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Assessment of the Northern Contingent of Atlantic Mackerel (*Scomber scombrus)* in 2022

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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

This document presents the data and methods used to assess the stock status of the northern contingent of Atlantic mackerel (*Scomber scombrus*) in the Northwest Atlantic. The presented and reviewed stock status indicators (February 20-22, 2023) were estimated with an age-structured stock assessment model that was fitted to landings data, landings-at-age and an egg survey index. The estimated 2022 spawning stock biomass (SSB) was at 42% of the Limit Reference Point, defined as 40% of $SSB_{40\%}$, placing the stock in the Critical zone of the Precautionary Approach Framework. The stock has been in or near the Critical zone since 2011. Recent average recruitment (2012-2022) has been low relative to the previous period (1969-2011) and the age structure of the stock remained truncated. Short-term projections indicated that the probability of the SSB leaving the Critical zone by 2025 varied around 37.5% for a total allowable catch (TAC) of 0 t and around 16% for a TAC of 8,000 t, given continued U.S. fishing and recreational fishing in Canada.

INTRODUCTION

This research document describes the data, methods, and supporting analyses contributing to the stock assessment of the northern contingent of Atlantic mackerel (*Scomber scombrus*) in the Northwest Atlantic over 1969-2022. In the introduction, we provide background information on population structure, fishery management, and a rationale for the assessment framework. For further information on this fish stock, see the online species profile as well as the review by Van Beveren et al. (2023). The 2023 assessment meeting was carried out by the Department of Fisheries and Oceans Canada (DFO) at the Maurice Lamontagne Institute (IML) in Mont-Joli, Quebec, Canada on February 20-22, 2023.

POPULATION STRUCTURE

Mackerel occur on both sides of the North Atlantic. Individuals from each side are genetically distinct and there is no evidence for trans-Atlantic migration (Rodríguez-Ezpeleta et al. 2016; Gíslason et al. 2020; Bourret et al. 2023).

In the Northwest Atlantic (NWA), there are two spawning contingents; a northern contingent which spawns predominantly in the southern Gulf of St. Lawrence in June-July (Van Beveren et al. 2023) and a southern contingent which spawns mostly in the Western Gulf of Maine and off southern New England, from Mid-April to June (Studholme et al. 1999). Both contingents mix in winter in deeper waters, in part on the U.S. shelf, where they are subject to the U.S. fishing fleet. There is small but significant genetic differentiation between the northern and southern contingents (Bourret et al. 2023). The level of mixing during winter remains highly uncertain, but is likely large and variable between years (Redding et al. 2020; Arai et al. 2021; Bourret et al. 2023).

FISHERY MANAGEMENT

In 2022, Fisheries Management division of DFO closed both the commercial and bait fisheries for the first time. Mackerel were previously harvested commercially and for bait across the Atlantic Provinces and Quebec in an open competitive fishery using a variety of gear types (gillnets, mechanical jiggers, purse and tuck seines, weirs, and traps), the predominance of which varied by region and season. Mackerel are also harvested through a popular recreational fishery that remained open, but for which there has been a daily possession limit of 20 fish per person since May 2021. While each regional fishery management sector implements its own license conditions and has its own catch monitoring system (a mixture of logbooks, purchase slips, and dockside monitoring), mackerel are managed on a national level. Although northern contingent mackerel is a transboundary stock that is also harvested by the U.S. fishing fleet, there is no joint management. The U.S. sets a NWA-wide allowable biological catch, which includes both countries, and then subtracts due to the differences in the timing of management a projected Canadian catch, with the remainder set as the US TAC.

The last assessment of mackerel in Canada took place in February 2021 (DFO 2021). The stock was estimated to be below its Limit Reference Point (LRP). Because the stock has been in or near the Critical zone according to DFO's Precautionary approach (DFO 2009) since 2011, a Rebuilding Plan was developed and published in 2020. The main objectives of the Rebuilding Plan were to "limit the probability of Atlantic mackerel spawning stock biomass (SSB) declining from one year to the next (i.e., maintain a positive growth trajectory)" and "to rebuild Atlantic mackerel SSB above the LRP". The last assessment indicated these objectives were not attained (Smith et al. 2022). As the objectives of the Rebuilding Plan are not being met, and because Atlantic Mackerel has been prescribed under the Fish Stock Provisions (FSP) of the revised *Fisheries Act* with new requirements for Rebuilding Plans, an updated plan for Atlantic Mackerel is required. The 2023 stock assessment therefore includes elements to inform this update, as requested by the Fisheries Resource Management Branch; an estimate of the time the stock would take to rebuild to a rebuilding target in the absence of all fishing and under prevailing conditions *(Tmin*), a summary of available knowledge on the ecosystem considerations (including how they are accounted for in the assessment and how they can affect rebuilding), and a description of the probable causes of the stock's decline, including whether habitat degradation or loss has occurred and whether it has contributed to the stock's decline.

ASSESSMENT FRAMEWORK

The northern contingent of Atlantic mackerel has historically been assessed based on three principal data sources: landings, landings-at-age and an egg survey index. Since the 2017 stock assessment (see Doniol-Valcroze et al. 2019), a custom state-space censored catch-at-age model (CCAM; Van Beveren et al. 2017) has been used to integrate the available information. State-space models can treat both biological stochasticity in population dynamics (referred to as process error) as well as observation error and are used to assess a broad range of stocks around the world (Aeberhard et al. 2018). A custom model was built to integrate the uncertainty in total removals (including discards, unreported, recreational and U.S. landings). Specifically, the model has a censored likelihood option to allow estimation of removals between an upper and lower bound (Van Beveren et al. 2017).

METHODS

For this assessment, all input data were revised. The details of all methods, robustness tests and comparisons with previous estimates are presented in other Research Documents focusing on specific input data: the egg survey[1], landings-at-age and maturity-at-age[2] and biological weight- and fecundity-at-age[3]. Supporting information on natural mortality, based on total consumption estimates by a variety of predators, is provided in Van Beveren et al.[4]. The below information therefore only provides the details essential to understand the approaches used.

All data were collected and estimated for 1968-2022. Code to generate input data and run the assessment model is accessible online.

LANDINGS

Data on mackerel landings within Canadian waters for 1968-1994 was downloaded from the NAFO landings database (STATLANT 21B) and data from 1995 to 2022 was downloaded from the most recent ZIFF files (Zonal Interchange File Format) produced by DFO's regional statistics bureaus. Total commercial landings for the two terminal years (2021 and 2022) are considered

[1] Lehoux et al. Results of the mackerel (*Scomber scombrus* L.) egg surveys conducted in the southern Gulf of St. Lawrence from 1979 to 2022. DFO Can. Sci. Advis. Sec. Res. Doc. In preparation.

[2] Van Beveren et al. Revision of catch- and maturity- at age used to assess the northern contingent of Atlantic mackerel (*Scomber scombrus*). DFO Can. Sci. Advis. Sec. Res. Doc. In preparation.

[3] Boudreau et al. Calculation of stock weight- and fecundity-at-age during the spawning season used to assess the northern contingent of Atlantic Mackerel (*Scomber scombrus*). DFO Can. Sci. Advis. Sec. Res. Doc. In preparation.

[4] Van Beveren et al. Consumption of northern contingent Atlantic mackerel (*Scomber scombrus*) by various predators. DFO Can. Sci. Advis. Sec. Res. Doc. In preparation.

preliminary (Table S1 and S2). Removals associated with the 2022 sample collection under a Section 52 fishing license (see commercial sampling) are not included in the ZIFF files but were added to the overall landings before their use within the assessment model.

In addition to the recorded landings, there are other sources of removals. Data from the U.S. commercial and recreational fisheries (1960-2022) were provided by the Northeast Fisheries Science Center (Kiersten Curti, NOAA, pers. comm.). The U.S. catch statistics were likewise considered preliminary for 2021 and 2022 (Table S1).

A maximum amount of unaccounted-for catches in Canadian waters was estimated by Van Beveren et al. (2017). For more recent years, we assumed that the amount of unaccounted-for catches (recreational fishing, discards, illegal and unreported landings) was at most 140% of recorded landings, in correspondence with estimated maximum ratios since 2005. Because of the 2022 closure, the only unaccounted-for catches were assumed to be from recreational fishing. Because mackerel by-catch is small (see further), discards from other fisheries are presumably minor. Precise estimates of the biomass caught by the recreational fishery are unavailable, but are likely to be between 187 t and 680 t, based on a simple extrapolation of values provided by a federal survey on recreational fishing (Table S3; DFO 2015). The upper bound (680 t) corresponds roughly to the presence of 3 to 5 fishers per day (depending on average fish weight) that fish their daily quota (20 fish / day / person) in 300 different locations around Atlantic Canada, over a three month period (July, August, September; when recreational fishing is commonly practiced). The lower bound (187 t) corresponds roughly to the presence of about 3 fishers per day that fish their daily quota (20 fish / day / person) in 100 different locations around Atlantic Canada, over a three month period (July, August, September; when recreational fishing is commonly practiced). Note that the aim of these estimates is to provide a reasonable lower and upper bound rather than a precise value, which cannot be determined with the information available.

COMMERCIAL SAMPLING

Fisheries and Oceans Canada has a systematic port sampling program that is designed specifically to estimate the catch composition of commercial landings. For mackerel, it is also the only data source available to determine biological characteristics of the stock.

Each year, a request is submitted for a certain number of samples per region, period and gear type (referred to as a stratum), in function of the expected importance of that stratum in terms of total landings. For mackerel, a sample typically consists of at least 150 randomly selected fish of which the fork length is measured to the nearest 0.5 cm. A length-stratified subsample (two fish per length bin) is usually sent to IML for the determination of age (standardized to January 1st) and additional biological characteristics (fork length, ± 1 mm; weight, ± 0.1 g; gonad weight, ± 0.01 g; sex; maturity stage). Biological data (age, maturity, etc.) from the port sampling program can be supplemented by samples collected for other purposes (e.g., specific research projects) and from other sources (e.g., research surveys or opportunistically collected small by-catch samples). The length-frequencies and biological ('bio') data are entered into two separate Oracle database tables and were accessed with the DFOdata package on github (version 0.1.1). Length-frequency data is only available from 1976 onwards, whereas the bio database has information available from 1973 onwards. We were unable to retrieve older data.

In 2022, samples had to be collected outside the commercial port sampling program because of the fishery closure. A license to fish for scientific purposes (Section 52 of the Fishery General Regulations) was issued to certain harvesters from each DFO region. License conditions, defined by each region, stipulated amongst other things that harvesters were allowed to keep 300 kg of mackerel for personal use and could fish only with certain gear types (e.g., no seining in Newfoundland). The standard rules around minimum fish size for retention applied (26.8 cm). Contracted harvesters were asked to collect a certain number of samples. The initial intent was to obtain samples similar to previous years in terms of quality, quantity and coverage to facilitate interannual comparison and secure continuity. Practical limitations imposed a more opportunistic approach (in function of gear types used, number of samples collected per region/period and overall spatio-temporal coverage). With the exception of Quebec region, where port samplers completed the sampling protocol as usual, samples were collected by harvesters or a technician from a fishery organization. Note that the total number of samples in the database and used within the assessment (73 length-frequencies) is not identical to the number of samples received, as some were for instance merged upon arrival (because of sample size, identical date/location). Some samples from Newfoundland were not subsampled prior to being shipped to IML for biological analyses because of time constraints, and one sample from the Maritimes was lost during transportation and likewise consists of only a length-frequency distribution. Samples from experimental licenses were supplemented with two by-catch samples from the Strait of Belle Isle (4R), multiple by-catch samples from the herring fishery in and around the Bay of Fundy, and samples from scientific surveys (used for biological information). Details of 2022 samples, as used within the assessment, are in Table S3. More detailed tables are provided in Van Beveren et al.[2].

LANDINGS-AT-AGE

Landings-at-age (LAA) from 1976-2022 were updated (see Van Beveren et al.[2] for details and a comparison with previously used values). In short, catches were decomposed by age with the help of length-frequencies and age-length keys built with the commercial port sampling databases using the catchR package (see Ouellette-Plante et al. 2022 for details on the algorithm). Landings were first totalled by so-called strata (a combination of trimester, gear type and region). For each strata, the most representative samples were then automatically selected based on a hierarchical approach. If a minimum of two corresponding samples (length-frequency or age-length key) was not achieved, the catchR algorithm became gradually less restrictive in its sample search. Length-frequency and age-length samples attributed to a given strata were subsequently combined to obtain a stratum-specific length-frequency (proportions) and a corresponding age-length key (proportions). Stratum-specific landings were divided into age classes by multiplying them by the proportions-at-length and the proportions-at-age for each length. This separation, together with year and trimester-specific information on average fish weight by age obtained from length-weight relationships, permits estimation of total landings-at-age in numbers. Weight-at-age for the early period (1968-1975) was extrapolated (Figure S1).

Because length-frequency data prior to 1976 could not be recovered, the new time-series is significantly shorter than what was previously used (1968-terminal year). Within this assessment, we considered three options;

- **Default**: start the assessment in 1968 using LAA estimated with two different methods (1968-1975: old time-series; 1976-2022: new time-series). Combining both series is reasonable as the update for 1976-2022 did not differ meaningfully from the old LAA matrix, despite changes in methodology and sometimes data.
- **Shorten**: shorten the assessment time-series to 1976-2022 to remove pre-1976 LAA estimates. Note that most biological data (maturity-, biological weight- and fecundity-at-age) also only start in 1973, and that estimates for the early years (1968-1972) are always extrapolations. Shortening an assessment time-series is nonetheless often perceived as undesirable because this can result in larger process uncertainty.

- **Exclude**: Start the assessment in 1968 for consistency with previous assessments, but treat LAA as missing for to determine years between 1968-1975, as the current assessment model does not necessitate LAA estimates for each year.

The best approach was again determined based on an assessment of the trade-off between increasing uncertainty through the removal of data and tolerating potential bias through the inclusion of ambiguous data.

Because of the fishery closure in 2022, there was likely an abrupt change in fishery selectivity associated with this years' LAA. Estimated LAA is a product of recorded total landings (which might have a true change in fishery selectivity) and samples that determine the age structure of those landings (which determine perceived changes in fishery selectivity). The distribution of the (small) reported 2022 landings across regions, gear types and time changed vastly relative to years prior to the fishery closure, and was essentially limited to by-catch and catches associated with scientific sample collection. Sample distribution and selectivity was likewise atypical. A new sampling program had to be established, and the observed length- and age-compositions were therefore expected to have reduced comparability with previous years. For instance, a relatively much higher number of samples was obtained from Newfoundland, but none were from the usually important purse seine fishery. For the first time, there were no samples collected in the beginning of the fishing or spawning season (May and most of June). Because harvesters went out fishing with the specific aim of collecting a sample (and up to 300 kg of mackerel for personal use), a change in behaviour might also have affected results (e.g., more nearshore fishing, shorter trips at times when harvester might otherwise not have gone out fishing). The large majority of samples were also collected by harvesters themselves rather than port samplers, with the exception of samples from the Quebec region.

Because this is a one-year issue, we could not fall back on common approaches (e.g., explicit estimation of changing selectivity, development of a separate index).

Within this assessment, we considered the following approaches;

- **Default**: estimate LAA as usual and include this within the model. This can result in biased age composition and especially recruitment strength of the final years, as the expected abrupt change in fishing selectivity is unaccounted-for.
- **Modify**: estimate a (partially) bias-corrected LAA and include this within the model. In this scenario, the average stratum-specific landings of 2017-2021 were used to determine LAA rather than the true landings, and the resulting LAA was rescaled to the total landings of 2022. This simulates a situation similar to if the fishery had stayed open, but it cannot account for changes in sample collection. A partial correction can be justified because overall removals were very low.
- **Exclude**: present LAA for 2022 but do not include it explicitly within the assessment model. Although the model can run without LAA data for one year (as well as potentially no information for total egg production, see further), it should increase uncertainty, especially in the terminal year estimates.

Note that LAA within the assessment is always calculated for the commercial and bait fishery, and that the age-composition of unaccounted-for removals (recreational fishing, U.S. fishing, commercial discards, etc.) can only be assumed identical. For the first time, unaccounted-for removals largely exceeded those reported (near-zero).

TOTAL EGG PRODUCTION

The mackerel egg survey, which covers the southern Gulf of St Lawrence in June, is the main indicator of stock trend. The basic concept of egg surveys is that if we know the number of eggs that have been spawned, then this can be used to determine the stock abundance or biomass as egg production and stock size are directly related through fecundity, the proportion of females in the stock and their proportion mature. Since the Management Strategy Evaluation (Van Beveren et al. 2020) and 2021 stock assessment (Smith et al. 2022), the assessment model is fitted directly to an index of Total Egg Production (TEP) rather than to the derived SSB index. The TEP index, likewise to LAA, was revised for this assessment for the full period (1979-2022[1]).

The mackerel egg survey consists of a 66 stations fixed grid, which is visited over about a 10-day period. At each station, a tow following a saw-tooth profile in the top 50 m of the water column is made with 61 cm bongo nets (333 µm mesh size) for about 10 minutes (less if there is clogging) while cruising at roughly 2.5 knots. For each year (*y*) and station (*i*), the volume of filtered seawater (*V*, m^3), depth sampled (*D*, m), and the mean temperature in the top 10 m of the water column (*T10*, °C) was calculated. Stage 1 and 5 eggs were counted (*N1* and *N5*) from a subsample (*Fr,* fraction) of each station.

