Fisheries and Oceans Canada

Pêches et Océans Canada

Ecosystems and Oceans Science

Sciences des écosystèmes et des océans

Evaluation of Rebuilding Strategies for northwestern Atlantic Mackerel (NAFO Subareas 3 and 4)

Elisabeth Van Beveren[1], Julie R. Marentette[2], Andrew Smith[1], Martin Castonguay[1], Daniel E. Duplisea[1]

[1] Fisheries and Oceans Canada
850 route de la Mer
Mont-Joli, QC
G5H 3Z4

[2] Fisheries and Oceans Canada
200 Kent St
Ottawa, ON
K1A 0A6

Canada

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.

TABLE OF CONTENTS

ABSTRACT

In 2017, the biomass of the northern spawning contingent of Western Atlantic mackerel was estimated to have been below its Limit Reference Point (LRP) since 2011, and this resulted in the establishment of a Rebuilding Plan Working Group (RPWG). Within this context and with the participation of all RPWG members, a Management Strategy Evaluation focusing on rebuilding strategies was developed. This included the specification of nine potential Harvest Control Rules (HCRs), of which the performance was measured in terms of three management objectives under eight uncertainty scenarios. The analyses corroborated the 2019 assessment results regarding the stock being below its LRP. Few HCRs met the developed objectives and no single HCR met all objectives under all uncertainty scenarios, mainly as a result of the current stock state and the large uncertainty in total removals. The HCR that most closely reflected the current 2019 Canadian TAC (8,000 t) failed to meet all candidate performance thresholds for all objectives and shorter-term milestones. Simulation also showed that high future floor catches (6,000 t to 10,000 t) were over the next 3 to 10 years progressively more likely to result in stock declines than increases. Given that stock rebuilding above the LRP might not be possible over the short term, the use of rebuilding milestones (3-5 years) is recommended, as well as improving management through a reduction of total catch uncertainty.

INTRODUCTION

BACKGROUND

Atlantic Mackerel (*Scomber scombrus*) is a widely distributed small pelagic species with a complex population structure. In eastern Canada, the northern spawning contingent of western Atlantic Mackerel supports an important commercial, bait and recreational fishery in NAFO Subareas 3 and 4. There is no formal harvest control rule in place to determine commercial fishery recommended catches. The stock is managed through a Total Allowable Catch (TAC), which was however only reached twice in the history of the fishery, in 2016 and 2018. Discards, as well as undeclared removals for personal bait and recreational use, occur in addition to commercial catches.

The estimated spawning stock biomass of the northern contingent of Atlantic Mackerel has shown significant declines in recent decades and has been below its Limit Reference Point since 2011 (DFO 2017), placing this stock in the Critical Zone of the Precautionary Approach policy (DFO 2009). In 2017, fisheries managers initiated a Rebuilding Plan Working Group for this stock with stakeholders, fishing interests and indigenous groups, and have requested science advice for this plan. This report details the evaluation of a range of potential rebuilding strategies for Atlantic Mackerel, under different scenarios of known and missing catches.

Overview of the population

Population structure

Atlantic Mackerel (*Scomber scombrus*) inhabits the waters of the North Atlantic Ocean and has genetically differentiated populations on each side (Nesbø et al. 2000). In the northeastern Atlantic, this species is found from the Mediterranean to Norway and in the last decade, their range expanded to Greenland, driven by a remarkable upsurge in abundance (Olafsdottir et al. 2019). The northwestern Atlantic Mackerel distribution ranges from North Carolina (United States) to Labrador (Canada). Each population is characterised by different spawning components or contingents, which are usually not spatially isolated throughout the year.

Since the work of Sette (1950), the northwestern Atlantic Mackerel population is thought to be composed of two spawning contingents (also referred to herein as stocks); the southern (US) contingent which spawns in southern New England (~May) and the northern (Canadian) contingent which spawns in the southern Gulf of St. Lawrence (June/July). After spawning, the northern contingent migrates through the Gulf and the Canadian part of the Atlantic (July-October) to finally mix with the southern contingent during the fall and winter in US waters. Sette (1950) arrived at this conclusion by tracking the size structure of US catch, which changed in winter when the northern contingent entered the fishery. Later tagging studies (Beckett et al. 1974; Moores et al. 1975; Waters et al. 2000) confirmed this migration pattern. Tagging studies also indicated that southern contingent mackerel likewise migrate over large distances, but typically remain in US waters (e.g., Sette 1950).

Despite the presence of two important spawning contingents, they cannot be discriminated based on biological characteristics (Moores et al. 1975), genetics (Lambrey de Souza et al. 2006) or otolith morphometrics (Castonguay et al. 1991). Only recently has it become possible to estimate natal origin, based on otolith stable oxygen isotopes (Redding, University of Maryland, pers. comm.), which reflect the differences in temperature and oceanographic conditions in the spawning habitats. Results from this approach are still limited in quantity and coverage, and only allow currently a limited understanding of spawning contingent intermixing. It

is, for example, unclear if Redding's results based on stable oxygen isotopes in otoliths from 1998 and 2000 are temporally stable. Additional analyses dealing with stock structure based on otolith isotopes and genetics are being performed and are planned.

Stock status

In contrast to the northeastern Atlantic Mackerel population, abundance of the northwestern Atlantic Mackerel population is estimated to be currently depressed and the age structure is truncated (NEFSC 2018). Canada estimates the northern contingent biomass (which is the only contingent assessed by Canada) to be in the Critical Zone, where it has been for at least the last decade (DFO 2017). Specifically, the most recent evaluation of stock status (DFO 2017) indicated that spawning biomass was estimated to be at 40% of the Limit Reference Point (LRP) calculated as 40% of SSB at $F_{40\%}$ (see section: performance metrics). Because the northern contingent is considered to be significantly larger than the southern contingent (Richardson et al. in press) and the US assesses both contingents combined (see section: overview of the scientific advice) the conclusion of the US stock assessment was analogous to the Canadian assessment. That is, the US reported that the entire northwestern Atlantic Mackerel population (Subareas 3 to 6) is overfished while undergoing overfishing (NEFSC 2018).

Overview of the fishery

History

We focus on the period after the 1960s, as current stock evaluations in both the US and Canada only span the last few decades (Canada starting in 1968 and the US in 1960). Atlantic Mackerel has however a long history of exploitation (Fig 1), as catches were already significant and highly variable before the evaluated time span. Over time various accounts of the exploitation patterns and rates have been given, for both the US and Canada (e.g., Hoy and Clark 1967 and thereafter in regularly produced research documents through the Canadian Science Advisory Secretariat or CSAS, and other sources). As previously mentioned, catches from US waters might consist of significant amounts of northern ("Canadian") contingent mackerel, so US landings are presented as well.

The largest mackerel landings occurred between 1968 and 1977, mainly by foreign fleets fishing in US waters (catch > 400,000 t, DFO 2008). The establishment of the Exclusive Economic Zone in 1977 ended foreign exploitation, with the exception of the years between 1982 and 1992, owing to agreements between the US and some Eastern European countries like USSR and Poland. Between 1968 and 2000, Canadian landings varied between 16 kt and 42 kt. Over the same time period, US landings increased from an all-time low to Canadian levels. Landings from both countries subsequently peaked around mid-2000, thanks to a strong 1999 cohort (> 50 kt each). In Canada, this increase in landings was the result of the expansion of the Newfoundland mackerel fishery. In 2011, Canadian and US catch dropped to 12 kt and 2 kt, respectively. Landings from both countries have each remained below 10 kt ever since, partly because of a limiting TAC.

In terms of fisheries management in Canada, commercial fishery TACs were set from 1987 to 2011 that covered both the Canadian and US landings. These TACs were not limiting (e.g., TACs of 200 kt until 2000 and 150 kt from 2001-2009, Figure 1), determined independently by Canada, and without participation by the US. Since 2012 the TAC has been set at a national level, and for Canada this started at 36 kt. After two years the TAC was substantially lowered to 8 kt (2014-2016) to become limiting for the first time in 2016. After the 2016 assessment, the TAC was increased (to 10 kt) and it was assumed that an additional estimated 6 kt was removed (16 kt total) which was not reported in Canadian statistics. In 2018 the TAC (10 kt) was reached and the Canadian fishery closed early for the second time in the history of the fishery.
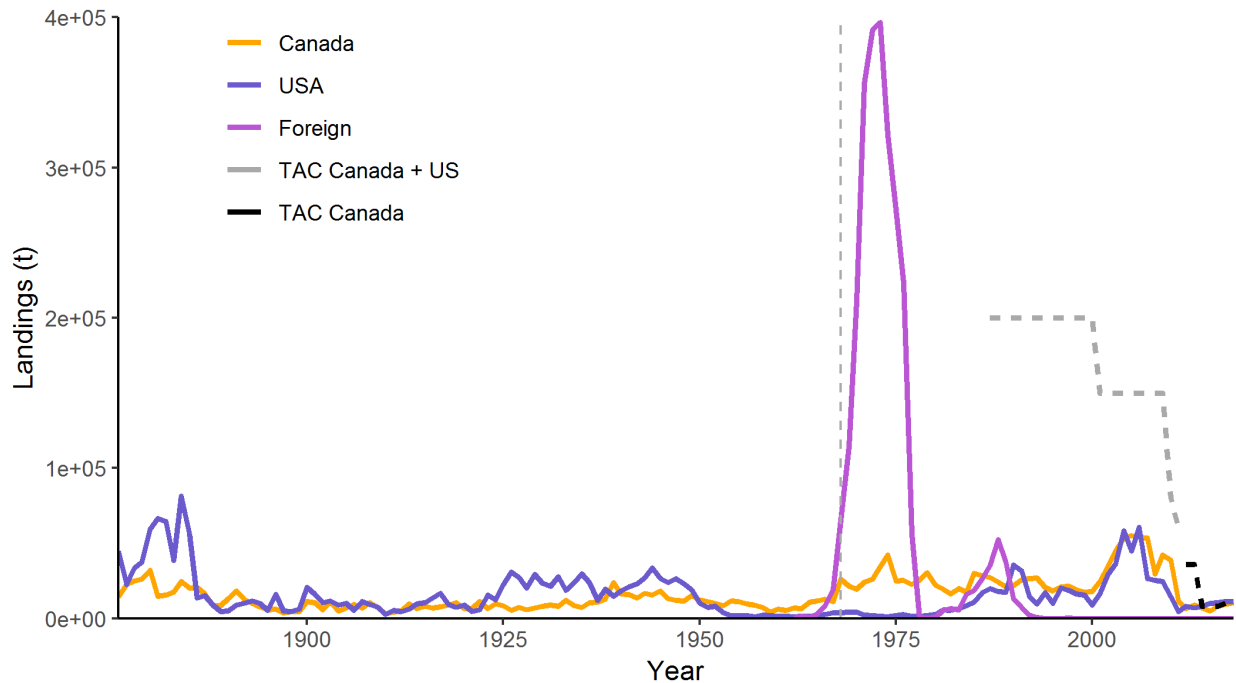
Figure 1. Historical mackerel landings (t) in Canada (NAFO areas 3 and 4) and the US (NAFO areas 5 and 6) since 1876. Foreign landings are from US waters. Newfoundland only joined Canada in 1949 and was therefore not included in prior data. The dashed vertical line indicates the time from which the Canadian stock is typically assessed (1968). Dashed horizontal lines indicate the TAC (Total Allowable Catch) for the entire area (Canada and US, colored grey) or Canada only (colored black).

Reported and missing catches

Underestimation of fishery catches has been a longstanding issue for Atlantic Mackerel (e.g., DFO 1997) and is unlikely to be fully resolved in the near future. Official Canadian landings statistics do not include several sources of the total removals, which together are thought to represent a substantial amount of unreported mackerel catch.

The bait and recreational fisheries have typically been identified as the key sources of uncertainty in total catches, as these fisheries are not universally required to report. Although mackerel is used as bait in various fisheries (e.g., tuna, snow crab, etc.), it is a particularly essential bait type in the economically important lobster fishery (Van Beveren et al. 2019a). For instance, a single lobster fisherman might on average use around 5 t of mackerel (or other bait) per season to bait pots (Harnish 2009). Angling, in contrast, is a common summer activity on the wharves, rocky points and recreational boats in Atlantic Canada. A quinquennial government survey (e.g., DFO 2019) provided very rough estimates of recreationally-caught mackerel, between 200 t and 800 t. Furthermore, recreational fishing is sometimes performed on a semi-professional scale (e.g. using a jigger or gillnet, Van Beveren et al. 2019a). Additionally, some mackerel might not be reported because they are discarded (e.g., ~2% in the Magdalen Islands; J. Aucoin, DFO, pers. comm.) or fished as bycatch in for instance the Atlantic herring fishery. All unreported catch from Canadian waters will from hereon be referred to as missing Canadian catch.

In winter, northern contingent mackerel moves into US waters to mix with the southern contingent (see section: overview of the population)(Sette 1950). During this migration, the stock is exposed to the US fleet, which primarily fishes for mackerel during this season. Therefore, we could expect that part of the US mackerel catch is composed of northern

contingent fish. Indeed, tagging experiments found some Canadian tagged mackerel back in US catches (Beckett et al. 1974; Moores et al. 1975; Waters et al. 2000). The extent to which intermixing occurs could however never be quantified. Tagging experiments had low recovery rates and both contingents are hard to discriminate (Moores et al. 1975; Castonguay et al. 1991; Lambrey de Souza et al. 2006). The fraction of northern contingent fish in US catches is likely also variable over time, as this might depend on, for instance, the relative size of both contingents and spatial migration and fishing patterns. Because of the poor knowledge of this process, intermixing has historically been ignored when the northern contingent was assessed separately in Canada. However, a new study used otolith stable isotopes as markers of natality and early results indicate that a significant proportion of US catch might be northern contingent mackerel (Redding, University of Maryland, pers. comm.). Redding showed that between 1998 and 2000, between on average 67% and 87% of their samples from US waters were northern contingent fish (n = 275). The dominance of northern contingent individuals occurred especially at older age classes. Based on this study, it is clear that US removals of northern contingent fish can no longer be discounted. Throughout this document we will refer to this class of catch underestimation as missing US catch.

Overview of the scientific advice process

Historically, both contingents were assessed as one stock and until 2012 a common TAC for both countries was applied by Canada (although the US set its own TACs independent of this). Since 2002, Canadian stock assessment reports focused only on the state of the northern contingent (NAFO Subareas 3-4, DFO 2002), using an indicator based approach. In 2010, a transboundary assessment took place which considered both contingents as one stock, by fitting an assessment model (VPA-ADAPT) to combined stock data (TRAC 2010). Stock estimates did not appear realistic, there was no consensus on stock status and the outcome was not used by management. From 2012 onwards, the Canadian TAC was set informed by model-based stock assessments of the northern contingent only (DFO 2012, 2014, 2017). Initially, model-derived stock status estimates were based on the reported Canadian landings (using the Integrated Catch-at-Age or ICA model, DFO 2012, 2014), but during the following assessment (DFO 2017) a custom model (censored catch-at-age model or CCAM) was built to account for catch uncertainty, at that time only attempting to account for missing Canadian catches. The US has always continued to evaluate both contingents as one population because of intermixing and data availability. Because sustainable exploitation rates determined from their analyses apply to the combined contingents, their quota decisions are adjusted for the Canadian TAC.

Intermixing and the possibility of straying might be motives to evaluate the entire population rather than the northern contingent alone. However, the rationale behind the choice to focus solely on one contingent has multiple arguments. Evidently, transboundary evaluation and management is practically and politically more complex to perform. Doing so might also be suboptimal for the stock itself, as neglecting contingents or subpopulations could result in the collapse of one component because fishing pressure cannot be exerted relative to their biomasses (Frank and Brickman 2000; Fu and Fanning 2004). To fully account for the population complexity, a spatial subpopulation model might be desirable, but this would at minimum require the annual decomposition of US catch data by contingent (Van Beveren et al. 2019b). As a consequence, the analyses presented here will continue to focus on the northern mackerel contingent.

REBUILDING STRATEGY EVALUATION

In a traditional fisheries management decision-making process, a stock assessment is provided which commonly focuses on the best current estimate of stock status, typically described by a single model or assessment method. From this knowledge, short-term projections might be made (e.g., under constant annual harvest or effort) upon which management can base its short-term tactical decisions for the next fishing season(s).

Management Strategy Evaluation (MSE) represents an alternative decision-making framework which tries to deal with some of the shortcomings of the traditional approach (Butterworth 2007) and is quickly gaining applications to fisheries management internationally (Punt et al. 2016). During an MSE, the performance of alternative management strategies or procedures (MPs), including full specification of input data, assessment method, and harvest control rule (HCR), are evaluated against a set of usually conflicting fisheries management objectives. Performance is evaluated using stochastic simulations over longer time periods than typically employed for traditional stock assessment projections. Multiple operating models (OMs) are considered that represent plausible hypotheses of uncertain stock or fishery dynamics. The goal is to provide stakeholders and decision-makers with information on the trade-offs in management procedure performance against the objectives for the fishery, that are robust to uncertainties captured by the set of OMs. Key to the process is that fisheries managers meet with stakeholders to agree upon objectives and potential management procedures, as well as advise on stock uncertainties to be considered in the simulations. Objectives to be defined are typically related to stock-specific conservation and exploitation goals, and stability of the fishery.

Rationale for Approach

Several elements contributed to the initiation of an MSE process for Atlantic Mackerel in NAFO Subareas 3-4. HCRs are primary components for fisheries harvest strategies under DFO's 2009 Precautionary Approach policy (DFO 2009), yet no formal HCR has been developed or implemented for the stock. In addition, as a result of high fishing mortality (DFO 2017), the stock biomass is estimated to be below the LRP and in the Critical Zone, thus requiring a rebuilding plan. An MSE-type framework, or at minimum feedback simulations, is eminently suitable to evaluate potential rebuilding measures since the relative performance of alternative measures can be evaluated over longer time frames (e.g., several species generations) than a typical stock assessment forecasts. Such longer time frames are better aligned with DFO guidance available for rebuilding and sustainability outcomes (DFO 2009). In December 2017, fisheries managers initiated a Rebuilding Plan Working Group (RPWG) for Atlantic Mackerel, which provided the forum for essential stakeholder participation in the MSE process. The RPWG included members from the Atlantic Mackerel Advisory Committee, composed of fisheries managers, science staff, industry representatives, indigenous groups and environmental non-government organizations.

Additionally, through the use of multiple OMs, science advice can be improved by means of an MSE framework. Past science advice for Atlantic Mackerel was affected by the uncertainty associated with true mackerel catches (see section: reported and missing catches). As MSE does not require the selection of a 'best' model but rather embraces multiple sources of uncertainty, including catch bias, results should better reflect system uncertainty by seeking management procedures robust to the range of OM hypotheses considered. This process may in turn increase confidence in recommended management measures. Furthermore, in the absence of clear stock objectives, previous stock assessments could give only general statements (DFO 2014), or evaluate the performance of short-term projections of constant catches using generic metrics (e.g., the probability of stock growth, DFO 2017). Through the

use of an MSE framework, science advice can be specifically tailored to stock-specific objectives (in this case, those objectives associated with rebuilding) and matching performance metrics developed in collaboration with fisheries managers and other stakeholders.

Stakeholder participation in Rebuilding Plan Working Group

The general concept of an MSE, and how the approach differed from a traditional stock assessment, was first presented to stakeholders and managers in the December 2017 RPWG meeting, and the process was officially initiated (Table 1). During the next working group meeting in March 2018, the MSE was explained in detail to stakeholders and preliminary objectives were put forward for consideration. A technical meeting with DFO scientists helped fine-tune the statistical framework and identify the key uncertainties that should be addressed in OMs. The next two RPWG meetings were held to report preliminary results of simulations using data available up to 2016, obtain stakeholder feedback on OMs and performance metrics, and finalize the development of the OMs to be carried forward into peer review. In March 2019, the MSE −now including data up to 2018− was reviewed by external reviewers during the biannual stock assessment and revised results were presented to the subsequent working group meeting. The current document provides up-to-date and completed results of the process, with all concerns and suggestions raised during previous meetings being addressed.

Table 1. Table of MSE-related meetings. Working group (RPWG) participants included scientists, managers, fishery representatives, indigenous groups and conservation organizations. The technical meeting only included the Science Branch researchers. For the CSAS assessment review two external reviewers were invited.

