Fisheries and Oceans Canada | Pêches et Océans Canada
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Canadian Science Advisory Secretariat (CSAS)

Research Document 2023/085

Quebec region

Scientific Elements of the Northern Gulf of St. Lawrence (NAFO 3Pn4RS) Atlantic Cod Rebuilding Plan

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November 2023

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.

Published by:

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

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

ISSN 1919-5044
ISBN 978-0-660-68719-3 Cat. No. Fs70-5/2023-085E-PDF

Correct citation for this publication:

Benoît, H.P., and Ouellette-Plante, J. 2023. Scientific Elements of the Northern Gulf of St. Lawrence (NAFO 3Pn4RS) Atlantic Cod Rebuilding Plan. DFO Can. Sci. Advis. Sec. Res. Doc. 2023/085. iv + 28 p.

Aussi disponible en français :

Benoît, H.P., et Ouellette-Plante, J. 2023. Éléments scientifiques du plan de rétablissement de la morue franche du nord du golfe du Saint-Laurent (OPANO 3Pn4RS). Secr. can. des avis sci. du MPO. Doc. de rech. 2023/085. iv + 29 p.

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ABSTRACT

The Atlantic cod (*Gadus morhua*) stock in the northern Gulf of St. Lawrence (NAFO 3Pn4RS) is below its limit reference point. Given the new Fish Stock Provisions that came into force by regulation in April 2022, this means that Fisheries and Oceans Canada (DFO) is legally required to develop a rebuilding plan for this stock. A rebuilding plan comprises several elements, many of which are defined or supported by information and analyses provided by DFO's Science sector. More specifically, it is under the purview of DFO Science to provide scientifically defensible options for a rebuilding target and rebuilding timeline (T_{min}), to evaluate the probability of meeting rebuilding objectives and timelines based on different fishery management options proposed, to identify indicators for tracking rebuilding progress and guide decisions for the periodic review of the rebuilding plan. Peer review of these new elements and analyses is an important step in ensuring that they constitute the best science possible based on the available data, resources and timeline for their development.

INTRODUCTION

The Atlantic cod (*Gadus morhua*) stock in the northern Gulf of St. Lawrence (NAFO[1] 3Pn4RS) is one of the 30 major stocks that are subject to the Fish Stock Provisions that came into force through regulation on April 4, 2022. As the 3Pn4RS cod stock is below its limit reference point (LRP), Fisheries and Oceans Canada (DFO) is legally required to develop a Rebuilding Plan for this stock that meets the requirements of the Fish Stock Provisions (DFO 2021a). The Department has committed to developing a Rebuilding Plan for 3Pn4RS Atlantic cod by April 2024.

A rebuilding plan comprises several elements, many of which are defined or supported by information and analyses provided by DFO's Science sector (DFO guidelines on writing rebuilding plans). The information required for some of the science-based elements is available from material that has been peer-reviewed and is published or soon to be. For instance, a description of stock status, trends and probable causes of the stock's decline and subsequent lack of rebuilding is available from the most recent assessment for 3Pn4RS cod (Ouellette-Plante et al. In prep[2]). These elements do not require additional peer review at this time. However, there are other elements requiring new analyses. Specifically, it is under the purview of DFO Science to provide scientifically defensible options for a rebuilding target and rebuilding timeline, to evaluate the probability of meeting rebuilding objectives and timelines based on different fishery management options proposed by a multi-sectorial and multi-stakeholder rebuilding plan working group, to identify indicators for tracking rebuilding progress and guide decisions for the periodic review of the rebuilding plan. Peer review of these new elements and analyses is an important step in ensuring that they constitute the best science possible based on the available data, resources and timeline for their development.

This document presents the new syntheses and analyses prepared for the rebuilding plan for 3Pn4RS Atlantic cod. This material was presented at a Canadian Science Advisory Secretariat (CSAS) peer review meeting which took place on October 12, 2023. This meeting was requested by DFO Science to conduct an independent review of the work that has been done to support the development of the 3Pn4RS Atlantic cod Rebuilding Plan. The results of the regional peer review will be used, amongst other things, to inform the development of candidate management procedures for the 3Pn4RS Atlantic cod Rebuilding Plan.

REBUILDING TARGET

With respect to defining a rebuilding target, current DFO guidelines on writing rebuilding plans state the following :

"The rebuilding target must be set at a level above the LRP so that there is a very low to low likelihood of the stock being below its LRP (<5-25% probability; […]). A rebuilding target has been reached when there is at least a 50% probability that the stock is at or above its rebuilding target."

Given that a quantitative model-based assessment is in place for NAFO 3Pn4RS cod, the setting of the rebuilding target and subsequent performance monitoring should be accomplished using the accepted model and therefore with respect to the uncertainty of quantities estimated

[1] Northwest Atlantic Fisheries Organization.

[2] Ouellette-Plante, J., Benoît, H.P., and Lussier, J.-F. 2023. The status of the northern Gulf of St. Lawrence (3Pn, 4RS) Atlantic cod (*Gadus morhua*) stock in 2022. In preparation.

from it, here notably the spawning stock biomass (SSB). Assuming that the quality of the assessment will not change, the relative errors on current estimates of SSB should reflect relative errors on future estimates and can be used to define rebuilding targets that satisfy the requirements stated above. Contrary to the approach used for the NAFO 3Ps cod stock, which set rebuilding targets based on projections (DFO 2023a), the approach used here is more direct, does not depend on assumptions made for the projections, is not confronted with large increases in uncertainty as the projection period increases, can be implemented regardless of the prospects for stock growth and is independent of projections used to estimate T_{min} (see definition in next section).

During the last assessment, which took place in February 2023, a limit reference point (LRP) of 71,970 t of SSB was set for this stock (DFO 2023b). The assessment model estimates SSB with reasonably high precision, as evidenced by the generally narrow confidence intervals around the estimates (Figure 1). In the model, SSB is estimated on the logarithmic scale (log) and the ratio of annual standard errors and log SSB estimates, which we term here the coefficients of variation (cv), are generally small, with values since 1997 varying around a mean of 0.0150 (Figure 2). The cv in the terminal year of the assessment is greater (0.0168), which is typical for these models.

Using the log of the LRP as the lower threshold and assuming a value for cv, it is possible to identify the mean log SSB associated with some defined probability of values of log SSB that are at or below this threshold, based on the quantiles of the Normal distribution. Here we considered probabilities of 5 and 25%, those associated with the boundaries that define a low likelihood according to the DFO guidelines. Smaller values (<5%), which would constitute a very low likelihood, could also easily be considered. We generated two sets of estimates. The first assumed the cv estimated in the terminal year (2022, value of 0.0168) of the 2023 assessment. This is meant to represent the relative error for log SSB in the terminal year of future assessments, which will serve to evaluate progress with the rebuilding plan, and was the value recommended to use by the rebuilding plan working group. The second set of estimates assumed the mean cv value for 1997-2022 (0.0150). The estimates of the rebuilding targets were obtained by exponentiating the log SSB values associated with the respective probabilities. The R code used to generate the estimates is presented in Appendix A and the estimated rebuilding targets are in Table 1 and vary between 80,741 and 99,211 t.

T_{MIN}

In addition to rebuilding objectives, a rebuilding plan requires a defined rebuilding timeline, which is necessary to evaluate different management options and subsequently to track rebuilding progress with respect to rebuilding objectives. The international standard and the approach recommended by DFO (DFO 2021a) is to estimate the time to reach the rebuilding target with zero fishing mortality (T_{min}) and to base the rebuilding timeline on some multiple of this value. Specifically, current DFO guidelines on writing rebuilding plans state:

"The timeline to rebuild a stock to its rebuilding target must be between T_{min} and a maximum of two to three times T_{min}, where T_{min} is the time the stock would take to rebuild to that target in the absence of all fishing (F=0) under prevailing productivity conditions."

A rebuilding target will have been achieved when there is a 50% chance that the stock indicator is at or above that target. Estimating T_{min} for NAFO 3Pn4RS cod requires projecting into the future the stock state from that estimated in the most recent assessment (February 2023, Ouellette-Plante et al. In prep[2]), under the assumption that current productivity conditions will prevail into the future. The elements that determine productivity are stock weights at age (reflecting somatic growth), the maturity ogive (proportions mature at age), annual recruitment and the age-specific natural mortality rate, M. In the absence of strong information to the contrary, the weights at age and maturity ogive used in the last year of the assessment were assumed for the projection period. In contrast, recruitment and M have varied non-negligibly for 3Pn4RS cod, and both require some stock-specific consideration. The rationale for the choices for recruitment and M assumptions for the simulations is provided in the following two sub-sections. A less technical summary of the rationale and choices is provided at the beginning of the third sub-section (T_{min} simulations).

RECRUITMENT

The relationship between spawning stock biomass and recruitment provides a strong compensatory mechanism in fish population dynamics and is often the only form of density dependence that is modelled in stock assessments and related processes, such as management strategy evaluation.

The assessment for 3Pn4RS cod reveals an incomplete stock-recruitment relationship for the stock, characterized by low recruitment at small stock sizes (SSB generally < 55,000 t) and high recruitment at large stock sizes (SSB > 125,000 t), with only two SSB-recruit estimates at intermediate stock sizes (Figure 3). Furthermore, those two sets of estimates are likely unrepresentative of the broader stock-recruitment relationship as they occurred in years (1989, 1990) when conditions for the stock were particularly unfavourable and stock surplus production was negative (Dutil and Lambert 2000, Lambert 2011, Ouellette-Plante et al. In prep[2]). Overall, the stock and recruitment dynamics are such that recruitment appears to be characterized by fluctuations around average levels for each of the two periods, 1973-1990 and 1991-present (Figure 4).

Poor physiological condition of adults not entirely accounted for in SSB, high abundance of pelagic fish predators of cod eggs and larvae (e.g., Atlantic mackerel [*Scomber scombrus*]), and below average bottom-temperatures contributing to higher mortality in settling and settled juveniles have all been previously identified as likely negative contributors to reproduction or recruitment for cod (Swain and Sinclair 2000; Duplisea and Robert 2008; Lambert 2011; DFO 2021b; Bryhn et al. 2022). These factors, individually or jointly, do not appear to explain recruit dynamics in 3Pn4RS cod (Figure 4, top panel). While these factors may have contributed to recruitment variation in some years, we note that they have all generally been at favourable levels for well over a decade (Figure 3).

In addition to the environmental factors considered above, the demographic composition of SSB may also have contributed to recruitment variation. Compared to younger cod, older and larger cod are expected to make a considerably larger contribution to recruitment on a mass-specific basis given that in a given season they produce more batches of better quality eggs, and produce many more eggs in total as a function of their body mass (Trippel 1998; Rideout et al. 2005; Barneche et al. 2018; Marshall et al. 2021). Furthermore, evidence from northeast Arctic cod and Barents Sea cod stocks indicates that recruitment success and resilience to environmental change are associated with SSB comprising older individuals (Ohlberger et al. 2022; Ottersen and Holt 2022). The proportion of older fish in the stock, which we define as the number of cod ages 8 and above, divided by the number ages 4 and above, has fluctuated somewhat cyclically since 1973. Years in which SSB comprised a high proportion of older fish often corresponded with years of good recruitment, particularly prior to 2010 (Figure 5). This relationship is not sufficiently strong to include in the stock projections. Nonetheless, given that the proportion of older fish is a function of past recruitment and especially adult survival, and that a rebuilding plan for this stock will almost certainly focus on improving survival, realized recruitment in the future could reasonably be better than that used in the projections.

