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Assessment of the northern contingent of Atlantic Mackerel (*Scomber scombrus) in 2020*

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Foreword0

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 the Northwest Atlantic mackerel (*Scomber scombrus* L.; henceforth mackerel) is assessed every two years using an age-structured stock assessment model. This document presents the data and methods used to calculate the main stock status indicators for mackerel that form the short-term advice given to Fisheries Management in the setting of quotas (i.e. Total Allowable Catch; TAC), potentially as part of a broader set of Harvest Control Rules (HCR). This stock assessment indicates that, in 2020, mackerel were still in the Critical Zone as per Fisheries and Oceans Canada's Precautionary Approach (PA) framework. Spawning stock biomass (SSB) in 2020 was the second lowest estimated since 1968. Low biomass is currently paired with overexploitation and the loss of older individuals from the population. The last notable recruitment event was in 2015 but fish belonging to this cohort now represent less than 8 % of the fish harvested in 2020. Rebuilding the stock above the Limit Reference Point by 2023 is about as likely as not (32%-56%) to happen under the various Total Allowable Catch (TAC) scenarios considered (0 t-1000 t) .Short term projections over three years indicate that stock growth (SSB 2023 > 2021) is likely (66%-86%) at TACs decreasing from 4000 t to 0 t and are just as likely as not (42%-57%) at TACs decreasing from 10 000 t to 6000 t.

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. This assessment is carried out every two years by Fisheries and Oceans Canada (DFO) by the Pelagics Section in the Pelagic and Environmental Science Direction (DSPE) at the Maurice Lamontagne Institute (IML) in Mont-Joli, Québec, Canada. The current assessment provides information on mackerel stock status with respect to reference points at the end of 2020 including spawning stock biomass, recruitment, and fishing mortality. Advice, including three year projections, are provided to Fisheries Management (FM) for the 2021 and 2022 fishing seasons.

Mackerel stock status has been evaluated with a state-space censored-catch-at-age stock assessment model (CCAM; Van Beveren et al. 2017a) since 2017 (DFO 2017, Doniol-Valcroze et al. 2019). State-space models can treat both process error in the population dynamics as well as observation error and are considered by many to be the best practice for stock assessments (Bolker 2008, Auger-Méthé et al. 2016, Aeberhard et al. 2018). The model is fit to both fisheries-independent and fisheries-dependent data as input and estimates, among other things, spawning stock biomass (SSB), recruitment (age 1 fish), and instantaneous fishing mortality (F). Fisheries-independent data included a total egg production index (TEP) which is derived from an annual mackerel egg survey (1979-2020) and fisheries-dependant data included catch statistics and biological samples acquired from the commercial mackerel fishery (1968-2020). The biological data is also used to calculate additional annual model input including mean masses, proportion mature, fecundity, as well a sex ratio (ages 1-10+).

The last stock assessment took place in March, 2019 and provided FM with advice for the 2019 and 2020 fishing seasons (DFO 2019; Smith et al., 2020). A Management Strategy Evaluation (MSE) was also peer-reviewed during the last assessment (DFO 2020b; Van Beveren et al., 2020a,b) and included the longer-term evaluation of Harvest Control Rules under a variety of uncertainties with respect to objectives defined by the Rebuilding Plan Working Group (RPWG). Results were presented to the RPWG to inform the Rebuilding Plan.

The results of the last stock assessment and MSE indicated that in 2018, mackerel had been in the Critical Zone since 2011 following a period of intense exploitation ($F > F_{ref}$). This low biomass was accompanied by an age truncation and an estimation of future lower mean recruitment. Following the 2019 stock assessment, FM recommended a TAC of 8 Kt to the Minister of Fisheries, Oceans, and the Canadian Coast Guard. This recommendation was approved for the 2019 fishing season and rolled-over for the 2020 fishing season.

METHODS

LANDINGS

Commercial fisheries data for mackerel caught in Canada's Exclusive Economic Zone (EEZ; i.e. portions of NAFO Subareas 2-5) were acquired from the most recent ZIFF (Zonal Interchange File Format) files produced by DFO's regional statistics bureaus for the years 1995-2020. 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). At the time of this assessment, landings data for the 2019 and 2020 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). Data from the U.S. commercial and recreational fisheries (1960-2020) were provided by the Northeast Fisheries Science Center (NEFSC). The U.S. catch statistics were also preliminary for 2019 and 2020.

COMMERCIAL SAMPLING

Mackerel have been monitored annually through DFO's commercial port sampling program since 1973 and spans the major ports in Eastern Canada where mackerel landings occur and covers the entire fishing season to ensure adequate spatio-temporal coverage. Port samplers provide length frequency data from a random sample of the catch (measured to the nearest 5 mm) and send a length-stratified subsample (two fish per length-class) to IML for further analyses. Biological samples acquired from research projects and/or DFO bottom trawl surveys have occasionally been used to complete age-length-keys. The measurements taken from the biological samples include: fork-length (± 1 mm), mass (± 0.1 g), sex, gonad mass (± 0.01 g), stage of sexual 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. 2009).

The number of length frequency and biological samples as well as the total number of fish measured in each dataset are summarized in Table S3 for the years 1985-2020. They are matched with their corresponding landings. While sampling effort for mackerel has varied over time and area, stratified landings by year, quarter, NAFO division, and gear type (i.e. the stratification used to aggregate age-length-keys and length frequency data to estimate catch at age) of over 1000 t are generally well sampled (Doubleday & Rivard, 1983). On average, 117 length frequency samples (13 193 fish) and 75 biological samples (2526 fish) are collected annually (1985-2020).

CATCH-AT-AGE

Catch-at-age was updated for the years 2015-2020 as landings and the number of biological and length frequency samples from the commercial fishery had been updated. Catch-at-age has been calculated using a variety of methods over the years including APL, MS Excel, and most recently a "black box" program written in Visual Basic (Grégoire et al. 2014c). Code to estimate catch-at-age was written in R based on equations detailed by Gavaris and Gavaris (1983) and functions in the FSA package (Ogle 2015) for the last stock assessment (Smith et al., 2020) as these programs were no longer maintained nor functioned in recent operating systems. The results were then compared to published data to verify that the numbers and proportions at age were consistent with what was previously calculated in the Visual Basic Program. Using landings data and corresponding commercial biological and length frequency samples, we were able to calculate the age compositions and mean masses-at-age of fish caught in the fishery for a given year.

Briefly, landings were tabulated by year, quarter, NAFO division, and gear type (hereafter strata k) for pairing with corresponding length frequency and biological samples judged to have the best representability. In the event that there were insufficient samples corresponding to a given stratum, samples were attributed to the strata using the following hierarchy: across similar gear types within a given NAFO division and quarter, across similar gear types and adjacent NAFO divisions within a quarter, and across similar gear types, adjacent NAFO Divisions, and adjacent quarters. Note that only quarters one and two were ever combined as there are generally sufficient samples otherwise. In cases where biological samples with no corresponding length frequency data occurred, we considered their numbers and proportions-at-age directly.

The stratum-specific numbers and proportions-at-age per length category of 5mm from biological samples were used to attribute ages to the corresponding stratified length-frequency data using the alkIndivAge() function in the FSA package (Kimura 1977; Isermann and Knight 2005; Ogle 2015). Stratified numbers at age were then calculated by summing across length categories. Mass-length relationships per year and quarter were calculated and predicted masses were assigned to the corresponding now age-assigned length frequency data. The sum of masses per strata were weighted by their corresponding stratified frequencies and proportions in the data to obtain the strata-specific sample mass. Total landings per stratum were then transformed to strata-specific catch-at-age by multiplying the numbers-at-age by the ratio between the strata-specific landings and their corresponding sample masses. Annual catch-at-age was then obtained by summing over all strata. Annual catch-at-age in terms of biomass was obtained by multiplying catch-at-age by the predicted mean-masses-at-age.

TOTAL EGG PRODUCTION

The TEP index is calculated from mackerel egg abundance data collected from a dedicated annual survey in the southern Gulf of Saint Lawrence (GSL). The survey ran almost continuously since 1979 but no surveys were conducted in 1980-1981, 1995, 1997, or 2020, the latter due to restrictions imposed by the Covid pandemic. Surveys conducted in 1982, 1999, and 2006 were invalidated during peer review due to either equipment failures or mission timing with respect to mackerel spawning. The survey samples the ichthyoplankton of the top 50 m of the water column along 65 fixed stations using 61 cm Bongo nets with 333 µm mesh deployed for a minimum of 10 minutes while cruising at roughly 2.5 knots. Tows were generally double oblique but could result in towyos at shallower stations (i.e. < 50 m). Filtered volume, sampled depth, and the mean temperature (C°) in the top 10 m of the water column are calculated at each station. Stage 1 and 5 eggs are summed from a subsample of each station and density ($\mathrm{N}\cdot\mathrm{m}^{-2}$) is estimated by accounting for the fractioned sample, the volume of sea water filtered, and the depth sampled.

Daily Egg Production (DEP_{sy}) was then calculated by accounting for the incubation time of eggs and the mean temperature (T) of the first ten metres of the water column at each station Lockwood et al. (1977). From these values, mean annual DEPs and their associated standard deviations were calculated.

$$DEP_{sy} = \frac{Egg\ density_{sy}}{e^{[-1.61 \cdot log(T) + 7.76]}} \cdot 24\ hours$$

Station-specific values were then extrapolated using ordinary krigging. Means and variances were calculated over the krigged surface and subsequently multiplied by the survey area (69 450 km^2) to calculate the annual DEP (DEP_y).

DEP_y was converted to the annual TEP index by multiplying it by the proportion of eggs spawned at the median day of the survey (S_y) (i.e. $TEP_y = DEP_y \cdot S_y$). S_y was estimated by fitting logistic models describing the annual seasonal progression of individual gonadal development during the spawning period. Specifically, the Gonado-Somatic-Index (GSI) was modelled as a function of the day of year (Julian day) using a four parameter logistic model:

$$GSI_y = y_0 + \frac{a}{\left[1 + \left(\frac{x}{x_0}\right)^b\right]}$$

where:

x the day the fish was caught (in Julian days),

y_0 is the upper asymptote,

a is the lower asymptote,

b is the slope,

And x_0 is the inflection point.

The proportion of eggs spawned on the median date of the mission is calculated by using the density curve obtained from the logistic model (above). From this, we derived the peak day of spawning and the beginning and end of the spawning season as defined by the 5% and 95% quantiles. Methods for the sampling protocol and subsequent analyses to calculate various aspects of mackerel egg production and the resulting biomass index are described in greater detail by Girard (2000) and Grégoire et al. (2014a,b,c).

MASS-AT-AGE

Mean masses-at-age were updated for 2017-2020. As per previous assessments, annual mean masses-at-age were calculated from the predicted masses of length frequency samples (Grégoire et al., 2014d). The predicted masses were estimated from individual mass-length models for each combination of year and quarter (see the catch-at-age section above).

MATURITY-AT-AGE AND L_{50}

Maturity-at-age (i.e. the proportion of mature individuals in the population at a given age) is used in the stock assessment model to convert numbers-at-age to SSB and was calculated from commercial samples collected during spawning (June-July) and was updated for 2017-2020. Since the last assessment (Smith et al. 2020) this has been calculated in R using annual generalised linear models (GLM) using the binomial family distribution with logit link functions. When no data were available for a given combination of year and age, gaps were filled via linear interpolation for ages 2-10+. For age 1 fish, gaps were filled with the mean value as age 1 fish are more poorly sampled by the fishery and the gaps were too numerous to be filled by linear interpolation. For the years where no data existed (1968-1973) the value for 1974 was used.

Maturity ogives were used to estimate the length at which 50% of individuals attain maturity (L_{50}). The proportion of mature individuals-at-length were fit by individual GLMs by cohort (1960-2018) and were subsequently used to calculate $L_{50.}$ During the last assessment, L_{50} was calculated by year, however, calculating L_{50} by cohort makes more biological sense. In instances where fewer than 10 mature or immature individuals were available in a given year, these were excluded from the analyses.

FECUNDITY

Annual fecundity was, for the first time, disaggregated by year and age, reflecting recent changes in the model structure (see the equations in the appendix of Van Beveren et al 2020a,b). First, raw fecundity data from Pelletier's (1986) study were extracted and the logs of the observed fecundities of stage 5 (i.e. ripe) females (fec_i) were modelled as a function of their respective gonad masses GM_i) and age (A_i) (i.e. $\log(fec_i) \sim \alpha + \beta 1(GM_i) + \beta 2(A_i) + \epsilon_i$). The model was fit in R using a GLM with a Gaussian distribution and identity link function.

The model was then used to predict individual fecundity from the available biological data on stage 5 females (see the commercial sampling section above) for all years. The means of the individual fitted values were then calculated by year and age. When no data were available for a given combination of year and age, gaps were filled via linear interpolation for ages 2-10+. For age 1 fish, the model coefficient for age was used as age 1 fish are more poorly sampled by the fishery and the gaps were too numerous to be filled by linear interpolation. For the years where no data existed (1968-1974) the mean values at age were used. As mackerel are indeterminate batch spawners and there is evidence of mass atresia during the spawning season in some samples, these estimates should be taken as potential fecundities (Pelletier 1986).

