Fisheries and Oceans Canada | Pêches et Océans Canada
Ecosystems and Oceans Science | Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2022/045

Quebec Region

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

Andrew Smith, Linda Girard, Mélanie Boudreau, Elisabeth Van Beveren, and Stéphane Plourde

Fisheries and Oceans Canada
Institut Maurice-Lamontagne
850, route de la Mer
Mont-Joli, Québec
G5H 3Z4

October 2022

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.

Published by :

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-45235-7 Cat. No. Fs70-5/2022-045E-PDF

Correct citation for this publication:

Smith, A.D., Girard, L., Boudreau, M., Van Beveren, E., and Plourde, S. 2022. Assessment of the northern contingent of Atlantic Mackerel (*Scomber scombrus*) in 2020. DFO Can. Sci. Advis. Sec. Res. Doc. 2022/045. iv + 44 p.

Aussi disponible en français:

Smith, A.D., Girard, L., Boudreau, M., Van Beveren, E. et Plourde, S. 2022. Évaluation du contingent nord du maquereau bleu (Scomber scombrus) en 2020. Secr. can. des avis sci. du MPO. Doc. de rech. 2022/045. iv + 45 p.

TABLE OF CONTENTS

ABSTRACT

The status of the northern contingent of Atlantic mackerel (*Scomber scombrus*) in the Northwest Atlantic is assessed every two years using an age-structured stock assessment model. This document presents the background information, data, and methods used to calculate the main stock status indicators for mackerel which form the basis of advice given to the Fisheries and Aquaculture Management Branch of Fisheries and Oceans Canada (DFO) in the setting of Total Allowable Catch (TAC). The present stock assessment took place on the 25-26 of February and March 3rd of 2021 and provides advice for the 2021-2022 fishing seasons. The main results of this assessment indicated that in 2020, the spawning stock biomass (SSB) of mackerel was estimated to be at an all-time low and in the Critical Zone, as per DFO's Precautionary Approach (PA), since 2011. Recruitment of age 1 fish was estimated to be near record lows in recent years and the age structure of the stock was severely truncated. The fishing mortality rate (F) was also above the reference point. Short-term projections indicated that the probability of the SSB leaving the Critical Zone by 2023 varied from 29%-37% (TAC = 10 000 t) to 51%-58% (TAC = 0 t) depending on the assumptions of future recruitment.

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

ECOLOGY AND POPULATION STRUCTURE

Mackerel are a highly migratory, pelagic, temperate water, forage fish, in the *Scombridae* family. They play a key role in the ecosystem through the transfer of energy from lower trophic levels to higher-order predators including a large range of fish, marine mammals, and sea birds. They have a broad distribution and occur on both sides of the North Atlantic. In the Northwest Atlantic (NWA), mackerel distribution can range from Cape Lookout, North Carolina to Hopedale, Labrador. The northern (i.e. Canadian) contingent of the stock spawns primarily in the southern Gulf of Saint Lawrence (GSL) in June and July. The southern (i.e. U.S.) contingent spawns primarily in the Mid-Atlantic Bight and the Gulf of Maine from mid-April to June (Studholme et al. 1999).

Year to year variation in mackerel distribution as well as their seasonal movements can be largely attributed to their biology, changes in water temperature (preferred range between 7-16 ˚C), and the availability of food (Mackay 1976; Studholme et al. 1999; Galbraith and Grégoire 2014). In the spring when water temperatures warm, schools of the northern contingent migrate inshore and northwards from their overwintering grounds on the edge of the continental shelf in successive, size segregated waves (Goode et al. 1883; Sette 1950; MacKay 1976). The bulk of sexually mature adults migrate into the southern GSL to spawn and limited spawning has been observed on the Scotian Shelf and the waters off the west coast of Newfoundland (Grégoire et al. 2012, 2013). Following the spawning season, both adults and juveniles disperse among the coastal waters of the Atlantic provinces and Quebec to opportunistically feed on zooplankton (e.g. copepods, krill, etc.) and small fish (Mackay 1976; Studholme et al. 1999). Optimal water temperatures, as well as food availability, have been shown to explain much of their summer and fall distributions as well as differences in catch among different regions (Smith et al. 2020; DFO 2019). Juveniles can, however, be found year-round on the Scotian Shelf (Kulka 1977; Mackay 1976; Grégoire and Showell 1994). In the fall, mackerel migrate South to overwinter in the deeper warmer waters on the edge of the continental shelf from Sable Island, Nova Scotia to the waters off Cape Lookout, North Carolina, U.S.A. (Studholme et al. 1999). While overwintering in U.S. waters, the northern and southern contingents of mackerel mix. The mixing and extent of the overlap between the two contingents from year to year are unknown but likely large (Redding et al. 2020; Arai et al. 2021).

Recent genetic analyses undertaken by DFO as well as evidence from several different sources have validated the long-established perception of mackerel population structure in the NWA (Sette 1950; MacKay 1976). These analyses confirmed that the stock in the NWA is genetically distinct from the one in the Northeast Atlantic (Gíslason et al. 2020).

The lack of meaningful differences in the age-structure of catches across regions as well as the migration patterns evidenced through multiple tagging studies or inferred from the seasonality of catches across regions support this assertion (Sette 1950, MacKay 1976; Smith et al. 2020). This distinction has been previously demonstrated through the analysis of the compositions of stable isotopes in mackerel otoliths from both contingents (Redding et al. 2020; Arai et al. 2021).

Most mackerel reach sexual maturity around 2-3 years old (Collette and Nauen 1983). Recruitment to the spawning stock is dependent on the biomass of the spawning stock and the presence of larger older females which are much more fecund than smaller individuals (Pelletier 1986). Recruitment has also been linked to the spatio-temporal overlap in the distributions of mackerel larvae with that of their preferred food. Optimal feeding conditions for adults lead to better individual condition (i.e. increased energy reserves) and have likewise been associated with relatively better recruitment (Brosset et al. 2020; Smith et al. 2020).

FISHERY MANAGEMENT

Mackerel in Canadian waters (primarily in the Northwest Atlantic Fisheries Organisation's subareas 3-4; NAFO) are exploited by commercial, bait, recreational, and food, social or ceremonial (FSC) fisheries. Harvesters from all of the Maritime provinces and Quebec participate in the commercial fishery while the bait and recreational fisheries are less common in Newfoundland. The commercial fishery is an inshore, open, competitive fishery that employs a variety of fixed and mobile gear types (e.g. traps, gillnets, various hand and mechanized hook and lines, as well as purse and tuck seines) the predominance of which varies by region and season. Landings from the commercial fishery are recorded through logbooks, purchase slips, and dockside monitoring companies whose respective coverage has varied over time and among regions. Records of landings from the bait fishery have been inconsistent or non-existent for much of the fisheries' history and have only begun to be recorded more thoroughly in recent years. Few estimates are available for landings made by the recreational fishery despite its widespread popularity (Van Beveren et al. 2017a,b, 2019). Mackerel are also caught as bycatch in several different fisheries. Discarding, particularly of smaller mackerel, is also known to occur but there is little information available on its prevalence. An unknown but likely large proportion of northern contingent mackerel is also caught by the winter U.S. fishery when the distributions of the two contingents overlap (Redding et al. 2020, Arai et al. 2021).

An Atlantic Mackerel Rebuilding Plan Working Group (RPWG), which includes members from the fishery and other stakeholders, was created in 2017. The main objectives of the Rebuilding Plan, published in 2020, were to "limit the probability of Atlantic mackerel spawning stock biomass declining from one year to the next (i.e., maintain a positive growth trajectory)" and "to rebuild Atlantic Mackerel Spawning Stock Biomass above the Limit Reference Point (goal to rebuild mackerel SSB)".

ASSESSMENT

Mackerel stock status has been evaluated with a state-space censored-catch-at-age stock assessment model (CCAM; Van Beveren et al. 2017a) since 2017 (DFO 2019, Doniol-Valcroze et al. 2019). State-space models can treat both process error in the population dynamics as well as observation error and are considered by many to be the best practice for stock assessments (Bolker 2008, Auger-Méthé et al. 2016, Aeberhard et al. 2018). The model is fit to both fisheries-independent (egg survey and research samples) and fisheries-dependent (landings, commercial samples, and catch-at-age) data. The main stock status indices produced by the model are spawning stock biomass (SSB), recruitment (age 1 fish), and instantaneous fishing mortality (F). More specifically, the fisheries-independent data included an egg index which is derived from an annual mackerel egg survey (1979-2020) and the fisheries-dependant data included catch statistics and biological samples (an upper and lower catch bound for the estimated total catch as well as the estimated catch-at-age) acquired from the commercial mackerel fishery (1968-2020). The biological data collected from dockside monitoring programs and from research surveys were also used to calculate several other metrics used as input in the stock assessment model including age-specific mean masses and lengths, the proportion of mature females, fecundity, and sex ratios (ages 1-10+).

The last stock assessment took place in March 2019 and provided FM with advice for the 2019 and 2020 fishing seasons (DFO 2019; Smith et al. 2020). A management strategy evaluation (MSE) was also peer-reviewed during the last assessment (Van Beveren et al. 2020a,b) and included the longer-term evaluation of HCRs under a variety of uncertainties with respect to objectives defined by the RPWG.

The results of the last stock assessment and MSE indicated that in 2018, mackerel had been in the Critical Zone since 2011 following a period of intense exploitation ($F > F_{ref}$). This low biomass was accompanied by the loss of older individuals in the population and lower estimated recruitment in recent years. Following the last assessment, FM recommended a TAC of 8000 t to the Minister of Fisheries, Oceans, and the Canadian Coast Guard. This recommendation was approved for the 2019 fishing season and rolled over for the 2020 fishing season.

METHODS

LANDINGS

Commercial fisheries data for mackerel caught in Canada's Exclusive Economic Zone (EEZ; i.e. NAFO Subareas 2-4 and parts of 5) were acquired from the most recent ZIFF (Zonal Interchange File Format) files produced by DFO's regional statistics bureaus for the years 1995-2020. For the years 1960-1994, we used data from the NAFO landings database (Grégoire 2000) and also included landings from non Canadian vessels during the 1995-2020 time period. At the time of this assessment, landings data for the 2019 and 2020 fishing seasons were still preliminary as landings data were still being compiled by the various DFO regions (i.e. Québec, Gulf, Maritimes, and Newfoundland regions). Data from the U.S. commercial and recreational fisheries (1960-2020) were provided by the Northeast Fisheries Science Center (NEFSC 2017). The U.S. catch statistics were also preliminary for 2019 and 2020 (Tables S1, S2). Catch-at-age data only exists from 1968-present for the northern contingent of mackerel therefore only landings data from 1968 onwards will be considered in most tables and figures in this document.

COMMERCIAL SAMPLING

Biological characteristics of mackerel are monitored annually through DFO's commercial port sampling program which covers the major ports in Eastern Canada where mackerel landings occur over the course of the fishing season. Port samplers collect length-frequency data from a random sample of a landed catch (measured to the nearest 5 mm) and send a length-stratified subsample (two fish per length-class) to IML for further analyses. The length-stratified samples acquired from research projects and/or DFO bottom trawl surveys have occasionally been used to complete age-length-keys. The measurements taken from the biological samples include fork-length (± 1 mm), mass (± 0.1 g), sex, gonad mass (± 0.01 g), maturity stage, and age standardized to January 1st as read through examination of the otoliths. The latter measure has been the subject of comparison with NOAA's stock assessment biologists in the late 2000s (Grégoire et al. 2009) and again in 2016.

The number of length-frequency and biological samples, as well as the total number of fish, analyzed, are summarized in Table S3 for the years 2000-2020. Data from 1973-2000 are summarized in previously published research documents (Gregoire et al. 2014a, Smith et al.

2020). An average of 67 length-frequency samples (average of 12 594 individual fish measured) and 80 biological samples (average of 2818 individual fish measured) are collected annually. This corresponds to an average annual ratio of 4 length-frequency samples and 4 biological samples per 1000 t of mackerel caught.

CATCH-AT-AGE

Data from landings, commercial length frequencies and a corresponding subset of biological samples were used to calculate the annual age and size composition of the catch (i.e. catch, length, and mass-at-age) for the years 2015-2020 inclusive. The equations used to calculate catch-at-age were taken from APL functions adapted to a Visual Basic program CATCH,exe (Anonymous 1986) developed at IML and based on methods described by Gavaris and Gavaris (1983) and Grégoire et al. (2014b). Code to calculate catch-at-age was rewritten in R (R Core Team 2020; v.4.0.2) using user manuals, worked examples of the CATCH software, and with the aid of functions found in the FSA package (Ogle 2015; Smith et al. 2020).

The methods consisted of aggregating the landings by year, quarter, NAFO division, and gear type (hereafter strata) and paired with their corresponding commercial length-frequency samples and biological subsamples (Table S4).

When there were few or no length frequency and/or biological samples to associate to landings in a given stratum, then the samples were combined together with samples from other strata that were judged to best represent the composition of the catch. The following hierarchy was used to assign samples to strata that did not have a corresponding sample (Table S5):

1. Year, adjacent quarter (Jan.-Mar., Apr.-Jun., Jul.-Sep., and Oct.-Dec.), NAFO division, and gear type
2. Year, quarter, adjacent NAFO division, and gear type
3. Year, quarter, NAFO division, and gear type with similar selectivity
4. Year and gear type or similar gear type

Biological samples for each strata were used to assemble the age-length keys (ALK, proportion at age 1-10+ as a function of 5 mm length classes). The ALK were used to assign ages to their corresponding length frequency data using the alkIndivAge() function of the FSA package (Ogle et al. 2021), yielding stratified numbers-at-age per length class. These were summed across length classes for a given age for each strata and then scaled to the catch by multiplying them by the ratio between landings and the estimated total mass of the sample in each strata. Annual mean masses-at-age (1-10+) were estimated for the catch using quarterly log-log mass-length linear regressions. Numbers-at-age were then summed across strata in a given year to obtain annual numbers-at-age (Table S5). Annual catch-at-age was obtained by multiplying the annual numbers-at-age by their corresponding mean masses-at-age (Table S6). To validate the calculations, the total catch-at-age for each year was compared with the reported annual landings as per Grégoire et al. (2014b).

EGG INDEX

The annual estimate of Total Egg Production (TEP; Table S7) is the main indicator of Atlantic mackerel SSB. The egg index is calculated from recently spawned mackerel egg abundance data collected from the dedicated annual survey in the southern GSL. The survey has run almost continuously since 1979 but no surveys were conducted in 1980-1981, 1995, 1997, and 2020, the latter due to restrictions imposed by the Covid pandemic. Surveys conducted in 1982, 1999, and 2006 were invalidated during past peer reviews due to either equipment failures or mission timing with respect to that of mackerel spawning. The survey samples the ichthyoplankton in the top 50 m of the water column at 65 fixed stations using double oblique tows with 61 cm Bongo nets (333 µm mesh) deployed for a minimum of 10 minutes while cruising at roughly 2.5 knots. The volume of filtered seawater, depth sampled, and the mean temperature (C°) in the top 10 m of the water column were calculated for each station (i) in a given year (y). Stage 1 and 5 eggs (Girard 2000) were counted from a subsample of each station and egg densities ($N \cdot m^{-2}$) were estimated by accounting for the volume of the fractioned sample, the volume of seawater filtered, and the depth sampled.

$$Egg\ density_{i,y}\ m^2 = \frac{(\text{number of stage 1 and stage 5 eggs} \div \text{sample fraction})_{i,y} \cdot \text{volume filtered}_{i,y}\ m^3}{\text{depth sampled}_{i,y}\ m}$$

Daily Egg Production ($DEP_{i,y}$) was then calculated by accounting for the incubation time of eggs with respect to the mean water temperature (T) in the top 10 m of the water column of each station according to equations developed by Lockwood et al. (1977). From these values, mean annual DEPs were calculated with the following equation:

$$DEP_{i,y} = \frac{Egg\ density_{i,y}\ m^2}{e^{[-1.61 \cdot log(T) + 7.76]}} \cdot 24\ hours$$

Ordinary kriging was then used to interpolate station specific DEPs across the entire surveyed area to obtain an annual mean DEP_y.

To account for differences between the survey dates and the seasonality of mackerel spawning, DEP_y were adjusted to reflect the egg production for the entire spawning season. To do this, the seasonal progression of female gonadal development was modelled every year using commercial samples of ripe (stage 5) females from NAFO 4T in June and July. From these samples, gonado-somatic indices (GSI) were calculated to describe gonadal development. The proportion of eggs spawned on the median day of a given survey was estimated by fitting GSI data to logistic models. Specifically, annual $\mathrm{GSI_y}$ were modelled as a function of the day of year using a four parameter logistic model:

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

where:

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

y_0 is the upper asymptote,

a is the lower asymptote,

b is the slope,

And x_0 is the inflection point.

