347.51	154.54	100.12	43.58	45.06	36.48	37.76	10.06	8.76
1976	215.06	434.95	299.36	111.79	65.17	28.61	32.89	25.83	24.62	11.51
1977	75.04	185.8	420.5	232.53	80.25	46.06	19.4	23.12	16.83	26.01
1978	66.76	43.96	137.11	337.65	180.67	69.54	34.52	16.12	15.51	28.35
1979	155.92	45.71	33.51	108.06	232.8	127.32	51.81	24.09	12.12	27.99
1980	87.16	122.5	35.35	27.92	78.07	149.7	78.3	34.29	17.03	26.22
1981	157.79	63.13	101.79	21.15	22.1	56.98	103.12	46.13	22.53	27.82
1982	266.27	110.8	37.96	76.25	12.09	17.09	41.76	79.07	28.77	35.09
1983	511.68	237.57	60.72	21.2	48.6	7.01	11.12	33.57	74.83	47.81
1984	99.1	630.04	257.82	33.21	13.34	27.6	4.56	7.21	23.71	83.99
1985	158.27	71.02	652.7	211.58	18.73	8.6	17.35	2.88	4.77	69.88
1986	115.19	124.19	60.31	620.82	153.5	12.19	6.39	9.18	1.86	32.41
1987	108.66	78.85	85.34	45.82	469.82	107.16	7.39	4.39	4.75	18.97
1988	280.49	68.71	42.94	50.67	30.59	417.04	69.48	4.98	2.82	13
1989	354.92	274.99	45.65	25.92	30.38	16.72	339.35	37.49	3.47	9.75
1990	161.71	342.45	230.68	32.2	16.71	19.45	12.2	263.77	20.37	7.65
1991	182.17	124.5	312.75	163.68	21.17	10.71	13.42	9.34	151.55	15.37
1992	157.01	144.41	76.9	225.18	106.1	14.36	6.67	8.58	6.14	98.53
1993	43.14	118.77	115.01	50.12	146.3	67.12	9.86	4.03	5.02	48.46
1994	151.72	22.05	77.65	74.8	28.19	103.49	42.01	5.81	2.17	22.17
1995	163.35	116.1	13.19	51.4	44.45	14.84	54.45	21.49	2.9	9.27
1996	138.41	119.41	63.68	7.55	30.62	27.4	7.11	31.52	9.44	5.43
1997	174.39	103.29	78.76	31.81	4	15.75	13.71	2.91	14.84	5.62
1998	83.02	139.18	61.5	43.33	14.98	1.87	6.73	5.92	1.16	5.74
1999	116.76	52.96	91.54	32.12	20.67	5.27	0.83	2.23	2.02	1.89
2000	431.65	85.43	27.5	43.68	12.05	7.87	1.32	0.23	0.66	1.19
2001	100.1	460.79	59.68	14.37	17.38	2.84	1.87	0.27	0.06	0.49
2002	101.96	65.3	397.83	32.01	7.74	6.56	0.82	0.43	0.06	0.1
2003	200.88	65.05	40.02	308.27	19.48	3.84	3.57	0.25	0.08	0.03
2004	309.53	165.83	38.21	22.58	188.03	7.07	2.12	1.17	0.07	0.02
2005	174.74	278.73	108.73	19.33	11.5	96.67	2.78	0.84	0.17	0.03
2006	237.48	131.01	202.23	56.81	9.71	4.34	37.67	0.95	0.21	0.03
2007	86.61	193.32	79.42	110.97	20.06	3.41	1.48	10.69	0.18	0.05
2008	160.26	53.57	133.43	37.27	47.74	4.49	0.94	0.35	3.04	0.05
2009	156.42	115.23	25.13	77.44	15.49	19.08	1.01	0.19	0.06	1.18
2010	45.97	110.09	58.44	7.68	26.47	3.27	4.31	0.18	0.02	0.3
2011	97.88	22.75	46.87	13.16	1.35	3.84	0.44	0.41	0.02	0.04
2012	65.48	69.26	9.81	13.57	1.96	0.14	0.37	0.06	0.03	0.01
2013	49.29	48.67	41.09	2.87	3.37	0.28	0.02	0.02	0.01	0.01
2014	59.25	32.37	31.94	16.81	0.99	0.51	0.02	0.01	0.01	0
2015	82.84	40.23	17.33	15.75	4.4	0.41	0.07	0.01	0	0
2016	164.39	60.02	20.37	7.33	6.13	1.38	0.11	0.01	0	0
2017	25.25	162.8	42.91	8.3	2.41	2.1	0.36	0.01	0	0
2018	61.38	17.12	107.35	20.8	2.91	0.5	0.69	0.03	0	0

Table S11: Estimated F (fishing mortality-at-age) by CCAM.