Recruitment of 3Pn4RS cod shows reasonably clear cycles relative to mean recruitment, especially since 1991 (Figure 4). Time series analyses based on a periodogram, which identifies principle frequencies in the time series, and the autocorrelation function, which identifies the strength of correlations of the original series with different lags of the same series, both indicate significant cycles with a period of about 8 years (Figure 6). This means that on average, one or two years of above-average recruitment, are followed four years later by one or two years of below-average recruitment, and so on. The drivers of this cycle are not clear, although fluctuations in the age composition mentioned previously may be part of the explanation (Figure 5). Rindorf et al. (2020) examined the evidence for different potential causes of recruitment cycles in cod stocks, which include intra-cohort competition, predation, cannibalism and cyclic fluctuations in SSB. Their cross-stock examination, suggested that the cycles observed for 3Pn4RS cod would be consistent with an effect of cannibalism, although the authors cautioned that data on cod feeding needed to be examined before drawing a conclusion. The available diet information for 3Pn4RS cod is primarily representative of summer feeding conditions, and indicates that smaller cod are a minor proportion of the diet of larger cod, very likely insufficient to explain the cycles (Ouellette-Plante et al. 2020, J. Ouellette-Plante, DFO, unpublished analyses). Because cod in this stock feed very little during the winter and early spring (Fordham and Trippel 1999; Schwalme and Chouinard 1999), cannibalism would have to be concentrated during the late spring or during the fall migration, periods during which few data are available. All else being equal, the impact of cannibalism might be expected to be greater when SSB was much higher in the 1970s and 1980s, but this is not evident in the recruitment cycles. Overall, the cannibalism hypothesis cannot be refuted, but existing support is not strong.

Based on the preceding, there is no mechanistic basis for simulating cycles in recruitment. While the cycles in recruitment could be simulated from an empirical basis (e.g., time series analyses), doing so accurately is not necessarily straightforward, and more importantly is not necessary for the T_{min} simulations, nor eventual simulations of rebuilding management scenarios. We demonstrate this lack of necessity using a simple fictitious simulation. We simulated two recruitment series, a cyclic one with an assumed period of 8.2 years (black line, top panel of Figure 7), and one in which the values from the first were randomly re-ordered, such that there was no pre-determined periodicity and that total cumulative recruitment over the simulated 50-year series was equal for the two. We then assumed a fixed natural mortality at age, based on average values from the assessment over the past 30 years and projected forward for 50 years, starting at a small SSB value. We simulated 1,000 cases based on different random re-ordering of the cyclic recruitment series. The bottom panel of Figure 7 presents the results for the SSB trends based on cyclic recruitment (bold black line), a 9-year smooth of that SSB series (dashed bold black line), the average SSB trend for the randomized recruitment cases (bold blue line), and SSB trends for three randomly chosen cases, which are presented for illustration of the variability among cases. The results indicate that within fewer than two recruitment cycles, both the cyclic and non-cyclic recruitment patterns produce the same SSB on average (Figure 7 bottom panel). In the first 13 years of the simulations, the smoothed average for the cyclic recruitment is above that for the randomized recruitment, but this is just a function of the starting point of the recruitment series with respect to the peak in the recruitment cycle. If the simulations are started at a slightly different part of the recruitment cycle, the smoothed average SSB that results is below the average SSB for randomized recruitment (Figure 8). Because we cannot be certain of where in the recruitment cycle to begin the T_{min} simulations, and because, on average, the cyclic and randomized recruitment patterns will generate the same SSB series, we proceeded with simulating recruitment as varying randomly about the mean recruitment.

Based on the preceding, we simulated two recruitment scenarios for the T_{min} projections. In the first we simulated (log) recruitment deviations around the mean recruitment estimate in the assessment for 1991-2022 (Figure 4). There is an over 30-year track-record for this mean level of recruitment and associated annual variation, and it is reasonable to assume that this constitutes recruitment under current conditions.

The principal drawback of the first scenario is that it does not allow for increases in average recruitment that are expected as SSB and the number of older fish in the population increases. Notably, it disregards assessment estimates for 1973 to 1990 of much higher recruitment at higher SSB. Given the inability to reliability estimate a stock-recruit function, we instead assumed a logistic function that transitions from lower average recruitment at a low SSB, to higher average recruitment at a high SSB as the basis for a second scenario (Figure 9). The shape of the function is arbitrary, and we discuss the consequences of alternative assumptions when we present the results below.

NATURAL MORTALITY

Stock assessments aim to distinguish between mortality caused by fishing (*F*), and mortality due to other causes, which is typically termed natural mortality (*M*). While many assessments assume fixed values of *M*, or estimate values that do not vary over time, the assessment for 3Pn4RS cod estimates time-varying *M*. While the aim is to account for all fishing mortality in *F*, in practice, some unaccounted fishing mortality may be subsumed into estimates of M, along with mortality resulting from ecological and biological factors. In the 3Pn4RS cod assessment, there is evidence that a non-negligible portion of *M* could result from fishing, which in principle is reducible under a rebuilding plan. When a moratorium on all directed fishing (commercial and recreational) was imposed in 2003, *M* for older cod decreased to lower levels, trending towards those estimated historically for the stock, prior to the mid-1980s (Figure 10). When the fishery re-opened the subsequent year, *M* increased. Subsequently, peaks in *F* in the late 2000s and late 2010s were associated with peaks in *M*. This provides strong evidence for unaccounted fishing mortality being subsumed into *M*. Furthermore, because catches in the recreational fishery are not monitored, mortality caused by that fishery likely also contributes to *M*, even though the assessments attempt to account for some of this mortality as *F* using a censored catch approach. Currently, it is not possible to establish which fraction of *M* is attributable to unaccounted fishing mortality, and therefore reducible with adequate management and enforcement, and which fraction is attributable to ecological and biological causes and therefore not subject to direct management control.

Simulations for T_{min} are meant to exclude mortality caused by fishing, and thus to model mortality exclusively from ecological and biological sources (while in principle, human activities other than fishing could induce mortalities, no such adverse activities have been identified for the stock). Due to our inability to reliably estimate contemporary rates of natural mortality resulting exclusively from ecology/biology, we simulated two contrasting cases.

In the first case, we based the simulations on the age-specific average *M* estimated in the assessment for the years 2019, 2020 and 2021. Estimates of *M* for 2022 were excluded from the average because the estimates for the terminal year of an assessment tend to be variable for this stock and in other assessments. This is evident for instance in retrospective analyses conducted for the 3Pn4RS cod assessment. The 2019-2021 average values represent current conditions for assessment *M* estimates known to include some unknown fraction of unaccounted fishing mortality.

In the second case, we based the simulations on the age-specific *M* estimated for 2003, the last year in which all directed fishing was prohibited and in which bycatch in other fisheries was small and likely largely accounted for in *F*. In the absence of fishing, estimates of *M* in 2003 are expected to reflect exclusively mortality from ecological and biological causes that year. The key assumption for this simulated case is that *M* resulting from current ecological and biological causes is the same. The 2023 assessment reviewed potential causes of *M* such as poor condition, adverse oceanographic conditions and predation by seals. It concluded that while these factors are unlikely to have contributed to strong increases in *M* over the past three decades, more recent conditions may not be favourable for cod. The 2003 *M* estimates may therefore underestimate current mortality values.

T_{MIN} SIMULATIONS

Two recruitment and two natural mortality scenarios were simulated. In the first recruitment scenario, recruitment was simulated based on random deviations around the estimated mean recruitment level for the past 32 years (Figure 4). This is entirely consistent with current productivity conditions, but disregards expected increases in recruitment as SSB increases. In the second scenario recruitment, recruitment was simulated based on random deviations around the mean levels estimated in the assessment respectively for low SSB (generally <55,000 t) and high SSB (generally >125,000 t), and at levels intermediate for intermediate SSB values (Figure 9). In both cases, variability in the estimated mean recruitment levels and in the recruitment deviations were simulated based on estimated parameter standard deviations from the assessment, which estimates parameter values for log recruitment.

In the first natural mortality scenario, the average *M* at age for the 2019-2021 period was assumed. This value is acknowledged to include some unaccounted fishing mortality that in principle could be reduced with effective fishery management. In the second natural mortality scenario, the estimated *M* at age values for 2003 were assumed. Given that all directed cod fishing was prohibited that year, the estimated values for *M* best reflect mortality due to natural factors only. This scenario assumes that current mortality due only to natural factors has remained unchanged. In both cases, variability in estimated *M* was simulated based on estimated standard deviations from the assessment, which estimates *M* via log-*M* deviations. The simulations begin with estimates of numbers at age for 2023. They are initiated based on the numbers at age and mortality rates for 2022 estimated by the assessment model. Uncertainty in those numbers is included in the simulations. The other inputs, weights and maturities at age were assumed fixed as stated earlier.

T_{MIN} RESULTS

A rebuilding target of 81,961 t for this stock, based on a 25% probability and the terminal year cv was chosen by the working group subsequent to the meeting at which rebuilding target options were presented by DFO-Science (Table 1).

Simulations assuming that natural mortality in the future will be equivalent to the average *M* values from the assessment for 2019-2021 project the stock to rapidly reach an equilibrium median SSB well below the rebuilding target, and comparable to the 2022 estimate of about 42,000 t (Figure 11). This result occurs regardless of the recruitment scenario because simulated SSB levels are very unlikely to reach intermediate values where mean recruitment increases in the second recruitment scenario. Because the assumed *M* values very likely include some fishing mortality that is in principle reducible, these scenarios are likely pessimistic.

Simulations assuming the estimated *M* values from 2003 have median SSB increasing to and surpassing the rebuilding target in 8 years for both recruitment scenarios (Figure 11). In simulations assuming low mean recruitment, on average the stock reaches a median equilibrium value of just under 100,000 t in about 20 years. Because mean recruitment is likely to increase with SSB, this scenario likely underestimates the equilibrium stock size achieved in the absence of fishing with the assumed *M*. In simulations assuming the arbitrary stock-recruitment function, the stock increases to a much higher equilibrium in about 40 years. While the equilibrium is consistent with mean recruitment patterns observed for the stock at both low and high SSB and is not sensitive to the arbitrary choice of the stock-recruitment function, the rate at which it is reached is sensitive to this choice. Equilibrium levels would be reached sooner if the arbitrary stock-recruit curve in Figure 9 is shifted to the left, and later if it is shifted to the right. In contrast, a shift to the right will not affect T_{min} as exemplified by the result for the constant low mean recruitment scenario, although a shift to the left would result in a lower T_{min}. As noted earlier, the *M* values from 2003 may underestimate true current values due to ecological and biological factors.

