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An example of how catch uncertainty hinders effective stock management and rebuilding

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ABSTRACT

The northern spawning contingent of Western Atlantic mackerel is currently at low biomass and catches are largely underestimated. Catch statistics for Canada are incomplete, and the amount of northern contingent fish caught in the US mackerel fishery is unclear. Our goal was to assess the impact of missing catch on quota management effectiveness and to provide advice for stock rebuilding in the face of large catch uncertainty. As part of a management strategy evaluation (MSE), we assessed how simple harvest control rules (HCRs) performed under different assumptions of catch uncertainty. Results showed that, at present low biomass levels, reducing missing catch was generally more important than the choice among certain HCRs. Canadian undeclared catch would need to be reduced markedly to achieve even short-term rebuilding objectives. To reach long-term rebuilding objectives, the proportion of northern contingent fish caught in the US fishery would also need to be accounted for. We demonstated how an MSE can help inform all involved parties of the trade-off between missing catch and quota magnitude and effectiveness, and provided directions for future developments in management and science.

1. Introduction

Fisheries management advice is commonly presented as catch options (quotas, or fishing mortality rates) on which managers can base their decisions. Such advice presumes that proposed catch levels represent all or most of the fisheries mortality. However, it is often the case that portions of the total catch are not encompassed by the advice (e.g., discards, recreational catches, and other forms of unreported landings), as the advice is directly contingent on the catch statistics available for the stock assessment and these might not capture all of the fisheries-induced mortality (e.g., ICES, 2016). When part of the total removals is ignored, the quality and credibility of science advice can be negatively affected and, as a consequence, the selected management action may not result in the predicted outcome (e.g., Griffiths, 2015; Rudd and Branch, 2016). Alternatively, even good-quality science advice may not lead to good fisheries management outcomes if management cannot effectively control fisheries-induced mortality at the regulated levels. Although there are several stocks for which efforts have been made to incorporate previously neglected catch proportions (e.g., DFO, 2018; ICES, 2013, 2011), the recurrence of non-inclusive catch data still remains a significant challenge for stock assessment practitioners (e.g., Eero et al., 2015; Kolody et al., 2008).

In situations where there are clear uncertainties, Management Strategy Evaluation (MSE) can be used to improve management advice. MSE is an elaborate multiparty process usually aimed at selecting a suitable management strategy that acceptably meets various fisheries management objectives, but the results can also be used to answer other research questions (e.g., Marasco et al., 2007). For instance, one can study questions related to the effect of different levels and patterns of catch uncertainties on the choice and efficiency (yield, exploitation risks, etc.) of management procedures (often referred to as implementation error, e.g. Christensen, 1997; Dichmont et al., 2006; Kelly et al., 2006; Rosenberg and Brault, 1993). The use of MSE in this context has however been limited and is often basic, despite the potential importance of implementation error in fisheries management (Fulton et al., 2011; Peterman, 2004).

An example of a fish population for which the assessment and catch advice routinely exclude a large fraction of the actual total catches is the Atlantic mackerel stock (*Scomber scombrus*) off the east coast of Canada (i.e., the northern spawning component or contingent, DFO,

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2008, 2012). Although part of the catch bias was statistically incorporated in the most recent advice (DFO, 2019, 2017), the traditional "best model" assessment framework was insufficient to fully explore the complex catch uncertainties. Specifically, discarded fish and mackerel caught recreationally or for personal use as bait in other fisheries are not uniformly required to be declared, unlike commercial landings. As a result, actual Canadian removals in recent years are considered to be roughly 1.5–2 times higher than the official catch statistics (Van Beveren et al., 2017). During the winter, this northern contingent of mackerel also mixes with the southern contingent in United States (US) waters (Sette, 1950), and is thus vulnerable to the US fleet. The fraction of each mackerel contingent in the US catch is unknown, but a recent study showed that the US mackerel catches could be comprised of roughly between 67 % and 87 % of northern contingent fish, depending on the year (Redding et al., 2020). Despite the large uncertainty in total removals and the temporal and spatial association between both contingents, Canada continues to evaluate and manage its fishery on the northern contingent alone as one stock, while the US evaluates and manages its fishery separately while taking into account both contingents.

Because the northern contingent is considered depleted (below its limit reference point) and is undergoing the development of a rebuilding plan in Canada, an MSE framework was proposed for the mackerel stock to better assess the impact of catch uncertainty on the effectiveness of such a rebuilding plan. The framework was developed to deal with different and important sources of catch uncertainty. Our methods, results and general conclusions based on the northern West Atlantic mackerel stock provide a useful and transferrable example for other fish stocks given the prevalence of catch bias issues globally (Pauly and Zeller, 2016). We show how MSE can be used as a tool for developing stock rebuilding plans in the short-term in addition to the primary rationale for initiating MSE development, which is the effective long-term planning for sustainable and valuable fisheries.