The proportion of eggs spawned on the median survey date (S) was calculated from the fitted curve (first derivatives) of the above model, as were the peak day of spawning and the beginning and end of the spawning season (defined by the 5% and 95% quantiles). The egg index (i.e. TEP: the annual number of eggs spawned in the survey area for the entire spawning season; Table S7) was then calculated by dividing the product of the annual mean DEP_y and the surface area (A) of the survey (6.945e+10 m^2) by the proportion of eggs spawned on the median date of the survey (S).

$$TEP_y = \frac{DEP_y \cdot A}{S_y}$$

Methods for the sampling protocol and subsequent analyses to calculate various aspects of mackerel egg production and the resulting egg index are described in greater detail by Girard (2000) and Grégoire et al. (2014a,b).

MATURITY-AT-AGE AND L_{50}

Maturity-at-age (i.e. the proportion of mature individuals in the population at a given age; Table S8) was used in the stock assessment model to convert catch-at-age to SSB using data from commercial samples collected during the spawning season (June-July) and was updated for 2017-2020. Since the last assessment (Smith et al. 2020), maturity ogives were calculated in R using annual generalised linear models (GLM) using the binomial family distribution with a logit link function. Once the maturity-at-age matrix was computed, missing values were imputed via linear interpolation using the data from adjacent years for a given age (ages 2-10+). For age 1 fish, missing values were estimated from the annual maturity ogive as age 1 fish are poorly sampled by the fishery and the gaps were too numerous to be filled reliably by linear interpolation.

Annual maturity ogives were also used to estimate the length at which 50% of individuals attain maturity (L_{50}). The proportion of mature individuals as a function of length were fit by individual GLMs by cohort (1960-2018) and were subsequently used to calculate L_{50}. During the last assessment, L_{50} was calculated by year, however, calculating L_{50} by cohort makes more biological sense. Instances where fewer than 10 mature or immature individuals were available in a given year were excluded from the analyses. The two most recent cohorts, 2019 and 2020, were also omitted from the analyses.

FECUNDITY AND SEX RATIO

Annual fecundity was disaggregated by year and age (Table S9), reflecting recent changes in the model structure since the MSE (see the equations in the appendix of Van Beveren et al. 2020a,b). First, raw fecundity data from Pelletier's (1986) study were extracted and the logs of the observed fecundities of stage 5 (i.e. ripe) females (fec_i) were modelled as a function of their respective gonad masses GM_i) and age (A_i) (i.e. $\log(fec_i) \sim \alpha + \beta 1(GM_i) + \beta 2(A_i) + \epsilon_i$). The model was fit in R using a GLM with a Gaussian distribution and identity link function. Fecundity (n = 222, R^2 = 0.55, RMSE = 0.34, AIC = 141.39, p < 2e-16) was estimated to increase by 1.4% for each age and by 0.83% for every gram of gonad mass (coefficients: intercept = 1.24e+01, age = 1.39e-02, gonad mass = 8.26e-03).

The model was then used to predict individual fecundities from the available biological data on stage 5 females during the months of June and July in NAFO 4T (see the commercial sampling section above) for all years. The means of the individual fitted values were then calculated by year and age. When no data were available for a given combination of year and age, gaps were filled via linear interpolation for ages 2-10+ using the na.approx() function in the zoo package in R. For age 1 fish, fecundity was estimated from the model coefficients. For the years where no data were available (1968-1973) the mean values at age were used. As there is evidence of atresia during the spawning season in some samples, these estimates should be taken as potential fecundities (Pelletier 1986).

Sex ratios were calculated for each combination of year and age (1-10+) using fish whose sex could be determined macroscopically. The sex ratio was simply the proportion of females observed in the aggregated annual commercial samples split by age (Table S10).

STOCK ASSESSMENT MODEL

The model (CCAM) was developed using the Template Model Builder (TMB; Kristensen et al. 2016) package in R (R Core Team 2020) 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 S11. The model is denoted "censored" as it uses an approach in which reported catches are explicitly considered uncertain, and are thus estimated to occur between a lower limit, corresponding to 110% of reported catches and an upper limit corresponding to estimates of the maximum unaccounted-for removals (Van Beveren et al. 2017a, 2019). All data, model code, and scripts for the current assessment are available online. Model configuration in the current assessment is the same as Core model 1 developed as part of the MSE process (Van Beveren et al. 2020a,b).

Input data were updated for total Canadian and U.S. catch, mean mass-at-age, proportion mature, fecundity, sex ratio, and the egg index (Figures 2-3, S2). Some changes were made in how input data were derived since the last assessment (see the sections on the egg index and fecundity above). These changes included fitting the model directly to the egg index as opposed to the SSB index (as per Van Beveren et al. 2020a,b) and updates into how fecundity was estimated. Several age-specific input matrices (fecundity, proportion mature, and mean masses-at-age) were also “smoothed” by way of cubic splines with the smoothing factor set to 0.5 to avoid biologically unrealistic changes. Changes to the upper bounds of catch estimates for 2018-2020 reflect improvements made to catch monitoring in the commercial and bait fisheries as well as newly proposed regulations to the recreational fishery; absolute values were iteratively lowered by 25% each year for 2018-2020. As the U.S. fishery targets mackerel during the winter when mixing between the northern and southern contingents occurs (Redding et al. 2020; Arai et al. 2021), 25% and 50% of total U.S. landings (including commercial, recreational, and discards) were added to the lower and upper bounds respectively. Detailed U.S. catch data was not available for 2020 and the mean landings of the last 5 years were used for 2020.

Short-term projections were performed as a basis for TAC advice for the 2021-2022 fishing seasons. Recruitment was projected using two methods that are thought to be possible as there are no strong arguments to favour one over the other. Projections were made over a three-year period to estimate the impact of different TACs (0-10 000 t) and recruitment scenarios on the projected SSB. Recruitment scenarios included SSB projected forward under the assumptions of the Beverton-Holt stock-recruitment relationship as estimated for the whole time series or using the mean recruitment over the past ten years with a 0.9 autocorrelation. These projections included stochastically projected unaccounted-for catches of both Canada and the US separately (i.e., implementation error). The TAC was added to these estimated catches to calculate total removals and the resulting next years’ stock biomass. During the last assessment there was agreement that the Canadian unaccounted-for catches would likely steadily decrease due to recent management measures aiming to improve catch monitoring and this was implemented in the projections. The fraction of the northern contingent in U.S. catches was presumed to remain at 25-50%. Modelling details are provided in Van Beveren et al. (2020a).

Stock status (SSB_y) was defined relative to an official limit (LRP) and a proposed upper (USR) stock reference point, which were set as 40% and 80% of SSB_{ref} respectively in correspondence with default values proposed for those reference points under the Canadian Precautionary Approach policy (DFO 2009). According to this framework, the LRP and USR delimit three stock status zones; the Critical Zone (SSB<LRP), the Cautious Zone (LRP<SSB<USR) and the Healthy Zone (SSB>USR). The reference biomass point (SSB_{ref}) was set as the SSB corresponding to $F_{40\%}$, a proxy for F_{MSY} (i.e. the fishing mortality that produces maximum sustainable yield in the long term), which has been customary for this stock (Van Beveren et al.

2020a,b). $F_{40\%}$ is the fishing mortality rate that reduces the spawning biomass-per-recruit (SPR) to 40% of its unfished levels (Goodyear 1977; Shepherd 1982).

The SPR was calculated using the mean values of fishing selectivity, natural mortality (M = 0.27), and mass and proportion mature at age values over the last 10 years. Sensitivity of the model to assumptions on natural mortality were tested for values between 0.15-0.30 and the model with the lowest AIC (M = 0.27) was retained.

Thus, the LRP was obtained by multiplying the the SPR value at $F_{40\%}$ with the average estimated recruitment between 1969 and 2020 (see Van Beveren et al. 2020a,b for details).

RESULTS AND DISCUSSION

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

LANDINGS

Nominal landings in Canadian waters were relatively low prior to 1960 (Figures 1, S1; Table S1). Landings increased during the 1960s through the late 1970s due to the presence of the distant water fleet fishing off the coasts of Atlantic Canada and the U.S. Following the establishment of the 200 nautical mile rule and Canada's Exclusive Economic Zone in 1977 (EEZ), landings on the Scotian Shelf (NAFO 4VWX5YZ) decreased whereas landings increased in the southern GSL (NAFO 4T) and off the northeast coast of Newfoundland (mostly NAFO 3K). Landings from 1980 to 1999 were relatively stable and averaged around 22 534 t per year. Over this time period, landings off the northeast coast of Newfoundland began to decrease in the 1990s while remaining stable or increasing in other regions. Annual landings increased substantially from 2000 to 2010, averaging 40 593 t. This period of greater landings reached a record high of 54 809 t in 2005 due to the marked increase in fishing effort by small and large seiners off the coasts of Newfoundland (NAFO 3KL and 4R), and coincided with the arrival of the large 1999 year class. This period was followed by a severe drop in landings that reached a recent low of 4272 t in 2015 (the fourth lowest value on record since 1876 (Hoy and Clark 1967). At the time of the current assessment, landings in Canada's EEZ for 2016-2020 were 8057 t (TAC 8000 t), 9786 t (TAC 10 000 t), 10 964 t (TAC 10 000 t), 8623 t (TAC 8000 t), and 7772 t (TAC 8000 t), respectively.

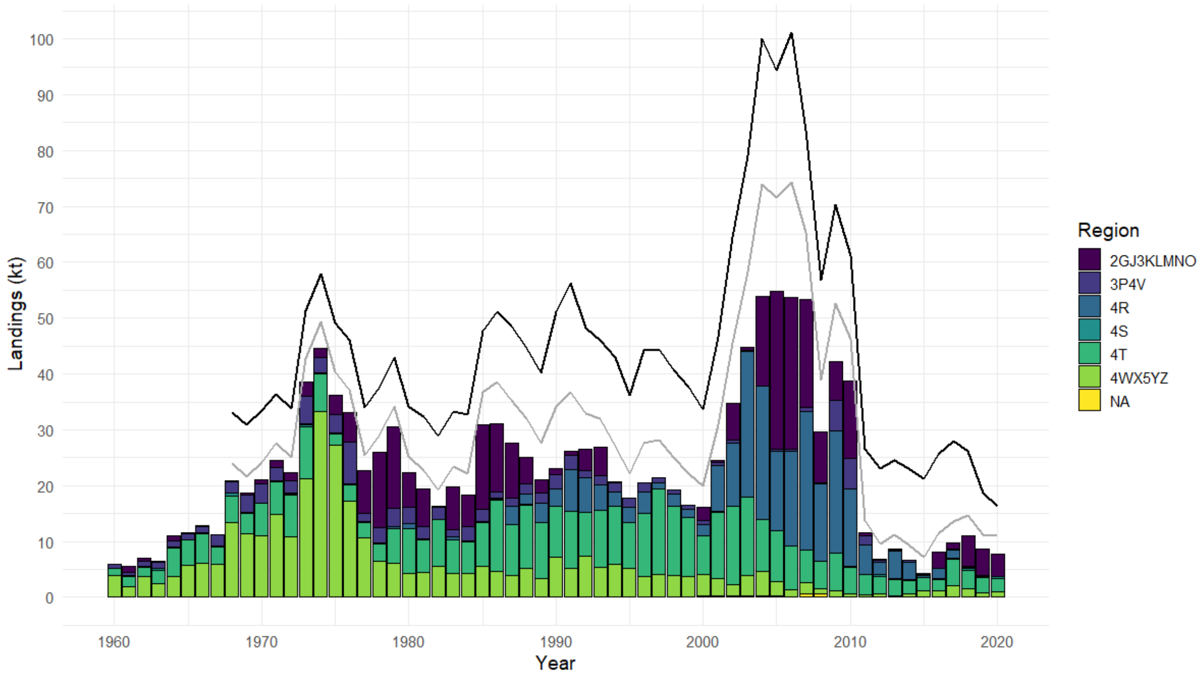

Figure 1. Landings (kt) within Canada's Exclusive Economic Zone by aggregated NAFO divisions. The grey and black lines represent the upper (black) and lower (grey) bounds in which total removals are estimated in the stock assessment model (1968-2020). The lower bound is informed by total recorded landings and 25% of U.S. landings and the upper bound is informed from estimates of maximum unaccounted-for removals from all sources (e.g. recreational catch, unaccounted-for bait, discards, and 50% of U.S. landings).

CATCH-AT-AGE

Strong year classes (i.e. 1968, 1973, 1974, 1982, and 1999) are apparent in the annual catch-at-age data (Figure 2; Table S5) and their progression from year to year can easily be tracked. Mackerel caught by the fishery that were 10 years and older were more common prior to the late 1990s. Since then, the age structure of the catches has become increasingly truncated. By the early 2010s, fish older than 6 were uncommon in the catch. The last notable cohort that could be tracked in the catch was that of 2015. Catches from this cohort were largest in 2018 (86% of the catch) when they were 3 years old. The contribution of this cohort to the fishery dropped to 19% of the catch in 2020, when the fish were 5 years old.

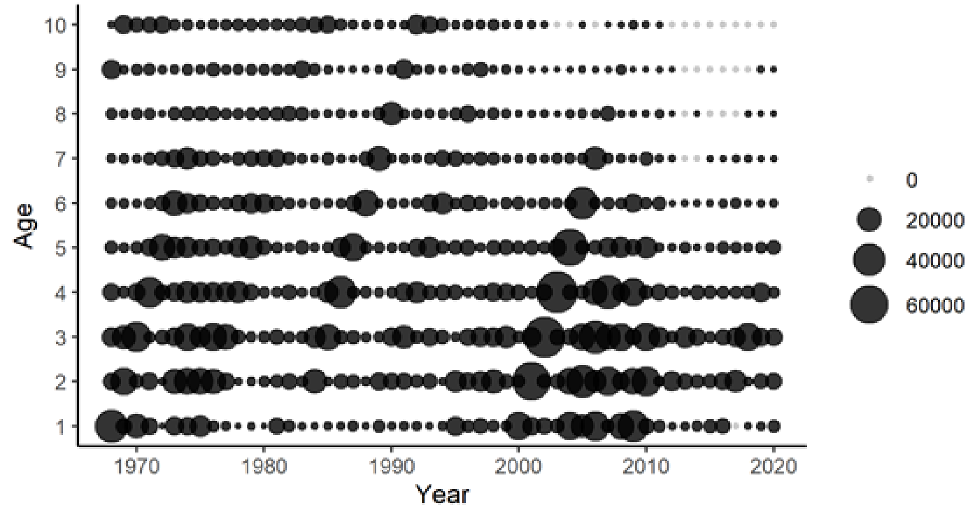

Figure 2. Bubble plot of mackerel catch-at-age data (ages 1-10+) from 1968-2020. Bubble size reflects the estimated number of fish caught in a given year and age class. Grey bubbles represent zeros.

EGG INDEX

The egg index (i.e. total egg production; TEP; Figure 3, Table S7) showed that despite some inter-annual variation, the total number of eggs produced over the course of the spawning season in the survey area has been declining and reached historic lows in the past decade. Mean TEP from 1979 to 1994 was 5.13e14 eggs with a peak in 1986 of 1.23e15 eggs. Between 1994 and 1999, TEP dropped by an order of magnitude to an average of 6.33e13 eggs per year, approximately 12% of the values observed from 1979-1994. TEP began to rise again in 2000 reaching a peak of 2.33e14 eggs in 2002 but started to decline the following year and subsequently reached a time series low value in 2012 at 8.67e12 eggs (approximately 2% and two orders of magnitude lower than the mean from 1979-1994). TEP has stayed low ever since. In 2018 and 2019, TEP was 3.88e13 and 5.68e13 eggs respectively and mean TEP derived from the last ten surveys (2010-2019) was 3.94e13 eggs. Furthermore, the area over which mackerel eggs are distributed during sampling as well as the duration of the spawning season have contracted (Brosset et al. 2020). As has been observed in recent years, spawning activity was limited to the western portions of the survey area in 2019.

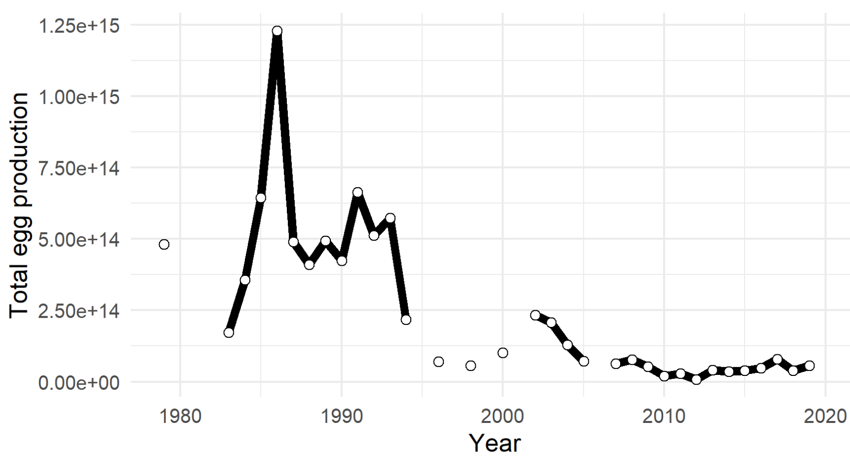

Figure 3. Total egg production derived from the annual spring mackerel egg survey in the southern Gulf of St. Lawrence.

