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Proceedings of the regional advisory meeting of the Northern Gulf of St. Lawrence Cod (3Pn4RS) Assessment Framework—Part 2: revision of the estimation models (at age) of the population

May 24-26, 2022
Virtual meeting

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Foreword

The purpose of these Proceedings is to document the activities and key discussions of the meeting. The Proceedings may include research recommendations, uncertainties, and the rationale for decisions made during the meeting. Proceedings may also document when data, analyses or interpretations were reviewed and rejected on scientific grounds, including the reason(s) for rejection. As such, interpretations and opinions presented in this report individually may be factually incorrect or misleading, but are included to record as faithfully as possible what was considered at the meeting. No statements are to be taken as reflecting the conclusions of the meeting unless they are clearly identified as such. Moreover, further review may result in a change of conclusions where additional information was identified as relevant to the topics being considered, but not available in the timeframe of the meeting. In the rare case when there are formal dissenting views, these are also archived as Annexes to the Proceedings.

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SUMMARY

This is the proceedings of the regional peer review on the assessment framework for northern Gulf of St. Lawrence Atlantic cod (3Pn, 4RS) — Part 2: Revision of the estimation models (at age) of the population. This review, which was conducted on May 24 to 26, 2022 via Zoom (virtual meeting), brought together about 30 participants from science, management and industry. These proceedings describe the highlights of the meeting presentations and discussions and outline the recommendations and conclusions resulting from the review.

INTRODUCTION

For more than 30 years, the assessment of the Atlantic cod stock in the northern Gulf of St. Lawrence (3Pn, 4RS; nGSL) has included sequential population analysis (SPA). Since 2015, the SPA has been conducted using the tool developed by the National Oceanic and Atmospheric Administration called Virtual Population Analysis, VPA/ADAPT (NOAA 2014). This tool makes it possible to estimate several of population dynamics parameters as well derive an indirect estimate of natural mortality (*M*). The pattern of residuals obtained for this stock suggests a lack of model fit. A new model should allow the following:

1. estimate the variability of biomass and catches, and possibly include modelling of censored catches;
2. estimate natural mortality;
3. have the ability to integrate multiple data sources, potentially including tagging, to improve the estimation of vital stock parameters;
4. allow us to make projections and to develop a custom model including fully integrated analyses.

The regional peer review on the assessment framework for nGSL Atlantic cod was divided into two parts. During Part 1, held on April 21-22 and May 12, 2021, the data available for establishing a new model were reviewed. Part 2, held on May 24-26, 2022, was dedicated to reviewing population dynamics models for nGSL cod, particularly those able to integrate unaccounted-for catches and natural mortality estimates. If a model is found to be appropriate for the assessment of 3Pn, 4RS cod, it would be used in the next stock assessment and could be used in the development of a rebuilding plan.

These proceedings describe the main points of the presentations and discussions arising from Part 2 of the peer review of the assessment framework for northern Gulf of St. Lawrence cod. The peer review is a process that is open to all participants who are able to provide a critical outlook on the information and analyses presented. Participants from outside DFO are invited to take part in the discussions in accordance with the terms of reference (Appendices 1 and 2). The proceedings also set out the recommendations made by the meeting participants.

PART 2: REVIEW OF POPULATION DYNAMICS MODELS

The meeting chair, Dr. Duplisea, went over the objectives and process for the science review as well as the role of the participants. Dr. Arnault Lebris (Memorial University of Newfoundland) and Dr. Divya Varkey (Fisheries and Oceans Canada, Newfoundland and Labrador) acted as external reviewers. The terms of reference and the agenda (Appendix 3) are provided. Attendees were invited to introduce themselves.

REVIEW OF INPUTS AND DATA PRE-PROCESSING

Dr. Hugues Benoît presented the model inputs that would be reviewed: fishery catch-at-age (CAA) and the associated uncertainty, individual weight-at-age, adjustment for changes in survey coverage and catchability, trend in surveys and associated discrepancies and input information for additional models.

Catches (landings, discards, recreational fishery) and a CAA were examined in Part 1 of the review of the framework assessment in spring 2021. However, no decision has been made about integrating these estimates in order to produce a complete CAA and uncertainty estimates for catches (catch bounds). A complete CAA is presented along with decisions regarding uncertainty associated with catches for the baseline model. The decision was made to add the following: catches at age 2, discards in the groundfish fisheries estimated using at-sea observer program data and discards in the shrimp fishery. The landings monitoring program appears to be rigorous, and uncounted-for catches appear to be small. The greatest amount of uncertainty is associated with the recreational fishery.

Individual weights

Two types of individual weights-at-age (and year) are used in the model. The beginning of year survey weights (SW) are used to estimate the population biomass (e.g. SSB) from the estimated numbers-at-age. The commercial fishery weights (CW) are used to calculate the predicted catch (tonnes) from the estimated numbers-at-age. Both of these include year- and age-specific values. Model fit is correct in terms of age, year and cohort. Greater variability is observed at younger and older ages. A mean survey weight was used for ages 2-3 as well as a mean SW/CW ratio for age 11 and for the years preceding 1985. The revised values seem to be more reasonable between years and over ages.

Adjustment for survey coverage

More shallow strata were added to the DFO research vessel (RV) survey in 1991 and to the sentinel bottom-trawl survey in 2003. Adjustments estimated in the model may be needed to account for changes in survey coverage. Conversion factors were therefore applied. Furthermore, an adjustment was also made to account for the change in vessel and gear in 1990 (Lady Hammond data converted to Needler equivalents). The uncertainty associated with the conversion factor is particularly high for small cod (ages 2 and 3). Although cohorts can be tracked at ages 2,3 and older, the level at ages 2 and 3 is lower than expected. The mortality trends that would be required to produce these age-related dynamics are opposite expectations with respect to cannibalism. Adjustments were therefore estimated for ages 2-3 in the model.