2. Material and methods

MSEs typically aim at finding a harvest control rule (HCR) and associated estimation framework that, under a set of uncertainties, performs acceptably against fisheries management objectives and that can be applied to the fishery over a long-term period. To do this, stakeholders and managers agree on the objectives, and scientists perform the simulations that provide them with feedback on the performance of each of the proposed HCRs.

The statistical core of the analysis is the operating model (OM), which reflects the "true" historical as well as projected future population dynamics of the stock. Here, the historical period is represented by a stock assessment model that explicitly adresses catch uncertainty, and the future is represented by 25-year projections assuming parameter values and dynamics conditioned on the past. During every future year, an HCR is applied that generates quota advice (Total Allowable Catch or TAC). For the Canadian mackerel fishery, the TAC only controls a fraction of the total removals as a large part of the Canadian catches are undeclared and the US also lands an unknown fraction of northern contingent mackerel (together referred to in this manuscript as 'missing catch'). Missing catches (MC), as part of the OM, are added to the calculated TAC and these total removals are used to predict the future stock state. Because useful HCRs, measured against predetermined objectives, need to be robust against a suit of uncertainties, the simulation framework encompasses model, observation, process, implementation and estimation errors. Given the the full MSE is too elaborate to capture in one paper, here, we focus only on the element of catch uncertainty.

2.1. Operating model

2.1.1. Historical dynamics

The historical component (based on Template Model Builder, Kristensen et al., 2016) is similar to the statistical catch-at-age assessment model used during the Canadian mackerel stock assessments (Smith et al., 2020; Van Beveren et al., 2017) and was based on the SAM model (Stock Assessment Model; Nielsen and Berg, 2014). Model specifications are provided in Appendix A and equations and parameters are summarised in Table A.1. The key aspect of the assessment model is the censored catch, whereby catch is predicted between upper and lower bounds to account for uncertainty (using the method of Cadigan, 2016). The model was fitted to the data available for Canadian mackerel stock assessments (Smith et al., 2020), which included a total egg production (TEP) index obtained through an annual egg survey, declared total landings and catch-at-age compositions. The OM settings spanned age classes 1 to 10 + and covered the period from 1968 to 2018.

2.1.2. Future dynamics

The future component or projections (see Appendix B, Table A.2) for each combination of HCR, historical OM and missing catch scenario were performed over 2000 simulations 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;
4) add missing catch to obtain the potential true 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) calculate all derived quantities for each simulation (spawning stock biomass, true catch, etc.); and
8) go to the next year.

The same equations, error distributions and parameter values were used as in the historical operating model, although we, however, added a temporal autocorrelation and bias correction factor to the stock-recruitment relationship (Appendix B; Table A.2). Potential catch can also be unrealistically high in simulations so that we limited the future instantaneous fishing mortality rate to 2.5yr^{-1} (92 % annual exploitation rate), which is higher than the maximum historically estimated fishing mortality rate of 2.2yr^{-1} (Kell et al., 2006).

The two key sources of missing catch (from both Canada and the US) are dissimilar in magnitude and characteristics and are hence considered separately ($MC_y = MCcan_y + MCus_y$). Undeclared Canadian catch is uncertain in quantity but has the potential to be improved if management measures are put into place to increase the catch reporting rate. Therefore, we modelled this as a linear trend by predefining future average values (μ_y), and drawing annual estimates from a normal distribution ($MCcan_y \sim N(\mu_y, \sigma^2)$, with $\sigma^2 = \mu_y/8$ and μ_y given in Table A.3) (see Section 2.1.3). More uncertainty is present in the quantity of northern contingent mackerel that the US fleet will fish over the projected period, as stock management is conducted independently by each country. Missing catch from the US was therefore modelled as a fraction of their future total catch ($MCus_y = CTus_y * Cprop_y$). Total US catches ($CTus_y$), including northern and southern contingent mackerel, would follow a restricted lag-1 autoregressive process. These time series were bounded between 5% and 30% of the estimated northern contingent stock biomass, as was the case in the last two decades and as is reasonable because the southern contingent is presently thought to be considerably smaller and the dominant northern contingent biomass is only partially available. Total predicted US catches could also at most double between years, and were limited to a maximum of 20,000 t. We presumed ranges of proportions ($Cprop_y$) matching the assumptions used in the corresponding historical portion of the OM (Section 2.1.3; rows in Fig. 1). Simulated fractions 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 (i.e., 0-25%, 25-50%, 50-75%, 75-100%). The simulations reflect the vast