STOCK ASSESSMENT MODEL

The model (CCAM) was developed using the Template Model Builder (TMB; Kristensen et al. 2016) package in R (R Core Team 2019) and is largely based upon SAM (stock assessment model; Nielsen and Berg 2014; Berg and Nielsen 2016) as well as elements from the Northern Cod assessment model (NCAM; Cadigan 2016). Model equations are provided in Table S5. The model is denoted "censored" as it uses an approach in which reported catches are explicitly considered uncertain, and are thus estimated to occur between a lower limit, corresponding to reported catches, and an upper limit corresponding to estimates of unaccounted-for removals. All data, model code, and scripts for the current assessment are available online. Model configuration in the current assessment is the same as Core model 1 developed as part of the MSE process (Van Beveren et al. 2020a,b).

Input data were updated for total Canadian and U.S. catch, mean mass-at-age, proportion mature, fecundity, sex ratio, and total egg production. Some changes were made in how input data were derived since the last assessment (see the sections on TEP and fecundity above). These changes include the use of TEP as opposed to the SSB index (as per Van Beveren et al., 2020a,b), updates into how fecundity was estimated as well as the “smoothing” of fecundity, proportion mature, and mean masses-at-age data by way of cubic splines with the smoothing factor set to 0.5. Changes to the upper bounds of catch estimates for 2018-2020 reflect improvements made to catch monitoring in the commercial and bait fisheries as well as newly proposed regulations to the recreational fishery; absolute values were iteratively lowered by 25% each year for 2018-2020. As mixing between the northern and southern contingents occurs (Redding et al. 2020), proportions of U.S. landings (commercial, recreational, and discards) were added to the lower and upper bounds (25% and 50% respectively). Detailed U.S. catch data was not available for 2020 so the mean landings of the last 5 years was used for projections.

Short-term projections were performed as a basis for TAC advice for the 2021-2022 fishing seasons. Recruitment was projected forwards using a Beverton-Holt Stock-Recruit relationship, which was deemed the most realistic scenario during the last stock assessment, with a temporal autocorrelation of 0.9 (Smith et al., 2020; Van Beveren et al., 2020a,b). Projections made the assumption that unaccounted for removals in Canadian waters would decrease.

In correspondence with the 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 (i.e. Spawners-Per-Recruit (SPR) at $F_{40\%}$ multiplied by the average recruitment over 1969-2020).

RESULTS AND DISCUSSION

The key indicators used as model inputs for this stock are total catch statistics, catch-at-age, TEP, proportion mature, 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

Following a period of greater exploitation in the Northwest Atlantic during the 1960s and 1970s , nominal landings in Canadian waters from 1980 to 1999 were relatively stable and averaged around 22 534 t per year (Figure 1). From 2000 to 2010, average landings increased to 40 593 t. This period of greater landings reached a record high of 54 809 t in 2005 due to the marked increase in fishing effort by small and large seiners off the coasts of Newfoundland, and the presence of the large 1999 year class (Patterson 2014). This period was followed by a severe drop in landings that reached a reaching a low of 4272 t in 2015 (the fourth lowest on record since 1876). At the time of the current assessment landings in Canada's EEZ for 2016-2020 were 8057.42 t (TAC 8000 t), 9786.36 t (TAC 10 000 t), 10 963.87 t (TAC 10 000 t), 8623.16 t (TAC 8000 t), and 7772.36 t (TAC 8000 t) respectively. Catch data since 1960 for the entire NWA stock are presented in Table S1 and Figure S1. Landings occurring solely within Canada's EEZ and split by DFO region and grouped NAFO divisions are presented in Tables S2-S3.

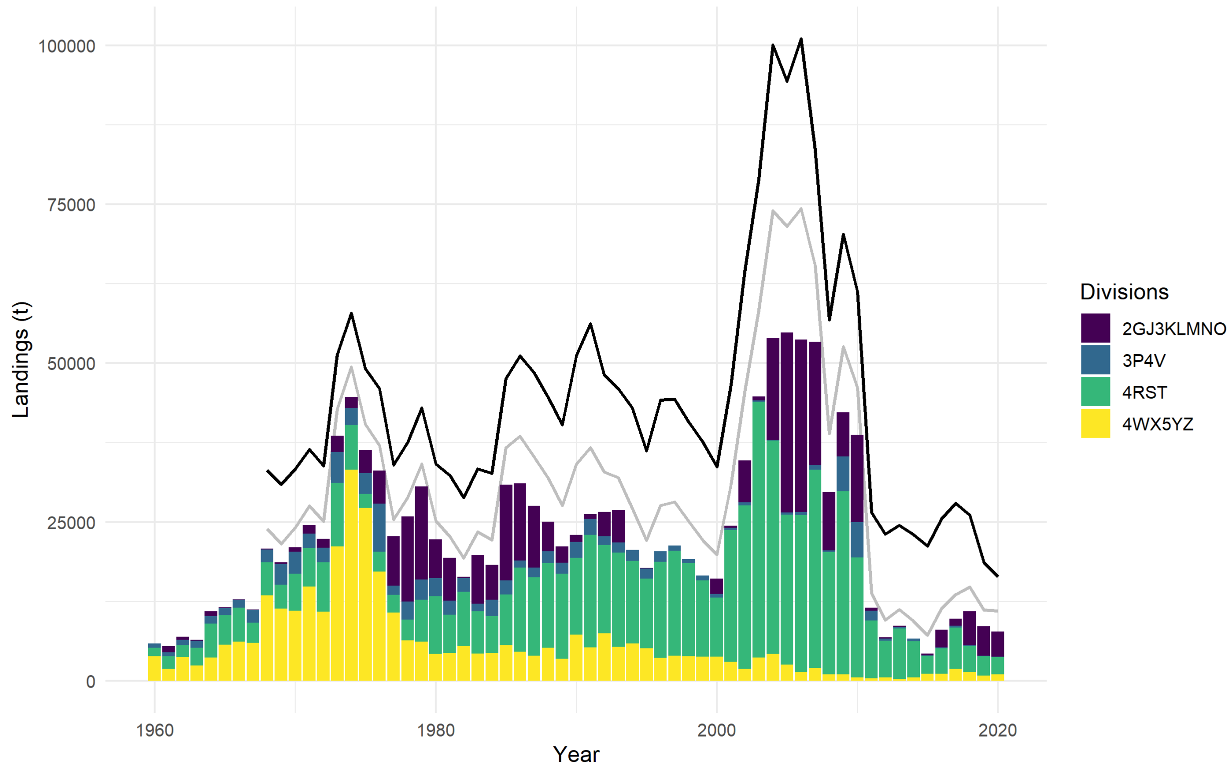

Figure 1. Landings (t) within Canada's Exclusive Economic Zone by large scale oceanographic regions defined by NAFO Divisions with indication of the lower (grey) and upper (black) bound of the estimated total removals (including unaccounted-for catches of Canada and the US).

CATCH-AT-AGE

Known strong year classes (i.e. 1968, 1973, 1974, 1982, and 1999) are clearly distinguished in the catch-at-age data (Figure 2) and their progression from year to year can be easily tracked. 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.

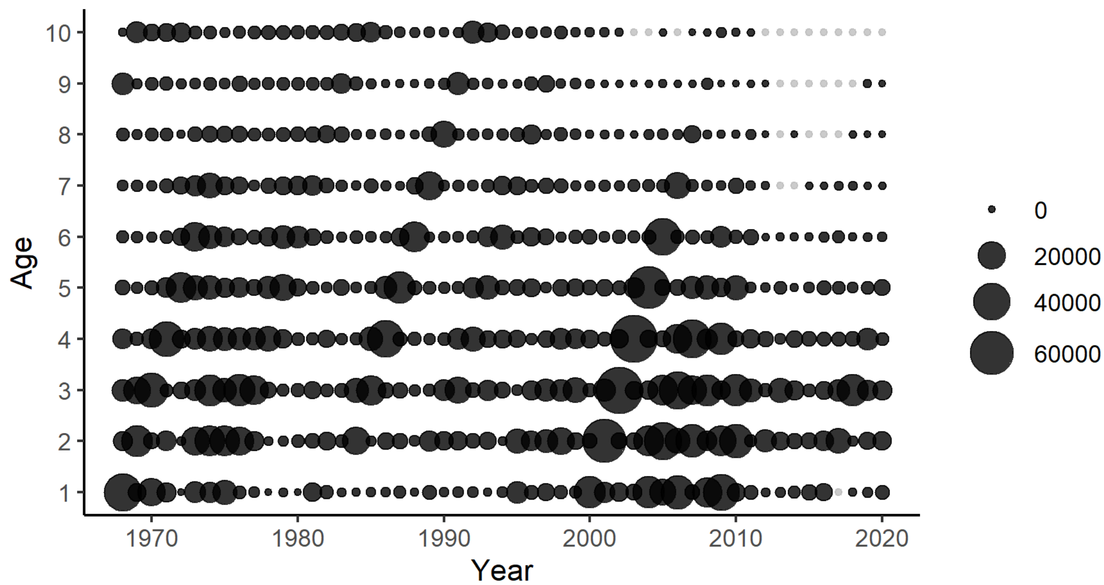

Figure 2. Catch-at-age (1-10+) from 1968-2020. Grey dots represent zeros.

TOTAL EGG PRODUCTION

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 the past decade (Figure 3). Mean TEP from 1979 to 1994 was 513 billion eggs. Between 1994 and 1999, TEP dropped to 63 billion eggs, approximately 12% of the values observed from 1979-1994. TEP began to rise again in 2000 reaching a peak of 233 billion eggs in 2003 but started to decline the following year and subsequently reached a time series low value in 2012 at 8.67 billion eggs (approximately 2% of the values observed from 1979-1994) and has continued to stay low since then. In 2018 and 2019,TEP was 38.76 and 56.82 billion eggs respectively and mean TEP from 2005 to 2019 was 47 billion eggs. Furthermore, the area over which mackerel eggs are distributed and the timing of spawning has contracted (Brosset 2020). As has been observed in recent years, spawning activity was limited to the western portions of the survey area in 2019.

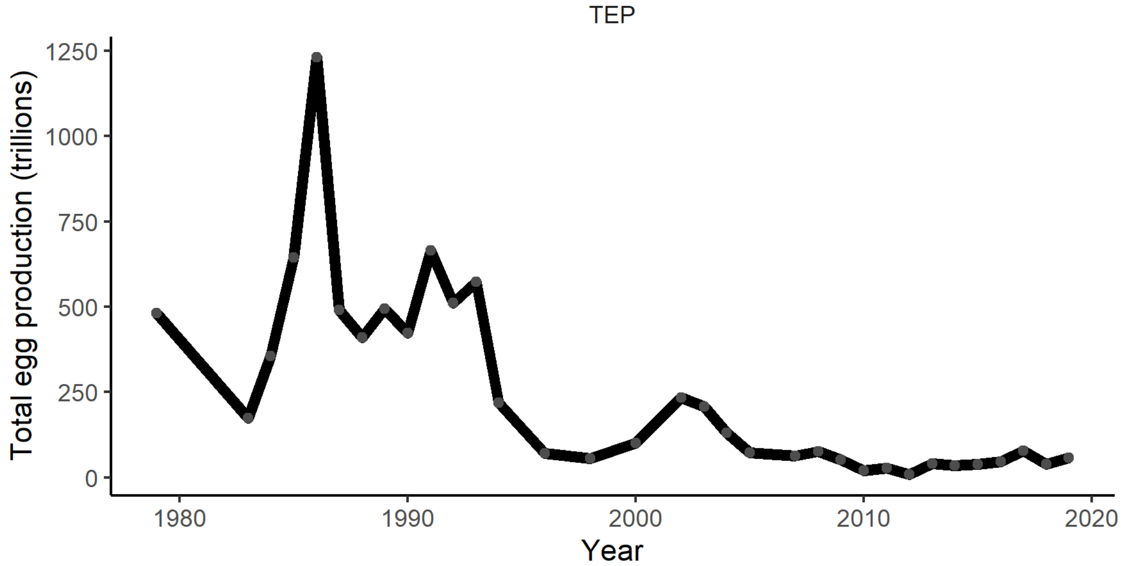

Figure 3. Relative total egg production index derived from the egg survey.

MASS-AT-AGE

Mean masses-at-age (Figure 4) are relatively stable over time but show some inter-annual variability. Values increased for all ages in the late 1970s and early 1980s and then decreased to remain relatively stable subsequently. Ages 1 and 2, however, continued to increase in mass-at-age until the early 1990s. Variation in the mean masses of older fish from 2000 onwards are likely due to the collapsed age structure of the stock and thus fewer sampled fish being available for calculations.