DISCUSSION

The two scenarios for natural mortality provide contrasting cases, one in which the value is almost certainly over-estimated with respect to mortality in the absence of all fishing (2019-2021 average *M*), and one in which the value might be underestimated if mortality from natural causes has increased (2003 M). The likelihood associated with scenarios intermediate to these is poorly defined, making objective selection of additional scenarios very difficult.

Obtaining more accurate estimates of *M* would improve the reliability of projections made as part of recovery planning, both for T_{min} but also for different management scenarios. The moratorium on directed commercial fishing in 2022 and 2023 will also have removed any unaccounted fishing mortality resulting from that fishery. To the extent that this unaccounted mortality was non-negligible, estimates of *M* for that year in future assessments should be more accurate. If removals of cod as bycatch in other fisheries remain small and well monitored, closures of all directed fishing (commercial and recreational) will allow for an estimation of *M* that reflects exclusively (or almost) that due to natural causes, as was the case in 2003 when *M* values tended towards past historical values. A revision of the rebuilding plan based on new assessment results would be warranted under such a scenario.

Rebuilding timelines for the rebuilding plan will be proposed based on the results for T_{min}. A relevant additional consideration for those timelines is the potential for predation-driven Allee effects (Gascoigne and Lipcius 2004). Cod in the neighbouring southern Gulf of St. Lawrence (NAFO 4TVn) stock have been experiencing particularly elevated *M* attributed to predation by grey seals (*Halichoerus grypus*), which is causing the stock to decline rapidly in the absence of directed fishing since 2009, leading to projected extinction of that stock within decades (Swain and Chouinard 2008; Neuenhoff et al. 2019). A key driver of this decline is the rise in *M* that results from an increase in per-seal mortality as cod abundance declines (Rossi et al. In prep[3]; Neuenhoff et al. 2019). The corollary to this result is that high cod abundance results in a smaller rate of predation and therefore smaller *M*. Although a review undertaken as part of the 2023 assessment concluded that predation by grey seals has probably not contributed to an important rise in *M* in 3Pn4RS cod over the past few decades given that grey seals have been much less prevalent in the northern Gulf of St. Lawrence compared to areas to the south, this situation could change in the near future given the close proximity of the two ecosystems and some evidence from satellite tracking and aerial surveys that grey seal use of the northern Gulf could be increasing (Mosnier et al. 2023, X. Bordeleau, DFO, pers. comm.). The best safeguard against increased grey seal presence in the 3Pn4RS cod area is to rapidly rebuild the stock to abundance levels at which predation rates will likely be lower. However, the magnitude of the

[3] Rossi, S.P., Cox, S.P., and Benoît, H.P. 2023. Extirpation of Atlantic Cod from a Northwest Atlantic ecosystem in the absence of predator control: inference from an ecosystem model of intermediate complexity. In preparation.

benefits of doing so depends on the shape of the functional response that defines the per-seal rate of predation as a function of cod SSB. The shape of this function is not known nor presently estimable for cod in the northern Gulf of St. Lawrence.

SIMULATIONS OF POTENTIAL MANAGEMENT MEASURES

SCOPE FOR MORTALITY

The simulations for T_{min} undertaken in the preceding section and presented at the June 16 2023 working group meeting were made on the basis of assumptions for future recruitment and natural mortality. Specifically:

- two recruitment scenarios: a) based on the 1991-2022 (32 year) average and b) assuming a stock-recruitment relationship allowing a transition to higher average recruitment when the spawning stock biomass increases; and,
- two scenarios for natural mortality (M), knowing that the calculations of Tmin are made in the absence of fishing mortality: i) according to the average values of M at age for 2019-2021 and ii) according to the values at age for 2003, the last year during which all directed fishing (commercial and recreational) was closed. In scenario (i) the values of M at age most likely include an unknown amount of unaccounted fishing, as previously explained, while in scenario (ii) these values most likely represent true ‘natural’ (ecological/biological) mortality which prevailed in 2003, but which could differ from current values.

The results of simulations for Tmin demonstrated that regardless of which recruitment scenario, the values of *M* equivalent to the averages of the estimates for 2019-2021 will not allow the stock to recover. In fact, under these assumptions, the stock would already be at equilibrium, with an SSB around 60% of the LRP. On the other hand, for M at age equivalent to 2003 values, the stock is projected to reach its recovery target in 8 years, regardless of the recruitment scenario. The recruitment scenario mainly influences the equilibrium SSB the stock could attain. These results are explained by the fact that in the assumed stock-recruitment relationship, recruitment increases especially when the SSB is near the target.

Two series of additional simulations were undertaken to better understand the scope for mortality that would allow rebuilding to the target, which in turn could inform possible management scenarios (harvest control rules). In both cases, we identified scenarios that at the very least allow a recovery, that is to say that would allow the stock to stabilize at a level of median SSB just above the target, assuming a recruitment similar to the average of the 1991-2022 period. This recruitment scenario seems the most likely in the future given the fact that recruitment has fluctuated around this average for more than three decades. Although an increase in recruitment linked to an increase in SSB is anticipated, the form of this relationship is very uncertain, which would make simulations of different forms of stock-recruitment relationship speculative and uninformative. We nevertheless present the results for simulations using the stock-recruitment relationship chosen arbitrarily for the T_{min} simulations for illustrative purposes.

In the first set of simulations, we initially assumed a total mortality at age equivalent to the average of the estimates of *M* at age from 2019-2021 (Figure 12, gray line). We then searched for the fraction of this mortality that would minimally allow recovery. We found that a mortality at age for ages 4+ (the ages vulnerable to fishing) equivalent to 68% of that of 2019-2021 (Figure 12, red dashed line) would achieve the objective, and would do so in 11 years, in the absence of additional fishing mortality (Figure 13). With the assumed stock-recruitment relationship, the stock would recover in 10 years and could reach a much higher equilibrium if the reduced mortalities were maintained (Figure 13).

In the second series of simulations, we assumed a natural mortality at age equivalent to that of 2003 and an average recruitment based on the 1991-2022 period from the assessment (Figure 12, blue line). We then searched for the total annual fishing removals that would minimally allow recovery, assuming fishing selectivity equivalent to that estimated for 2022 from the February 2023 stock assessment. We found that annual removals of 4,300 t would allow the stock to recover in 19 years (therefore in 2.4 times a T_{min} of 8 years) and to stabilize at an equilibrium just above its target (Figure 14). With the assumed stock-recruitment relationship, the stock would reach its target in 13 years and could reach a much higher equilibrium if annual removals of 4,300 t were maintained for about 40 years (Figure 14). This set of simulations is highly dependent on the assumption for *M* equivalent to the 2003 values, and that the simulated annual removals constitute total fishery removals from all sources (landings from directed and non-directed commercial fisheries, the recreational fishery, First Nations fisheries, as well as any mortalities associated with discards, depredation in fishing gear and unreported catches, in addition to scientific sampling).

Together, the two sets of simulations indicate that a significant reduction in the currently estimated total natural mortality (2019-2021), which is linked to biological/ecological factors as well as unaccounted fishing, is necessary to rebuild the stock. To the extent that mortality linked to biological/ecological factors might currently be at levels similar to values considered typical historically (e.g. before 1990 and in 2003), an annual maximum of 4,300 t of total removals would allow recovery with the estimated recruitment level for the last three decades. According to this scenario, currently all of these catches would be from unaccounted sources, and would constitute only a part of all unaccounted catches, since the stock would not recover with the values of *M* estimated by the model for the recent years (2019-2021).

SIMULATIONS FOR EXAMPLE HARVEST CONTROL RULES

Three example candidate fishery management harvest control rules were developed by DFO Fisheries Management and provided to DFO Science for simulation testing. These are termed ‘options’ in what follows, but this is not meant to imply that these are the definitive and exclusive set of options that the working group may choose to evaluate before finalizing the rebuilding plan, and are merely intended to facilitate working group discussion on decision rules. The three options, which are based on total fishery removals are plotted in Figure 15 and detailed in Table 2.

The simulations were undertaken as described previously. A single recruitment scenario was simulated, based on the 32-year mean recruitment (1991-2022). This choice was made because that longstanding recruitment pattern is the most likely for the near future, given its persistence. Furthermore, alternative recruitment scenarios based on a stock-recruitment relationship would be speculative, do not affect the probability of rebuilding and have a minor effect on rebuilding times, as shown above. Simulation results are shown only for scenarios based on the 2003 estimates of *M* given that the alternative assumption based on recent estimates results in no possibility of rebuilding, as previously shown.

Separate simulations were undertaken for the three harvest control rule options, each involving 10,000 simulation threads. For each, we identify the year in which the rebuilding target and interim objective were reached. Specifically, the rebuilding target was considered achieved when SSB in 50% of threads reached the nominal SSB value of 81,961 t, while the interim objective, defined previously by the working group, was considered achieved when SSB in 75% of threads reached the nominal value of 57,576 t, which is 80% of the LRP (71,970 t).

Control rule options 1 and 2 resulted in nearly identical stock trajectories, with both resulting in achieving the interim rebuilding objective in 6 years and the rebuilding target in 9 years (Figure 16). Over the 9-year rebuilding period, options 1 and 2 resulted in median cumulative total fishery removals of 3,950 and 6,150 t respectively. Option 3, which involves larger fishery removals at most levels of SSB above 36,000 t, resulted in a slightly increased anticipated rebuilding time of 11 years. Over the 11-year rebuilding period, option 3 resulted in median cumulative total fishery removals of 19,000 t. The projected equilibrium SSB is lower for option 3 because removals are three times greater once the stock has recovered in this scenario. All three options result in an anticipated rebuilding timeline that is well within two to three times the estimated T_{min} of 8 years for the assumed natural mortality scenario. By the end of the 9-year rebuilding period, options 1 and 2 resulted respectively in a median SSB value of about 83,100 t and 82,300 t. Overall, these two options therefore result in little to no difference in rebuilding time or status at the end of that time, but differ by about 2,400 t of total fishery removals over the rebuilding period. In contrast, within that same timeframe, option 3 achieved a median SSB value of about 78,300 t, a 5-6% difference from the two other options. This could, in turn, result in foregone recruitment, the magnitude of which would depend on the slope of the stock-recruitment relationship, and possibly increased predation-related *M*, depending on the form of the functional response.

SSB MONITORING

INDICATORS OF STOCKS STATUS

The principal metric of stock status for the 3Pn4RS cod stock is the SSB estimated from the analytical stock assessment. However, annual assessments for this stock are neither feasible, due to available resources, nor warranted, given the low frequency variation in SSB that characterizes this and other cod stocks. As such, an indicator of SSB is required for the application of harvest control rules in years when there is no full analytical assessment. During the February 2023 assessment, DFO Science demonstrated that the biomass of cod measuring ≥43 cm, estimated using data from the annual multi-species research vessel survey and smoothed using a Loess smoother, provides a reasonable proxy for SSB as estimated in the analytical assessment (Figure 17, Ouellette-Plante et al. In prep[2]). This index can therefore be used to track stock rebuilding in years in which a full assessment is not undertaken.