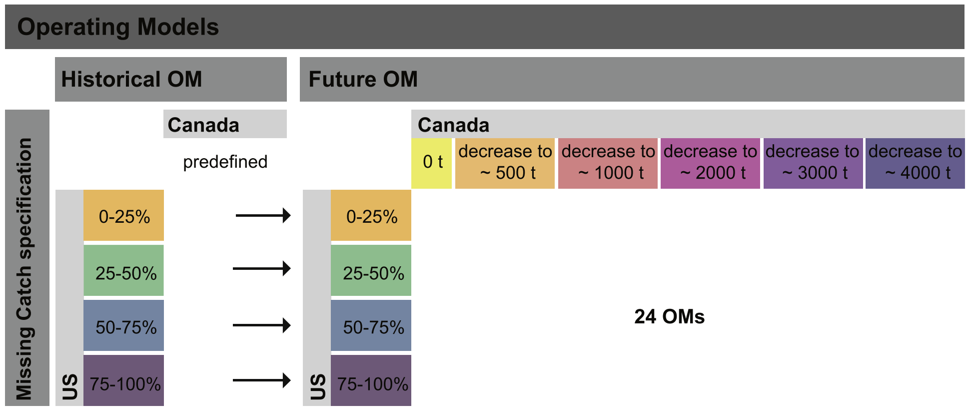

Fig. 1. Operating model (OM) assumptions on catch. Missing catch for the US is given as a percentage of their landings.

uncertainty in US landings of Canadian contingent fish, and examples are shown in Fig. A.1.

2.1.3. Uncertainty in operating models

Each OM makes assumptions or hypotheses about historical and future processes, where some of these processes may be fairly well understood, but others less so (Punt et al., 2016). Testing HCRs against different OMs, therefore, becomes a robustness test of an HCR against hypothesised processes. A potentially large number of plausible OMs exist, and even less likely or unlikely “black swan” events (Anderson et al., 2017) may be important considerations when there are great implications of not considering them. The scope of this study was however strictly on missing catch as the driver of the stock state and HCR performance; therefore, only OMs that represented our main preoccupation of uncertainty in the total catch were considered (Fig. 1).

Missing Canadian catch in the historical OMs was always included as one level of uncertainty (as defined in Van Beveren et al., 2017). In contrast, we specified four levels of uncertainty around the proportions of US landings to be northern contingent mackerel (Fig. 2). In the first historical OM, the lower total catch bound was set to 110 % of the observed Canadian landings. To obtain the upper bound we summed the estimates of maximal missing Canadian catch and 25 % of US landings. Hence we assumed that around 0–25 % of mackerel caught by the US fleet might be from the northern contingent. In the other three historical OM types, the catch bounds were set higher so that the presumed fraction of northern contingent fish in US landings was respectively around 25-50%, 50-75% and 75-100%. Although the last two OMs (assuming 50-75% or 75-100% of northern contingent fish in the historical US catch) best reflected the results from Redding et al., 2020, more conservative values were closer to previous perceptions and were perceived as acceptable by those involved in the process.

Future dynamics were simulated under various stochastic scenarios of missing Canadian and US catch. Specifically, the four previously defined scenarios concerning the magnitude of US catch of northern contingent fish were transferred into the future and we developed six scenarios of missing Canadian catch. All these scenarios were cross-tested to obtain a good understanding of each source of uncertainty, leading to a total of 24 different OMs (Fig. 1).

For projections of missing US catch, ranges corresponding to the historical OM assumptions were considered to be taken from future trajectories of total US catches (0-25%, 25-50%, 50-75%, 75-100%). Five future scenarios of missing Canadian catch presumed a decrease (to ~4000 t, ~3000 t, ~2000 t, ~1000 t, and ~500 t, Fig. 3), of which the decrease to roughly 3000 t was used in both the last stock assessment (Smith et al., 2020) and as a base scenario in the full MSE. Other scenarios of missing Canadian catch were selected as conceivable alternatives. There was also a baseline scenario, under which all Canadian catches were presumed to be reported (missing Canadian catch = 0 t).