Survey indices

There are five main age-disaggregated abundance indices from surveys: 1) DFO research vessel survey, 1984-2020, ages 2-11+ (midshore and offshore zone); 2) sentinel mobile gear survey, 1995-2020, ages 2-11+ (mainly midshore and offshore); 3) sentinel longline summer index, 1995-2020, ages 3-11+ (exclusively nearshore); 4) sentinel longline fall index, 1995-2020, ages 3-11+ (nearshore, possibly an index of the entire stock); 5) sentinel gillnet index, 1995-2020, ages 4-11+ (exclusively nearshore). There are some diverging trends between the nearshore mobile gear surveys and the offshore mobile gear surveys. They produced significant patterns of residuals in the previous assessment model. A few model variants were examined (one of them in-depth) which could better correspond to these models.

Total mortality (*Z*) estimated from surveys

While the trends for total mortality (*Z*) are very similar for fixed gear and mobile gear surveys, there is a much larger range for fixed gear surveys. It is presumed that this reflects sensitivity to cod movements into and out of coastal waters, but it could also reflect age-specific differences in *Z*.

Other published and useful information

Other already published information will be reviewed at this meeting (historical surveys, estimates of fishing mortality (*F*) from tagging experiments involving cod representative of ages 6+).

- For the calculation of SW, it was pointed out that a geometric mean is used. In recent years, summer data have been used predominantly since a problem was noted with catchability in winter, which created uncertainty. Sampling issues are also undoubtedly present. A comparison of weights was made between the new and old methods in relation to the fisheries, and the new method was found to be more realistic.
- It is assumed that selectivity changed considerably between the pre- and post-moratorium periods.
- Participants wondered what could explain the variability observed in surveys in relation to older fish.
- A small clarification was provided concerning the conversion factor used for vessels. This detail can be found in the research document.

STRUCTURE AND JUSTIFICATION OF THE BASELINE MODEL

Dr. Benoît presented the structure and justification of the baseline model. For more than three decades, the assessment has been based on the use of sequential population analysis (SPA) in the ADAPT framework. Historically, the SPA/VPA model has assumed that natural mortality (*M*) does not vary with age or time. In 1997, for the assessment of the nGSL stock it was assumed that *M* changed from 0.2 to 0.4 in 1985. In 2003, *M* began to be estimated in five-year blocks in the ADAPT framework. Estimates of *M* are now subject to external adjustment given the adoption of the NOAA Fisheries Toolbox to implement the SPA model. The disadvantages of this procedure are as follows: the new “estimates” are dependent on the previously adopted values, and correlations with other model parameters are ignored. In addition, an age-invariant *M* is unlikely to be appropriate. Significant retrospective patterns and strong patterns of residuals were identified, which suggest a potentially significant error of misspecification in the model. There was also concern that the approach could not properly estimate changes in *M*, which could be significant considering the strong increases in *M* estimated for the cod stock adjacent to NAFO 4TVn. The SPA model assumes that the fishery catch-at-age is known without error, which is a tenuous assumption considering the potentially significant unaccounted-for catch quantities that are estimated.

The new model is based on the paradigm of state-space modelling, taking into account measurement errors in the inputs/data separately from process error or variability in population dynamics. Unlike the widely used state-space assessment model (SAM), which assumes that process errors act on the entire population equation (all the rates affecting changes in age-specific abundance), we assume that process errors are only associated with natural mortality rates. None of the existing assessment models (for example, SAM, WHAM, SS3) were used owing to the difficulty in implementing many of the customized functionalities that we sought for the nGSL cod model. Process errors in age-specific natural mortality are modelled as a stochastic process in year and age. Catches are modelled using the Baranov equation. *F*’s are modelled as a stochastic process about 16 mean values. The estimates of Myers et al. (1996) are incorporated as priors using a normal likelihood. The total catch weight and age composition were modelled using a log-normal likelihood. Catches before 2006 were considered more accurate and precise and were modelled using a log-normal likelihood. Catches after 2006 were considered more variable, and a certain degree of uncertainty exists with respect to the quantity of unreported catches in the recreational fishery.