DFO Science argued at the last assessment that a full assessment undertaken every five years, with updates in interim years based on the survey SSB indicator, is sufficient for advisory purposes, as is the case for cod from the southern GSL stock (DFO 2023b). Interim year updates will allow tracking of stock status with respect to stock trends projected at the full assessments. Deviations in stock trajectory relative to projected trends more than a specific amount could trigger the need for a full assessment under an exceptional circumstance protocol. The magnitude of deviation that would trigger an assessment, likely to be defined as a percentage difference, remains to be defined.

SOME CONSIDERATIONS FOR THE PERIODIC REVIEW OF THE REBUILDING PLAN

The science underpinning the projections for the rebuilding plan involves key uncertainties for the current and anticipated productivity of the stock. There are reasons to believe these uncertainties could be attenuated to some extent in the next few years.

First, the form of the stock-recruitment relationship is highly uncertain given that estimates of past recruitment are associated exclusively with low or more elevated SSB levels. Recruitment at intermediate SSB levels, such as those near the LRP and rebuilding target are therefore highly uncertain. However, as the stock rebuilds, estimates of recruitment at these intermediate levels of SSB will become available and will allow the stock-recruitment relationship to be more accurately characterized, thereby improving the accuracy of stock projections.

Similarly, there is high uncertainty with respect to current levels of natural mortality, as well as unaccounted fishing mortality which might be reduced by management actions implemented as part of the rebuilding plan. The closure of the directed commercial fishery for the 2022-2023 and 2023-2024 fishing seasons will have eliminated one potential source of unaccounted fishing mortality. While other known or potential sources will remain, such as the recreational fishery, estimates of natural mortality in the next analytical assessment should be more accurate. Similarly, improvements that might be made to the monitoring of the quantity and demographic composition of fishery removals (not to be confused with regulatory compliance monitoring), could improve the accuracy of mortality estimates.

Given these considerations, we recommend that projections of stock trajectories based on the rebuilding framework that will be chosen for this stock be undertaken following the next full assessment to determine if the prospects and timelines for rebuilding need to be revised. These analyses could help inform decisions about the need for modifications to the rebuilding plan. More generally, we recommend that such projections be made as part of subsequent analytical assessments in the multi-year assessment cycle, especially if estimates of stock productivity or the understanding of the causes of mortality are improved.

ACKNOWLEDGEMENTS

The analyses presented here benefited from input received during meetings of the rebuilding plan working group. Thanks are extended to Jean-Martin Chamberland and Andrew Smith for their excellent review of this document. Also, the authors would like to thank those present at the CSAS meeting related to this document.

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TABLES

Table 1. Estimates of rebuilding targets based on four scenarios involving different probabilities of being below the LRP value (71,970 t of spawning stock biomass) and using different coefficients of variation (cv).

Probability (%)	Assumed cv	Rebuilding target estimates (t)
5	0.0168 (Terminal year 2022)	99,211
25	0.0168 (Terminal year 2022)	81,961
5	0.0150 (1997-2022 average)	95,702
25	0.0150 (1997-2022 average)	80,741

Table 2. Details of the three example harvest control rule options for total removals used in the current analyses.

SSB range (% of LRP)	Option 1	Option 2	Option 3
< 25	150	150	150
26-49	150	150	150
50-59	150	150	500
60-69	150	500	500
70-79	150	500	1,000
80-89	500	1,000	1,500
90-99	500	1,000	2,000
100-113	1,000	1,000	3,000

FIGURES

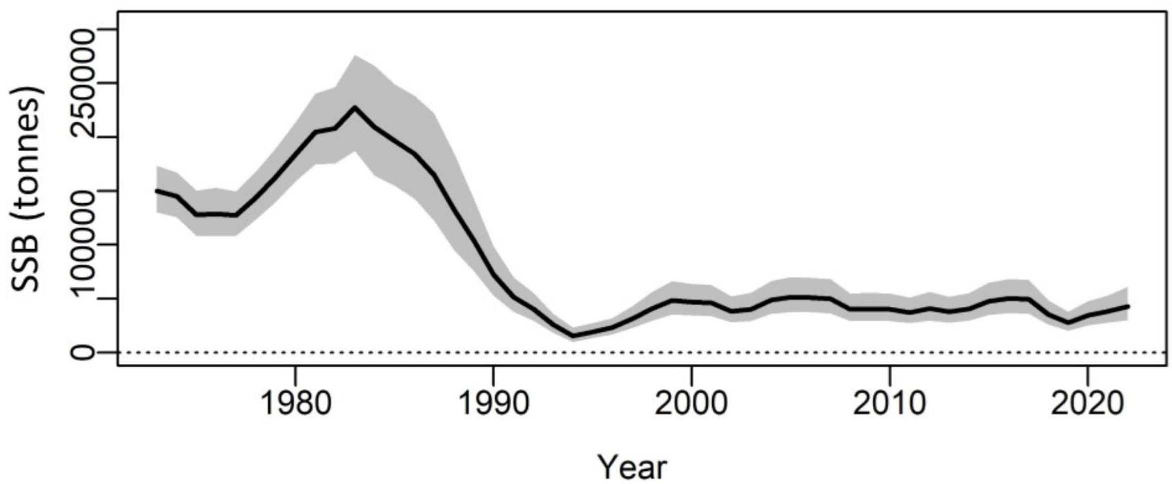

Figure 1. Estimated SSB (t) and associated 95% confidence intervals from the February 2023 assessment.

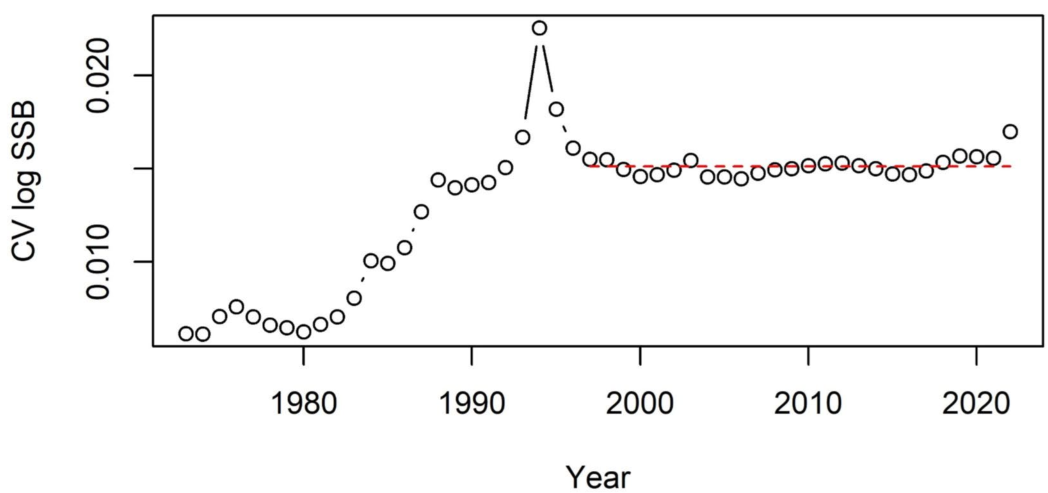

Figure 2. Coefficient of variation of annual logarithm of SSB estimates. The dashed red line indicates the 1997-2022 average (0.0150).

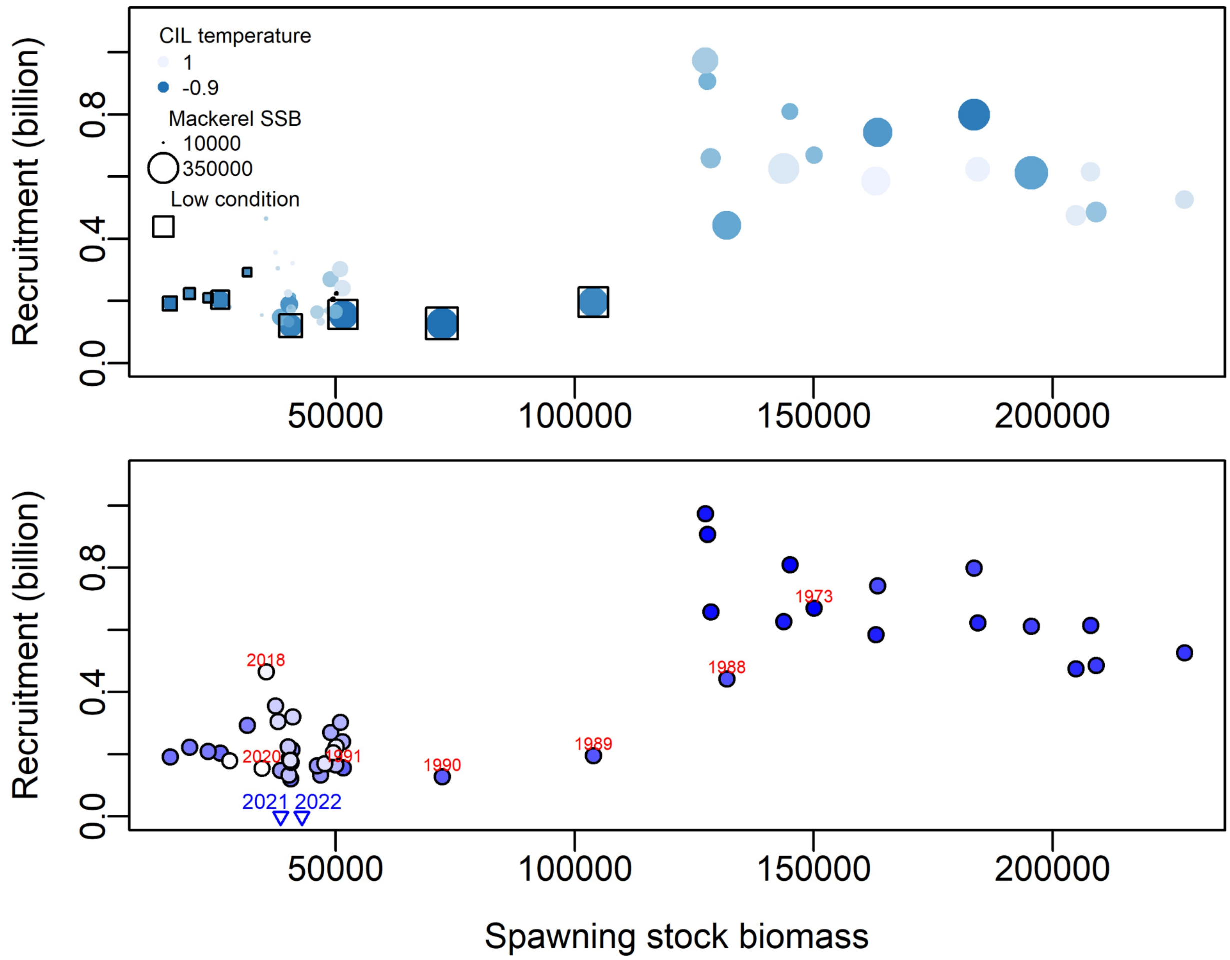

Figure 3. Top - Stock-recruitment relationship estimated in the assessment with symbols defining the conditions in the year the stock originated: blue shading indicates the mean core temperature in the cold intermediate layer (CIL, from Galbraith et al. 2022), symbol size corresponds to the SSB for mackerel (from DFO 2021b) and boxes indicate years associated with low physiological condition in adults (updated from Lambert 2011). Bottom – The same stock-recruitment estimates as the top panel, but with symbols shaded according to year, with the earlier years in dark blue and the most recent years in light shade. The estimated SSB values for 2021 and 2022, the recruitment from which has not yet been estimated, are indicated along the x-axis.