Year	1	2	3	4	5	6	7	8	9	10
1968	0.01	0.03	0.07	0.09	0.13	0.13	0.13	0.13	0.13	0.13
1969	0.01	0.03	0.07	0.09	0.13	0.13	0.13	0.13	0.13	0.13
1970	0.01	0.03	0.07	0.09	0.13	0.13	0.13	0.13	0.13	0.13
1971	0.01	0.03	0.07	0.09	0.14	0.14	0.14	0.14	0.14	0.14
1972	0.01	0.04	0.08	0.1	0.15	0.15	0.15	0.15	0.15	0.15
1973	0.01	0.05	0.1	0.13	0.19	0.19	0.19	0.19	0.19	0.19
1974	0.01	0.04	0.09	0.12	0.17	0.17	0.17	0.17	0.17	0.17
1975	0.01	0.04	0.08	0.1	0.15	0.15	0.15	0.15	0.15	0.15
1976	0.01	0.03	0.07	0.09	0.14	0.14	0.14	0.14	0.14	0.14
1977	0.01	0.03	0.07	0.09	0.13	0.13	0.13	0.13	0.13	0.13
1978	0.01	0.03	0.07	0.09	0.13	0.13	0.13	0.13	0.13	0.13
1979	0.01	0.03	0.07	0.09	0.13	0.13	0.13	0.13	0.13	0.13
1980	0.01	0.03	0.07	0.09	0.13	0.13	0.13	0.13	0.13	0.13
1981	0.01	0.03	0.07	0.09	0.14	0.14	0.14	0.14	0.14	0.14
1982	0.01	0.04	0.08	0.1	0.14	0.14	0.14	0.14	0.14	0.14
1983	0.01	0.04	0.08	0.1	0.15	0.15	0.15	0.15	0.15	0.15
1984	0.01	0.04	0.08	0.1	0.15	0.15	0.15	0.15	0.15	0.15
1985	0.01	0.04	0.08	0.11	0.16	0.16	0.16	0.16	0.16	0.16
1986	0.01	0.04	0.08	0.1	0.15	0.15	0.15	0.15	0.15	0.15
1987	0.01	0.04	0.08	0.1	0.15	0.15	0.15	0.15	0.15	0.15
1988	0.01	0.03	0.07	0.1	0.14	0.14	0.14	0.14	0.14	0.14
1989	0.01	0.03	0.07	0.1	0.14	0.14	0.14	0.14	0.14	0.14
1990	0.01	0.04	0.09	0.11	0.17	0.17	0.17	0.17	0.17	0.17
1991	0.01	0.05	0.1	0.13	0.2	0.2	0.2	0.2	0.2	0.2
1992	0.01	0.06	0.12	0.16	0.23	0.23	0.23	0.23	0.23	0.23
1993	0.01	0.07	0.15	0.19	0.28	0.28	0.28	0.28	0.28	0.28
1994	0.02	0.08	0.18	0.23	0.34	0.34	0.34	0.34	0.34	0.34
1995	0.02	0.1	0.21	0.27	0.4	0.4	0.4	0.4	0.4	0.4
1996	0.02	0.13	0.28	0.35	0.52	0.52	0.52	0.52	0.52	0.52
1997	0.03	0.16	0.34	0.44	0.65	0.65	0.65	0.65	0.65	0.65
1998	0.03	0.19	0.41	0.53	0.78	0.78	0.78	0.78	0.78	0.78
1999	0.04	0.23	0.5	0.63	0.94	0.94	0.94	0.94	0.94	0.94
2000	0.05	0.26	0.56	0.71	1.05	1.05	1.05	1.05	1.05	1.05
2001	0.04	0.24	0.52	0.66	0.98	0.98	0.98	0.98	0.98	0.98
2002	0.04	0.2	0.43	0.55	0.82	0.82	0.82	0.82	0.82	0.82
2003	0.04	0.2	0.43	0.54	0.81	0.81	0.81	0.81	0.81	0.81
2004	0.04	0.21	0.45	0.57	0.85	0.85	0.85	0.85	0.85	0.85
2005	0.04	0.24	0.51	0.65	0.96	0.96	0.96	0.96	0.96	0.96
2006	0.05	0.26	0.56	0.72	1.06	1.06	1.06	1.06	1.06	1.06
2007	0.05	0.27	0.59	0.75	1.12	1.12	1.12	1.12	1.12	1.12
2008	0.05	0.27	0.59	0.75	1.11	1.11	1.11	1.11	1.11	1.11
2009	0.06	0.36	0.77	0.98	1.46	1.46	1.46	1.46	1.46	1.46
2010	0.08	0.47	1.01	1.29	1.91	1.91	1.91	1.91	1.91	1.91
2011	0.09	0.5	1.07	1.37	2.02	2.02	2.02	2.02	2.02	2.02
2012	0.08	0.43	0.92	1.18	1.75	1.75	1.75	1.75	1.75	1.75
2013	0.06	0.34	0.73	0.93	1.38	1.38	1.38	1.38	1.38	1.38
2014	0.05	0.28	0.59	0.76	1.12	1.12	1.12	1.12	1.12	1.12
2015	0.05	0.26	0.56	0.72	1.06	1.06	1.06	1.06	1.06	1.06
2016	0.05	0.26	0.56	0.72	1.06	1.06	1.06	1.06	1.06	1.06
2017	0.05	0.28	0.59	0.76	1.13	1.13	1.13	1.13	1.13	1.13
2018	0.05	0.28	0.6	0.76	1.13	1.13	1.13	1.13	1.13	1.13

Table S12: Variables and time periods used in testing the effects of environmental variables on recruitment, gain in adult condition, and distribution of landings.