Date	Place	Type
05/12/2017	Moncton, NB	Working Group
18/03/2018	Halifax, NS	Working Group
18/06/2018	Mont-Joli, QC	Technical Meeting
12/09/2019	Halifax, NS	Working Group
18/12/2018	Halifax, NS	Working Group
06/03/2019	Mont-Joli, QC	CSAS Assessment review
26/03/2019	Halifax, NS	Working Group
06/03/2019	Mont-Joli, QC	Review

METHODS

DATA

We used the same data as typically available during mackerel stock assessments (DFO 2012, 2014, 2017) and which is presented in detail in the most recent stock assessment research document (Smith et al. 2020). All information was updated so that the most recent years were included in the analyses (1968-2018). The OM is based on an age-structured model, which required matrices of weight-at-age (Figure S1), proportion mature-at-age (Figure S1), catch-at-age (Figure S1), an annual egg survey index (Figure S1) and total catches (Figure S2) (see Smith et al. 2020 for details). Although in the 2017 and 2019 assessments the raw proportion mature-at-age data was used (Doniol-Valcroze et al. 2019; Smith et al. 2020), for the purpose of this MSE this data was smoothed with a cubic smoothing spline to remove unlikely interannual variations. Since the last assessment (DFO 2017), true catches are considered to be higher than the reported Canadian landings and therefore we also collected data and estimates on

missing catch fractions, which include US and foreign landings as well as maximal underreported catches from the bait and recreational fishery (e.g. Van Beveren et al. 2019a).

SIMULATIONS

At the technical heart of MSE process is a closed-loop simulation framework, used to estimate the relative performance of candidate management procedures (consisting of a HCR, assessment method and data) relative to the policy and stakeholder defined stock and fisheries objectives. All simulations are based on an OM, which represents the hypothesized true dynamics of the stock and fishery, and encompasses a historical and future component as well as implementation error or so-called missing catch (Figure 2). We distinguish between components because historical estimations are data-driven and represented by an assessment model, whereas the future part projects the stock 25 years ahead assuming parameter values and dynamics conditioned on the past data and OM assumptions. To determine future stock dynamics, annual fisheries removals need to be specified. This is partly done through a HCR, which generates a TAC for the Canadian commercial fishery (Subareas 3-4, Figure 2) based on inputs derived from the annual egg survey index. For the northwestern Atlantic Mackerel stock, however, the TAC does not reflect true removals as a large portion of all Canadian catches are unreported and the US catches consist of an unknown fraction of northern contingent mackerel. Hence, unaccounted-for catches (to which for simplicity we will refer to as *missing catches*) are added to the calculated TAC so that the potential total catch is removed from the population tracked by the OM (Figure 2). Once total removals are set, the next years' stock state can be calculated and this process is repeated annually over the time period of interest. In several steps of the process, uncertainty is present, against which HCRs should be robust. Specifically, this simulation framework encompasses model, observation, process and estimation errors in the presentation of performance metrics (Figure 2).
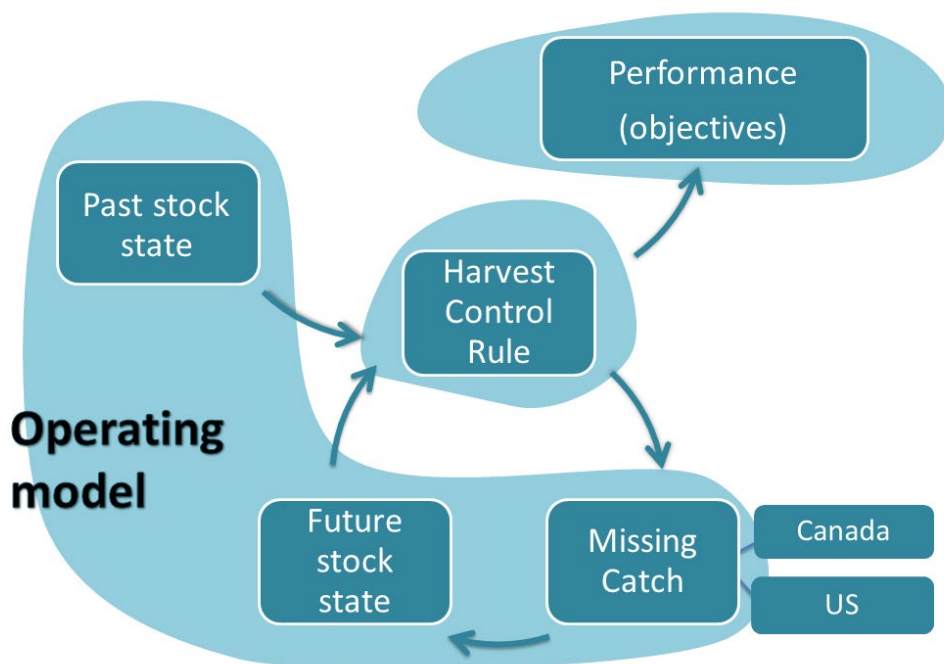

Figure 2. Schematic representation of the simulations performed within the Management Strategy Evaluation.

Details are provided below and all code and data were made available online ([Rproject](#) and [CCAM package](#)). Code was built upon the [R *stockassessment* package](#) (Nielsen et al. 2019).

Operating Model (OM)

Historical OM

The historical component (built with Template Model Builder, Kristensen et al. 2016) is quasi-identical to the statistical catch-at-age assessment model used during the last Canadian mackerel stock evaluation (Van Beveren et al. 2017; Doniol-Valcroze et al. 2019). It is currently a modified version of the SAM model (Stock Assessment Model, Nielsen and Berg 2014) that incorporates censored catch, i.e., catch is predicted between an upper and lower bound to account for uncertainty, using the method from NCAM (Northern Cod Assessment Model, Cadigan 2016). Hence, this model can be perceived as a hybrid of the European SAM model and the Canadian NCAM model used to assess northern cod (DFO 2018a). Equations and parameters are summarized in Table S1. Differences with the 2017 version of CCAM (Doniol-Valcroze et al. 2019) include the modelling method of fishing mortality-at-age (F_a on a log scale was replaced by selectivity at age, Sel_a, on a logit scale; $Sel_a = F_a/\max(F_a)$) and process error on abundance (now identical to SAM rather than NCAM). In contrast to the 2017 (Doniol-Valcroze et al. 2019) and 2019 assessment (Smith et al. 2020), the model was calibrated directly on the estimates of Total Egg Production (TEP) rather than the derived SSB values from the egg survey (see Table S1).

Future OM

The future component (the projections, Table S1) is performed using the following annual steps:

1) Calculate abundance at the start of the next year;

2) Apply process error;

3) Apply the HCR to obtain a TAC (see section 'Harvest Control Rules');

4) Add missing catch to obtain the potential true catch (see section 'Missing catch');

5) Calculate the fishig mortality rate that would result from total fishing-induced mortality;

6) Generate a new set of TEP observations for that year;

7) Get all derived quantities for each simulation (SSB, true catch, etc.);

8) Go to the next year.

The same equations, likelihood distributions and parameter values are assumed as in the historical OM. The only exception is recruitment, for which two different parametric methods were selected. These two methods assume recruitment either follows a Beverton-Holt relationship ($r_{det} = \frac{\alpha SSB_{y-1}}{1+\beta SSB_{y-1}}$, as estimated within the model, Table S1) or fluctuates around an average value ($r_{det} = \mu_r$). Temporal autocorrelation and process variance were included (see Johnson et al. 2016), so that;

$$r_y = r_{det}e^{\varepsilon_y-\sigma_{N_1}^2/2} \, ,$$

where $\sigma_{N_1}^2/2$ is a bias-correction factor for the use of a log-scale and ε_y is the recruitment deviation calculated as $\varepsilon_y = \rho\varepsilon_{y-1} + \varepsilon_{a=1,y}^N\sqrt{1-\rho^2}$, where $\varepsilon_{a=1,y}^N$ is the potential recruitment deviation and ρ is the autocorrelation coefficient. The average value (μ_r) and lag 1 autocorrelation (ρ) were estimated outside the model based on the estimated recruitment series, excluding the first year (using for the latter the acf function in R, R core team 2019).

Non-parametric methods such as the 'expanding window' approach (e.g., DFO 2010, 2011) and simple recruitment sampling (Nielsen et al. 2019) were also considered but were deemed less appropriate. Approaches based on the ratio of recruits over spawners were also tested but appeared less preferable, in particular when dealing with the current low recruitment situation. Independent of the recruitment method employed, when a stock reaches spawning biomass below a given threshold level, it is considered extinct and recruitment stops. Without setting a minimum viable population size, sporadic high recruitment levels might revive a stock that in reality would not have the power to do so anymore, in particular in the absence of a stock-recruitment relationship. Here, the minimum viable biomass was set at 1,000 t, which corresponds roughly to a "guestimate" for highly fecund fish such as mackerel (Dulvy et al. 2004) and is slightly below 1% of $SSB_{F40\%}$.

Potential catch can be unrealistically high so that we limited the future instantaneous fishing mortality rate to 2.5, which is only slightly higher than the maximum historically estimated F of 2.2 (see Kell et al. 2006).

Futher details and equations are published in Van Beveren et al. (2020), in which the same base operating model is used.

Missing catch

Management Procedures provide a simulated TAC through the implementation of a HCR, but in order to appropriately simulate the future stock and fisheries dynamics, the actual fisheries removals are of importance and these can be very different than the adopted TAC (something often referred to as implementation error). In the case of mackerel, two key sources of missing catch can be identi0fied: missing Canadian catch (including mackerel caught for bait, recreationally or discarded) and missing US catch (northern contingent fish caught in US waters). Although both involve catch that is missing from the Canadian statistics, their magnitude and characteristics are different and hence they are considered separately.

Missing Canadian catch is currently uncertain and cannot properly be estimated. Available information is scarce, spatially or temporarily limited or lacks detail (e.g., Van Beveren et al. 2019a). This uncertainty could be reduced in future through measures intended to increase reporting compliance, something that resource users and fisheries managers may pursue. Because the amplitude and speed of change remain subjective estimates, different scenarios of potentially missing future Canadian catches were proposed during 2018 Rebuilding Plan Working Group meetings, some of which incorporated improved reporting rates. During the 2019 assessment, one scenario was selected that best reflected the participants' knowledge and perception of this catch fraction. In this scenario, missing catch is presumed to decrease to 3,000 t. Values are drawn from a normal distribution ($N(\mu, \sigma^2)$, with $\sigma^2 = \mu/8$ and μ following the described patterns, lower panel of Figure 3).

More uncertainty is present in the quantity of northern contingent mackerel the US fleet will fish over the projected period, as stock management occurs independently in the two countries. Under most configurations, we presumed that US landings will follow a restricted lag-1 autoregressive process. Because US landings are likely to be partially dependent on northern contingent stock biomass, the US landings were bound to remain between 5% and 30% of the estimated northern contingent stock biomass, as was the case in the last two decades. Predicted US catches were restricted to at most double between years and were limited to a maximum total of 20,000 t. Northern contingent mackerel represent a part of these US catches, and we presumed composition ranges corresponding to the OMs (OMbase presumes 25-50%, see next paragraphs). Simulated fractions of Canadian fish ($Cprop_y$) followed a bounded random walk ($Cprop_y = Cprop_{y-1} + \varepsilon_y$, $\varepsilon_y \sim N(0,0.08)$) starting at a random value sampled from

a uniform distribution spanning the presumed range. The simulations reflect the vast uncertainty in US landings of northern (Canadian) contingent fish.

Future catch by the US could not be fine-tuned for the next 2 to 3 years because quotas have not been approved yet. Council recommendations for the US mackerel ABC (Allowable Biological Catch) for 2019-2021 are significantly higher than the current TAC of 9,177 t (from 19,184 t in 2019 to 23,474 t in 2021). The future catch will likely be a function of mackerel availability and realized strength of the presumed strong 2015 year-class, the river herring/shad bycatch cap (which shut down the US mackerel fishery in 2018) and potentially Atlantic Herring bycatch (whose quotas have decreased in recent years).

The total potential future catch is the sum of the TAC specified by the HRC and the Canadian and US sources of missing catch. A non-random number seed was always used to make projections comparable among scenarios.
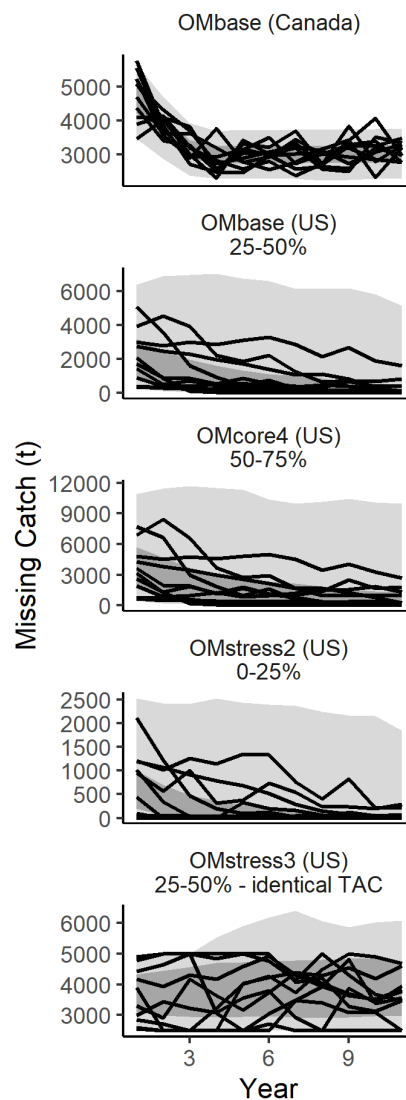

Figure 3. Plots of different missing catch assumptions, for both Canada (upper plot) and the US (lower plots) under HCR 11. The shaded areas indicate the 95% confidence interval (light grey) and the 50% confidence interval (dark grey). Black lines are example trajectories (10 out of 2000).

OM configuration

The base model configuration for the historical part of the simulations is similar to the final settings used during the assessment (Smith et al. 2020). The simulations span age classes 1 to 10 (10 being a plus-group) and cover the period 1968 to 2018. The model was configured so that fish were fully selected from age 5 onwards (flat-topped curve) and fishing mortality was represented as the average value (F_{bar}) over fully selected age classes (5 to 10), which corresponds to the value of F_y. Catch-at-age observation errors were age-class dependent (σ^2_{crl-A} for a=1, σ^2_{crl-B} for a=2, 8 and 9, σ^2_{crl-C} for 1<a<8) and recruitment follows a 2-parameter Beverton-Holt curve (Table S1). For the model conditioning (historical part), a constant natural mortality rate of M=0.27 was used. We tested a multitude of plausible options for M but retained a constant 0.27 value because this provided a reasonable AIC value (Figure S3) and is in correspondence with the assumptions made during the US mackerel assessment. Among the considered options were several constant values in the range of 0.15-0.30, as well as an arbitrarily defined age-dependent M (DFO 2017) and biological index derived values (see Grégoire and McQuinn 2014).

In contrast to the 2016 assessment, the lower and upper catch bounds for the censored likelihood model component were however set differently. During the previous assessment, true catch was presumed to fall between the reported numbers and an upper limit defined based on sparse knowledge of bait use, recreational fishing and discarding. Hence, uncertainty in total removals caused by the US fishery was not incorporated, mainly because of a lack of knowledge. Preliminary results of a new study showed that northern contingent mackerel can represent a significant fraction of US catch, from 67% to 87% (Redding, University of Maryland, pers. comm.). The lower catch bound was here set as the sum of 110% of the declared Canadian landings and 25% of the US landings (excluding foreign fishing). The upper catch bound was the same as defined during the previous assessment (DFO 2017, doubling Canadian catch during the last 2 years) but with an extra 50% of US catch. That is, in addition to the uncertainty around Canadian missing catch we now also presumed that the US catches between 25% and 50% of Canadian contingent mackerel each year (Figure S2). Although this is somewhat more conservative than the values given by Redding (University of Maryland, pers. comm.), this range is closer to previous perceptions and is therefore likely to be perceived as plausible by all involved parties. Given the current age structure of the stock, which is dominated by young individuals less than 5 years of age, insertion of northern contingent fish in US catches might also be somewhat lower than what was estimated by Redding (University of Maryland, pers. comm.) who focused on years (1998-2000) when older fish were more abundant.

For the projection part, the last 25 years of the observed time-series were used to predict data (proportion mature, weight-at-age, etc.) and recruitment was forecasted using the Beverton-Holt stock-recruitment relationship.

Diagnostics of the base case OM (parameter estimations, residual patterns and retrospective analyses) are provided in the supplementary materials (Table S2, Figure S4, Figure S5).

OM uncertainty

During typical stock assessments, a 'best' model is selected and used to provide scientific advice, typically using a short-term forecast under assumptions of fixed annual catch or fishing mortality. There are however always many assumptions that go into both stock reconstruction and forecasting. Some subjective 'choices' among different assumptions are also known to potentially have significant effects (e.g., recruitment relationships Punt et al. 2016). MSE acknowledges these uncertainties explicitly and seeks to find management procedures that provide acceptable trade-offs while being robust to uncertain stock and fishery dynamics.

Specifically, alternative OMs are presented that make different assumptions about historical and/or future aspects of the stock and fishery dynamics. Some of these assumptions are generally perceived to be more likely than others, and can, therefore, be categorized as core (plausible hypotheses) versus stress-test (less plausible, potentially high impact hypotheses). We adopted a '3-classes approach' to categorizing OMs (base, core and stress, sometimes referred to as the reference set (base and core) and robustness tests), as this approach is in line with previous Canadian MSE exercises (e.g., redfish and Atlantic pollock, DFO 2018b; Rademeyer and Butterworth 2011). In this study, core models have quasi-identical credibility as the base OM and management procedures should perform acceptably under their assumptions, whereas stress models are speculative and will mainly be used to diagnose whether imperative conservation objectives can be met under challenging conditions and as supplementary information. The numbering of stress and core model is arbitrary, and all core models are considered to have equal weight when scoring HCRs.

We identified several key uncertainties, which were discussed and supplemented by stakeholder input received during RPWG or technical meetings so that they address concerns stated by all involved (Table 2). Three major axes of uncertainty were identified; recruitment, natural mortality and US catch of northern contingent mackerel.

Table 2. Table with all the operating models (OM) and their description and type. Note that either or both the historical ('Past') and future component of the OM are adapted from the base model ('Period'). All core and stress models have the same configuration as the base model, with one adaptation ('Factor'). (rec = recruitment; M = natural mortality rate; C = total catch)

No.	Type	Factor	Period	details
1	Base	-	-	Recruitment follows a Beverton-Holt curve (past and future) M = 0.27 (past and future) Total catches are assumed to include 25-50% of randomly varying US landings as well as unaccounted-for Canadian catch
1	Core	rec	Future	Future recruitment varies around mean with autocorrelation 0.9
2	Core	M	Future + Past	M = 0.15 (less overall mortality, corresponding to the ICES M value for mackerel)
3	Core	M	Future	M = 120% of M (future increase in natural mortality)
4	Core	C	Future + Past	Total catches are assumed to include 50-75% of US landings
1	Stress	rec	Future	Future recruitment varies around mean with estimated autocorrelation
2	Stress	C	Future + Past	Total catches are assumed to include 0-25% of US landings
3	Stress	C	Future	Total catches are assumed to include 25-50% of US landings and US sets a TAC identical to Canada

Different recruitment forecasting methods exist (e.g. AGEPRO software currently provides 20 stochastic options, Brodziak 2018), and for several, there is little to no reason to select one method over another, although such arbitrary choices can influence results substantially (Punt et al. 2016). This is especially true for mackerel, as the stock is currently dominated by fish younger than 5 years so that recruits quickly comprise an important fraction of the total biomass. To account for this uncertainty, we tested a core model that presumed recruitment to fluctuate around an average value. This method of simulating recruitment is somewhat more optimistic than the base OM (Beverton-Holt) because here we assume recruitment rises to average values over time, and past recruitment has been higher than recruitment in recent years. Because recruitment is currently low, an autocorrelation factor of 0.9 was used to avoid rapid increases (OMcore1). Alternatively, a stress model was included that considers the same approach ('average recruitment'), but with the estimated temporal autocorrelation (ρ=0.26) (OMstress1). In other words, this stress OM represents a scenario in which average recruitment will continue to increase to historical levels, independent of biomass levels. This scenario was perceived to be unlikely by all involved in the RPWG, but was kept within the analyses as a scenario against which others could be compared, reflecting the most optimistic view of the stock dynamics.

The second axis of uncertainty concerns the presumed fixed natural mortality rate. We considered an additional core model with a fixed value of M=0.15 instead (OMcore2). This value is considerably lower than the natural mortality rate set within the base OM (M=0.27) and was selected because of its application to northeastern Atlantic Mackerel by ICES (ICES 2018). Natural mortality might also change in the future; for instance, stakeholders indicated that predation by grey seals is increasing in the Gulf of St. Lawrence. A core model (OMcore3) was therefore developed in which projections include a 20% increase in M.

The third and perhaps largest axis of uncertainty is related to the fraction of US catches made up of Canadian contingent fish. In a fourth core model (OMcore4), the fraction of US catches of northern contingent fish was consequently set to be between 50% and 75% rather than the previously assumed 25% and 50% (Fig S2). This involves using increased upper and lower bounds in the model fit (historical part) and the prediction of a larger quantity of future missing catch (future missing catch part). This core model (OMcore4) reflects more closely the findings of Redding (University of Maryland, pers. comm.). Alternatively, a stress model was added in which US catch is considered to be of lower importance (0-25%, OMstress2; Figure S2). This OM can be used to better assess the impact of US catches. For OMstress3, we presumed that US catches, instead of following an autoregressive process, would be determined based on the Canadian HCR. That is, under this stress test scenario, the US and Canadian quota decisions would be identical. Although this does not reflect current management regimes, this scenario shows the potential effect of joint management; and, under HCR 2 (Canadian TAC and hence US TAC = 0) the effect of exclusively removing Canadian missing catch. Examples of all missing catch scenarios are given in Figure 3.