Daily Egg Densities (DED, n/m^2) were calculated as follows:

$$DED_{y,i} = \frac{\left(\left(N1_{y,i} + N5_{y,i}\right)/Fr_{y,i}\right)}{V_{y,i}} * \ D_{y,i}$$

These values were subsequently corrected for variations in egg incubation time as a function of temperature, using the equation from Lockwood and Nichols (1977), giving Daily Egg Production (DEP, n/m^2/day):

$$DEP_{y,i} = \frac{DED_{y,i}}{e^{\left(-1.61*\log\left(T10_{y,i}\right)+7.76\right)}} \cdot 24$$

DEP for missing stations was predicted with a spatial mixed model (R INLA, details in Lehoux et al.[1]). The average DEP across all stations was scaled to Total annual Egg Production (TEP, n) based on an estimate of the proportion of eggs spawned at the time of the survey (*S*) and the total survey area (*A*, 6.945^{10} m²):

$$TEP_y = \frac{\left(\sum_{i=1}^{66} DEP_{y,i}\ /66\right) * A}{S_y}$$

The proportion of eggs spawned on the median survey date S_y, relative to the entire spawning period, is calculated based on the seasonal progression of female gonads. As eggs are released over the spawning season, the gonado-somatic index (GSI, percentage of fish weight determined by the gonads) of female mackerel (NAFO areas 4T, 4V and 4W) reduces. This decrease is modelled with a logistic function $f(GSI, Asym, scal, xmid) = \frac{Asym}{1+exp\left(\frac{xmid-x}{scal}\right)}$, where *Asym* is the curve's maximum value, *scal* is the logistic growth or steepness of the curve (determining the spawning duration) and *xmid* is the sigmoid's midpoint (or the peak spawning day). A mixed model (R package nlme) is used with year as a random effect. The scaled slope of a logistic curve for a given year and day is equal to the proportion of eggs spawned at that moment. S_y is then defined as the proportion of eggs spawned at the median survey day. For certain years (1991, 1999 and 2022), there were difficulties with the logistic fit, and hence S_y was uncertain (see Lehoux et al.[1] for details). For 1991 and 1999, there was independent evidence based on the proportion of larvae observed that S_y was indeed biased and both years were excluded. For 2022 no such evidence was detected.

The daily proportions of eggs spawned are also used to estimate spawning duration and seasonality. The latter information is important to validate the results; when the median survey date was outside the period when 70% of eggs were produced, the index value was assumed to be less precise (true for 2006, 2017 and 2019). It is currently impossible to feed (partially) estimated uncertainties into the assessment model or to downweigh the influence of certain datapoints, as the model assumes only one index-specific observation error.

During this assessment, we presented a default option but also considered progressively removing TEP values for which the uncertainty was assumed to be relatively large:

- **Default**: Keep the maximum number of years for which an estimate of TEP was available. This includes all years during which the survey was completed, with the exception of 1991 and 1999, which were demonstrated to have a large bias. In previous stock assessments, only 1999 was excluded for the same reason.
- **Without 2022**: Based on the default scenario, also exclude 2022 because of the uncertainty in the estimation of S_y (without indication of bias), related to the absence of samples from early in the spawning period.
- **Without uncertain years**: Based on the “without 2022” scenario, also exclude 2006, 2017 and 2019 because of the timing of the survey relative to the timing of spawning.

MATURITY-AT-AGE

Maturity-at-age (MAA), or the proportion of mature fish at a given age, is used within the assessment model to convert biomass into SSB and to link observed with predicted egg production. The entire time-series was updated (see Van Beveren et al.[2]). In short, June-July data from the commercial port-sampling program was used to fit annual Generalized Linear Models (GLMs) that predict maturity as a function of age. Age-specific spline smoothers were subsequently used to reduce the noise in the predicted time-series.

WEIGHT-AT-AGE (BIOLOGICAL)

The stock assessment model requires three weight-at-age (WAA) matrices as inputs; WAA of the stock on January 1st (to estimate January 1st SSB, if of interest), WAA of the stock during spawning (to estimate June SSB, necessary within the stock-recruitment relationship and presented by default) and WAA of landed fish (to convert estimated numbers of landed fish into landed weight). Changes in the latter can reflect both fluctuations in the stock and shifts in the fishery (e.g., occurring later in the year when fish weigh more). In previous assessments, biological WAA was not computed and WAA of landed fish was used as a substitute. For this assessment, we estimated WAA of fish in June-July (see Boudreau et al.[3]; also used as WAA on January 1st) not only to improve modelling of the stock dynamics, but also to provide an index that has more biological meaning. Unless mentioned otherwise, June SSB is typically reported.

The WAA during spawning was determined as the average weight by age of fish in the “bio” database, sampled during June-July from the gillnet fishery in NAFO areas 4TVWX. Age-year combinations with less than 10 fish were discarded. A mixed model that assumes a first order autoregressive (AR1) process over age, year and cohort was applied to reduce noise and fill in gaps.

FECUNDITY-AT-AGE

Fecundity is the intrinsic link between TEP and the abundance of spawning female fish. In the past, age-aggregated average annual values of fecundity were used to help transform TEP into an SSB index outside the model (Smith et al. 2020 and prior). Currently, we work with a matrix of fecundity-at-age (FAA) that is used by the model to perform the abundance-at-age to TEP conversion. Under the current approach, the model estimated age structure of the stock should determine overall stock fecundity and hence TEP.

The FAA model input matrix was reviewed and re-estimated (see Boudreau et al.[3]). Pelletier (1986) determined potential fecundity of Atlantic mackerel sampled in Canadian waters. Potential fecundity estimates, in contrast to realised fecundity estimates, include oocytes that might not be spawned (see follicular atresia) and exclude oocytes that might develop throughout the spawning period. Based on Pelletier's fecundity data, a robust linear regression (R package robust) between fecundity (*fec*), age (with fishes older than 9 years as a 10+ group), and the GSI was estimated ($log(fec) = 10.8 + 0.41 * log(age) + 0.71 * log(GSI)$). The average GSI of stage 5 (i.e., ready to spawn) females was determined for each age class and year ("bio" database). Using the estimated robust linear regression, this GSI-at-age matrix was transformed into FAA. To reduce the amount of noise and fill in gaps, the previously mentioned mixed model used for WAA and that assumes an AR1 process in three dimensions was again applied.

PROPORTION OF FEMALES-AT-AGE

The proportion of females in the population by age and year is used to transform TEP by spawning females to total spawning stock abundance. During previous assessments, these values were computed based on the "bio" database and unsurprisingly fluctuated around 0.5 (95% within [0.48-0.54]; Smith et al. 2022). For this assessment, we assumed that the true value was always 0.5 (typically within the confidence interval of computed values) and that any deviation was a result of observation error.

STOCK ASSESSMENT MODEL

Framework

The model (CCAM; Van Beveren et al. 2017) 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 and parameter definitions are provided in Table S5 and S6.

In brief, instantaneous fishing mortality ($F_{a,y}$, with *a* = age and *y* = year) is modelled as a separable process, i.e., a product of fishing selectivity and annual fishing mortality. The instantaneous natural mortality rate ($M_{a,y}$) is provided as an input matrix to the model. The standard cohort equations are used to let a cohort evolve over time under the prevailing total mortality rate ($F_{a,y}$+$M_{a,y}$) and include process error. A Beverton-Holt stock-recruitment relationship is applied, although a random walk option is integrated. There are three observation equations that link stock state to the indices; one for the TEP index, one for the LAA proportions and one for the total landings.

The following settings were used:

- Age classes 1 to 10 with a plus group
- Time-invariant flat-topped fishery selectivity from age 5 onwards

- Relative TEP index (survey catchability estimated)
- Age-class dependent process errors (σ^2_{N1} for a = 1 or recruitment, σ^2_{N2+} for a = 2-10)
- Age-class dependent observation errors for LAA proportions (σ^2_{cp-A} for a=1, σ^2_{cp-B} for a=2, 8 and 9, σ^2_{cp-C} for 2<a<8; note that there is no a=10 because of the continuation ratio logit transformation)
- Recruitment follows a 2-parameter Beverton-Holt stock-recruitment relationship
- Annual fishing mortality (Fbar) is standardly presented as the average of fully selected age classes (5 to 10), which also corresponds to the value of F_y
- Relative timing of the survey/spawning (ts) set to 0.47 (June 21st)
- M = 0.3 (constant over time and age). Natural mortality was slightly increased relative to the rate used in the previous assessment (0.27), to better connect with the estimates of consumption of mackerel by various predators (Van Beveren et al.[4]), and because a more productive stock results in a better model fit (improved residuals, lower AIC; Figure S2)

The following input data was used:

- Index data (with observation error)
  - Landings (Table S7): the model is denoted "censored" as it uses an approach in which true removals are assumed to fall between a lower and an upper limit, where the lower limit is based on Canadian recorded landings and a minimum amount of U.S. landings (lower limit = recorded landings * 110% + 20% * U.S. landings) and the upper limit is based on an estimated ceiling for Canadian landings (Van Beveren et al. 2017; section "landings") and a maximum amount of U.S. landings (upper limit = estimated upper limit + 80% * U.S. landings). Note that in this assessment we assumed that the proportion of northern contingent fish within U.S. landings ranged from 20-80% rather than 25-50% assumed in previous assessments, in accordance with the most recent knowledge on stock mixing (Arai et al. 2023).
  - LAA (Table S8)
  - TEP (Table S9)
- Data to transform quantities (no observation error)
  - Stock weight-at-age on July 1st (Table S10): estimated, whereas in previous assessments catch weight-at-age was used. This matrix was also used for stock weights on January 1st.
  - Catch weight-at-age (Table S11)
  - Maturity-at-age (Table S12)
  - Fecundity-at-age (Table S13)
  - Proportion of females-at-age: constant 0.5, whereas in previous assessments annual values-at-age were estimated.

Key sensitivity runs

1) *Landings-at-age for 1968-1975: use the default approach, shorten the time-series, or exclude part of the data from the model*

The model did not converge when started in 1968 and LAA missing in only the first year. We therefore only considered the default approach (continue as usual) and a shortening of the modelled time-series (start post-1968). Omitting 1968 from the assessment, which has an uncertain estimate of the proportion of age 1 fish in the landings, avoided estimation of a spurious peak in recruitment in the first year and overestimation of recruitment variance (see results of previous assessments). Because 1968 was already excluded from all derived analyses (recruitment projection, reference point estimation), we here excluded this year completely (in tables S7-S13 estimates for 1968 were nonetheless presented). All following model runs were thus started in 1969. A later start of the model, justifiable because of the loss of raw data underlying the input matrices up to 1973, did not result in visible changes to the model output (estimated parameter uncertainty, SSB or *F*). For consistency with previous assessments, the model's starting year was therefore not pushed further into the future. Note that we thus used historic estimates of LAA for the period 1969-1975 and short-term interpolations of biological data for 1969-1972.

2) *Landings-at-age for 2022: use the default approach, use a modified estimate of LAA, or exclude 2022 for model fitting*

When 2022 LAA was excluded, the model relied heavily on 2021 data to estimate abundance-at-age of 2022. Catches of age 1 fish in 2021 were low (see Figure 2), and this approach resulted in the estimation of a correspondingly low abundance of age 2 fish in 2022. This contradicted markedly with the observations from 2022; a notable number of samples were overall dominated by age 2 fish, a pattern which was consistent across all regions and periods. Removing 2022 LAA from the assessment might thus increase estimation error, in spite of the uncertainty in sampling. Further, ignoring 2022 LAA resulted in a considerable and perhaps excessive expansion of the 2022 confidence interval around *F* and recruitment. We therefore considered that the best model prediction was obtained by keeping 2022 LAA. The modified version of LAA was thought to be the most realistic, as less weight was given to the large number of young fish (age 1) caught in Maritimes region, resulting in a likely overestimation of 2022 recruitment. When modified estimates of 2022 LAA were included in the model, there were no noteworthy residuals associated with them (Figure S3). The modified LAA approach differed the least with the two other options (excluding LAA or using the default approach).

3) *Years for which the egg index values was included or excluded*

Estimates for 2006, 2017, 2019 and 2022 were retained to generate the final model fit, as despite the presence of larger uncertainties, there was no evidence of bias. Specifically, the estimated proportion of eggs spawned by the time of the survey aligned with the percentage of larvae observed, and there were no red flags in the data, the logistic model fit or the predictions. Although the model residuals associated with these years were above average, they were not conspicuously different from several other years.

Projections

Short-term projections (3 years) for a range of different Total Allowable Catches (TACs) were performed as a basis for advice for the 2023-2024 fishing seasons. Projection specifications and equations are provided in the supplementary information of Van Beveren et al. (2020).

Projections included stochastically projected unaccounted-for catches of both Canada and the U.S. separately (i.e., implementation error). The TAC was added to these estimated catches to calculate total removals and the resulting next years' stock biomass. Because of the fishery closure, Canadian unaccounted-for catches were assumed to be limited to the recreational fishery, as the amount of unaccounted-for removals from other sources (by-catch, S52 Licenses, discards) was considered to be negligible (see results "landings"). Because of a bag-limit put in place and no indication that recreational fishing will decrease in the near-future, we drew independent values for each year from a normal distribution ($N(433.5, 123.25)$, generating results mostly within the range of 187 to 680 t; see Table S3), which was consistent with the 2022 upper catch limit set in the assessment model. Importantly, we made the assumption that if the fishery reopens (projections with TAC > 0 t), there will be no extra implementation error as all bait, commercial and by-catch landings will be reported and counted under the TAC (with no additional mortalities from discards or other). A baseline scenario was also provided, in which Canadian total removals were set to 0 t (fishery closure with strictly no unaccounted-for removals). Such a scenario is informative but unrealistic, as a minimum amount of removals should always be expected (by-catch, S52 Licenses, illegal fishing activity).

Future U.S. removals were assumed to be aligned with their 2022 landings (3,302 t) and 2023 TAC (3,639 t) ($UScatch_{2023-2025} \sim pert(500{,}3302{,}3639)$). The U.S. has not yet determined a TAC for 2024 and 2025. Between 20 and 80% of U.S. landings were assumed to be from the northern contingent ($unif(0.2{,}0.8)$). Again no temporal autocorrelation was included because implementation error is relatively small and therefore changes in absolute number from one year to the next could be high.

Recruitment can be forecasted using various methods, which generate meaningful differences (e.g., Van Beveren et al. 2021). Two different methods were used and presented; under scenario one, recruitment was projected using the estimated Beverton-Holt stock-recruitment relationship (autocorrelation estimated over full time-series) and under scenario two, the average recruitment since 2011 was used (autocorrelation set to 0.9). We averaged the results generated by each approach and provided the range between brackets.

Reference points

Stock status in terms of SSB was defined relative to the official LRP and Upper Stock Reference point (USR), which were set as 40% and 80% of SSBref, respectively, in correspondence with the default approach outlined in the Canadian Precautionary Approach policy (DFO 2009). The biomass reference point (SSBref) for mackerel was previously defined as the SSB corresponding to F40%, a proxy for F_{MSY}. F40% is the fishing mortality rate that reduces the spawning biomass-per-recruit (SPR) to 40% of its unfished levels (Goodyear 1977; Shepherd 1982). SSBref was calculated based on the average biological WAA and MAA of the last 15 years, and recruitment of the full time-series.

Tmin

The minimum time to rebuild was estimated by projecting the stock 10 years into the future, using either F=0 or TAC = 0 t. In the latter scenario, a small implementation error was added for U.S. catches, identical to the one used for short-term projections (i.e., future U.S. landings between 500 t and 3,639 t, with the highest likelihood at 3,302 t). Forecasts over medium- to long-term periods can be highly sensitive to a range of model or data assumptions, some of them being more influential than others. We performed forecasts for *Tmin* using five different operating models (Table 1), which reflect key framework uncertainties already highlighted during the Management Strategy Evaluation (Van Beveren et al. 2020). Each model differed in one aspect from the base model, which was defined as the assessment model with recruitment projected using the Beverton-Holt recruitment relationship.

Table 1. Details of the operating models used to determine Tmin.

Operating model name	Details
OM.BASE	Assessment model (Beverton-Holt recruitment projections)
OM.RECMEAN	projections using average recruitment (2011-2022)
OM.M0.25	M = 0.25
OM.US25-50	25-50% of U.S. landings
OM.US50-75	50-75% of U.S. landings

ADDITIONAL BIOLOGICAL INFORMATION

Length at 50% maturity (L_{50}) is not used within the assessment model but is presented as a biological indicator that can reflect fishery-induced changes in maturation (Lappalainen et al. 2016), changes in environmental conditions, and density-dependent mechanisms (Cardinale and Modin 1999; Meyer et al. 2003). Importantly, this information can also be used to help establish minimal legal sizes. Because of its use as a biological indicator, L_{50} was computed by cohort rather than annually, which has more biological meaning as it better reflects the life-history of mackerel. One maturity ogive by cohort (1973-2019) was fitted to estimate L_{50}, using a generalized linear model (GLM) with a binomial distribution and a logit link function and with maturity class as the binary response variable (immature = stages 1 and 2, mature = stages 3 to 8, following the staging key of Maguire 1981) and length as the explanatory variable. There was insufficient data to consistently use additional explanatory variables for all cohorts (e.g., month, gear, region). We instead subsetted commercial port sampling data for May-July, which corresponds to the beginning of the fishing season. Fitted models were bootstrapped over 999 iterations using the "car" package in R to produce 95% confidence intervals. Cohorts with less than 10 immature individuals, a poor model fit (i.e., 1990), or insufficient age classes (i.e., the most recent cohorts) were excluded.