Response variable	*Hypothesis tested*	*Explanatory variables tested*	
Recruitment	Match/Mismatch for larvae and food availability	Physical variables (1985-2016)	Spring timing (Proxy for plankton timing)
			SST MayJune (SST for first stages of larval development)
			SST MayNov (SST experienced during first feeding season)
			Last ice (Proxy for bloom timing)
			St Lawrence runoffs (Proxy for plankton availability in 4T) (inshore vs offshore)
		Biological variables (2001-2016)	Bloom timing
			Bloom duration
			Bloom magnitude
			C. finmarchicus abundance between June and September (preferred adult prey)
			C. hyperboreus abundance between June and September (preferred adult prey)
			Pseudocalanus spp. abundance between June and September (preferred larval prey)
			C. finmarchicus phenology in June
			C. hyperboreus phenology in June
			Pseudocalanus spp. phenology in June
Adult body condition increase in 4T and 4R	Match/Mismatch for adults and food availability	Physical variables (1985-2016)	SST Aug (Proxy for cold or warm water copepod species dominance)
			SST MayNov (Proxy for cold or warm water copepod species dominance)
			St Lawrence runoffs Proxy for plankton availability in 4T (inshore vs offshore)
			Bloom timing
		Biological variables (2001-2016)	Bloom duration
			Bloom magnitude
			C. finmarchicus abundance between June and September (prefered adult prey)
			C. hyperboreus abundance between June and September (prefered adult prey)
			C. finmarchicus phenology in June
			C. hyperboreus phenology in June
Proportion of landings (%) in 4R, 3K, or 3L	Distributions determined by food availability, densitiy dependance, and temperature	1982-2016	SSB (model output)
			Adult body condition increase in 4T or 4R
			Fall cooling timing (Proxy for GSL warming over the summer)
		2000-2016	SSB (model output)
			Adult body condition increase in 4T or 4R
			Fall cooling timing (Proxy for GSL warming over the summer)
			C. finmarchicus abundance in 3K, 3L, 4R, or 4T
			SST anomalies in 3K, 3L, 4R, or 4T

Table S13: Retained Generalised Additive Models describing the effects of environmental variables on recruitment and gain in condition (K_{GAIN}) over different time periods as per the availability of data. Deviance explained in bold brackets. Only the 2001-2016 time series are described in the text. Non significance of model or variable indicated by bold NS.

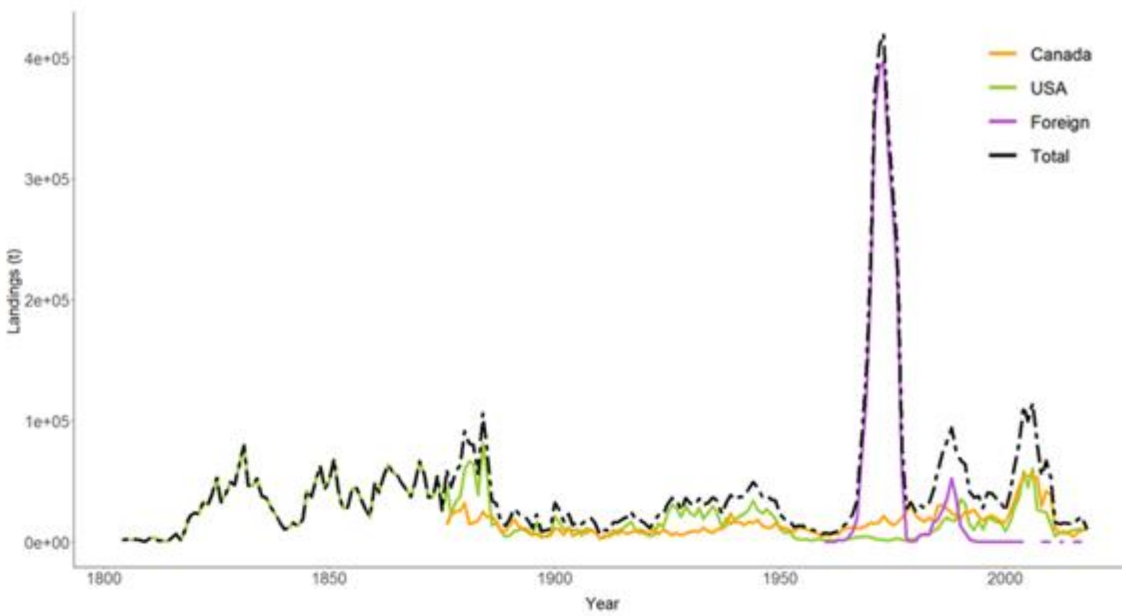
1982-2014	*1985-2016*	*2001-2016 (only physical variables)*	*2001-2016 (both physical and biological variables)*
Recruitment **~** Last Ice + *C. finmarchicus* abundance + *Pseudocalanus spp.* abundance **[62%]**	Recruitment ~ St. Lawrence runoffs^{ns} + Spring timing **[37%]**	Recruitment ~ SST May-Nov + St. Lawrence runoffs **[57%]**	Recruitment ~ Spring timing + *C. finmarchicus* abundance + Pseudocalanus spp. phenology **[75%]**
	K_{GAIN_4R} ~ **NS**	K_{GAIN_4R} ~ **NS**	K_{GAIN_4R} **~** Bloom amplitude + *C. hyperboreus* abundance + C. finmarchicus phenology **[80%]**
	K_{GAIN_4T} ~ **NS**	K_{GAIN_4T} ~ SST May-Nov + St. Lawrence runoffs + Spring Timing **[62%]**	**K_{GAIN_4T}** ~ St. Lawrence runoffs + Bloom timing + C. finmarchicus phenology **[83%]**