Harvest Control Rules (HCRs)

Many types of HCRs are proposed in the literature (e.g., Huynh et al. 2018), and we only focus on a few empirical HCRs which appear promising for this mackerel stock (listed in Table 3). Model-based HCRs were withdrawn from consideration because they have to deal with biased catches, are by consequence highly complex and necessitate a biannual stock assessment. Each of the HCRs tested resulted in an annual TAC.

No quota

We investigated the effect of setting the TAC at 0 t for the whole projection period (with and without implementation error; HCR 1 and HCR 2). These simulations were performed because

of their ease of understanding and their help in providing a benchmark for the effects of fishing. Specifically, simulations under no quota provide estimates of minimum stock rebuilding time, growth, etc. For this HCR, we made a distinction between simulations where implementation error (missing catch) still occurs (HCR 2) and where F=0 (no missing catches, including from the US, HCR 1).

Egg index based

The annual estimate of Total Egg Production (TEP) is the main indicator of Atlantic mackerel SSB. Focussing on this index exclusively has the advantage that HCRs are easy to understand and calculate (no models are required) and that the TAC could, if worthwhile, be applied on a yearly basis as the workload is relatively small. Despite their simplicity, such HCRs have been shown to perform well in some contexts (Geromont and Butterworth 2015; Carruthers et al. 2016) and avoid the use of unreliable catch data in calculating TAC recommendations. We analysed two types of TEP-based HCRs, that differed in complexity.

Relative change ('simple egg index')

The first method increases or decreases the TAC annually and proportionally to the observed change in the TEP (HCR 3, Table 3):

$$TAC_{y+1} = TAC_y \, \frac{I_y^{recent}}{I_{y-1,y-2,y-3}^{ref}}$$

where I_y^{recent} is the last year TEP value and $I_{y-1,y-2,y-3}^{ref}$ is the geometric mean of the 3 previous values. The ratio between both values is the relative change in TAC from one year to the next. As TEP can fluctuate considerably from one year to the next, we limited this relative change to a decrease by 50% or a 200% increase (halving or doubling). Note that this approach requires a 'starting TAC', which was set as the current TAC (10,000 t).

Target based ('target egg index')

The second approach uses egg index (TEP) target points, and the TAC is set based on the recent index values relative to these targets (modified from Geromont and Butterworth 2015). A lower (I_{low}) and upper (I_{high}) target are defined, which shape three potential TAC regimes depending on relative stock status (Figure 4A);

$$I_y < I_{low} \qquad\qquad TAC_{y+1} = TAC_{low}\left(\frac{I_y}{I_{low}}\right)^3 \text{or } TAC_{y+1} = TAC_{low}$$

$$I_{high} \geq I_y \geq I_{low} \qquad TAC_{y+1} = TAC_{low} + \left(TAC_{target} - TAC_{low}\right)\left(\frac{I_y - I_{low}}{I_{high} - I_{low}}\right)$$

$$I_y > I_{high} \qquad\qquad TAC_{y+1} = TAC_{target}$$

where I_{low} and I_{high} are the geometric means of predefined reference periods (Figure 4A), I_y is the geometric mean of the 3 most recent TEP values and TAC_{low} and TAC_{target} are the Total Allowable Catch corresponding to I_{low} and I_{high} respectively.

We analysed several variations of this curve, shown in Figure 4B. For instance, some HCRs (HCR 4 and HCR 5) set the minimum (floor) TAC to be zero as soon as $I_y^{recent} < I_{low}$, because from a management point of view, it might be easier to close the fishery than to manage extremely low quotas. In general, HCRs that output significant stepwise changes in removals can cause disagreement on whether the stock status is below or above the threshold causing the change. The disadvantage of HCR 4, which allows a jump from 0 t to 8 000 t (I_{low} in middle

stage replaced by 8 000 t), is that small differences in the egg survey when around I_{low} could result in drastic changes for the fishery. This might be a less desirable scenario if relative TAC stability were to become a fishery objective. Therefore, we also tested a HCR (HCR 6) that puts in place a ramp between 0 t and 8 000 t (quadratic term in first stage). At the request of managers and stakeholders in the RPWG, different lower catch caps were also tested when the stock is perceived to be in low biomass state (HCRs 7 to 11). A gradual TAC increase can occur once the lower index target (I_{low}) is surpassed. Note that because the current index value is below I_{low}, next year's TAC under target based HCRs is equal to this minimum TAC (except for the HCR that specifies a ramp).

Table 3. Table of Harvest Control Rules (HCRs) used in candidate management procedures considered for the Northwest Atlantic mackerel (Subareas 3-4) MSE. (TAC = total allowable catches). HCRs 1 and 2 (in grey) are used for baseline projections to set a benchmark for the effects of fishing.

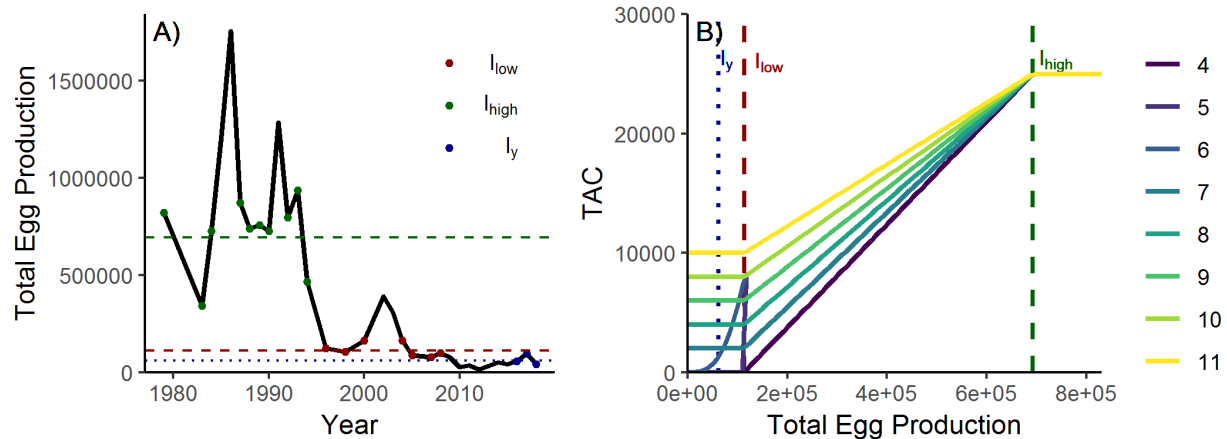| No.	HCR	Floor, or Minimum TAC	Notes
1	F=0	0 t	This HCR produces a baseline of stock potential rebuilding, when there are no fisheries removals by Canada or the US (no implementation error)
2	TAC=0 in Canada	0 t	This HCR produces a baseline of stock potential rebuilding, but includes implementation error (where actual fishing mortality varies above 0).
3	Simple Egg Index	none	TAC is calculated each year based on the relative change in the total egg production estimate
4	Target Egg Index	0 t (increase: linear)	The HCR calculates TAC each year according to Figure 4. In the rule, TAC is capped at a maximum of 25,000 t once the 3-year running egg survey average reaches the target.
5		0 t (increase: jump)	
6		0 t (increase: ramp)	
7		2,000 t	
8		4,000 t	
9		6,000 t	
10		8,000 t	
11		10,000 t	

Figure 4. A) Annual Total Egg Production estimates from the egg survey with indication of the target reference points (I_{low}, I_{high} and I_y) and B) the Harvest Control Rules (HCRs 4 to 11) that define the TAC based on the presumed current stock state (I_y).

Performance metrics

The state of the stock (SSB_y) was defined relative to a limit (LRP) and proposed upper stock reference point (USR), which were set as respectively 40% and 80% of SSB_{ref}, 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} which has been customary for this stock (see Doniol-Valcroze et al. 2019; Duplisea and Grégoire 2014; TRAC 2010). This reference point is the fishing mortality rate that reduces the spawning biomass-per-recruit (SPR) to 40% of its unfished levels (Goodyear 1977; Shepherd 1982). The OM specific SPR was calculated as in the *stockassessment* package (Nielsen et al. 2019) and was based on estimated fishing selectivity, M and weight- and proportion mature-at-age values averaged over the last 15 years. The corresponding SSB was obtained by multiplying the the SPR value at $F_{40\%}$ with the average estimated recruitment.

The spawning stock biomass was estimated to be below the LRP, i.e., assigned to be in the Critical Zone since 2011 (SSB at 40% of the LRP, DFO 2009, 2017). To calculate a *reasonable timeframe* to get out of this zone (which policy guidance suggests as 1.5 to 2 generations; DFO 2009), several approaches based on generation time were used (Appendix: Rebuilding timeframe), which provided guideline estimates of a generation time of roughly around five years, and less if the currently truncated age structure is taken into account (Figure S6). Additionally, the minimum time necessary for spawning stock biomass to grow above the LRP (Tmin) was determined based on preliminary simulation results, using data for the stock up to 2016 (presented at the September 2018 RPWG meeting). Estimates of Tmin build in the effects of generation time and current stock depletion and are used by New Zealand's Ministry of Primary Industry to set rebuilding timeframes (2*Tmin, New Zealand Ministry of Fisheries 2014). This analysis showed that under all OMs, it would take approximately three years for the stock to rebuild above the LRP in the complete absence of any fishing mortality (HCR 1, F = 0). The estimated time to rebuild above the LRP increased substantially with increasing levels of catches (both declared catches associated with the TAC and both Canadian and US missing catches). Although in this document minimum rebuilding times were updated, it was apparent earlier on in the process that the stock is very likely to remain below the LRP over the next

couple of years. As a consequence, at the time of writing there was no prior agreement by the RPWG as to what a reasonable timeframe might be to reach rebuilding objectives and a candidate period between 5 and 10 years was suggested by management and stakeholders.

The preliminary results also showed that several long-term objectives related to the stock reaching the USR (i.e., the Healthy Zone), developed by the RPWG in March 2018, might be hard to reach within proposed time horizons. Simulations across OMs showed that sustained high levels of missing catches, including US catches, could preclude rebuilding to above the USR over 25-year simulation timespans, even under HCRs setting low or no TACs for Canadian declared catches.

The list of objectives and performance metrics (Table 4) was therefore further refined in September and December 2018 and March 2019 by the RPWG, focusing only on short-term objectives aimed at rebuilding the stock above the LRP. Given the depleted state of the mackerel stock, this list includes an additional set of short-term performance metrics that could help to set milestones in accordance with the guidelines for the development of rebuilding plans developed by DFO (DFO 2009). Milestones are very short-term targets (e.g., Brattey et al. 2018) that are defined in order to track rebuilding progress as the stock grows through and out of the Critical Zone to higher rebuilding targets (DFO 2009). Milestones should assist in the realisation of the primary rebuilding objective to rebuild the stock above the LRP (Table 4), i.e., they are objectives defined for shorter time frames.

Long-term objectives related to the stock achieving higher biomass levels (e.g. a USR or target reference point, DFO 2009), while not being evaluated further here, were considered useful for the future development of the Rebuilding Plan when stock status has improved (Table S3). Long-term objectives could be refined and used to identify acceptable HCRs in future stages of the MSE process. Because of the short-term focus of the process, exceptional circumstances have likewise not been defined to date.

For each combination of OM (8) and HCR (11), we performed 2000 simulations. Performance metrics were calculated for each scenario as an aggregation of these simulations (e.g., a median or the percentage of simulations reaching a certain goal or threshold specified by the performance metric; Table 4).

Table 4. Candidate objectives and milestones (following the March 2019 meeting), to be used to guide the present analysis and science advice for the rebuilding plan for Atlantic Mackerel. The focus is on rebuilding objectives. (LRP = Limit Reference Point; SSB = Spawning Stock Biomass)

No.	Goal	Objective	Performance Metrics	Prob.	Time	Details
1	Rebuild SSB.	Rebuild Atlantic Mackerel SSB above the LRP.	Probability that SSB > LRP	75%	5 and 10 years	The number of times SSB at the beginning of the year is simulated to be below the LRP (defined as $0.4*SSB_{F40\%}$) at a given moment in time (3, 5 or 10 years) divided by the total number of simulations (2000).
			Milestones	**Prob.**	**Time**	
			Probability that SSB > LRP	65%	3 years	
2	Avoid stock decline.	Limit the probability of SSB declining from one year to the next.	P(decline)	95%	5 and 10 years	The number of times there is decline ($SSB_{y+1} < SSB_y$) over all specified years and simulations divided by this total.
			Milestones	**Prob.**	**Time**	
			P(decline)	75%	3 years	
3	Maximize catch	Keep annual catch as high as possible	Median catch	n/a	5 and 10 years	Median catches over a given time span, whereby the median is taken over all years and simulations.

RESULTS

OM FITS, DIAGNOSTICS AND ESTIMATES

All OM conditioning fits converged and maximum gradient components were <0.001. Inspection of residuals (Figure S4) for the survey index showed that survey values were somewhat more likely to be overestimated than underestimated, possibly due to non-stationary processes that have not been considered in the current model formulation. Attempts to correct the bias by allowing for changes in fishery or survey selectivity (2 blocks reflecting pre- and post-2000) did not significantly improve the pattern of survey residuals. Other causes could include changes in natural mortality or fecundity, for which however no data are available. There were no important retrospective patterns (Figure S5). Only final year F estimates varied, but generally within the confidence interval, when retrospective peels were performed, as a result of the model's flexibility created by the censored catches.

Estimated patterns of spawning stock biomass, fishing mortality and recruitment (Figure 5) do not differ significantly from the 2017 assessment (Doniol-Valcroze et al. 2019) and are discussed in more detail in Smith et al. (2020). Note that recruitment estimates of the last decade have been among the lowest in the time series and that, on average, recruitment has been decreasing. Although there has been a decline in fishing mortality since 2010, exploitation has remained fairly constant in the last 5 years and at levels coincident with stock decline from the late 1990s to date. All four historical OM fits resulted in similar patterns and differed mainly in the magnitude of estimated biomass and recruitment, particularly in the first half of the time series when the stock was more abundant and stock indexing was not available. When overall natural mortality is assumed to be lower (OMcore2 with M=0.15) this is partially compensated by increased fishing mortality, although the stock is estimated to be less productive as a result and therefore had lower estimated biomass. Predictably, biomass and recruitment are estimated to be higher relative to the base model when a larger quantity of US catch was included (OMcore4, missing US catch 50-75%) and vice versa (OMstress2, missing US catch 0-25%). All OMs place this stock within their respective Critical Zones (each OM has a different biomass scale and LRP absolute value, although the LRP of $0.4SSB_{F40\%}$ is calculated the same way for each OM configuration, Table 5). The 2018 spawning biomass was estimated at values ranging from 56% to 84% of the model's corresponding LRP, so all models indicate the stock is currently in the Critical Zone (Table 5). Parameter estimates and AIC values for all historical OM fits are given in Table S2. The base case model only had the second lowest AIC value (6 units higher than OMstress2), but this stress-test OM (presuming 0-25% of northern contingent mackerel in US catch) is less plausible assuming the results of Redding (University of Maryland, pers. comm.) obtained for 1998 to 2000 persist over longer time periods.
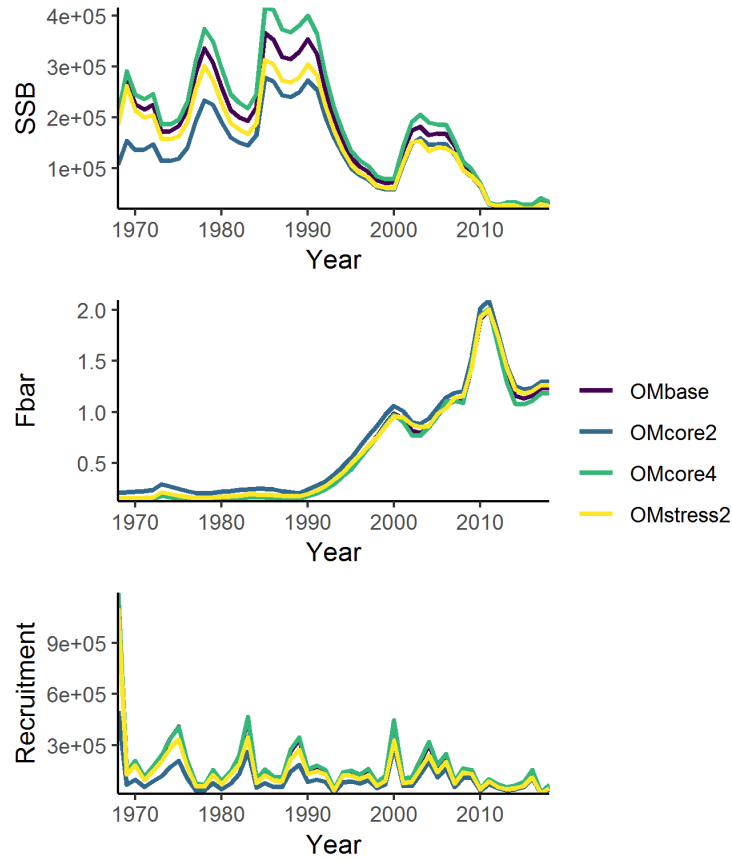
Figure 5. Patterns of SSB, $F_{\overline{5-10}}$ and recruitment for the different historical operating models.

Table 5. Reference point values for the different historical OMs (LRP = Limit Reference Point or 40% of $SSB_{F40\%}$; USR = candidate Upper Stock Reference or 80% of $SSB_{F40\%}$, and candidate Removal Reference of $F_{40\%}$), estimated 2018 SSB and F (averaged over ages 5 to 10) and the ratio of SSB over the LRP. Biomasses are given in kt and SSB is given for the beginning of the year.

OM	$F_{40\%}$	$SSB_{F40\%}$	LRP	USR	F_{2018}	SSB_{2018}	SSB_{2018}/LRP
OMbase	0.70	108.55	43.42	86.84	1.24	34.91	0.80
OMcore2	0.28	135.06	54.02	108.05	1.29	30.16	0.56
OMcore4	0.66	115.35	46.14	92.28	1.19	38.98	0.84
OMstress2	0.72	94.10	37.64	75.28	1.27	29.92	0.79

MINIMUM REBUILDING TIMEFRAME

Minimum rebuilding timeframes were calculated to inform management on timeframes to reach the objectives. In Figure 6, we show trajectories of the probability to get out of the Critical Zone for the 8 OMs under the two baseline HCRs. Under F = 0 (HCR 1, total absence of fisheries removals) the minimum time to rebuild the stock above the LRP (with 75% probability) would likely be between 3 to 8 years, depending on the OM assumptions. With a Canadian TAC of 0 t but with missing catches on both the Canadian and US side (HCR 2), the time to get above the LRP with high probability (75% or higher) would likely take at least 5 years, and possibly longer than 10. Under this catch scenario, the probability of getting out of the Critical Zone can reach a

plateau in the future below the 75% threshold because of the missing catch alone. Shorter rebuilding time spans were generally more probable if future recruitment levels increase relative to recent years (OMstress1 and OMcore1), whereas the longest probable time to rebuild corresponded to the scenario in which natural mortality increased by 20% compared to present levels (OMcore3).
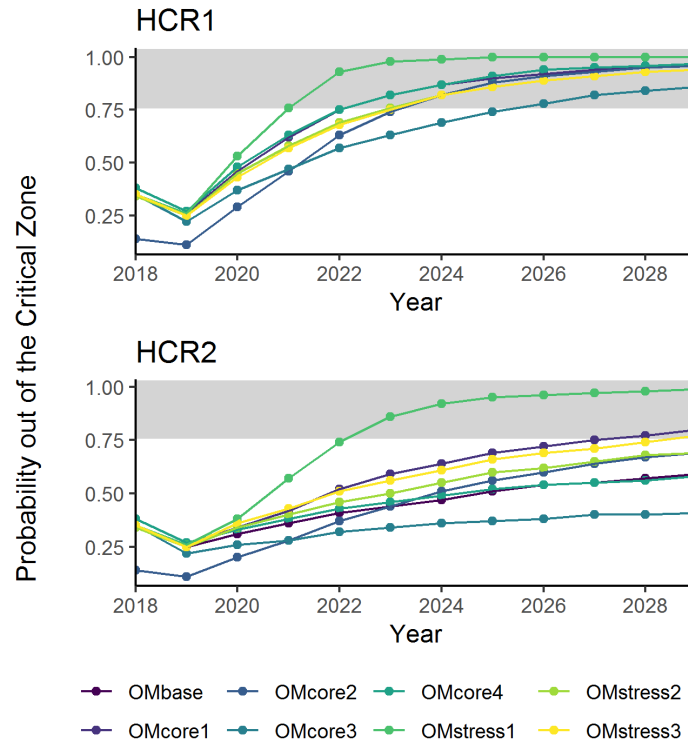

Figure 6. Minimum number of years to get out of the Critical Zone under various OMs and baseline fishing scenarios (HCR1 with F=0 and HCR2 with TAC=0 but missing Canadian and US catch levels corresponding to the OM assumptions).