RESULTS

LANDINGS

Recorded commercial and bait landings of mackerel within Canadian waters ranged between 55 kt and 4.3 kt prior to the 2022 fishery closure (1968-2021; Figure 1). Earlier in the time-series, most landings were recorded from the Scotian Shelf (NAFO 4VWX5YZ) but by the late 1990s the southern Gulf (4T) became the dominant region for mackerel fishing. Annual landings increased substantially from 2000 to 2010, reaching record highs of around 53-55 kt between 2004 and 2007. This period of greater landings was due to a marked increase in fishing effort by small and large seiners off the coasts of Newfoundland (3KL and 4R), and coincided with the arrival of the large 1999 year class. This period was followed by a large decrease in landings that reached a low of 4,272 t in 2015. The TAC was reached for the first time the year after (2016 TAC of 8,000 t) and has since limited total landings, with the exception of 2017. At the time of this assessment, recorded Canadian mackerel landings for 2021 and 2022 were 4,505 t (TAC 4,000 t) and 56 t (fishery closure, excluding landings under S52 licenses), respectively. In 2021, the three dominant fisheries, in order of importance, were the Gulf gillnet fleet, the Maritimes fixed gear fleet and the Newfoundland seiners. In 2022, 38 t out of 55 t was caught during only two fishing trips. The ZIFF data format does not include information on the fishing licenses that were used to land mackerel, and the target species is often not indicated or inaccurate. Regional management confirmed that no landings were made under a mackerel fishing license, and that the recordings reflect mackerel caught as by-catch in, for example, the herring, flounder and silver hake fisheries, for which there is a 10% by-catch tolerance. At the time of the assessment, mackerel caught and used for bait in the 2022 tuna fishery (20 mackerel per day per fisher) were not yet included.

On top of the 55 t landed commercially, 19 t was landed under Section 52 licenses (preliminary maximum numbers used for certain samples).

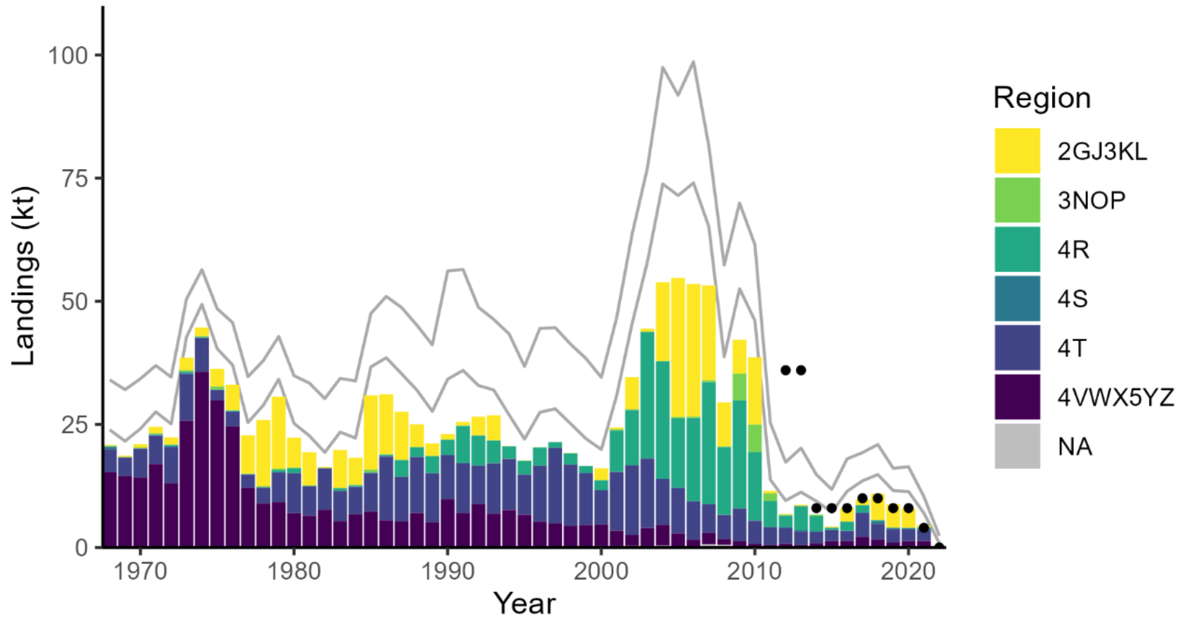

Figure 1. Mackerel landings (1968-2022) from Canadian waters (kt). Bars show recorded landings by NAFO division(s). Dots indicate the Total Allowable Catch (TAC; earlier TACs are not shown because they were set for the entire West-Atlantic mackerel stock). The grey lines represent the upper and lower bounds between which total removals are estimated in the stock assessment model.

LANDINGS-AT-AGE

Strong year classes (e.g., 1968, 1973, 1974, 1982, and 1999) are apparent in the annual landings-at-age data (Figure 2) and their progression from year to year can easily be tracked. Mackerel 10 years and older were more common prior to the late 1990s. Since then, the age structure of the catches became increasingly truncated. By the early 2010s, fish older than 6 years were uncommon in the catch. The last notable cohort that could be tracked in the catch was produced in 2015. In 2021, landings were dominated by age classes 2, 3 and 4 (estimated 80% of landings).

Because of the fishery closure of 2022, the default estimated age composition of the landings for this year (by-catch and experimental fishing licenses) resulted from an abrupt change in fishery selectivity, hindering comparison with previous years. Below we present a partially corrected estimate of LAA (see Van Beveren et al.[2]), which assumes that low landings (75 t) were made similarly to previous years. For instance, landings and thus samples from the southern gulf and Newfoundland collected later in the year were assumed to be more important than in reality, to avoid major changes in fishery selectivity. Although this did account for the change in the sampling program, so that some change in selectivity should still be expected, there was a strong signal that age class 2 dominated or would have dominated 2022 landings. This dominance was relatively consistent across the 73 samples collected in 2022, and it was demonstrated that major patterns are relatively robust to changes in landings or sample collection (see Van Beveren et al.[2]). There was no evidence that fish age 5+ represented or would have represented an important part of the landings.

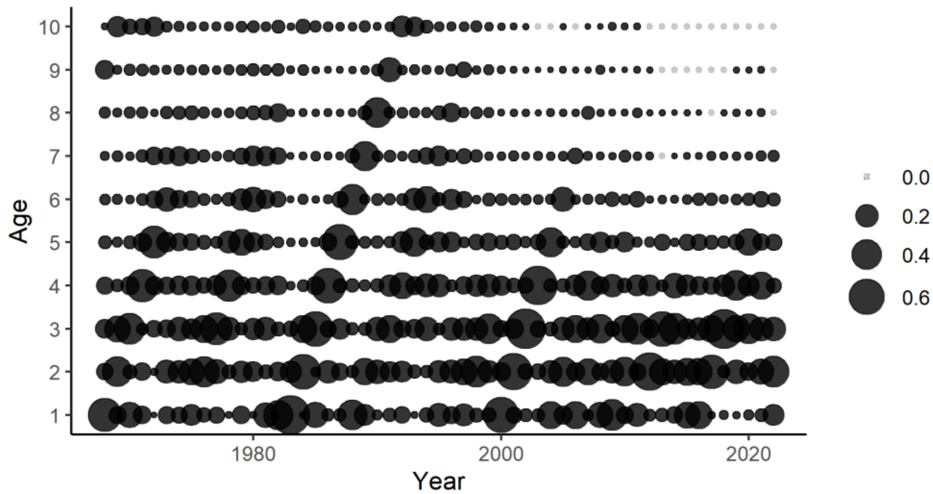

Figure 2. Bubble plot of mackerel landings-at-age (ages 1-10+) from 1968-2022 (annual proportions). Grey bubbles represent zeros. The time-series is a combination of historic (1968-1975) and new (1976-2022) estimates. Note that 2022 is distinct from previous years as it is based on a theoretical distribution of landings.

TOTAL EGG PRODUCTION

The time-series of Total Egg Production (Figure 3) showed that despite large variability between some years, the total number of eggs produced has been declining to historic lows in the past decade. Prior to 1995, egg production was around 500 billion eggs; TEP then dropped by about an order of magnitude over the period 1994-1999. Between 2002 and 2004, TEP was at higher levels again (average of 260 billion eggs), corresponding with the strong 1999 cohort (see LAA). Since 2006, TEP has remained low (<100 billion eggs). The estimated value for 2021 (16 billion eggs) was the second lowest value in the time-series (2012, at 11 billion eggs). Although the index slightly increased in 2022 (37 billion eggs), it remained among the lowest values observed.

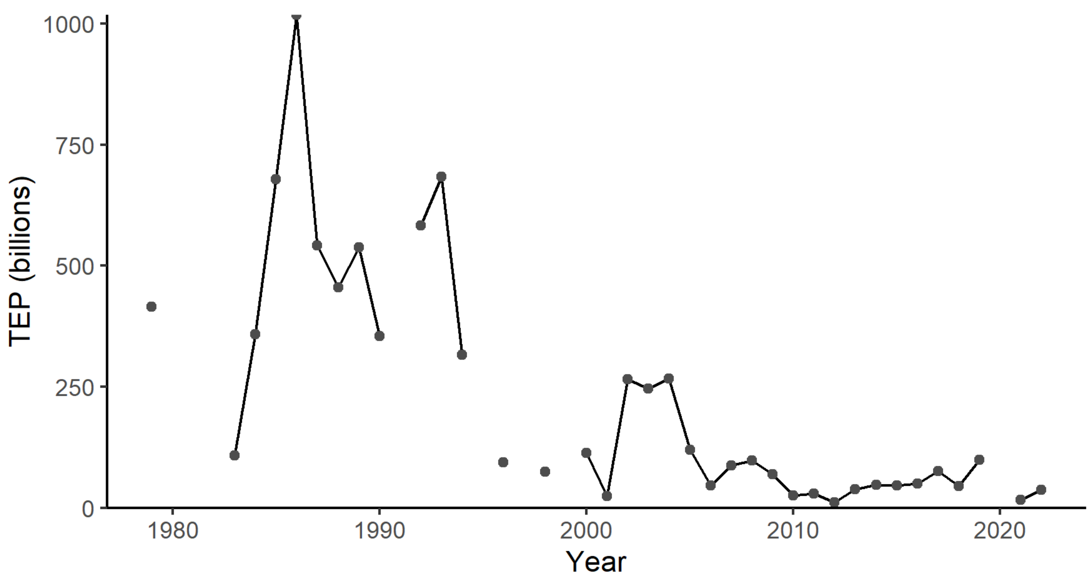

Figure 3. Total Egg Production derived from the annual spring mackerel egg survey in the southern Gulf of St. Lawrence (1991 and 1999 were removed because of bias).

MATURITY-, WEIGHT- AND FECUNDITY-AT-AGE

Nearly all mackerel (>95%) are mature by age 3 (Figure 4). The proportion of mackerel mature at age 2 was estimated to be around 0.77 (range: 0.56-0.90). Only about 1 out of 4 age-1 fish reach maturity each year (0.02-0.48). The interannual variability in the proportion of mature fish of age 1 and 2 cannot be precisely estimated and depends on the level of smoothing used.

Weight-at-age of mackerel was lowest at the beginning of the time-series (1968-1974; Figure 4). The largest growth was observed in cohorts spawned in and around 1980. The average weight of fish for any given age class has since remained rather stable. On average, an age 1 mackerel weighs about 140 g, whereas by age 10+ they reach 750 g. Weight-at-age of fish in the landings follows a similar pattern (Figure S1; unsmoothed to ensure the product of landed fish weights and numbers total reported landings).

Fecundity-at-age has slightly increased since about 2000 (Figure 4). Mackerel fecundity in 2022 was estimated to be 106% of 1968 values. An increase in fecundity indicates that for the same amount of TEP observed, less fish should be present in the water. This change is driven by the observed increase in the GSI, which is unrelated to sampling factors such as collection date. The presented values are smoothed, and it should be noted that the exact level of interannual variability is again unknown.

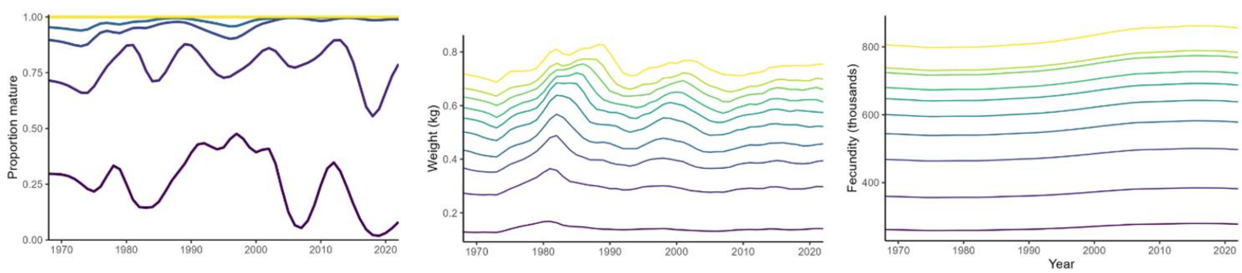

Figure 4. Maturity-(Left panel), stock weight-(Middle panel) and fecundity-at-age (Right panel) from 1968 to 2022. Age classes are indicated by different colors (age 1 = purple, age 10+ = yellow).

STOCK ASSESSMENT MODEL

Validation and robustness

Residual plots and retrospective patterns are shown in Figures S3 and S4-S5, respectively. There were no important retrospective or residual patterns. There were four outliers in the TEP index, suggesting that TEP in 2001, 2006, 2010 and 2012 was underestimated. In some previous assessments, or with model runs with a lower *M*, there was a linear decrease over time in the residuals of Total Egg Production (e.g., Fig. S3 in Smith et al. 2022). This pattern was largely removed by increasing *M* to 0.3, as under the assumption of a more productive stock, relatively fast changes in TEP can more easily be tracked. Sensitivity tests demonstrated that the model output was also robust against various assumptions (LAA, TEP, smoothing of biological input matrices, etc.). Estimated model parameters are presented in Table S14 and the derived estimates in Table S15. Estimated annual numbers-at-age in the stock are presented in Table S16 and annual age-specific fishing mortalities in Table S17.

Output

Estimated SSB decreased below the LRP (42,450 t) in 2011 (Figure 5A, Table S15, SSBref = 106,124 t). With the arrival of the 2015 cohort, the ratio between SSB and the LRP increased to around 1 in 2017 and 2018 (0.99 and 1.05, respectively), but subsequently decreased to lower levels into the Critical Zone again. SSB was estimated to be at 40% and 42% of the LRP in 2021 and 2022, respectively. The last notable recruitment event was in 2015, but this cohort only represented a minor fraction (3% or less) of the stock in 2021 and 2022. There was no indication of substantial recruitment since 2015 (Figure 5B-C).

Fishing mortality rates (including catch uncertainty) decreased below the reference level (F40% = 0.68) in 2022 as a result of the fishery closure and low U.S. landings (Figure 5E-F, Table S15). According to the model, the estimated fishing mortality rate on fully exploited mackerel (ages 5 to 10) in 2022 was 0.42 (0.149-1.196 95%CI). 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 (Figure 5B). The fishing mortality rate across all age classes, weighted by their abundance, was 0.25 for 2022. Estimates of fishing mortality for the terminal assessment year showed a large confidence interval because of the explicitly acknowledged large uncertainty in total removals (censored approach). Fishing mortality in 2022 could be somewhat overestimated because of the sharp decrease in overall removals in combination with the use of a random walk to track annual F and the imposed flexibility to estimate catch.

Projections

Projected short-term trends in SSB with respect to the LRP are provided in a decision table for different TACs and two recruitment scenarios (Table 2). The level of unaccounted-for catch for each TAC scenario is shown in the grey columns and the distribution of these values is plotted in Figure S6. The probability of reaching the LRP (42,450 t) by 2025 with a TAC of 0 t (but with a recreational and U.S. fishery) was estimated to be around 37.5% (37-38%; range shows values from each recruitment scenario). This probability decreased to 25.5% (25-26%) with a TAC of 4,000 t (TAC of 2021). With a TAC of 0 t, there was a high likelihood that the SSB will increase by 2025 (>75% probability). With a TAC between 1,000 t and 3,000 t, this likelihood was moderately high, whereas for higher TACs there was either a neutral or low probability of stock growth. The difference in terms of probability of growth (2.5%) and probability of growing out of the Critical zone (1%) by 2025 between a scenario with a TAC of zero that includes or excludes recreational fishing was small and within statistical uncertainty.