We also ran simulations for a range of future deterministic and

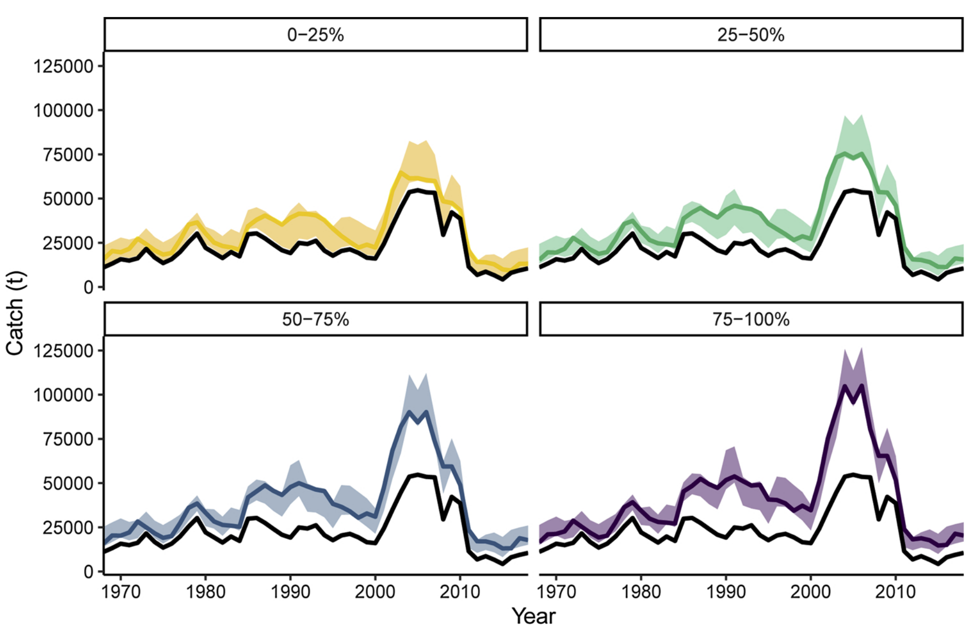

Fig. 2. Historical operating model assumptions on catch. Catch bounds (shaded areas) and the predicted catch (coloured lines) resulting from the model fit. Panel labels indicate the added percentage of US catch and the solid black line represents the Canadian catch statistics for Atlantic mackerel. Although catch bounds were set to include different sources of missing catch (Canadian and US), they cannot be separated upon prediction.

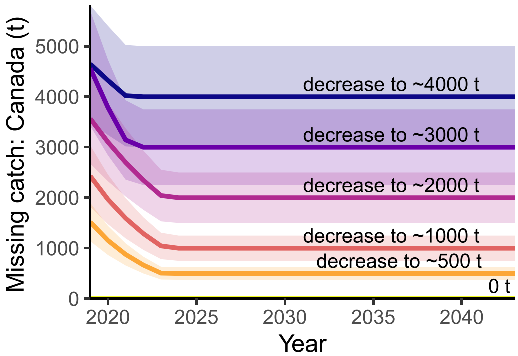

Fig. 3. Six scenarios of potential future missing Canadian catch (average and 95 % simulation confidence interval, values are in Table A.3).

constant total missing catch levels ($MC_y = x$, with x spanning 0 t to 15,000 t) to better understand the direct link between the magnitude of missing catch and the performance of HCRs. Sets of simulations still presumed different historical levels of US catch (0-25%, 25-50%, 50-75%, 75-100%). This deterministic approach does not discriminate between the sources of missing catch (from Canada or the US).

2.2. Harvest Control Rules

Each of the HCRs tested resulted in a TAC. A baseline scenario (HCR 1) involved a TAC continuously set to 0 and for the aim of this paper, we retained 8 HCRs (HCR 2–9) that are based solely on the annual TEP index, the main proxy of stock state. Although relatively simple, such HCRs might still perform well (Carruthers et al., 2016; Geromont and Butterworth, 2015) and avoid the use of unreliable catch data. Target points were first defined based on historically observed values (Fig. 4A) and each HCR then defined a relationship between the current TEP (geometric mean of the last 3 year values) and the next years' TAC (Fig. 4B) (see Geromont and Butterworth, 2015, Appendix C). As a comparison, the 2017 and 2018 TACs for mackerel was 10,000 t, up from the historically low 8000 t of 2014-2016.

2.3. Performance statistics

The state of the spawning stock (SSB_y) was defined relative to a limit (LRP) and upper stock (USR) reference point, which were set as 40% and 80% of SSB_{ref} respectively, in correspondence with the default values of the Canadian precautionary approach decision-making framework (DFO, 2009). In this framework, the LRP and URP delimit three 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 F40 % (F at which the spawning stock biomass per recruit is at 40 % of its unfished levels, Duplisea and Grégoire, 2014).

Currently, the stock is in the critical zone and for the purpose of this paper, two key rebuilding objectives were used to evaluate the effectiveness of the HCRs:

1 rebuild the stock out of the critical zone (above the LRP) with 75 % probability within a reasonable time frame (5–10 years); and
2 rebuild the stock into the healthy zone (above the USR) with 75 % probability within a reasonable time frame (10–20 years).

These draft objectives were developed by a Canadian rebuilding plan working group (established in 2017), comprising fisheries management, scientists, fisheries industry members, representatives of Indigenous communities and environmental non-government organizations. At the time of writing, there has been no *a priori* agreement on what a reasonable time frame is for rebuilding, with current time ranges representing a combination of both biological information on Atlantic mackerel generation time (3–5 years, depending on the definition used) and stakeholder inputs through the rebuilding working group.

3. Results

3.1. Objective 1: rebuilding to above the critical zone

Because all of the OMs estimated that the stock was below the LRP and recent recruitment has been at historically low levels, the stock will likely (75 %, or a high probability; DFO, 2009) need a minimum of six years to surpass this threshold, presuming status quo US fishing activities (Fig. 5). During this first stage, the performance of each HCR was mainly determined by its floor TAC level (which is principally applied when the stock is below its LRP). Rebuilding the stock above the LRP with high probability (75 %) within at most 10 years was also highly dependent on how much missing Canadian catch there would be in the future. With significant Canadian quantities caught outside the commercial quota (~1000 t, ~2000 t, ~3000 t or ~4000 t), even the most conservative HCRs (e.g., HCR 1, with a TAC = 0) were unlikely to meet the first rebuilding objective (to rebuild above the LRP with 75 % probability) over the length of simulations. Assuming a continued absence of co-management with the US, the only implementable management strategies for northern contingent mackerel that could also meet objective 1 with 75% probability under all OM scenarios and in no