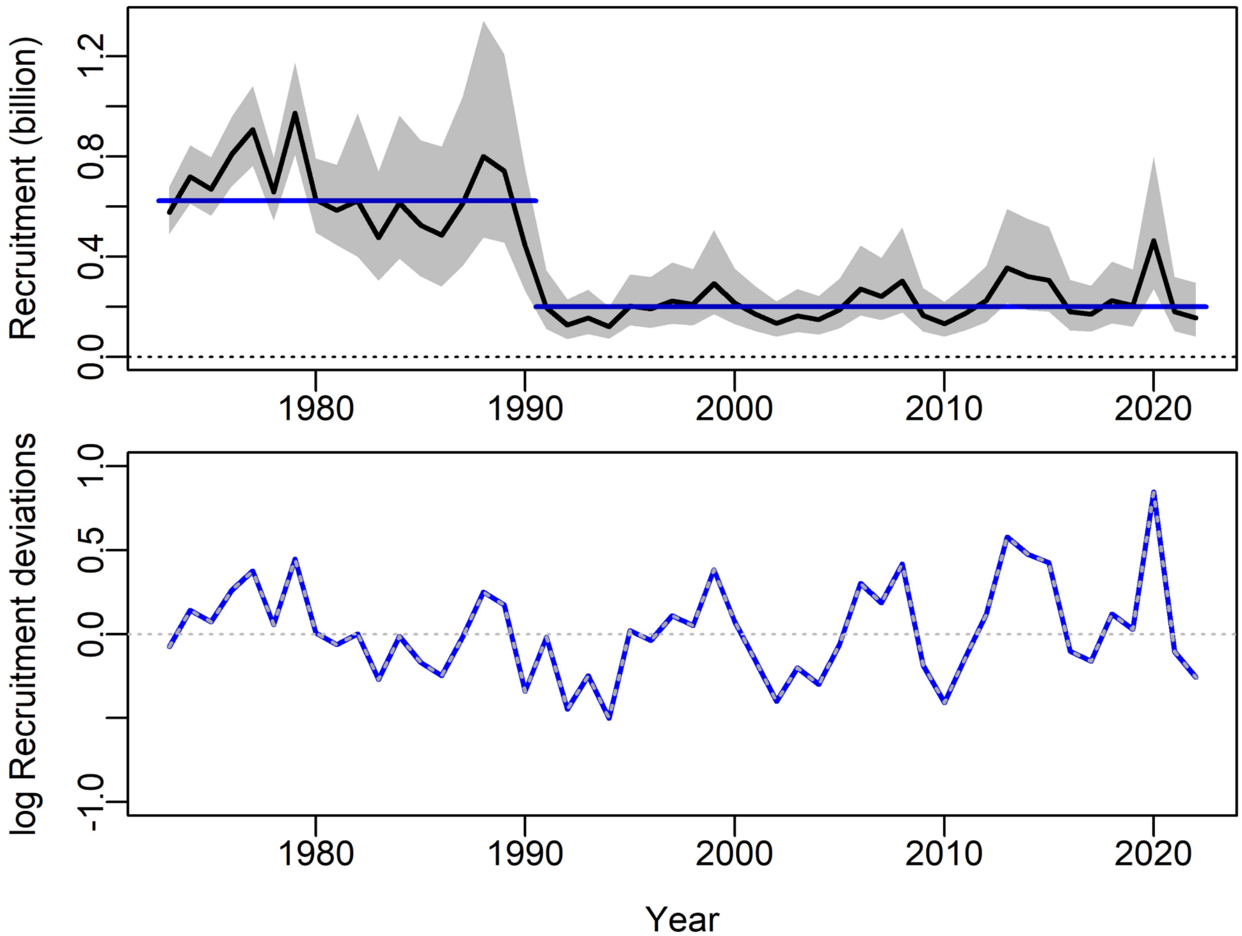

Figure 4. Top - Model estimates of recruitment at age 2 with 95% confidence interval (shaded region), along with the model estimated mean recruitment for years <1990 and 1990+ (blue lines). Bottom – Model estimated recruitment deviations from the means.

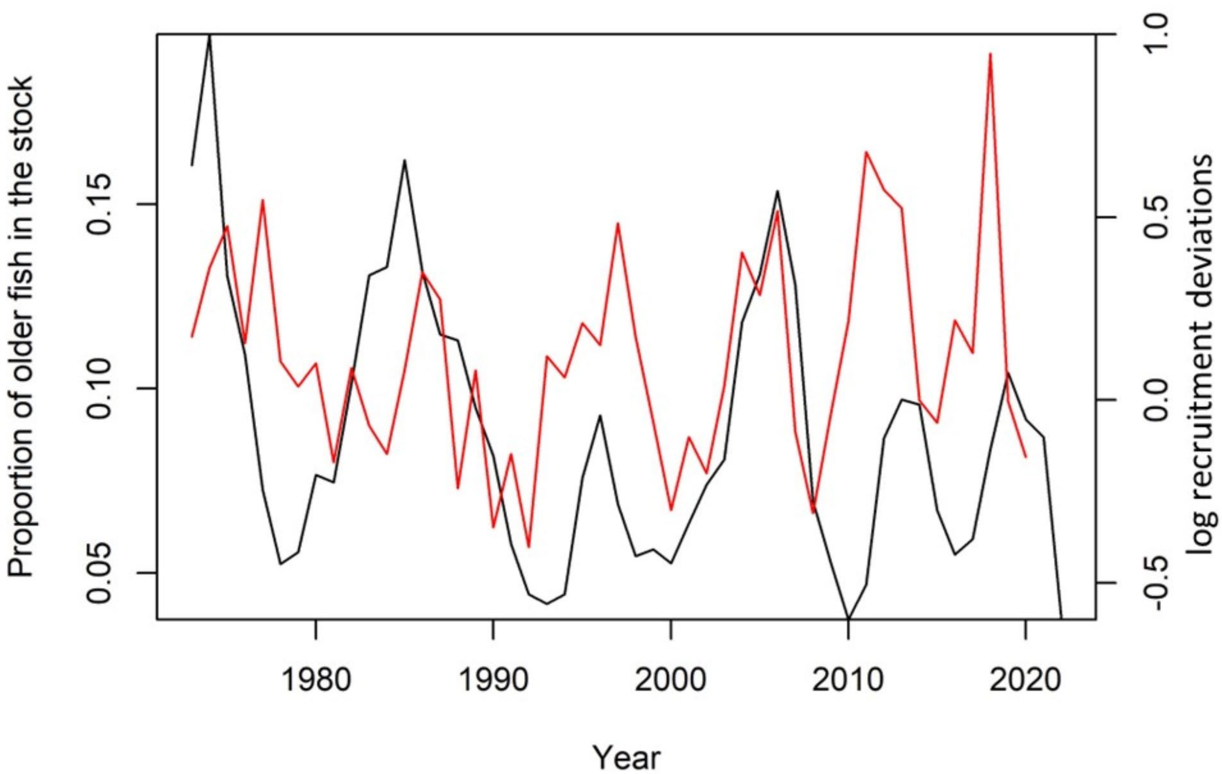

Figure 5. Assessment model estimated log recruitment deviations (red line, right-side y-axis) and the estimated proportion of older fish in the stock in the year the cohort was born (black line, left-side y-axis). The proportion of older fish was estimated as the number of cod ages 8+ divided by the number of cod ages 4+.

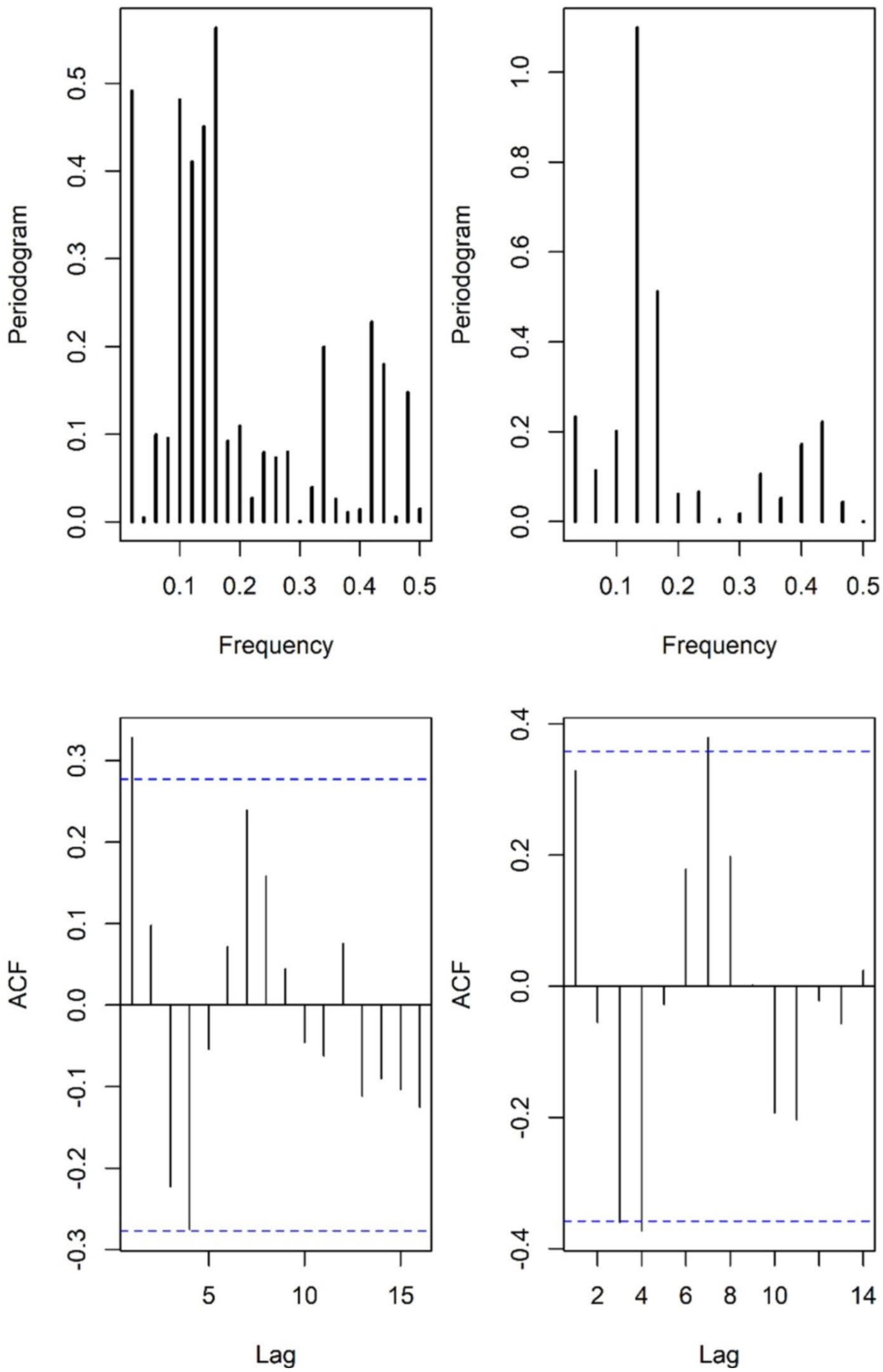

Figure 6. Periodograms (top row) and autocorrelation functions (bottom row) for the log recruitment deviations based either on the entire assessment series (left column) or only the last 30 years (right column). Periodograms summarize periodicities in the time series as a function of frequency (1/years), while the autocorrelation functions summarize autocorrelation in the time series as a function of difference lags.