Other factors also contribute to the estimated rebuilding trajectories. Regardless of OM, the stock biomass at present is within the Critical Zone and needs to increase significantly in order to reach the LRP. This is especially true given the predicted biomass decline in 2019, caused by high 2018 catches (further diminishing the 2015 year class) and low recruitment in recent years. Indeed, recruitment levels during the last decade and especially the last 2 years have been particularly low (Figure 5). Because all forecasts presume a certain level of temporal autocorrelation in recruitment and depend on a stock-recruitment relationship (OMbase), large recruitment events are estimated to be relatively unlikely to happen in the near future as well.

PERFORMANCE OF MANAGEMENT PROCEDURES

Objective 1: Rebuild Atlantic Mackerel SSB above the LRP

To address this objective and the associated 3-year milestone, we estimated the probability (percentage of simulations) that the estimated January SSB will be above the LRP in 3, 5 and 10 years (2022, 2024 and 2029; Figure 7). Over a 5- or 10-year period and under most scenarios, the vast majority of management procedures did not reach the candidate 75% probability threshold initially specified by the RPWG and considered in the PA policy (DFO 2009) to represent a "high probability." This was often the case even under OMs representing

optimistic recruitment scenarios (OMcore1 and OMstress1). The first objective was met within the shortest period (5 years) only under the baseline "management procedure" using HCR 1 (F = 0; i.e., no fishing mortality from either Canada or the US), and only so if there would be no increase in natural mortality. Although the likelihood for rebuilding to the LRP increased over a longer time span (10 years or by 2029), most management procedures under most scenarios still did not reach the objective with 75% probability. Over either 5 or 10 years, the least conservative HCRs (e.g. HCRs 8 to 11) generally had a probability of rebuilding out of the Critical Zone that was lower than 50% in the majority of core OM scenarios, indicating this objective was more likely not to be reached than reached.

Similar to objective 1, milestone 1 is a performance metric aimed at evaluating the performance of HCRs in rebuilding the SSB above the LRP, but over a shorter time interval (Table 4). The candidate performance threshold for the simulations was thus set at 3 years (2022) with a probability of the SSB exceeding the LRP by 65%, based on preliminary inputs from the RPWG. Results showed that this candidate performance threshold could not be attained by most management procedures under most scenarios, similar to the results for the corresponding longer-term objective (Figure 7).

The probability of rebuilding above the LRP was influenced by several factors, some more important than others. Among baseline management procedures, the large difference in performance between HCR 1 and HCR 2 demonstrates the magnitude of the effect of missing Canadian and US catch on management procedure performance. Within a given management procedure, performance is slightly improved if it is assumed that the US would set quotas in parallel with Canada, particularly under management procedures using HCRs with relatively lower floor TACs (OMstress3). Likewise, preliminary analyses showed that uncertainty concerning the quantity of Canadian missing catches (i.e., a future decrease to ~ 3,000 t) can also cause differences between the OMs within a single HCR, especially for the least conservative ones. However, its assumed magnitude was lower than the floor TAC levels of HCRs 9 to 11 (6,000 t to 10,000 t), indicating that even in the complete absence of Canadian missing catches, these less conservative HCRs would perform poorly in terms of the rebuilding objective.

Another important driver of performance against the rebuilding objective was recruitment. If average future recruitment increased over time (slowly so under OMcore1 and quickly under OMstress1), chances of the stock biomass rebuilding above the LRP sooner became significantly higher, especially over the long-term (Figure 10). Nonetheless, without an improvement in stock status and environmental conditions, such recruitment scenarios are considered to be less likely (Smith et al. 2020) compared to the scenarios used in the base OM.

Assumptions around natural mortality and the fraction of northern contingent mackerel in the US fishery were on the other hand of lesser influence, especially if floor TACs were relatively high (e.g., HCR 11, Figure 10). This is because estimated stock productivity was directly related to the incorporated fraction of US catch or natural mortality. If historical removals were thought to be higher, the stock was estimated to be more productive and hence capable of withstanding larger future mortalities. Thus, removals and stock productivity partially balance each other, generating smaller effects on rebuilding objectives.

The simplest HCR (HCR 3), starting at a TAC of 10,000 t and adjusting thereafter based on a 3-yr average of the egg index, always performed poorly in terms of the specified objectives and thus its results will not be discussed further.
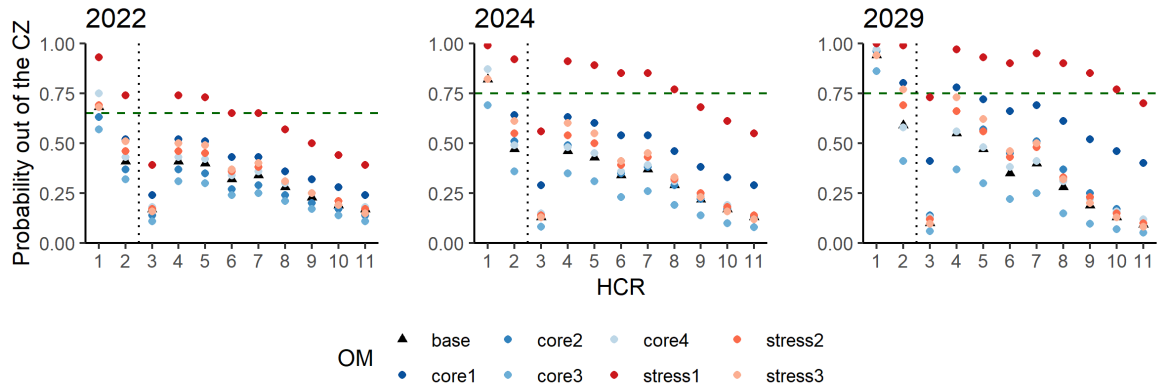
Figure 7. Probability of getting out of the Critical Zone (CZ) after 3, 5 and 10 years (2021, 2023 and 2028) when applying different Harvest Control Rules (HCRs), for different operating models (OMs). The dashed horizontal line indicates the 65 % (3 year milestone) or 75% (5 or 10 years objective) probability threshold. The dotted line separated the baseline HCRs (HCR 2 and 3).
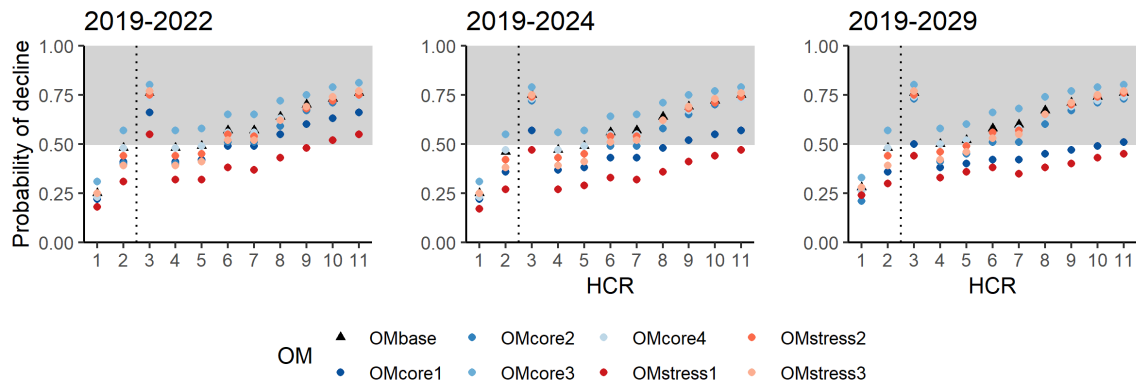
Figure 8. Probability of stock decline from one year to the next over 3, 5 and 10 years (2019 to 2021, 2023 and 2028) when applying different Harvest Control Rules (HCRs), for different operating models (OMs). The grey area indicates probabilities above 50%, when interannual decline is more likely than growth. The dotted line separated the baseline HCRs (HCR 2 and 3).
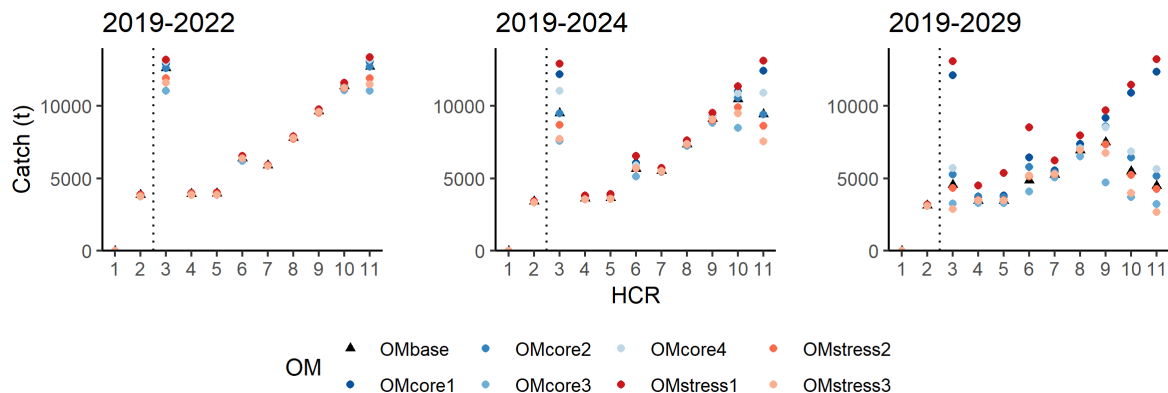
Figure 9. Median Canadian catch (including catches reported under TAC and missing Canadian catch) over the specified periods of 3, 5 and 10 years (2019 to 2021, 2023 and 2028) when applying different Harvest Control Rules (HCRs), for different operating models (OMs). The dotted line separated the baseline HCRs (HCR 2 and 3).
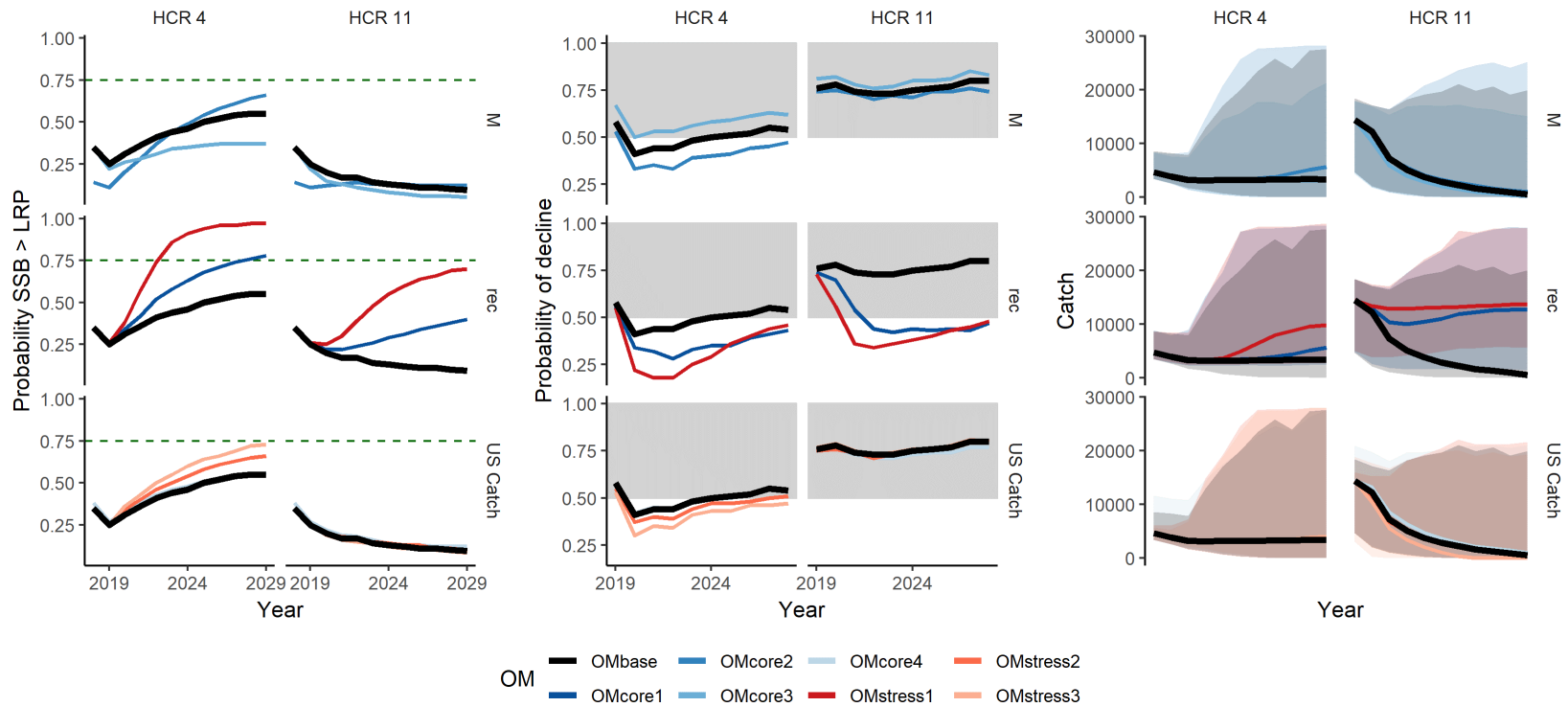
Figure 10. Ten year trajectories of the performance metrics for three objectives (probability of Spawning Stock Biomass (SSB) > Limit Reference Point (LRP), probability of year-to-year decline and median projected Canadian catch) under different Operating Models (OMs) for two Harvest Control Rules (HCRs, 4 and 11 with a floor TAC of 0 t and 10 000 t, respectively). OMs are categorized by the uncertainty they reflect (M: natural mortality, OMcore2, OMcore3; rec: recruitment, OMcore1 and OMstress1; US Catch, US catch of northern contingent fish, OMcore4, OMstress2, OMstress3), compared with OMbase in all cases. For the probability of the SSB rebuilding above the LRP (left panel), the 75% probability threshold is indicated with a dashed green line. For the probability of decline (center panel), the grey area indicates when stock decline is more likely than stock increase. For the catch objective (right panel) the shaded areas indicated the 95% confidence interval.

Objective 2: Limit the probability of interannual SSB decline

The second rebuilding objective spoke to avoiding a decline in SSB, or inversely maintaining a positive growth trajectory in SSB. In the performance metric for this objective (2), the probability of decline was defined as the number of times there was a decline ($SSB_{y+1}<SSB_y$) over a given number of years and all simulations, divided by this total. As for objective 1, we considered a 3, 5 and 10 year period (2019-2022, 2019-2024 and 2019-2029). Although the RPWG did not specify a performance threshold, the probability of interannual decline was never below 17%, indicating that a biomass decrease from year to year could never be fully excluded. Inversely, the maximal probability of interannual decline was 81%. Probabilities above 50% mean that interannual stock decline is more likely than interannual stock growth (grey area, Figure 8).

Again, there was a clear trade-off between this probability and the floor TAC of each HCR (Fig 9). HCRs that started with floor TACs of 2,000 t or above had significant probabilities of year-to-year decline (>50% probability of decline) over the next 5 or 10 years. That is, under the base OM scenario, HCRs 6 to 11 scored higher than 50% over both timespans, meaning decline is more likely than growth. Most OM scenarios generally provided rather similar estimates of this metric, especially with higher floor TACs (Figure 9, 10). The only exceptions were again the OMs that were optimistic about recruitment (OMcore1 and especially OMstress1). However, even under these specific scenarios, interannual decline can be more probable than stock growth. Indeed, at a 3-year milestone, results indicated that even with optimal recruitment some HCRs (e.g. HCR 11) perform poorly (probability of decline >50%). The relatively large probabilities of interannual decline over the three-year period, compared with the longer time spans, resulted in part from the below average recruitments estimated for 2017 and 2018, which makes the stock more vulnerable to overexploitation and biomass decline in subsequent years (Figure 10). Even under current low recruitment conditions, the probability of interannual biomass decline was however still below 50% for the most conservative HCRs (HCRs 1, 2, 4 and 5).

Objective 3: Maximise catches

The third objective aimed to maximise catch while trying to rebuild the stock and was used to provide an axis against which trade-offs with objectives 1 and 2 could be examined. We were only interested in projected Canadian catch (TAC + missing Canadian catch) and hence had to remove the presumed quantity of future US removals of northern contingent fish (missing US catch). In all simulations in which potential catch was not attained (potential F exceeded the imposed maximum possible F of 2.5 in the model in 32% of all simulations), the 'lost potential' can be suffered by Canada, the US or both nations (Figure S7). The arbitrary modelling choice of who gets the fish when insufficient abundances are present was however only consequential for the HCRs with large floor TACs, as these HCRs most often pushed exploitation rates to the model limits (Figure S7). Results presented (Figure 9) are based on a roughly 50% split, which did however not alter our conclusions.

Median Canadian catches for different HCRs and OMs over the next 3, 5 and 10 years are given in Figure 9. Because the stock was estimated to be within the Critical Zone, in which zone the floor TAC levels generally apply according to the HCR, the floor TAC levels from each HCR were often consistently applied in projections, especially over the shorter term (that is, consistent with the stock being projected to continue to be in the Critical Zone in those future years). This resulted in median catch values that were highly contingent on floor TAC levels and relatively independent on OM uncertainties (except for the HCRs with the highest floor TACs as noted above). Nonetheless, it was clearly noticeable that at high floor TAC levels (HCR 11 and nearby), median catches drop over the long term as a result of continued high exploitation rates.

Without increased recruitment levels, median catches associated with floor TACs of 6,000 t to 10 000 t were predicted to be unsustainable over the long term due to projected declines in stock biomass.

Trade-offs

Trade-offs show the relationship between performance against the various objectives, as for instance fisheries objectives to maximize catches and rebuilding objectives to increase biomass are inherently conflicting. We focused on the relationship between objective 3 (median catch) and rebuilding objective 1 (SSB>LRP, Figure 11) and 2 (avoid decline, Figure 12).

HCRs with higher floor TACs had a lower probability of reaching the LRP. This relationship was however not always linear, as chances of rebuilding often varied most at lower median catches. That is, under most OMs the probability of rebuilding increased for instance more steeply between median catches from 5,000 t to 0 t than from 10,000 t to 5,000 t. Unless future recruitment on average increased (OMcore1 and OMstress1), the trade-off plots also showed a clear turning point, at which both the probability of rebuilding and median catches started to decrease (HCR 3 and 9 to 11), especially over the next 5 to 10 years.

The considered time span had the most significant influence at the extremes of the trade-off plot. At low median catches rebuilding probabilities increased quickly over time (upper left corner, Figure 11), whereas at the other end of the spectrum (lower right corner, Figure 11) median catch could drop meaningfully over the defined periods. For HCRs with intermediate catches, the difference between the 3 year (for milestones), 5 year and 10 year timespan was generally small (Figure 11, broken out by time span in Figure S8).
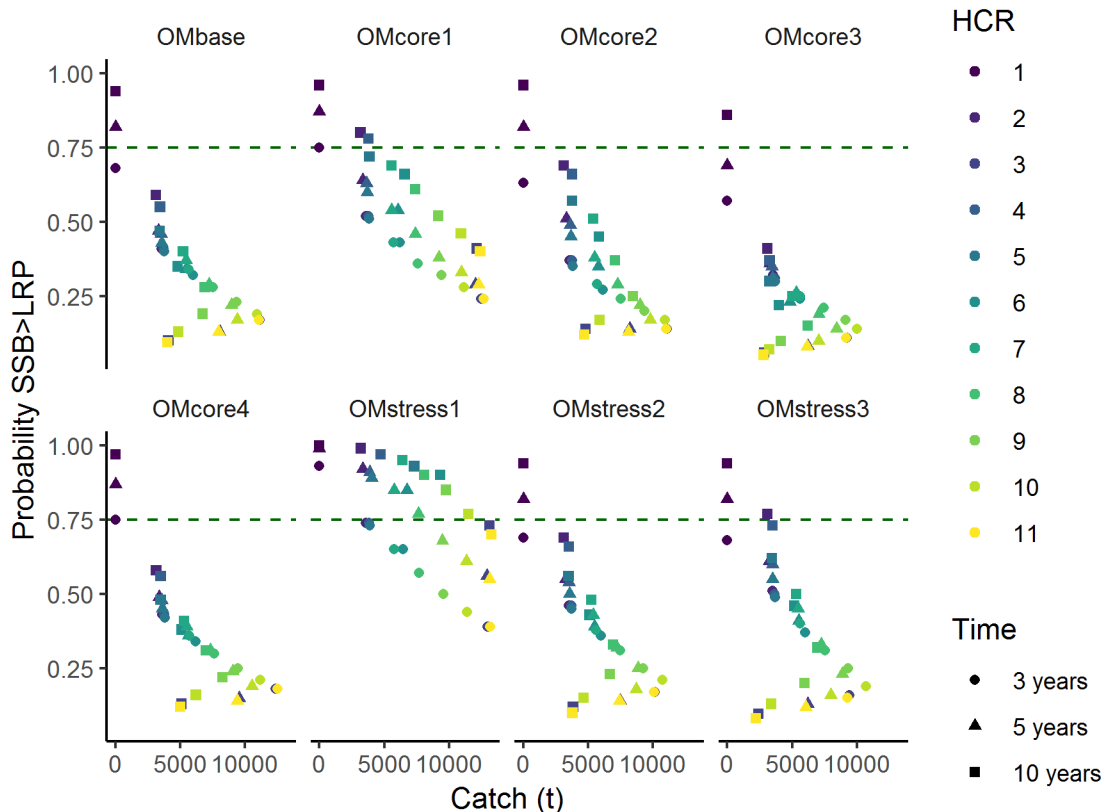
Figure 11. Trade-off between objective 3 (median catch) and objective 1 (probability SSB>LRP) for different HCRs (colors) over the three time spans (dot types). Panels show the OMs.