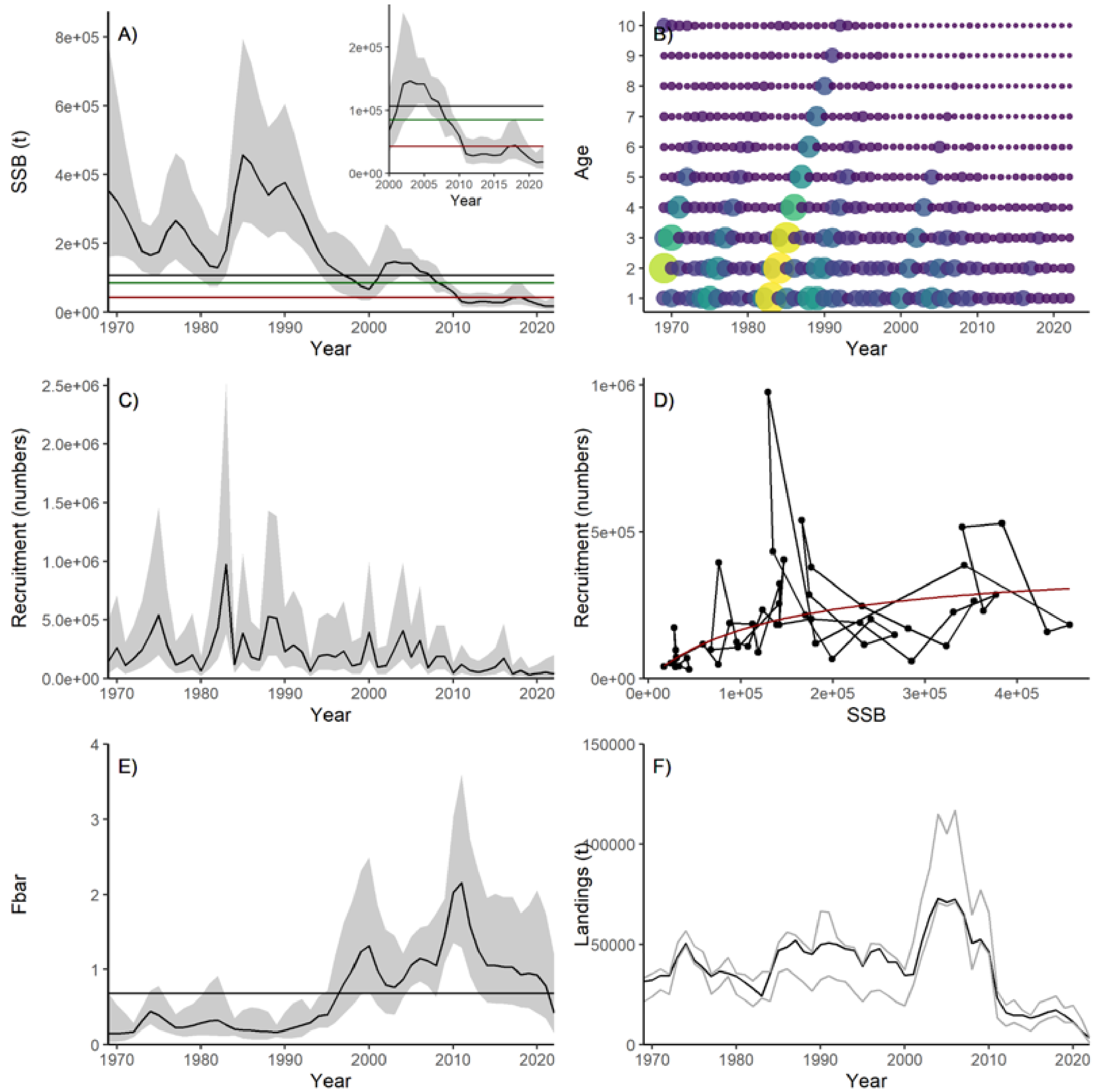

Figure 5. Model output: (A) Spawning Stock Biomass (SSB) in June (t) with a zoom for 2000-2022 and horizontal lines indicating the SSB reference point ($SSB_{F40\%}$; black), the Upper Stock Reference point (80%$SSB_{F40\%}$; green) and the Limit Reference Point (40%$SSB_{F40\%}$; red), (B) numbers-at-age in the stock (with the largest abundances indicated by large yellow bubbles), (C) recruitment (age 1, numbers), (D) stock-recruitment, (E) fishing mortality, Fbar = $F_{\overline{5-10}}$ (averaged over the fully selected age classes 5-10), (F) estimated catch (t, black) between the pre-determined bounds (grey).

Table 2. Three-year projections under different constant Total Allowable Catch (TAC). Projections were performed under the assumption that mackerel will also be caught outside of the TAC, by both the Canadian (recreational fishing) and U.S. fleets (shaded columns; 95%CI, time-invariant). For a TAC of 0 t there is a scenario with and without recreational fishing in Canada, whereas for a TAC>0 t recreational fishing is always included. Recruitment was projected using two different methods (individual values in grey), and the average of both is provided in black. For each TAC scenario, the probabilities of June spawning stock biomass (SSB) being greater than the Limit Reference Point (SSB/LRP) in 2024 and 2025 are provided. The probabilities of SSB growth from 2023 to 2025 are also provided (SSB_{2025} > SSB_{2023}). The ratios between SSB with respect to the LRP (SSB/LRP) for each scenario are likewise given for 2024 and 2025.

TAC (t)	**Prob(SSB > LRP)**		**SSB_{2025} > SSB_{2023}**	**SSB/LRP**		**Unaccounted-for landings**			
2023 2024 2025	2024	2025	2023→2025	2024	2025	Canada		U.S.A.	
						2.5%	97.5%	2.5%	97.5%
0	28.5% (28-29)	38.5% (38-39)	81 % (78-84%)	0.68 (0.67-0.68)	0.8 (0.79-0.82)	0	0	489	2682
0	27.5% (27-28%)	37.5% (37-38%)	78.5 % (75-82%)	0.66 (0.65-0.67)	0.78 (0.77-0.79)	192	674	489	2682
1000	25.5% (25-26%)	33.5% (33-34%)	70.5 % (67-74%)	0.62 (0.61-0.63)	0.72 (0.71-0.73)	192	674	489	2682
2000	24% (24-24%)	31.5% (31-32%)	63 % (59-67%)	0.58 (0.57-0.59)	0.66 (0.64-0.67)	192	674	489	2682
3000	22.5% (22-23%)	28.5% (28-29%)	56 % (52-60%)	0.54 (0.54-0.55)	0.59 (0.57-0.61)	192	674	489	2682
4000	20.5% (20-21%)	25.5% (25-26%)	50 % (46-54%)	0.5 (0.5-0.51)	0.52 (0.51-0.54)	192	674	489	2682
5000	19.5% (19-20%)	23.5% (23-24%)	45 % (41-49%)	0.46 (0.45-0.47)	0.46 (0.44-0.48)	192	674	489	2682
6000	18.5% (18-19%)	21.5% (21-22%)	40.5 % (37-44%)	0.42 (0.42-0.43)	0.4 (0.38-0.42)	192	674	489	2682
7000	17.5% (17-18%)	19.5% (19-20%)	35.5 % (32-39%)	0.38 (0.38-0.39)	0.34 (0.32-0.36)	192	674	489	2682
8000	16% (16-16%)	17.5% (18-17%)	32.5 % (29-36%)	0.34 (0.34-0.35)	0.3 (0.27-0.32)	192	674	489	2682

Tmin

The minimum time for the stock to get out of the Critical zone (F=0) with a 75% likelihood was estimated at 6 to 7 years (7 years for the base model; Figure 6). Under a scenario in which the U.S. would remove up to 3,639 t (2023 TAC) annually, this rebuilding time would increase to between 7 and 9 years (9 years for the base model; Figure 6). Because of the low fishing mortality rate in 2022, which partly defines the SSB for 2023, the probability of getting out of the Critical zone increased directly from 2023 onwards.

There was no fixed SSB associated with a 75% probability of being above the LRP. The higher SSB and the lower the estimation error, the more likely this probability threshold will be reached. However, based on historical SSB estimates, which typically have less uncertainty associated with them than terminal year estimates, a 75% probability of being above the LRP is expected to correspond to a biomass roughly around 1.4 times the LRP (1.3-1.5 95%CI; Figure S7).

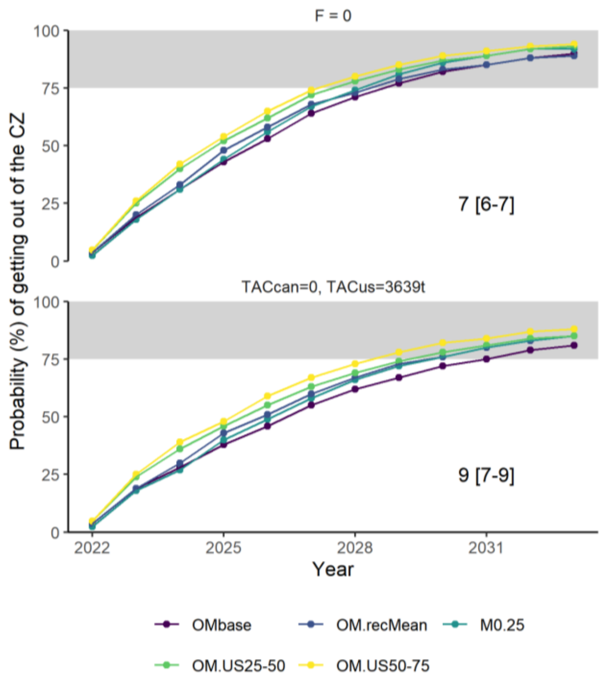

Figure 6. Probability (%) of getting out of the Critical zone (CZ) within the next 10 years, under F = 0 and TACcan = 0 t (no mackerel catches within Canadian waters, but some U.S. fishing). The minimum time to rebuild with a 75% probability under the base operating model (OMbase) is annotated and the range of values across operating models (OM) is provided between square brackets.

L_{50}

The length at 50% maturity (L_{50}) of the 1974-2019 cohorts has fluctuated between 243 mm and 298 mm, with a time-series mean of 265 mm (Figure S7). The L_{50} of the last two cohorts (2018 and 2019) was 258 mm (95%CI: 255-261 mm) and 257 mm (95%CI: 254-260 mm) respectively.

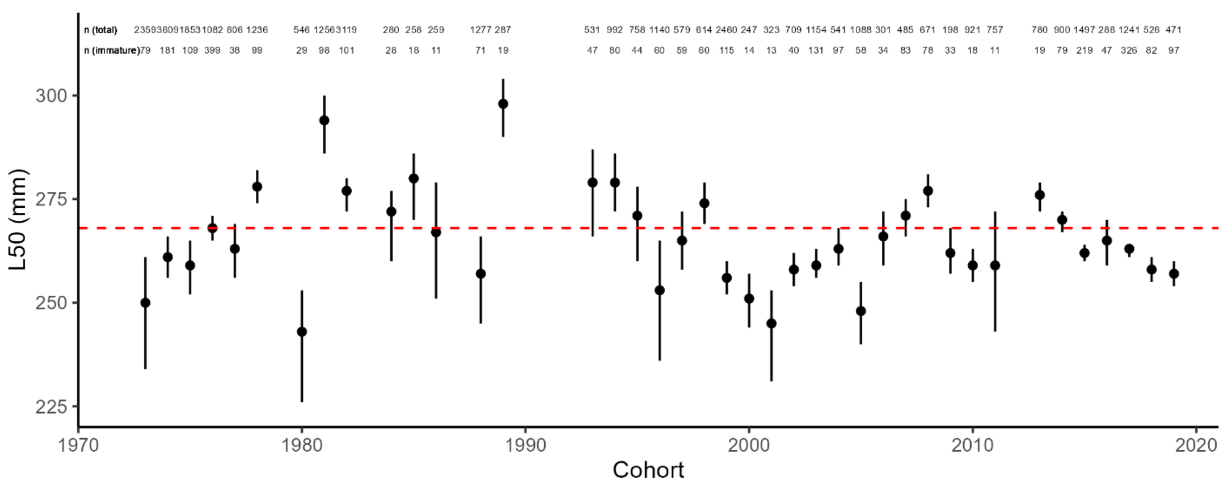

Figure 7. Length at 50% maturity (L_{50}, mm) by cohort (1974-2019) with a 95% confidence interval. The horizontal red line indicates the current minimum commercial length of 268 mm. Numbers of individuals used to calculate the L_{50} of each cohort (n total) as well as the number of immature individuals (n immature) are displayed at the top of the figure.

DISCUSSION

ECOSYSTEM CONSIDERATIONS

Ecosystem Effects on the stock

This section summarises available knowledge on how ecosystem factors affect three fundamental productivity processes (recruitment, natural mortality and growth) which determine the rate at which the mackerel stock will rebuild, and how this knowledge was integrated within the assessment.

The drivers of northern contingent mackerel **recruitment** variability have been analysed several times (Runge et al. 1999; Castonguay et al. 2008; Plourde et al. 2015). The latest and most in-depth study demonstrated that mackerel recruitment is determined by stock state (including SSB and maternal body condition) and larval food conditions; the intensity of the spatial and temporal match between specific larval prey and egg production is correlated to recruitment strength (match- mismatch hypothesis; Brosset et al. 2020). This knowledge could theoretically be used to inform one-year ahead predictions of recruitment. However, projections are currently performed over a three-year period and although the first projected year is most influential, the demonstrated fine-scale nature of the recruitment process makes ecosystem-informed longer-term projections extremely hard. In the absence of directional trends in known environmental drivers, we acknowledge uncertainty in future recruitment by stochastically projecting this process under different statistical assumptions.

Natural mortality caused by a range of predators can be substantial, especially when SSB is low (Van Beveren et al.[4]). There is currently no evidence that natural mortality had a key role in causing the stock decline (no corresponding increase). Under lower SSB, predators are however likely to remove a relatively larger proportion of the stock and an increase in M will affect stock rebuilding. Although an effort was made to estimate a minimum biomass removed by predators, this information remains uncertain and this uncertainty, compounded with technical challenges, currently prevent its explicit incorporation into the assessment model.

The ecosystem factors affecting northern contingent mackerel **growth** have not yet been specifically investigated. However, between-year changes and within-year gains in body condition show correlation with plankton abundance (Plourde et al. 2015; Smith et al. 2020). Mackerel WAA, used as an assessment input, also does not display prominent patterns over time, and small-amplitude variations caused by changing environmental conditions do not significantly affect the assessment. Although ecosystem components associated with mackerel growth are currently unaccounted-for, they are considered to be of minor importance in determining stock productivity relative to recruitment and natural mortality.

Although environmental conditions drive the annual mackerel migration pattern (see Van Beveren et al. 2023 for a summary of available knowledge), there is currently no evidence that changes in spatial distribution have a direct impact on stock productivity and thus rebuilding.

Fishery Effects on the ecosystem

Atlantic mackerel is a forage fish species at the middle of the food web (e.g., Savenkoff et al. 2005). They play a key role in the ecosystem through the transfer of energy from lower trophic levels to higher-order predators. The effect of fishery-induced changes in mackerel stock state on most predators is unknown, with the exception of northern gannets. This seabird species is the only predator known to feed predominantly on mackerel when they are available. The decline in breeding success of northern gannets in the southern Gulf has been associated with the decrease in mackerel SSB (Guillemette et al. 2018).

By-catch of other species in the mackerel fishery is small and not known to significantly affect these stocks.

PROBABLE CAUSES OF STOCK DECLINE

During the stock's decline into the Critical zone (2005-2011), total landings were high and estimated fishing pressure was above the reference level. There is currently no evidence that natural mortality increased during that period (Van Beveren et al.[4]) or that recruitment was low (Figure 4).

Habitat loss or degradation is of no known concern to this stock.

QUALITY OF THE ANALYTICAL ANALYSIS AND DATA GAPS

Many of the key uncertainties within the data that were highlighted in previous assessments (e.g., related to total removals), 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 (see next paragraph), stock status trends across different indices are consistent and large enough to consider stock status robust. For this assessment, the egg index was examined in terms of coverage (Van Beveren et al. 2023; preliminary results of the 2022 Newfoundland egg survey) and robustness to various assumptions (Lehoux et al.[1]). The trends and derived conclusions were consistent across a range of sensitivity analyses.

The two main uncertainties are considered to be (not in order of importance) 1) potential variations in the natural mortality rate and 2) the proportion of northern contingent mackerel caught in the U.S. mackerel fishery (see Redding et al. 2020; Arai et al. 2021; Bourret et al. 2023). An increased appreciation of the level of mixing should improve model estimates and projections.

CONCLUSIONS

The northern contingent of West-Atlantic mackerel is currently in the Critical zone as defined by DFO's PA framework (DFO 2009) and has been in or around this zone since 2011. The age structure of the stock is truncated and average recruitment has been low, in relation with SSB. Stock projections provided in Table 2 will allow decision makers to weigh the trade-offs between SSB and different TACs over a period of three years.

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SUPPLEMENTARY TABLES

Table S1. Recorded landings of Atlantic mackerel. The United States (U.S.) total used within the assessment does not include landings from the Foreign fleet.

Year	CANADA	CANADA FOREIGN	TOTAL	U.S. COMMERCIAL	U.S. RECREATIONAL	DISCARDS	TOTAL	FOREIGN
1968	11118	9720	20838	3929	NA	NA	3929	65747
1969	13257	5379	18636	4364	NA	NA	4364	114189
1970	15710	5296	21006	4049	NA	NA	4049	210864
1971	14942	9554	24496	2406	NA	NA	2406	355892
1972	16253	6107	22360	2006	NA	NA	2006	391464
1973	21566	16984	38550	1336	NA	NA	1336	396759
1974	16701	27954	44655	1042	NA	NA	1042	321837
1975	13540	22718	36258	1974	NA	NA	1974	271719
1976	15746	17319	33065	2712	NA	NA	2712	223275
1977	19852	2913	22765	1377	NA	NA	1377	56067
1978	25429	470	25899	1605	NA	NA	1605	841
1979	30244	368	30612	1990	NA	NA	1990	440
1980	22135	161	22296	2683	NA	NA	2683	566
1981	19294	61	19355	2941	2627	NA	5568	5361
1982	16380	3	16383	3330	1877	NA	5207	6647
1983	19797	9	19806	3805	2792	NA	6597	5955
1984	17320	913	18233	5954	2716	NA	8670	15045
1985	29855	1051	30906	6632	4088	NA	10720	32409
1986	30325	772	31097	9637	7661	NA	17298	26507
1987	27488	71	27559	12310	7555	NA	19865	36564
1988	24060	956	25016	12309	5420	NA	17729	42858
1989	20795	347	21142	14556	2829	160	17545	36823
1990	19190	3857	23047	31261	3252	827	35340	30678
1991	24914	597	25511	26961	3540	1098	31599	15714
1992	24307	2255	26562	11761	919	2072	14752	0
1993	26158	690	26848	4662	1231	3902	9795	0
1994	20564	49	20613	8917	2654	5409	16980	0
1995	17627	62	17689	8468	1697	54	10219	0
1996	20282	76	20358	15728	2466	2053	20246	0
1997	21294	116	21410	15403	2857	229	18489	0
1998	19176	10	19186	14525	1553	97	16176	0
1999	16526	12	16538	12031	2832	771	15634	0
2000	16053	26	16079	5649	3054	153	8856	0
2001	24336	11	24347	12340	3300	718	16358	0
2002	34600	7	34607	26530	2678	155	29364	0
2003	44463	9	44472	34298	1870	264	36433	0
2004	53861	14	53875	54990	1169	2141	58300	0
2005	54764	0	54764	42209	1694	1083	44985	0
2006	53503	3	53506	56640	3911	135	60687	0
2007	53223	0	53223	25546	761	159	26467	0
2008	29474	4	29478	21734	2731	747	25212	0
2009	42205	0	42205	22634	1768	126	24529	0
2010	38646	0	38646	9877	4288	97	14261	0
2011	11485	0	11485	533	4040	38	4610	0
2012	6841	0	6841	5333	2670	33	8036	0
2013	8674	0	8674	4372	2406	20	6798	0
2014	6678	0	6678	5905	2296	51	8252	0
2015	4272	1	4273	5616	4274	13	9904	0
2016	8045	0	8045	5687	4569	18	10274	0
2017	9749	3	9752	6975	4161	83	11219	0
2018	10907	1	10908	8717	2394	177	11288	0
2019	8750	0	8750	5379	2117	200	7696	0
2020	7947	0	7947	8306	2017	192	10515	0
2021	4505*	0	4505*	5752	2168	133	8053	0
2022	56*	0	56*	1908	1350*	44*	3302*	0

**Preliminary numbers*

Table S2. Recorded landings (t) of Atlantic mackerel by DFO region.