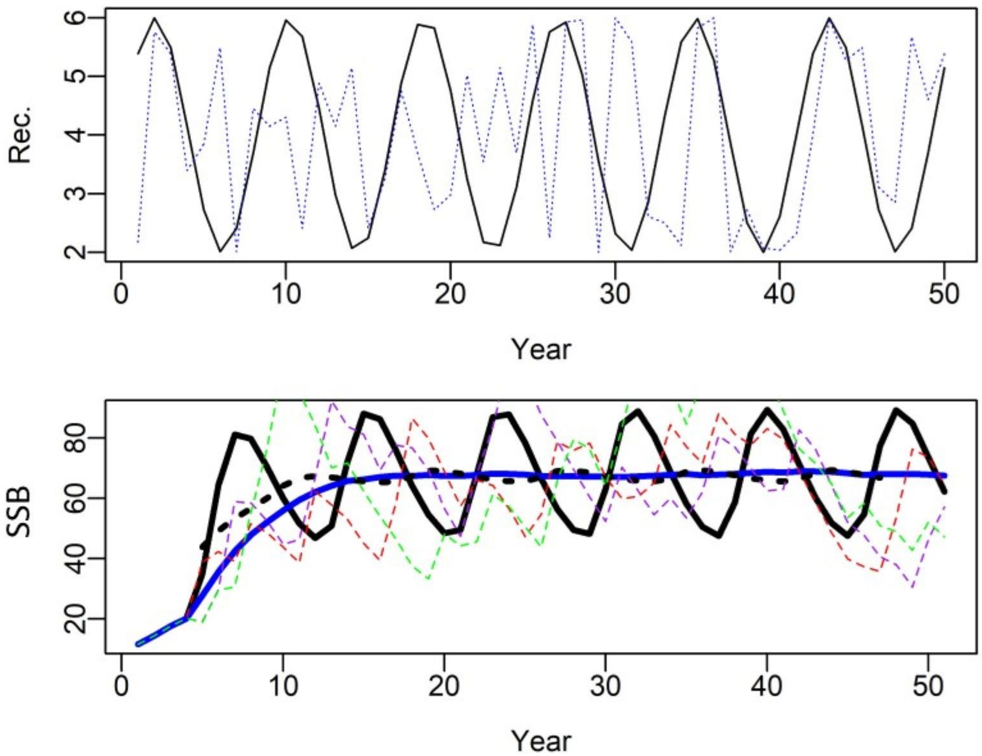

Figure 7. Top – Simulated recruitment series based on a cyclic function (black line), or permuted values of the cyclic function (dashed blue line). Bottom – Mean SSB based on projections using the cyclic recruitment series (bold black line) or permuted values of that series (bold blue line). The bold dashed line is a 9-year running average of mean SSB based on cyclic recruitment, and the other colored dashed lines are three examples of simulated SSB series based on permuted recruitment.

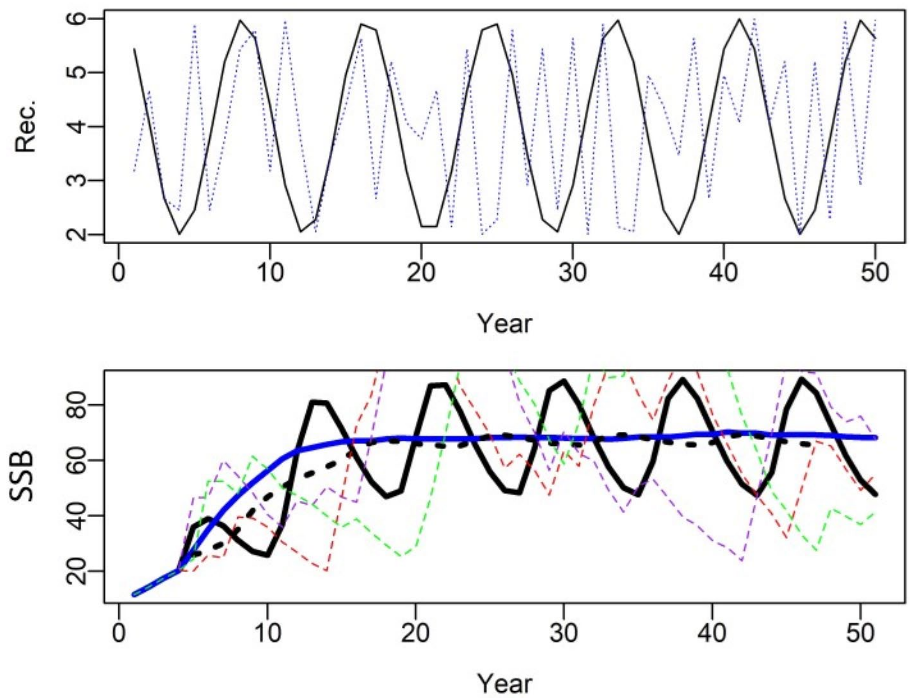

Figure 8. Same as the previous figure, but with a recruitment time series that is out of phase.

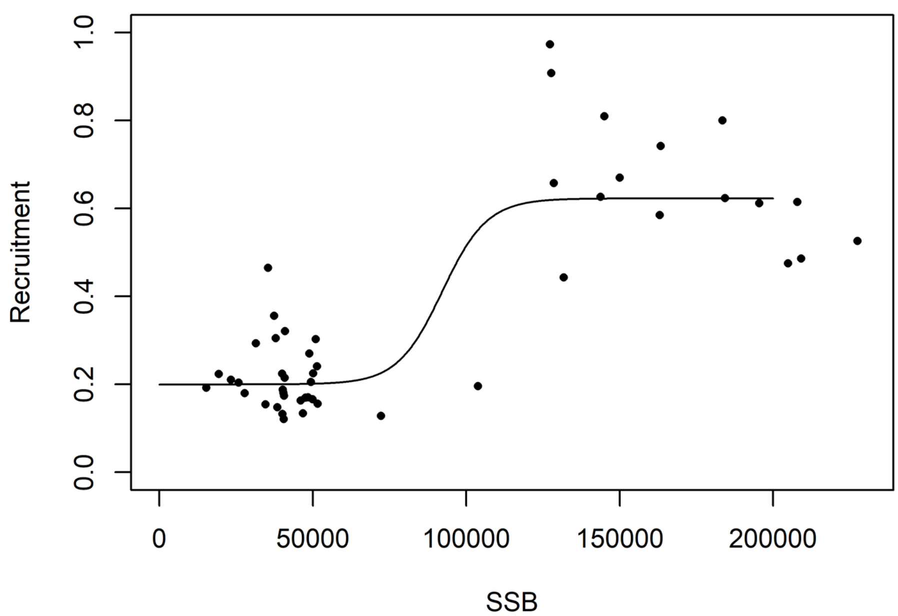

Figure 9. SSB and recruitment estimates for 3Pn4RS cod (points) and the assumed logistic function that joins the recruitment mean levels at low SSB and high SSB, which was used in some T_{min} projections.

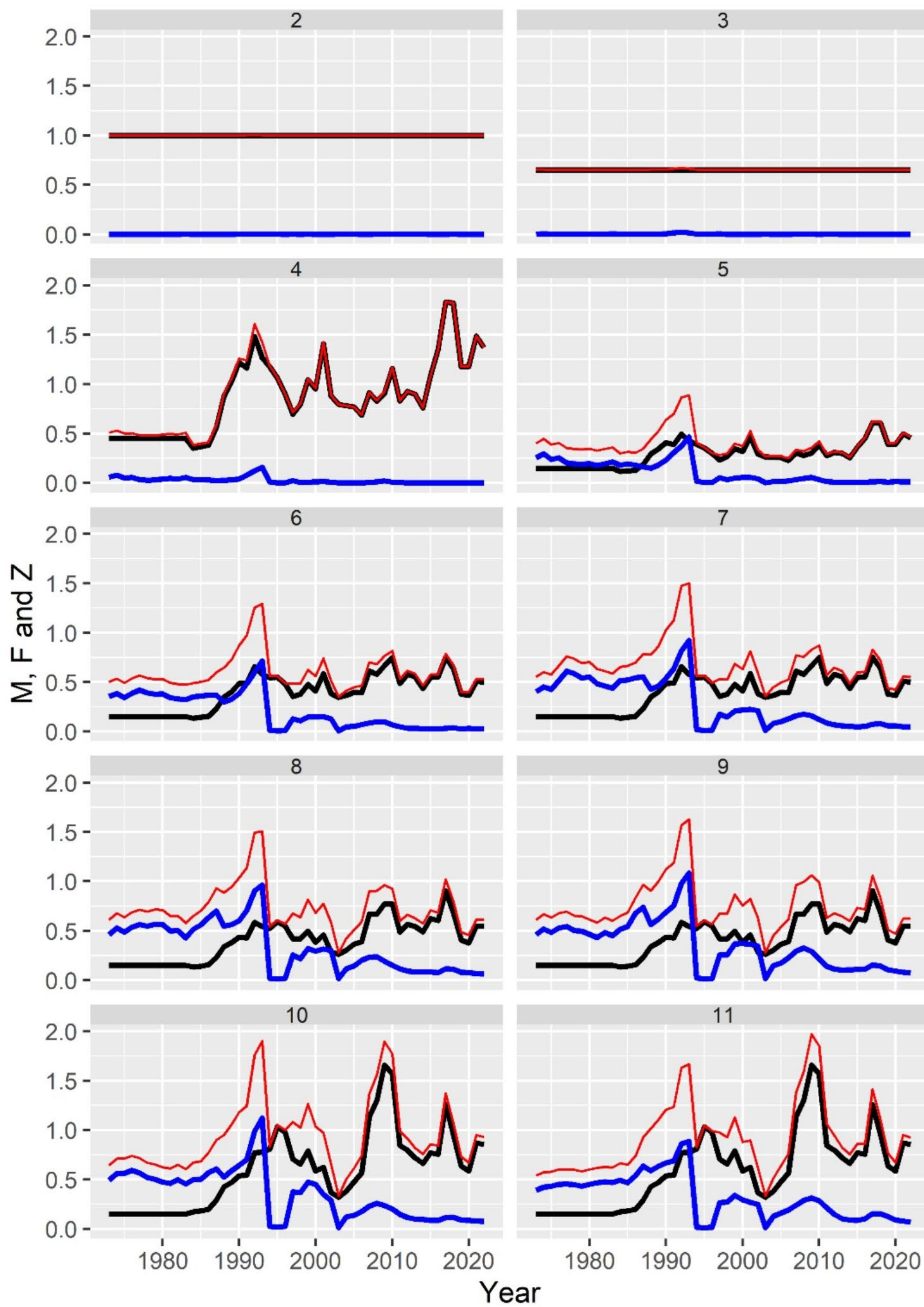

Figure 10. Estimates of age-specific fishing mortality (F, blue lines), natural mortality (M, black lines) and total mortality (Z= M+F; red lines) from the 2023 assessment. Each panel presents mortality trends for a given age, whereas the bottom right panel presents results for age 11+ cod.