The baseline model estimated lower values for SSB compared to the SPA for the years before 1990 and higher values in subsequent years. Stock depletion since the peak levels recorded from the early 1980s to the mid-1980s was about 80% compared to about 90% with the SPA. The baseline model estimated a considerably higher number of age-2 recruits compared to the SPA, although the trend is similar. This reflects the large difference in assumed natural mortality at age 2, with *M*=1 in the new model and between 0.2 and 0.7 in the SPA. This has an effect on estimated catchability. Catchability at age was higher for all surveys and all ages in the SPA. Catchability for fixed gear sentinel surveys was a few orders of magnitude higher in the SPA, which could partly reflect a difference in the units of the input data used in these indices. In the SPA, the function q_{sa} from the DFO RV survey culminates at age 4 and then declines, which likely reflects the assumption of an age-invariant *M*. The baseline model produced higher estimates of mean fishing mortalities than the SPA for the years 1970 and 1980. However, the SPA estimated a much more pronounced peak of fishing mortality for ages 6 to 9 in the early 1990s, culminating in 1993, and a larger *F* in most years between 1997 and 2011. With the baseline model the estimate of fishing mortality was highest for cod of about 7 to 10 years of age before the first moratorium, but increasingly higher estimates were derived for older cod after 1997. This reflects the shift to the exclusive use of fixed gear. Estimates of *M* (ages 4-9), which began in 1984, show an initial decline followed by increases, indicating that the assumed levels for the years before 1984 were reasonable in the context. Estimates of *M* in the late 1980s were considerably higher than what had been assumed/estimated in previous years. For cod aged about 5 to 9, total mortality fluctuated around a common level over the entire 1974-2020 time series. For cod ages 10-11+, it is believed that *M* fluctuated considerably after 1990, with large spikes. At ages 5-11+, *F* was higher than *M* in all the years before 1993, but the reverse is observed after 1993. The SPA estimated age-specific *F* values that fluctuated with a greater amplitude and reached implausible levels. The high *M* estimated for 1987-2000 is consistent with a period of poor body condition. Since about 2000, natural mortality has fluctuated roughly in line with the TAC and, during low TAC periods it has trended downward toward historically typical levels representative of moratorium periods. Estimated catches closely followed input catches until 2006, as would be expected assuming that the coefficient of variation (CV) for catch error was about 10%. When catch bounds and a censored catch probability were assumed, the model estimated catch to be at an intermediate level in relation to the bounds until 2009, close to the upper bound for 2011-2016 and 2019-2020, and close to the lower bound in 2017-2018. The extra catch that might otherwise have been subsumed into *M* was estimated by assuming that the value of *M* was the same as in 2003/2020. Catches may have exceeded landings, input catches and model-estimated catches by about 10% in 2000-2001, by about 20% to 30% around 2007-2009 and 2017-2018, and by over 80% to 90% in 2012-2016.

While the output from the baseline model corresponds reasonably well to the survey abundance indices, the model systematically under-estimated the sentinel longline indices at age 3 during the first half of these series. The residuals from the model generally appear to be correct. Variability is a little higher than expected at ages 11+ and possibly at ages 2 and 3. Certain trends are observed in the residuals, such as a tendency to over-estimate abundance at younger ages since the mid-2010s in the DFO research vessel survey. Year effects can be observed (RV 2002-2003; sentinel mobile gear 2011-2012). There are few irregularities in the residuals as a function of year or age. However, certain trends were noted with respect to cohorts. There were no trends in the residuals standardized according to age or year in the Minet surveys conducted annually for four years starting in 1973. The estimated composition of fishery catches in the model corresponds well to the input catch composition. The model tended to under-estimate the contribution at an age where the proportion of inputs increased in a given year, such as at age 11+ in 2017 and 2019. On the whole, there was little correlation between most of the model parameters. The survey catchability parameters were strongly correlated, which is in turn reflected in the correlations with abundance-related parameters, such recruitment parameters and some of the main effects of fishing mortality.

- A few clarifications on the structure of the model were provided.
- It was noted that modelling represents a compromise and that it is never perfect.
- After the first meeting, it seemed appropriate to review the lower and upper bounds of the model, considering recreational fishery catches in particular. We will return to this later.
- When the results of the two models are compared in terms of biomass estimates, questions arise concerning the magnitude of the difference. We should not be overly concerned about this difference, as different assumptions are used and they will influence the scales. We should not focus unduly on absolute values. However, the two periods can be compared (pre- and post-moratorium).
- It was noted that the fixed-gear fisheries select larger fish.
- It was pointed out that, at age 4, young fish are no longer as vulnerable to cannibalism or predation.
- After the moratorium, the inshore fishery was very different. It became difficult to distinguish between fishing mortality and natural mortality. When inshore quotas are higher, a larger decline is noted.
- With regard to concerns about natural mortality at age 4, a study will be conducted to separate out age 4.
- Owing to the change in selectivity associated with the first moratorium, commercial weights may no longer be the same. Commercial weights will be re-examined.
- A better fit was sought by slightly modifying logistic selectivity.
- Unreported catches are strongly suspected. Catches could be higher than landings.
- It was asked whether the estimation of observation errors could affect the results. We could look at the shift parameters. The data seem to be comparable, however, despite the surveys.
- Unreported catches may underpin the other catchability problems (value higher than 1).
- To end the day, a list was compiled of the work to be done for the following day on commercial weights, the deviation in delta, estimates from surveys, assumptions related to mean recruitment values and the effect of correction factors.

DAY 1 RECAP AND REVIEW OF HOMEWORK

The chair, Dr. Duplisea, gave a brief summary of the previous day. The new model estimates natural mortality, a variable that appears to be very important for making projections in the context of an assessment. Questions emerged during the first day, including four points which required some homework. Dr. Hugues Benoît reviewed these points.

- The first point concerns the aggregation of age-specific mortality estimates and concerns expressed about natural mortality at age 4. This was deemed to result in over-estimation and an age-specific increase that could cause problems in the model. Dr. Benoît examined

3 iterations by isolating age 4. It was found that separating out age 4 does not make much of a difference. A difference was noted at older ages, with peaks that are not as high.