Year	Gulf	Maritimes	Newfoundland and Labrador	Quebec
1985	6125	6265	14883	2179
1986	8518	4799	2400	3004
1987	9611	5233	9902	2753
1988	9469	6065	4234	3662
1989	9686	4814	1911	2252
1990	9634	8499	1208	1971
1991	14451	7270	834	3256
1992	9888	8622	1283	3480
1993	6996	6718	9683	3175
1994	6875	7608	2800	3546
1995	4831	6574	2953	3382
1996	7049	5170	3869	4317
1997	9590	4762	1188	5769
1998	8676	4431	2331	3738
1999	5462	4550	1445	5104
2000	5294	4359	4406	2022
2001	9123	3113	8981	3212
2002	10069	2190	17982	4421
2003	9727	3737	26675	4597
2004	7728	4241	40003	1979
2005	8238	2691	42660	1221
2006	6043	1603	44277	1818
2007	4685	2357	44602	1750
2008	3599	1173	23036	1863
2009	4562	1116	34237	2316
2010	3278	554	33159	1709
2011	2417	409	7337	1345
2012	2258	692	2619	1278
2013	1648	403	5169	1453
2014	1042	703	3432	1502
2015	1226	1172	701	1182
2016	1241	1215	4633	966
2017	3726	2057	2653	1347
2018	2390	1522	5625	1426
2019	2170	912	4814	859
2020	1952	1205	4015	788
2021*	1824	1232	602	859
2022*	0.25	54.674	0.141	0.614

**Preliminary numbers*

Table S3. Estimates of recreational mackerel fishing in Canada from DFO (2015). No data exists for Quebec and therefore the same numbers as for Nova Scotia were used. Weights are based on the 2022 data.

Year	Newfoundland	Prince Edward Island	Nova Scotia	New Brunswick	Quebec	TOTAL
2010	356836	98182	646399	-	-	-
2005	546126	41434	481822	164970	-	-
2000	477720	43069	-	-	-	-
1995	225236	63145	-	157169	-	-
1990	213063	84440	681745	258013	-	-
Max numbers	546126	98182	681745	258013	681745	2265811
Max fish weight (kg)	0.3	0.3	0.3	0.3	0.3	-
Max biomass (t)	164	29	205	77	205	**670**
Min numbers	213063	41434	481822	157169	41434	934922
Min fish weight (kg)	0.2	0.2	0.2	0.2	0.2	-
Min biomass (t)	43	8	96	31	8	**187**

Table S4. Length-Frequency samples for 2022 by NAFO area and month.

	3K	3L*	4R	4S	4T***	4W	4X	
June	0	0	0	0	1	0	0	1
July	0	0	0	1***	6	3	1	11
August	4	1	5	0	6	3	2	21
September	6	1	5	0	5	1	3	21
October	4	1	5**	0	0	1	3	14
November	2	0	0	0	0	1	2	5
	16	3	15	1	18	9	11	**73**

**samples combined (same date/location and/or too small)*
***including 2 by-catch samples with very similar length-distributions*
****collected by a port sampler (instead of harvester or technician associated with a fishery organization)*

Table S5. Assessment model equations (a = age, y = year, SSB = spawning stock biomass (on January first and during spawning/survey time), 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	$C_{a,y}{=}N_{a,y} \frac{F_{a,y}}{Z_{a,y}} [1 - \exp(-Z_{a,y})]$
	$CT_y = \sum_{a=1}^{A} C_{a,y} W_{a,y}$
	$CP_{a,y} = \frac{C_{a,y}}{\sum_{a=1}^{A} C_{a,y}}$
	$X_{a,y} = crl(CP_{a,y})$
	$l(C_{o_1}, \ldots, C_{o_Y} \mid \theta) = \sum_{y=1}^{Y} log \left\{ \phi_N \left[\frac{log(CU_y/CT_y)}{0.01} \right] - \phi_N \left[\frac{log(CL_y/CT_y)}{0.01} \right] \right\}$
	$l\left(X_{o_{a,y}} \middle| \theta\right) = \sum_{\boldsymbol{a=1}}^{\boldsymbol{A-1}} \sum_{Y=1}^{Y} \left[\varphi_N \left(\frac{X_{o_{a,y}} - X_{a,y}}{\sigma_{cp}} \right) \right]$
Survey index	$TEP_y = q \sum_{a=1}^{A} N_{a,y} exp(-Z_{a,y} t_s) fec_{a,y} Fem_{a,y} P_{a,y}$
	$l\left(TEP_{o_y} \middle| \theta\right) = \sum_{\boldsymbol{a=1}}^{\boldsymbol{A}} \sum_{Y=1}^{Y} log \left[\varphi_N \left(\frac{TEP_{o_y} - TEP_y}{\sigma_S} \right) \right]$
Spawning Stock Biomass	$SSB^0_y = \sum_{a=1}^{A} N_{a,y} W^0_{a,y} P_{a,y}$
	$SSB^{june}_y = \sum_{a=1}^{A} N_{a,y} exp(-Z_{a,y} t_s) W^{june}_{a,y} P_{a,y}$

Table S6. Assessment model parameters.

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_N^2	Process error variance	Fixed
σ_{F_y}	Annual fishing mortality variance	Fixed
$\sigma_{cp_a}^2$	Catch-at-age proportions measurement error variance	Fixed
σ_S^2	Survey measurement error variance	Fixed

Table S7. Catch limits (t), based on 20-80% of U.S. landings.

Year	Lower bound	Upper bound
1968	23708	35227
1969	21372	33372
1970	23916	35490
1971	27427	37666
1972	24997	35210
1973	42672	50864
1974	49329	56734
1975	40279	49083
1976	36914	46480
1977	25317	35112
1978	28810	38428
1979	34071	43449
1980	25062	35687
1981	22404	35055
1982	19063	31794
1983	23106	36329
1984	21790	36415
1985	36141	50727
1986	37666	56180
1987	34288	54696
1988	31063	50445
1989	26765	46423
1990	32420	66755
1991	34382	65935
1992	32169	53217
1993	31492	49247
1994	26070	48469
1995	21501	39845
1996	26443	50548
1997	27249	50207
1998	24339	46144
1999	21319	43076
2000	19458	37207
2001	30054	51586
2002	43940	72358
2003	56206	87988
2004	70923	114994
2005	69237	105339
2006	70994	116867
2007	63839	89431
2008	37468	64904
2009	51331	77308
2010	45363	65759
2011	13555	26707
2012	9133	19738
2013	10901	22227
2014	8996	17287
2015	6681	14760
2016	10905	21092
2017	12971	22628
2018	14256	24301
2019	11164	18407
2020	10845	19538
2021	6566	12750
2022	722	3377

Table S8. Landings-at-age ('000s of fish). Values from 1968-1975 were taken from previous assessments, values from 1976-2021 were re-estimated, and for 2022 values were calculated under the assumption that landings were distributed similarly to 2017-2021.

Year	1	2	3	4	5	6	7	8	9	10+
1968	43062	7157	10343	7393	2819	1349	721	1658	10425	97
1969	5692	26359	18057	2027	929	855	1099	440	462	9656
1970	20277	3654	33584	8047	2496	451	425	1578	1645	4335
1971	7156	7389	1702	35931	7620	1753	2203	1526	1879	5517
1972	1	136	4401	5541	24826	4975	5248	77	546	6833
1973	9176	20624	9649	9333	13972	22293	8317	2771	837	1603
1974	8618	24340	26703	14602	12594	12417	15377	4053	1714	1749
1975	14206	24905	13049	11636	7052	7526	5456	3917	825	581
1976	5080	37835	28806	6419	4401	2359	2919	2008	1341	636
1977	4738	14741	29710	8831	1637	913	616	656	402	416
1978	78	2801	12088	25956	10683	2357	1153	545	685	448
1979	6742	11350	1892	7476	18990	11867	4834	1589	1096	1043
1980	55	5644	6818	2593	5096	10051	5681	1925	1120	949
1981	9477	1758	7835	3988	2553	4571	4983	2054	664	344
1982	13994	4498	1633	4177	598	2335	3065	4116	1068	1346
1983	78918	17821	7124	558	650	74	60	198	448	256
1984	42	26081	14354	1190	279	628	136	180	708	2526
1985	24874	1026	52656	10199	719	232	885	197	134	2121
1986	2405	15674	5864	45165	7578	535	217	245	76	751
1987	1812	5616	8866	2834	35731	4405	168	113	50	269
1988	25187	1981	1896	2716	2635	26505	3466	180	96	417
1989	6973	13161	1653	966	1057	603	16674	2036	277	866
1990	668	10057	9736	1870	1336	1142	790	17874	1097	173
1991	2095	8072	16474	8833	1124	1059	1289	1006	12392	477
1992	4773	9503	5505	16736	9205	1357	552	978	655	9294
1993	70	2088	6432	5499	18946	9797	1818	714	681	6796
1994	2311	1315	9949	9355	2683	11969	3754	550	338	1523
1995	8310	7697	1089	8018	5814	1607	5627	1981	255	443
1996	3950	8875	8578	1027	5772	6352	1234	5106	1140	337
1997	8943	13843	9997	4822	773	3583	2896	660	3285	481
1998	2309	22532	10384	8602	3293	268	1603	1272	246	1041
1999	2117	7213	15843	7631	3982	1397	231	529	496	197
2000	34934	6038	4677	7604	2545	1499	268	52	197	150
2001	5084	45546	9929	3823	4717	1140	872	154	46	85
2002	3257	6208	71875	6277	1869	1652	309	147	15	25
2003	3488	6495	7141	73199	6927	895	743	49	2	0
2004	43886	28441	7049	5617	54033	2144	805	421	7	0
2005	15975	53982	30633	5588	4103	34126	1550	291	106	26
2006	44178	15490	45343	22877	3229	1633	9884	275	20	0
2007	2232	32888	22434	45128	9469	1418	949	3970	22	5
2008	21028	7034	28852	7699	11794	1102	303	130	681	2
2009	52872	26612	7421	25230	4802	7001	221	83	6	509
2010	8928	34960	29991	4794	12722	1543	2312	98	1	60
2011	6495	2721	13411	4863	440	2011	188	291	19	17
2012	475	12219	2079	2988	266	26	55	4	2	0
2013	850	6044	12723	602	1654	101	0	5	0	0
2014	1278	3465	7058	4072	83	63	1	1	0	0
2015	3699	4074	1997	2115	952	124	13	4	0	0
2016	7803	7457	4990	2740	1930	757	30	1	0	0
2017	68	17349	9914	3152	1457	1022	248	0	0	0
2018	272	895	23828	5348	962	205	110	11	0	0
2019	42	5354	7402	9596	1699	376	109	63	3	0
2020	259	1986	7746	3187	5589	561	76	6	4	0
2021	440	3034	2645	3725	937	758	146	50	7	0
2022	41	116	59	15	19	9	5	0	0	0

Table S9. Total Egg Production (TEP, in numbers).

YEAR	TEP
1979	4.15708E+14
1980	NA**
1981	NA**
1982	NA**
1983	1.08184E+14
1984	3.58959E+14
1985	6.78277E+14
1986	1.01798E+15
1987	5.4255E+14
1988	4.55014E+14
1989	5.38021E+14
1990	3.54432E+14
1991	NA***
1992	5.83212E+14
1993	6.83366E+14
1994	3.15624E+14
1995	NA**
1996	9.4333E+13
1997	NA*
1998	7.46718E+13
1999	NA***
2000	1.12656E+14
2001	2.40261E+13
2002	2.66152E+14
2003	2.46169E+14
2004	2.67238E+14
2005	1.19165E+14
2006	4.59616E+13*
2007	8.7145E+13
2008	9.8367E+13
2009	6.97687E+13
2010	2.57265E+13
2011	2.95126E+13
2012	1.08644E+13
2013	3.84104E+13
2014	4.77354E+13
2015	4.56354E+13
2016	4.95203E+13
2017	7.55853E+13*
2018	4.53662E+13
2019	9.96199E+13*
2020	NA**
2021	1.64158E+13
2022	3.71718E+13

**Imprecise because of a certain mismatch between the timing of the survey and the timing of spawning.*
***No estimate available because no survey was conducted.*
**** Removed because of poor estimation of the proportion of eggs spawned during the survey and indication of bias.*

Table S10. Weight-at-age (kg) of the stock (June-July).

Year	1	2	3	4	5	6	7	8	9	10+
1968	0.128	0.273	0.368	0.434	0.502	0.554	0.593	0.632	0.665	0.718
1969	0.128	0.270	0.361	0.429	0.498	0.550	0.588	0.628	0.661	0.714
1970	0.127	0.268	0.356	0.420	0.491	0.545	0.583	0.623	0.656	0.709
1971	0.128	0.267	0.353	0.415	0.481	0.537	0.578	0.617	0.650	0.703
1972	0.128	0.268	0.352	0.411	0.474	0.526	0.569	0.610	0.643	0.696
1973	0.127	0.267	0.352	0.409	0.469	0.517	0.556	0.600	0.635	0.687
1974	0.132	0.277	0.365	0.426	0.486	0.533	0.569	0.611	0.651	0.707
1975	0.139	0.289	0.381	0.444	0.509	0.554	0.589	0.628	0.665	0.727
1976	0.146	0.299	0.390	0.454	0.520	0.569	0.601	0.638	0.671	0.729
1977	0.151	0.310	0.400	0.460	0.527	0.576	0.612	0.644	0.675	0.728
1978	0.156	0.321	0.413	0.470	0.533	0.582	0.617	0.654	0.679	0.730
1979	0.161	0.332	0.429	0.488	0.547	0.591	0.626	0.663	0.693	0.739
1980	0.167	0.350	0.454	0.518	0.579	0.619	0.649	0.686	0.717	0.769
1981	0.168	0.365	0.480	0.549	0.617	0.658	0.682	0.714	0.744	0.798
1982	0.163	0.359	0.488	0.568	0.639	0.685	0.709	0.733	0.757	0.810
1983	0.154	0.335	0.462	0.556	0.636	0.682	0.709	0.733	0.748	0.793
1984	0.150	0.317	0.435	0.530	0.627	0.684	0.713	0.739	0.753	0.789
1985	0.148	0.313	0.416	0.504	0.604	0.682	0.722	0.750	0.768	0.803
1986	0.147	0.308	0.408	0.479	0.570	0.652	0.715	0.755	0.774	0.813
1987	0.144	0.303	0.398	0.466	0.539	0.612	0.679	0.742	0.774	0.814
1988	0.141	0.301	0.398	0.461	0.531	0.586	0.646	0.715	0.772	0.825
1989	0.139	0.296	0.397	0.464	0.529	0.582	0.622	0.685	0.748	0.828
1990	0.139	0.290	0.387	0.459	0.527	0.575	0.613	0.654	0.710	0.796
1991	0.137	0.290	0.381	0.449	0.523	0.574	0.607	0.646	0.680	0.757
1992	0.137	0.286	0.379	0.439	0.510	0.567	0.603	0.636	0.667	0.722
1993	0.137	0.286	0.375	0.439	0.501	0.555	0.598	0.635	0.661	0.712
1994	0.139	0.291	0.380	0.440	0.507	0.552	0.592	0.638	0.668	0.713
1995	0.140	0.297	0.391	0.451	0.514	0.566	0.597	0.640	0.679	0.730
1996	0.140	0.299	0.399	0.464	0.527	0.572	0.611	0.643	0.680	0.741
1997	0.140	0.300	0.402	0.474	0.542	0.587	0.619	0.659	0.685	0.743
1998	0.141	0.301	0.404	0.478	0.554	0.604	0.636	0.668	0.703	0.749
1999	0.140	0.299	0.400	0.475	0.553	0.611	0.647	0.679	0.704	0.760
2000	0.137	0.295	0.396	0.468	0.545	0.606	0.651	0.687	0.711	0.757
2001	0.136	0.290	0.391	0.464	0.540	0.600	0.647	0.693	0.722	0.767
2002	0.135	0.284	0.379	0.452	0.528	0.586	0.632	0.680	0.719	0.769
2003	0.134	0.281	0.371	0.439	0.514	0.573	0.617	0.664	0.705	0.764
2004	0.132	0.278	0.367	0.428	0.498	0.558	0.602	0.647	0.688	0.749
2005	0.132	0.277	0.366	0.426	0.489	0.543	0.590	0.635	0.674	0.735
2006	0.131	0.278	0.367	0.428	0.491	0.538	0.579	0.627	0.667	0.726
2007	0.132	0.277	0.367	0.428	0.492	0.538	0.572	0.614	0.657	0.717
2008	0.134	0.282	0.370	0.435	0.498	0.546	0.579	0.614	0.651	0.714
2009	0.136	0.288	0.379	0.441	0.509	0.556	0.592	0.626	0.655	0.713
2010	0.137	0.290	0.384	0.448	0.512	0.564	0.598	0.635	0.663	0.712
2011	0.138	0.292	0.387	0.454	0.520	0.567	0.606	0.641	0.671	0.720
2012	0.137	0.290	0.386	0.453	0.521	0.571	0.604	0.643	0.672	0.722
2013	0.138	0.291	0.387	0.454	0.524	0.576	0.611	0.645	0.678	0.727
2014	0.140	0.297	0.391	0.460	0.531	0.585	0.624	0.661	0.688	0.742
2015	0.140	0.297	0.395	0.460	0.532	0.587	0.627	0.667	0.697	0.745
2016	0.138	0.294	0.393	0.461	0.529	0.584	0.624	0.665	0.698	0.749
2017	0.137	0.289	0.387	0.458	0.528	0.578	0.619	0.660	0.694	0.747
2018	0.137	0.289	0.384	0.455	0.529	0.583	0.618	0.660	0.695	0.750
2019	0.138	0.289	0.383	0.449	0.524	0.581	0.621	0.658	0.693	0.748
2020	0.140	0.293	0.385	0.451	0.520	0.578	0.622	0.663	0.693	0.749
2021	0.141	0.298	0.391	0.455	0.523	0.576	0.622	0.668	0.702	0.753
2022	0.141	0.298	0.395	0.457	0.523	0.574	0.613	0.660	0.699	0.755

Table S11. Weight-at-age (kg) of landed fish.