MODEL OUTPUT

Residual plots and retrospective patterns are shown in Figures S3 and S4-S5 respectively. There were no important retrospective patterns but residuals for the egg index showed a linear tendency towards recent overestimation, possibly due to non-stationary processes that have not been considered in the current model formulation. Attempts to correct the bias in the past by allowing for changes in fishery or survey selectivity (2 blocks reflecting pre- and post-2000) or natural mortality (Van Beveren et al. 2020a,b) did not significantly improve the pattern of survey residuals. Estimated model parameters are presented in Table S12 and the model summary in Table S13. Annual numbers at age are presented in Table S7 and annual age-disaggregated fishing mortalities in Table S8.

Estimated SSB dropped below the LRP in 2011 (Figure 4A, Table S13). The ratio between SSB and the LRP increased to close to 1 in 2017 and 2018 with the arrival of the 2015 cohort but fell to values similar to those observed between 2011 and 2015 afterward. SSB was estimated to be at 67% and 58% of the LRP in 2019 and 2020 respectively.

The last relatively large recruitment event was in 2015 but fish belonging to this cohort only represented around 21% and 7% of the spawning stock in terms of numbers-at-age for 2019 and 2020 respectively (Table S14, Figure 4B). In terms of catch-at-age, the 2015 cohort represented 38% and 19% of the catch in 2019 and 2020 respectively, down from a peak of 86% of the catch in 2018. In 2019 and 2020 no single year class appeared to dominate the population. For 2019 and 2020, fishes aged1-5 represented around 99% of the spawning population in terms of numbers and biomass.

Fishing mortality rates (including catch uncertainty) were estimated to remain above the reference level (Figure 4E-F, Table S15). According to the model, the estimated fishing mortality rate on fully exploited mackerel (ages 5 to 10) was 1.33 and 1.34 for 2019 and 2020 respectively (exploitation rates of approximately 74% during both years). Although exploitation rate is usually given for fish that are fully recruited to the fishery, these mackerel do not compose a large fraction of the population anymore. The mean fishing mortality rate of fish aged 2 through 5 was F = 0.82 (exploitation rate of 56%). Note that this exploitation rate is still relatively high, especially given that most fish in the population fall between the ages of 2-5 and are not yet fully selected by the fishery.

Projections were made over a three-year period to estimate the impact of different TACs (0-10 000 t) and recruitment scenarios on the projected SSB. Recruitment scenarios included SSB projected forward under the assumptions of the Beverton-Holt stock-recruitment relationship as estimated for the whole time series or using the mean recruitment with a temporal auto-correlation of 0.9 over the past ten years (Figures S6). These projections included stochastically projected unaccounted-for catches of both Canada and the US separately (i.e., implementation error; Figure S7, Table 1). The TAC was added to these estimated catches to calculate total removals and the resulting next years' stock biomass. During the last assessment there was agreement that the Canadian unaccounted-for catches would likely steadily decrease due to recent management measures aiming to improve catch monitoring. The fraction of northern contingent mackerel in U.S. catches was presumed to remain at 25-50%. Total landings in the U.S. in 2020 were not available for the stock assessment so the 5-year mean was used for 2020. Modelling details are provided in Van Beveren et al. (2020a,b).

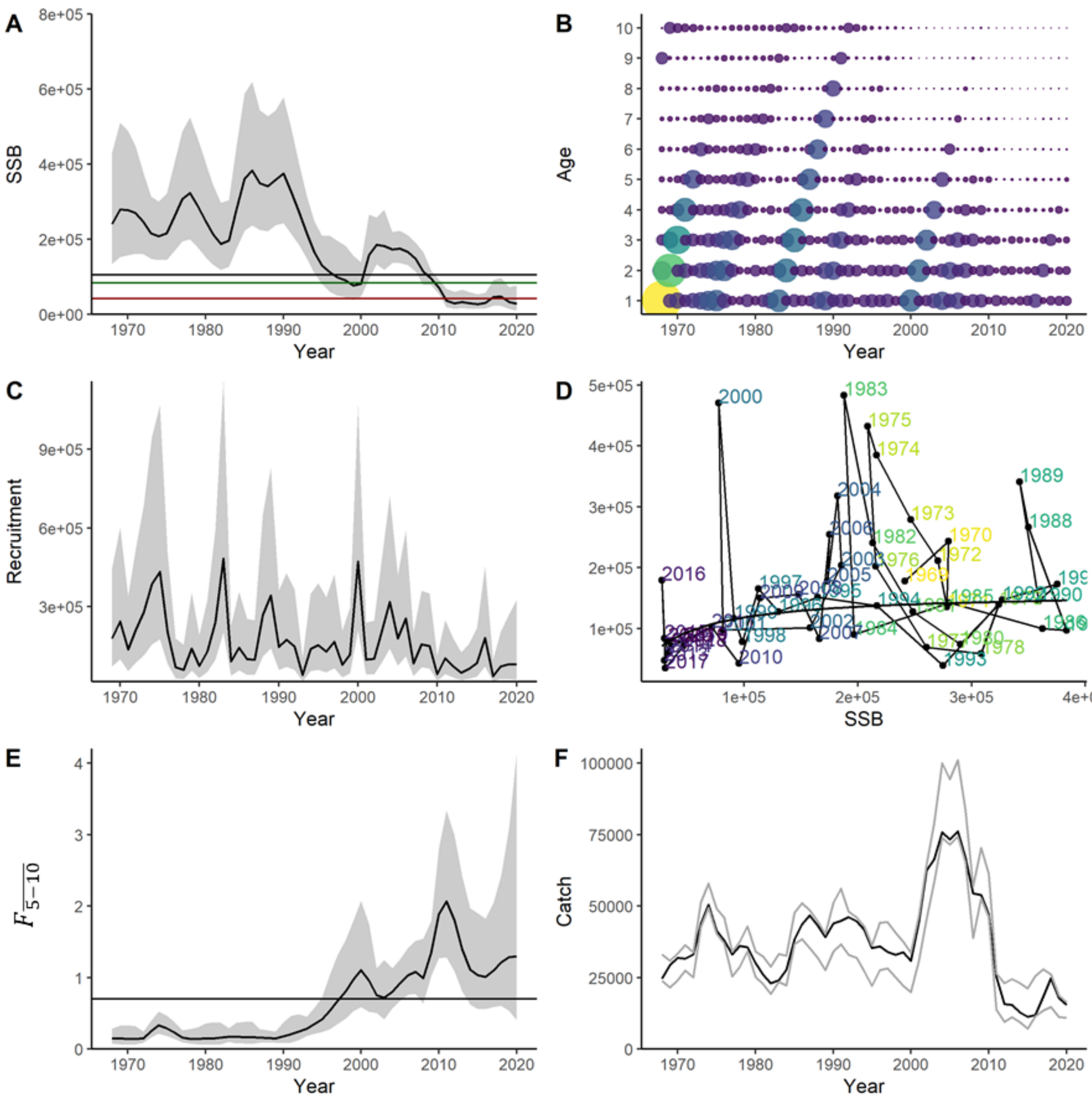

Figure 4. Model output: (A) Spawning Stock Biomass (t) with horizontal lines indicating the reference point ($SSB_{F40\%}$; black), proposed USR ($80\%SSB_{F40\%}$; green) and LRP ($40\%SSB_{F40\%}$; red), (B) numbers-at-age, (C) recruitment (numbers), (D) stock-recruitment, (E) fishing mortality $F_{\overline{5-10}}$ (averaged over the fully selected age classes 5-10), (F) estimated catch (black) between the pre-determined bounds (grey).

Projected short-term trends in SSB with respect to the LRP under different TACs and two recruitment scenarios were provided in a decision table (Table 1; Figures S6-S7). Considering both recruitment scenarios, projections showed that the probability of reaching the LRP by 2023 is 33% or 41% at the current TAC of 8000 t. Under the same TAC scenario, the probability of SSB in 2023 being greater than SSB in 2021 is 46% or 66%. Finally, with respect to the LRP, SSB in 2023 is projected to be at 0.46 or 0.60 of that value for a TAC of 8000 t. Depending on the TAC (0-10 000 t) and recruitment projection, the probability of the SSB exiting the Critical Zone by 2023 is either 29% or 37% for a TAC of 10 000 t and 51% or 58% for a TAC of 0 t. These projections also indicate that the probability SSB in 2023 being greater than SSB in 2021 was either 39% or 59% for a TAC of 10 000 t and 85% or 92% for a TAC of 0 t.

Table 1. Three-year projections under different Total Allowable Catch (TAC) and recruitment scenarios. Recruitment was projected assuming a Beverton-Holt stock-recruit relationship (BH: 1968-2020) or the average recruitment with a temporal auto-correlation of 0.9 over the last 10 years (mean; 2011-2020). For each TAC scenario, the probabilities of spawning stock biomass being greater than the Limit Reference Point (SSB/LRP) in 2022 and 2023 are provided. The probabilities of SSB growth from 2021 to 2023 are also provided (SSB_{2023} > SSB_{2021}). The ratios between SSB with respect to the LRP (SSB/LRP) for each scenario are likewise given for 2022 and 2023. Projections were performed under the assumption that mackerel will also be caught outside of the TAC, by both the Canadian and U.S.A. fleets (shaded columns; uncertainties represented by the 5th and 95th quantiles taken over the three years; details in Figure S7).

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

MATURITY-AT-AGE AND L_{50}

Most mackerel reach sexual maturity around age 3 while maturity at ages 1 and 2 is more variable. L_{50} has varied between 237-316 mm for the 1974-2018 cohorts with a time series mean of 281 mm (mean standard error = 3.95 mm) Figure 5). The L50s for the 2014 to 2018 cohorts were 274 mm, 275 mm, 270 mm, 271 mm, and 283 mm respectively (mean = 275 mm).

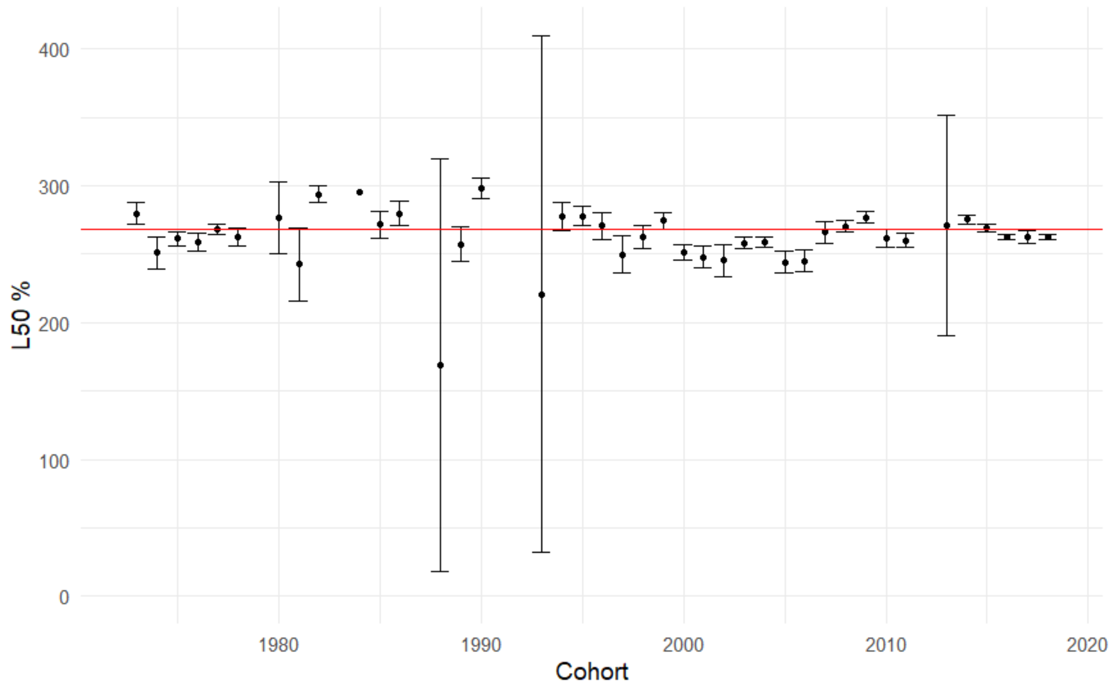

*Figure 5. Length at 50% maturity (L_{50} mm) by cohort (1974-2018) and their 95% C.I.s (1.96*S.E.). The horizontal red line indicates the current minimum commercial length of 268 mm. Numbers of individuals used to calculate the L50 of each cohort are displayed at the top of the figure.*

CONCLUSIONS AND ADVICE

Many of the key uncertainties within the data highlighted in previous assessments, as well as our knowledge of stock dynamics, have in large part been accounted for through the use of the current stock assessment model. Although some uncertainties remain, stock status trends across different indices are consistent and large enough to lend confidence as to stock status. The trends and derived conclusions are also consistent when the different stock assessment models and sensitivity analyses were performed. However, the proportion of northern population mackerel caught in the U.S. mackerel fishery is not known but is yet likely to be high (Redding et al. 2020, Arai et al. 2021). An increased appreciation for the proportion of the northern population being landed by the U.S. fishery as well as the proportion of the southern population being caught in Canadian waters should reduce uncertainty in and also improve model estimates and projection. Improved monitoring of commercial landings, discards, and implementing a recreational fishing monitoring program will improve future assessments certainty.

The northern contingent of Northwest Atlantic mackerel is currently in the Critical Zone as defined by DFO's PA framework (DFO 2009) and has been since 2011. Fishing mortality is above the reference level, stock productivity is low as is evidenced from the stock recruitment relationship and the age structure of the population is severely truncated which can also contribute to low productivity. Stock projections provided in Table 1 will allow decision makers to weigh the trade-offs between stock size and different TACs over a period of three years. The quality of advice and efficiency of management measures could be improved by ensuring that all mackerel fisheries are accurately accounting for all removals (i.e. actively monitoring the bait and recreational fisheries and keeping detailed catch statistics (Van Beveren et al. 2017, 2020a,b*)*.

These stock projections must also be considered within the context of the species' biology and the ecosystem in which it lives. Stock productivity is currently low due to changes in the environment and the collapsed age structure of the population (Brosset et al. 2020). It should be kept in mind that the collapse in age structure is due solely to overfishing. As there is a stock-recruit relationship, the currently high fishing mortality and low recruitment may impede the stock's ability to renew itself and grow under current TACs. Variation in mackerel recruitment, how well individuals grow during the summer season, and their distributions, are likely to continue to vary with respect to the relative availability of food in a given region and other environmental features such as water temperature.

A wide range of Harvest Control Rules (HCR) had previously been tested in a MSE framework against proposed management objectives (including rebuilding the SSB and avoiding declines in SSB) under eight uncertainty scenarios (including different assumptions on past and future recruitment, natural mortality, and the proportion of northern contingent fish caught by the U.S. fleet) (Van Beveren et al. 2020). The results of these analyses showed that the HCR that most reflected the 2019 and 2020 TACs of 8000 t (HCR 10) had a low probability for SSB to increase above the LRP in 3, 5, and 10 years under all uncertainty scenarios. Similarly, analyses showed that this HCR would probably lead to stock decline in 3, 5, and 10 years for all uncertainty scenarios. These results corroborated the conclusions of the 2018 stock assessment and are in line with the results of the current assessment (i.e. the stock has not increased past the LRP since the last assessment and SSB was at a record low in 2020).

ACKNOWLEDGMENTS

The stock assessment of mackerel requires the collaboration and coordination of people and resources from across Ontario, Québec, New Brunswick, Prince Edward Island, Nova Scotia, Newfoundland & Labrador, and the United States of America. Public servants, private citizens, and other stakeholders have all contributed to the process and it would be impossible to name them all. We would also like to acknowledge the contributions made by the Canadian Coast Guard and the crew of the CCGS Teleost, Reformar and the crew of the Coriolis II, everyone who participated in and contributed to the peer review of this stock assessment, colleagues from the Maritimes, Gulf, and Newfoundland regions who provided data and code, the technical support staff at the Maurice Lamontagne Institute (DAISS), the network of DFO port samplers, the regional statistics bureaus of DFO, members of the Atlantic Mackerel Rebuilding Plan Working Group and the Atlantic Mackerel Advisory Committee, national and regional fisheries managers, our colleagues at the NEFSC and NAFO, and finally to all the stakeholders who provided their knowledge, historical context, and samples.

Thanks also to Karen Cogliati and Jean-Martin Chamberland for reviewing the document.

REFERENCES CITED

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

Anonymous. 1986. CAFSAC Assessment software catalog. CAFSAC Res. Doc. 86/96.