- With regard to the impact of a change in vessel, participants asked about the possibility of erroneous conversion factors and the impact on recruitment of cod ages 2 and 3. It appears that recruitment values were under-represented. One year more or one year less does not seem to have a major impact on recruitment deviations. The baseline model was retained.
- Concerning individual weights, if a change in selectivity was associated with the first moratorium, it is possible that commercial weights are no longer the same. We therefore plotted regression lines and the uncertainties remain the same. There is nothing to indicate that this would change.
- With regard to the deviation in the survey index, the deviation values obtained suggest that the indices are adequate.
- Another point that was raised concerns recreational fisheries and whether these fishing activities affect the interpretation of the model. The upper bound of the model takes into account these additional catches, but precise estimation remains impossible (maybe 2 to 3 times the reported catches). The upper bound seems to be conservative. By contrast, the age groups that make up these catches remain unknown, notably with regard to natural mortality. Here, we assume that catch composition is the same.
- Furthermore, this assessment does not take into account movement between 3Pn and 3Ps. We do not have any robust information on this topic.

SIMULATION TESTING OF THE BASELINE MODEL

The baseline model was subjected to simulation self-testing. This testing is used to determine whether the parameters can be estimated and whether rough estimates could be used. The correspondence between the original model fit and the adjustments to the simulated data also confirms that the model was correctly coded. Model-independent simulation testing is recommended for models with random walks, like our natural mortality process errors. These errors fall outside of the scope of the present work. However, we noted that the ability to estimate natural mortality (*M*) trends in age- and size-structured models has already been demonstrated in simulation studies. The first series of simulations revealed small biases in certain estimated parameters and derived quantities. We initially thought that these biases could consist of a non-linear bias associated with the model’s use of random effects, but this is not the case. Instead, there is some association with the prior on fully recruited catchability in the RV survey. We do not know whether the difference between the two sets of simulations relate to a characteristic of the simulation algorithm in TMB or whether biases actually exist when the standard deviation of prior probability is larger. Even if the estimated biases are correct and are a characteristic of the model, their magnitude is considered small (10) and therefore not worrisome. In addition, the biases appear to be consistent across the model time series, which points to internal consistency between the model parameters and quantities, such that decision making based on the model should not be affected by these small biases.

- Thus, it appears that the results are consistent. There is no reason for concern.
- By using a prior for catchability, the model will seek to bring catchability to a value of 1. Values higher than 1 seem to indicate that something else is going on, which could relate to unaccounted-for catches.

MODEL VARIANTS AND VALIDATION

Two alternative model formulations were considered to deal with the somewhat diverging trends in the bottom trawl surveys (offshore/midshore) compared to the fixed gear sentinel surveys (nearshore): a model with two subpopulations (not continued) and a distribution shift model. The model with two subpopulations produced strange results (very high *F* recently) and the fit to data was lower than in the baseline model. In the distribution shift model, no change was made to the population equations used in the baseline model, and the cod population was assumed to be homogeneous. However, the spatial distribution of cod is not necessarily homogeneous, hence cod availability to surveys may differ between nearshore and offshore areas. Consequently, only the survey observation equations were modified (years ≥1995). The estimated catchability deviations in the distribution shift model ranged from 0.4 to -0.4, and are therefore significant. The trends in deviations are linked to age. A greater availability of young fish has been observed in the offshore environment over the past five years, and a greater availability was observed in older fish in the early 2000s, and in ages 10 and 11+ around 2010. These models clearly reflect the diverging trends present in the data from surveys.

In summary, the distribution shift model offers a better overall fit to the data (AIC; residuals for certain surveys), but the deviations have little effect on estimates of the quantities of interest for the assessment, in particular the SSB, biomass, abundance, recruitment and mortality rates. It is not clear whether this additional complexity is useful for the routine assessment model. For example, the projections from this model needed to formulate advice on catches would also require projecting changes in distribution. It was suggested that the model not be retained for the routine assessment of the nGSL stock. It could be useful as a secondary model or for research, for example to evaluate causes of deviations between survey indices and model results over time. A spatial statistical model that integrates data from the different surveys and produces a single index, if properly validated, would be very useful and also preferable.

- Questions were raised about changes over time in the recreational fishery, particularly before and after 1994. It was pointed out that there is insufficient information and so we cannot make assumptions.
- Some participants were of the view that, given the challenges that remain, a more targeted research project is needed to move forward if the objective is to incorporate spatial aspects into the model. This is a simplification of reality.
- The offshore and inshore phenomenon appears to be more recent.

ALTERNATIVE PARAMETERIZATIONS AND SENSITIVITY

Sensitivity was examined for some of the choices relating to the baseline model: parameterization of the age groups used to estimate the natural mortality process errors, use of *F* priors from Myers et al. (1996), and assumptions about errors in input catches, which we call the catch-error runs.

As discussed earlier, the baseline model estimates the mortality process errors for four age groups. Models with 3 groups (3-5 years, 6-8 and 9-11+) and 2 groups (3-6 years and 7+) were also examined. The baseline model gave the lowest AIC. The estimates of *M* and *F* were generally very similar. Other parameters and quantities in the model were also nearly identical.

When the *F* priors from Myers et al. (1996) were excluded, the mean *F* estimated for ages 6 to 9 in 1986 and the peak in the early 1990s were reduced somewhat in comparison to the baseline model estimates. The change in catchability was associated with a change in scale of the SSB. When the priors were excluded, the SSB was higher across the entire series. The ratio of the lowest to the highest SSB was 0.07 for the baseline model and 0.11 when the priors were excluded. Estimated recruitment at age 2 was very similar for the different formulations. Despite the impacts on the model estimates, there is no reason to exclude the priors.

- The meeting participants agreed with this conclusion.
- Questions were raised about what happens to *M*, with or without the priors; this aspect was not examined.
- Participants questioned the fact that tagging was done in nearshore regions and yet the pre-moratorium fisheries were conducted predominantly offshore. It appears that the level of survival is higher when fishing is carried out in the nearshore area.