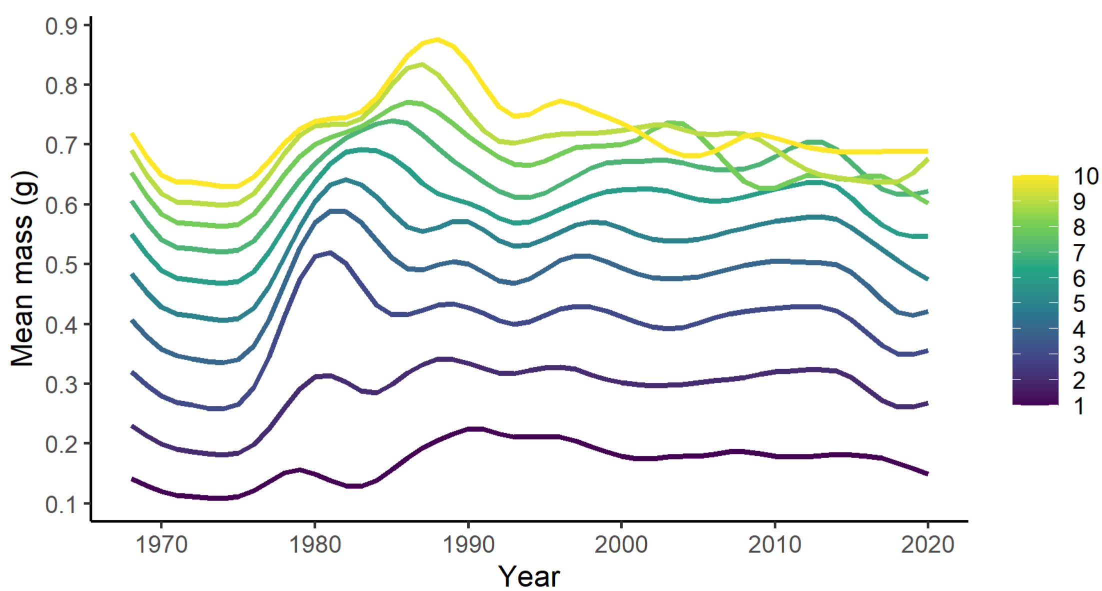

Figure 4. Smoothed mean mass-at-age (g) for ages 1-10+ from 1968-2020. Colours representing ages range from violet (age 1) to yellow (ages 10+).

MATURITY-AT-AGE AND L_{50}

Most mackerel reach sexual maturity around age 3 (Figure 5). More inter-annual variation is observed for age 1 and 2 fish. the proportion of mature age 1 and 2 fish showed similar trends over time which were characterized by an increase in values during the 1980s, a decrease in the 1990s, and an increase in the early 2000s. Trends for ages 1 and 2 started to differ from 2010 onwards with a greater proportion of age 1 fish becoming mature but fewer mature age 2 fish.

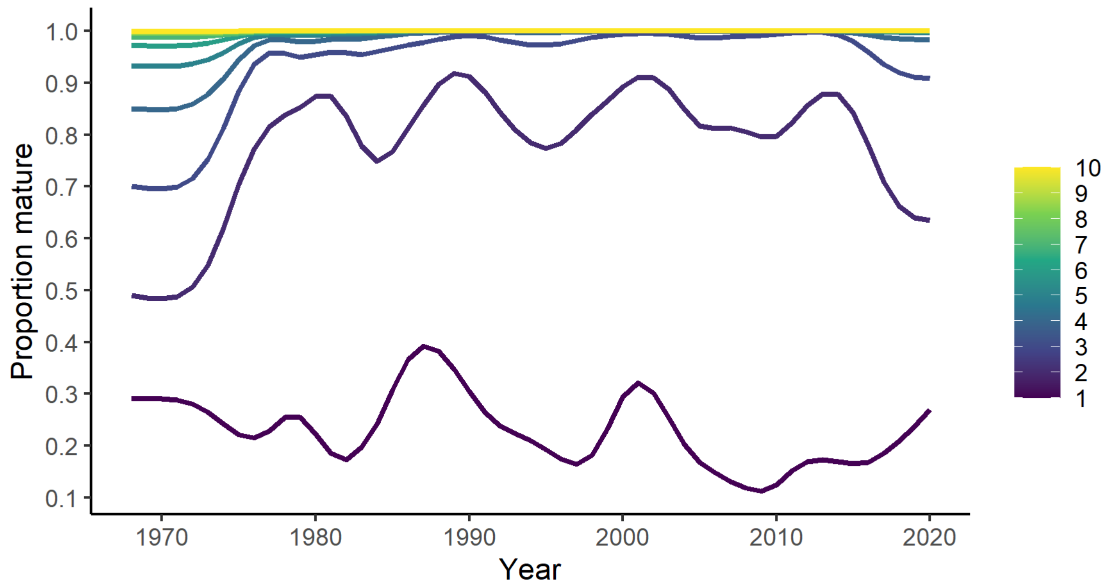

Figure 5. Smoothed estimates of the proportion of mature fish-at-age for ages 1-10+ from 1968-2020. Colours representing ages range from violet (age 1) to yellow (ages 10+).

L_{50} has varied between 169-298 mm for the 1974-2018 cohorts with a time series mean of 262 mm +/- 25.7 (the mean standard errors; Figure 6). The mean L50 for the 2014 to 2018 cohorts was 266 mm +/- 1.50 (the mean of the standard errors).

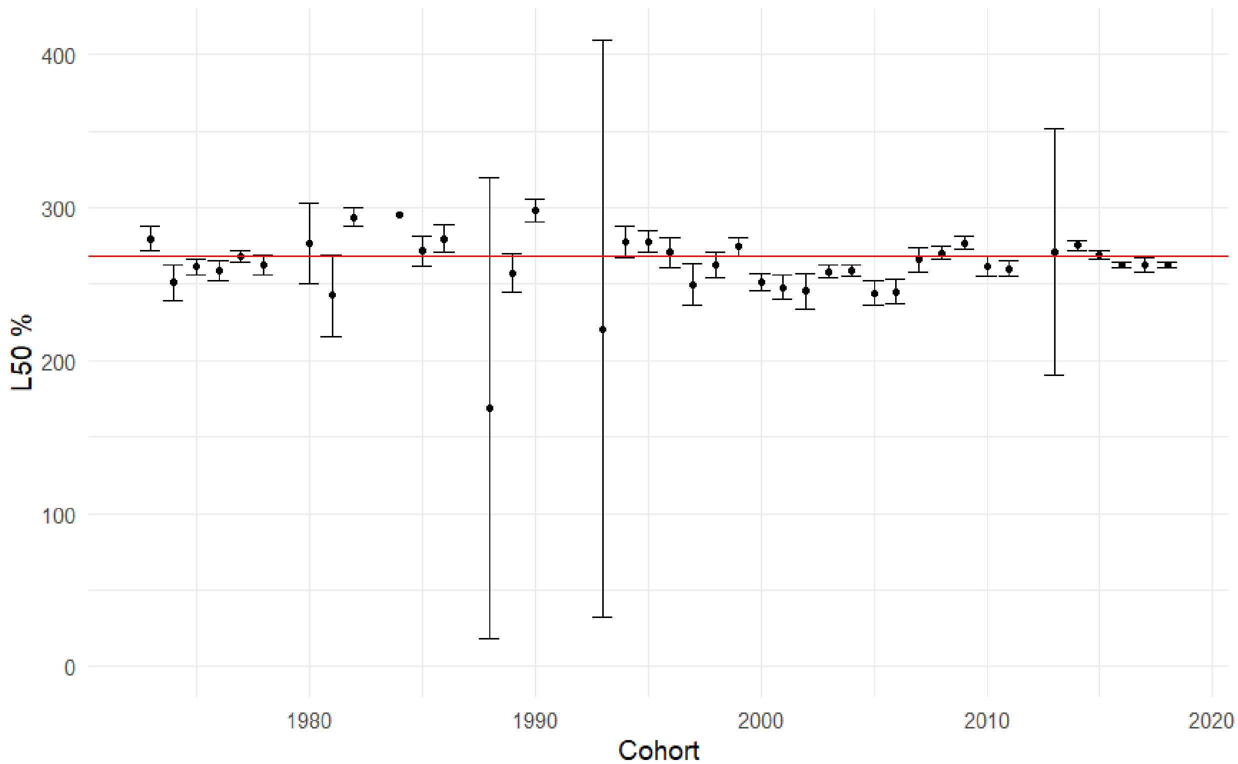

*Figure 6. Length at 50 % maturity (L_{50}) by cohort (1974-2018) and their 95% C.I.s (1.96*S.E.). The horizontal red line indicates the current minimum commercial length of 268 mm.*

FECUNDITY

Fecundity (n = 222, R^2 = 0.55, RMSE = 0.34, AIC = 141.39, p < 2e-16) was estimated to increase by 1.4% for each age and by 0.83 % for every gram of gonad mass (coefficients: intercept = 1.24e+01, age = 1.39e-02, gonad mass = 8.26e-03). Age 1-5 fecundities showed less inter-annual variation when compared to older ages except for an increase in values in the late 1970s and early 1980s as well as the mid-2010s. Increases in fecundity also occurred in older fish during these time periods but with greater magnitudes of variation. Fecundities seem to follow the progression of year classes. This trend is most visible in the 1980s when the population was dominated by several strong year classes that followed each other (i.e. 1968, 1973, and 1974). This trend is less evident for later notable year classes (e.g. 1999 and 2015). From 2015 onwards, fecundity in ages 2-10+ fell precipitously while age 1 fecundity remained stable. Following this drop, the fecundities of ages 7 and older appeared to rebound slightly.

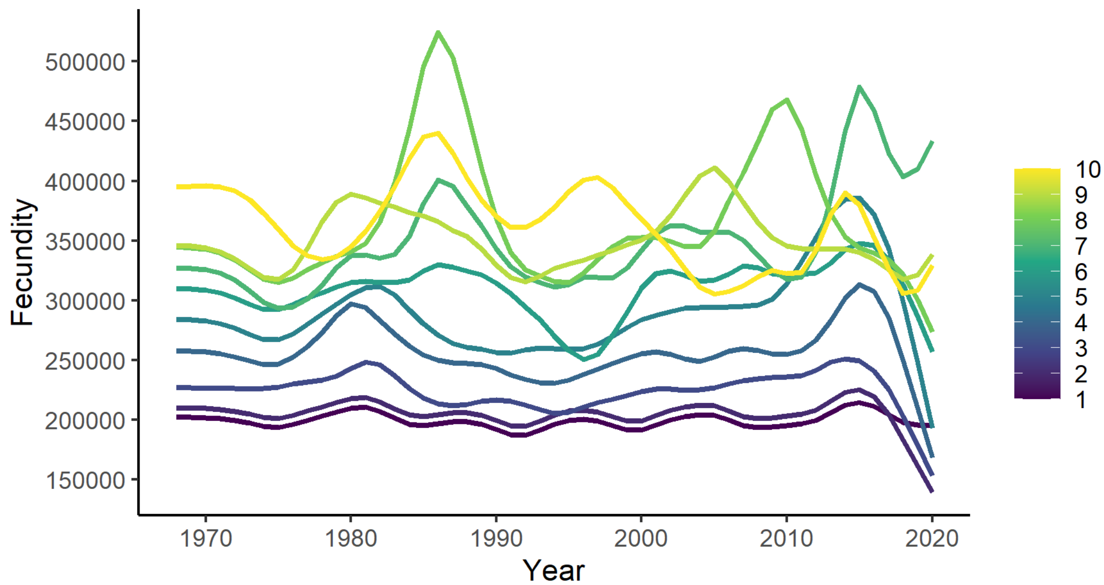

Figure 7. Estimated mean fecundities-at-age (potential number of eggs per ripe female) for ages 1-10+ for 1968-2020. Colours representing ages range from violet (age 1) to yellow (ages 10+).

MODEL OUTPUT

Residual plots and retrospective patterns are shown in Figures S2 and S3. 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., 2020a,b) did not significantly improve the pattern of survey residuals. Estimated model parameters are presented in Table S6 and the model summary in Table S7. Annual numbers at age are presented in Table S8 and annual age-disaggregated fishing mortalities in Table S9.

The SSB dropped below the LRP in 2011 (Figure 4A) and was estimated to be 72% and 63% of the LRP in 2019 and 2020 respectively. This ratio increased to close to 1 in 2017 and 2018 with the arrival of the 2015 cohort but is now similar to values observed from 2011-2015.

The last relatively large recruitment event was in 2015 but fish belonging to this cohort now represent less than 8 % of the fish harvested in 2020 in terms of numbers-at-age and 13% in terms of biomass (Table S10, Figure 4B). Indeed, from 2016 to 2020 the numbers of fish from the 2015 year class went from representing 65.7%, 66.2%, 51.0%, 22.0%, to 7.2% of the population respectively. In 2019 and 2020 no single year class appeared to dominate the population. For both years, age 1-5 represented around 99% of the spawning population in terms of both numbers and biomass.

Fishing mortality rates (including catch uncertainty) were estimated to remain above the reference level (Figure 4E,F). According to the model, the estimated fishing mortality rate on fully exploited mackerel (ages 5 to 10) was 1.29 and 1.30 for 2019 and 2020 respectively (exploitation rates of 72% and 73%). 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 in 2020 ($F_{overall} = \sum_{a=1}^{A} F_a * N_a / \sum_{a=1}^{A} N_a$) was F = 0.97 (exploitation rate of 62%). Note that this exploitation rate is still relatively high, especially given that most fish in the population fall between the ages of 1-5 and some are not fully selected by the fishery yet (Table S9).

