Northwest Atlantic Fisheries Organization

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Report of the NAFO Precautionary Approach Working Group (PA-WG)

19 May 2022
By Webex

NAFO Precautionary Approach Working Group (PA-WG)

Report May 19, 2022, meeting by WebEx

Co-chairs; Fernando González-Costas and Steve Cadrin

1. Opening.

The meeting was opened by the co-Chairs Fernando González-Costas and Steven Cadrin at 09:00 hours (Atlantic Daylight Time in Halifax, Nova Scotia) on Thursday, 19 May 2022.

The co-Chairs welcomed all the participants (Annex 1)

Tom Blasdale, the NAFO Secretariat Scientific Council Coordinator, was appointed as Rapporteur of this meeting.

The provisional agenda was adopted as previously circulated without amendment (Annex 2).

2. Appointment of new co-chair

Karen Dwyer, the previous co-Chair of this group and the current SC Chair, explained the main reasons that made it impossible for her to continue with the PA WG co-chair tasks and the appointment of Fernando Gonzalez-Costas as the new co-Chair of the PA WG.

3. Review of Progress on ToRs

a) Subgroup 1

Karen Dwyer presented the preliminary results of subgroup 1 (Annex III) on the structural aspects of how the Framework is set up and a review of reference points, risk zones and buffers. This report is to summarize these structural aspects of PA Frameworks across various jurisdictions and countries. Below is a summary of the main points contained in the report of Subgroup 1.

The risk zones and buffers used in the following PA frameworks reviewed by SC WG-PAF were presented: ICES, Canada, USA, New Zeeland and Tuna RFMOs. Figure 1 shows Stock status categories used in different frameworks. Comparisons highlight similarities but also the somewhat arbitrary nature of value judgements inherent in such status categories. Side-by-side comparisons of stock status schemes from around the world show similarities, but also highlight the arbitrary nature of status classifications. New Zealand's Harvest Strategy Standard focuses on stock states representing breached limits in both biomass and fishing mortality. Traditional "Kobe" plots, widely used in many states and Regional Tuna Fisheries Management Organizations, treat both F_{msy} and B_{msy} as limits to undesirable stock states. The precautionary frameworks of NAFO and ICES, on the other hand, use buffers or precautionary reference points to nuance the range of acceptable stock states. This is accomplished by adding a zone of "caution" or "increased risk" between desirable and undesirable stock states on one or both axes, generally representing the boundary where stocks have greater than 5-20% probability of breaching limits in either the F or B axes. Such zones are comparable to the Cautious Zone of the Canadian framework.

The diversity in sustainability reporting schemes reflects differences in sustainable fisheries management criteria across international contexts. Some frameworks emphasize achieving maximum sustainable yield, some focus on avoiding states of impaired reproductive capacity, and others strive for a mix of both. The differences across organizations and jurisdictions are also reflected in varying and sometimes conflicting usage of terms such as "overfished" and "overfishing" that may reflect the values applied to stocks and fisheries.