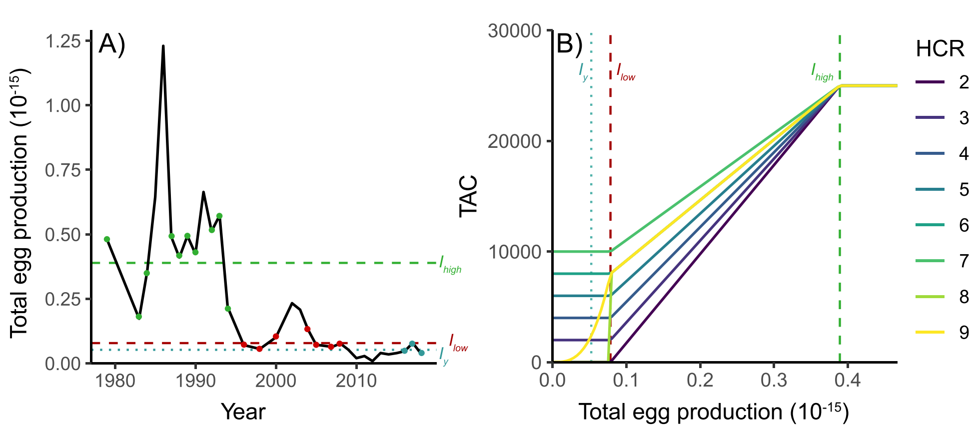

Fig. 4. A) Total egg production (TEP) estimates with an indication of the low (I_{low}, red dashed line) and high (I_{high}, green dashed line) target reference points, as well as the current value (I_y, aqua dotted line). All three horizontal lines (I_{low}, I_{high} and I_y) correspond to the geometric mean of the correspondingly coloured TEP estimates. B) Harvest Control Rules (HCRs 2–9) that define the TAC based on the presumed current stock state (I_y) relative to the target reference points (I_{low} and I_{high}) as defined in A) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