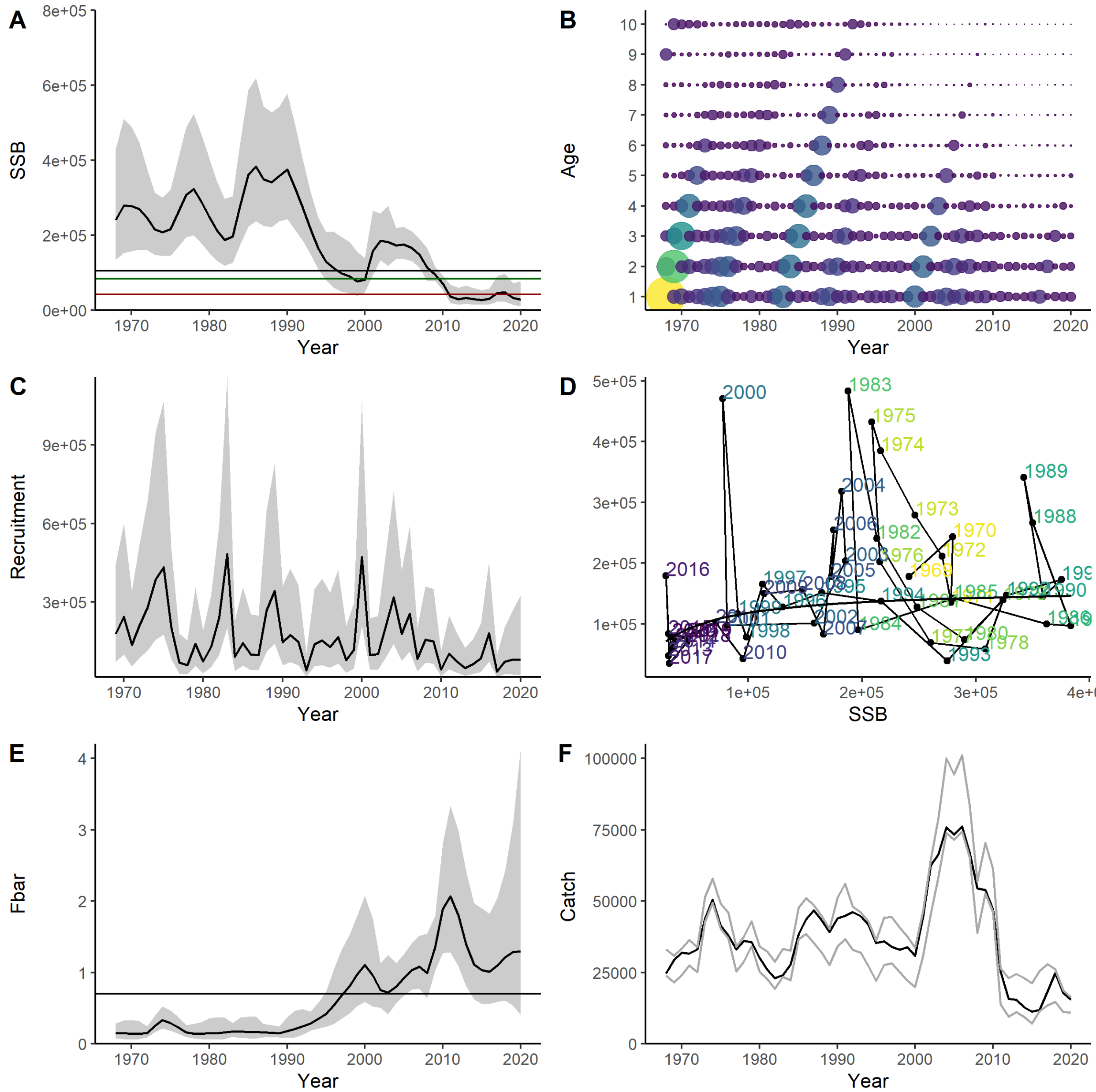

Figure 4. Model output: (A) Spawning Stock Biomass (t) with horizontal lines indicating $SSB_{F40\%}$ (black), USR (green) and LRP (red), (B) abundance at age, (C) recruitment (numbers), (D) stock-recruitment, (E) fishing mortality (averaged over the fully selected age classes 5-10), (F) estimated catch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

Projections (Figures 5, S4) were made over a three-year period to estimate the impact of different TACs (0-10 000 t) on the projected SSB. These projections included stochastically projected unaccounted-for catches of both Canada and the US separately (i.e., implementation error). The TAC was added to these estimated catches to calculate total removals and the resulting next years' stock biomass. During the last assessment there was agreement that the

Canadian unaccounted-for Canadian catches had likely decreased due to the imposition of recent management measures, whereas the direction of possible U.S. catches of northern contingent fish was unknown (although it was presumed the fraction remained at 25-50%). Total landings in the U.S. were not available at the time of this assessment so the 5-year mean was used for 2020. 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., 2020).

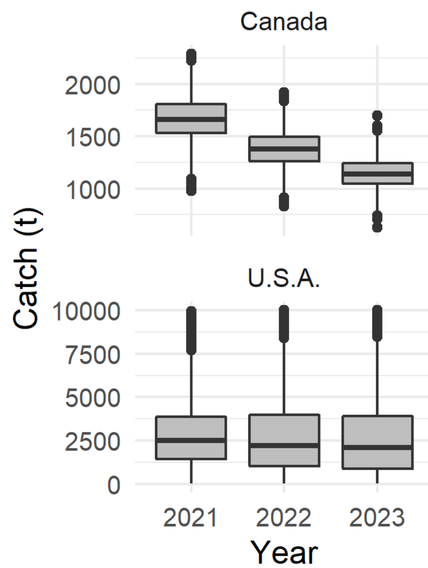

Figure 5. Boxplots of the assumed unaccounted-for catch over the next 3 years (2019-2021), for Canada (upper panel) and the US (lower panel) (generated with functions IEindep2021 and IEdep2550, CCAM package).

The projection table below was provided within the Stock Advisory Report. With increasing TACs from 0 to 10 000 t, the probability of attaining the LRP by 2023 were about as likely as not for all TAC scenarios. Positive stock growth by at least one fish from 2022 to 2023 was likely for TACs ranging from 0 to 4000 t and about as likely as not for TACs above 4000 t. (Table 1).

Table 1. Three-year projections under different Total Allowable Catch (TAC) and recruitment scenarios. Recruitment scenarios include recruitment through a Beverton-Holt stock-recruit relationship (BH) and the 10 year mean recruitment (2011-2020) projected forwards with a temporal autocorrelation of 0.9 (mean). For each TAC scenario, the probabilities of spawning stock biomass (SSB) being greater than the Limit Reference Point (LRP) in 2022 and 2023 are provided. The probabilities of SSB growth from 2021 to 2023 are also provided. The ratios between SSB at the beginning of the year with respect to the median LRP (SSB/LRP) for each scenario are likewise given for 2022 and 2023. Projections were performed under the assumption that mackerel will also be caught outside of the TAC, by both the Canadian and American fleets (column g; uncertainties represented by the 5^th^ and 95^th^ quantiles taken over the three years). Figures 5 shows the assumed annual unaccounted-for catch distributions in detail.

TAC			SSB > LRP				SSB_{2023} > SSB_{2021}		SSB/LRP				Unaccounted-for landings			
2021	2022	2023	2022		2023		2021→2023		2022		2023		Canada		U.S.A.	
													5%	95%	5%	95%
			BH	mean	BH	mean	BH	mean	BH	mean	BH	mean				
0			42%	46%	51%	58%	85%	92%	0.73	0.78	0.85	0.97	982	1883	410	7735
2000			39%	44%	46%	54%	75%	86%	0.67	0.72	0.76	0.88	982	1883	410	7735
4000			37%	40%	41%	49%	64%	79%	0.61	0.66	0.65	0.79	982	1883	410	7735
6000			34%	38%	36%	45%	55%	72%	0.55	0.61	0.55	0.69	982	1883	410	7735
8000			32%	36%	33%	41%	46%	66%	0.50	0.55	0.46	0.60	982	1883	410	7735
10000			30%	34%	29%	37%	39%	59%	0.44	0.50	0.39	0.52	982	1883	410	7735

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 indices 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 population mackerel caught in the U.S. mackerel fishery is not known but is yet likely to be high (Redding et al. 2020). Improved monitoring of commercial landings, discards, and recreational catches will improve future assessments certainty. An improved appreciation for the proportion of the northern population being landed by the U.S. fishery as well as the proportion of the southern population being caught in Canadian waters will also improve model estimates and projections in the future.

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 2009. Stock projections provided in Table 1 will allow decision makers to weight the trade-offs between stock size and different TACs 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., 2017, 2020b).

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 (Brosset et al., 2020). 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 TACs. 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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REFERENCES

Aeberhard, W.H., Flemming, J.M., and Nielsen, A. 2018. Review of State-Space Models for Fisheries Science. Annual Review of Statistics and Its Application 5, 215-235. DOI: 10.1146/annurev-statistics-031017-100427

Auger-Méthé, M., Field, C., Albertsen, C.M., Derocher, A.E., Lewis, M.A., Jonsen, I.D., and Flemming, J.M. 2016. State-space model's dirty little secrets: even simple linear Gaussian models can have estimation problems.

Berg, C.W., Nielsen, A., 2016. Accounting for correlated observations in an age-based state-space stock assessment model. ICES J. Mar. Sci. 73, 1788–1797. http://dx.doi.org/10.1093/icesjms/fsw046.

Bolker, B.M. 2008. Ecological Models and Data in R. Princeton University Press. Princeton, New Jersey. ISBN-10 : 0691125228

Brosset, P., Smith, A.D., Plourde, S., Castonguay, M., Lehoux, C., and Van Beveren, E. 2020. A fine-scale multi-step approach to understand fish recruitment variability. Sci Rep 10, 16064 (2020). https://doi.org/10.1038/s41598-020-73025-z

Cadigan, N., 2016a. A state-space stock assessment model for northern cod, including under-reported catches and variable natural mortality rates. Can. J. Fish. Aquat. Sci. 73, 296–308.

Cadigan, N., 2016b. Updates to a Northern Cod (Gadus morhua) State-Space Integrated Assessment Model. DFO Can. Sci. Advis. Sec. Res. Doc. No. 2016/022.

DFO. 2009. Sustainable Fisheries Framework (SFF) : A Fishery Decision-Making Framework Incorporating the Precautionary Approach. Guidance for the Development of Rebuilding Plans under the Precautionary Approach Framework: Growing Stocks out of the Critical Zone.

DFO. 2017. Assessment of the Atlantic Mackerel Stock for the Northwest Atlantic (Subareas 3 and 4) in 2016. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2017/034.

DFO. 2018. Update of the projections for Atlantic mackerel (subareas 3 and 4). DFO Can. Sci. Adv. Sec. Sci. Rep. 2018/024.

DFO. 2019. Assessment of the Atlantic Mackerel stock for the Northwest Atlantic (Subareas 3 and 4) in 2018. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/035

Doniol-Valcroze, T., Van Beveren, E., Légaré, B., Girard, L., and Castonguay, M. 2019. Atlantic mackerel (*Scomber scombrus L.*) in NAFO Subareas 3 and 4 in 2016. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/062. v + 51 p.

Gavaris, S., and Gavaris, C.A. 1983. Estimation of catch at age and its variance for groundfish stocks in the Newfoundland regions. in Doubleday, W.G., and Rivard, D. (Editors). Sampling Commercial Catches of Marine Fish and Invertebrates. Can. Spec. Pub. Fish. Aq. Sci. 66.

Grégoire, F. (Editor). 2000. The Atlantic mackerel (*Scomber scombrus* L.) of NAFO Subareas 2 to 6. DFO Can. Sci. Advis. Sec. Res. Doc. 2000/021.

Girard, L. 2000. Identification of mackerel (*Scomber scombrus* L.) eggs sampled during abundance surveys in the southern Gulf of St. Lawrence. Chapter 4. *in* Grégoire, F. (Editor). The Atlantic mackerel (*Scomber scombrus* L.) of NAFO Subareas 2 to 6. DFO Can. Sci. Advis. Sec. Res. Doc. 2000/021. Pp. 119-138.

Grégoire, F., Shepherd, N., and Sutherland, S. J. 2009. Inter-laboratory ageing exchange of Atlantic mackerel (*Scomber scombrus*) otoliths for the 2009 Transboundary Resources Assessment Committee. Transboundary Resources Assessment Committee (TRAC). Ref. Doc. 2009/008. 9 pp.

Grégoire, F., Girard, L., Beaulieu, J.-L., Lussier, J.-F., et Gendron, M.-H. 2014a. Détection des tendances communes dans les abondances d'oeufs et de larves de poissons récoltés dans le sud du golfe du Saint-Laurent entre 1983 et 2012. Secr. can. de consult. sci. du MPO. Doc. de rech. 2014/074. v + 34 p.

Grégoire, F., Girard, L. et Boudreau, M. 2014b. Résultats des relevés du programme de monitorage zonal atlantique (PMZA)-maquereau bleu (*Scomber scombrus* L.) réalisés dans le sud du golfe du Saint-Laurent en 2012 et 2013. Secr. can. de consult. sci. du MPO. Doc. de rech. 2014/075. v + 82 p.

Grégoire, F., Girard, L., and Boudreau, M. 2014c. La pêche au maquereau bleu (*Scomber scombrus* L.) dans les sous-régions 3 et 4 de l'OPANO en 2013. Secr. can. de consult. sci. du MPO. Doc. de rech. 2014/077. vi + 119 p.

Grégoire, F., Girard, L., et Beaulieu, J.-L. 2014d. Analyses de similarité appliquées sur les abondances de larves de poissons récoltées dans le sud du golfe du Saint-Laurent entre 1983 et 2012. Secr. can. de consult. sci. du MPO. Doc. de rech. 2014/080. v + 16 p.

Isermann, D.A. and Knight, C.T. 2005. A computer program for age-length keys incorporating age assignment to individual fish. North Amer. J. Fish. Manag. 25:11531160.