Arai, K., Castonguay, M. and Secor, D.H. 2021. Multi-decadal trends in contingent mixing of Atlantic mackerel (*Scomber scombrus*) in the Northwest Atlantic from otolith stable isotopes. Sci Rep 11, 6667.

Auger-Méthé, M., Field, C., Albertsen, C.M., Derocher, A.E., Lewis, M.A., Jonsen, I.D., and Flemming, J.M. 2016. State-space models' dirty little secrets: even simple linear Gaussian models can have estimation problems. Sci. Rep. 6, 26677 (2016).

Berg, C.W., and Nielsen, A. 2016. Accounting for correlated observations in an age-based state-space stock assessment model. ICES J. Mar. Sci. 73, 1788–1797.

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

Brosset, P., Smith, A.D., Plourde, S., Castonguay, M., Lehoux, C., and Van Beveren, E. 2020. A fine-scale multi-step approach to understand fish recruitment variability. Sci. Rep. 10, 16064 (2020).

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

Collette, B.B. and Nauen, C.E. 1983. FAO Species Catalogue. Vol. 2. Scombrids of the world. An annotated and illustrated catalogue of tunas, mackerels, bonitos and related species known to date. Rome: FAO. FAO Fish. Synop. 125(2):137 p.

DFO. 2009. A Fishery Decision-Making Framework Incorporating the Precautionary Approach.

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

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

Galbraith, P. S., and Grégoire, F. 2014. Habitat thermique du maquereau bleu; profondeur de l'isotherme de 8 °C dans le sud du golfe du Saint-Laurent entre 1960 et 2014. Secr. can. de consult. sci. du MPO. Doc. de rech. 2014/116. v + 13 p.

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

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

Gíslason, D., Helyar, S.J., Óskarsson, G.J., Ólafsdóttir, G., Slotte, A., Jansen, T., Jacobsen, J.A., Ólafsson, K., Skirnisdottir, S., Dahle, G., Siegstad, H., Joensen, H., Curti, K.L., Grégoire, F., Masse, J., Sveinsson, S., Daníelsdóttir, A.K., and Pampoulie, C. 2020. The genetic composition of feeding aggregations of the Atlantic mackerel (*Scomber scombrus*) in the central north Atlantic: a microsatellite loci approach, ICES J. Mar. Sci. 77, 604–612

Goode, G. B., Collins, J. W., Earl, R. E., and Clark, A. H. 1883. Materials for a history of the mackerel fishery. 441 pp.

Goodyear, C. P. 1977. Assessing the impact of power plant mortality on the compensatory reserve of fish populations. In Proceedings of a conference on assessing the effects of powerplant induced mortality on fish populations., pp. 186–195. Ed. by Van Winkle. Pergamon Press, New York, USA.

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

Grégoire, F. and Showell, M. 1994. Description of the mackerel catches (*Scomber scombrus L.*) of the foreign fishery in NAFO Divisions 4Vn, 4W and 4X between 1990 and 1992. Can. Data Rep. Fish. Aquat. Sci. 947.

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

Grégoire, F., Beaulieu, J.-L., Gendron, M.-H., and LeBlanc, D. 2012a ou b. Results of the Atlantic mackerel (*Scomber scombrus* L.) egg survey conducted on the Scotian Shelf and Newfoundland's South Coast in 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/127

Grégoire, F., Beaulieu, J.-L., Gendron, M.-H., and LeBlanc, D. 2012a ou b. Calculation of the Atlantic mackerel (*Scomber scombrus* L.) spawning biomass from the ichthyoplankton surveys conducted on the west coast of Newfoundland between 2004 and 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/137

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

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

Hoy, D. L., and Clark, G. M. 1967. Atlantic mackerel fishery, 1804-1965. Fishery Leaflet, 603. United States Department of Interior, Washington.

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

Kulka, D. 1977. An hypothesis concerning the migration and distribution of Atlantic mackerel (*Scomber scombrus*). CAFSAC Res. Doc. 77/7

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

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

Nielsen, A., and Berg, C.W. 2014. Estimation of time-varying selectivity in stock assessments using state-space models. Fish. Res. 158, 96–101.

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

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

Ogle, D.H., Doll, J.C., Wheeler, P., Dinno, A. 2021. FSA: Fisheries Stock Analysis. R package version 0.9.3

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

R Core Team. 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.

Redding, S. G., Cooper, L. W., Castonguay, M., Wiernicki, C. and Secor, D. H. 2020. Northwest Atlantic mackerel population structure evaluated using otolith δ18O composition. ICES J. Mar. Sci. 77, 2582–2589

Sette, O.E. 1950. Biology of Atlantic mackerel (*Scomber scombrus*) of North America. Part II. Migrations and habits. U.S. Fish Wildl. Serv. Fish. Bull. 51: 251-358

Shepherd, J. G. 1982. A versatile new stock–recruitment relationship of fisheries and construction of sustainable yield curves. Cons. Perm. Int. Explor. Mer, 40: 67–75.

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

Studholme, A.L., Packer, D.B., Berrien, P.L., Johnson, D.L., Zetlin, C.A., and Morse, W.M. 1999. Essential Fish Habitat Source Document: Atlantic Mackerel, *Scomber scombrus*, Life History and Habitat Characteristics. NOAA Technical Memorandum NMFS-NE-141.

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

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

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

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

Van Beveren, E., Duplisea, D.E., Marentette, J.R., Smith, A.D., and Castonguay, M. 2020b. An example of how catch uncertainty hinders effective stock management and rebuilding. Fish. Res. 224.

SUPPLEMENTARY INFORMATION

TABLES

Table S1. Nominal landings of mackerel in NAFO divisions 2-6 grouped by fishery and Exclusive Economic Zone.

Year*	Canada EEZ**			U.S.A. EEZ***				
	Commercial	Foreign landings	Total Canada EEZ	Commercial	Recreational	Discards	Foreign Landings	Total USA EEZ
1968	11118	9720	20838	3929	-	-	56043	59972
1969	13257	5379	18636	4364	-	-	108811	113175
1970	15710	5296	21006	4049	-	-	205568	209617
1971	14942	9554	24496	2406	-	-	346338	348744
1972	16253	6107	22360	2006	-	-	385358	387364
1973	21566	16984	38550	1336	-	-	379828	381164
1974	16701	27954	44655	1042	-	-	293883	294925
1975	13540	22718	36258	1974	-	-	249005	250979
1976	15746	17319	33065	2712	-	-	205956	208668
1977	19852	2913	22765	1377	-	-	53664	55041
1978	25429	470	25899	1605	-	-	371	1976
1979	30244	368	30612	1990	-	-	72	2062
1980	22135	161	22296	2683	-	-	406	3089
1981	19294	61	19355	2941	2628	-	5300	10869
1982	16380	3	16383	3330	1877	-	6471	11678
1983	19797	9	19806	3805	2793	-	5882	12480
1984	17320	913	18233	5954	2726	-	14957	23637
1985	29855	1051	30906	6632	4088	-	17639	28359
1986	30325	772	31097	9637	7662	-	25735	43034
1987	27488	71	27559	12310	7555	-	34951	54816
1988	24060	956	25016	12309	5421	-	51463	69193
1989	20795	347	21142	14556	2829	160	37209	54755
1990	19190	3796	22986	31261	3254	827	9232	44575
1991	24914	1281	26195	26961	3540	1098	5989	37588
1992	24307	2255	26562	11761	921	2072	-	14754
1993	26158	690	26848	4662	1231	3902	-	9796
1994	20564	49	20613	8917	2654	5409	-	16980
1995	17740	62	17802	8468	1697	54	-	10219
1996	20406	76	20482	15728	2466	2053	-	20246
1997	21309	116	21425	15403	2857	229	-	18489
1998	19176	10	19186	14525	1553	98	-	16176
1999	16561	12	16573	12031	2832	771	-	15634

Year*	Canada EEZ**			U.S.A. EEZ***				
	Commercial	Foreign landings	Total Canada EEZ	Commercial	Recreational	Discards	Foreign Landings	Total USA EEZ
2000	16080	26	16106	5649	3055	153	-	8857
2001	24429	11	24440	12340	3301	718	-	16359
2002	34662	7	34669	26530	2679	155	-	29364
2003	44736	12	44748	34298	1874	264	-	36436
2004	53951	15	53966	54990	1169	2141	-	58300
2005	54809	-	54809	42209	1694	1083	-	44986
2006	53741	3	53744	56640	3911	135	-	60687
2007	53394	-	53394	25546	763	159	-	26468
2008	29671	4	29675	21734	2731	747	-	25212
2009	42231	42	42273	22634	1769	126	-	24529
2010	38700	1	38701	9877	4288	97	-	14261
2011	11508	-	11508	533	4040	38	-	4610
2012	6847	2	6849	5333	2671	33	-	8037
2013	8674	1	8675	4372	2406	20	-	6799
2014	6680	-	6680	5905	2296	51	-	8252
2015	4280	1	4281	5616	4275	13	245	10150
2016	8055	2	8057	5687	4572	18	1	10278
2017	9783	3	9786	6975	4173	83	132	11362
2018	10926	1	10927	-	-	-	-	10784
2019*	8704	-	8704	-	-	-	52	6857
2020*	7838	-	7838	8025	-	-	-	8025

* Preliminary data
** For convenience, exclusive economic zones of the U.S.A. and Canada were applied even for years where the boundaries did not exist. In addition, the exclusive economic zone of France (St. Pierre & Miquelon) was included within the Canadian EEZ for convenience since 1995.
*** Total landings in the U.S. EEZ for 2018, and 2019 were acquired from NOAA's website and estimates of discards and recreational catches were not available for 2020. So called foreign landings from 2015-2020 are from Canadian vessels fishing in NAFO subarea 5 and presumably did not inscribe the NAFO subdivision correctly in their logbook.

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

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

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

Table S3. Aggregated annual commercial landings by grouped NAFO divisions (2000-2020) corresponding to the Newfoundland and Labrador Shelf (2J3KL), Cabot Strait (3P4V), Estuary and Gulf of Saint Lawrence (4RST), and the Scotian Shelf, Gulf of Maine, Bay of Fundy, and Georges Bank (4WX5YZ) and the corresponding number of length frequency (N_lf) and biological samples collected (N_bio) as well as the total number of fish therein (n_lf and n_bio respectively). Landings greater than 1000 t are highlighted in bold. The data presented here do not include landings by foreign vessels, ship-to-ship sales, or Canadian allocations to foreign vessels.

Year	Area	Landings (t)	N_lf	n_lf	N_bio	n_bio
2000	2J3KL	**2384.96**	16	1673	4	89
2000	4RST	**9317.10**	74	9363	38	1323
2000	4V3P	595.27	15	1983	9	355
2000	4WX5YZ	**3783.15**	5	559	1	31
2001	2J3KL	332.22	-	-	-	-
2001	4RST	**20707.32**	86	14056	55	2009
2001	4V3P	398.00	20	2991	6	199
2001	4WX5YZ	**2991.79**	16	2353	5	222
2002	2J3KL	**6568.66**	14	729	0	0
2002	4RST	**25737.35**	76	14193	51	1674
2002	4V3P	469.81	11	1640	7	260
2002	4WX5YZ	**1886.04**	-	-	-	-
2003	2J3KL	588.12	-	-	-	-
2003	4RST	**40261.68**	90	15536	62	1975
2003	4V3P	208.68	20	3201	15	549
2003	4WX5YZ	**3677.56**	3	250	1	33
2004	2J3KL	**16050.71**	26	2349	6	250
2004	4RST	**33580.46**	73	11206	44	1594
2004	4V3P	92.12	14	1720	6	215
2004	4WX5YZ	**4228.14**	38	5266	15	570
2005	2J3KL	**28305.71**	29	750	28	1178
2005	4RST	**23574.98**	98	10461	60	2079
2005	4V3P	363.39	14	1436	9	405
2005	4WX5YZ	**2565.14**	24	2738	11	323
2006	2J3KL	**27136.66**	60	2088	51	2004
2006	4RST	**24734.93**	121	11996	66	2252
2006	4V3P	490.11	17	1913	11	414
2006	4WX5YZ	**1378.99**	-	-	-	-
2007	2J3KL	**19468.17**	46	567	53	1585
2007	4RST	**31214.66**	108	11840	62	1866
2007	4V3P	723.88	18	1473	11	426
2007	4WX5YZ	**1987.17**	3	452	0	0
2008	2J3KL	**9129.04**	10	27	11	315
2008	4RST	**19202.95**	92	9071	52	1861
2008	4V3P	276.18	8	22	10	374
2008	4WX5YZ	**1062.88**	6	1097	0	0
2009	2J3KL	**6937.62**	15	66	18	652
2009	4RST	**28791.51**	99	10341	61	2064
2009	4V3P	**5441.60**	18	1982	12	430
2009	4WX5YZ	**1060.76**	6	779	2	70
2010	2J3KL	**13746.62**	63	1665	63	2435
2010	4RST	**18857.66**	109	11597	65	1771
2010	4V3P	**5548.43**	7	574	5	200
2010	4WX5YZ	546.94	1	255	1	39
2011	2J3KL	487.09	13	65	14	592
2011	4RST	**9068.04**	76	8153	47	1494
2011	4V3P	**1545.50**	5	20	6	308

Year	Area	Landings (t)	N_lf	n_lf	N_bio	n_bio
2011	4WX5YZ	407.11	4	417	2	89
2012	2J3KL	209.45	6	10	14	580
2012	4RST	**5797.68**	84	7517	43	1249
2012	4V3P	298.84	1	1	2	128
2012	4WX5YZ	541.32	1	1	1	134
2013	2J3KL	234.71	-	-	-	-
2013	4RST	**8010.24**	59	5988	36	1083
2013	4V3P	171.35	-	-	-	-
2013	4WX5YZ	257.66	1	3	1	129
2014	2J3KL	31.46	-	-	-	-
2014	4RST	**5699.11**	62	7528	46	1385
2014	4V3P	389.53	-	-	-	-
2014	4WX5YZ	559.71	1	1	1	406
2015	2J3KL	262.11	4	507	5	224
2015	4RST	**2846.59**	54	6654	39	1246
2015	4V3P	58.02	-	-	-	-
2015	4WX5YZ	**1113.57**	-	-	-	-
2016	2J3KL	**2796.56**	6	889	5	182
2016	4RST	**4043.67**	77	9496	52	1863
2016	4V3P	123.84	-	-	-	-
2016	4WX5YZ	**1091.34**	5	319	2	742
2017	2J3KL	**1144.08**	-	-	-	-
2017	4RST	**6538.35**	97	11171	64	2240
2017	4V3P	212.91	-	-	-	-
2017	4WX5YZ	**1888.01**	1	4	9	236
2018	2J3KL	**5369.21**	8	622	6	251
2018	4RST	**4026.66**	65	8536	36	1265
2018	4V3P	137.31	3	245	3	243
2018	4WX5YZ	**1393.22**	14	561	20	1074
2019*	2J3KL	**4689.95**	12	1671	9	300
2019*	4RST	**3031.67**	49	6707	64	1610
2019*	4V3P	83.48	4	199	24	122
2019*	4WX5YZ	821.06	12	24	99	1830
2020*	2J3KL	**3967.61**	14	1034	14	683
2020*	4RST	**2741.92**	54	5633	65	1084
2020*	4V3P	80.46	-	-	-	-
2020*	4WX5YZ	**1048.03**	-	-	-	-

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

Table S4. Stratification used to aggregate and apply age-length-keys to the corresponding strata of length frequencies. For each strata, the associated landings in tonnes, the number of fish in the aggregated length frequency samples (n_lf), and the number of fish used in the construction of age-length-keys (n_bio) are shown. Higher order aggregations prior to calculating annual estimates are defined by the index variable.