Table S14: Retained Generalised Additive Models describing the proportion (%) of landings (Deb) as a function of physical and biological environmental variables over different time periods as per the availability of data. Deviance explained in bold brackets.

1982-2016	*2000-2016*
%Deb 3K ~ SSB + K_{GAIN}_4R **[56%]**	%Deb 3K ~ K_{GAIN}_4R + *C. finmarchicus abundance_3K* + SSB^{ns} **[80%]**
%Deb 3L ~ SSB + K_{GAIN}_4R **[49%]**	%Deb 3L ~ SSB + K_{GAIN}_4R + *C. finmarchicus abundance_3L* **[63%]**
%Deb 4R ~ SSB + K_{GAIN}_4T + Fall timing **[67%]**	%Deb 4R ~ K_{GAIN}_4T + Fall timing **[49%]**

APPENDIX II – SUPPLEMENTARY FIGURES

A



B

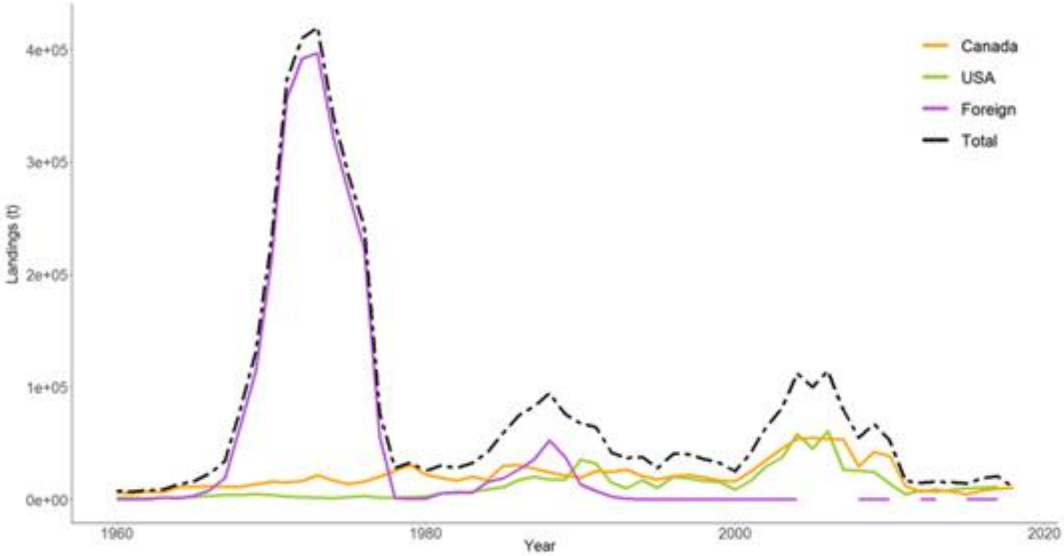


Figure S1. A) Atlantic mackerel catches (t) in the Northwest Atlantic since 1804 and B) since 1960.