Kimura, D.K. 1977. Statistical assessment of the age-length key. J. Fish. Res. Board Can., 34:317324.

Kristensen, K., Nielsen, A., Berg, C.W., Skaug, H., and Bell, B.M. 2016. TMB: Automatic Differentiation and Laplace Approximation. J. Statistical Software. 70(5). doi: 10.18637/jss.v070.i05

Lockwood, S. J., Nichols, J. H., and Coombs, S. H. 1977. The development rates of mackerel (*Scomber scombrus* L.) eggs over a range of temperatures. ICES CM 1977/J: 13. 13 pp.

Mackay, K.T. 1976. Population biology and aspects of energy use of the northern population of Atlantic mackerel Scomber scombrus L. Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Dalhousie University.

Nielsen, A., Berg, C.W., 2014. Estimation of time-varying selectivity in stock assessments using state-space models. Fish. Res. 158, 96–101. http://dx.doi.org/10.1016/j.fishres.2014.01.014.

Northeast Fisheries Science Center (NEFSC). 2017. 64th Northeast Regional Stock Assessment Workshop (64th SAW) Assessment Report. Northeast Fish Sci. Cent. Ref. Doc. 18-03.

Ogle, D.H. 2015. Introductory Fisheries Analyses with R. Chapman and Hall/CRC. USA.

Patterson, B. 2014. Study of the small pelagic fisheries for Atlantic herring and Atlantic mackerel on the west coast of Newfoundland (NAFO Division 4R). Project Report. Memorial University of Newfoundland, St. John's, Newfoundland.

Pelletier, L. 1986. Fécondité du maquereau bleu, *Scomber scombrus* L., du golfe du Saint-Laurent. Rapp. tech. can. sci. halieut. aquat. 1467: v + 37 p.

R Core Team. 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.

SAS Institute Inc. 2011. Base SAS® 9.3 Procedures Guide. Cary, NC: SAS Institute Inc.

Smith, A.D., Van Beveren, E., Girard, L., Boudreau, M., Brosset, P., Castonguay, M., and Plourde, S. 2020. Atlantic mackerel (Scomber scombrus L.) in NAFO Subareas 3 and 4 in 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/013. iv + 37 p.

Van Beveren, E., Duplisea, D., Castonguay, M., Doniol-Valcroze, T., Plourde, S., and Cadigan, N. 2017a. How catch underreporting can bias stock assessment of and advice for northwest Atlantic mackerel and a possible resolution using censored catch. Fish. Res. 194. 146-154. 10.1016/j.fishres.2017.05.015.

Van Beveren, E., Castonguay, M., Doniol-Valcroze, T., and Duplisea, D. 2017. Results of an informal survey of Canadian Atlantic mackerel commercial, recreational and bait fishers. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/029. v + 26 p

Van Beveren, E., Duplisea, D., Castonguay, M., and Smith, A.D. 2019. Results of an informal survey of Canadian Atlantic mackerel commercial, bait and recreational fishers (2018). DFO Can. Sci. Advis. Sec. Res. Doc. 2019/045. iv + 24 p.

Van Beveren, E., Marentette, J.R., Smith, A.D., Castonguay, M., and Duplisea, D.E. 2020a. Evaluation of Rebuilding Strategies for northwestern Atlantic Mackerel (NAFO Subareas 3 and 4). DFO Can. Sci. Advis. Sec. Res. Doc. 2020/021. v + 56 p.

Van Beveren, E., Duplisea, D.E., Marentette, J.R., Smith, A.D., and Castonguay, M. 2020b. An example of how catch uncertainty hinders effective stock management and rebuilding. Fisheries Research. 224. https://doi.org/10.1016/j.fishres.2019.105473

SUPPLEMENTARY INFORMATION

TABLES

Table S1. Annual nominal landings of mackerel in the Northwest Atlantic (1968-2020) by exclusive economic zones (EEZ) and fleet. Commercial landings in Canada's EEZ from 1968-1994 as well as landings from foreign nations from 1968-2020 were acquired from the NAFO statlant21A database

Year*	***Canada EEZ****			***U.S.A. EEZ*****				
	Commercial	Foreign landings	Total Canada EEZ	Commercial	Recreational	Discards	Foreign Landings	Total USA EEZ
1968	11118	9720	20838	3929			56043	59972
1969	13257	5379	18636	4364			108811	113175
1970	15710	5296	21006	4049			205568	209617
1971	14942	9554	24496	2406			346338	348744
1972	16253	6107	22360	2006			385358	387364
1973	21566	16984	38550	1336			379828	381164
1974	16701	27954	44655	1042			293883	294925
1975	13540	22718	36258	1974			249005	250979
1976	15746	17319	33065	2712			205956	208668
1977	19852	2913	22765	1377			53664	55041
1978	25429	470	25899	1605			371	1976
1979	30244	368	30612	1990			72	2062
1980	22135	161	22296	2683			406	3089
1981	19294	61	19355	2941	2628		5300	10869
1982	16380	3	16383	3330	1877		6471	11678
1983	19797	9	19806	3805	2793		5882	12480
1984	17320	913	18233	5954	2726		14957	23637
1985	29855	1051	30906	6632	4088		17639	28359
1986	30325	772	31097	9637	7662		25735	43034
1987	27488	71	27559	12310	7555		34951	54816
1988	24060	956	25016	12309	5421		51463	69193
1989	20795	347	21142	14556	2829	160	37209	54755
1990	19190	3796	22986	31261	3254	827	9232	44575
1991	24914	1281	26195	26961	3540	1098	5989	37588
1992	24307	2255	26562	11761	921	2072	0	14754
1993	26158	690	26848	4662	1231	3902	0	9796
1994	20564	49	20613	8917	2654	5409	0	16980
1995	17740	62	17802	8468	1697	54	0	10219
1996	20406	76	20482	15728	2466	2053	0	20246
1997	21309	116	21425	15403	2857	229	0	18489
1998	19176	10	19186	14525	1553	98	0	16176
1999	16561	12	16573	12031	2832	771	0	15634
2000	16080	26	16106	5649	3055	153	0	8857
2001	24429	11	24440	12340	3301	718	0	16359
2002	34662	7	34669	26530	2679	155	0	29364
2003	44736	12	44748	34298	1874	264	0	36436
2004	53951	15	53966	54990	1169	2141	0	58300
2005	54809	0	54809	42209	1694	1083	0	44986
2006	53741	3	53744	56640	3911	135	0	60687
2007	53394	0	53394	25546	763	159	0	26468
2008	29671	4	29675	21734	2731	747	0	25212
2009	42231	42	42273	22634	1769	126	0	24529
2010	38700	1	38701	9877	4288	97	0	14261
2011	11508	0	11508	533	4040	38	0	4610
2012	6847	2	6849	5333	2671	33	0	8037
2013	8674	1	8675	4372	2406	20	0	6799
2014	6680	0	6680	5905	2296	51	0	8252
2015	4280	1	4281	5616	4275	13	245	10150
2016	8055	2	8057	5687	4572	18	1	10278
2017	9783	3	9786	6975	4173	83	132	11362
2018	10926	1	10927				0	10784
2019*	8704	0	8704	6805			52	6857
2020*	7838	NA	7838	8025				

** For convenience, exclusive economic zones of the U.S.A. and Canada were applied even for years where the boundaries did not exist. In addition, the exclusive economic zone of France (St. Pierre & Miquelon) was included within the Canadian EEZ for convenience since 1995.

*** Total landings in the U.S. EEZ for 2018, and 2019 were acquired from NOAA's website and estimates of discards and recreational catches were not available for 2020. So called foreign landings from 2015-2020 are from Canadian vessels fishing in NAFO subarea 5 and presumably did not inscribe the NAFO subdivision correctly in their logbook.

Table S2. Annual landings (t) in Canada's exclusive economic zone (EEZ) by DFO region from 1985-2020. The data presented here do not include landings by foreign vessels, ship-to-ship sales, or Canadian allocations to foreign vessels.

YEAR	GULF	NEWFOUNDLAND	QUEBEC	MARITIMES
1985	6124.71	14883.14	2179.07	6264.85
1986	8517.92	2399.96	3004.39	4798.79
1987	9610.74	9901.84	2752.82	5233.12
1988	9469.41	4234.35	3662.38	6064.56
1989	9685.64	1911.07	2252.44	4813.76
1990	9633.97	1208.18	1970.86	8499.24
1991	14450.53	833.68	3255.63	7270.02
1992	9887.58	1283.30	3480.32	8622.27
1993	6995.61	9683.41	3175.43	6717.96
1994	6874.73	2799.87	3545.85	7608.11
1995	4831.42	2952.50	3382.29	6573.59
1996	7049.45	3869.09	4317.36	5169.86
1997	9590.04	1188.33	5769.24	4761.76
1998	8675.78	2330.69	3738.36	4431.11
1999	5462.02	1444.75	5103.57	4550.36
2000	5294.08	4405.85	2021.99	4358.57
2001	9123.24	8981.08	3211.81	3113.19
2002	10069.32	17981.97	4420.71	2189.85
2003	9726.87	26675.11	4596.87	3737.19
2004	7728.49	40002.70	1979.37	4240.87
2005	8238.10	42659.74	1220.60	2690.80
2006	6042.66	44276.74	1818.43	1602.88
2007	4684.98	44601.66	1749.84	2357.41
2008	3598.55	23036.12	1862.95	1173.43
2009	4562.47	34237.19	2316.02	1115.81
2010	3277.64	33158.87	1709.22	553.92
2011	2417.41	7336.81	1344.88	408.65
2012	2258.48	2619.15	1277.99	691.66
2013	1648.35	5169.49	1452.87	403.26
2014	1042.23	3432.06	1502.33	703.20
2015	1225.78	700.56	1182.35	1171.58
2016	1241.30	4632.60	966.22	1215.30
2017	3726.16	2653.29	1347.13	2056.79
2018	2200.74	5625.21	1426.38	1521.60
2019	2229.00	4813.75	753.98	907.74
2020	1885.64	4013.92	679.14	1128.49

** Values for 2019-2020 are preliminary. Values may not add due to rounding errors.*

Table S3: Aggregated annual commercial landings by grouped NAFO divisions corresponding to the Newfoundland and Labrador Shelf (2J3KL), Cabot Strait (3P4V), Estuary and Gulf of Saint Lawrence (4RST), and the Scotian Shelf, Gulf of Maine, Bay of Fundy, and Georges Bank (4WX5YZ) and the corresponding number of length frequency (N_lf) and biological samples collected (N_bio) as well as the total number of fish therein (n_lf and n_bio respectively). Landings greater than 1000 t are highlighted in bold. The data presented here do not include landings by foreign vessels, ship-to-ship sales, or Canadian allocations to foreign vessels.

Year	*Area*	*Landings (t)*	*N_lf*	*n_lf*	*N_bio*	*n_bio*
1985	2J3KL	**14520.17**	30	100	36	1598
1985	4RST	**7965.96**	112	14194	58	1780
1985	4V3P	**2401.47**	1	4	1	46
1985	4WX5YZ	**4564.17**	8	40	8	249
1986	2J3KL	**2369.86**	39	358	39	1554
1986	4RST	**11414.70**	91	11129	42	1252
1986	4V3P	**1103.44**	4	44	4	140
1986	4WX5YZ	**3833.05**				
1987	2J3KL	**9735.90**	19	222	19	681
1987	4RST	**12352.56**	146	17864	51	1419
1987	4V3P	**1524.00**	3	26	3	125
1987	4WX5YZ	**3886.08**	12	548	8	236
1988	2J3KL	**4195.95**	18	123	18	796
1988	4RST	**13124.92**	122	20799	35	956
1988	4V3P	**1857.23**	12	477	8	232
1988	4WX5YZ	**4252.60**	25	2796	1	23
1989	2J3KL	**1851.05**	25	158	25	952
1989	4RST	**11935.49**	134	20159	47	1453
1989	4V3P	**1748.27**	8	639	7	237
1989	4WX5YZ	**3128.10**	11	434	6	293
1990	2J3KL	**1114.89**	11	82	11	433
1990	4RST	**11601.23**	84	10570	40	1309
1990	4V3P	**2498.55**	6	22	6	192
1990	4WX5YZ	**6097.59**	1	7	1	16
1991	2J3KL	742.10	6	12	6	251
1991	4RST	**17701.08**	82	11104	43	1487
1991	4V3P	**2483.02**	5	119	8	277
1991	4WX5YZ	**4883.68**	9	1440	0	0
1992	2J3KL	**1278.91**	8	29	9	364
1992	4RST	**13315.96**	86	11443	46	1780
1992	4V3P	**1401.05**	2	4	2	93
1992	4WX5YZ	**7277.55**				
1993	2J3KL	**5061.80**	13	113	13	401
1993	4RST	**14757.44**	94	11553	47	1643
1993	4V3P	**1598.29**	9	50	9	303
1993	4WX5YZ	**5154.87**	1	5	1	43
1994	2J3KL	21.90	2	89	2	4
1994	4RST	**13154.11**	59	10118	40	1397
1994	4V3P	**1735.53**	5	544	4	88
1994	4WX5YZ	**5917.01**	10	1419	1	2
1995	2J3KL	21.70				
1995	4RST	**11020.75**	106	13204	54	1790
1995	4V3P	**1598.59**	13	2088	8	319
1995	4WX5YZ	**5098.77**	12	1905	4	173
1996	2J3KL	3.29				
1996	4RST	**15160.83**	73	10108	41	1513
1996	4V3P	**1662.40**	17	2250	6	213
1996	4WX5YZ	**3579.24**	5	629	1	39
1997	4RST	**16539.87**	74	10808	43	1665
1997	4V3P	845.24	11	1392	4	164
1997	4WX5YZ	**3924.25**	1	157	1	38
1998	2J3KL	6.65				
1998	4RST	**14644.30**	81	10754	44	1568
1998	4V3P	646.22	16	1906	7	284
1998	4WX5YZ	**3878.77**	4	662	1	39
1999	4RST	**12002.00**	91	11974	44	1726
1999	4V3P	769.11	14	1452	7	332
1999	4WX5YZ	**3789.59**	5	578	2	97
2000	2J3KL	**2384.96**	16	1673	4	89
2000	4RST	**9317.10**	74	9363	38	1323