When median catches increased, so did the probability of interannual biomass decline (Figure 12, Figure S9). This relationship generally had a non-linear pattern, as the chances of decline increased quickly in the beginning (lower end of the catch metric), but started to stagnate at higher catch levels. Again, the overexploitation threshold was visible, at which HCRs produced increasingly lower catches but also peak probabilities of decline.
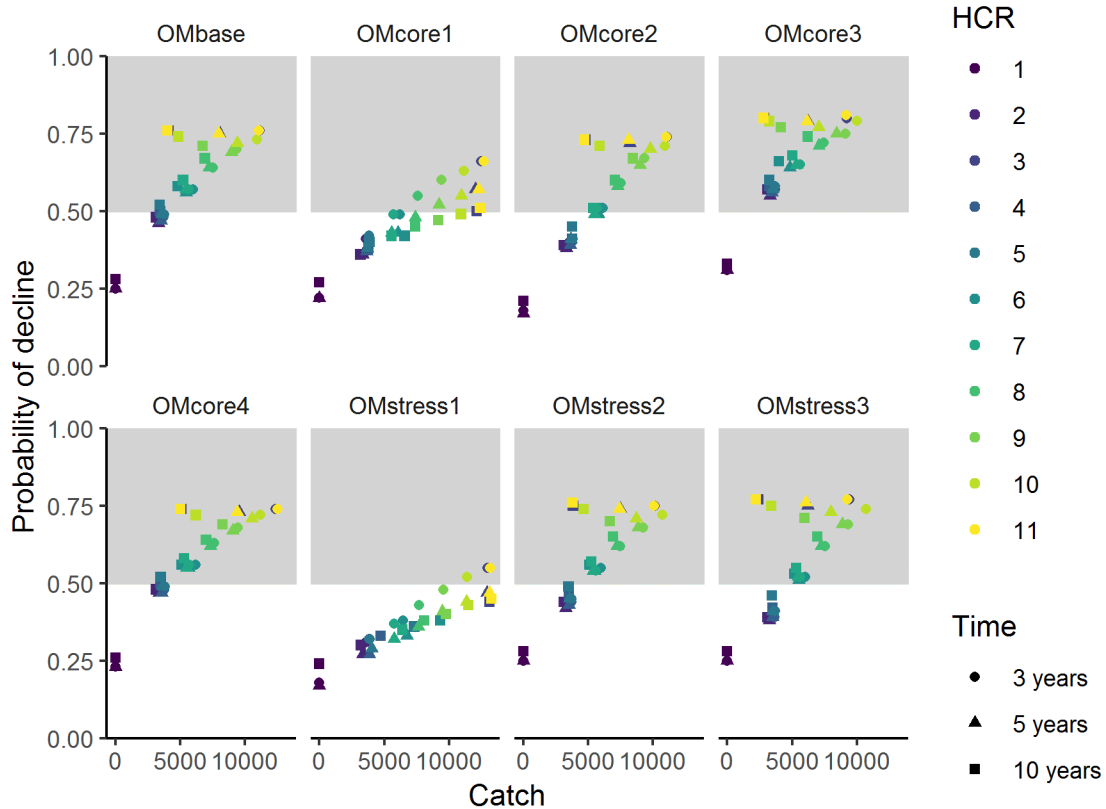
Figure 12. Trade-off between objective 3 (median catch) and objective 2 (probability of decline) for different HCRs (colors) over the three time spans (dot types). Panels show the OMs.

Summary of Results

To assist with evaluating the performance of the 11 HCRs against the candidate objectives, milestones and associated performance thresholds prepared by the RPWG as of this writing are presented in a summary table below (Table 6). This table focuses on the range end scores of the suite of base and core OMs, as any HCR should ideally perform adequately under all such OMs. Individual scores for each OM, HCR and time span were compiled in Table S4.

Table 6. Minimum (objective 1 and 3) or maximum score (objective 2) of base and core OMs for the three objectives by HCRs included in management procedures. The base OM score is in brackets. Note that HCR 1 and 2 represent a constant TAC of 0 t (without and with US catches of northern contingent fish, respectively) regardless of stock status and represent a baseline for comparison with other HCRs. Scores were color coded for the rebuilding objectives (1 and 2) according to the criteria that is first met:

Dark Blue   scores under all core and base OMs meet the objective with the candidate performance threshold indicated in the table

Light Blue   scores under base OM conditions meet the objective with candidate performance threshold indicated in the table

Dark Green   scores under all core and base OMs more likely than not (>50% - objective 1, or < 50% - objective 2) to meet the objective

Light Green   scores under base OM conditions are more likely than not (>50% - objective 1, or < 50% - objective 2) to meet the objective

		Objective 1 (probability SSB>LRP)			Objective 2 (probability of decline)			Objective 3 (median catches)		
Time(y)		3	5	10	3	5	10	3	5	10
Thresh.		>65%	>75%	>75%	<25%	<25%	<25%	NA	NA	NA
Harvest Control Rule	1	57% (68%)	69% (82%)	86% (94%)	31% (25%)	31% (25%)	33% (28%)	0 kt (0 kt)	0 kt (0 kt)	0 kt (0 kt)
	2	32% (41%)	36% (47%)	41% (59%)	57% (48%)	55% (46%)	57% (48%)	3.6 kt (3.6 kt)	3.3 kt (3.3 kt)	3.1 kt (3.1 kt)
	3	11% (17%)	8% (13%)	6% (10%)	80% (76%)	79% (75%)	80% (76%)	9.2 kt (11.1 kt)	6.2 kt (8 kt)	2.8 kt (4.1 kt)
	4	31% (41%)	35% (46%)	37% (55%)	57% (48%)	56% (47%)	58% (50%)	3.7 kt (3.7 kt)	3.5 kt (3.5 kt)	3.3 kt (3.4 kt)
	5	30% (40%)	31% (43%)	30% (47%)	58% (49%)	57% (49%)	60% (52%)	3.7 kt (3.8 kt)	3.5 kt (3.6 kt)	3.3 kt (3.4 kt)
	6	24% (32%)	23% (34%)	22% (35%)	65% (57%)	64% (56%)	66% (58%)	5.6 kt (6 kt)	4.8 kt (5.4 kt)	4.0 kt (4.8 kt)
	7	25% (34%)	26% (37%)	25% (40%)	65% (57%)	65% (57%)	68% (60%)	5.6 kt (5.7 kt)	5.3 kt (5.4 kt)	5.0 kt (5.2 kt)
	8	21% (28%)	19% (29%)	15% (28%)	72% (64%)	71% (64%)	74% (67%)	7.4 kt (7.5 kt)	7.1 kt (7.2 kt)	6.2 kt (6.9 kt)
	9	17% (23%)	14% (22%)	10% (19%)	75% (70%)	75% (69%)	77% (71%)	9.1 kt (9.3 kt)	8.4 kt (8.9 kt)	4.1 kt (6.7 kt)
	10	14% (19%)	10% (17%)	7% (13%)	79% (73%)	77% (72%)	79% (74%)	10.0 kt (10.9 kt)	7.0 kt (9.4 kt)	3.2 kt (4.9 kt)
	11	11% (17%)	8% (13%)	5% (9%)	81% (76%)	79% (75%)	80% (76%)	9.2 kt (11.1 kt)	6.1 kt (8 kt)	2.8 kt (4 kt)

An alternative way to view the results of management procedure performance, with a specific focus on management procedures that are considered candidates for implementation (e.g., excluding baseline HCRs 1 and 2) would be to compare the relative ranks of performance measures (Table 7; (Williams et al. 2016).

Table 7. Relative performance of candidate management procedures evaluated against three objectives for the northwestern Atlantic Mackerel MSE, at three different time periods (3, 5 and 10 years). Only the base OM ranked results are included here, as performance under the most conservative core OM (i.e., as used in Table 6) generally paralleled the results of the base model. Ranks are in descending order of performance (white to red); a rank of 1 indicates that the management procedure scored the highest of procedures against that objective. Tied ranks are indicated with an asterisk (*). Candidate management procedures for implementation are distinguished by HCRs (3 through 11). SSB = spawning stock biomass. LRP = Limit Reference Point.

HCR	Objective 1 probability SSB >LRP			Objective 2 avoiding decline			Objective 3 maximizing catches		
	3 yrs	5 yrs	10 yrs	3 yrs	5 yrs	10 yrs	3 yrs	5 yrs	10 yrs
3	8*	8*	8	8*	8*	8*	1*	3*	6
4	1	1	1	1	1	1	9	9	8*
5	2	2	2	2	2	2	8	8	8*
6	4	4	4	3*	3	3	6	6	5
7	3	3	3	3*	4	4	7	6	3
8	5	5	5	5	5	5	5	5	1
9	6	6	6	6	6	6	4	2	2
10	7	7	7	7	7	7	3	1	4
11	8*	8*	9	8*	8*	8*	1*	3*	7

A summary of relative performance is as follows (after Williams et al. 2016).

Management procedures using HCRs 4 (target egg index with linear increase) and 5 (target egg index with jump increase) consistently outperformed all other tested procedures against an objective to rebuild the mackerel spawning stock biomass above the LRP and avoid future interannual stock declines, over both the short- and long-term. These management procedures also showed strong trade-offs; they scored poorly against a contrasting fishery objective to maximize median projected catches.

Management procedures using HCRs 6 and 7 performed moderately well against objectives to rebuild above the LRP and avoid stock decline consistently over the next 10 years. Performance against a fishery objective to maximize median projected catches was moderately poor in the short-term but improved to average or above average performance after 10 years.

A management procedure using HCR 8 showed consistent average performance against objectives to rebuild above the LRP and avoid future stock decline over the next 10 years, and average performance against a fishery objective to maximize median projected catches within the next 5 years. However, this management procedure outperformed all other tested procedures in maximizing median projected catches after 10 years.

Management procedures using HCRs 9 and 10 consistently scored moderately poorly against objectives to rebuild above the LRP and avoid future stock decline, but moderately to very well against a fishery objective to maximize median projected catches over the next 3-5 years. At 10 years, however, performance in maximizing catches stabilized or decreased, while remaining above average.

Management procedures using HCRS 3 and 11 were outperformed by all other procedures against objectives to rebuild above the LRP and avoid future stock declines. Strong trade-offs were apparent, but only in the short-term; these management procedures scored the highest in maximizing projected median catches at 3 years, but declined to moderately poor performance at 10 years.

DISCUSSION

The results presented here describe the performance of a range of candidate management procedures for consideration for Atlantic Mackerel, evaluated against candidate fishery and rebuilding objectives related to rebuilding the spawning stock biomass above the LRP and avoiding negative stock growth trajectories. They are intended to support ongoing discussions with the RPWG in developing a rebuilding plan for Atlantic Mackerel and to provide science advice in support of fisheries management decision-making for the 2020 fishing season. In the absence of any new significant scientific information, these simulation results are considered final.

This MSE framework encapsulates what are expected to be the most significant areas of uncertainty in the northern contingent of Atlantic Mackerel apart from missing Canadian catch: namely, the proportion of US catches that comprise northern contingent fish (in both the past and future); natural mortality; and future recruitment. The results of all four different historical OMs indicate that Atlantic Mackerel continues to be in the Critical Zone, consistent with Smith et al. (2020), with SSB estimates that vary between 56 and 84% of the corresponding LRP (Table 5). It is important to note that specific values of reference points (LRP, proposed USR, proposed Removal Reference of $F_{40\%}$) under the precautionary approach framework are recalculated in each model, and each time the stock is assessed. In the case of an MSE where multiple OMs are used, multiple reference point estimates are generated depending on the specific assumptions used about Atlantic Mackerel stock dynamics in the past, such as varying the proportion of northern contingent fish that may be harvested in the US fishery (OMcore4, OMstress2) and less overall natural mortality (OMcore2); however, all represent the same value (i.e., LRP of 40% of $SSB_{F40\%}$).

OBJECTIVES

As currently formulated, few HCRs met the objectives developed to date by the RPWG and no single HCR met all objectives under all base and core OM scenarios. Some general conclusions can be drawn, however.

Initial performance thresholds here for a *reasonable timeframe* were informed both by Atlantic mackerel generation time and stakeholder inputs received through the RPWG, suggesting a time interval of 5-10 years; the draft table of risk tolerances in the PA Policy indicates that "high probability" could range from 75-95% (DFO 2009). Thus, the candidate performance thresholds used here for Objective 1 were set to a 75% probability that the stock would be out of the Critical Zone in 10 years or less.

Rebuilding fish stocks out of the Critical Zone (defined by the LRP) is the "primary objective of any rebuilding plan" (DFO 2009). More specifically, for stocks in the Critical Zone, "a rebuilding plan must be in place with the aim of having a high probability of the stock growing out of the Critical zone within a reasonable timeframe" (DFO 2009). As shown in Figure 7 and in Tables 6 and S4, no true management procedure (HCRs 3-11) were able to meet this performance threshold; the only "HCR" that passed the objectives was a complete absence of fisheries removals (including US catches). When considering only the base OM, a HCR with a floor TAC

of 0 t (HCR 4) was as expected the closest to approaching the first objective with the desired candidate performance threshold. Under conditions of relatively higher levels of exploitation (e.g. HCRs 8 to 11), there was generally a less-than-even chance of recovering, even under the base OM.

Candidate Objective 2 was to limit the probability of Atlantic mackerel stock decline from one year to the next; i.e., to maintain a positive growth trajectory irrespective of the magnitude of SSB in relation to the LRP. As shown in Figure 9 and in Tables 6 and S4, no management procedure had a "low" (<25%, DFO 2009) probability of interannual stock decline. Some management procedures (HCRs 5-11) generally had probabilities of stock decline of > 50% in most scenarios, indicating that year-to-year stock decline was more likely than stock growth over the next 5 or 10 years. Stock decline is especially likely in the short term, due to the estimated low recruitments in 2017 and 2018, which are insufficient to boost the stock biomass under significant exploitation.

Objective 3 is a fishery objective; keep annual catches as high as possible while rebuilding. That is, if multiple HCRs would perform adequately in terms of the rebuilding objective, the HCR that is most favorable to the fishery would ultimately have the best performance. Because objective 1 and 2 showed that, at higher floor TACs, the stock is increasingly unlikely to reach the LRP and the chances of year-to-year decline exceed the chances of stock growth, the stock biomass would decline in turn and would likely not be capable of sustaining higher catches at higher exploitation rates. As a result, most OMs showed that under management procedures with the highest floor TACs (HCRs 9-11), the median projected catches over the long term are actually lower than for management procedures with lower floor TACs (HCRs 4-8).

Within HCRs 3 to 11, which have a feedback component linking stock biomass to TAC, there is thus a clear trade-off between higher rates of exploitation (higher floor TACs, in addition to Canadian missing catch) and the probability and time required for the stock biomass to rebuild above the LRP (objective 1). There is also a clear trade-off between higher rates of exploitation and the probability of a negative growth trajectory (Objective 2). Trade-off analyses also showed that the largest gain in rebuilding metrics (objectives 1 and 2) is gained at the lowest fishing intensities (HCRs 4 and 5).

The HCR that most closely reflects the 2018 *status quo* Canadian TAC (HCR 11, with a floor TAC of 10,000 t) failed to meet all candidate performance thresholds for all objectives and milestones under all OMs, including the stress scenario which allowed for a quick recruitment increase. Under core and base model assumptions, under HCR 11 the stock would never rebuild above the LRP with 75% certainty. Simulation results also showed that HCR 11 was associated with a great likelihood of interannual stock decline (>50%) and a long term drop in median catch because of likely overexploitation.

As mentioned above, a management procedure using a simple egg index rule (HCR 3) to adjust commercial TACs in concert with increases or decreases in SSB performed quite poorly in comparison to others that used HCRs employing a target egg index rule with a floor TAC. The floor TAC is applied at low levels of stock abundance − similar to constant-catch rules (HCRs 4—11). Although the poor performance of the simple egg index rule is likely related to the use of a starting TAC of 10,000 t, it is noted that the target egg index rule with the same starting TAC level (HCR 11) also performed poorly, but better than HCR 3.

MILESTONES

According to DFO's rebuilding guidelines:

"[Milestones] are specific and measureable targets that represent interim "steps" that can be achieved as the stock grows through and out of the Critical Zone. Milestones may be based on such characteristics as positive stock trajectory, biomass targets, restoration (or progress towards restoration) of desirable stock and/or ecological characteristics, and fishing mortality reductions. Milestones may be achievable over relatively short timeframes (e.g. 3-5 years) when compared to the overall period required to grow the stock above the LRP, and can provide a valuable and measurable indicator to ensure rebuilding is on track as determined through performance reviews (Section 11.0). Indeed, the development of milestones plays a dual role; the process will also assist in determining what indicators can be tracked to measure plan performance." (DFO 2009)

Like objectives, milestones should specify a target, a timeframe, and the desired probability. Here, we explored two possible milestones (short-term performance metrics) related to the candidate rebuilding objectives 1 and 2, following initial discussions with the RPWG. The choice for both metrics follows the same reasoning as the objectives and they only differ in their timeline (3 years) and performance threshold (lower than the objectives).

Likewise to the objectives, few simulations of any HCR were able to meet the candidate performance thresholds of both milestones (Table 6). Regarding milestones 1 which relates SSB to the LRP, it is important to note that, under assumptions of multiple OMs, the current SSB estimate for Atlantic mackerel ranges in magnitude from 56 to 84% of the LRP (depending on the historical portion of the OM in question). Thus, future development of milestones set to determine the magnitude of the SSB in relation to the LRP should ensure that the milestone represents an increase in SSB and not a decrease under some sets of assumptions. The second milestone was explored to enable the RPWG to set a milestone for year-to-year stock growth irrespective of the magnitude of SSB. Any milestone should, in this case, ensure that the probability of decline is at the utmost 50%, as otherwise, the stock is more likely to decline than to grow. The HCRs with the highest floor TACs (HCRs 6—11) were increasingly likely to be linked to probable (>50%) stock decline and not growth.

UNDERSTANDING RESULTS OF PERFORMANCE METRICS

Relative performance aside, most HCRs did not meet candidate performance thresholds for rebuilding objectives, even under some of the more optimistic OMs. For 2018, the SSB of this stock was estimated at 56-84% of the LRP, and hence would require an 18-79% increase to reach the first objective. Because metrics are usually calculated for the beginning of the year, the projected 2019 biomass was determined by the fishing pressure exerted throughout 2018 and not yet influenced by any potential HCR. Because estimated exploitation in 2018 far exceeded the candidate removal reference fishing mortality rate ($F_{40\%}$>1.7) and new recruitment (2017-2018) is thought to be limited relative to past conditions, the 2019 stock biomass was always projected to be even further away from the LRP (Figure 10). Hence, to reach rebuilding objectives, any HCR needs to result in a biomass increase larger than 18-79%, as 2018 is already in the past.

Recruitment for 2017 and 2018 was estimated to be at historic lows (Smith et al. 2020). Therefore, no new cohorts exist to boost stock growth in the immediate future, as the current stock is predominantly reliant on the 2015 year class. In the near future, recruitment is therefore considered unlikely to reach historical peaks, because of temporal autocorrelation and the now

visible stock-recruitment relationship. As a result of the latter, HCRs that yield high median catches and keep biomass low, or cause a decline, risk impairing future recruitment.

Finally, note that in the last decade exploitation rates were estimated to be largely above reference values (Table 5, Figure 5). Stock growth can thus only happen through significant reductions of fisheries removals, especially given the current poor recruitment situation. Such a reduction might be particularly hard to achieve in the presence of large quantities of unaccounted-for catches. For instance, although the difference in TAC floor between HCR 10 and 11 (8,000 t and 10,000 t, respectively) might appear substantial (20%), the actual decrease in overall exploitation is much smaller if missing Canadian and US catch remains similar in magnitude.