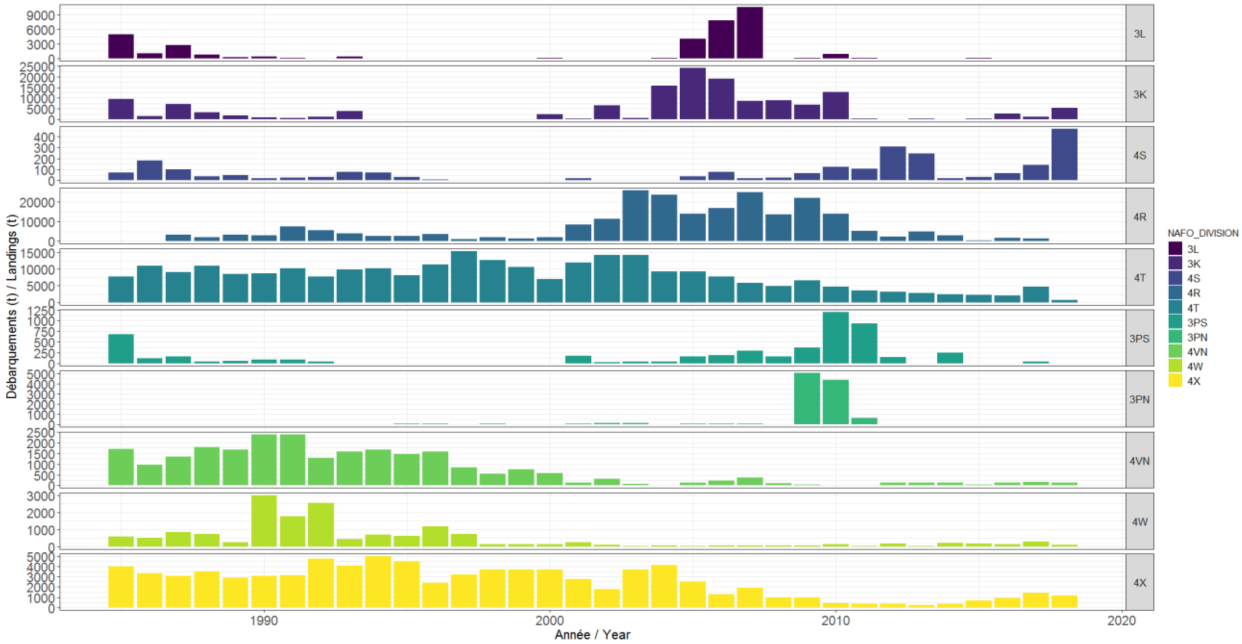


Figure S2. Landings by NAFO Divisions from 1985-2018. Scale varies among NAFO Divisions.

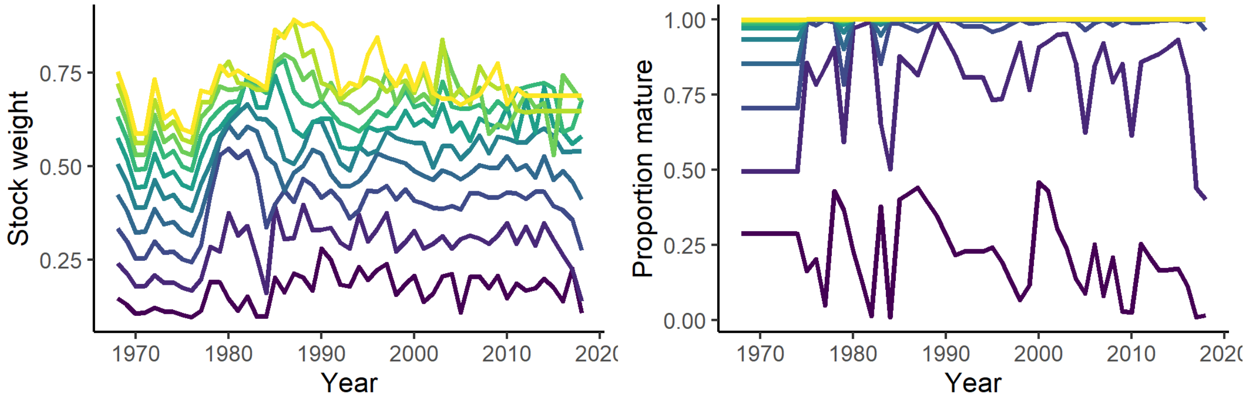


Figure S3. Stock weight (left panel) and proportion mature (right panel, ages 1 to 10+) data. Used deterministically within the assessment model to transform abundances to biomass.

Figure S4: Mean length-at-age from commercial samples from NAFO subareas 3-4 from 1973-2018.