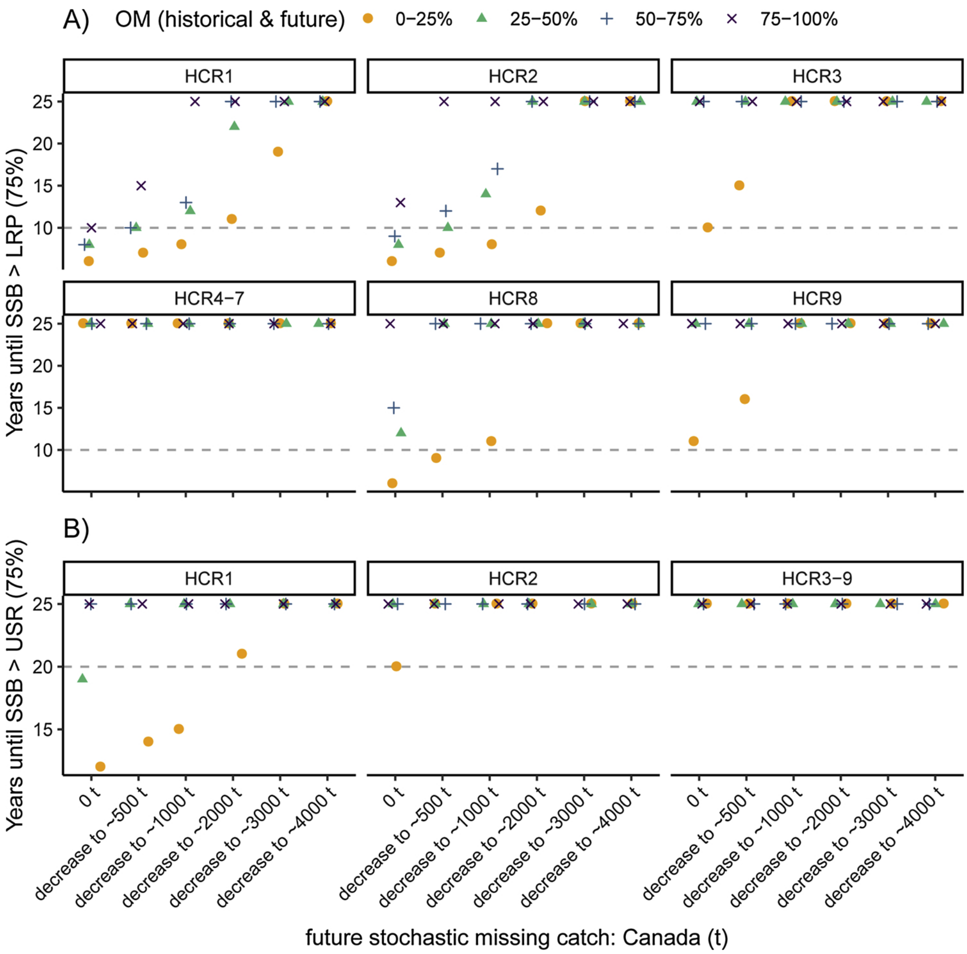

Fig. 5. Years for the stock to rebuild A) out of the critical zone (spawning stock biomass > limit reference point) and B) into the healty zone (spawning stock biomass > upper stock reference point) with a 75 % probability, in function of Canadian missing catch and under various harvest control rules (HCRs). The different dots account for different levels of uncertainty in the fraction of northern contingent fish in the US catch (both in the past and the future, OM = operating model). All scenarios include a large uncertainty in US catch, assuming independent management of the stock continues. The dashed horizontal line indicates the upper limit of a "reasonable timeframe" that represents the performance threshold for the rebuilding objective.

more than 10 years, required both the (unrealistic) outright elimination of missing Canadian catch and an initial closure of the fishery. Under the specific scenario of 25–50 % of northern contingent mackerel being caught by the US (used as a base in the actual MSE), a very strong reduction in both quantities (TAC and Canadian missing catch) would still be required to meet the objective. Under the 2017–2018 quota, i.e. a TAC of 10,000 t while in the critical zone (as would be the case in HCR 7) and significant missing Canadian catches, the time for the stock to rebuild out of the critical zone will likely (75 % probability) exceed 25 years.

The number of years for the stock to rebuild above the LRP was influenced by the assumptions represented in the different operating models. Depending on the assumed level of US catch of northern contingent fish, the time for the spawning stock biomass to leave the critical zone might vary by at least 4 years. The required time period to attain the first objectives was generally longer when the US catches were assumed to comprise a larger fraction of northern contingent fish (e.g., OM 75–100 %), but this relationship was not always linear.

We also modelled implementation error as a set of deterministic missing catch levels that included both Canadian and US (Fig. 6). Although this approach undervalues the uncertainty and complexity of missing catches, it facilitates the assessment of the direct relationship between their magnitudes and the rebuilding objectives. Even under the most opportune assumptions for rebuilding, i.e. under the historical OM based on 75–100 % of US catch comprising northern contingent fish (a stock able to sustain higher catches) and a severe reduction in fishing pressure (Canadian TAC of 0 or HCR 1), growing the stock out of the critical zone within at most 10 years was still largely dependant on total missing catch not exceeding ~6000 t. The magnitude of the combined Canadian and US missing catch is unlikely to be much below this value given the scenario's assumption that almost all US catches (in 2018 ~11,000 t) were northern contingent fish. In forecasts with slower SSB growth (OM 0–25 %, a smaller stock able to sustain less fishing mortality) and still with a TAC of 0 t (HCR 1), this same objective could not be met unless missing catch did not exceed ~2000 t. When compared to the Canadian TAC, these missing catch numbers might still appear relatively high. Deterministic projections do however not include implementation error and neglect the interdependence of Canadian and US missing catch. They are therefore likely to be more optimistic and the estimated numbers should at least be seen as upper limits to missing catch.

3.2. Objective 2: rebuilding to the healthy zone

The capacity of the stock to rebuild to the healthy zone (objective 2) was also heavily influenced by the quantity of future missing catch and the floor TAC level of each HCR. Under the various modelled scenarios of missing catch (Fig. 5), the probability of the stock reaching the healthy zone most often stagnated at a level below 75% probability (e.g., HCRs 5–7), such that it was increasingly unlikely that the stock will ever rebuild with a high probability of success (although projections were stopped at 25 years). Only the baseline HCR (TAC = 0) in combination with a decrease in Canadian missing catch could potentially meet objective 2 (75 % probability within 20 years or less), assuming no changes in US management of the stock. Because the baseline HCR is unrealistic (lasting closure of the fishery under quota and no feedback between stock size and TAC), meeting long-term objectives would require a decrease in uncertainty around both Canadian and US missing catch fractions. For instance, future US catches became disproportionately more important for the rebuilding of northern