OTHER CONSIDERATIONS

It is important to note that the HCRs simulated here assume annual data inputs of TEP as derived from the annual egg survey in the Gulf of St. Lawrence. Atlantic mackerel science advice, however, is normally provided on a biannual cycle, although non-comprehensive stock status updates in the form of the most recent TEP value may be possible to provide on an annual basis. The final selection of rebuilding objectives and milestones for a rebuilding plan through the RPWG, which will include time intervals at which stock status updates would be required, will need to be set taking into consideration the resource requirements of DFO Science staff.

RESEARCH AND PROCESS RECOMMENDATIONS

The following elements merit further exploration:

The proportion of US catches that comprise northern contingent fish (both past and present) are imperfectly known, although recent work employing otolith microchemistry suggests that the proportion of northern contingent mackerel could be quite high. If sufficient data were to become available to enable a narrower range of possible proportions to be explored in simulation, some OMs contained here could be ruled out as less likely or adjusted accordingly. The increased knowledge of the proportion of northern contingent fish caught by the US fishery could result in a different suite of OMs used for future performance evaluation of potential mackerel rebuilding strategies. With fewer uncertainties, HCRs could be improved and performance could increase. Research on the US catch composition or joint or coordinated management might, therefore, represent efficient means of increasing management effectiveness.

Likewise, the quantity of Canadian missing catches represents another influential axis of uncertainty in this stock. If current quantities of missing Canadian catches could be known with more certainty, and if future management actions either decreased this quantity, or brought it in under the catches governed by the TAC, then the missing catch scenario tested here could be reduced and HCR performance, in general, would be improved relative to the candidate rebuilding objectives and milestones explored in this work.

Although the current framework has been under development over more than a year and is the product of various meetings and reviews, improvements or adjustments can always be made. For instance, the RPWG may wish to finalize rebuilding time frames, biannual HCRs could be tested in future MSE iterations, and the different OMs could be prioritized (i.e., weighted) for evaluating potential HCR performance in the development of a rebuilding plan. When a HCR would be implemented, exceptional circumstances are ideally also defined to outline when a HCR is not performing as expected anymore.

CONCLUSIONS

The biomass of the northern contingent of northwestern Atlantic Mackerel is estimated to be below the LRP of $0.4SSB_{F40\%}$ (i.e., in the Critical Zone). Consequently, a rebuilding plan is currently under development for this stock. MSE feedback simulations performed for a variety of simple empirical HCRs suggest that the rebuilding capacity of northern contingent Atlantic mackerel is largely dependent on (a) Canadian TACs, (b) the quantity of Canadian and US missing catches and (c) future recruitment.

Trade-offs between exploitation rates and the rapidity of potential stock rebuilding indicated that the likelihood of the stock SSB exceeding the LRP and exiting the Critical Zone in the next 10 years was frequently less than 75% for HCRs evaluated in this study. Under a range of OM assumptions, HCRs starting with above zero TACs (HCRs 6-11) were progressively more likely to result in stock declines than increases over the next 3 to 10 years, with the exception of scenarios in which average recruitment increased gradually over time.

Work towards the development of a rebuilding plan is ongoing with the Atlantic Mackerel RPWG. Given that many simulations show that time to rebuild the stock above the LRP with high probability (75%) could take in excess of 10 years depending on the exploitation rate, continued exploration of desirable candidate rebuilding milestones over shorter time horizons (3-5 years) is recommended.

ACKNOWLEDGMENTS

REFERENCES CITED

Beckett, J. S., Stobo, W. T., and Dickson, C. A. 1974. Southwesterly migration of Atlantic mackerel, *Scomber scombrus*, tagged off Nova Scotia. ICNAF Res.Roc., 74/94.

Brattey, J., Cadigan, N., Dwyer, K. S., Healey, B. P., Ings, D. W., Lee, E. M., Maddock Parsons, D., Morgan, M. J., Regular, P., and Rideout, R. M. 2018. Assessment of the Northern Cod (Gadus morhua) stock in NAFO Divisions 2J3KL in 2016. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/018. v + 107p.

Brodziak, J. 2018. AGEPRO Reference Manual. NOAA Fisheries.

Butterworth, D. S. 2007. Why a management procedure approach? Some positives and negatives. ICES J. Mar. Sci., 64: 613–617.

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.

Carruthers, T. R., Kell, L. T., Butterworth, D. D. S., Maunder, M. N., Geromont, H. F., Walters, C., McAllister, M. K., Hillary, R., Levontin, P., Kitakado, T., and Davis, C.R. 2016. Performance review of simple management procedures. ICES J. Mar. Sci., 73: 464–482.

Castonguay, M., Simard, P., and Gagnon, P. 1991. Usefulness of Fourier Analysis of Otolith Shape for Atlantic Mackerel (*Scomber scombrus*) Stock Discrimination. Can. J. Fish. Aquat. Sci. 48: 296–302.

COSEWIC. 2019. Status Reports.

Cox, S. P., Kronlund, A. R., and Benson, A. J. 2013. The roles of biological reference points and operational control points in management procedures for the sablefish (*Anoplopoma fimbria*) fishery in British Columbia, Canada. Envir. Conserv. 40: 318–328.

DFO. 1997. Atlantic mackerel in the Northwest Atlantic. DFO Science, Stock Status Report, B4-04.

DFO. 2002. Atlantic mackerel of the Northwest Atlantic - Update (2001). Stock Status Report B4-04 (2002).

DFO. 2008. Assessment of the Atlantic Mackerel stock for the Northwest Atlantic (Subareas 3 and 4) in 2007. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2008/041.

DFO. 2009. Guidance for the Development of Rebuilding Plans under the Precautionary Approach Framework: Growing Stocks out of the Critical Zone.

DFO. 2010. Proceedings of the Newfoundland and Labrador Regional Atlantic Cod Framework Meeting: Reference Points and Projection Methods for Newfoundland cod stocks. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2010/053.

DFO. 2011. Recovery Potential Assessment of the Maritime Designatable Unit of American Plaice (*Hippoglossoides platessoides*). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep., 2011/043.

DFO. 2012. Assessment of the Atlantic Mackerel stock for the Northwest Atlantic (Subareas 3 and 4) in 2011. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2012/031.

DFO. 2014. Assessment of the Atlantic Mackerel stock for the Northwest Atlantic (Subareas 3 and 4) in 2013. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2014/030.

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

DFO. 2018a. Stock assessment of northern cod (NAFO divisions 2J3KL) in 2018. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2018/038. (Erratum: August 2018).

DFO. 2018b. Units 1+2 Redfish Management Strategy Evaluation. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2018/033.

DFO. 2019. Survey of Recreational Fishing in Canada in 2015. Economic Analysis and Statistics Strategic Policy.

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

Dulvy, N. K., Ellis, J. R., Goodwin, N. B., Grant, A., Reynolds, J. D., and Jennings, S. 2004. Methods of assessing extinction risk in marine fishes. Fish and Fisheries, 5: 255–276.

Duplisea, D., and Grégoire, F. 2014. A biomass limit reference point for NAFO subareas 3 and 4 Atlantic mackerel (*Scomber scrombus*). DFO Can. Sci. Advis. Sec. Res. Doc. 2014/066.

Frank, K. T., and Brickman, D. 2000. Allee effects and compensatory population dynamics within a stock complex. Can. J. Fish. Aquat. Sci. 57: 513–517.

Fu, C., and Fanning, L. P. 2004. Spatial Considerations in the Management of Atlantic Cod off Nova Scotia, Canada. N. Am. J. Fish. Manag. 24: 775–784.

Geromont, H. F., and Butterworth, D. S. 2015. Complex assessments or simple management procedures for efficient fisheries management: a comparative study. ICES J. Mar. Sci. 72: 262–274.

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., et McQuinn, I. 2014. Estimation empirique du taux instantané de mortalité naturelle (M) du maquereau bleu (*Scomber scrombus* L.) des sous-régions 3 et 4 de l'OPANO. Secr. can. de consult. sci. du MPO. Doc. de rech. 2014/078. v + 25 p.

Harnish, L. 2009. Efficiency of bait usage in the Nova Scotia lobster fishery: a first look. Dalhousie University, Halifax, Canada. 41 pp.

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

Huynh, Q., Carruthers, T., Hordyk, A., and Grandin, C. 2018. MSEtool: Management Strategy Evaluation Toolkit. R package version 1.2.1.

ICES. 2018. Mackerel (*Scomber scombrus*) in subareas 1–8 and 14, and in Division 9.a (the Northeast Atlantic and adjacent waters). ICES Advice on fishing opportunities, catch, and effort, mac. 27.nea. doi.org/10.17895/ices.pub.4537.

IUCN. 2014. Guidelines for Using the IUCN Red List Categories and Criteria. Version II. IUCN Standards and Petitions Subcommittee.

Johnson, K. F., Councill, E., Thorson, J. T., Brooks, E., Methot, R. D., and Punt, A. E. 2016. Can autocorrelated recruitment be estimated using integrated assessment models and how does it affect population forecasts? Fish. Res. 183: 222–232.

Kell, L. T., Pilling, G. M., Kirkwood, G. P., Pastoors, M. A., Mesnil, B., Korsbrekke, K., Abaunza, P., Aps, R., Biseau, A., Kunzlik, P., Needle, C.L., Roel, B.A., and Ulrich, C. 2006. An evaluation of multi-annual management strategies for ICES roundfish stocks. ICES J. Mar. Sci. 63: 12–24.

Kristensen, K., Nielsen, A., Berg, C. W., Skaug, H., and Bell, B. M. 2016. TMB: Automatic Differentiation and Laplace Approximation. J. Stat. Soft. 70: 1–21.

Lambrey de Souza, J., Sévigny, J.-M., Chanut, J.-P., Barry, W. F., and Grégoire, F. 2006. High genetic variability in the mtDNA control region of a Northwestern Atlantic teleost, *Scomber scombrus* L. Can. Tech. Rep. Fish. Aquat. Sci. 2625.

Moores, J. A., Winters, G. H., and Parsons, L. S. 1975. Migrations and Biological Characteristics of Atlantic Mackerel (*Scomber scombrus*) Occurring in Newfoundland Waters. J. Fish. Res. Board Can. 32: 1347–1357.

NEFSC. 2018. 64th Northeast Regional Stock Assessment Workshop (64th SAW) Assessment Summary Report. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 18-03; 27 p. doi: 10.7289/V5/RD-NEFSC-18-03.

Nesbø, C. L., Rueness, E. K., Iversen, S. A., Skagen, D. W., and Jakobsen, K. S. 2000. Phylogeography and population history of Atlantic mackerel (*Scomber scombrus* L.): a genealogical approach reveals genetic structuring among the eastern Atlantic stocks. Proceedings of the Royal Society of London. Series B: Biol. Sci. 267: 281–292.

New Zealand Ministry of Fisheries. 2014. Operational guidelines for New Zealand's Harvest Strategy Standard Wellington: Ministry of Fisheries.

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

Nielsen, A., Berg, C. W., Kristensen, K., Brooks, M., and Albertsen, C. M. 2019. stockassessment. R package version 0.8.1.

Olafsdottir, A. H., Utne, K. R., Jacobsen, J. A., Jansen, T., Óskarsson, G. J., Nøttestad, L., Elvarsson, B. Þ., Broms, C. and Slotte, A. 2019. Geographical expansion of Northeast Atlantic mackerel (*Scomber scombrus*) in the Nordic Seas from 2007 to 2016 was primarily driven by stock size and constrained by low temperatures. Deep Sea Res. Part II: Topical Studies in Oceanography, 159: 152–168.

Punt, A. E., Butterworth, D. S., de Moor, C. L., De Oliveira, J. A. A., and Haddon, M. 2016. Management strategy evaluation: best practices. Fish and Fisheries, 17: 303–334.

R core team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Rademeyer, R. A., and Butterworth, D. S. 2011. Technical details underlying the management strategy evaluation process leading to selection of a mangement procedure for Western Component (4Xopqrs5) Pollock. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/090. vi + 33 p.

Restrepo, V. R., Thompson, G. G., Mace, P. M., Gabriel, W. L., Low, L. L., and MacCall, A. D. 1998. Technical Guidance On the Use of Precautionary Approaches to Implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act. NOAA Tech. Memo, NMFS-F/SPO-31.

Richardson, D., Carter, L., Curti, K., Marancik, K. E., and Castonguay, M. *in press*. Changes in the spawning distribution and biomass of Atlantic mackerel (*Scomber scombrus*) in the western Atlantic over four decades. Fish. Bull. U.S.

Sette, E. O. 1950. Biology of the Atlantic mackerel (*scomber scombrus*) of North America Part II-migrations and habits. Fish. Bull. 49, 51: 249–358.

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

TRAC. 2010. Atlantic mackerel in the Northwest Atlantic [NAFO Subareas 2 - 6]. TRAC Status Report 2010/01.

Van Beveren, E., Duplisea, D., Castonguay, M., Doniol-Valcroze, T., Plourde, S., and Cadigan, N. 2017. 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.

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

Van Beveren, E., Duplisea, D., Brosset, P., and Castonguay, M. 2019b. Assessment modelling approaches for stocks with contingents, seasonal and spatial dynamics, and limited resources for data collection. PLOS ONE, 14.

Van Beveren, E., Duplisea, D. E., Marentette, J. R., Smith, A., and Castonguay, M. 2020. An example of how catch uncertainty hinders effective stock management and rebuilding. Fish. Res. 224: 105473.

Waters, C. L., Stephenson, R. L., Clark, K. J., Fife, F. J., Power, M. J., and Melvin, G. 2000. Report of the PRC/DFO 4VWX herring and mackerel tagging program. DFO Can. Sci. Advis. Sec. Res. Doc. 2000/67.

Williams, A. J., Larcombe, J., and Patterson, H. M. 2016. Standardising the presentation of MSE results to provide clear advice for managers. Technical Report. Australian Bureau of Agricultural and Resource Economics and Sciences, Autralia.

APPENDICES

REBUILDING TIMEFRAME

Following DFO guidelines (DFO 2009), a reasonable timeframe to get above the LRP would represent the time for a cohort to recruit to the spawning biomass and then contribute to rebuilding the productive capacity of the stock. The guidelines stipulate that this will correspond to a period of 1.5 – 2 generations, depending on the species. Generation time can however be calculated in many ways (see e.g. IUCN 2014)(Figure S6).

We first calculated generation time based on the abundance per age class (N_a) and the proportion of mature individuals ($PropMature_a$), as is for instance advised by NOAA (National Oceanic and Atmospheric Administration, Restrepo et al. 1998);

$$G = \frac{\sum_{a=1}^{A} a PropMature_a N_a}{\sum_{a=1}^{A} PropMature_a N_a} \qquad \text{(method 1a)}$$

It is often advised that this is calculated for unfished (pristine) conditions, in which case N_a is replaced by;

$$N_a = N_1 exp\left(\sum_{j-1}^{a-1} M_j\right) \qquad \text{(method 1b)}$$

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) on the other hand usually applies the generation time in function of the age at first reproduction (approximated by the age at which 50% of the adults are mature or a_{50}) and the natural mortality rate M (COSEWIC 2019; method 2 described by IUCN 2014);

$$G = a_{50} + \frac{1}{M} \qquad \text{(method 2)}$$

Previous MSEs performed by DFO relied also on the calculation of generation time in function of proportion mature and the annual survival rate S_a, which is a function of M (Cox et al. 2013; method 1 described by IUCN 2014);

$$G = \frac{\sum_{a=1}^{A} a S_a PropMature_a}{\sum_{a=1}^{A} S_a PropMature_a} \qquad \text{(method 3)}$$

For all methods, we used data from the last stock evaluation and presumed a natural mortality rate of 0.27. Depending on the method used, generation time equals roughly 5 years, and less if the current truncated age structure is taken into account (method 1a). Note that currently (2018), the population is largely dominated by fish younger than 4 years (Smith et al. 2020). According to the presented analyses and DFO guidelines, a reasonable timeframe would be somewhere between 6 and 10 years.
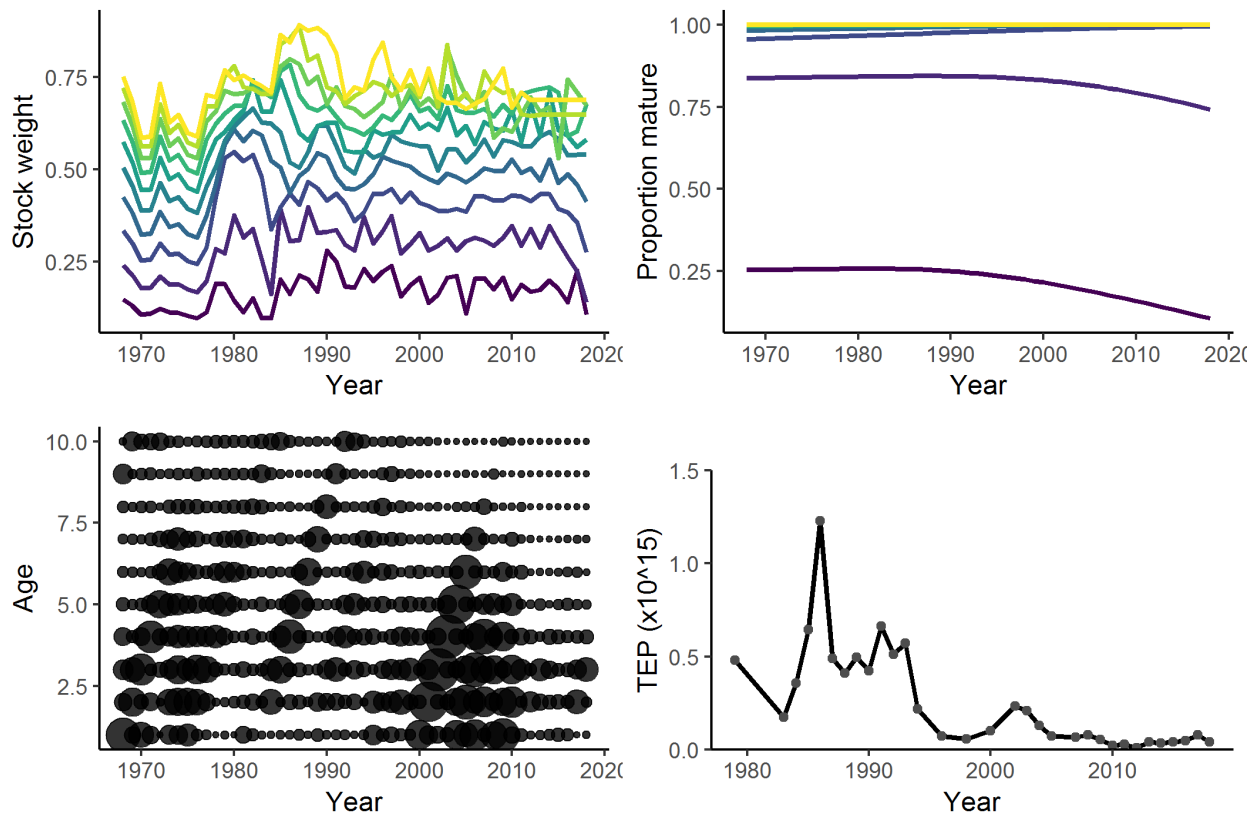
Figure S1. Operating Model input data. Stock weight (upper left panel) and proportion mature (upper right panel) data are used deterministically to transform abundances to biomass whereas catch-at-age (lower left panel) and Total Egg Production (TEP, lower right panels) are used to calibrate the model and are assumed to have an observation error. Total landings are shown in Figure S2.

FIGURE S2: CATCH DATA
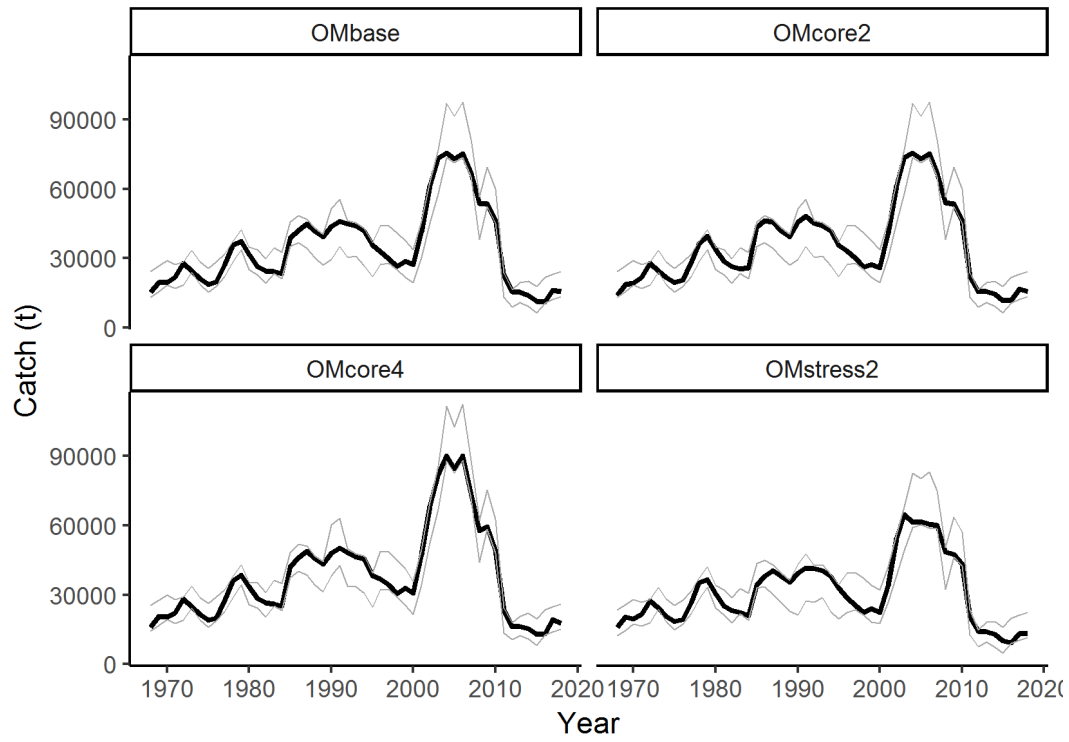
Figure S2. Total catch estimates (black) and upper and lower bounds (grey) for the four historical Operating Models.