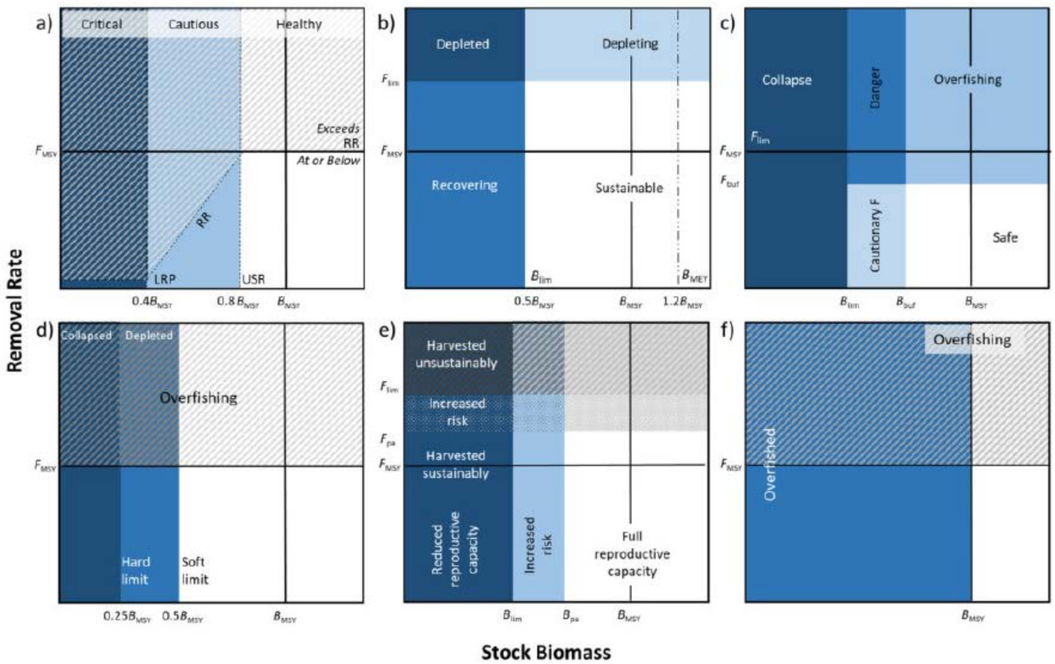

Figure 1. Stock status categories used in precautionary or risk-based fisheries management frameworks for a) Canada, b) Australia, c) NAFO, d) New Zealand, e) ICES, and f) a generalized Kobe plot used in many international contexts. Placement of each jurisdiction's reference points and labels relative to either Fmsy or Bmsy (including provisional or default values, where given) are specified. Provisional default values for Canadian reference points (LRP as 0.4 Bmsy, USR as 0.8 Bmsy, and three-part RR declining linearly from Fmsy) are presented in panel a) Other jurisdictions also specify default values of reference points (e.g., a Blim of 0.5 Bmsy (or 0.2 B0); Australia, New Zealand and Bmsy of the generalized Kobe plot). From Marentette et al 2021.

The structure (reference points and definition of zones) is quite similar between the different frameworks except for the USA where its structure is a bit different. Generally speaking, limits define thresholds to unacceptable outcomes. These include unacceptably high fishing mortality and unacceptably low biomass or abundance levels. The basis for limit reference points is in avoiding irreversible, or only slowly reversible harm due to long-term impacts of fishing or other anthropogenic activities.

Various non-limit thresholds (also called buffers, triggers or precautionary reference points) may be defined in relation to either limits or targets and are used in multiple jurisdictions.

Targets, like limits, are fundamental to the precautionary approach and are set to reflect a variety of considerations relevant to decision-makers. Targets are required elements under the United Nations Fish Stocks Agreement, the FAO Code of Conduct for Responsible Fisheries and the FAO technical guidelines for implementing the precautionary approach. Based on ICES WKREF1, several international best practices for reference points were determined:

- Reference points should use the best available information
- RPs should be updated every 3-5 years
- F_{msy} is the maximum acceptable or limit level for fishing. Because it is difficult to calculate, proxies can be used
- Key biological reference points are B_{msy} and B_0.

- Default policy guidance on limit reference points are often some fraction of either Bmsy or B0 (based on ICES WKREF1 this fraction can vary widely).

Acceptably sustainable stock states vary among jurisdictions, where some evaluation frameworks emphasize achieving maximum sustainable yield, or avoiding states of impaired reproductive capacity, and others strive for a mix of both considerations.

In the discussion of the report different comments were made on the following points:

The problems that exist in many of the frameworks that work with the specific risk tolerances (e.g., 0.05 probability) to establish buffer reference points due to the difficulty of estimating these values well.

The possibility of establishing a biomass reference point (soft limits) greater than B_{lim} that could be justified with ecological reasons. The current B_{lim} in almost all frameworks are established based on monospecific sustainability reasons. These new soft limits can be justified for reasons of ecological sustainability and productivity.

A possible added advantage of these soft B_{lim} could be that a higher level of risk could be accepted than the current B_{lim}, which would facilitate a better estimation of the risk by avoiding the queues of the distributions.

The reference point F_{ecco} developed by ICES was also discussed as a good tool to include qualitative ecosystem information in the production of management advice.

b) Subgroup 2

Steve Cadrin presented the preliminary results of subgroup 2 (Annex IV) on the estimation of uncertainty, risk and data-limited approaches associated with Terms of Reference 1e and 1f.