2000	4V3P	595.27	15	1983	9	355
2000	4WX5YZ	**3783.15**	5	559	1	31
2001	2J3KL	332.22				
2001	4RST	**20707.32**	86	14056	55	2009
2001	4V3P	398.00	20	2991	6	199
2001	4WX5YZ	**2991.79**	16	2353	5	222
2002	2J3KL	**6568.66**	14	729	0	0
2002	4RST	**25737.35**	76	14193	51	1674
2002	4V3P	469.81	11	1640	7	260
2002	4WX5YZ	**1886.04**				
2003	2J3KL	588.12				
2003	4RST	**40261.68**	90	15536	62	1975
2003	4V3P	208.68	20	3201	15	549
2003	4WX5YZ	**3677.56**	3	250	1	33
2004	2J3KL	**16050.71**	26	2349	6	250
2004	4RST	**33580.46**	73	11206	44	1594
2004	4V3P	92.12	14	1720	6	215
2004	4WX5YZ	**4228.14**	38	5266	15	570
2005	2J3KL	**28305.71**	29	750	28	1178
2005	4RST	**23574.98**	98	10461	60	2079
2005	4V3P	363.39	14	1436	9	405
2005	4WX5YZ	**2565.14**	24	2738	11	323
2006	2J3KL	**27136.66**	60	2088	51	2004
2006	4RST	**24734.93**	121	11996	66	2252
2006	4V3P	490.11	17	1913	11	414
2006	4WX5YZ	**1378.99**				
2007	2J3KL	**19468.17**	46	567	53	1585
2007	4RST	**31214.66**	108	11840	62	1866
2007	4V3P	723.88	18	1473	11	426
2007	4WX5YZ	**1987.17**	3	452	0	0
2008	2J3KL	**9129.04**	10	27	11	315
2008	4RST	**19202.95**	92	9071	52	1861
2008	4V3P	276.18	8	22	10	374
2008	4WX5YZ	**1062.88**	6	1097	0	0
2009	2J3KL	**6937.62**	15	66	18	652
2009	4RST	**28791.51**	99	10341	61	2064
2009	4V3P	**5441.60**	18	1982	12	430
2009	4WX5YZ	**1060.76**	6	779	2	70
2010	2J3KL	**13746.62**	63	1665	63	2435
2010	4RST	**18857.66**	109	11597	65	1771
2010	4V3P	**5548.43**	7	574	5	200
2010	4WX5YZ	546.94	1	255	1	39
2011	2J3KL	487.09	13	65	14	592
2011	4RST	**9068.04**	76	8153	47	1494
2011	4V3P	**1545.50**	5	20	6	308
2011	4WX5YZ	407.11	4	417	2	89
2012	2J3KL	209.45	6	10	14	580
2012	4RST	**5797.68**	84	7517	43	1249
2012	4V3P	298.84	1	1	2	128
2012	4WX5YZ	541.32	1	1	1	134
2013	2J3KL	234.71				
2013	4RST	**8010.24**	59	5988	36	1083
2013	4V3P	171.35				
2013	4WX5YZ	257.66	1	3	1	129
2014	2J3KL	31.46				
2014	4RST	**5699.11**	62	7528	46	1385
2014	4V3P	389.53				
2014	4WX5YZ	559.71	1	1	1	406
2015	2J3KL	262.11	4	507	5	224
2015	4RST	**2846.59**	54	6654	39	1246
2015	4V3P	58.02				
2015	4WX5YZ	**1113.57**				
2016	2J3KL	**2796.56**	6	889	5	182
2016	4RST	**4043.67**	77	9496	52	1863
2016	4V3P	123.84				
2016	4WX5YZ	**1091.34**	5	319	2	742
2017	2J3KL	**1144.08**				
2017	4RST	**6538.35**	97	11171	64	2240
2017	4V3P	212.91				
2017	4WX5YZ	**1888.01**	1	4	9	236

2018	2J3KL	**5369.21**	8	622	6	251
2018	4RST	**4026.66**	65	8536	36	1265
2018	4V3P	137.31	3	245	3	243
2018	4WX5YZ	**1393.22**	14	561	20	1074
*2019**	2J3KL	**4689.95**	12	1671	9	300
*2019**	4RST	**3031.67**	49	6707	64	1610
*2019**	4V3P	83.48	4	199	24	122
*2019**	4WX5YZ	821.06	12	24	99	1830
*2020**	2J3KL	**3967.61**	14	1034	14	683
*2020**	4RST	**2741.92**	54	5633	65	1084
*2020**	4V3P	80.46				
*2020**	4WX5YZ	**1048.03**				

* *Values for 2019-2020 are preliminary. Not all samples from 2020 have been counted or analysed at the time of the 2021 assessment. Values may not add due to rounding errors.** Small portions of Canada's EEZ occur in NAFO Division 5.*

Table S5. Equations and random and fixed effect parameters used in the operating model. Parameters are a = age, y = year, SSB = spawning stock biomass, Sel = selectivity, N = abundance, F = fishing mortality, M = natural mortality, W = mass, P = proportion mature, CU = upper catch limit, CL = lower catch limit, CT = total catch, CP = catch proportion, TEP = Total Egg Production, fec= fecundity, Fem = proportion of females, ts = timing of the survey, o = observed, MVN = multivariate normal, crl = continuation-ratio logit.

Parameter	Formula
Cohort abundance	$N_{1,y} = \frac{\alpha SSB_{y-1}}{1+\beta SSB_{y-1}} e^{\varepsilon^N_{1,y}}$
	$N_{a,y} = N_{a-1,y-1} e^{-Z_{a-1,y-1}+\varepsilon^N_{a,y}}$
	$N_{A,y} = [N_{A-1,y-1} e^{-Z_{A-1,y-1}} + N_{A,y-1} e^{-Z_{A,y-1}}] e^{\varepsilon^N_{A,y}}$
	$\varepsilon^N_{a,y} \sim MVN(0, \sigma^2_{N_a})$
Mortality rates	$F_{a,y} = Sel_a F_y$
	$Z_{a,y} = F_{a,y} + M_{a,y}$
	$F_y = F_{y-1} e^{\varepsilon^F_y}$
	$\varepsilon^F_y \sim N(0, \sigma^2_{F_y})$
Catch	$C_{a,y} = N_{a,y} \frac{F_{a,y}}{Z_{a,y}} [1 - \exp(-Z_{a,y})]$
	$CT_y = \sum_{a=1}^{A} C_{a,y} W_{a,y}$
	$CP_{a,y} = \frac{C_{a,y}}{\sum_{a=1}^{A} C_{a,y}}$
	$X_{a,y} = crl(CP_{a,y})$
	$l(C_{o_1}, \dots, C_{o_Y} \mid \theta) = \sum_{y=1}^{Y} log \left\{ \phi_N \left[\frac{log(CU_y/CT_y)}{0.01} \right] - \phi_N \left[\frac{log(CL_y/CT_y)}{0.01} \right] \right\}$
	$l\left(X_{o_{a,y}} \middle| \theta\right) = \sum_{a=1}^{A-1} \sum_{Y=1}^{Y} log \left[\varphi_N \left(\frac{X_{o_{a,y}} - X_{a,y}}{\sigma_{cp}} \right) \right]$
Survey index	$TEP_y = q \sum_{a=1}^{A} N_{a,y} exp(-Z_{a,y} t_s) fec_{a,y} Fem_{a,y} P_{a,y}$
	$l\left(TEP_{o_y} \middle| \theta\right) = \sum_{a=1}^{A} \sum_{Y=1}^{Y} log \left[\varphi_N \left(\frac{TEP_{o_y} - TEP_y}{\sigma_S} \right) \right]$
Spawning Stock Biomass	$SSB_y = \sum_{a=1}^{A} N_{a,y} W_{a,y} P_{a,y}$

Parameter	Definition	Effect
$N_{a,y}$	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^2_N	Process error variance	Fixed
σ_{F_y}	Annual fishing mortality variance	Fixed
$\sigma^2_{cp_a}$	Catch-at-age proportions measurement error variance	Fixed
σ^2_S	Survey measurement error variance	Fixed

Table S6: Estimated model parameters.

Parameters	**estimate**	***s.d.***
$logq$	7.84	0.07
$log\sigma_{F_y}$	-1.14	0.13
$log\sigma^2_{N_1}$	-0.30	0.16
$log\sigma^2_{N_{2-10}}$	-0.91	0.11
$log\sigma^2_{caa_1}$	0.77	0.10
$log\sigma^2_{caa_{2,8,9}}$	-0.08	0.10
$log\sigma^2_{caa_{2-7}}$	-0.50	0.08
$log\sigma^2_{s}$	-0.36	0.07
$logitSel_1$	1.23	0.40
$logitSel_2$	-10.80	0.49
$logitSel_3$	-3.11	0.33
$logitSel_4$	-1.12	0.19

Table S7: Summary of model output showing estimated spawning stock biomass (SSB), estimated age-1 recruitment (Recruitment), estimated total catch (Catch), the mean instantaneous rate of fishing mortalitiy on ages 5-10+ (Fbar (5-10+)), Total annual mortality of the spawning stock due to fishing (Exploitation rate), and spawning stock biomass with respect to the Limit Reference Point (SSB/LRP).

Year	SSB	Recruitment	Catch	Fbar (5-10+)	Exploitation rate (%)	SSB/LRP (%)
1968	241456	1543516	24669.23	0.15	14.19	519.94
1969	279704	177955	29488.9	0.15	13.76	602.30
1970	278181	243472	31913.36	0.15	13.58	599.02
1971	270594	135792	31613.86	0.15	13.58	582.68
1972	246749	211241	33090.8	0.15	14.02	531.34
1973	216412	278895	43829.6	0.25	22.43	466.01
1974	208715	385087	50535.95	0.34	28.54	449.44
1975	215802	432452	41497.1	0.29	25.47	464.70
1976	260372	202707	38028.55	0.24	20.94	560.67
1977	308231	69016	33086.09	0.16	14.87	663.73
1978	323960	59115	36082.09	0.15	13.67	697.60
1979	290124	140041	35638.3	0.15	13.58	624.74
1980	248460	73887	30232.97	0.15	13.76	535.02
1981	213133	128152	25949.72	0.15	14.10	458.95
1982	187662	240731	23029.15	0.16	14.87	404.10
1983	196668	483554	24122.89	0.18	16.05	423.49
1984	280974	90455	27750.84	0.17	15.80	605.03
1985	362281	142614	38287.89	0.17	15.72	780.12
1986	383438	99717	43697.83	0.17	15.46	825.68
1987	349876	97500	46827.38	0.16	14.87	753.40
1988	342029	266808	43249.08	0.16	14.36	736.51
1989	358793	341231	39241.25	0.15	14.10	772.61
1990	375115	145587	43985.12	0.18	16.31	807.75
1991	327054	173394	44888.42	0.21	18.86	704.26
1992	274814	147109	46221.03	0.25	21.89	591.77
1993	216752	39227	44687.63	0.29	25.02	466.74
1994	164959	137340	41736.93	0.36	29.88	355.21
1995	130162	151761	35322.9	0.42	33.97	280.28
1996	112829	127730	36009.76	0.54	41.96	242.96
1997	98492	165387	34065.92	0.68	49.34	212.09
1998	91225	78672	32988.31	0.81	55.56	196.44
1999	77742	116896	33841.56	0.98	62.32	167.41
2000	81509	470917	30943.19	1.11	66.95	175.52
2001	158216	97915	44542.44	0.96	61.71	340.69
2002	185517	101167	62501.58	0.76	53.00	399.48
2003	182285	203730	66371.62	0.72	51.47	392.52
2004	173504	317876	75864.31	0.81	55.29	373.61
2005	175363	177789	73287.98	0.92	60.11	377.62
2006	166233	254933	76076.86	1.04	64.51	357.96
2007	147960	83309	66931.03	1.08	66.18	318.61
2008	114370	156356	54425.37	0.99	62.88	246.28
2009	95497	149938	53819.83	1.35	74.18	205.64
2010	71641	43170	47108.37	1.89	84.85	154.27
2011	36314	102038	25251.94	2.07	87.37	78.20
2012	30276	71675	15792.2	1.80	83.49	65.19
2013	33535	47861	15514.08	1.40	75.27	72.21
2014	30149	61352	12862.97	1.11	67.11	64.92
2015	27977	84109	11337.89	1.03	64.44	60.24
2016	30968	179331	11958.47	1.01	63.54	66.68
2017	46654	35078	18439.16	1.10	66.65	100.46
2018	47412	70877	24816.21	1.21	70.24	102.09
2019	33410	79768	17807.2	1.29	72.39	71.94
2020	29109	78982	15501.93	1.30	72.66	62.68