Two distinct versions were run with greater uncertainty related to catches entered in the model: 1) censored likelihood for the 1973-2020 series, assuming the catch bounds for the years ≤ 2005 ranged from 90% of input catches as the lower bound and 400% of input catches as the upper bound. For the remaining years, we multiplied the initially higher catch by 4; 2) we retained the revised assumption for the catch bounds for the years since 2006, but returned to the log-normal probability for the catches for the years ≤ 2005, which increased the standard deviation of logarithmic catches by a value ranging from 0.1 to 0.5.

The estimated catches were slightly higher than the input catches for 1973-1993; they were generally much higher than the input catches in 1994-1998 and 2003-2020; and they were at the same level as the input catches in 1999-2002. The level of catches estimated since the 2003 moratorium was considerably higher than in the reference scenarios and, not surprisingly, unaccounted-for catches included in *M* represented a small fraction of the estimated total catches. The scale of mean fishing mortality values differed little, although the high frequency variation was smoothed considerably. The peak *F* was more pronounced in 1992-1993 and the mean *F* was a little higher after 2000. Whereas the total estimated age-specific mortality was similar to that in the baseline model, natural mortality was reduced, particularly for certain years. There was an unexpected decrease in the catchability of fully recruited cod in the RV survey, to a value of 1.28, which affected the reduction in catchability in the other surveys.

An increase was noted in the level of SSB and the biomass of cod ages 2+, along with larger confidence intervals for the estimates for the 1980s. The recruitment scale differed little between the scenario and the baseline model, and the trend in recruitment was very similar. Model fit to catch composition data and survey data was very similar for this scenario and the baseline model. It therefore appears that it is mainly the scale of the model that was affected by modifying the catch bounds and using censored likelihood for the entire series. An increase was observed in the strength of the correlations between the model parameters and a considerable increase in correlations related to abundance in 1973 and the catchability parameters from the Minet survey. The estimated catches were lower than the input catches for most of the years prior to 2003. The estimated catches in subsequent years were often much lower than those in the first catch error scenario. The two scenarios gave very similar estimates of mean fishing mortality. Age-specific fishing mortality, and even total mortality, exhibited higher values for many years. If the peaks and troughs in the estimates of *F* and *Z* are disregarded, mean fishing mortality since 2000 has fluctuated around levels comparable to those observed prior to 2000 for older ages. During this period, the estimated natural mortality was much lower at all ages. The second catch error scenario produced survey catchability values similar to those in the first scenario, hence lower than those in the baseline model. The estimated abundance and the biomass quantities were nearly identical to those in the first series of catch errors.

The results of the catch error scenarios appear to indicate that a discrepancy in the input catches for the first part of the series compared to the second part may underlie the relatively high estimated level of catchability for the DFO RV survey. To reduce fully recruited catchability towards the assumed prior, the model seems to seek to greatly increase the estimated catch for the most recent period compared to the estimated catch in the first part of the series. The results for the scenarios excluding the priors derived by Myers also appear to support the finding that catch discrepancies affected the survey catchability values, since they caused a reduction in *F* during a portion of the 1980s and a reduction in survey Q. It is not clear how this discrepanciy can be resolved with only the information available on existing catches, given that this information was recently studied in great detail and the input data used here are the best data available at present.

Integrating into the model the results of the tagging experiments conducted over the past two decades could help to reduce, or even resolve, the discrepancy. This should be a research priority in the near future. However, there appear to be a few problems with the tagging data and it is not clear whether tags are returned when cod are caught in the recreational fishery, or for unreported catches of cod.

- Some participants mentioned that if the model is given space to make a choice between *M* and *F*, it tends toward a constant *F*. It seems that it will put everything under *M* without nuance. Since *F* influences other parameters (catchability, catches), this poses a problem. With fairly robust survey data, the *Z* will be an all-inclusive value where there is no distinction between *M* and *F*. The censored catch approach is not ideal for distinguishing between the two sources of mortality (*M* and *F*) owing to sensitivity to the bounds that are selected. An additional source of information (e.g. tagging) may be useful to help distinguish the two sources of mortality.
- Questions were raised about whether this space can be limited by using narrower bounds. How would the model react? At present, it is the baseline model that comes the closest in this regard. By limiting *F* to catches, for example, we might learn something about how the model reacts, but there is no guarantee that this would resolve the problem we face.
- The deviation plots could shed some light on things. We need to look at *M* over time, to see how it adjusts if we force *F*. The *F* value would not be affected by the bounds. The patterns would be the same, regardless of the deviation.
- If the true catches are not known, it will be difficult to distinguish between *M* and *F*. We should think only in terms of *Z*.
- If we want *q* to have a value of 1, something appears to be missing. According to some participants, the range of *q* values was not all that bad.
- If the TACs remain low, it may be possible to estimate the true value of *M*.
- Is there a way to find information on the age structure associated with *F?* The problem is that we do not have any information on high-grading. With regard to the depredation of catch from fishing gear, it is difficult to derive an age composition. Therefore, there is a lack of information (and we do not know the respective scales) for deriving an age composition for unaccounted-for catches.
- Participants were reminded about the current popularity of recreational fishing. The magnitude of this activity is far from insignificant.
- Acoustic tagging could provide an estimate of the mortality rate and enable us to differentiate *M* and *F*.
- To come up with a better stock assessment model, it is important to gain a better understanding of *F* and *M*. A lot more data are needed. Questions were raised about how to proceed until such time as more information becomes available.