A summary of the preliminary results was the following: Approaches to estimating risk, accounting for uncertainty, and data limited approaches vary widely among other fishery management organizations. Uncertainty is typically accounted for in status determination and catch advice. Although estimates of estimation error can be produced by most stock assessments, they do not include some major sources of uncertainty, so best practices for estimating risk involve management strategy evaluation, in which major sources of uncertainty are accounted for in multiple operating models, and risk can be quantified for meeting specific management objectives (e.g., attaining optimum yield, avoiding overfishing, avoiding stock depletion). The risk tolerances specified in the current NAFO precautionary approach framework (20% probability of $F > F_{lim}$, 5-10% probability of B<Blim) or applied in MSEs (e.g., probability of $B < B_{lim}$) are generally consistent with other precautionary approach systems. Data-limited stock assessments cannot support the information needed for precautionary status determination or catch advice, but data-limited management procedures can be evaluated to quantify risk for meeting management objectives. PA-WG recommends that the precautionary framework should be implemented using information from stock assessment (e.g., estimation error and stochastic projection), and MSE should be developed for a subset of NAFO managed stocks to test performance of a more general precautionary framework.

In the discussion of the report different comments were made on the following points:

Each reference point may require a different risk tolerance. For example, risk of irreversible harm should be lower than risk of an arbitrary biomass threshold.

Many of the methods used in other frameworks present challenges for the implementation of the PA in the data poor stocks. These problems are related to the assumptions that many of these data poor models make to estimate proxies related to the MSY reference points (Example F_{msy} =M). Therefore, some flexibility for applying appropriate methods should be considered when proposing the implementation of the PA framework in these data poor stocks.

It was also commented that the choice of the model to estimate the proxies in these stocks will depend mainly on the available data, so the less quality data available, the level of precaution should be increased when managing the stock.

4. Proposal of recommendations

Steve Cadrin presented the preliminary recommendations base on the Action 1 (Review of and proposal for ToR 1 items related to mapping objectives: ToRs 1a, 1c and 1g, (NAFO SCS Doc. 22/02)), and Action 2 (Review of and proposal for ToR 1 items related to structural aspects and quantification of uncertainty and risk. ToRs 1b, 1d, 1e and 1f) results.

The Mapping objectives recommendations already discussed by SC are the following:

- All options for the NAFO Precautionary Approach Framework, including the existing framework require full implementation to achieve objectives.
- Some flexibility will be needed in the Precautionary Approach Framework to achieve NAFO's objectives and conform to principles for all NAFO stocks.
    - For example, management procedures that are expected to perform well for longer-lived stocks may not perform well for short-lived stocks, like squid and capelin.
    - Several NAFO stocks are data-moderate to data-rich, and stock assessments are often complicated by important environmental factors that influence Precautionary Approach reference points.
- It may not be possible to maintain all stocks at B_{msy} at all times with high probability in a dynamic ecosystem with many interactions among species.
- The Precautionary Approach Framework will be implemented to manage fishing mortality which will not directly control stock size because it is also influenced by the ecosystem.
- Therefore, the framework should be intended to maintain stocks above B_{msy} more often than not.
- All options considered for a revised NAFO PA framework should be performance tested with respect to whether management measures set in accordance with the framework could achieve the following objectives:
    - Achieve very low risk of stock depletion (i.e., $B< B_{lim}$)
    - Rebuild stocks to B_{msy}
    - Maintain stocks above B_{msy} more often than not
    - Maintain approximately MSY in the long-term
- The decision to estimate either MSY reference points or proxies should be reconsidered when the content and quality of information substantially changes.
- Reference points should be re-evaluated when there is strong evidence of a shift in productivity regime, the mechanism of the shift is understood, the current productivity has persisted, the current productivity is expected to continue, the stock would be viable if managed with the revised reference points, and there is sufficient information to estimate revised reference points.
    - evidence that current reference points are unsustainable is sufficient to revise reference points
    - operational stock assessments should routinely test for a shift back to greater productivity.
- Reference points can be revised when new information indicates that management procedures based on current reference points do not perform well for meeting NAFO Convention objectives, and alternative management procedures are expected to perform better.