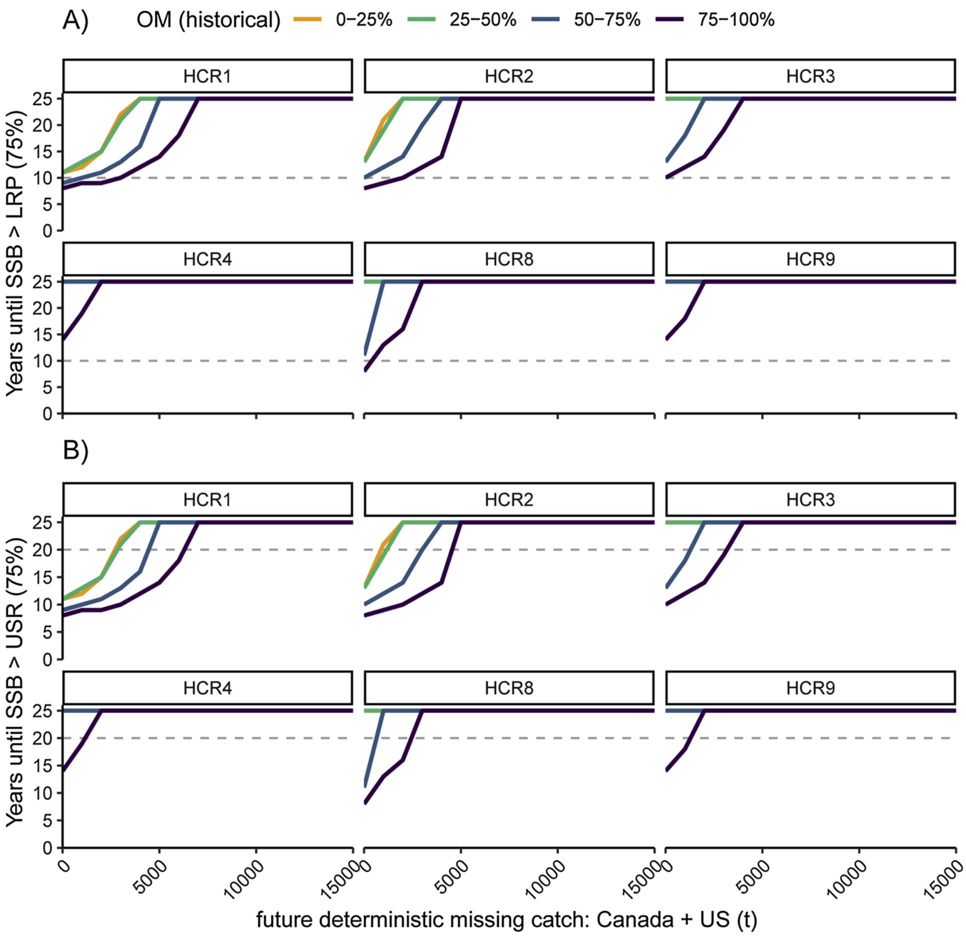

Fig. 6. Years for the stock to rebuild A) out of the critical zone (spawning stock biomass > limit reference point) and B) into the healty zone (spawning stock biomass > upper stock reference point) with a 75 % probability, under deterministic and constant levels of missing catch (including both Canadian and US missing catch) for Harvest Control Rules 1–4 and 8–9 (HCR, panels). HCRs 5–7 are not shown because time to rebuild is generally around 25 years. Differently coloured lines account for uncertainty in the fraction of northern contingent fish in the US catch (historical Operating Models). Note that when this fraction was higher in the past, future missing catch (x-axis) will likely also be higher. The dashed horizontal line indicates the upper limit of a “reasonable timeframe” that represents the performance threshold for this rebuilding objective.

contingent mackerel because of the great uncertainty associated with this quantity. If there were an important portion of missing catch from both Canadian and US sources that could be brought under management control and reduced, full recovery might be possible in a reasonable time frame (10–20 years). Deterministic and simplified projections of implementation error showed that rebuilding could still occur with some missing catches (Fig. 6). Such analyses directly show the trade-off between increasing TACs and missing catch; less fishery-restrictive HCRs (higher TACs) could be implemented and meet the performance threshold of Objective 2, but only when the total missing catch is much lower.

4. Discussion

We undertook MSE feedback simulations to support the development of a rebuilding plan for a depleted stock with a large amount of unaccounted-for removals. Results showed that as long as the majority of currently undeclared fishery removals are not brought under effective management control (i.e., reduced or declared under the TAC), quotas would need to be reduced to almost zero to achieve the performance thresholds associated with rebuilding objectives. The long-recognized issue of the unaccounted-for catch of Atlantic mackerel (DFO, 1997) biases catch statistics, increases the risk of poor management decision-making (Griffiths, 2015; Rudd and Branch, 2016), and as a consequence might prevent stock rebuilding. A suitable rebuilding procedure for mackerel should thus combine management actions to improve catch reporting with an effective HCR.

The unknown Canadian discards, bait and recreational catches and misspecified US catch of northern contingent mackerel can be considered a form of implementation error, which is known to compromise stock recovery (Kelly et al., 2006). Understandably, it is challenging to provide advice for or to manage a stock where total catches can only partially be known and controlled. If this implementation error were smaller (i.e., less missing catch) it may be possible to compensate for this adverse effect on rebuilding through controlled catch reductions. However, the current level of missing catch might be on the same order of magnitude as that of the TAC itself. This means that without some way to reduce missing catch or bring a much larger proportion of total removals under the TAC, management options for achieving even simple rebuilding objectives are limited.