- There appears to be a consensus regarding the new baseline model. It is more amenable to adjustments and its performance is quite good. It is a work in progress.
- It was noted that *q* declines when the bounds are increased.
- It was suggested that a model with narrower bounds be examined.
- A participant asked whether looking at different age compositions could help resolve the problem.
- The *M*/*F* ratio varies for different age groups.

MODEL PROJECTIONS

Projections are used in stock assessments to evaluate the likelihood of attaining different management results depending on the management measures implemented (e.g. TAC options) and the characteristics of the stock and the fishery as estimated by the assessment model. The model is well suited for short-term projections. It can project uncertainty and temporal autocorrelation in key characteristics (recruitment, natural mortality and fishery selectivity, as implied in the estimation of age-specific *F*). Over the longer term, the projected values will tend toward mean values equivalent to assessment values, but they are probably inappropriate, and therefore require more assumptions. For example, projecting recruitment directly from the model will not produce estimated values for a larger SSB. Projections using recent recruitment rates may be too optimistic for the near future with a low SSB. From an operational assessment stand-point (horizon of 2 to 5 years), the projections should be fine. Projections intended to support rebuilding over the longer term require a certain amount of development and would definitely involve different scenarios.

Two catch scenarios were evaluated: 2,000 t and 100 t annually. The projections for the two scenarios suggest a high probability of an increase in the stock, where there is a > 50% chance that the SSB will exceed 100,000 t in 10 years and a > 90% chance of exceeding the current level of the SSB over 10 years. The abundance of age 5+ cod should increase at a moderate pace over the next 2 years, and then a little faster in years 3 and 4. There was little difference in the results of the projections for the two scenarios, because the catch levels assumed in the projections are low in relation to the SSB, particularly once the 2018 cohort enters the mature population. The 2018 cohort, observed in the DFO RV survey every year since 2019, seems to be the largest cohort recorded in at least three decades. In light of this and the decrease in *M* towards low values, the outlook seems positive.

- A participant pointed out that the scenario using 100 t reflects an *F* value near 0.
- Participants asked whether *M* would increase with a higher TAC. Is there a strong correlation between the TAC and *M*?
- Should we take the 2018-2020 average into account for recruitment? There is an extremely strong reliance on the year 2018.
- There was a consensus among the participants that natural mortality is low at present. It appears that the context is very favourable to cod.
- Questions were asked about how to project *M*. If we use the mean, are we being too conservative? Various scenarios can be put forward.
- Some participants reiterated that until a solution is found for unaccounted-for catches, there will be a flaw in the system.

DAY 2 RECAP

Dr. Hugues Benoît explained why the model assigns unaccounted-for catches to *M*. He presented possible solutions, which included, notably, collecting the data required to estimate the composition of unaccounted-for catches (which is probably impossible), assuming that the age composition of unaccounted-for catches is unknown and must be estimated (will be confused with *M*), increasing fishery and compliance monitoring, trying to improve estimates of *M* by using data from other sources (e.g. tagging), and making assumptions about *M* based on low-TAC periods. The last option was explained in greater depth.

- It was noted that the variability between surveys can also confuse things.
- The magnitude of unaccounted-for catches (commercial fishery discards, recreational fishery) is indisputable, which adversely affects our estimates.
- Fisheries Management expressed unease with the method used to deal with unaccounted-for catches.
- The five surveys all provide the same information on total mortality, which cannot be explained solely by the commercial fishery. Besides natural mortality, a great deal of unaccounted-for mortality is known to occur (discards, recreational fishery, predation, etc.). When quotas are small, the value for natural mortality is closer to the real value. When a TAC is set, these unaccounted-for catch phenomena have greater significance.
- It was also suggested that constraints on *F* be reduced, namely by using autocorrelation, and that a more constant *F* be obtained by giving the parameter more space. The first objective of stock assessments is to understand what has happened so far; consequently, putting everything under *M* (i.e. everything aside from reported catches) is not too concerning. The second objective is to identify what is allowable in the fishery in order to achieve a certain management objective. If *M* includes a large portion of the unaccounted-for catches and the latter vary with what is allocated to the directed fishery, how can we make projections on removal options and on how the stock will react to these options? How can we allow a TAC, knowing that the losses will be greater?
- Our model suggests that there are patterns of residuals in catchability (gillnets and longlines).
- One approach could be to create one fleet with recorded catches and another fleet with unaccounted-for catches, but we would have to continue to make assumptions about *M* based on low-TAC periods. The model appears to be adequate when the deviations have been eliminated. Having a commercial *F* and an unaccounted-for *F* might result in a better model, but it would be a new type of model.
- In the baseline model, recreational fishery removals are included in the catches. The model takes account of *M* in making projections and issuing the TAC (*F*). The problem is that *M* co-varies with the TAC. This is acceptable in the short term but, in the long term, *M* is more difficult to adjust since it varies with the TAC and the environment. The recreational fishery must remain as a component in the baseline model. We can get by with making only short-term projections.

RELEVANT ELEMENTS IN A REVISED PRECAUTIONARY APPROACH AND A NEW REBUILDING PLAN

In the revised model, the range of stock characteristics used to establish reference points was modified. The reference point values used in managing nGSL cod must be updated. A new rebuilding plan, which has been needed for several years, must now be completed by April 2024. The development of a precautionary approach requires an understanding of stock status (e.g. SSB) and productivity (i.e. recruitment, growth and natural mortality) that is as extensive as possible, and ideally takes account of, or at least recognizes, past periods of high and low productivity. Although various approaches were examined, the development of an extended model (going back to 1966) and estimates for 1953 and 1958, appeared to be the most appropriate solution.