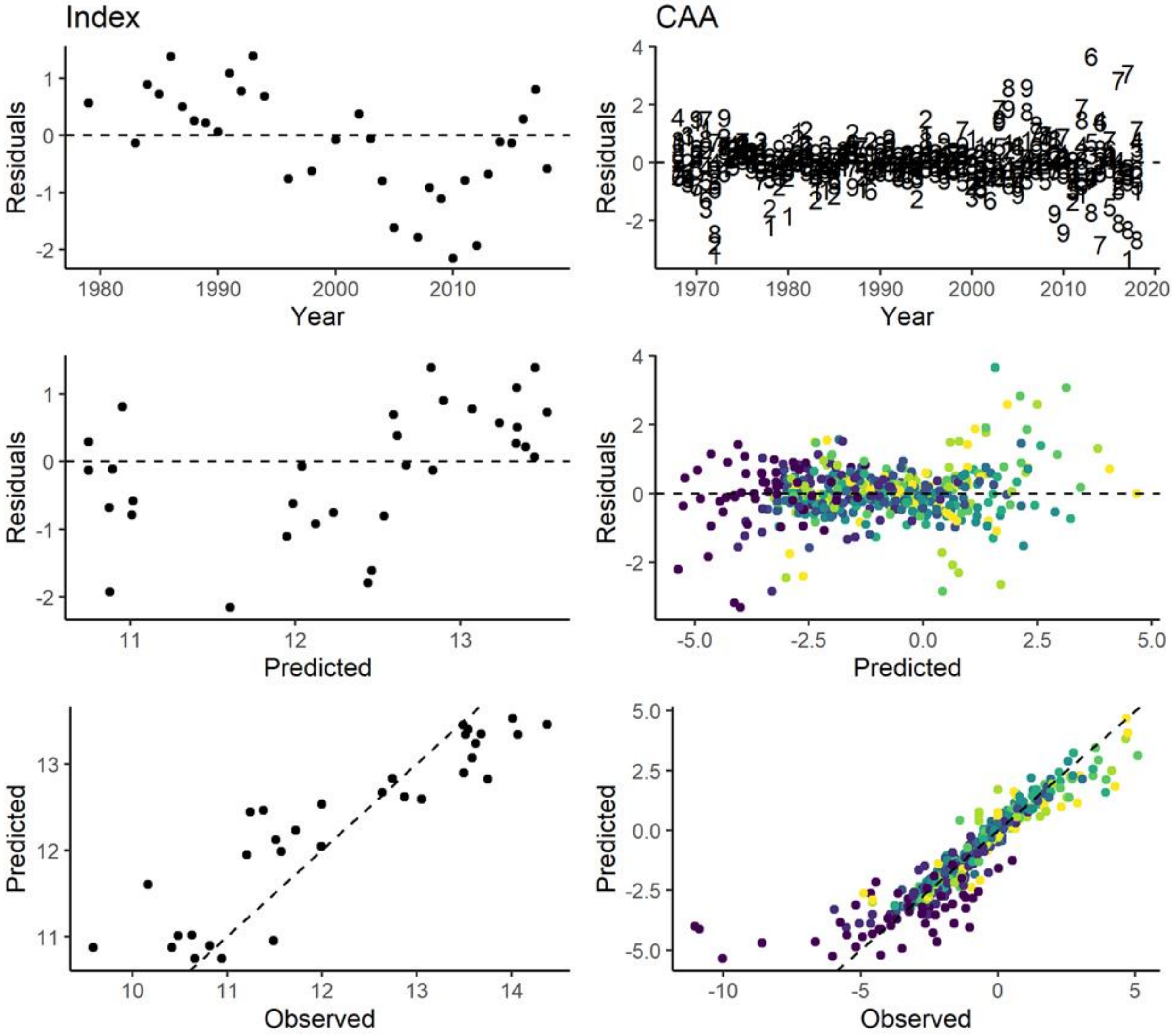


Figure S5: Model residuals. The color scale indicates the age classes (young to old as violet to yellow).