FIGURE S3: SENSITIVITY TO M

A)
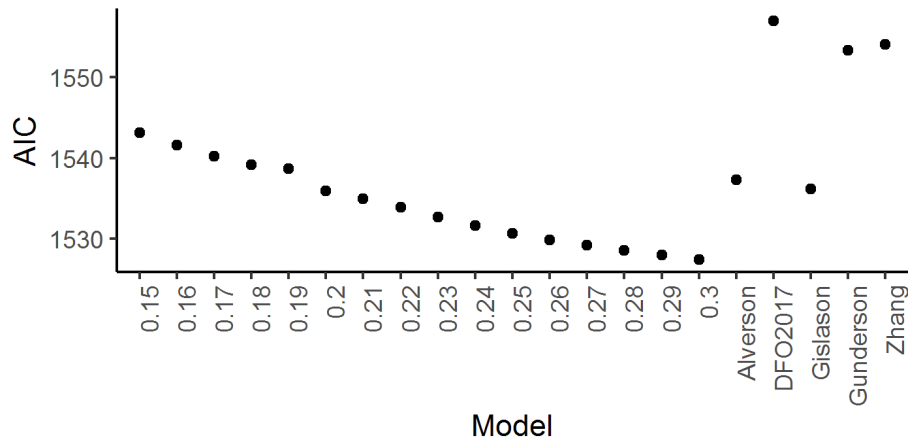
B)
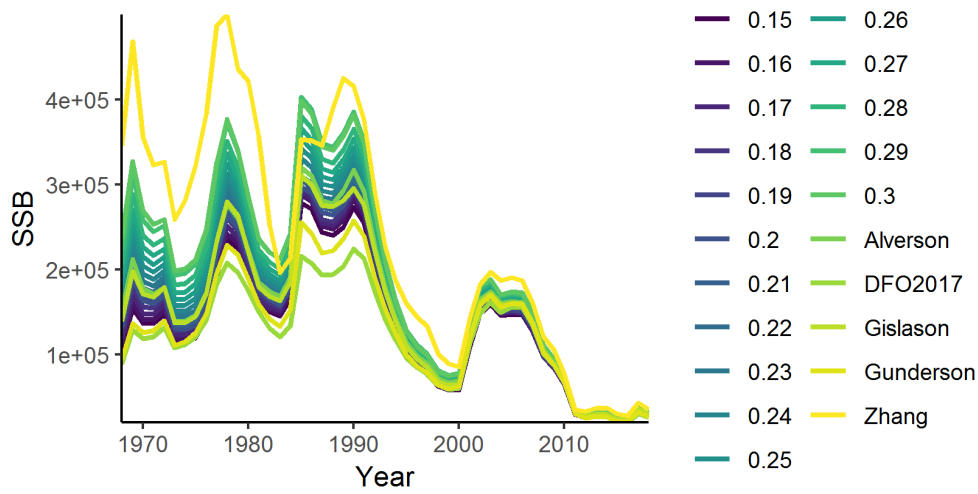
Figure S3. A) AIC (Akaike's Information Criteria) values and B) Spawning Stock Biomass (SSB) for base model fits with different natural mortality values, which could be constant (0.15-0.30), index derived (Alverson, Gislason, Gunderson or Zhang) or taken from the previous mackerel assessment (DFO 2017, M increasing exponentially with age from 0.2 to 0.4).

FIGURE S4: RESIDUAL PLOTS
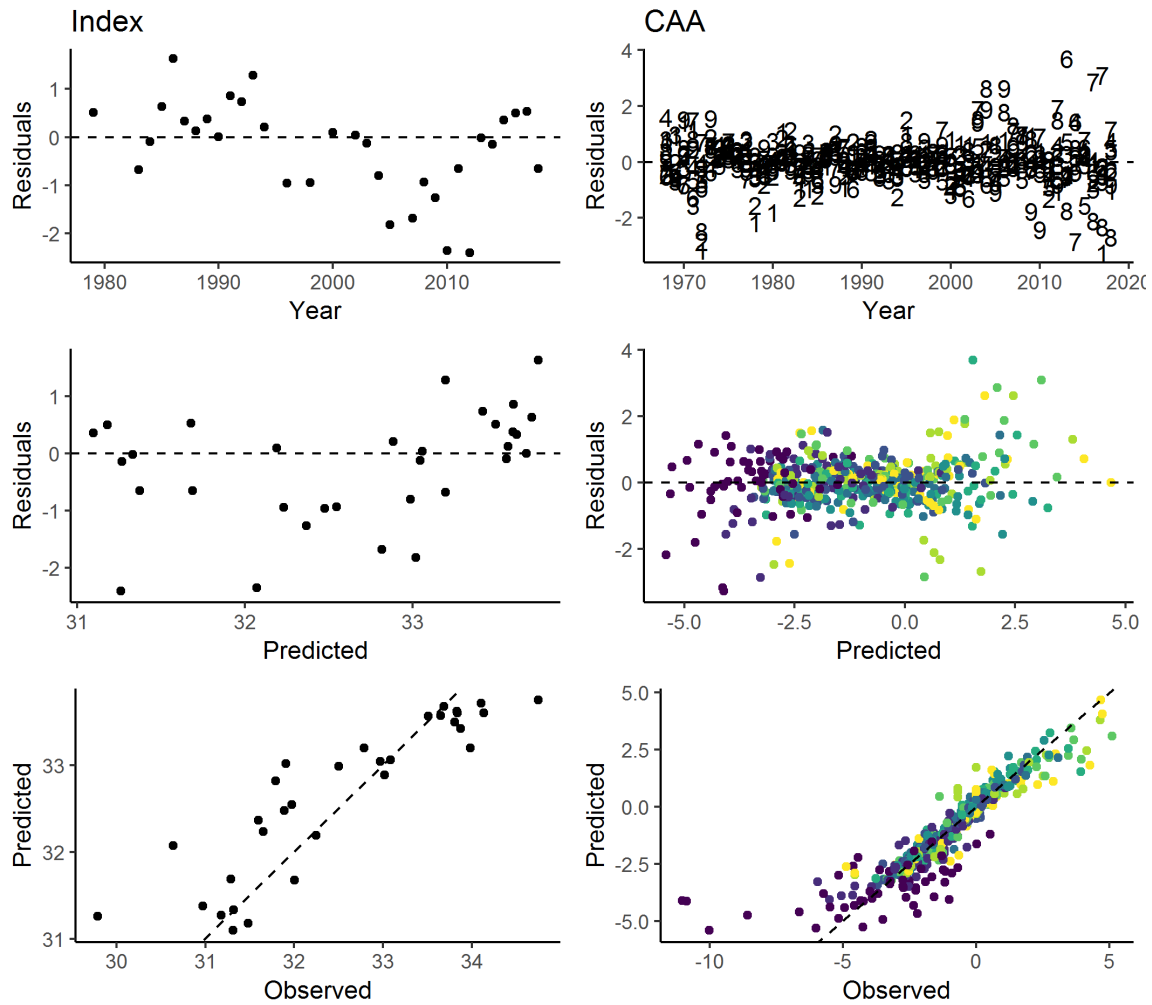
Figure S4. Residual plots for the Total Egg Production index and catch-at-age data. The color scale indicates the age classes (young to old as violet to yellow). Results are shown only for the base OM, as others are similar.

FIGURE S5: RETROSPECTIVE PATTERNS
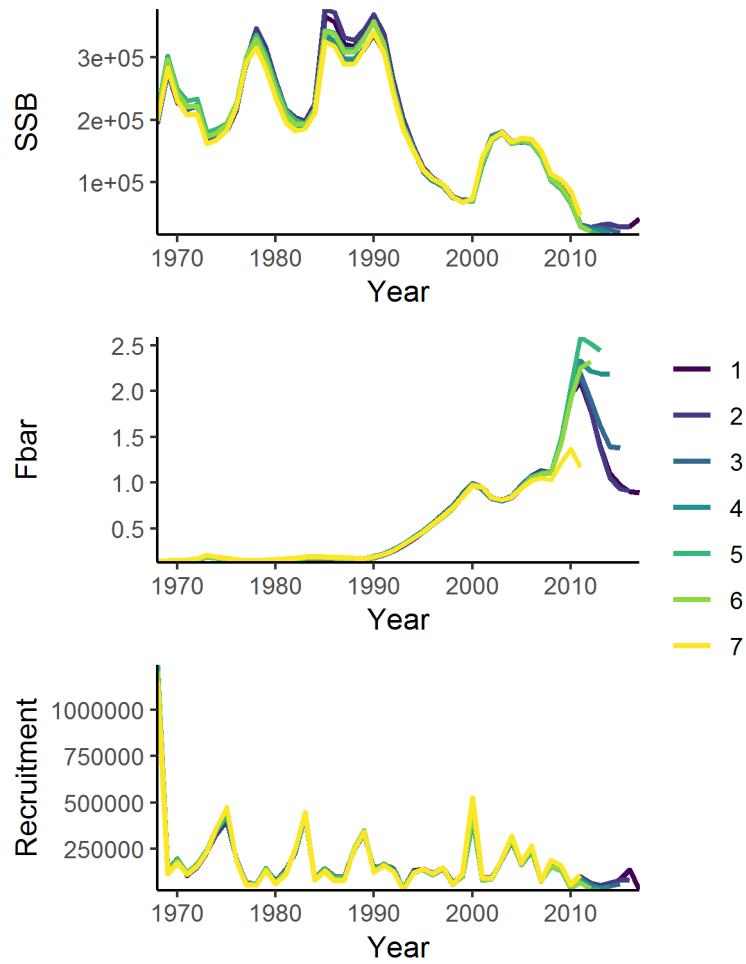
Figure S5. Retrospective patterns in Spawning Stock Biomass (SSB), fishing mortality (F of fully selected fish, ages 5 to 10) and recruitment, for the base Operating Model.

FIGURE S6: GENERATION TIMES
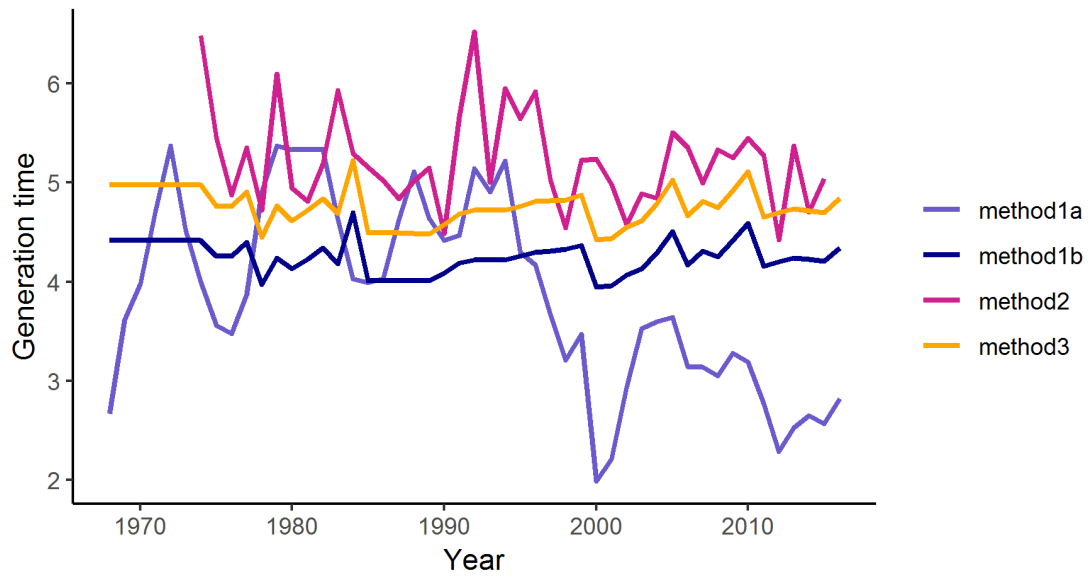
Figure S6. Generation time calculated based on different methods (see Appendix: Rebuilding timeframe).

FIGURE S7: MEDIAN FUTURE CATCH UNDER DIFFERENT SPLITTING ASSUMPTIONS
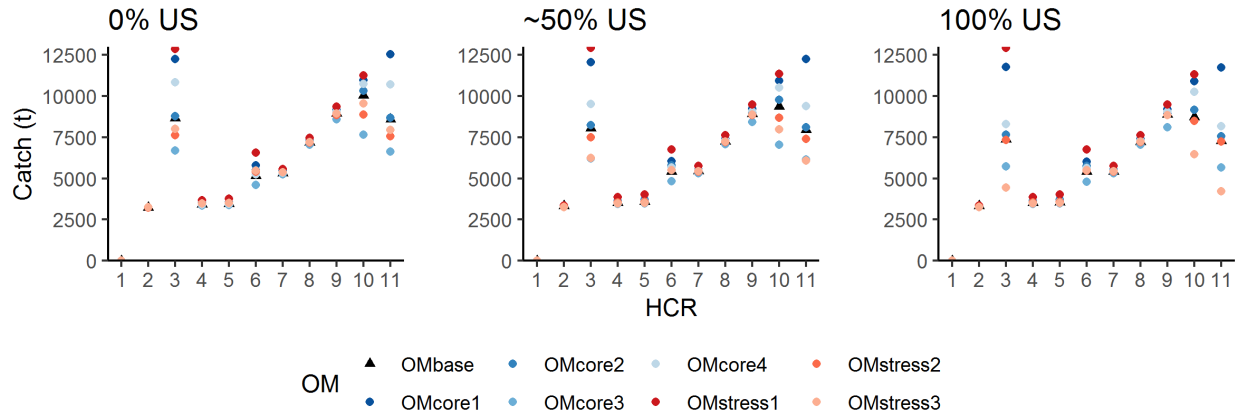
Figure S7. *Median projected future Canadian catch (including catch under TAC and missing Canadian catch) for different Harvest Control Rules (HCRs) and Operating Models (OMs) over the next 5 years (2019-2024). Panels show the effect of different rules to split predicted catch between the US and Canada, when potential catch could not be reached (i.e. the combination of TAC and missing Canadian and US catch exceeded F=2.5). In such case, catch could entirely be taken first by Canada (0% US) or the US (100% US). Alternatively, both countries could not reach their prospective catch (in which case we presumed the US would reach around 50% ($\sim N(0.5,1)$) of its projected catch of northern contingent mackerel).*

FIGURE S8: TRADE-OFF PLOT BETWEEN OBJECTIVE 3 AND 1
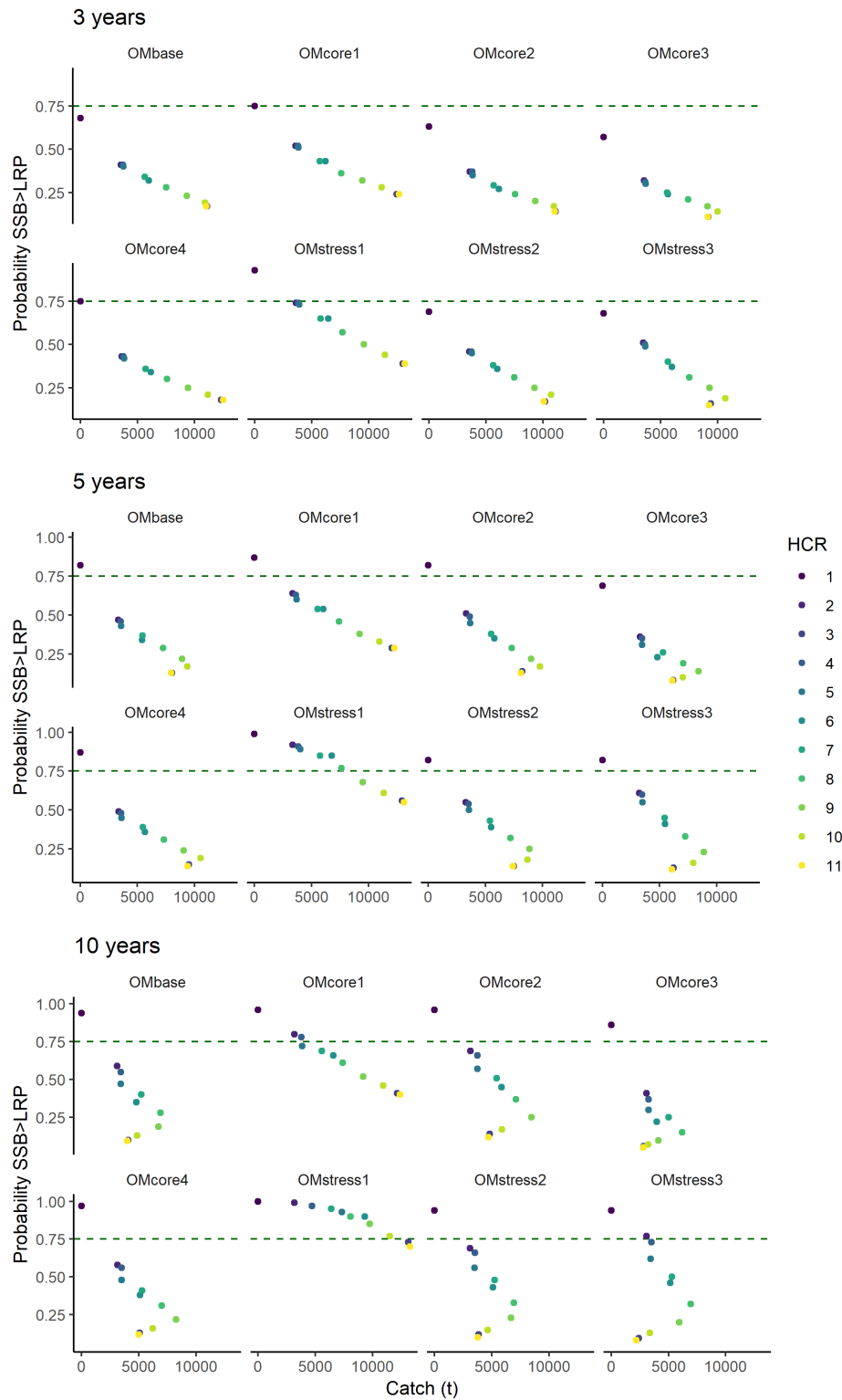
Figure S8. Trade-off between objective 3 (median catch) and objective 1 (probability SSB>LRP) for different HCRs (colors) over the three time spans (figures). Panels show the OMs.