The approximations that are often used to define reference points for fishing mortality and stock status were also examined. They are derived from the calculations of yield per recruit (*YPR*) and spawners per recruit (*SPR*). In the extended model, potential fishing mortality and the stock status reference points—although based on very different reasoning—correspond in magnitude to the *YPR* and *SPR* proxies. Even though this is mainly coincidental, it has the advantage of reducing the range of choices. Although the values derived from the extended model are based on ad-hoc reasoning to some extent, they benefit from being rooted in an understanding of the history of the exploitation of the stock. In many respects, this is preferable to approaches to establishing reference points that are based on equilibrium simulations and tenuous assumptions on stock-recruitment dynamics. Although the new modelling revealed uncertainties over population removals, particularly in recent decades, the model and model-based projections seem well adapted to guiding the development of a comprehensive precautionary approach for the stock, including harvest control rules. Furthermore, although some key uncertainties remain, such as concerns over recruitment dynamics at intermediate stock status levels (i.e. a normally exploited stock), this framework seems appropriate for supporting the development of a new rebuilding plan.

A rebuilding plan requires a rebuilding target and rebuilding timeline. DFO Fisheries Management is responsible for defining these, although DFO Science will provide support. The rebuilding target should be set above the limit reference point (LRP) in order to ensure a high probability of the stock remaining above the LRP. Some other jurisdictions, including the US and New Zealand, as well as international agreements such as the UN Fish Stocks Agreement, also use B_{MSY} as a rebuilding target. We made the same assumption in our case, presuming that the objective was achieved when there was at least a 50% chance of the SSB being above this target. We used a B_{MSY} of 168,340 t, derived from the results of the extended model. Best international practices include estimating the minimum time required to achieve the rebuilding objective, assuming zero fishing mortality (T_{min}), and establishing a maximum rebuilding time that is two to three times the value of T_{min}. The following projections were made: (1) baseline model projections to estimate T_{min} (15 years under current productivity conditions); and (2) projections assuming total removals of 100 t/year (“lowest possible catches” scenario). Subsequently, a series of simulations were performed to identify the quantity of annual removals that would result in a 50% probability of achieving the rebuilding objective in 30 years, or 2 x T_{min}.

- Some participants found the extended model approach promising. Under DFO’s decision-making framework incorporating the precautionary approach, 80% and 40% of B_{MSY} can be used as the upper stock reference (USR) point and LRP, respectively. The details will be presented at the next stock assessment.
- Regarding the rebuilding plan, questions were raised about the differences between the extended model (which includes all the historical data) and the baseline model, which pose certain challenges. Concerns were expressed about the impact on the variables of selecting the entire time series. In addition, the risk of the two models (base and extended) overlapping was noted. Participants were not convinced of the importance of going back so

far in time. The baseline model, which includes data from the 1970s, would likely be sufficient.

- Questions were raised about the uncertainties surrounding the projections and which variables had the greatest impact and therefore created the greatest uncertainty (e.g. recruitment, natural mortality). There was more concern over the long-term projections than the short-term ones. The uncertainty associated with the long-term projections must be taken into account in the rebuilding plan.
- Participants were reminded that, in order for the rebuilding plan to meet international standards, the objective (i.e. the rebuilding target) cannot be achieved until there is at least a 50% chance of the SSB being greater than B_{MSY}.

The chair, Dr. Daniel Duplisea, closed the meeting, noting that the new model had been explored exhaustively. Participants agreed that great progress had been made. Important elements had been addressed, such as the issue of unaccounted-for catches and, indirectly, *M*. Regarding the precautionary approach, participants seemed to favour the approach used in the extended model for now. On the other hand, the baseline model (with data from 1973) could be sufficient. The details would be presented in a subsequent process. Taking account of the uncertainty associated with the long-term projections in the rebuilding plan will be crucial.

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APPENDIX 1 — TERMS OF REFERENCE

Northern Gulf of St. Lawrence Cod (3Pn, 4RS) Assessment Framework

Regional Peer Review – Quebec Region

Part 1: April 21-23, 2021

Part 2: May 24-26, 2022

Chair person: Daniel Duplisea

Context

The assessment framework meeting will focus on the available data and methodology for estimating the population size and other indicators of the stock status of Atlantic cod in the northern Gulf of St. Lawrence (Subdivision 3Pn and NAFO Divisions 4R and 4S) (DFO 2019; Brassard et al. 2020).

For more than 30 years, the assessment of this stock has included a virtual population analysis (VPA). As of 2015, the ASP has been performed using the National Oceanic and Atmospheric Administration's Virtual Population Analysis, VPA / ADAPT (NOAA 2014). This program is a model for estimating the age structure of a population, it was developed from the model of Gavaris (1988), in which features from other versions of ADAPT were incorporated. This tool makes it possible to estimate several parameters of population dynamics as well as an indirect estimate of natural mortality (M). The pattern of residuals obtained for this stock suggests a lack of fit of the model.

A new model should allow; 1) estimate the variability of catches, and possibly include modeling censored catches; 2) estimate natural mortality; 3) have the ability to integrate multiple data sources, including tagging, to improve the estimation of vital stock parameters; 4) to provide the opportunity to make projections and ultimately to turn it into a custom model with fully integrated analyzes.

This assessment framework meeting will review the data available for the establishment of a new model (Part 1) and examine models of population dynamics of 3Pn, 4RS cod, in particular those that may incorporate unaccounted for catches and estimation of natural mortality (Part 2).