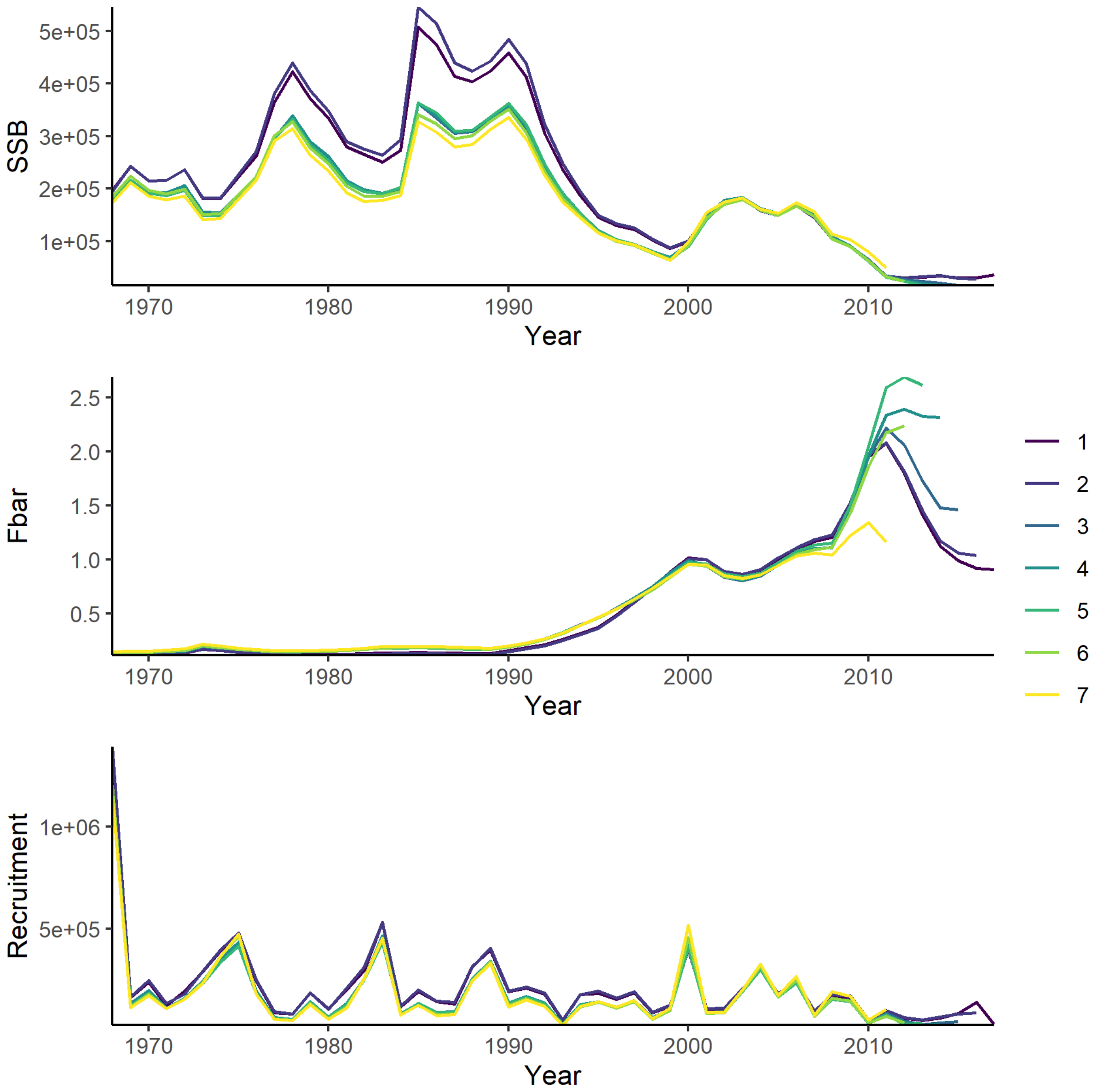


Figure S6: Retrospective patterns (Fbar = F over aged fully recruited to the fishery, i.e., ages 5-10).