FIGURE S9: TRADE-OFF PLOT BETWEEN OBJECTIVE 3 AND 2
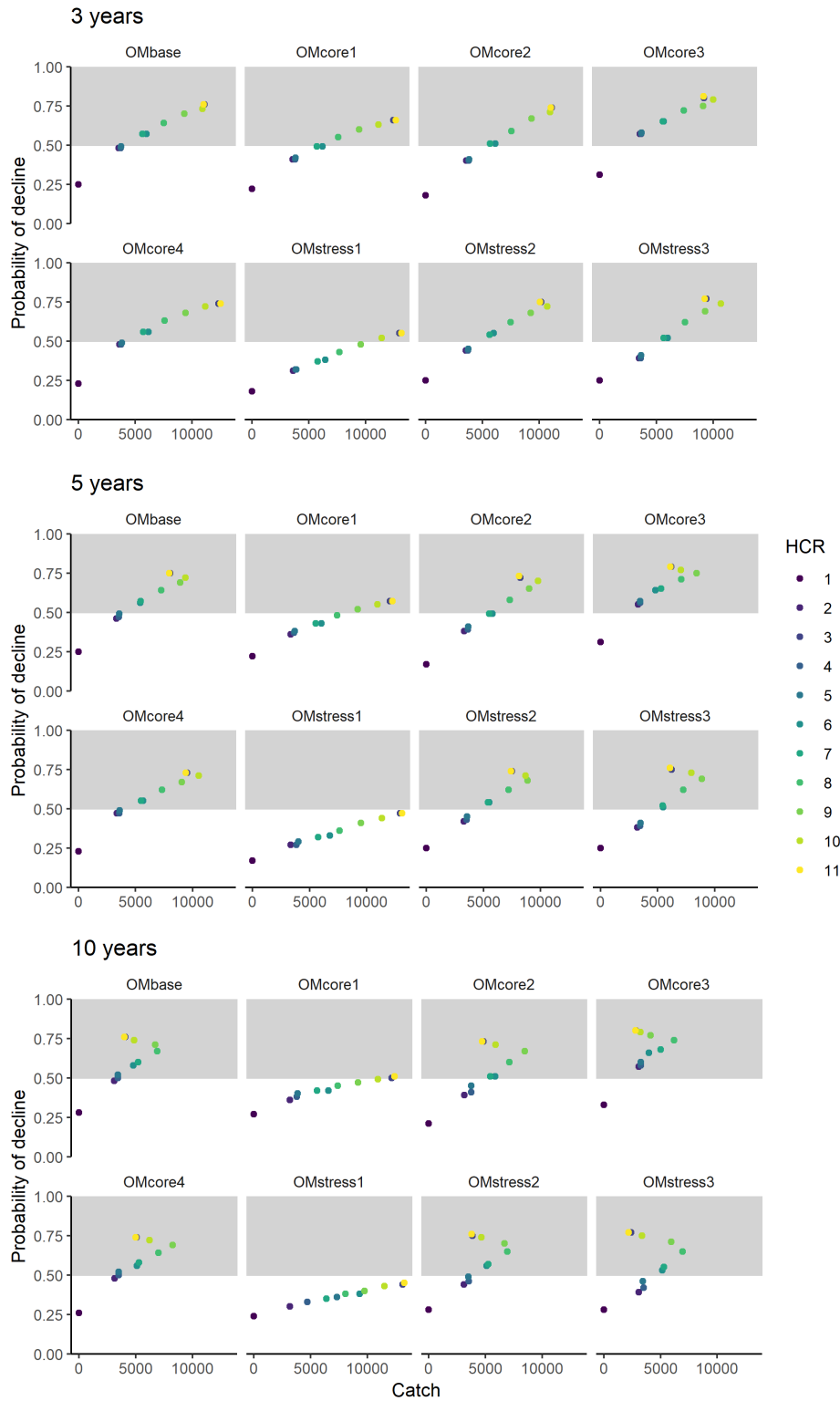
Figure S9. Trade-off between objective 3 (median catch) and objective 2 (probability of decline) for different HCRs (colors) over the three time spans (figures). Panels show the OMs.

TABLE S1: OM EQUATIONS AND PARAMETERS

Table A.1. 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 = weight, 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.

Equations (historical OM)

Parameter	Formula	No.
Cohort abundance	$$N_{1,y} = \frac{\alpha SSB_{y-1}}{1 + \beta SSB_{y-1}} e^{\varepsilon_{1,y}^N}$$	1.1
	$$N_{a,y} = N_{a-1,y-1} e^{-Z_{a-1,y-1} + \varepsilon_{a,y}^N}$$	1.2
	$$N_{A,y} = [N_{A-1,y-1} e^{-Z_{A-1,y-1}} + N_{A,y-1} e^{-Z_{A,y-1}}] e^{\varepsilon_{A,y}^N}$$	1.3
	$$\varepsilon_{a,y}^N \sim MVN(0, \sigma_{N_a}^2)$$	1.4
Mortality rates	$$F_{a,y} = Sel_a F_y$$	2.1
	$$Z_{a,y} = F_{a,y} + M_{a,y}$$	2.2
	$$F_y = F_{y-1} e^{\varepsilon_y^F}$$	2.3
	$$\varepsilon_y^F \sim N(0, \sigma_{F_y}^2)$$	2.4
Catch	$$C_{a,y} = N_{a,y} \frac{F_{a,y}}{Z_{a,y}} [1 - \exp(-Z_{a,y})]$$	3.1
	$$CT_y = \sum_{a=1}^{A} C_{a,y} W_{a,y}$$	3.2
	$$CP_{a,y} = \frac{C_{a,y}}{\sum_{a=1}^{A} C_{a,y}}$$	3.3
	$$X_{a,y} = crl(CP_{a,y})$$	3.4
	$$l(C_{o_1}, \dots, C_{o_Y}|\theta) = \sum_{y=1}^{Y} \log \left\{ \phi_N \left[\frac{\log(CU_y/CT_y)}{0.01} \right] - \phi_N \left[\frac{\log(CL_y/CT_y)}{0.01} \right] \right\}$$	3.5
	$$l\left(X_{o_{a,y}}|\theta\right) = \sum_{a=1}^{A-1} \sum_{Y=1}^{Y} \log \left[\varphi_N \left(\frac{X_{o_{a,y}} - X_{a,y}}{\sigma_{cp}} \right) \right]$$	3.6
Survey index	$$TEP_y = q \sum_{a=1}^{A} N_{a,y} \exp(-Z_{a,y} t_s) fec_{a,y} Fem_{a,y} P_{a,y}$$	4.1
	$$l\left(TEP_{o_y}|\theta\right) = \sum_{a=1}^{A} \sum_{Y=1}^{Y} \log \left[\varphi_N \left(\frac{TEP_{o_y} - TEP_y}{\sigma_S} \right) \right]$$	4.2

Parameter	Formula	No.
Spawning Stock Biomass	$$SSB_y = \sum_{a=1}^{A} N_{a,y} W_{a,y} P_{a,y}$$	5.1

Equations (future OM)

Parameter	Formula	No.
Cohort abundance	$SSB_{y-1} > 1{,}000\ t,\ \ N_{1,y} = r_{det}\, e^{(\rho \varepsilon_{y-1} + \delta_y \sqrt{1-\rho^2}) - \sigma_{\delta_1}^2/2}$	11.1a
	$SSB_{y-1} \le 1{,}000\ t,\ \ N_{1,y} = 0$	11.1b
	$N_{a,y} = N_{a-1,y-1}\, e^{-Z_{a-1,y-1} + \varepsilon_{a,y}^N}$	11.2
	$N_{A,y} = [N_{A-1,y-1}\, e^{-Z_{A-1,y-1}} + N_{A,y-1}\, e^{-Z_{A,y-1}}]\, e^{\varepsilon_{A,y}^N}$	11.3
	$\varepsilon_{a,y}^N \sim MVN(0, \sigma_{N_{a_{n^*}}}^2)$	11.4
Mortality rates	$F_{a,y} = Sel_a F_y$	12.1
	$Z_{a,y} = F_{a,y} + M_{a,y}$	12.2
Input matrices	$W_{a,y} = W_{a,Y} + e^{\varepsilon_{a,y}^W},\qquad \varepsilon_{a,y}^W \sim MVN(0, \sigma_W^2)$	13.1
	$P_{a,y} = P_{a,Y} + e^{\varepsilon_{a,y}^P},\qquad \varepsilon_{a,y}^P \sim MVN(0, \sigma_P^2)$	13.2
	$fec_{a,y} = fec_{a,Y} + e^{\varepsilon_{a,y}^{fec}},\qquad \varepsilon_{a,y}^{fec} \sim MVN(0, \sigma_{fec}^2)$	13.3
	$Fem_{a,y} = Fem_{a,Y} + e^{\varepsilon_{a,y}^{Fem}},\qquad \varepsilon_{a,y}^{Fem} \sim MVN(0, \sigma_{Fem}^2)$	13.4
Catch	$C_{a,y} = N_{a,y} \dfrac{F_{a,y}}{Z_{a,y}} [1 - \exp(-Z_{a,y})]$	14.1
	$CT_y = \sum_{a=1}^{A} C_{a,y} W_{a,y}$	14.2
	$CT_y = TAC_y + MC_y$	14.3
Survey index	$TEP_y = q \sum_{a=1}^{A} (N_{a,y}\, exp(-Z_{a,y} t_s)\, fec_{a,y}\, Fem_{a,y}\, P_{a,y})\, e^{\varepsilon_y^S}$	15.1
	$e^{\varepsilon_y^S} \sim N(0, \sigma_{s_{n^*}}^2)$	15.2
Spawning Stock Biomass	$SSB_y = \sum_{a=1}^{A} N_{a,y} W_{a,y} P_{a,y}$	16.1

Parameters

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

TABLE S2: OM PARAMETER ESTIMATES

Table S2. Estimates (est.) and standard deviations (s.d.) of parameters for all operating model (OM) configurations. At the bottom row the AIC value for each configuration is given.

Parameters	OMbase		OMcore2		OMcore4		OMstress2	
	est.	s.d.	est.	s.d.	est.	s.d.	est.	s.d.
$\log q$	7.84	0.07	7.95	0.11	7.73	0.07	8.00	0.09
$\log\sigma_{F_y}$	-1.14	0.13	-1.27	0.13	-1.05	0.13	-1.29	0.10
$\log\sigma^2_{N_1}$	-0.30	0.16	-0.33	0.16	-0.38	0.14	-0.36	0.15
$\log\sigma^2_{N_{2\text{-}10}}$	-0.91	0.11	-0.90	0.12	-0.90	0.09	-0.83	0.12
$\log\sigma^2_{caa_1}$	0.77	0.10	0.83	0.10	0.78	0.09	0.78	0.11
$\log\sigma^2_{caa_{2,8,9}}$	-0.08	0.10	-0.06	0.10	-0.05	0.10	-0.10	0.10
$\log\sigma^2_{caa_{2\text{-}7}}$	-0.50	0.08	-0.51	0.08	-0.50	0.07	-0.54	0.09
$\log\sigma^2_s$	-0.36	0.07	-0.35	0.11	-0.44	0.07	-0.34	0.09
$logitSel_1$	1.23	0.40	1.32	0.65	1.37	0.33	1.16	0.40
$logitSel_2$	-10.80	0.49	-10.11	0.74	-10.74	0.34	-10.77	0.42
$logitSel_3$	-3.11	0.33	-2.80	0.34	-3.10	0.32	-3.10	0.35
$logitSel_4$	-1.12	0.19	-0.83	0.17	-0.93	0.12	-1.18	0.19
AIC	1529		1543		1534		1523	

TABLE S3: LONG-TERM CANDIDATE OBJECTIVES

Table S3. Long-term candidate objectives suggested before the focus was put on short-term rebuilding, potentially reusable once the stock gets out of the Critical Zone. Note that these objectives would need to be refined. (SSB = Spawning Stock Biomass; USR = Upper Stock Reference, HZ = Healthy Zone, TBD = to be discussed)

No.	Goal	Objective	Performance Metrics	Prob.	Time	Details
1	Rebuild SSB.	Rebuild Atlantic Mackerel SSB above the USR.	Probability that SSB > USR	75%	TBD*	*3 COSEWIC generations after rebuilding was suggested.
2	Remain out of the CZ	SSB greater than LRP over the long term	Probability that SSB > LRP	95%	TBD*	* to end of simulations
3	Maximize catch	Keep annual catch as high as possible	Median catch	/	TBD*	*as above
4	Maximize fishery stability	Stable catches	Year to year changes in TAC	<25%	TBD*	*as above

TABLE S4: SUMMARY TABLE OF OBJECTIVES

Table S4. Score for the three objectives for all Harvest Control Rules (HCR) and Operating Models (OMs). Note that HCR 1 and 2 represent a constant TAC of 0 t (without and with missing catches of northern contingent fish, respectively) regardless of stock status and represent a baseline for comparison with other HCRs.

		Objective 1 (probability SSB > LRP)			Objective 2 (probability of decline)			Objective 3 (median catches)		
Time		3	5	10	3	5	10	3	5	10
Thresh.		>68%	>75%	>75%	<25%	<25%	<25%	NA	NA	NA
					OM BASE					
	1	68%	82%	94%	25%	25%	28%	0 kt	0 kt	0 kt
	2	41%	47%	59%	48%	46%	48%	3.6 kt	3.3 kt	3.1 kt
	3	17%	13%	10%	76%	75%	76%	11.1 kt	8 kt	4.1 kt
	4	41%	46%	55%	48%	47%	50%	3.7 kt	3.5 kt	3.4 kt
Harvest Control Rule	5	40%	43%	47%	49%	49%	52%	3.8 kt	3.6 kt	3.4 kt
	6	32%	34%	35%	57%	56%	58%	6 kt	5.4 kt	4.8 kt
	7	34%	37%	40%	57%	57%	60%	5.7 kt	5.4 kt	5.2 kt
	8	28%	29%	28%	64%	64%	67%	7.5 kt	7.2 kt	6.9 kt
	9	23%	22%	19%	70%	69%	71%	9.3 kt	8.9 kt	6.7 kt
	10	19%	17%	13%	73%	72%	74%	10.9 kt	9.4 kt	4.9 kt
	11	17%	13%	9%	76%	75%	76%	11.1 kt	8 kt	4 kt
					OM CORE 1					
	1	75%	87%	96%	22%	22%	27%	0 kt	0 kt	0 kt
	2	52%	64%	80%	41%	36%	36%	3.6 kt	3.3 kt	3.2 kt
	3	24%	29%	41%	66%	57%	50%	12.5 kt	12.1 kt	12.1 kt
	4	52%	63%	78%	41%	37%	38%	3.8 kt	3.6 kt	3.8 kt
Harvest Control Rule	5	51%	60%	72%	42%	38%	40%	3.8 kt	3.7 kt	3.9 kt
	6	43%	54%	66%	49%	43%	42%	6.2 kt	6 kt	6.6 kt
	7	43%	54%	69%	49%	43%	42%	5.7 kt	5.5 kt	5.6 kt
	8	36%	46%	61%	55%	48%	45%	7.6 kt	7.4 kt	7.4 kt
	9	32%	38%	52%	60%	52%	47%	9.4 kt	9.2 kt	9.2 kt
	10	28%	33%	46%	63%	55%	49%	11.1 kt	10.9 kt	10.9 kt
	11	24%	29%	40%	66%	57%	51%	12.7 kt	12.3 kt	12.4 kt
					OM CORE 2					
	1	63%	82%	96%	18%	17%	21%	0 kt	0 kt	0 kt
	2	37%	51%	69%	40%	38%	39%	3.6 kt	3.3 kt	3.1 kt
	3	14%	14%	14%	74%	72%	73%	11.1 kt	8.2 kt	4.8 kt
Harvest Control Rule	4	37%	49%	66%	40%	39%	41%	3.8 kt	3.6 kt	3.7 kt
	5	35%	45%	57%	41%	41%	45%	3.8 kt	3.7 kt	3.7 kt
	6	27%	35%	45%	51%	49%	51%	6.1 kt	5.8 kt	5.8 kt
	7	29%	38%	51%	51%	49%	51%	5.7 kt	5.5 kt	5.4 kt

		Objective 1 (probability SSB > LRP)			Objective 2 (probability of decline)			Objective 3 (median catches)		
	8	24%	29%	37%	59%	58%	60%	7.5 kt	7.3 kt	7.1 kt
	9	20%	22%	25%	67%	65%	67%	9.3 kt	9 kt	8.5 kt
	10	17%	17%	17%	71%	70%	71%	10.9 kt	9.8 kt	5.9 kt
	11	14%	13%	12%	74%	73%	73%	11 kt	8.1 kt	4.7 kt
OM CORE 3										
Harvest Control Rule	1	57%	69%	86%	31%	31%	33%	0 kt	0 kt	0 kt
	2	32%	36%	41%	57%	55%	57%	3.6 kt	3.3 kt	3.1 kt
	3	11%	8%	6%	80%	79%	80%	9.2 kt	6.2 kt	2.8 kt
	4	31%	35%	37%	57%	56%	58%	3.7 kt	3.5 kt	3.3 kt
	5	30%	31%	30%	58%	57%	60%	3.7 kt	3.5 kt	3.3 kt
	6	24%	23%	22%	65%	64%	66%	5.6 kt	4.8 kt	4 kt
	7	25%	26%	25%	65%	65%	68%	5.6 kt	5.3 kt	5 kt
	8	21%	19%	15%	72%	71%	74%	7.4 kt	7.1 kt	6.2 kt
	9	17%	14%	10%	75%	75%	77%	9.1 kt	8.4 kt	4.1 kt
	10	14%	10%	7%	79%	77%	79%	10 kt	7 kt	3.2 kt
	11	11%	8%	5%	81%	79%	80%	9.2 kt	6.1 kt	2.8 kt
OM CORE 4										
Harvest Control Rule	1	75%	87%	97%	23%	23%	26%	0 kt	0 kt	0 kt
	2	43%	49%	58%	48%	47%	48%	3.6 kt	3.3 kt	3.1 kt
	3	18%	15%	13%	74%	73%	74%	12.3 kt	9.5 kt	5.1 kt
	4	43%	48%	56%	48%	47%	50%	3.8 kt	3.6 kt	3.5 kt
	5	42%	45%	48%	49%	49%	52%	3.8 kt	3.6 kt	3.5 kt
	6	34%	36%	38%	56%	55%	56%	6.2 kt	5.7 kt	5.1 kt
	7	36%	39%	41%	56%	55%	58%	5.7 kt	5.5 kt	5.3 kt
	8	30%	31%	31%	63%	62%	64%	7.6 kt	7.3 kt	7 kt
	9	25%	24%	22%	68%	67%	69%	9.4 kt	9.1 kt	8.3 kt
	10	21%	19%	16%	72%	71%	72%	11.2 kt	10.5 kt	6.2 kt
	11	18%	14%	12%	74%	73%	74%	12.5 kt	9.4 kt	5 kt
OM STRESS 1										
Harvest Control Rule	1	93%	99%	100%	18%	17%	24%	0 kt	0 kt	0 kt
	2	74%	92%	99%	31%	27%	30%	3.6 kt	3.3 kt	3.2 kt
	3	39%	56%	73%	55%	47%	44%	13 kt	12.9 kt	13.1 kt
	4	74%	91%	97%	32%	27%	33%	3.8 kt	3.9 kt	4.7 kt
	5	73%	89%	93%	32%	29%	36%	3.9 kt	4 kt	7.3 kt
	6	65%	85%	90%	38%	33%	38%	6.4 kt	6.8 kt	9.3 kt
	7	65%	85%	95%	37%	32%	35%	5.8 kt	5.8 kt	6.4 kt
	8	57%	77%	90%	43%	36%	38%	7.7 kt	7.6 kt	8.1 kt
	9	50%	68%	85%	48%	41%	40%	9.6 kt	9.5 kt	9.8 kt
	10	44%	61%	77%	52%	44%	43%	11.4 kt	11.3 kt	11.5 kt
	11	39%	55%	70%	55%	47%	45%	13.2 kt	13.1 kt	13.3 kt

		Objective 1 (probability SSB > LRP)			Objective 2 (probability of decline)			Objective 3 (median catches)		
		OM STRESS 2								
Harvest Control Rule	1	69%	82%	94%	25%	25%	28%	0 kt	0 kt	0 kt
	2	46%	55%	69%	44%	42%	44%	3.5 kt	3.3 kt	3.1 kt
	3	17%	14%	12%	75%	74%	75%	10.2 kt	7.5 kt	3.8 kt
	4	46%	54%	66%	44%	43%	46%	3.7 kt	3.5 kt	3.5 kt
	5	45%	50%	56%	45%	45%	49%	3.7 kt	3.6 kt	3.5 kt
	6	36%	39%	43%	55%	54%	56%	6 kt	5.5 kt	5.1 kt
	7	38%	43%	48%	54%	54%	57%	5.6 kt	5.4 kt	5.3 kt
	8	31%	32%	33%	62%	62%	65%	7.5 kt	7.2 kt	6.9 kt
	9	25%	25%	23%	68%	68%	70%	9.2 kt	8.9 kt	6.7 kt
	10	21%	18%	15%	72%	71%	74%	10.7 kt	8.7 kt	4.6 kt
	11	17%	14%	10%	75%	74%	76%	10.1 kt	7.4 kt	3.8 kt
		OM STRESS 3								
Harvest Control Rule	1	68%	82%	94%	25%	25%	28%	0 kt	0 kt	0 kt
	2	51%	61%	77%	39%	38%	39%	3.5 kt	3.2 kt	3.1 kt
	3	16%	13%	10%	77%	75%	77%	9.4 kt	6.2 kt	2.4 kt
	4	50%	60%	73%	39%	39%	42%	3.6 kt	3.5 kt	3.5 kt
	5	49%	55%	62%	41%	41%	46%	3.7 kt	3.5 kt	3.5 kt
	6	37%	41%	46%	52%	51%	53%	6 kt	5.5 kt	5.2 kt
	7	40%	45%	50%	52%	52%	55%	5.6 kt	5.4 kt	5.3 kt
	8	31%	33%	32%	62%	62%	65%	7.5 kt	7.3 kt	6.9 kt
	9	25%	23%	20%	69%	69%	71%	9.3 kt	8.9 kt	6 kt
	10	19%	16%	13%	74%	73%	75%	10.7 kt	8 kt	3.4 kt
	11	15%	12%	8%	77%	76%	77%	9.3 kt	6.1 kt	2.2 kt