Part 1: Review of data available for modeling

Objectives

The objective of this first part is to examine the available data, and their statistical treatment, which would be used for the population estimation models including:

- Catches at age in the commercial fishery;
- Unaccounted catches;
- Catches at age and standardized indices for scientific surveys:
    - DFO research vessel surveys,
    - Mobile sentinel fisheries,
    - Sentinel fisheries with gillnets, and
    - Sentinel longline fisheries.

Part 2: Revision of the estimation models (at age) of the population

Objectives

Evaluate potential assessment models for possible use as the basis for providing science advice on cod in the northern Gulf. If a model is found to be appropriate for the assessment of 3Pn, 4RS cod, it would be used subsequently during the next stock assessment and could be used in the development of a recovery plan. Specifically, the framework meeting will address the following:

- Evaluate potential assessment models to determine if they provide a sufficient framework for providing scientific advice on the impact of exploitation on 3Pn, 4RS cod, in particular estimating the stock size (biomass and abundance), recruitment, fishing mortality, and potentially natural mortality of the population.
- Provide direction on projection methods for future catch options.
- Provide direction for an approach to estimating reference points for this stock.
- Discuss whether the assessment methodology has the potential to support quantitative evaluation of harvest control rules.
- Identify uncertainties and knowledge gaps.
- Identify priority short and medium-term research recommendations to improve data sources, assessment model formulation and estimation, and projection methods.

Expected Publications

- Proceedings
- Research document(s)

Expected Participation

- Fisheries and Oceans Canada (DFO) (Science and Fisheries Management Branches)
- Industry
- Academia
- Non-Governmental Organizations

References

Brassard, C., Lussier, J-F., Benoît, H, Way, M. and Collier, F. 2020. The status of the northern Gulf of St. Lawrence (3Pn, 4RS) Atlantic cod (*Gadus morhua*) stock in 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/075. x + 117 p.

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Gavaris, S. 1988. An adaptive framework for the estimation of population size. CAFSAC Res. Doc. 1988/029.

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APPENDIX 2 — LIST OF PARTICIPANTS

Name	Affiliation	May 24	May 25	May 26
Benoît, Hugues	DFO — Science	X	X	X
Bois, Samantha	ACPG	X	X	-
Boudreau, Mathieu	DFO — Science	X	X	X
Bourdages, Hugo	DFO — Science	X	X	X
Brassard, Claude	DFO — Science	X	X	X
Byrne, Vanessa	Gov. NL	X	X	X
Cadigan, Noel	Memorial University	X	X	X
Carruthers, Erin	FFAW	X	X	X
Chamberland, Jean-Martin	DFO — Science	X	X	X
Chlebak, Ryan	DFO — Science	X	X	X
Collier, Frank	LNSFA	X	X	X
Cyr, Charley	DFO — Science	X	X	X
Denis, Marcel	ACPG	X	-	-
Desgagnés, Mathieu	DFO — Science	X	X	X
Desjardins, Christine	DFO — Science	X	-	-
Dubé, Sonia	DFO — Science	X	X	X
Duplisea, Daniel	DFO — Science	X	X	X
Dwyer, Shelley	DFO — Fisheries management	X	X	X
Le Bris, Arnaud	Memorial University	X	X	X
Lussier, Jean-François	DFO — Science	X	-	-
Nadeau, Paul	APBCN	X	-	X
Ouellette-Plante, Jordan	DFO — Science	X	X	X
Pond, Nancy	DFO — Fisheries management	X	-	X
Rayner, Gemma	Oceans North	X	X	X
Ricard, Daniel	DFO — Science	X	X	X
Rivierre, Antoine	DFO — Fisheries management	X	-	X
Senay, Caroline	DFO — Science	X	X	X
Smith, Andrew	DFO — Science	X	X	X
Turcotte, François	DFO — Science	X	X	X
Van Beveren, Elisabeth	DFO — Science	X	X	X
Varkey, Divya	DFO — Science	X	X	X

APPENDIX 3 — AGENDA

Agenda for the Meeting on the Northern Gulf of St. Lawrence Cod (3Pn, 4RS) Assessment Framework – part 2: Models review; May 24-26, 2022

Day 1 – May 24, 2022

Time (EDT)	Topic
8:30-9:00	Introductions and word from the chairperson
9:20-10:00	Presentation: review of input data and data pre-processing
10:00-10:15	Health break
10:15-11:45	Questions and discussion: input data and pre-processing
11:45-12:30	Lunch break
12:45-14:00	Presentation: Base model structure and justification
14:00-15:00	Questions: Overarching issues and homework for the modelling team, if required
15:00	Meeting adjourned

Day 2 – May 25, 2022

Time (EDT)	Topic
8:30-9:00	Recap of day 1 and review of homework (if required)
9:00-10:15	Presentation: Model variants and validation
10:15-10:30	Health break
10:30-12:15	Questions and discussion: Model structure, variants and validation
12:15-13:15	Lunch break
13:15-15:00	Presentation: Model structure and justification of the basic model
14:00-15:00	Questions and discussion: Model structure, variants and validation. Homework for modelling team, if required.
15:00	Meeting adjourned

Day 3 – May 26, 2023

Time (EDT)	Topic
8:30-9:30	Recap of day 2 and review of homework (if required)
9:30-10:00	Presentation: model projections
10:00-10:15	Health break
10:15-11:15	Questions and discussion: projections
11:15-12:15	Lunch break
12:15-13:00	Presentation: relevant elements for a revised precautionary approach and new rebuilding plan
13:00-14:15	Questions and discussion: relevant elements for a revised precautionary approach and new rebuilding plan
14:15-15:00	Conclusion