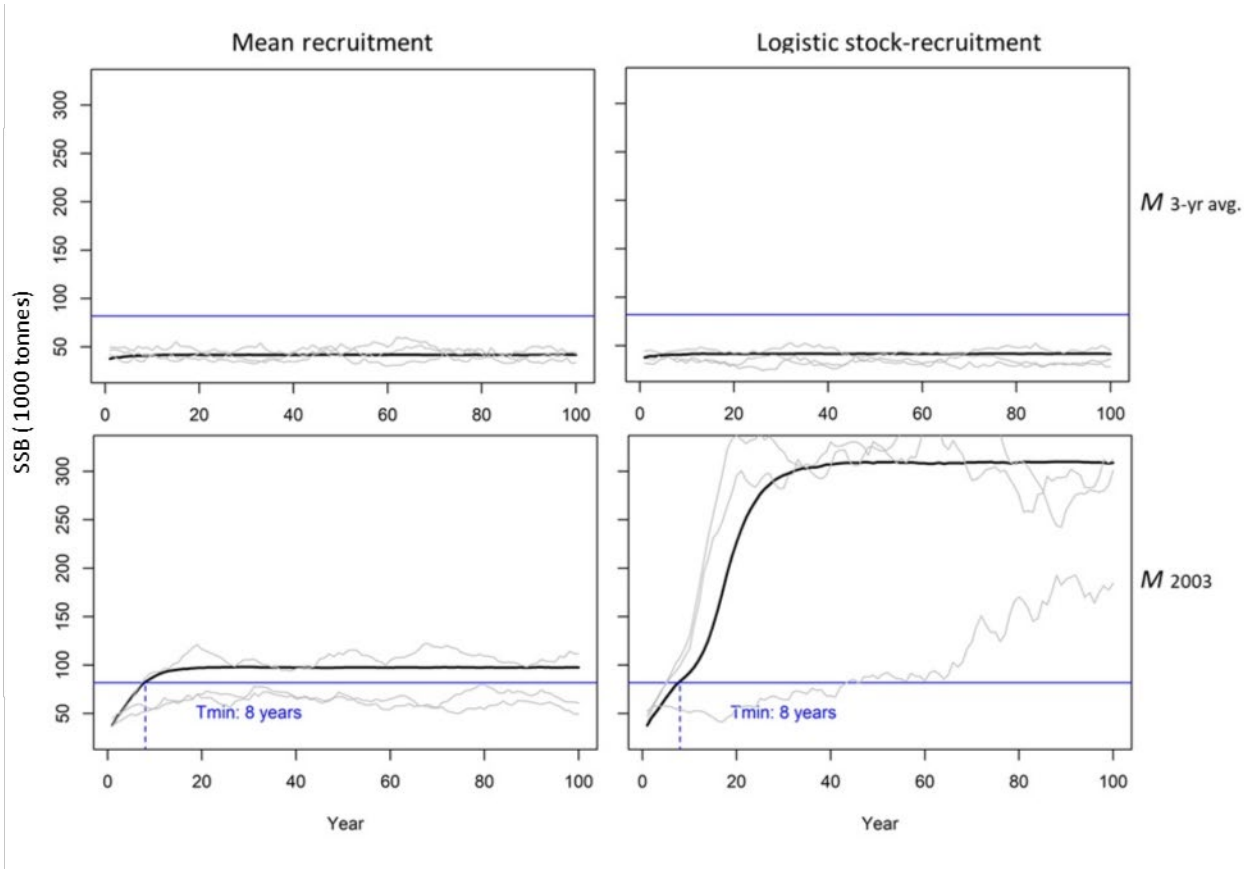

Figure 11. Results of projections to estimate T_{min} based on the two recruitment scenarios (columns) and two natural mortality scenarios (rows). Each panel shows the projected median SSB (black line) and stock trajectories for three randomly chosen simulations out of 10,000 (grey lines), along with the rebuilding target based on a 75% probability of being above the limit reference point (horizontal blue line). For projections in which the median SSB met or exceeded the target, a dashed blue vertical line is drawn at the year at which that occurred and the year is written as text in the figure.

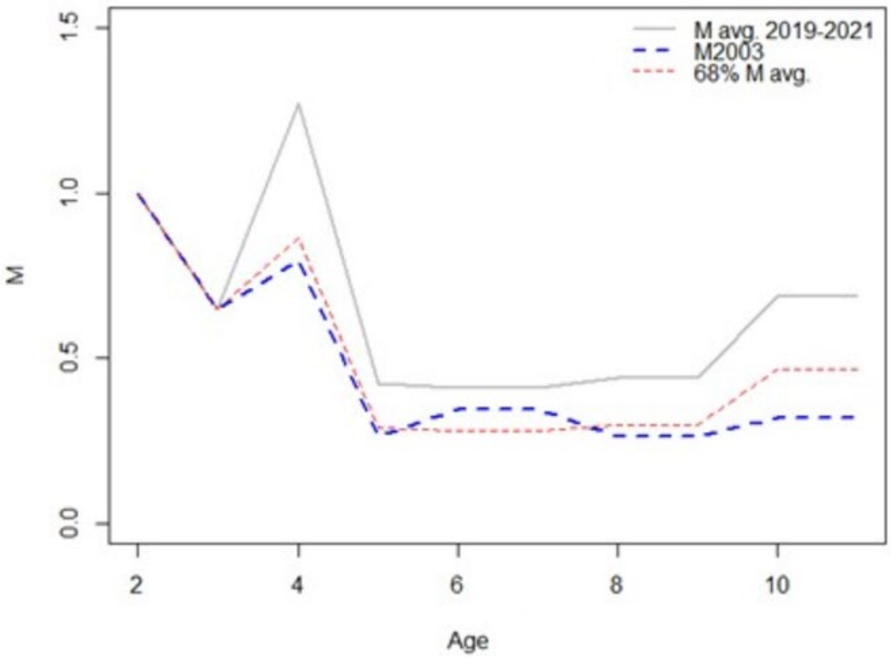

Figure 12. Different assumptions for mortality at age used in the two sets of additional simulations.

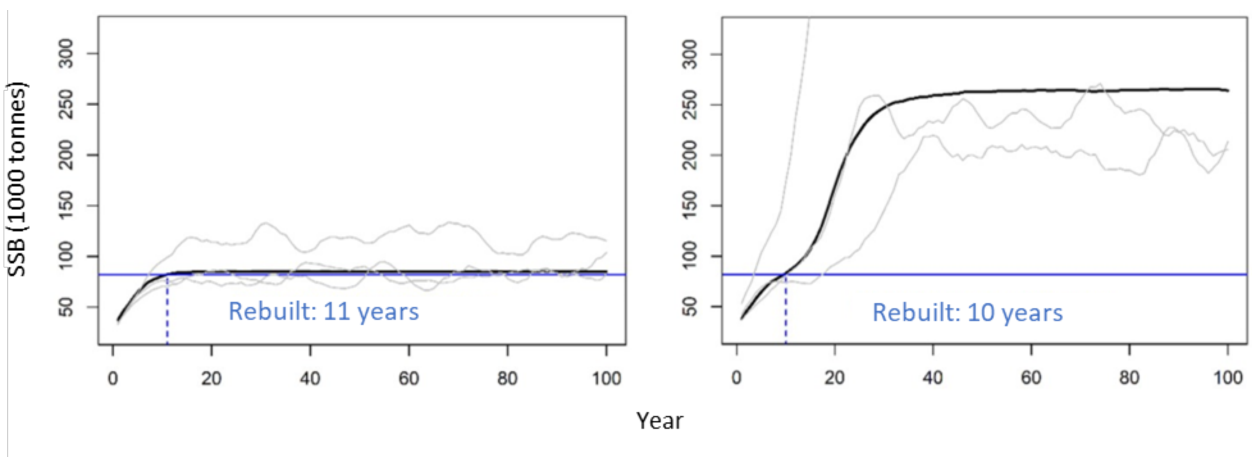

Figure 13. Results from the first set of simulations, assuming total mortalities at age for ages 4+ equivalent to 68% of the M at age from the 2019-2021 period. Simulation results begin in January 2023, year 1 on the x-axis. The panel on the left shows results for simulations assuming recruitment based on mean recruitment over the 1991-2022 period, while the panel on the right shows results for simulations based on the assumed stock-recruitment relationship. Each panel shows the projected median SSB (black line) and stock trajectories for three randomly chosen threads out of 10,000 (grey lines), along with the rebuilding target based on a 75% probability of being above the limit reference point (horizontal blue line) and the year in which the rebuilding target was reached for at least 50% of simulation threads (vertical dashed blue line).