Improving catch reporting is, therefore, a recommended management priority, even when stock abundance is higher and missing catches may be small relative to those under effective management control. If a stock drops below a lower reference point or limit, the management situation becomes especially difficult because required management actions to achieve fisheries objectives are necessarily more extreme and harder to implement than would otherwise be the case. Implementing new kinds of management measures when stocks are in severely depleted states can also bring a whole new complexity to the management of the stock. Unreported portions of the fishery often also have a greater cultural or social value for some participants than the economic value (e.g., recreational fisheries). When the stock and presumably catch efficiency decreases (CPUE or Catch Per Unit of Effort), these removals are therefore unlikely to weaken because of economic disincentives, making rebuilding efforts more challenging and potentially driving the stock to even lower levels.

Our MSE, based around missing catch scenarios, showed that only the most conservative HCRs (starting at a TAC of 0) would perform acceptably to enable stock rebuilding given the thresholds for performance described here (75 % probability of exceeding a limit or upper stock reference point), in either the short- (5–10 years) and long-term (20+ years). The performance of all HCRs might be improved if future

US catch of Atlantic mackerel could be roughly separated by spawning contingent so that uncertainty in implementation error would decrease. This suggests that research on the US catch composition might be one of the most efficient means of increasing management effectiveness. The availability of catch data split by spawning contingent in the future might also allow for spatial modelling of the stock (Van Beveren et al., 2019), which would better reflect the current stock structure and improve catch estimation, resulting in better-quality science advice (e.g., Punt and Hobday, 2009). The use of a spatial operating model in the MSE might also facilitate potential future joint management of the stock between Canada and the US, which may be required to achieve long-term rebuilding objectives for the northern contingent. Embarking upon joint management approaches could also help with short-term Canadian rebuilding objectives for the stock, as some fishers may be more inclined to accept restrictive HCRs in the short term if they know there will be effective long-term solutions involving the USA.

Total uncertainty of stock and fishery dynamics can never fully be captured, and hence probabilities specified as management objectives never represent exact risk profiles (Kraak et al., 2010). Particularly, alternative hypotheses about recruitment dynamics, natural mortality rates, spatial distribution and migrations were not included here, despite expected sensitivity to these processes (Punt et al., 2016). If the presented MSE framework were to be used for HCR selection in a future rebuilding or fishery management plan, multiple OMs addressing these key uncertainties should also be considered. The MSE assumptions around missing catch used here were, although simplified, likely closer to the truth than if the past ignorance situation would have continued ("reverting to the traditional default", Butterworth, 2008). Overall, including more uncertainty would likely deepen the need for even more aggressive management actions to meet performance thresholds, which may be even more challenging to implement.

When a stock is below a limit reference biomass and recovery in a reasonable timeframe appears unachievable, MSEs are generally more likely to “fail” in the sense of readily identifying acceptable and implementable management procedures (National Research Council, 1998). The low stock state often means that even very different management procedures (e.g., status quo TAC vs moratorium) have comparable and poor performance for meeting objectives. Rebuilding requirements might be so drastic from an economic, social or political point of view, that they might be effectively un-implementable. Additionally, when missing catch needs to be reduced, it would in many cases require additional research, monitoring effort or changes in legislation. Implementation of, for example, management measures such as logbooks, recreational bag limits and control for Canadian domestic bait and recreational fisheries cannot be achieved instantly. Long-term rebuilding will also, at a minimum, require a deeper knowledge of US winter catches of northern contingent fish and possibly require a means to control this catch. As key uncertainties, rebuilding objectives and the statistical framework are now on the table, MSE projections might however easily be updated in the future so that a rebuilding plan could be refined or (re)defined (Cox et al., 2013; Punt and Ralston, 2007). This MSEshowed that for stocks that require rebuilding and face a complex and challenging management environment, the focus should especially be on short-term goals, despite the fact that MSEs are usually developed with long-term goals in mind.

Even when an MSE does not immediately lead to the selection of an HCR, the process can still provide useful science and management advice (e.g., Kolody et al., 2008). For instance, our findings emphasize the need for the disentanglement of both mackerel contingents in the US catch (Redding et al., 2020) and genetic studies to improve our knowledge of stock structure. The MSE framework used in this case is a crucial tool to show the limited number of effective management options actually available for this stock. Compared to the traditional approach, the framework allows for better implementation of past and future catch uncertainty, stronger collaboration with stakeholders and indigenous groups essential to define uncertainties (e.g., Cox et al., 2013) and has defined limits to missing catch that would still allow effective implementation of management or rebuilding plans. The MSE, through the rebuilding plan working group, has enabled fishery participants to better understand the nature of the science and management issues around the fishery (e.g., Cox et al., 2013) and because the focus is on management actions that will lead to the achievement of objectives, the impact of missing catch has become clearer to all involved. Showing the direct trade-offs between the quantity of missing catch and both Canadian quotas and rebuilding probabilities has contributed to a sense of urgency among stakeholders to address the issue of unreported removals and the role of the US mackerel fishery now dominates some rebuilding plan working group discussions. To all participants, the process has clearly demonstrated that missing catch might not only lead to biased science advice but also reduce the effectiveness of management measures and thus detract from the stock’s economic potential.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2019.105473.

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