Table S8: Numbers-at-age ($N_{ay,}$ 000s of fish)

Year	1	2	3	4	5	6	7	8	9	10+
1968	1543.52	342.16	105.86	42.17	24.73	23.84	11.47	16.23	132.90	1.24
1969	177.95	1113.75	265.12	62.29	20.29	15.07	18.80	8.38	10.03	121.35
1970	243.47	136.09	783.58	163.39	42.66	10.90	9.96	15.86	6.89	79.04
1971	135.79	194.83	95.96	557.27	100.09	30.03	7.03	7.80	11.31	54.48
1972	211.24	95.10	140.94	94.25	335.91	64.04	26.61	3.19	5.04	50.55
1973	278.89	215.81	94.79	108.24	87.22	179.37	45.54	18.22	2.52	21.95
1974	385.09	242.16	180.42	78.80	80.37	65.07	94.33	24.72	10.21	12.70
1975	432.45	370.24	175.00	116.26	51.48	53.20	42.35	46.50	12.17	10.75
1976	202.71	422.14	302.07	117.09	70.12	29.89	33.66	26.17	26.25	12.37
1977	69.02	169.10	371.22	214.18	77.35	43.75	18.41	21.21	15.52	24.40
1978	59.12	42.34	124.44	294.72	160.97	61.90	30.99	14.18	13.78	25.54
1979	140.04	40.67	31.28	96.12	206.54	110.68	44.85	21.15	10.22	24.91
1980	73.89	108.79	30.09	24.99	69.58	134.13	68.47	29.74	14.62	22.91
1981	128.15	52.74	86.77	18.23	19.26	49.94	91.87	40.90	19.53	24.27
1982	240.73	88.91	32.20	63.49	10.57	14.28	35.92	68.85	25.62	30.07
1983	483.55	207.69	50.35	18.46	40.54	6.08	9.20	27.45	60.24	40.43
1984	90.45	551.00	206.68	28.14	11.58	23.04	3.82	5.85	18.74	68.08
1985	142.61	65.53	561.53	172.81	16.37	7.45	14.31	2.39	3.80	56.38
1986	99.72	109.59	53.31	538.59	129.89	10.57	5.41	7.86	1.54	28.05
1987	97.50	68.66	75.26	40.13	425.55	91.63	6.52	3.71	4.25	16.62
1988	266.81	63.78	39.35	46.22	27.32	380.98	60.20	4.37	2.39	11.72
1989	341.23	250.81	42.78	24.23	28.51	15.73	314.58	33.86	2.99	8.77
1990	145.59	317.71	206.01	29.91	15.61	18.15	11.20	237.65	18.97	6.99
1991	173.39	111.25	280.46	148.12	19.87	9.87	12.20	8.22	137.59	14.61
1992	147.11	137.48	71.01	207.26	98.71	13.27	6.09	7.68	5.30	88.75
1993	39.23	111.77	107.02	46.08	137.70	61.96	8.87	3.64	4.47	44.08
1994	137.34	21.55	74.69	70.85	26.62	95.56	38.48	5.26	1.98	20.89
1995	151.76	103.86	13.03	49.26	43.31	13.96	51.80	20.00	2.67	9.17
1996	127.73	111.60	59.43	7.41	29.45	25.84	6.68	29.17	8.96	5.33
1997	165.39	95.01	74.07	29.75	3.89	14.59	12.62	2.73	13.26	5.45
1998	78.67	130.34	57.41	40.20	13.73	1.72	6.02	5.27	1.06	5.40
1999	116.90	52.21	87.13	29.10	18.99	4.61	0.71	1.97	1.76	1.79
2000	470.92	86.14	28.36	41.48	10.89	6.65	1.13	0.19	0.56	1.02
2001	97.92	484.97	58.54	13.95	16.34	2.51	1.54	0.23	0.05	0.40
2002	101.17	66.62	416.36	30.93	7.35	6.06	0.74	0.38	0.06	0.09
2003	203.73	67.18	41.93	313.46	18.31	3.65	3.17	0.25	0.09	0.03
2004	317.88	167.77	41.13	23.90	201.85	7.19	2.03	1.11	0.08	0.03
2005	177.79	283.11	111.21	20.68	12.07	100.02	2.83	0.83	0.20	0.04
2006	254.93	136.14	212.77	56.50	10.10	4.47	38.77	0.98	0.23	0.04
2007	83.31	208.33	84.78	115.84	20.24	3.38	1.47	11.24	0.21	0.06
2008	156.36	53.53	142.58	39.00	50.04	4.65	0.93	0.36	3.26	0.06
2009	149.94	113.72	27.14	81.87	17.02	20.38	1.16	0.22	0.08	1.32
2010	43.17	106.90	60.63	8.73	29.51	3.89	4.83	0.22	0.03	0.35
2011	102.04	22.67	49.87	13.64	1.63	4.20	0.54	0.49	0.03	0.05
2012	71.68	71.38	9.60	13.36	2.00	0.16	0.39	0.07	0.03	0.01
2013	47.86	54.16	41.86	2.52	3.17	0.25	0.02	0.03	0.01	0.01
2014	61.35	31.40	34.83	16.31	0.75	0.51	0.02	0.01	0.01	0.00
2015	84.11	42.02	16.90	17.64	4.86	0.22	0.09	0.01	0.00	0.00
2016	179.33	60.61	21.27	7.29	6.93	1.62	0.06	0.01	0.00	0.00
2017	35.08	168.92	37.39	8.12	2.75	2.06	0.60	0.01	0.00	0.00
2018	70.88	25.66	119.89	14.97	2.70	0.61	0.48	0.15	0.00	0.00
2019	79.77	52.73	19.31	41.86	5.03	0.54	0.14	0.07	0.06	0.00
2020	78.98	56.84	31.26	7.09	13.60	1.13	0.11	0.03	0.02	0.01

Table S9: Fishing mortality (F_{ay})

YEAR	1	2	3	4	5	6	7	8	9	10+
1968	0.01	0.04	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1969	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1970	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1971	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1972	0.01	0.04	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1973	0.01	0.06	0.14	0.17	0.25	0.25	0.25	0.25	0.25	0.25
1974	0.02	0.08	0.19	0.23	0.34	0.34	0.34	0.34	0.34	0.34
1975	0.01	0.07	0.16	0.20	0.29	0.29	0.29	0.29	0.29	0.29
1976	0.01	0.06	0.13	0.16	0.24	0.24	0.24	0.24	0.24	0.24
1977	0.01	0.04	0.09	0.11	0.16	0.16	0.16	0.16	0.16	0.16
1978	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1979	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1980	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1981	0.01	0.04	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1982	0.01	0.04	0.09	0.11	0.16	0.16	0.16	0.16	0.16	0.16
1983	0.01	0.04	0.10	0.12	0.17	0.17	0.17	0.17	0.17	0.17
1984	0.01	0.04	0.10	0.12	0.17	0.17	0.17	0.17	0.17	0.17
1985	0.01	0.04	0.09	0.12	0.17	0.17	0.17	0.17	0.17	0.17
1986	0.01	0.04	0.09	0.11	0.17	0.17	0.17	0.17	0.17	0.17
1987	0.01	0.04	0.09	0.11	0.16	0.16	0.16	0.16	0.16	0.16
1988	0.01	0.04	0.09	0.10	0.16	0.16	0.16	0.16	0.16	0.16
1989	0.01	0.04	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1990	0.01	0.04	0.10	0.12	0.18	0.18	0.18	0.18	0.18	0.18
1991	0.01	0.05	0.12	0.14	0.21	0.21	0.21	0.21	0.21	0.21
1992	0.01	0.06	0.14	0.17	0.25	0.25	0.25	0.25	0.25	0.25
1993	0.01	0.07	0.16	0.19	0.29	0.29	0.29	0.29	0.29	0.29
1994	0.02	0.08	0.20	0.24	0.35	0.35	0.35	0.35	0.35	0.35
1995	0.02	0.10	0.23	0.28	0.41	0.41	0.41	0.41	0.41	0.41
1996	0.03	0.13	0.30	0.37	0.54	0.54	0.54	0.54	0.54	0.54
1997	0.03	0.16	0.38	0.46	0.68	0.68	0.68	0.68	0.68	0.68
1998	0.04	0.19	0.45	0.55	0.81	0.81	0.81	0.81	0.81	0.81
1999	0.05	0.23	0.54	0.66	0.98	0.98	0.98	0.98	0.98	0.98
2000	0.05	0.26	0.61	0.75	1.11	1.11	1.11	1.11	1.11	1.11
2001	0.05	0.23	0.53	0.65	0.96	0.96	0.96	0.96	0.96	0.96
2002	0.04	0.18	0.42	0.51	0.75	0.75	0.75	0.75	0.75	0.75
2003	0.04	0.17	0.40	0.49	0.72	0.72	0.72	0.72	0.72	0.72
2004	0.04	0.19	0.45	0.54	0.80	0.80	0.80	0.80	0.80	0.80
2005	0.05	0.22	0.51	0.62	0.92	0.92	0.92	0.92	0.92	0.92
2006	0.05	0.24	0.57	0.70	1.04	1.04	1.04	1.04	1.04	1.04
2007	0.05	0.25	0.60	0.73	1.08	1.08	1.08	1.08	1.08	1.08
2008	0.05	0.23	0.55	0.67	0.99	0.99	0.99	0.99	0.99	0.99
2009	0.07	0.32	0.75	0.91	1.35	1.35	1.35	1.35	1.35	1.35
2010	0.09	0.44	1.05	1.27	1.89	1.89	1.89	1.89	1.89	1.89
2011	0.10	0.49	1.15	1.40	2.07	2.07	2.07	2.07	2.07	2.07
2012	0.09	0.42	1.00	1.22	1.80	1.80	1.80	1.80	1.80	1.80
2013	0.07	0.33	0.77	0.94	1.40	1.40	1.40	1.40	1.40	1.40
2014	0.05	0.26	0.62	0.75	1.11	1.11	1.11	1.11	1.11	1.11
2015	0.05	0.24	0.57	0.70	1.03	1.03	1.03	1.03	1.03	1.03
2016	0.05	0.24	0.56	0.68	1.01	1.01	1.01	1.01	1.01	1.01
2017	0.05	0.26	0.61	0.74	1.10	1.10	1.10	1.10	1.10	1.10
2018	0.06	0.28	0.67	0.82	1.21	1.21	1.21	1.21	1.21	1.21
2019	0.06	0.30	0.71	0.87	1.29	1.29	1.29	1.29	1.29	1.29
2020	0.06	0.30	0.72	0.88	1.30	1.30	1.30	1.30	1.30	1.30

FIGURES

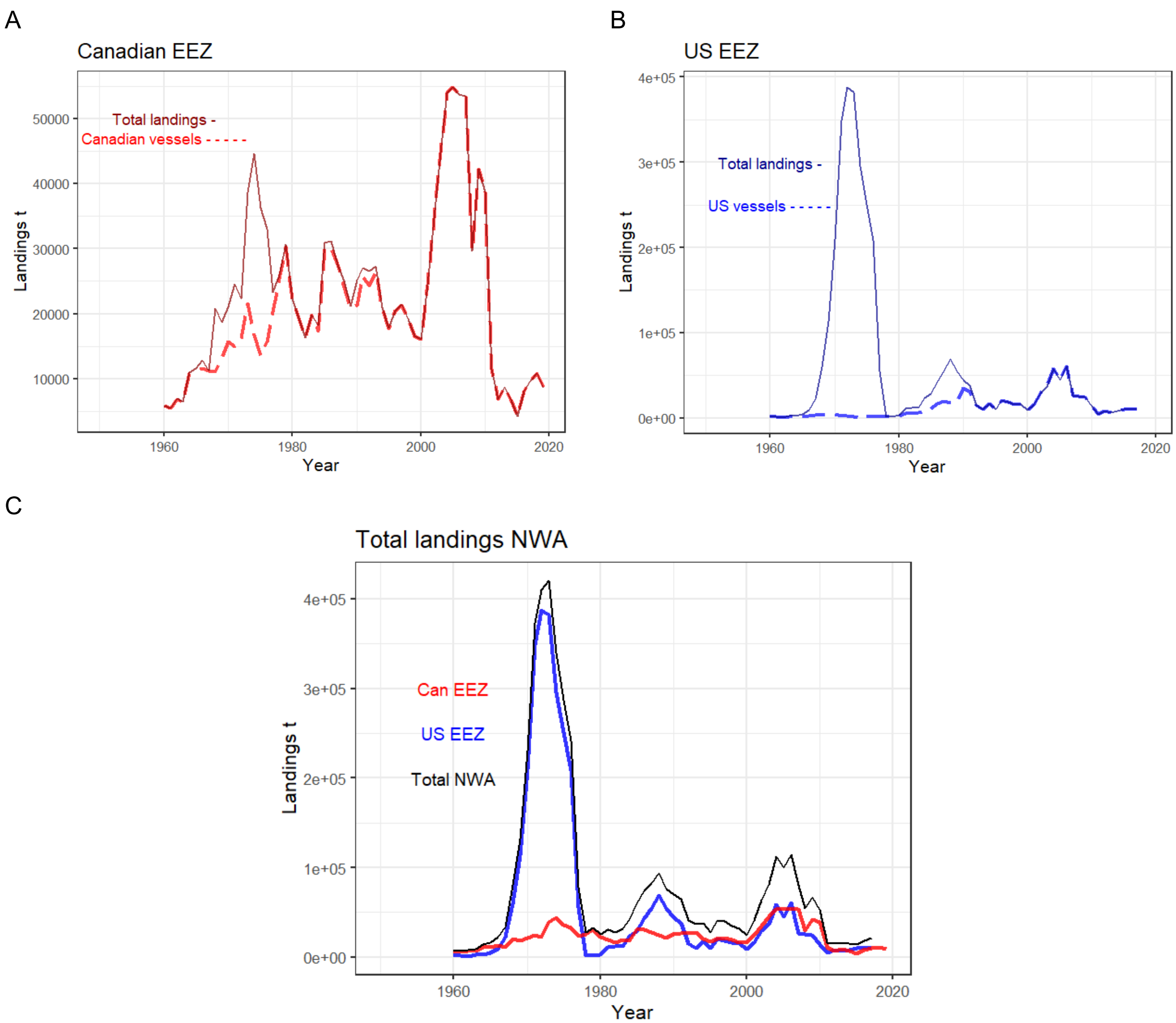

Figure S1. Atlantic mackerel landings (t) from 1960-2020 in A) Canada's exclusive economic zone (EEZ), B) The EEZ of the U.S.A., and C) the entire Northwest Atlantic (NWA).