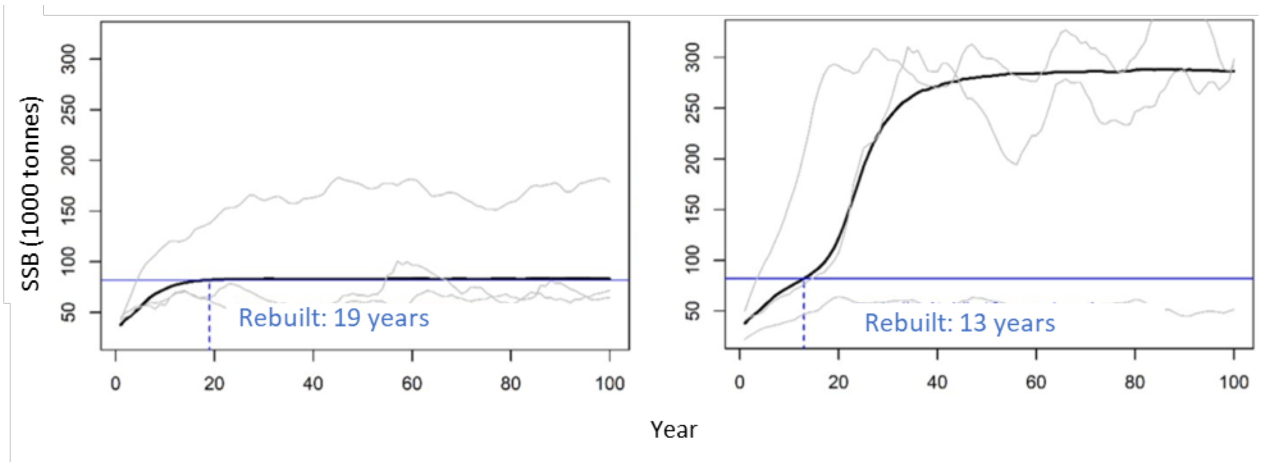

Figure 14. Results from the second set of simulations, assuming 2003 M at age values, the 2022 fishery selectivity and total annual fishery removals of 4,300 t. Simulation results begin in January 2023, year 1 on the x-axis. The panel on the left shows results for simulations assuming recruitment based on mean recruitment since 1991, while the panel on the right shows results for simulations based on the assumed stock-recruitment relationship. Each panel shows the projected median SSB (black line) and stock trajectories for three randomly chosen threads out of 10,000 (grey lines), along with the rebuilding target based on a 75% probability of being above the limit reference point (horizontal blue line) and the year in which the rebuilding target was reached for at least 50% of simulation threads (vertical dashed blue line).

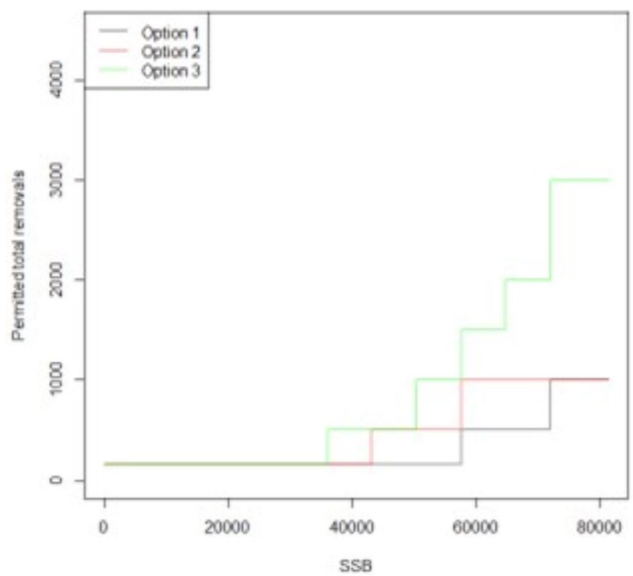

Figure 15. The three example harvest control rule options for total removals up to the rebuilding target SSB. The permitted total removals represent catches from all sources (landings from directed and non-directed commercial fisheries, the recreational fishery, First Nations fisheries, as well as any mortalities associated with discards, depredation in fishing gear and unreported catches, in addition to scientific sampling).

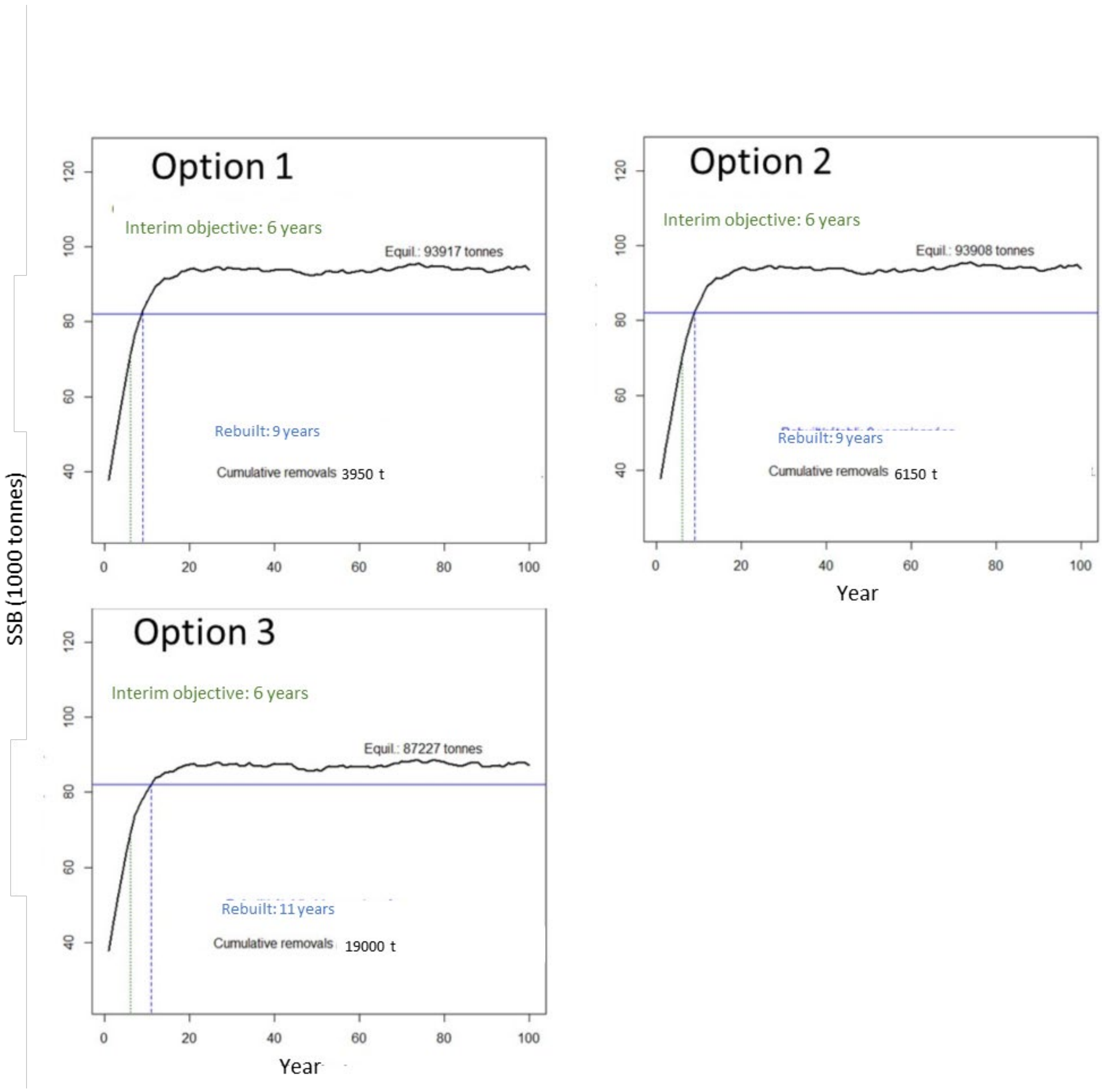

Figure 16. Results of simulations for each of the three harvest control rule options, in all cases based on the 32-year mean recruitment and 2003 M at age. Each panel shows the projected median SSB (black line), along with the rebuilding target based on a 75% probability of being above the limit reference point (horizontal blue line), and the years in which the interim objective (vertical dashed green line) and rebuilding target (vertical dashed blue line) were achieved.

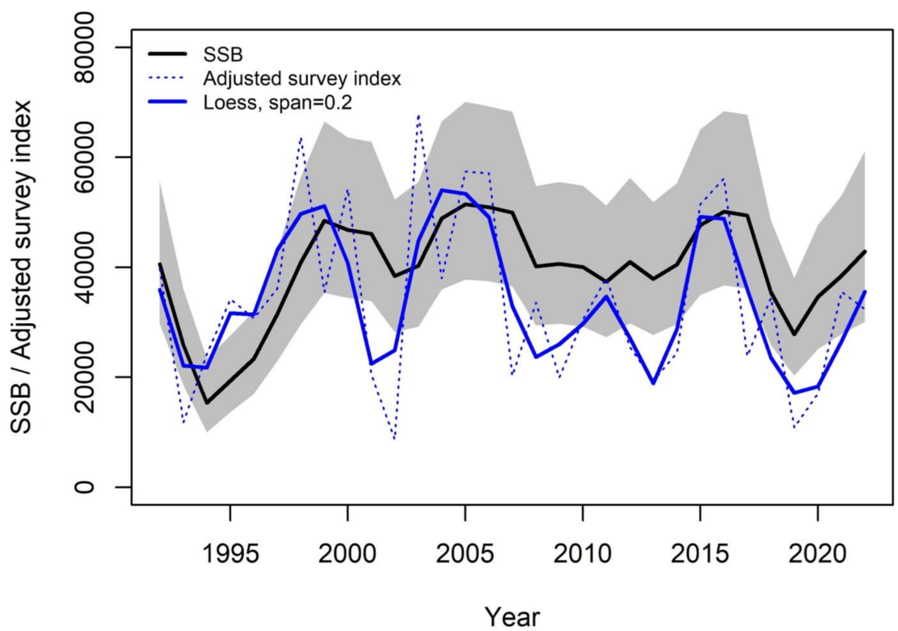

Figure 17. Model estimated spawning stock biomass (SSB; black line with 95% confidence interval), and the adjusted DFO research vessel survey biomass index for cod ≥43 cm (dotted blue line) along with a loess smooth of the adjusted index using a span of 0.2 (solid blue line). Figure taken from the February 2023 assessment for the NAFO 3Pn4RS cod stock.

APPENDIX A. R CODE USED TO GENERATE THE REBUILDING TARGET ESTIMATES

```
LRP <- 71970
lLRP <- log(LRP)
USR <- 143939 # the proposed value, used here simply as an upper limit for the sequence
lUSR <- log(USR)
lRT <- seq(lLRP, lUSR, by = 0.001) # sequence of log rebuilding target values
cv.terminal <- 0.0168
mcv <- 0.0150

# estimates based on the cv value in the terminal year
quant <- pnorm(lLRP, mean = lRT, sd = lRT*cv.terminal) # generates quantiles of the normal dis
tribution

# rebuilding target value associated with a 5% probability of being below the LRP
RT.95 <- exp(lRT[which.min(abs(quant-0.05))])

# rebuilding target value associated with a 25% probability of being below the LRP
RT.75 <- exp(lRT[which.min(abs(quant-0.25))])

# estimates based on the mean cv value for 1997-2022
quant <- pnorm(lLRP, mean = lRT, sd = lRT* mcv) # generates quantiles of the normal distributi
on

# rebuilding target value associated with a 5% probability of being below the LRP
RT.95m <- exp(lRT[which.min(abs(quant-0.05))])

# rebuilding target value associated with a 25% probability of being below the LRP
RT.75m <- exp(lRT[which.min(abs(quant-0.25))])
```