Year	Quarter	Divisions	Gear types	Index	Landings	n_lf	n_bio
2015	Q1	4RST	seines_nets_traps_weirs_misc	a	137	-	-
2015	Q1	4WX5YZ	seines_nets_traps_weirs_misc	a	0	-	87
2015	Q2	4RST	gillnets	a	326	3390	533
2015	Q2	4RST	lines	a	53	150	29
2015	Q2	4RST	seines_nets_traps_weirs_misc	a	2	-	-
2015	Q2	4V3P	gillnets	a	0	-	-
2015	Q2	4V3P	seines_nets_traps_weirs_misc	a	43	-	-
2015	Q2	4WX5YZ	gillnets	a	22	-	-
2015	Q2	4WX5YZ	seines_nets_traps_weirs_misc	a	149	-	-
2015	Q3	2J3KL	seines_nets_traps_weirs_misc	d	0	1	60
2015	Q3	4RST	gillnets	b	208	-	-
2015	Q3	4RST	lines	b	1295	2441	566
2015	Q3	4RST	seines_nets_traps_weirs_misc	c	261	151	34
2015	Q3	4V3P	lines	c	11	-	-
2015	Q3	4V3P	seines_nets_traps_weirs_misc	b	0	-	-
2015	Q3	4WX5YZ	gillnets	b	41	-	-
2015	Q3	4WX5YZ	lines	c	200	-	-
2015	Q3	4WX5YZ	seines_nets_traps_weirs_misc	b	228	-	6
2015	Q4	2J3KL	seines_nets_traps_weirs_misc	d	262	506	164
2015	Q4	4RST	gillnets	f	9	-	-
2015	Q4	4RST	lines	e	110	344	60
2015	Q4	4RST	seines_nets_traps_weirs_misc	f	446	178	24
2015	Q4	4V3P	gillnets	f	3	-	-
2015	Q4	4V3P	lines	e	0	-	-
2015	Q4	4WX5YZ	gillnets	f	35	-	-
2015	Q4	4WX5YZ	lines	e	117	-	-
2015	Q4	4WX5YZ	seines_nets_traps_weirs_misc	f	321	-	-
2016	Q1	4RST	seines_nets_traps_weirs_misc	g	153	-	-
2016	Q1	4WX5YZ	seines_nets_traps_weirs_misc	g	2	5	724
2016	Q2	4RST	gillnets	g	782	3768	549
2016	Q2	4RST	lines	g	5	350	35
2016	Q2	4RST	seines_nets_traps_weirs_misc	g	14	-	-
2016	Q2	4V3P	gillnets	g	0	-	-
2016	Q2	4V3P	seines_nets_traps_weirs_misc	g	92	-	-
2016	Q2	4WX5YZ	gillnets	g	12	-	-
2016	Q2	4WX5YZ	lines	g	0	-	-
2016	Q2	4WX5YZ	seines_nets_traps_weirs_misc	g	298	167	-
2016	Q3	2J3KL	gillnets	i	2	-	-
2016	Q3	2J3KL	seines_nets_traps_weirs_misc	i	410	-	7
2016	Q3	4RST	gillnets	i	60	-	-
2016	Q3	4RST	lines	h	888	3277	747
2016	Q3	4RST	seines_nets_traps_weirs_misc	i	499	961	231
2016	Q3	4V3P	gillnets	i	3	-	-
2016	Q3	4V3P	lines	h	9	-	-
2016	Q3	4V3P	seines_nets_traps_weirs_misc	i	17	-	-
2016	Q3	4WX5YZ	gillnets	i	48	-	-
2016	Q3	4WX5YZ	lines	h	384	147	-
2016	Q3	4WX5YZ	seines_nets_traps_weirs_misc	i	120	-	18
2016	Q4	2J3KL	gillnets	j	1	-	-
2016	Q4	2J3KL	seines_nets_traps_weirs_misc	j	2384	889	182
2016	Q4	4RST	gillnets	j	0	-	-
2016	Q4	4RST	lines	k	117	522	140
2016	Q4	4RST	seines_nets_traps_weirs_misc	l	1527	618	161
2016	Q4	4V3P	gillnets	l	0	-	-
2016	Q4	4V3P	lines	j	1	-	-

Year	Quarter	Divisions	Gear types	Index	Landings	n_lf	n_bio
2016	Q4	4V3P	seines_nets_traps_weirs_misc	j	1	-	-
2016	Q4	4WX5YZ	gillnets	j	21	-	-
2016	Q4	4WX5YZ	lines	k	151	-	-
2016	Q4	4WX5YZ	seines_nets_traps_weirs_misc	j	56	-	-
2017	Q1	4RST	gillnets	m	0	-	-
2017	Q1	4RST	seines_nets_traps_weirs_misc	m	136	-	-
2017	Q1	4V3P	gillnets	m	0	-	-
2017	Q1	4WX5YZ	seines_nets_traps_weirs_misc	m	2	-	163
2017	Q2	4RST	gillnets	m	931	2864	485
2017	Q2	4RST	lines	m	3	-	-
2017	Q2	4RST	seines_nets_traps_weirs_misc	m	2	-	-
2017	Q2	4V3P	gillnets	m	0	-	-
2017	Q2	4V3P	seines_nets_traps_weirs_misc	m	54	-	-
2017	Q2	4WX5YZ	gillnets	m	38	-	-
2017	Q2	4WX5YZ	lines	m	6	-	-
2017	Q2	4WX5YZ	seines_nets_traps_weirs_misc	m	155	-	-
2017	Q3	2J3KL	gillnets	n	0	-	-
2017	Q3	2J3KL	seines_nets_traps_weirs_misc	n	263	-	-
2017	Q3	4RST	gillnets	n	2832	480	79
2017	Q3	4RST	lines	o	655	5570	1091
2017	Q3	4RST	seines_nets_traps_weirs_misc	n	437	468	172
2017	Q3	4V3P	gillnets	n	22	-	-
2017	Q3	4V3P	lines	o	29	-	-
2017	Q3	4V3P	seines_nets_traps_weirs_misc	n	93	-	-
2017	Q3	4WX5YZ	gillnets	n	63	-	-
2017	Q3	4WX5YZ	lines	o	688	-	-
2017	Q3	4WX5YZ	seines_nets_traps_weirs_misc	n	678	4	236
2017	Q4	2J3KL	gillnets	q	0	-	-
2017	Q4	2J3KL	seines_nets_traps_weirs_misc	q	880	-	30
2017	Q4	4RST	gillnets	q	69	-	-
2017	Q4	4RST	lines	p	26	675	153
2017	Q4	4RST	seines_nets_traps_weirs_misc	q	1448	1114	260
2017	Q4	4V3P	gillnets	q	1	-	-
2017	Q4	4V3P	seines_nets_traps_weirs_misc	q	13	-	-
2017	Q4	4WX5YZ	gillnets	q	2	-	-
2017	Q4	4WX5YZ	lines	p	94	-	-
2017	Q4	4WX5YZ	seines_nets_traps_weirs_misc	q	163	-	31
2018	Q1	4RST	seines_nets_traps_weirs_misc	r	160	-	-
2018	Q1	4WX5YZ	seines_nets_traps_weirs_misc	r	2	-	-
2018	Q2	4RST	gillnets	r	561	2602	391
2018	Q2	4RST	lines	r	7	-	-
2018	Q2	4RST	seines_nets_traps_weirs_misc	r	6	-	-
2018	Q2	4V3P	gillnets	s	4	-	-
2018	Q2	4V3P	seines_nets_traps_weirs_misc	s	107	242	43
2018	Q2	4WX5YZ	gillnets	s	62	-	-
2018	Q2	4WX5YZ	lines	s	1	-	-
2018	Q2	4WX5YZ	seines_nets_traps_weirs_misc	s	442	152	248
2018	Q3	2J3KL	gillnets	t	0	-	-
2018	Q3	2J3KL	lines	t	0	-	-
2018	Q3	2J3KL	seines_nets_traps_weirs_misc	t	2870	309	53
2018	Q3	4RST	gillnets	v	1834	-	-
2018	Q3	4RST	lines	u	384	4131	493
2018	Q3	4RST	seines_nets_traps_weirs_misc	v	861	1351	270
2018	Q3	4V3P	gillnets	v	2	-	-
2018	Q3	4V3P	lines	u	2	3	200
2018	Q3	4V3P	seines_nets_traps_weirs_misc	u	9	-	-
2018	Q3	4WX5YZ	gillnets	u	69	-	-
2018	Q3	4WX5YZ	lines	u	446	7	221
2018	Q3	4WX5YZ	seines_nets_traps_weirs_misc	u	281	402	605
2018	Q4	2J3KL	seines_nets_traps_weirs_misc	w	2499	313	198
2018	Q4	4RST	gillnets	w	89	-	-

Year	Quarter	Divisions	Gear types	Index	Landings	n_lf	n_bio
2018	Q4	4RST	lines	x	24	452	111
2018	Q4	4RST	seines_nets_traps_weirs_misc	w	100	-	-
2018	Q4	4V3P	seines_nets_traps_weirs_misc	w	13	-	-
2018	Q4	4WX5YZ	gillnets	w	3	-	-
2018	Q4	4WX5YZ	lines	x	50	-	-
2018	Q4	4WX5YZ	seines_nets_traps_weirs_misc	w	38	-	-
2019	Q1	4WX5YZ	seines_nets_traps_weirs_misc	y	3	2	451
2019	Q2	4RST	gillnets	z	1190	2005	375
2019	Q2	4RST	lines	z	11	-	-
2019	Q2	4RST	seines_nets_traps_weirs_misc	z	3	-	39
2019	Q2	4V3P	gillnets	z	2	195	40
2019	Q2	4V3P	seines_nets_traps_weirs_misc	z	64	-	40
2019	Q2	4WX5YZ	gillnets	y	102	-	-
2019	Q2	4WX5YZ	lines	y	0	-	-
2019	Q2	4WX5YZ	seines_nets_traps_weirs_misc	y	221	1	149
2019	Q3	2J3KL	seines_nets_traps_weirs_misc	aa	4690	1671	300
2019	Q3	4RST	gillnets	bb	3323	146	34
2019	Q3	4RST	lines	cc	235	4084	748
2019	Q3	4WX5YZ	lines	dd	126	2	292
2019	Q3	4WX5YZ	seines_nets_traps_weirs_misc	dd	315	19	938
2019	Q4	4RST	gillnets	bb	8	-	-
2019	Q4	4RST	lines	cc	0	-	-
2019	Q4	4RST	seines_nets_traps_weirs_misc	bb	12	-	52
2019	Q4	4V3P	seines_nets_traps_weirs_misc	dd	1	-	-
2019	Q4	4WX5YZ	gillnets	dd	0	-	-
2019	Q4	4WX5YZ	lines	dd	0	-	-
2019	Q4	4WX5YZ	seines_nets_traps_weirs_misc	dd	40	-	57
2020	Q1	4WX5YZ	seines_nets_traps_weirs_misc	ee	3	-	-
2020	Q2	4RST	gillnets	ee	592	1063	217
2020	Q2	4RST	lines	ee	10	172	36
2020	Q2	4RST	seines_nets_traps_weirs_misc	ee	15	-	-
2020	Q2	4V3P	gillnets	ee	4	-	-
2020	Q2	4V3P	seines_nets_traps_weirs_misc	ee	68	-	-
2020	Q2	4WX5YZ	gillnets	ee	106	-	-
2020	Q2	4WX5YZ	lines	ee	12	-	-
2020	Q2	4WX5YZ	seines_nets_traps_weirs_misc	ee	674	-	-
2020	Q3	2J3KL	gillnets	ff	0	104	149
2020	Q3	2J3KL	seines_nets_traps_weirs_misc	ff	704	10	147
2020	Q3	4RST	gillnets	gg	1335	-	-
2020	Q3	4RST	lines	gg	194	3961	518
2020	Q3	4RST	seines_nets_traps_weirs_misc	gg	444	309	279
2020	Q3	4V3P	lines	gg	2	-	-
2020	Q3	4V3P	seines_nets_traps_weirs_misc	gg	6	-	-
2020	Q3	4WX5YZ	gillnets	gg	3	-	-
2020	Q3	4WX5YZ	lines	gg	35	-	-
2020	Q3	4WX5YZ	seines_nets_traps_weirs_misc	gg	188	-	-
2020	Q4	2J3KL	gillnets	hh	0	2	249
2020	Q4	2J3KL	seines_nets_traps_weirs_misc	hh	3263	918	138
2020	Q4	4RST	gillnets	hh	146	-	-
2020	Q4	4RST	lines	hh	3	128	34
2020	Q4	4RST	seines_nets_traps_weirs_misc	hh	4	-	-
2020	Q4	4V3P	seines_nets_traps_weirs_misc	hh	1	-	-
2020	Q4	4WX5YZ	lines	hh	12	-	-
2020	Q4	4WX5YZ	seines_nets_traps_weirs_misc	hh	16	-	-

Table S5. Annual catch-at-age (‘000s of fish).

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	1686	21171	27110	10982	7740	3868	4922	3977	3123	1165
1977	740	7136	22566	11319	3683	2570	809	1443	897	1721
1978	2	182	3831	14733	11575	6358	3157	1649	1402	2497
1979	204	480	1189	6615	17202	12321	5590	2282	1702	2457
1980	6	1455	2156	1463	5087	9833	6148	2692	1604	1998
1981	6145	2836	5143	1183	1656	4669	7743	3309	1595	1892
1982	2145	5899	1609	5004	715	1609	2623	4828	1549	2504
1983	244	1622	2459	915	4012	478	946	3119	7770	3601
1984	60	19774	14060	1413	781	1551	339	479	2022	5640
1985	357	511	23790	12844	1252	656	2197	289	551	7605
1986	363	4282	3259	40844	11522	933	485	635	117	1915
1987	1291	3118	3358	2288	27133	5692	232	183	83	716
1988	117	703	1028	1932	2481	24769	4493	227	131	572
1989	2399	8862	1276	937	1541	575	20957	2693	369	781
1990	390	6222	9737	1457	888	966	639	16765	923	277
1991	646	6106	17808	9560	1212	762	1052	849	10964	557
1992	628	2627	3014	14148	8630	1411	733	1048	884	11142
1993	117	4900	8493	4497	13011	7686	1660	651	699	6882
1994	672	231	3896	5905	2856	13672	5977	929	244	2925
1995	10603	14206	698	4674	4093	1768	5757	2281	203	590
1996	2505	8050	7052	1013	5380	6519	1622	7094	1806	893
1997	5083	11823	10923	4604	638	3709	3081	545	4212	785
1998	1927	18525	9977	9560	4291	505	2432	2024	412	1472
1999	1348	4463	14625	7509	4698	2049	478	681	663	354
2000	28460	2689	1800	5465	2869	2941	458	65	195	371
2001	8215	60111	11234	2482	4184	842	870	144	33	371
2002	6088	3832	70334	6047	2275	2136	538	407	48	73
2003	3763	4381	5832	73840	8480	1123	1199	32	5	0
2004	27524	24574	6017	4753	56010	2457	1322	606	9	0
2005	17391	42971	24381	4007	3807	40391	1680	746	81	45
2006	31651	14756	41630	21769	3765	1917	17117	448	36	0
2007	2968	31233	22784	43885	11105	2471	1328	4819	39	7
2008	23622	8120	25964	8655	12703	1631	633	218	1033	9
2009	38026	24443	6613	28416	6363	9425	358	127	5	482
2010	5402	31923	28384	3829	13988	2033	3286	83	1	132
2011	2288	1230	11611	6091	639	3100	336	474	25	40
2012	193	10775	1969	3142	332	34	113	7	1	0
2013	574	5685	13651	776	1593	101	0	0	0	0
2014	1134	3475	6902	4397	119	80	0	1	0	0
2015	3541	3908	1593	2704	617	68	33	0	0	0
2016	4778	8026	5380	2327	2586	589	30	0	0	0
2017	0	15050	10260	2548	1598	1118	221	0	0	0
2018	71	487	27928	3017	707	106	145	16	0	0
2019	479	5268	8865	10151	1465	160	40	8	59	0
2020	2203	6111	7341	1629	4024	307	21	8	3	0

Table S6. Annual mean mass-at-age (kg).