Year	1	2	3	4	5	6	7	8	9	10+
1968	0.177	0.294	0.358	0.458	0.499	0.568	0.592	0.618	0.645	0.673
1969	0.177	0.294	0.358	0.458	0.499	0.568	0.592	0.618	0.645	0.673
1970	0.177	0.294	0.358	0.458	0.499	0.568	0.592	0.618	0.645	0.673
1971	0.177	0.294	0.358	0.458	0.499	0.568	0.592	0.618	0.645	0.673
1972	0.177	0.294	0.358	0.458	0.499	0.568	0.592	0.618	0.645	0.673
1973	0.177	0.294	0.358	0.458	0.499	0.568	0.592	0.618	0.645	0.673
1974	0.177	0.294	0.358	0.458	0.499	0.568	0.592	0.618	0.645	0.673
1975	0.177	0.294	0.358	0.458	0.499	0.568	0.592	0.618	0.645	0.673
1976	0.177	0.294	0.358	0.458	0.499	0.568	0.592	0.618	0.645	0.673
1977	0.123	0.297	0.378	0.435	0.510	0.560	0.628	0.655	0.668	0.730
1978	0.184	0.309	0.410	0.454	0.488	0.540	0.593	0.633	0.690	0.685
1979	0.164	0.246	0.415	0.507	0.531	0.564	0.584	0.654	0.676	0.724
1980	0.202	0.410	0.441	0.522	0.595	0.612	0.636	0.680	0.718	0.737
1981	0.183	0.424	0.549	0.569	0.642	0.665	0.682	0.710	0.754	0.798
1982	0.109	0.389	0.565	0.640	0.708	0.748	0.739	0.755	0.757	0.858
1983	0.133	0.298	0.359	0.479	0.633	0.679	0.768	0.750	0.762	0.778
1984	0.220	0.301	0.434	0.514	0.695	0.725	0.730	0.818	0.788	0.823
1985	0.143	0.346	0.361	0.462	0.583	0.707	0.721	0.717	0.789	0.865
1986	0.158	0.288	0.403	0.414	0.494	0.593	0.754	0.812	0.829	0.853
1987	0.212	0.308	0.410	0.467	0.489	0.574	0.614	0.760	0.913	0.895
1988	0.128	0.359	0.434	0.486	0.527	0.559	0.629	0.714	0.857	0.878
1989	0.156	0.315	0.457	0.534	0.612	0.637	0.661	0.776	0.826	0.907
1990	0.271	0.295	0.400	0.557	0.613	0.638	0.677	0.668	0.721	0.878
1991	0.230	0.327	0.387	0.469	0.582	0.621	0.635	0.709	0.693	0.893
1992	0.163	0.276	0.393	0.446	0.509	0.580	0.611	0.692	0.682	0.709
1993	0.173	0.290	0.374	0.458	0.484	0.540	0.598	0.648	0.690	0.712
1994	0.239	0.345	0.373	0.455	0.535	0.527	0.585	0.634	0.694	0.723
1995	0.198	0.336	0.450	0.476	0.515	0.595	0.602	0.647	0.723	0.793
1996	0.206	0.323	0.445	0.536	0.555	0.601	0.644	0.667	0.716	0.805
1997	0.219	0.351	0.447	0.525	0.593	0.591	0.643	0.743	0.704	0.744
1998	0.155	0.244	0.398	0.505	0.569	0.620	0.658	0.661	0.710	0.714
1999	0.190	0.278	0.408	0.478	0.547	0.602	0.667	0.665	0.708	0.712
2000	0.179	0.294	0.375	0.465	0.552	0.604	0.653	0.726	0.713	0.703
2001	0.151	0.291	0.423	0.486	0.569	0.639	0.686	0.729	0.842	0.774
2002	0.168	0.277	0.379	0.451	0.517	0.605	0.634	0.681	0.692	0.731
2003	0.218	0.311	0.377	0.468	0.532	0.617	0.678	0.709	0.848	0.706
2004	0.202	0.289	0.390	0.479	0.541	0.588	0.655	0.773	0.710	0.681
2005	0.108	0.288	0.366	0.452	0.516	0.596	0.631	0.672	0.730	0.656
2006	0.220	0.316	0.417	0.473	0.529	0.547	0.641	0.708	0.634	0.633
2007	0.207	0.318	0.434	0.502	0.587	0.613	0.676	0.714	0.757	0.693
2008	0.165	0.302	0.423	0.505	0.535	0.613	0.682	0.584	0.706	0.767
2009	0.204	0.318	0.418	0.489	0.578	0.591	0.660	0.619	0.784	0.803
2010	0.085	0.357	0.435	0.500	0.564	0.645	0.651	0.635	0.834	0.705
2011	0.180	0.285	0.412	0.473	0.552	0.566	0.684	0.632	0.676	0.706
2012	0.220	0.338	0.406	0.496	0.552	0.639	0.768	0.648	0.648	0.708
2013	0.176	0.287	0.424	0.470	0.545	0.561	0.641	0.620	0.663	0.708
2014	0.188	0.348	0.427	0.509	0.582	0.691	0.742	0.671	0.678	0.708
2015	0.174	0.283	0.411	0.479	0.575	0.623	0.591	0.487	0.693	0.708
2016	0.147	0.277	0.407	0.484	0.534	0.563	0.597	0.753	0.708	0.708
2017	0.163	0.211	0.334	0.423	0.507	0.532	0.570	0.696	0.722	0.708
2018	0.124	0.175	0.329	0.403	0.520	0.536	0.635	0.638	0.737	0.708
2019	0.126	0.279	0.339	0.372	0.500	0.573	0.613	0.638	0.752	0.708
2020	0.143	0.306	0.387	0.438	0.454	0.540	0.618	0.631	0.773	0.708
2021	0.165	0.269	0.370	0.440	0.496	0.515	0.625	0.572	0.756	0.708
2022	0.126	0.221	0.343	0.424	0.474	0.580	0.574	0.684	0.693	0.708

Table S12. Maturity-at-age (proportions).

Year	1	2	3	4	5	6	7	8	9	10+
1968	0.296	0.715	0.897	0.954	1.000	1.000	1.000	1.000	1.000	1.000
1969	0.296	0.710	0.893	0.952	1.000	1.000	1.000	1.000	1.000	1.000
1970	0.293	0.703	0.888	0.949	1.000	1.000	1.000	1.000	1.000	1.000
1971	0.287	0.692	0.882	0.946	1.000	1.000	1.000	1.000	1.000	1.000
1972	0.274	0.676	0.874	0.942	1.000	1.000	1.000	1.000	1.000	1.000
1973	0.253	0.661	0.869	0.939	1.000	1.000	1.000	1.000	1.000	1.000
1974	0.229	0.659	0.877	0.944	1.000	1.000	1.000	1.000	1.000	1.000
1975	0.217	0.688	0.904	0.958	1.000	1.000	1.000	1.000	1.000	1.000
1976	0.238	0.734	0.929	0.970	1.000	1.000	1.000	1.000	1.000	1.000
1977	0.287	0.778	0.937	0.973	1.000	1.000	1.000	1.000	1.000	1.000
1978	0.333	0.810	0.931	0.969	1.000	1.000	1.000	1.000	1.000	1.000
1979	0.317	0.839	0.928	0.967	1.000	1.000	1.000	1.000	1.000	1.000
1980	0.250	0.871	0.939	0.972	1.000	1.000	1.000	1.000	1.000	1.000
1981	0.181	0.874	0.950	0.978	1.000	1.000	1.000	1.000	1.000	1.000
1982	0.147	0.831	0.951	0.980	1.000	1.000	1.000	1.000	1.000	1.000
1983	0.145	0.760	0.950	0.981	1.000	1.000	1.000	1.000	1.000	1.000
1984	0.147	0.712	0.957	0.985	1.000	1.000	1.000	1.000	1.000	1.000
1985	0.171	0.715	0.967	0.990	1.000	1.000	1.000	1.000	1.000	1.000
1986	0.217	0.751	0.973	0.993	1.000	1.000	1.000	1.000	1.000	1.000
1987	0.266	0.802	0.977	0.995	1.000	1.000	1.000	1.000	1.000	1.000
1988	0.304	0.850	0.978	0.995	1.000	1.000	1.000	1.000	1.000	1.000
1989	0.342	0.878	0.975	0.993	1.000	1.000	1.000	1.000	1.000	1.000
1990	0.391	0.873	0.967	0.990	1.000	1.000	1.000	1.000	1.000	1.000
1991	0.428	0.845	0.954	0.985	1.000	1.000	1.000	1.000	1.000	1.000
1992	0.434	0.808	0.942	0.980	1.000	1.000	1.000	1.000	1.000	1.000
1993	0.420	0.771	0.931	0.975	1.000	1.000	1.000	1.000	1.000	1.000
1994	0.406	0.742	0.920	0.970	1.000	1.000	1.000	1.000	1.000	1.000
1995	0.415	0.727	0.910	0.963	1.000	1.000	1.000	1.000	1.000	1.000
1996	0.453	0.733	0.902	0.957	1.000	1.000	1.000	1.000	1.000	1.000
1997	0.476	0.751	0.906	0.959	1.000	1.000	1.000	1.000	1.000	1.000
1998	0.454	0.769	0.920	0.968	1.000	1.000	1.000	1.000	1.000	1.000
1999	0.415	0.790	0.939	0.979	1.000	1.000	1.000	1.000	1.000	1.000
2000	0.393	0.819	0.957	0.987	1.000	1.000	1.000	1.000	1.000	1.000
2001	0.405	0.848	0.970	0.991	1.000	1.000	1.000	1.000	1.000	1.000
2002	0.409	0.860	0.978	0.993	1.000	1.000	1.000	1.000	1.000	1.000
2003	0.343	0.847	0.986	0.995	1.000	1.000	1.000	1.000	1.000	1.000
2004	0.228	0.813	0.992	0.998	1.000	1.000	1.000	1.000	1.000	1.000
2005	0.125	0.780	0.996	0.999	1.000	1.000	1.000	1.000	1.000	1.000
2006	0.066	0.772	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2007	0.053	0.783	0.994	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2008	0.087	0.795	0.990	0.999	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.156	0.811	0.985	0.998	1.000	1.000	1.000	1.000	1.000	1.000
2010	0.246	0.834	0.982	0.998	1.000	1.000	1.000	1.000	1.000	1.000
2011	0.320	0.867	0.984	0.998	1.000	1.000	1.000	1.000	1.000	1.000
2012	0.347	0.895	0.989	0.999	1.000	1.000	1.000	1.000	1.000	1.000
2013	0.308	0.896	0.994	0.999	1.000	1.000	1.000	1.000	1.000	1.000
2014	0.238	0.864	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2015	0.162	0.796	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2016	0.096	0.696	0.992	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2017	0.047	0.597	0.988	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2018	0.022	0.555	0.985	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2019	0.019	0.587	0.985	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2020	0.031	0.662	0.988	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2021	0.053	0.736	0.989	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2022	0.081	0.789	0.989	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table S13. Fecundity-at-age (numbers of eggs).

Year	1	2	3	4	5	6	7	8	9	10+
1968	261362	359515	468323	544391	600688	647393	680303	724178	738038	806131
1969	260999	359015	467672	543634	599853	646493	679357	723172	737012	805010
1970	260618	358490	466989	542840	598976	645549	678364	722115	735935	803834
1971	260217	357940	466272	542006	598056	644557	677322	721006	734804	802599
1972	259797	357362	465519	541131	597090	643516	676229	719842	733618	801304
1973	259356	356755	464729	540212	596077	642424	675081	718620	732373	799943
1974	258893	356119	463900	539249	595013	641278	673876	717338	731066	798516
1975	258705	355859	463562	538856	594580	640811	673386	716815	730534	797935
1976	258727	355890	463602	538903	594632	640866	673444	716877	730597	798004
1977	258896	356122	463903	539253	595018	641283	673882	717344	731072	798523
1978	259017	356289	464121	539506	595298	641584	674199	717680	731415	798898
1979	259155	356478	464368	539793	595615	641926	674557	718062	731805	799323
1980	259196	356534	464441	539878	595708	642026	674663	718175	731919	799448
1981	259158	356483	464374	539800	595622	641933	674565	718071	731813	799332
1982	259176	356508	464406	539837	595663	641978	674612	718121	731864	799388
1983	259447	356881	464892	540403	596287	642650	675319	718873	732630	800225
1984	259737	357280	465412	541007	596953	643369	676074	719677	733450	801120
1985	260153	357851	466156	541872	597908	644397	677155	720827	734622	802401
1986	260682	358579	467104	542974	599124	645708	678532	722293	736116	804032
1987	261097	359149	467847	543838	600077	646735	679611	723442	737287	805312
1988	261500	359704	468571	544678	601005	647735	680662	724560	738427	806556
1989	261939	360308	469356	545592	602012	648821	681803	725776	739665	807909
1990	262294	360796	469993	546332	602829	649701	682728	726760	740669	809005
1991	262734	361401	470781	547247	603839	650790	683872	727978	741910	810361
1992	263322	362210	471835	548472	605191	652247	685403	729608	743571	812175
1993	264121	363309	473266	550136	607027	654225	687482	731821	745826	814639
1994	264780	364216	474448	551510	608543	655859	689199	733648	747689	816673
1995	265662	365429	476028	553347	610569	658043	691494	736092	750179	819392
1996	266565	366671	477646	555227	612645	660280	693845	738594	752729	822178
1997	267489	367943	479302	557153	614769	662570	696251	741155	755339	825029
1998	268514	369353	481139	559288	617126	665109	698919	743996	758234	828191
1999	269572	370807	483034	561491	619556	667729	701672	746926	761220	831453
2000	270690	372345	485037	563820	622126	670498	704582	750024	764377	834901
2001	271847	373937	487111	566230	624785	673365	707594	753230	767645	838471
2002	272812	375264	488839	568239	627002	675753	710105	755902	770369	841445
2003	273816	376646	490639	570331	629311	678242	712720	758686	773205	844544
2004	274758	377941	492327	572293	631475	680575	715171	761295	775865	847448
2005	275750	379306	494104	574359	633755	683032	717753	764044	778666	850508
2006	276590	380462	495610	576110	635686	685113	719940	766372	781039	853100
2007	277086	381143	496497	577141	636824	686340	721229	767744	782437	854627
2008	277414	381595	497086	577825	637580	687154	722084	768655	783365	855641
2009	277605	381857	497428	578223	638019	687627	722582	769184	783904	856230
2010	277916	382285	497985	578871	638733	688397	723391	770045	784782	857189
2011	278261	382760	498604	579590	639526	689252	724289	771002	785757	858253
2012	278442	383009	498929	579967	639943	689701	724761	771504	786269	858812
2013	278910	383653	499767	580942	641018	690860	725979	772801	787590	860256
2014	279235	384099	500348	581618	641764	691663	726823	773699	788506	861256
2015	279454	384401	500741	582074	642268	692206	727394	774307	789125	861932
2016	279492	384453	500809	582153	642355	692300	727493	774412	789233	862049
2017	279409	384339	500661	581981	642165	692096	727278	774183	788999	861795
2018	279251	384121	500377	581651	641801	691703	726865	773744	788552	861306
2019	279106	383922	500118	581349	641468	691344	726488	773342	788142	860859
2020	278741	383420	499464	580589	640629	690440	725538	772331	787112	859733
2021	278117	382562	498346	579290	639195	688895	723914	770603	785350	857809
2022	277643	381910	497497	578303	638107	687722	722681	769290	784013	856348

Table S14. Estimated model parameters (sd = standard deviation).

Parameter	**Estimate**	***sd***
$logq$	0.73	0.04
$log\sigma_{F_y}$	-0.75	0.06
$log\sigma_{N_1}^2$	-0.19	0.19
$log\sigma_{N_{2-10}}^2$	-0.92	0.08
$log\sigma_{caa_1}^2$	0.6	0.08
$log\sigma_{caa_{2,8,9}}^2$	-0.24	0.11
$log\sigma_{caa_{2-7}}^2$	-0.69	0.07
$log\sigma_s^2$	-0.41	0.06
$log\alpha$	1.03	0.24
$log\beta$	-11.88	0.57
$logitSel_1$	-2.21	0.18
$logitSel_2$	-0.85	0.16
$logitSel_3$	0.19	0.16
$logitSel_4$	1.03	0.31

Table S15. Summary of model estimates showing spawning stock biomass (SSB) in tonnes on both January first (SSB0) and June first (SSB), age-1 recruitment (Recr.), mean instantaneous rate of fishing mortality of fully selected fish ($F_{\overline{5-10}}$ or F), the Limit Reference Point (LRP), and the SSB with respect to the LRP (SSB/LRP).