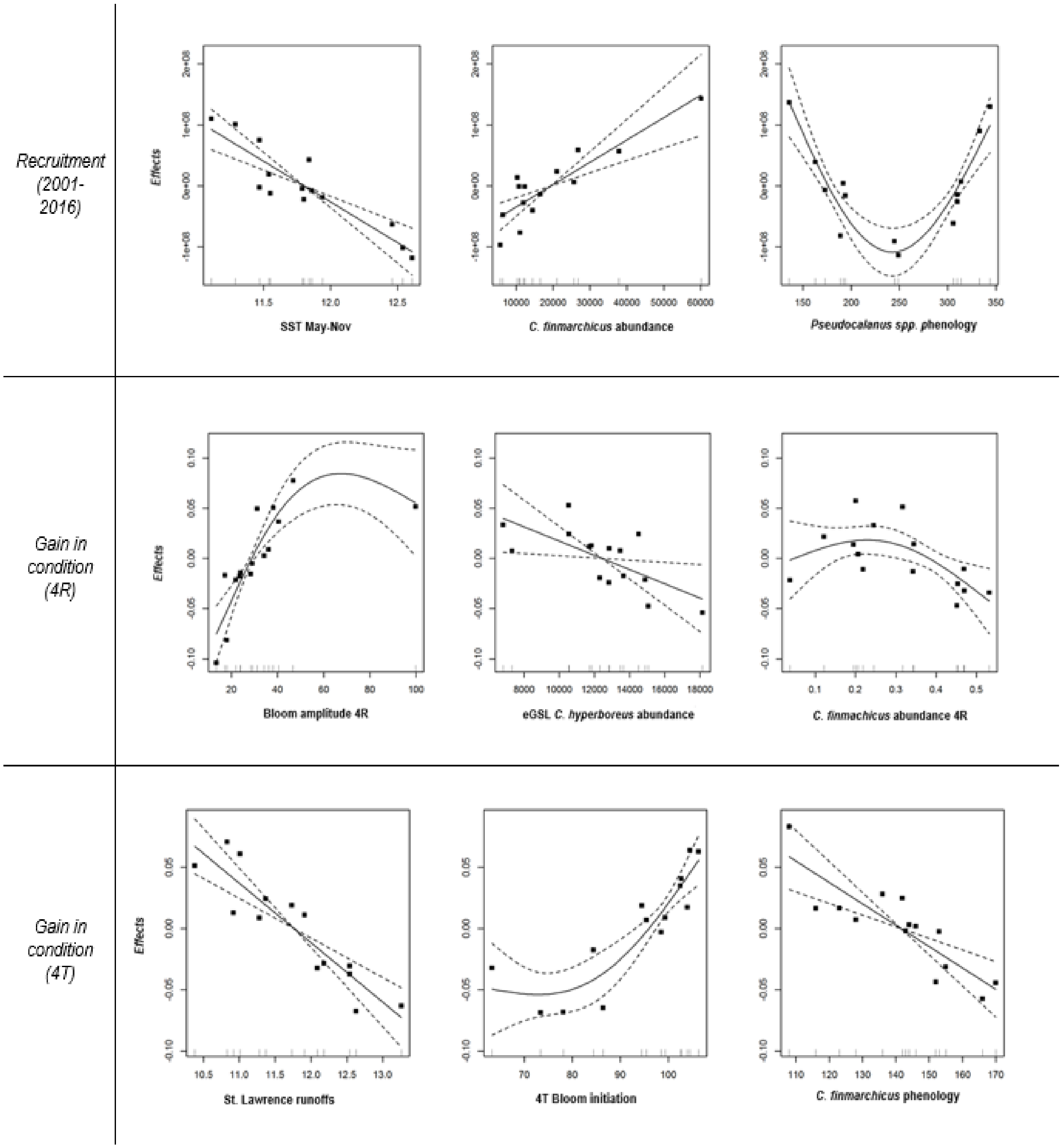
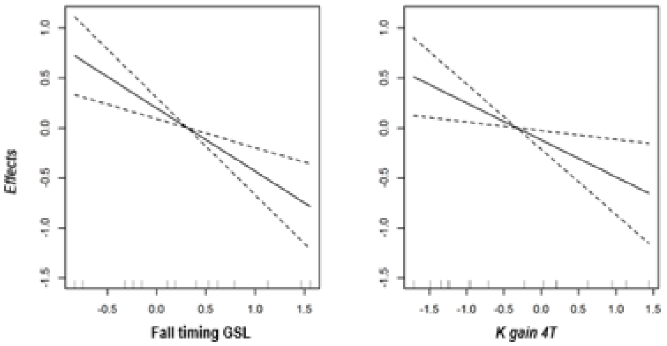
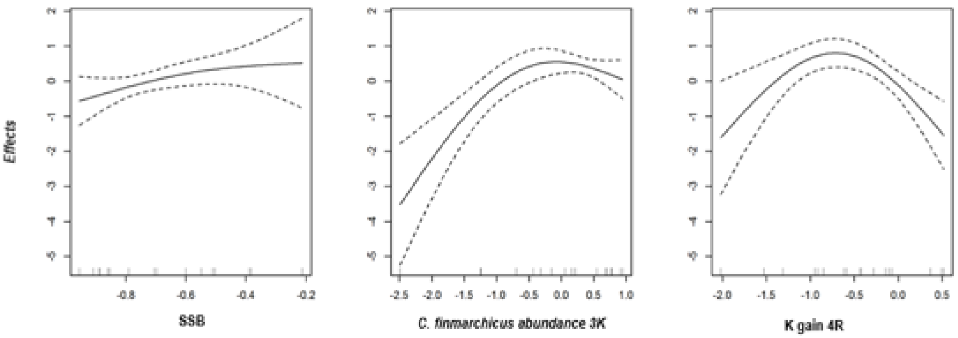


Figure S7: Effects plots of retained generalised additive models. Only models including both biological and physical variables are shown (see Tables S12-S14 for variable and model details).

% Landings in 4R



% Landings in 3K



% Landings in 3L

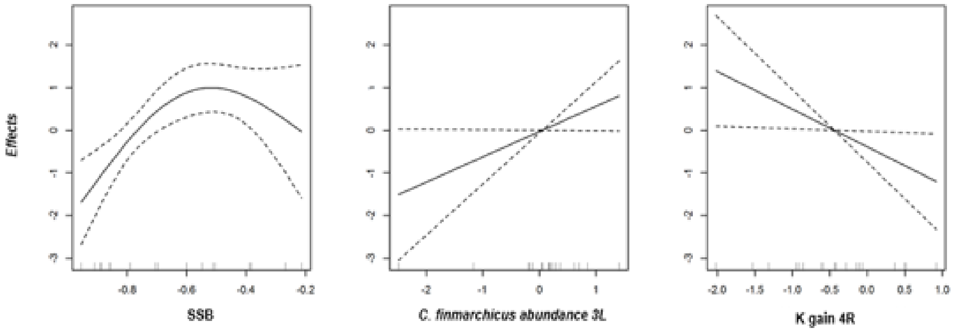


Figure S7 (continued): Effects plots of retained generalised additive models. Only models including both biological and physical variables are shown (see Tables S12-S14 for variable and model details).