Year	1	2	3	4	5	6	7	8	9	10
1968	0.15	0.24	0.34	0.43	0.51	0.58	0.63	0.68	0.72	0.75
1969	0.13	0.21	0.30	0.38	0.46	0.52	0.57	0.62	0.65	0.68
1970	0.11	0.18	0.25	0.32	0.39	0.44	0.49	0.53	0.56	0.59
1971	0.11	0.18	0.26	0.33	0.39	0.45	0.49	0.53	0.56	0.59
1972	0.12	0.21	0.30	0.39	0.46	0.53	0.59	0.64	0.68	0.73
1973	0.11	0.19	0.27	0.35	0.41	0.47	0.52	0.57	0.60	0.63
1974	0.11	0.19	0.27	0.35	0.43	0.49	0.54	0.59	0.62	0.65
1975	0.10	0.18	0.25	0.33	0.39	0.45	0.50	0.54	0.57	0.60
1976	0.10	0.17	0.24	0.32	0.38	0.44	0.49	0.53	0.56	0.59
1977	0.11	0.20	0.29	0.38	0.45	0.52	0.58	0.63	0.67	0.70
1978	0.19	0.29	0.43	0.46	0.51	0.58	0.63	0.66	0.67	0.70
1979	0.19	0.27	0.53	0.57	0.58	0.60	0.65	0.71	0.75	0.77
1980	0.15	0.38	0.55	0.61	0.62	0.64	0.67	0.71	0.78	0.74
1981	0.11	0.32	0.52	0.58	0.64	0.66	0.67	0.71	0.72	0.76
1982	0.15	0.34	0.54	0.61	0.67	0.74	0.74	0.72	0.72	0.74
1983	0.10	0.26	0.48	0.59	0.63	0.66	0.71	0.71	0.71	0.73
1984	0.10	0.16	0.34	0.53	0.63	0.66	0.70	0.72	0.71	0.71
1985	0.20	0.39	0.40	0.51	0.60	0.74	0.77	0.78	0.84	0.87
1986	0.16	0.31	0.44	0.44	0.52	0.67	0.78	0.80	0.86	0.84
1987	0.21	0.31	0.41	0.48	0.51	0.60	0.70	0.79	0.89	0.89
1988	0.20	0.40	0.47	0.50	0.55	0.58	0.67	0.73	0.80	0.88
1989	0.17	0.33	0.45	0.55	0.62	0.62	0.66	0.75	0.81	0.88
1990	0.28	0.33	0.42	0.53	0.62	0.63	0.68	0.68	0.72	0.86
1991	0.25	0.34	0.44	0.48	0.56	0.63	0.64	0.72	0.71	0.82
1992	0.18	0.30	0.41	0.45	0.51	0.55	0.62	0.67	0.68	0.69
1993	0.18	0.28	0.36	0.45	0.49	0.55	0.61	0.66	0.70	0.72
1994	0.23	0.37	0.38	0.46	0.55	0.55	0.59	0.64	0.71	0.71
1995	0.20	0.30	0.44	0.49	0.53	0.61	0.62	0.66	0.74	0.80
1996	0.22	0.33	0.43	0.54	0.54	0.60	0.65	0.68	0.73	0.85
1997	0.24	0.38	0.45	0.52	0.59	0.60	0.64	0.76	0.70	0.75
1998	0.16	0.27	0.41	0.52	0.58	0.60	0.67	0.67	0.72	0.72
1999	0.19	0.30	0.44	0.51	0.57	0.65	0.70	0.72	0.73	0.77
2000	0.21	0.33	0.41	0.49	0.56	0.61	0.66	0.67	0.70	0.70
2001	0.14	0.28	0.40	0.48	0.56	0.63	0.67	0.69	0.76	0.78
2002	0.16	0.29	0.39	0.46	0.50	0.61	0.64	0.67	0.67	0.70
2003	0.21	0.31	0.39	0.49	0.55	0.67	0.73	0.83	0.84	0.68
2004	0.21	0.28	0.39	0.48	0.55	0.59	0.66	0.75	0.68	0.68
2005	0.11	0.31	0.39	0.47	0.52	0.62	0.65	0.70	0.71	0.67
2006	0.20	0.32	0.43	0.48	0.54	0.57	0.66	0.68	0.67	0.68
2007	0.21	0.31	0.43	0.50	0.58	0.63	0.67	0.71	0.77	0.69
2008	0.18	0.29	0.42	0.50	0.54	0.61	0.64	0.59	0.72	0.73
2009	0.21	0.32	0.42	0.50	0.58	0.61	0.68	0.61	0.71	0.78
2010	0.15	0.35	0.43	0.53	0.58	0.66	0.65	0.60	0.72	0.67
2011	0.19	0.29	0.43	0.49	0.57	0.57	0.70	0.65	0.65	0.71
2012	0.17	0.34	0.41	0.50	0.56	0.68	0.71	0.70	0.65	0.69
2013	0.17	0.29	0.43	0.47	0.59	0.59	0.72	0.66	0.65	0.69
2014	0.20	0.35	0.43	0.53	0.60	0.71	0.72	0.67	0.65	0.69
2015	0.19	0.36	0.43	0.52	0.57	0.59	0.65	0.49	0.65	0.69
2016	0.14	0.27	0.39	0.47	0.52	0.59	0.66	0.76	0.65	0.69
2017	0.23	0.26	0.35	0.45	0.52	0.54	0.57	0.67	0.65	0.69
2018	0.15	0.23	0.33	0.40	0.53	0.56	0.65	0.64	0.65	0.69
2019	0.16	0.26	0.32	0.34	0.46	0.52	0.57	0.57	0.56	0.69
2020	0.15	0.29	0.39	0.48	0.49	0.57	0.65	0.62	0.74	0.69

Table S7. Egg index (i.e. annual or total egg production (TEP) in trillions of eggs). Blank cells indicate when either no mission occurred or surveys were omitted from the analyses (see Methods for details).

Year	TEP
1979	481.00
1980	-
1981	-
1982	-
1983	173.00
1984	356.00
1985	644.00
1986	1230.00
1987	490.00
1988	410.00
1989	494.00
1990	424.00
1991	664.00
1992	512.00
1993	573.00
1994	218.00
1995	-
1996	70.80
1997	-
1998	55.80
1999	-
2000	101.00
2001	-
2002	233.00
2003	208.00
2004	130.00
2005	72.00
2006	-
2007	64.00
2008	77.00
2009	52.80
2010	20.20
2011	28.30
2012	8.67
2013	40.00
2014	34.80
2015	39.74
2016	47.16
2017	79.16
2018	38.77
2019	56.82
2020	-

Table S8. Annual proportion of mature fish by age in the commercial samples.

Year	1	2	3	4	5	6	7	8	9	10
1968	0.29	0.50	0.71	0.85	0.93	0.97	0.99	1.00	1.00	1.00
1969	0.29	0.50	0.71	0.85	0.93	0.97	0.99	1.00	1.00	1.00
1970	0.29	0.50	0.71	0.85	0.93	0.97	0.99	1.00	1.00	1.00
1971	0.29	0.50	0.71	0.85	0.93	0.97	0.99	1.00	1.00	1.00
1972	0.29	0.50	0.71	0.85	0.93	0.97	0.99	1.00	1.00	1.00
1973	0.29	0.50	0.71	0.85	0.93	0.97	0.99	1.00	1.00	1.00
1974	0.29	0.50	0.71	0.85	0.93	0.97	0.99	1.00	1.00	1.00
1975	0.16	0.86	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1976	0.20	0.79	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1977	0.05	0.84	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1978	0.43	0.91	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1979	0.37	0.59	0.79	0.90	0.96	0.98	0.99	1.00	1.00	1.00
1980	0.23	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1981	0.12	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1982	0.02	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1983	0.38	0.65	0.85	0.95	0.98	0.99	1.00	1.00	1.00	1.00
1984	0.01	0.50	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1985	0.40	0.88	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1986	0.42	0.85	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1987	0.44	0.82	0.96	0.99	1.00	1.00	1.00	1.00	1.00	1.00
1988	0.40	0.90	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1989	0.35	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1990	0.28	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1991	0.22	0.88	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1992	0.23	0.81	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1993	0.23	0.81	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1994	0.23	0.81	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1995	0.24	0.73	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1996	0.20	0.74	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1997	0.13	0.83	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1998	0.07	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1999	0.12	0.77	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2000	0.46	0.91	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2001	0.43	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2002	0.31	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2003	0.24	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2004	0.14	0.86	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2005	0.09	0.62	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2006	0.25	0.85	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2007	0.08	0.92	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2008	0.21	0.79	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2009	0.03	0.85	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2010	0.03	0.62	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2011	0.26	0.86	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2012	0.21	0.87	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2013	0.17	0.89	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2014	0.17	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2015	0.17	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2016	0.12	0.82	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2017	0.19	0.57	0.89	0.98	1.00	1.00	1.00	1.00	1.00	1.00
2018	0.25	0.66	0.92	0.99	1.00	1.00	1.00	1.00	1.00	1.00
2019	0.20	0.59	0.89	0.98	1.00	1.00	1.00	1.00	1.00	1.00
2020	0.29	0.70	0.93	0.99	1.00	1.00	1.00	1.00	1.00	1.00

Table S9. Annual fecundity estimates of ripe females by age (number of eggs).

Year	1	2	3	4	5	6	7	8	9	10
1968	201625.40	209480.94	226738.65	256954.17	282774.21	308581.14	325327.21	342656.58	344072.60	394143.18
1969	201625.40	209480.94	226738.65	256954.17	282774.21	308581.14	325327.21	342656.58	344072.60	394143.18
1970	201625.40	209480.94	226738.65	256954.17	282774.21	308581.14	325327.21	342656.58	344072.60	394143.18
1971	201625.40	209480.94	226738.65	256954.17	282774.21	308581.14	325327.21	342656.58	344072.60	394143.18
1972	201625.40	209480.94	226738.65	256954.17	282774.21	308581.14	325327.21	342656.58	344072.60	394143.18
1973	201625.40	209480.94	226738.65	256954.17	282774.21	308581.14	325327.21	342656.58	344072.60	394143.18
1974	201625.40	209480.94	227696.08	240295.46	248009.11	269604.80	274861.18	291169.64	299501.97	369245.73
1975	163010.65	169361.71	216254.05	234467.04	262745.21	287675.04	293272.51	308762.69	314496.84	382888.99
1976	213089.72	221391.91	236438.40	254167.13	267412.21	295254.26	294074.23	303937.08	311148.94	311503.88
1977	201625.40	209480.94	246590.52	273144.82	290434.37	322105.38	295333.37	359353.81	307355.94	344539.59
1978	201625.40	209480.94	227398.75	248888.28	291933.87	287973.51	290774.29	307545.04	405336.72	339260.18
1979	201625.40	209480.94	213839.75	246320.58	284282.83	317569.96	331461.58	370725.94	386933.41	325622.34
1980	201625.40	209480.94	228922.31	400281.30	308955.80	317195.47	389155.65	349522.78	426468.66	343610.31
1981	233527.21	242625.67	284297.68	266885.21	301059.39	327762.88	341457.04	328810.90	366554.72	371660.01
1982	208981.19	217123.31	263345.03	273055.10	333221.82	312978.92	326845.00	349298.94	348033.47	362938.35
1983	201625.40	209480.94	226863.50	270994.09	329508.20	308581.14	325245.15	378200.51	396780.20	377576.02
1984	180815.06	187859.80	216256.93	252433.32	267010.54	309969.91	278752.32	407051.28	406141.46	391724.45
1985	188925.08	196285.80	210971.12	257856.36	265954.06	273365.79	337869.50	362076.65	274008.45	466601.52
1986	201625.40	209480.94	226738.65	247457.98	292024.77	438201.40	603673.22	904663.39	499084.85	533169.20
1987	201625.40	209480.94	192983.23	243747.35	245703.59	276177.14	338286.04	338384.43	226920.93	361834.01
1988	201625.40	209480.94	212640.77	245605.80	251025.01	296772.31	313001.75	504017.50	439197.04	403414.88
1989	201625.40	209480.94	226738.65	256954.17	288683.01	374354.90	430964.03	358929.54	344072.60	358734.96
1990	201625.40	209480.94	221577.35	253110.56	254805.15	270124.14	301734.45	346951.79	306184.47	409822.35
1991	175156.33	181980.60	213352.90	225257.20	220010.38	347078.20	325327.21	342656.58	338957.65	319110.92
1992	167058.71	173567.49	210833.41	235159.51	279297.26	248875.44	300511.05	287128.57	258286.49	361287.90
1993	201625.40	209480.94	229241.45	238560.53	276696.24	328726.11	369724.96	374850.36	344372.88	389076.67
1994	201625.40	209480.94	181097.70	214454.13	245710.14	255630.48	276541.45	342656.58	344072.60	336987.02
1995	201625.40	209480.94	191035.91	230641.44	278034.88	282792.60	259478.65	239384.37	344072.60	420381.27
1996	201625.40	209480.94	232025.55	256954.17	227652.75	218074.43	411777.61	351184.37	294786.92	380268.52
1997	201625.40	209480.94	216139.81	224836.36	282774.21	217851.66	325327.21	342656.58	375821.33	455601.30
1998	211168.95	219396.32	216161.39	262917.58	254746.95	308581.14	258666.28	319292.39	305419.03	394086.10
1999	170875.49	177532.97	213803.33	240050.04	277145.44	259389.57	325327.21	418691.79	388705.11	343927.62
2000	173484.77	180243.92	220510.80	250208.05	304269.79	326249.68	333516.85	298964.64	343983.46	367324.17
2001	213336.80	221648.62	241509.73	276158.33	289662.34	359626.19	391341.51	361270.12	312874.31	374771.13
2002	201625.40	209480.94	221862.81	261357.06	251529.03	316188.82	362744.75	385979.34	407891.62	318726.94
2003	201625.40	209480.94	226738.65	256167.77	341581.27	341524.96	401411.96	342656.58	344072.60	394143.18
2004	201625.40	209480.94	213186.18	205713.23	272802.56	258811.45	293574.40	327180.22	386859.94	241593.60
2005	210003.64	218185.60	228926.14	262045.39	293173.45	351997.99	335136.74	266649.62	530013.79	297914.55
2006	226332.50	235150.65	233315.80	267904.00	293937.54	250111.81	412548.74	500090.10	353905.05	335804.30
2007	153802.73	159795.05	233321.24	273578.05	312323.76	422784.31	358960.13	375522.73	374380.90	293857.23
2008	201625.40	209480.94	235814.03	262366.83	300745.06	318931.07	324366.95	342656.58	355716.45	287923.40
2009	198977.62	206730.00	237837.66	244865.03	270415.69	290757.77	336399.17	475594.57	344072.60	432115.06
2010	201625.40	209480.94	241823.98	251557.32	302635.72	305110.79	322894.68	632083.10	344072.60	305669.98
2011	201625.40	209480.94	232324.76	275459.20	379616.38	391246.97	325327.21	413790.14	344072.60	270525.77
2012	176685.65	183569.50	200660.14	230946.86	256774.28	252856.91	268812.15	360108.31	344072.60	250261.42
2013	201625.40	209480.94	292642.07	256954.17	472511.76	308581.14	325327.21	342656.58	344072.60	394143.18
2014	224459.20	233204.36	236866.21	315906.85	324962.86	403105.76	325327.21	342656.58	344072.60	526720.83
2015	225561.96	234350.08	248946.28	344747.56	427196.72	308581.14	927608.30	342656.58	344072.60	394143.18
2016	223756.69	232474.49	254576.78	322631.32	358816.66	383961.69	325327.21	342656.58	344072.60	266735.02
2017	201625.40	209480.94	227655.72	287998.66	367014.35	322578.17	339973.12	342656.58	344072.60	414179.96
2018	170741.31	177393.57	212191.03	263903.05	312908.57	328412.92	380994.15	341785.00	344072.60	230366.42
2019	201625.40	145861.35	155547.57	167825.78	213944.43	275361.66	337605.96	312555.84	184210.77	220745.29
2020	201625.40	145156.47	158844.01	177417.62	194212.66	250837.64	512096.03	251371.16	420932.14	415377.90

Table S10. Annual sex ratio (females to males) in the commercial samples.

Year	1	2	3	4	5	6	7	8	9	10
1968	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1969	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1970	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1971	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1972	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1973	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1974	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1975	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1976	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1977	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1978	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1979	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
1980	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1981	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1982	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1983	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
1984	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
1985	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
1986	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
1987	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
1988	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
1989	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
1990	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
1991	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
1992	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
1993	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
1994	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1995	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1996	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
1997	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1998	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
1999	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
2000	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
2001	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
2002	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
2003	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
2004	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
2005	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
2006	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
2007	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
2008	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
2009	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
2010	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
2011	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
2012	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
2013	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
2014	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
2015	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
2016	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
2017	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
2018	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
2019	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
2020	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56

Table S11. Equations and random and fixed effect parameters used in the operating model. Parameters are a = age, y = year, SSB = spawning stock biomass, Sel = selectivity, N = abundance, F = fishing mortality, M = natural mortality, W = mass, P = proportion mature, CU = upper catch limit, CL = lower catch limit, CT = total catch, CP = catch proportion, TEP = Total Egg Production, fec= fecundity, Fem = proportion of females, ts = timing of the survey, o = observed, MVN = multivariate normal, crl = continuation-ratio logit.

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

Parameter	Definition	Effect
$N_{a,y}$	Stock abundance	Random
F_y	Fishing mortality	Random
α	Stock-recruitment coefficient	Fixed
β	Stock-recruitment coefficient	Fixed
Sel_a	Fishing selectivity	Fixed
q	Survey index catchability	Fixed
σ^2_N	Process error variance	Fixed
σ_{F_y}	Annual fishing mortality variance	Fixed
$\sigma^2_{cp_a}$	Catch-at-age proportions measurement error variance	Fixed
σ^2_S	Survey measurement error variance	Fixed

Table S12. Estimated model parameters.

Parameters	**estimate**	***s.d.***
$logq$	8.24	0.14
$log\sigma_{F_y}$	-0.87	0.10
$log\sigma^2_{N_1}$	-0.37	0.13
$log\sigma^2_{N_{2-10}}$	-1.03	0.08
$log\sigma^2_{caa_1}$	0.76	0.10
$log\sigma^2_{caa_{2,8,9}}$	-0.04	0.09
$log\sigma^2_{caa_{2-7}}$	-0.48	0.06
$log\sigma^2_s$	-0.31	0.12
$log\alpha$	1.47	0.45
$log\beta$	-10.53	0.60
$logitSel_1$	-3.09	0.33
$logitSel_2$	-1.23	0.14
$logitSel_3$	0.16	0.17
$logitSel_4$	0.74	0.22

Table S13. Summary of model estimates showing spawning stock biomass in tonnes (SSB), age-1 recruitment (Recruitment), mean instantaneous rate of fishing mortality of fully selected fish ($F_{\overline{5-10}}$), and the associated exploitation rate (Exploitation rate (%), total catch in tonnes (Catch), mean age in the catch (Mean age), and the spawning stock biomass with respect to the Limit Reference Point (SSB/LRP).