Year	SSB0	SSB	Recr.	F	LRP	SSB/LRP
1969	406549	353083.5	146683.5	0.14	42449.67	8.32
1970	371623.9	322751.4	263498.6	0.14	42449.67	7.6
1971	324098	281475.6	110159	0.15	42449.67	6.63
1972	267047.8	231928.2	169248.3	0.17	42449.67	5.46
1973	203352.5	176609.5	245333.8	0.31	42449.67	4.16
1974	191124	165989.1	378385.4	0.44	42449.67	3.91
1975	200909.7	174487.9	539011	0.39	42449.67	4.11
1976	269290.7	233876.1	285309.8	0.31	42449.67	5.51
1977	307283.6	266872.5	114748.7	0.23	42449.67	6.29
1978	277800.1	241266.4	147912.2	0.23	42449.67	5.68
1979	229290.8	199136.6	200702	0.25	42449.67	4.69
1980	196039.4	170258.1	65413.71	0.28	42449.67	4.01
1981	155272.2	134852.2	215432	0.31	42449.67	3.18
1982	148990.1	129396.3	431715.7	0.32	42449.67	3.05
1983	208866.9	181398.7	974763.4	0.26	42449.67	4.27
1984	394550.4	342662.8	119310	0.2	42449.67	8.07
1985	525735.8	456596	386260.7	0.2	42449.67	10.76
1986	498111	432604	182562.6	0.19	42449.67	10.19
1987	441535.3	383468.7	157658.2	0.18	42449.67	9.03
1988	391725	340209	528291.8	0.17	42449.67	8.01
1989	418101.7	363116.9	515835.3	0.16	42449.67	8.55
1990	433901.8	376839.1	230569.8	0.19	42449.67	8.88
1991	380682.6	330618.8	285107.7	0.22	42449.67	7.79
1992	328682.9	285457.6	226185.9	0.26	42449.67	6.72
1993	264303.3	229544.6	59164.03	0.29	42449.67	5.41
1994	203660.3	176876.8	190160.2	0.38	42449.67	4.17
1995	160270.9	139193.6	203279.3	0.4	42449.67	3.28
1996	142321	123604.2	182644.1	0.59	42449.67	2.91
1997	124561.3	108180.2	233169.6	0.81	42449.67	2.55
1998	110000.7	95534.42	108407.4	0.99	42449.67	2.25
1999	87864.55	76309.42	123908.3	1.24	42449.67	1.8
2000	78039.67	67776.62	393781.9	1.32	42449.67	1.6
2001	111509.1	96844.42	97525.33	0.99	42449.67	2.28
2002	163247.2	141778.5	105526.7	0.79	42449.67	3.34
2003	169245.1	146987.6	254557.7	0.76	42449.67	3.46
2004	163368.8	141884	404847.9	0.87	42449.67	3.34
2005	163831.7	142286.1	181911.3	1.05	42449.67	3.35
2006	136916	118910.1	322497.8	1.15	42449.67	2.8
2007	130329.6	113189.9	88896.85	1.11	42449.67	2.67
2008	101280	87960.59	184925.8	1.05	42449.67	2.07
2009	87127.01	75668.88	188133.1	1.45	42449.67	1.78
2010	67957.69	59020.52	47629.07	2.03	42449.67	1.39
2011	35101.61	30485.38	116291	2.16	42449.67	0.72
2012	31358.51	27234.53	68394.96	1.58	42449.67	0.64
2013	34631.86	30077.4	53494.85	1.25	42449.67	0.71
2014	34302.55	29791.4	71764.34	1.05	42449.67	0.7
2015	31883.82	27690.76	95754.25	1.05	42449.67	0.65
2016	33559.6	29146.16	172155.8	1.03	42449.67	0.69
2017	48183.83	41847.14	38444.94	1.03	42449.67	0.99
2018	51098.17	44378.21	69146.36	0.93	42449.67	1.05
2019	38424.72	33371.46	29826.51	0.95	42449.67	0.79
2020	27570.84	23944.98	40726.63	0.93	42449.67	0.56
2021	19436.13	16880.07	51982.29	0.78	42449.67	0.4
2022	20321.11	17648.67	39919.26	0.42	42449.67	0.42

Table S16. Estimated numbers-at-age (thousands of fish).

Year	1	2	3	4	5	6	7	8	9	10+
1969	146.68	879.59	274.22	41.31	12.06	12.16	20.59	9.42	6.19	129.27
1970	263.5	100.34	632.89	139.54	30.47	7.44	7.98	16.65	8.16	67.47
1971	110.16	171.15	62.57	446.98	76.83	21.45	5.48	6.81	11.27	43.1
1972	169.25	59.72	102.54	64.69	259.33	46.45	21.46	1.99	4.19	43.43
1973	245.33	159.25	62.44	68.79	57.88	114.48	31.34	12.9	1.7	13.49
1974	378.39	172.07	117.19	50.01	46.97	39.11	51.9	14.17	6.13	6.8
1975	539.01	306.56	97.94	61.78	28.93	28.79	21.96	20.58	5.56	4.76
1976	285.31	475.02	226.63	52.46	29.57	14.91	16.22	11.16	8.74	4.56
1977	114.75	221.05	381.05	137.47	30.02	15.77	8.82	9.28	5.6	6.31
1978	147.91	65.92	145.04	252.84	94.28	23.05	10.82	5.64	5.64	5.75
1979	200.7	109.59	35.72	79.54	140.24	62.08	18.53	7.24	3.77	5.89
1980	65.41	132.6	63.29	25.54	47.26	76.78	35.43	11.18	4.68	5.37
1981	215.43	40.23	83.04	27.24	17.46	31.38	43.68	18.64	6.61	4.96
1982	431.72	146.33	23.43	41.6	8.35	9.97	19.09	29.71	9.7	7.57
1983	974.76	353.95	98.87	13.82	19.41	3.72	3.78	9.48	18.13	10.06
1984	119.31	983.28	268.35	30.61	5.99	10.6	2.15	2.17	6.63	29.35
1985	386.26	87.33	943.92	163.81	12.9	3.62	7.13	1.58	1.32	21.61
1986	182.56	275.44	78.45	668.77	104.72	7.49	2.9	3.63	0.98	11.3
1987	157.66	115.97	154.03	51.55	495.28	73.29	4.35	2.21	1.91	6.92
1988	528.29	96.87	58.7	66.11	32.62	401.55	46.66	2.81	1.43	6.35
1989	515.84	400.75	57.86	31.48	31.32	17.35	324.1	26.06	1.89	6.05
1990	230.57	417.95	250.45	34.7	19.66	19.52	12.4	248.38	15.66	4.17
1991	285.11	167.26	323.48	153.32	19.56	11.69	13.37	9.2	145.35	10.25
1992	226.19	208.46	99.63	232.9	98.77	13.12	6.39	8.06	5.53	84.23
1993	59.16	150.04	131.3	56.72	168.21	63.73	8.74	3.94	4.33	38.57
1994	190.16	33.37	119.13	92.59	28.52	99.67	33.85	4.78	2.26	14.7
1995	203.28	127.63	17.5	73.67	53.7	14.27	50.91	16.92	2.34	5.75
1996	182.64	137.01	74.62	9.09	39.05	32.47	7.16	29.4	7.33	3.25
1997	233.17	127.95	82.23	34.17	4.23	17.51	14.08	2.9	12.92	3.58
1998	108.41	167.35	69.11	41.23	13.69	1.5	6.22	4.93	0.93	4.23
1999	123.91	68.63	94.74	31.63	15.54	3.86	0.55	1.68	1.33	1.03
2000	393.78	78.63	32.41	36.96	9.06	4	0.71	0.13	0.37	0.41
2001	97.53	311.37	42.21	12.43	11.16	1.83	0.82	0.13	0.03	0.1
2002	105.53	64.54	336.98	24.41	5.48	4.1	0.55	0.16	0.02	0.03
2003	254.56	66.04	39.34	267.76	14.85	2.48	2.04	0.2	0.03	0.01
2004	404.85	193.32	37.51	22.18	160.62	5.53	1.21	0.81	0.05	0.01
2005	181.91	305.51	115.08	18.21	10.43	70.78	2.12	0.36	0.13	0.02
2006	322.5	116.87	182.01	53.8	7.5	3.6	23.2	0.58	0.09	0.02
2007	88.9	224.03	66.76	99.35	15.91	2.15	1.09	7.42	0.08	0.02
2008	184.93	52.16	138.22	29.93	40.14	3.36	0.58	0.25	2.25	0.02
2009	188.13	119.71	24.8	69.48	11.33	14.99	0.76	0.12	0.05	0.95
2010	47.63	116.51	54.56	7.4	21.12	2.25	3.29	0.17	0.01	0.17
2011	116.29	22.23	44.7	10.7	0.98	2.81	0.24	0.3	0.02	0.02
2012	68.39	73.04	7.96	11.5	1.3	0.09	0.25	0.02	0.02	0
2013	53.49	51.34	42.5	2.07	2.91	0.21	0.01	0.03	0	0
2014	71.76	35.84	34.55	18.8	0.67	0.4	0.02	0	0.01	0
2015	95.75	49.66	19.97	15.48	5.27	0.28	0.05	0.01	0	0
2016	172.16	66.45	24.24	9.1	5.7	1.68	0.06	0.01	0	0
2017	38.44	144.48	40.09	10.05	3.23	1.86	0.46	0.01	0	0
2018	69.15	26.36	93.84	18.34	3.7	0.88	0.51	0.06	0	0
2019	29.83	49.44	22.35	38.56	6.13	1.24	0.27	0.16	0.01	0
2020	40.73	18.13	28.77	9.84	13.61	1.83	0.46	0.07	0.03	0
2021	51.98	26.36	9.96	12.06	3.55	2.86	0.44	0.18	0.03	0.01
2022	39.92	37.27	15.07	3.96	3.82	1.33	0.83	0.1	0.07	0.02

Table S17. Estimated instantaneous fishing mortality-at-age.

Year	1	2	3	4	5	6	7	8	9	10+
1969	0.01	0.04	0.08	0.11	0.14	0.14	0.14	0.14	0.14	0.14
1970	0.01	0.04	0.08	0.11	0.14	0.14	0.14	0.14	0.14	0.14
1971	0.02	0.05	0.08	0.11	0.15	0.15	0.15	0.15	0.15	0.15
1972	0.02	0.05	0.09	0.13	0.17	0.17	0.17	0.17	0.17	0.17
1973	0.03	0.09	0.17	0.23	0.31	0.31	0.31	0.31	0.31	0.31
1974	0.04	0.13	0.24	0.33	0.44	0.44	0.44	0.44	0.44	0.44
1975	0.04	0.12	0.22	0.29	0.39	0.39	0.39	0.39	0.39	0.39
1976	0.03	0.09	0.17	0.23	0.31	0.31	0.31	0.31	0.31	0.31
1977	0.02	0.07	0.12	0.17	0.23	0.23	0.23	0.23	0.23	0.23
1978	0.02	0.07	0.12	0.17	0.23	0.23	0.23	0.23	0.23	0.23
1979	0.03	0.08	0.14	0.19	0.25	0.25	0.25	0.25	0.25	0.25
1980	0.03	0.09	0.16	0.21	0.28	0.28	0.28	0.28	0.28	0.28
1981	0.03	0.09	0.17	0.23	0.31	0.31	0.31	0.31	0.31	0.31
1982	0.03	0.1	0.18	0.24	0.32	0.32	0.32	0.32	0.32	0.32
1983	0.03	0.08	0.14	0.19	0.26	0.26	0.26	0.26	0.26	0.26
1984	0.02	0.06	0.11	0.15	0.2	0.2	0.2	0.2	0.2	0.2
1985	0.02	0.06	0.11	0.15	0.2	0.2	0.2	0.2	0.2	0.2
1986	0.02	0.06	0.1	0.14	0.19	0.19	0.19	0.19	0.19	0.19
1987	0.02	0.05	0.1	0.13	0.18	0.18	0.18	0.18	0.18	0.18
1988	0.02	0.05	0.09	0.13	0.17	0.17	0.17	0.17	0.17	0.17
1989	0.02	0.05	0.09	0.12	0.16	0.16	0.16	0.16	0.16	0.16
1990	0.02	0.06	0.1	0.14	0.19	0.19	0.19	0.19	0.19	0.19
1991	0.02	0.07	0.12	0.16	0.22	0.22	0.22	0.22	0.22	0.22
1992	0.03	0.08	0.14	0.19	0.26	0.26	0.26	0.26	0.26	0.26
1993	0.03	0.09	0.16	0.22	0.29	0.29	0.29	0.29	0.29	0.29
1994	0.04	0.11	0.21	0.28	0.38	0.38	0.38	0.38	0.38	0.38
1995	0.04	0.12	0.22	0.3	0.4	0.4	0.4	0.4	0.4	0.4
1996	0.06	0.18	0.32	0.44	0.59	0.59	0.59	0.59	0.59	0.59
1997	0.08	0.24	0.44	0.6	0.81	0.81	0.81	0.81	0.81	0.81
1998	0.1	0.3	0.54	0.73	0.99	0.99	0.99	0.99	0.99	0.99
1999	0.12	0.37	0.68	0.91	1.24	1.24	1.24	1.24	1.24	1.24
2000	0.13	0.39	0.72	0.97	1.32	1.32	1.32	1.32	1.32	1.32
2001	0.1	0.3	0.54	0.73	0.99	0.99	0.99	0.99	0.99	0.99
2002	0.08	0.24	0.43	0.59	0.79	0.79	0.79	0.79	0.79	0.79
2003	0.08	0.23	0.42	0.56	0.76	0.76	0.76	0.76	0.76	0.76
2004	0.09	0.26	0.47	0.64	0.87	0.87	0.87	0.87	0.87	0.87
2005	0.1	0.32	0.58	0.78	1.05	1.05	1.05	1.05	1.05	1.05
2006	0.11	0.34	0.63	0.84	1.15	1.15	1.15	1.15	1.15	1.15
2007	0.11	0.33	0.61	0.82	1.11	1.11	1.11	1.11	1.11	1.11
2008	0.1	0.32	0.57	0.77	1.05	1.05	1.05	1.05	1.05	1.05
2009	0.14	0.44	0.79	1.07	1.45	1.45	1.45	1.45	1.45	1.45
2010	0.2	0.61	1.11	1.5	2.03	2.03	2.03	2.03	2.03	2.03
2011	0.21	0.65	1.18	1.59	2.16	2.16	2.16	2.16	2.16	2.16
2012	0.16	0.48	0.87	1.17	1.58	1.58	1.58	1.58	1.58	1.58
2013	0.12	0.38	0.68	0.92	1.25	1.25	1.25	1.25	1.25	1.25
2014	0.1	0.31	0.57	0.77	1.05	1.05	1.05	1.05	1.05	1.05
2015	0.1	0.31	0.57	0.77	1.05	1.05	1.05	1.05	1.05	1.05
2016	0.1	0.31	0.56	0.76	1.03	1.03	1.03	1.03	1.03	1.03
2017	0.1	0.31	0.56	0.76	1.03	1.03	1.03	1.03	1.03	1.03
2018	0.09	0.28	0.51	0.69	0.93	0.93	0.93	0.93	0.93	0.93
2019	0.09	0.29	0.52	0.7	0.95	0.95	0.95	0.95	0.95	0.95
2020	0.09	0.28	0.51	0.69	0.93	0.93	0.93	0.93	0.93	0.93
2021	0.08	0.23	0.43	0.58	0.78	0.78	0.78	0.78	0.78	0.78
2022	0.04	0.13	0.23	0.31	0.42	0.42	0.42	0.42	0.42	0.42

SUPPLEMENTARY FIGURES

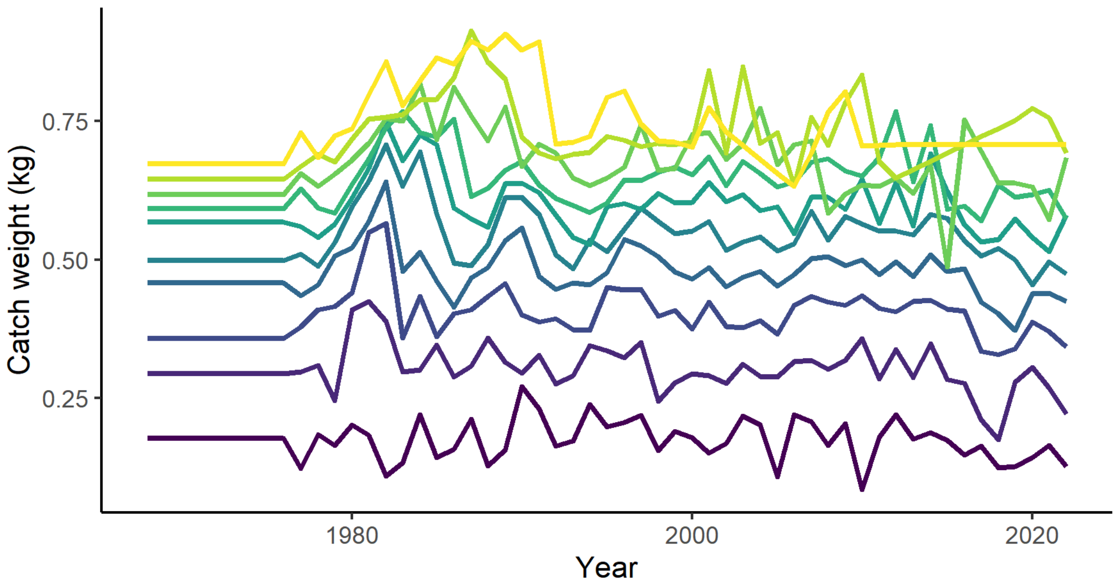

Figure S1. Weight-at-age (kg) of fish in the landings.