The recommendations related with the structural aspects and quantification of uncertainty and risk from other PA systems to discuss in the SC were the following:

- Reference points and definition of biomass zones are similar among PA frameworks:
  - Collapsed zone:
    $B <= B_{lim}$ based on unacceptable or irreversible outcomes
    F_{msy} Triggers management for reduction in F to rebuild stock
  - Cautious zone:
    $B_{lim} < B < B_{target}$
    Management based on low risk of $B <= B_{lim}$ or $F > F_{lim}$ for rebuilding toward B_{target}
  - Healthy zone:
    $B \sim B_{target}$ based on optimal yield objectives
    Management based on low risk of overfishing ($F_{target} < F_{lim}$) or maintaining biomass above a precautionary threshold
- F_{ecco} is a candidate for F_{target}.
  - based on on uncertainty of based on uncertainty of Fmsy and/or depending on the situation of the general ecosystem
  - higher when ecosystem is more productive, lower when it is not
- The NAFO precautionary framework should be implemented using information from stock assessment (e.g., estimation error and stochastic projection).
  - MSE should be developed for a subset of NAFO managed stocks to test performance of a more general precautionary framework.
  - Development of MSE for this purpose is beyond the scope and schedule of PA-WG.
- Risk tolerances specified in the current NAFO PA framework are generally consistent with other systems.
  - 20% probability of $F > F_{lim}$, 5-10% probability of $B < B_{lim}$, 30% probability of $F > F_{msy}$ in MSE for 3M cod
  - Low risk (e.g., 5%) is more difficult to estimate than higher risk (e.g., 10%)
  - Risk should be associated with definition of limits.
  - The Joint Commission-Scientific Council Working Group on Risk-Based Management Strategies would be the appropriate group to confirm or revise these risk tolerances.
- Data-limited assessments cannot support the information needed for precautionary status determination or catch advice, but data-limited management procedures can be evaluated to quantify risk for meeting management objectives using MSE.

The discussion focused on the recommendations related to the structural aspects and quantification of uncertainty and risk which are the recommendations that the SC has not yet discussed and approved. The recommendations related with the structural aspects and quantification of uncertainty and risk to discuss in the SC

Comments made to these preliminary recommendations were related to:

The definition of the different biomass zones. The possible need to use a B_{buffer} smaller than B_{target} to define the Caution Zone. And if this B_{buffer} and the management actions in this zone would be defined based on whether we move away from the B target or on the low probability of falling below B_{lim}.

Whether the healthy zone should be a zone around B_{target} rather than the zone greater than B_{target} and if the management in that zone should be carried out due to a low risk of $F > F_{lim}$ or simply a risk less level than 50%.

Apart from establishing risk ranges, it would be convenient for the framework to establish default risk levels to facilitate the work of the SC when proposing possible management measures.

5. Planning for the PA workshop (provisional dates, 15-16 August 2022)

The final dates of the workshop are August 15-16, 2022 and it will probably take place in Halifax since the impossibility of carrying it out in Brussels (EU) was confirmed.

Under this item a draft of the PA workshop agenda was discussed. It was agreed that the proposed draft focused a lot on giving information on the work carried out in Action 1 and 2 and that it left very little time for the objective of presenting and discuss the proposals for possible revised frameworks.

It was agreed that the Co-Chairs develop and present a new agenda next week to solve this problem. This new agenda should spend less time (one morning) in presenting the results of actions 1 and 2 and leave more time to present and discuss possible new frameworks with the managers.

Another of the problems discussed was how to develop these possible frameworks for review in the next SC in June. It was agreed to create a subgroup to start preparing these frameworks to try to have them available for discussion at the June 2022 SC. The subgroup would initially be composed of Daniel Howell, Jan Horbowy, Steve Cadrin, Mariano Alonso, Karen Dwyer and Fernando Gonzalez-Costas.

6. Discussion of likely extension of the project into 2023.

Due to different problems, it has not been possible to advance in all the work according to the established schedule. The contract with the external experts ends in December 2022 and it was agreed to see the possibility of extending it, considering the availability of the experts, until the second workshop scheduled for spring 2023. This point will be discussed with the NAFO Secretariat at the June 2022 SC meeting.

7. Close

The meeting was adjourned at 12:45 hours (Atlantic Daylight Time in Halifax, Nova Scotia) on 19 May 2022.

APPENDIX I. AGENDA

NAFO Precautionary Approach Working Group (PA-WG)

May 19, 2022, by WebEx

Co-chairs; Fernando González-Costas and Steve Cadrin

Agenda

1) Opening
2) Appointment of new co-chair (Fernando González-Costas)
3) Review of Progress on ToRs
    a) Subgroup 1 (reference points and risk buffers (Terms of Reference 1b and 1d))
    b) Subgroup 2 (The estimation of uncertainty, risk and data-limited approaches (Terms of Reference 1e and 1f))
4) Proposal of recommendations
5) Planning for the PA workshop (provisional dates, 15-16 August 2022)
6) Discussion of likely extension of the project into 2023.
7) Close