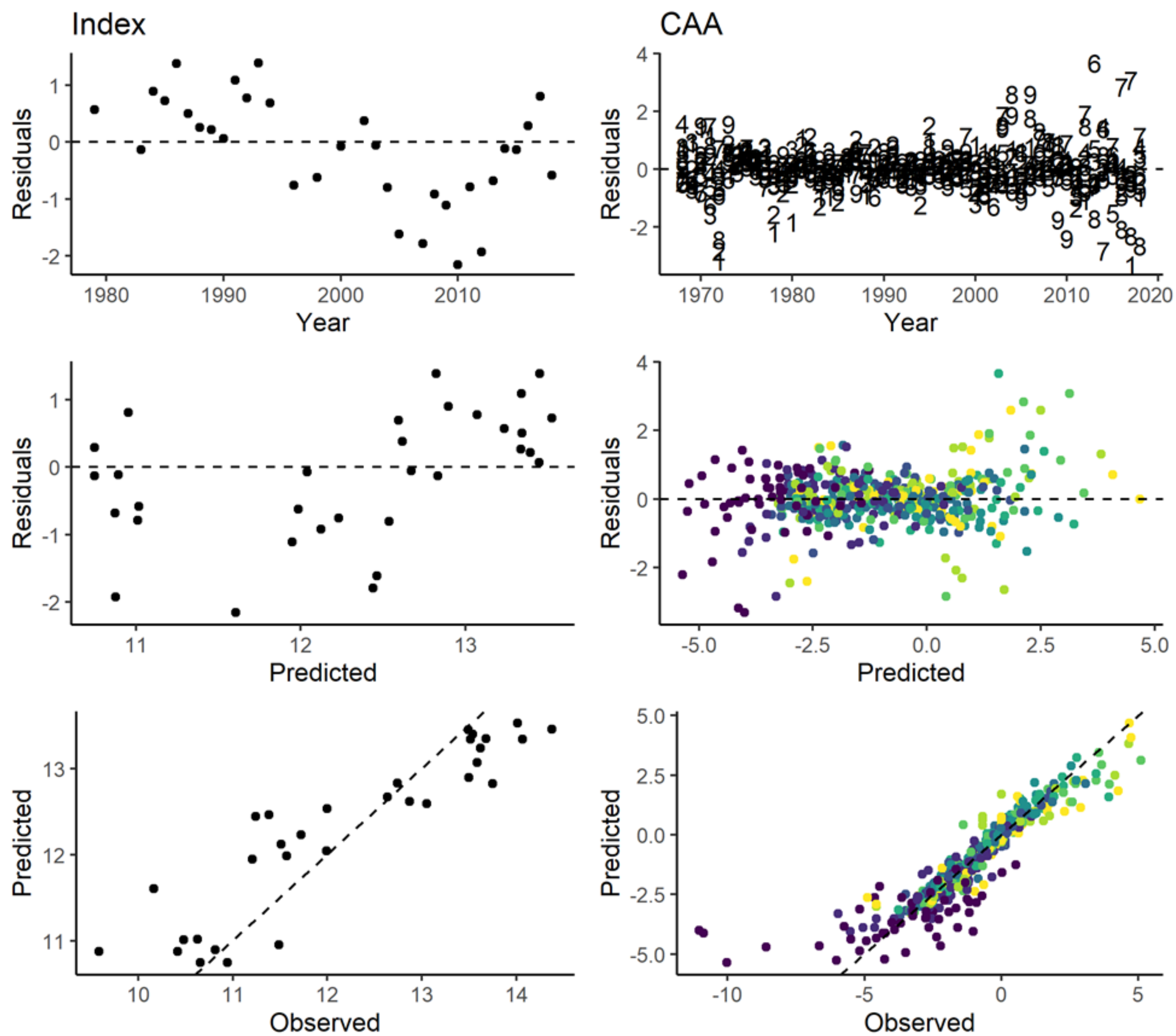

Figure S2: Model residuals. The color scale indicates the age classes (young to old as violet to yellow).

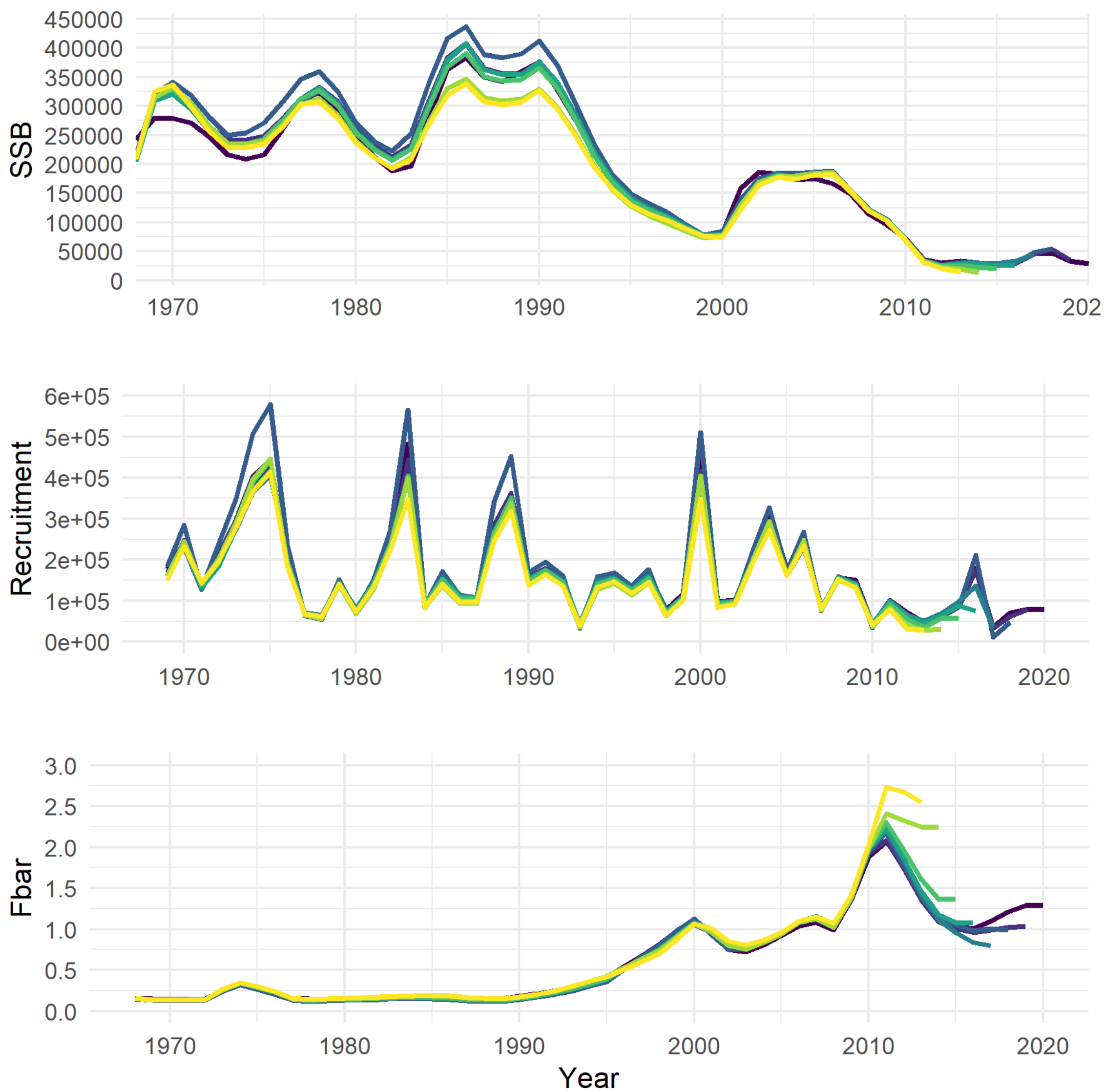

Figure S3: Retrospective patterns (SSB = Spawning stock biomass; Recruitment = the number of estimated age 1 fishFbar = F over aged fully recruited to the fishery, i.e., ages 5-10).

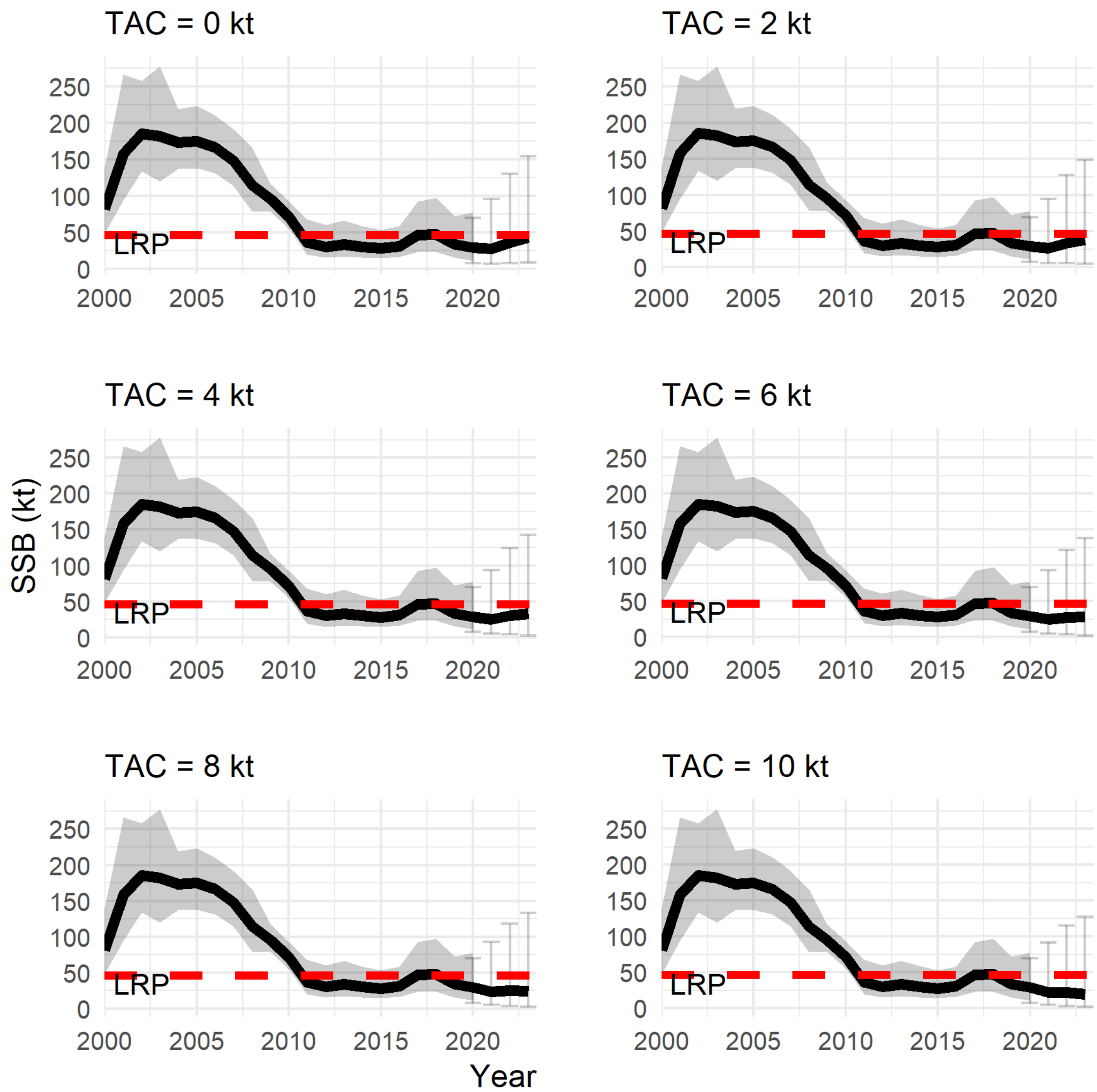

Figure S4. Spawning stock biomass and three year projections (2021-2023) under different TAC scenarios.