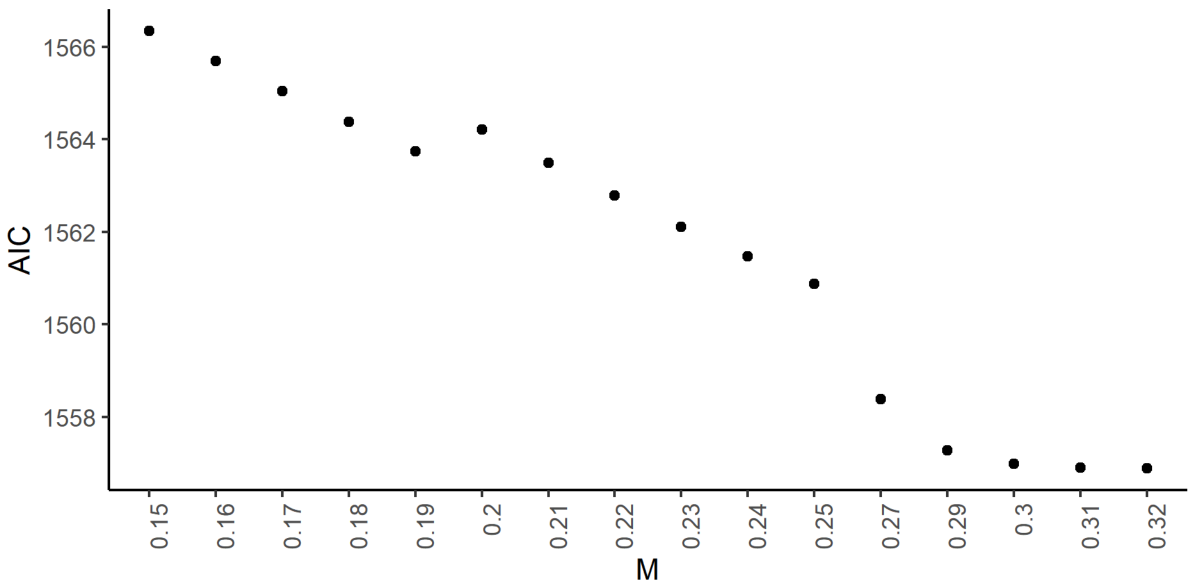

Figure S2. Model fit (AIC) in function of time- and age invariant natural mortality (M).

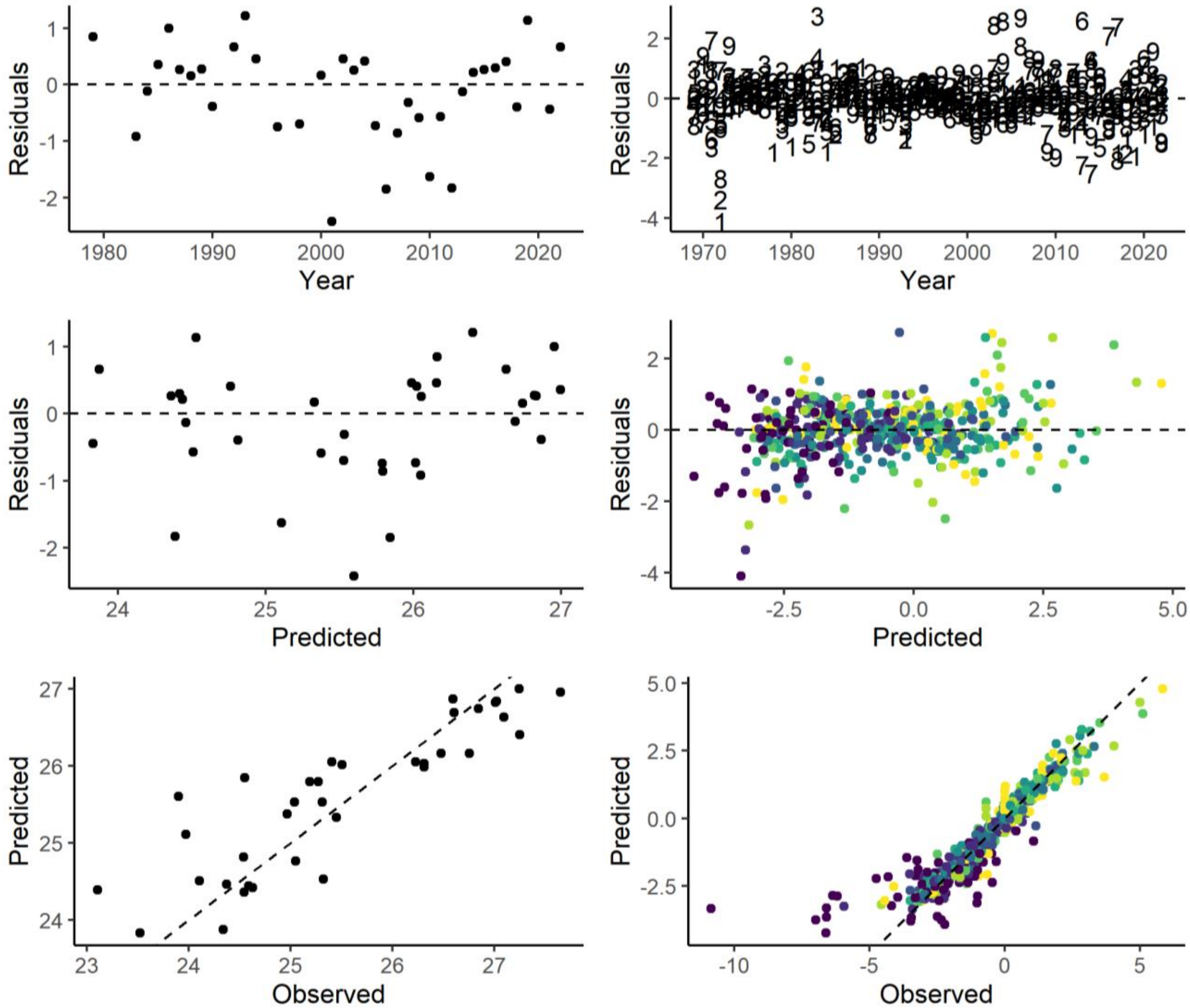

Figure S3. Model residual plots for the index of Total Egg Production (left column) and landings-at-age (right column). The top row shows the standardized residuals plotted against year, the middle row shows the standardized residuals plotted against the predicted values, and the bottom row shows predicted values plotted against the observed values. The numbers and colours in the landings-at-age plots (right column) indicate the age classes from 1 to 10+ (young to old from violet to yellow).

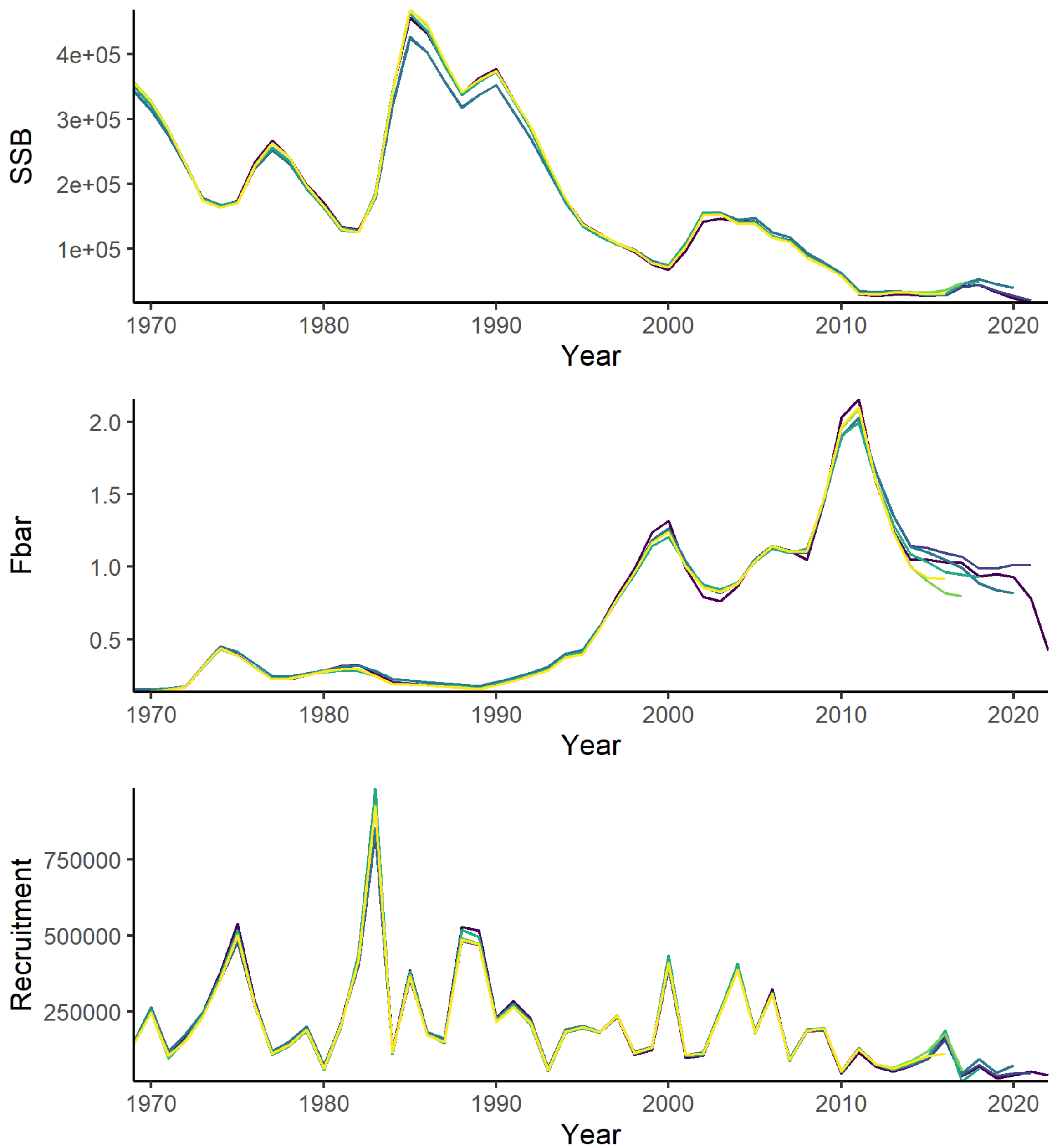

Figure S4. Retrospective plots for the June Spawning Stock Biomass (SSB in kg; top row); the instantaneous fishing mortality rate Fbar ($F_{\overline{5-10}}$; middle row) and recruitment ('000s; middle row). Each peel is in a different color.

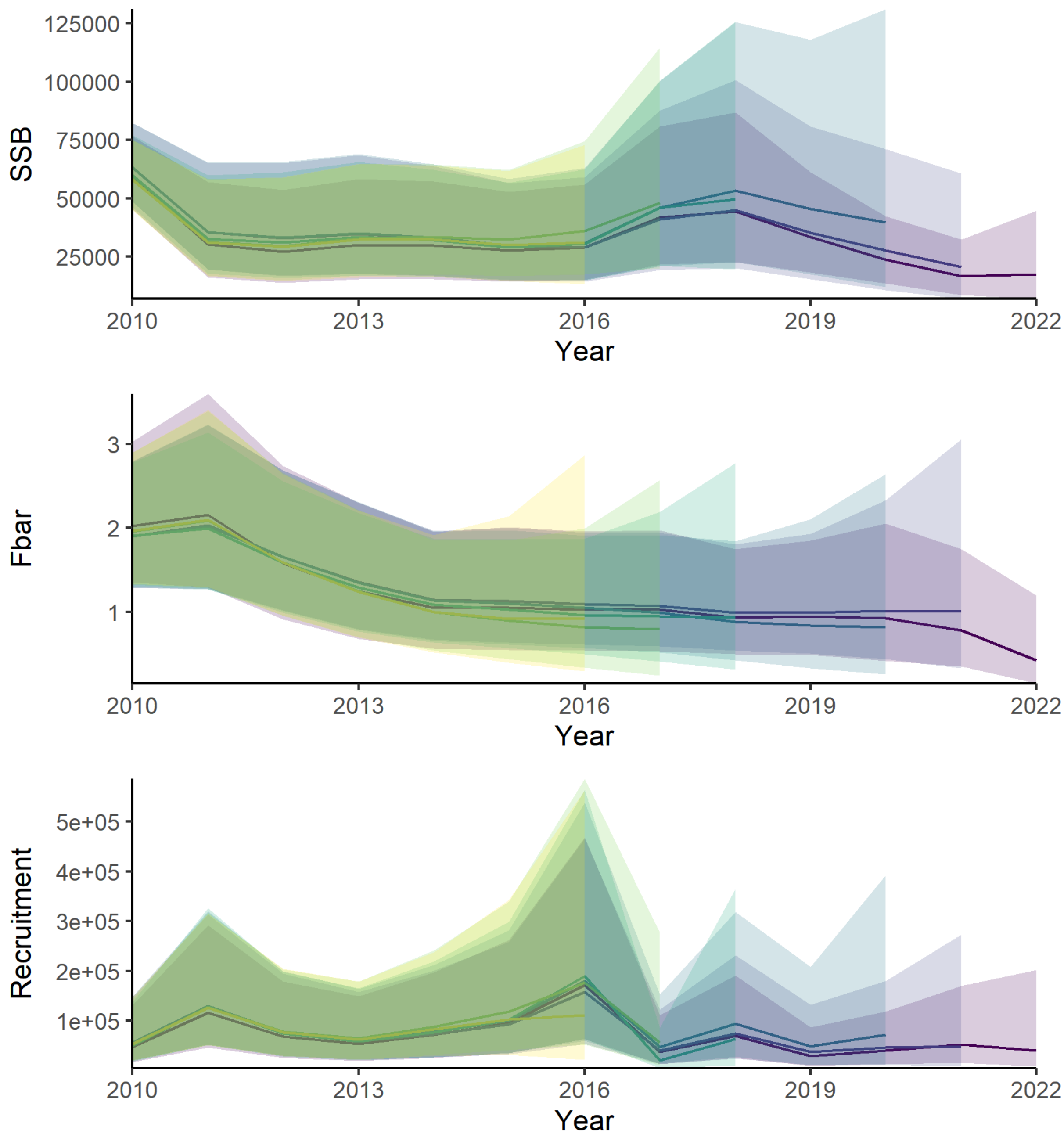

Figure S5. Retrospective plots for the recent period (2010-2022) with 95% confidence interval for the June Spawning Stock Biomass (SSB in kg; top row); the instantaneous fishing mortality rate Fbar ($F_{\overline{5-10}}$; middle row) and recruitment ('000s; middle row). Each peel is in a different color.

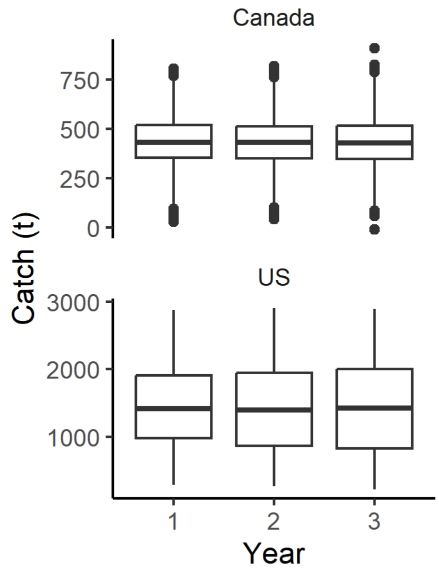

Figure S6. Boxplots of the assumed unaccounted-for catch over the next 3 years (2023-2025), for Canada (upper panel, limited to recreational fishing) and the U.S. (lower panel).

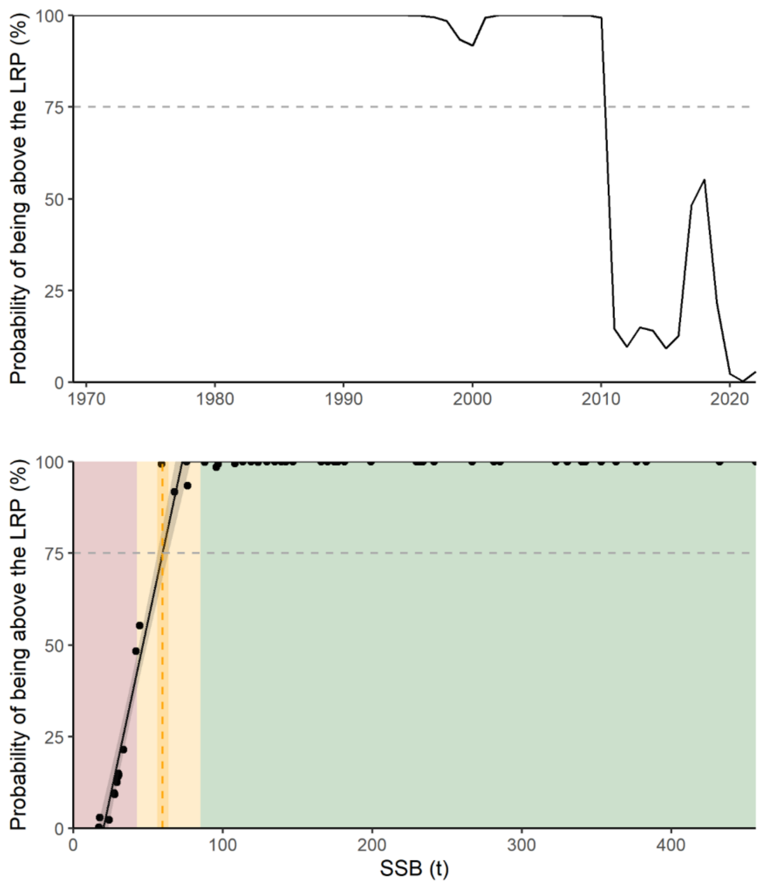

Figure S7. Probability of being above the Limit Reference Points (LRP) over time (upper panel) and in function of estimated June spawning stock biomass (SSB, lower panel). The orange vertical line indicates the SSB associated with a 75% probability of being above the LRP (past estimates).