Year	SSB	Recruitment	$F_{\overline{5-10}}$	Exploitation rate (%)	Catch	Mean age	SSB/LRP
1968	240192	1553689	0.16	14.79	24662	1.95	509
1969	278861	178359	0.15	13.93	29463	2.82	591
1970	277459	243706	0.15	13.93	31906	3.24	588
1971	268901	139399	0.15	13.93	31805	3.74	570
1972	244748	214116	0.15	13.93	33089	3.90	518
1973	215590	279785	0.26	22.89	43833	3.45	457
1974	208457	385569	0.34	28.82	50538	3.06	442
1975	215720	434122	0.3	25.92	41498	2.76	457
1976	260593	204081	0.24	21.34	38026	3.02	552
1977	308786	70937	0.16	14.79	33083	3.61	654
1978	324084	61209	0.15	13.93	36093	4.31	687
1979	291152	143916	0.15	13.93	35715	4.41	617
1980	250139	75738	0.15	13.93	30273	4.67	530
1981	215394	129861	0.15	13.93	26011	4.41	456
1982	189859	247589	0.16	14.79	23111	3.65	402
1983	199915	493905	0.17	15.63	24125	2.73	423
1984	287559	94134	0.17	15.63	27735	3.01	609
1985	371946	147288	0.17	15.63	38371	3.34	788
1986	394405	102598	0.17	15.63	44271	3.80	835
1987	358863	100999	0.16	14.79	46907	4.30	760
1988	350632	274868	0.15	13.93	43262	4.10	743
1989	368680	351389	0.15	13.93	39248	3.65	781
1990	386314	149308	0.18	16.47	44275	3.89	818
1991	336648	178992	0.21	18.94	45315	3.84	713
1992	281882	151194	0.24	21.34	46484	3.93	597
1993	222109	40969	0.28	24.42	44705	4.24	471
1994	169041	140442	0.35	29.53	41752	3.92	358
1995	133661	155546	0.4	32.97	35338	3.35	283
1996	116535	130662	0.54	41.73	36606	3.11	247
1997	101864	168241	0.68	49.34	34863	2.62	216
1998	94025	80176	0.81	55.51	33741	2.66	199
1999	80000	119443	0.98	62.47	34586	2.47	169
2000	83274	473589	1.12	67.37	31342	1.57	176
2001	160397	99164	0.97	62.09	44531	2.09	340
2002	188423	102984	0.76	53.23	62518	2.68	399
2003	185024	205517	0.73	51.81	67372	2.85	392
2004	175092	317289	0.8	55.07	75883	2.56	371
2005	176913	178299	0.92	60.15	73288	2.62	375
2006	167714	255108	1.04	64.65	76072	2.46	355
2007	149093	83984	1.09	66.38	66929	2.73	316
2008	115476	156417	0.99	62.84	54191	2.59	245
2009	96584	148455	1.35	74.08	53820	2.48	205
2010	72344	43658	1.89	84.89	47102	2.66	153
2011	36804	101965	2.08	87.51	25225	2.02	78
2012	30694	72652	1.8	83.47	15683	1.85	65
2013	34406	48673	1.4	75.34	15548	2.07	73
2014	31163	62142	1.12	67.37	13098	2.08	66
2015	28770	84003	1.05	65.01	11586	1.92	61
2016	31209	174759	1.03	64.30	12006	1.60	66
2017	45774	34565	1.14	68.02	18254	2.16	97
2018	45516	68241	1.26	71.63	24040	2.39	96
2019	31707	76306	1.33	73.55	17045	2.20	67
2020	27599	75852	1.34	73.82	14672	2.05	58

Table S14. Estimated N_{ay} (numbers-at-age in '000s of fish)

Year	1	2	3	4	5	6	7	8	9	10+
1968	1553.69	344.93	105.65	41.76	24.47	23.47	11.19	16.13	130.85	1.22
1969	178.36	1120.04	266.42	61.74	19.99	14.87	18.49	8.14	9.96	119.69
1970	243.71	136.21	785.86	162.78	42.19	10.71	9.82	15.60	6.64	78.37
1971	139.40	194.90	95.86	554.18	99.22	29.66	6.89	7.71	11.08	53.92
1972	214.12	98.04	140.74	93.90	331.64	63.34	26.35	3.10	4.98	50.07
1973	279.79	217.80	96.77	107.91	86.91	177.52	45.13	18.04	2.43	21.77
1974	385.57	242.99	181.97	79.74	80.05	64.83	93.45	24.46	10.09	12.56
1975	434.12	371.11	175.88	116.69	51.64	52.97	42.17	46.02	12.01	10.61
1976	204.08	424.79	303.31	117.18	69.95	29.80	33.49	26.05	25.95	12.20
1977	70.94	170.16	374.37	214.06	77.06	43.53	18.28	21.08	15.45	24.13
1978	61.21	43.59	125.27	295.16	160.40	61.70	30.83	14.07	13.70	25.38
1979	143.92	42.06	31.97	96.71	206.90	110.71	44.81	21.06	10.14	24.89
1980	75.74	111.88	30.92	25.38	69.89	134.35	68.61	29.74	14.56	22.91
1981	129.86	53.90	89.01	18.58	19.49	50.26	92.33	41.12	19.56	24.30
1982	247.59	90.09	32.90	64.76	10.72	14.45	36.18	69.31	25.84	30.17
1983	493.91	214.71	51.12	18.76	41.17	6.15	9.31	27.67	60.72	40.82
1984	94.13	564.97	213.33	28.56	11.76	23.42	3.87	5.93	18.92	69.09
1985	147.29	68.46	577.34	177.41	16.62	7.57	14.60	2.43	3.86	57.45
1986	102.60	113.48	55.55	554.22	133.20	10.76	5.52	8.05	1.56	28.60
1987	101.00	70.60	77.93	41.54	435.61	93.97	6.65	3.79	4.37	16.93
1988	274.87	66.25	40.51	47.62	28.13	389.44	61.82	4.47	2.45	12.01
1989	351.39	258.83	44.35	24.90	29.27	16.15	322.38	34.82	3.07	9.04
1990	149.31	328.47	212.84	30.86	16.02	18.63	11.51	243.89	19.55	7.22
1991	178.99	114.14	290.13	152.26	20.42	10.14	12.54	8.45	141.00	15.14
1992	151.19	142.25	72.88	212.15	100.76	13.62	6.25	7.90	5.45	91.12
1993	40.97	115.06	110.52	47.22	140.15	63.27	9.11	3.75	4.61	45.27
1994	140.44	22.57	76.84	72.80	27.20	97.34	39.41	5.42	2.05	21.45
1995	155.55	106.31	13.60	50.78	44.40	14.33	53.00	20.59	2.76	9.46
1996	130.66	114.98	61.32	7.75	30.44	26.71	6.91	30.12	9.30	5.55
1997	168.24	97.60	76.74	30.89	4.06	15.15	13.09	2.83	13.73	5.71
1998	80.18	133.12	59.30	41.73	14.24	1.79	6.25	5.46	1.10	5.61
1999	119.44	53.38	89.44	30.18	19.63	4.78	0.74	2.04	1.82	1.86
2000	473.59	88.51	29.01	42.67	11.21	6.85	1.17	0.20	0.58	1.05
2001	99.16	490.33	60.03	14.28	16.61	2.54	1.57	0.23	0.05	0.40
2002	102.98	67.84	422.63	31.59	7.45	6.12	0.74	0.38	0.06	0.09
2003	205.52	68.64	42.77	317.89	18.60	3.69	3.21	0.24	0.09	0.03
2004	317.29	169.38	41.96	24.42	203.29	7.27	2.05	1.13	0.08	0.03
2005	178.30	283.28	112.72	21.18	12.30	101.19	2.87	0.84	0.20	0.04
2006	255.11	136.99	213.94	57.57	10.30	4.56	39.23	0.99	0.23	0.05
2007	83.98	209.43	85.52	116.88	20.42	3.43	1.49	11.29	0.21	0.06
2008	156.42	54.09	144.27	39.57	50.24	4.66	0.94	0.37	3.25	0.06
2009	148.46	114.09	27.56	83.42	17.22	20.55	1.17	0.22	0.08	1.31
2010	43.66	106.29	61.44	9.01	30.14	3.96	4.91	0.23	0.03	0.35
2011	101.97	23.13	50.20	14.04	1.67	4.30	0.55	0.49	0.03	0.05
2012	72.65	71.86	9.85	13.71	2.04	0.17	0.40	0.07	0.03	0.01
2013	48.67	55.66	42.86	2.62	3.25	0.26	0.02	0.03	0.01	0.01
2014	62.14	32.27	36.12	16.94	0.78	0.52	0.02	0.01	0.01	0.00
2015	84.00	42.83	17.49	18.38	5.02	0.23	0.09	0.01	0.00	0.00
2016	174.76	60.67	21.69	7.53	7.13	1.66	0.06	0.01	0.00	0.00
2017	34.57	163.96	37.15	8.19	2.78	2.07	0.60	0.01	0.00	0.00
2018	68.24	25.15	114.48	14.56	2.63	0.59	0.47	0.15	0.00	0.00
2019	76.31	50.53	18.63	39.33	4.71	0.50	0.13	0.06	0.06	0.00
2020	75.85	54.61	29.86	6.73	12.48	1.02	0.09	0.03	0.01	0.01

Table S15. Estimated F_{ay} (instantaneous fishing mortality-at-age)

Year	1	2	3	4	5	6	7	8	9	10+
1968	0.01	0.04	0.08	0.11	0.16	0.16	0.16	0.16	0.16	0.16
1969	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1970	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1971	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1972	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1973	0.01	0.06	0.14	0.17	0.26	0.26	0.26	0.26	0.26	0.26
1974	0.01	0.08	0.18	0.23	0.34	0.34	0.34	0.34	0.34	0.34
1975	0.01	0.07	0.16	0.20	0.30	0.30	0.30	0.30	0.30	0.30
1976	0.01	0.05	0.13	0.16	0.24	0.24	0.24	0.24	0.24	0.24
1977	0.01	0.04	0.09	0.11	0.16	0.16	0.16	0.16	0.16	0.16
1978	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1979	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1980	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1981	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1982	0.01	0.04	0.09	0.11	0.16	0.16	0.16	0.16	0.16	0.16
1983	0.01	0.04	0.09	0.12	0.17	0.17	0.17	0.17	0.17	0.17
1984	0.01	0.04	0.09	0.12	0.17	0.17	0.17	0.17	0.17	0.17
1985	0.01	0.04	0.09	0.11	0.17	0.17	0.17	0.17	0.17	0.17
1986	0.01	0.04	0.09	0.11	0.17	0.17	0.17	0.17	0.17	0.17
1987	0.01	0.04	0.08	0.11	0.16	0.16	0.16	0.16	0.16	0.16
1988	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1989	0.01	0.03	0.08	0.10	0.15	0.15	0.15	0.15	0.15	0.15
1990	0.01	0.04	0.09	0.12	0.18	0.18	0.18	0.18	0.18	0.18
1991	0.01	0.05	0.11	0.14	0.21	0.21	0.21	0.21	0.21	0.21
1992	0.01	0.05	0.13	0.16	0.24	0.24	0.24	0.24	0.24	0.24
1993	0.01	0.06	0.15	0.19	0.28	0.28	0.28	0.28	0.28	0.28
1994	0.02	0.08	0.19	0.24	0.35	0.35	0.35	0.35	0.35	0.35
1995	0.02	0.09	0.22	0.27	0.40	0.40	0.40	0.40	0.40	0.40
1996	0.02	0.12	0.29	0.37	0.54	0.54	0.54	0.54	0.54	0.54
1997	0.03	0.15	0.37	0.46	0.68	0.68	0.68	0.68	0.68	0.68
1998	0.04	0.18	0.44	0.55	0.81	0.81	0.81	0.81	0.81	0.81
1999	0.04	0.22	0.53	0.67	0.98	0.98	0.98	0.98	0.98	0.98
2000	0.05	0.25	0.61	0.76	1.12	1.12	1.12	1.12	1.12	1.12
2001	0.04	0.22	0.52	0.66	0.97	0.97	0.97	0.97	0.97	0.97
2002	0.03	0.17	0.41	0.52	0.76	0.76	0.76	0.76	0.76	0.76
2003	0.03	0.16	0.39	0.49	0.73	0.73	0.73	0.73	0.73	0.73
2004	0.03	0.18	0.43	0.54	0.80	0.80	0.80	0.80	0.80	0.80
2005	0.04	0.21	0.50	0.62	0.92	0.92	0.92	0.92	0.92	0.92
2006	0.05	0.24	0.56	0.71	1.04	1.04	1.04	1.04	1.04	1.04
2007	0.05	0.25	0.59	0.74	1.09	1.09	1.09	1.09	1.09	1.09
2008	0.04	0.22	0.53	0.67	0.99	0.99	0.99	0.99	0.99	0.99
2009	0.06	0.30	0.73	0.91	1.35	1.35	1.35	1.35	1.35	1.35
2010	0.08	0.43	1.02	1.28	1.89	1.89	1.89	1.89	1.89	1.89
2011	0.09	0.47	1.12	1.41	2.08	2.08	2.08	2.08	2.08	2.08
2012	0.08	0.41	0.97	1.22	1.80	1.80	1.80	1.80	1.80	1.80
2013	0.06	0.31	0.75	0.95	1.40	1.40	1.40	1.40	1.40	1.40
2014	0.05	0.25	0.60	0.76	1.12	1.12	1.12	1.12	1.12	1.12
2015	0.05	0.24	0.56	0.71	1.05	1.05	1.05	1.05	1.05	1.05
2016	0.04	0.23	0.56	0.70	1.03	1.03	1.03	1.03	1.03	1.03
2017	0.05	0.26	0.61	0.77	1.14	1.14	1.14	1.14	1.14	1.14
2018	0.05	0.28	0.68	0.86	1.26	1.26	1.26	1.26	1.26	1.26
2019	0.06	0.30	0.72	0.90	1.33	1.33	1.33	1.33	1.33	1.33
2020	0.06	0.30	0.72	0.91	1.34	1.34	1.34	1.34	1.34	1.34

FIGURES

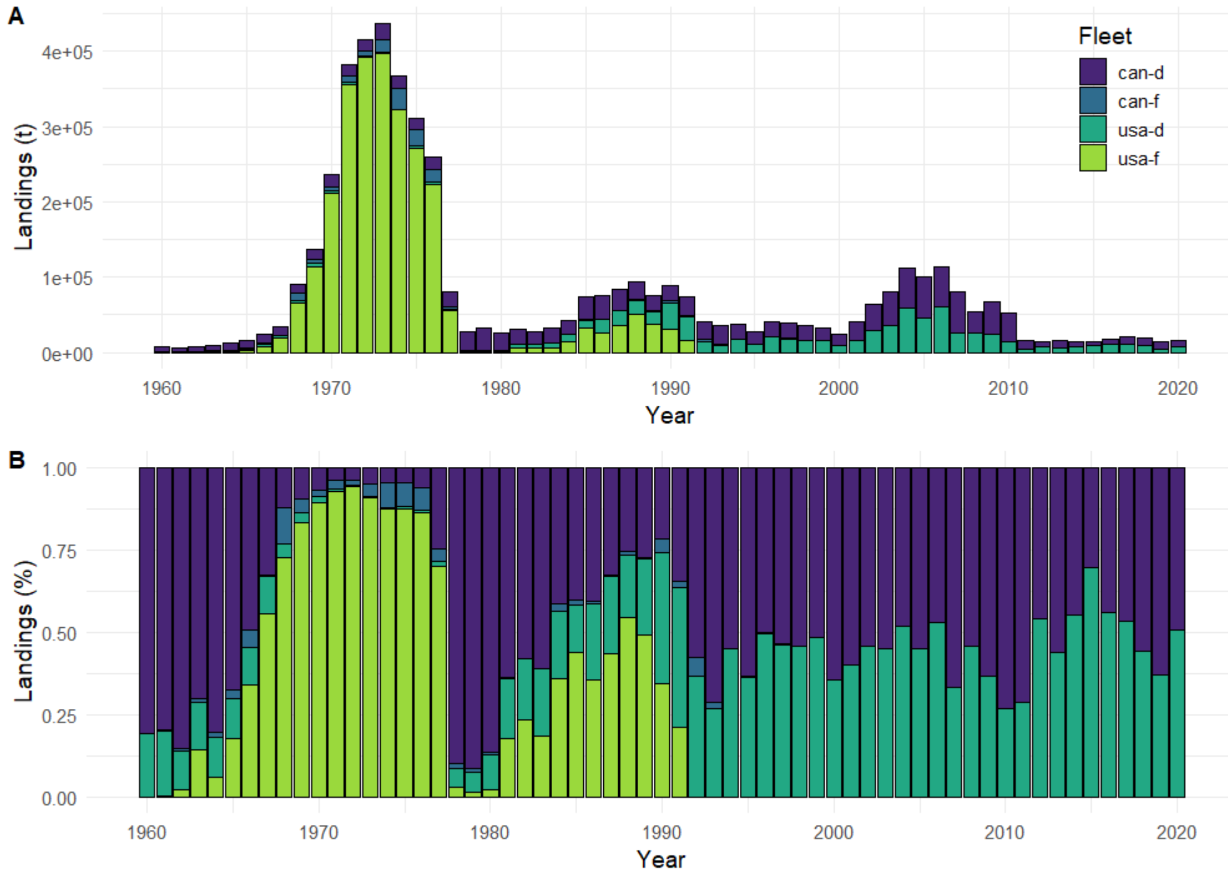

Figure S1. A) Total Atlantic mackerel landings (t) in the Northwest Atlantic (NAFO 2-6) from 1960-2020 split by fleet and B) in terms of the proportion of the total landings caught by fleet. Fleets are represented by different colours with the domestic Canadian fleet (can-d) and the foreign distant water fleet (can-f) that fished in Canada's exclusive economic zone (EEZ) in violet and blue respectively as well as the landings caught by the combined sum of commercial landings, recreational landings, and discards by the US domestic fleet (usa-d) and the foreign distant water fleet (usa-f) in the EEZ of the U.S.A. in teal and light green respectively.

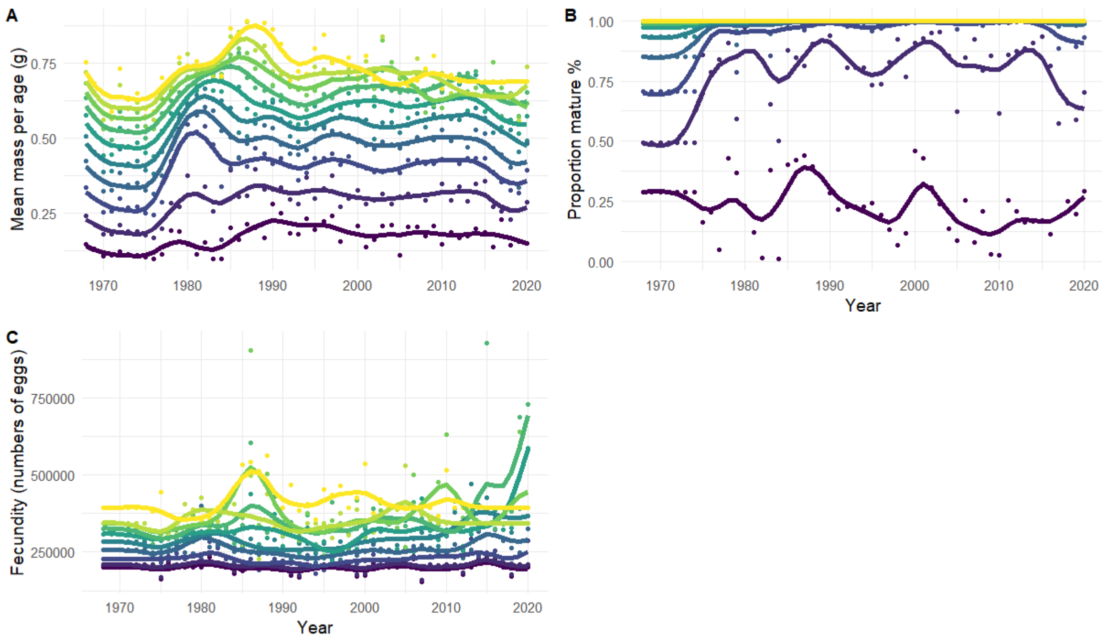

Figure S2. Raw (points) and smoothed (lines) of model input data (1968-2020) including A) the mean mass-at-age (g) of fish, B) the proportion of sexually mature fish at age, and fecundity in terms of the estimated number of eggs produced by a mature female on the verge of spawning for ages 1-10+. Colours represent ages ranging from violet (age 1) to yellow (ages 10+).

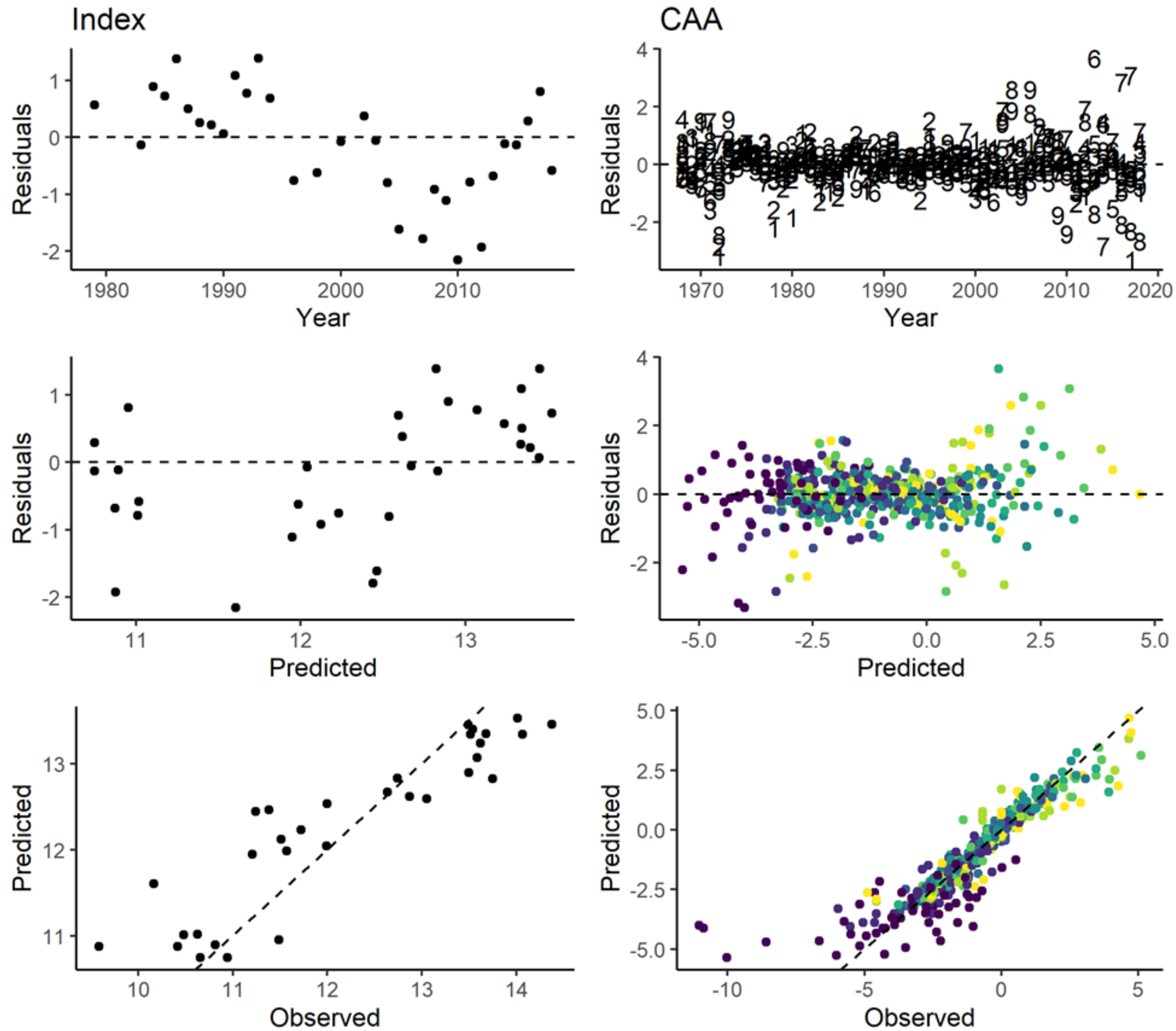

Figure S3. Model residual plots for the egg index (Index; left column) and catch-at-age (CAA; right column). The top row shows the standardized residuals plotted against year, the middle row shows the standardized residuals plotted against the predicted values, and the bottom row shows predicted values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

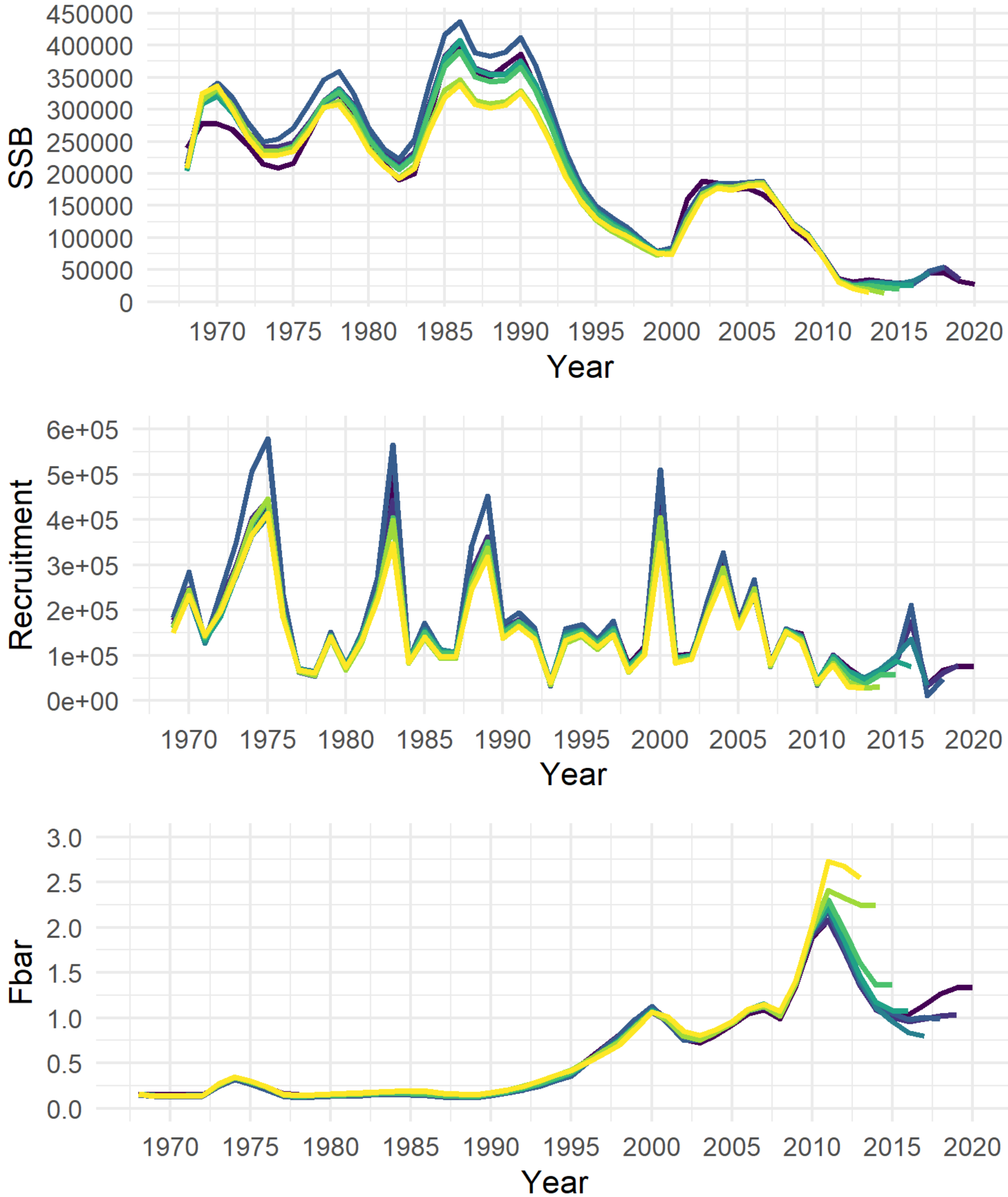

Figure S4. Retrospective plots showing 7 peels of SSB (top row; Spawning stock biomass in tonnes); Recruitment (middle row; estimated number of age 1 fish in '000s), and Fbar ($F_{\overline{5-10}}$; the mean annual instantaneous fishing mortality of fully selected (ages 5-10+) fish). Colours indicate the different peels from violet (i.e. the terminal year 2020), to yellow (2013).

Figure S5. Retrospective plots showing 7 peels of SSB (top row; Spawning stock biomass in tonnes); Recruitment (middle row; estimated number of age 1 fish in '000s), and Fbar ($F_{\overline{5-10}}$; the mean annual instantaneous fishing mortality of fully selected (ages 5-10+) fish). Colours indicate the different peels from violet (i.e. the terminal year 2020), to yellow (2013).

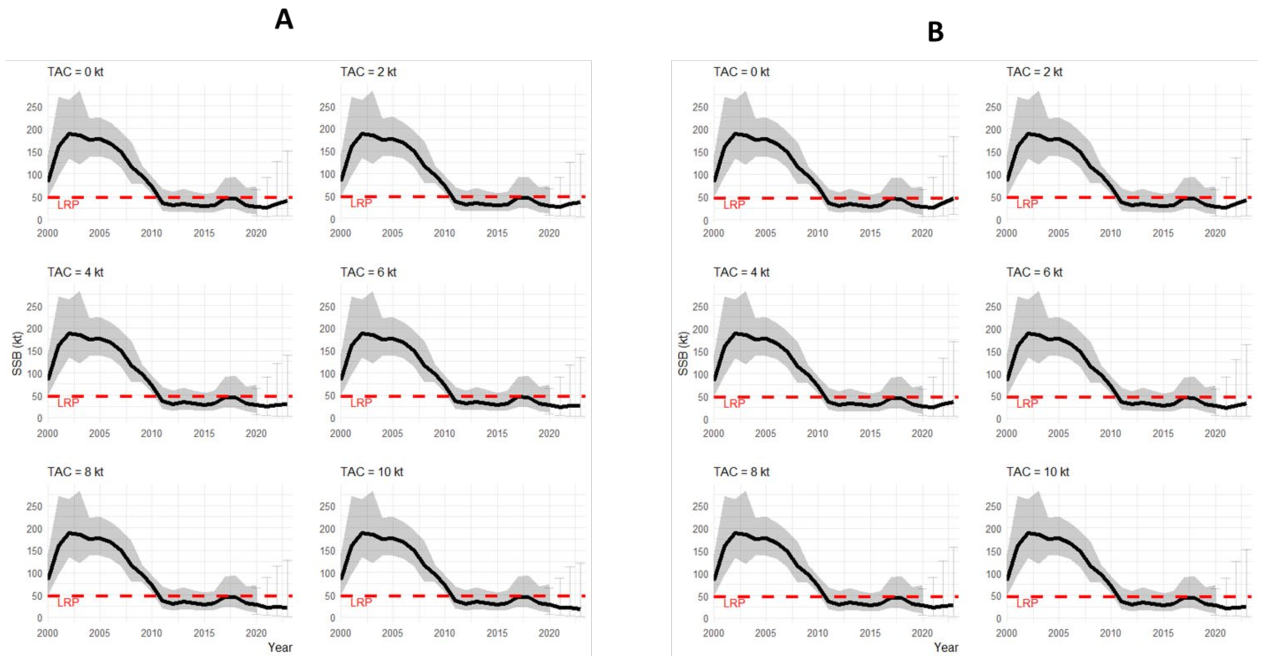

Figure S6. Estimated spawning stock biomass in kilotons (SSB; black line and grey confidence intervals) and three year projections (2021-2022) under different TAC scenarios (indicated in upper left of each panel) and recruitment assumptions A) under a Beverton-Holt stock-recruit relationship using values from 1969 to 2020 or B) using mean recruitment from 2011-2020 with a temporal autocorrelation of 0.9. The limit reference point (LRP) is indicated by the red dotted line in each panel.

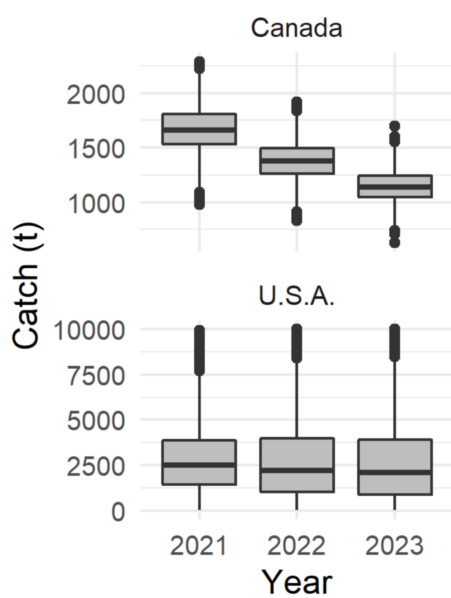

Figure S7. Boxplots of the assumed unaccounted-for catch over the next 3 years (2021-2023), for Canada (upper panel) and the US (lower panel). Boxes include 50% of all observations as they are delimited by the 1st and 3rd quantile, with the median value represented by the central horizontal line.