APPENDIX II. LIST OF PARTICPANTS, 19 MAY 2022

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APPENDIX III. REPORT OF SUBGROUP 1

Draft Progress Report Subgroup 1 for Action Item 2

The first aspect of the work begun to revise the NAFO addresses the mapping of the PAF to the NAFO Convention objectives. Action 2 subgroup 1 was commissioned to report on the structural aspects of how the Framework is set up and a review of reference points, risk zones and buffers in different jurisdictions. This report is to summarize such structural aspects of PA Frameworks across various jurisdictions and countries. Specifically, to:

1. **Compile information on risk zones and buffers used in the PA frameworks reviewed by SC WG-PAF, as well as other relevant sources (e.g. FAO, other jurisdictions), summarize these findings, and highlight the main similarities and differences.**

i) ICES

The ICES system is based on a requirement for advice to be precautionary, defined there as a maximum of 5% risk of breaching B_{lim}, and then ideally either the ICES Advice Rule based around delivering Maximum Sustainable Yield (MSY) or alternatively, an agreed-upon stock-specific Management Plan (or Harvest Control Rule) that is considered to be suitably precautionary. If neither can be applied, then ICES will default to purely precautionary advice (i.e., based on Fpa). This summary discusses data-rich ("Category 1 and 2") stocks, as the principles are similar for data-limited ("Category 3-6") stocks. However the implementation details differ between data-rich and data-poor scenarios. The full basis for ICES advice is laid out in the advice on fisheries opportunities overview (ICES 2021), this is an attempt at a concise summary.

ICES has a suite of reference points, of which two are key in implementing the precautionary approach, B_{lim} and F_{pa}. B_{lim} is defined as the Spawning Stock Biomass (SSB) below which recruitment is impaired. F_{pa} is typically defined as the fishing pressure which, if applied constantly in a simulation with stochastic recruitment would lead to an exactly 5% chance of reducing the SSB to or below B_{lim} in the long term (i.e. F_{p05}). If such calculations are not possible, then a deterministic evaluation is also possible. The B_{lim} is used as the limit reference point for checking if a fishing rule is precautionary using both the ICES Advice Rule and any Management Plan, while the F_{pa} is only used directly in the ICES Advice Rule (a specific Management Plan can exceed F_{pa} if there are other components which render the Plan precautionary). In the standard ICES procedure, B_{lim} is estimated from the data, with a series of stock classifications leading to different methods for this estimation (break point of a hockey stick, lowest observed stock size with good recruitment and so on, based on different stock types). As noted below this can lead to ambiguities in practice, and is under revision (ICES 2022).

Other reference points include F_{MSY} and MSY $B_{trigger}$, which comprise parts of a standard "hockey stick" HCR in the ICES Advice Rule (Figure 1). MSY $B_{trigger}$ is an operational control point; above MSY $B_{trigger}$, advice is given as a maximum advised fishing mortality rate, i.e., F_{MSY}. In ICES, F_{MSY} is defined as "the fishing level which gives MSY while also giving no more than a 5% chance to breach B_{lim}." In many stocks F_{pa} is estimated to be higher than F_{MSY}, so this is an issue in theory only; however, there are cases where the ICES F_{MSY} is constrained by F_{pa}. Strictly speaking, F_{MSY} is used as a limit in advice for quotas, such that the standard ICES advice formulation is "catches shall be no more than XXX tonnes". In practice, however, this is frequently used as a target, and quotas are set at exactly this level. MSY $B_{trigger}$ was historically set equal to B_{pa}, a precautionary biomass reference point intended to avoid stocks falling below B_{lim} given the uncertainties in the assessment. B_{pa} is set above B_{lim} based on the uncertainty in the assessment, with a frequently used default of a coefficient of variation of 0.2, giving B_{pa} as circa 1.4 * B_{lim}. ICES is in the process of moving to using a MSY-based $B_{trigger}$, set such that MSY $B_{trigger}$ is defined as the lower bound of SSB fluctuations (fifth percentile of B_{msy}) when fished at F_{MSY}. Note that B_{msy} is not used directly in the ICES advice system, but can indirectly influence the MSY $B_{trigger}$. This approach has only been adopted, however, for stocks with a history of being fished at or near MSY conditions for a number of years. As a result, implementation of the ICES Advice Rule for many stocks continues to use B_{pa} as MSY $B_{trigger}$.

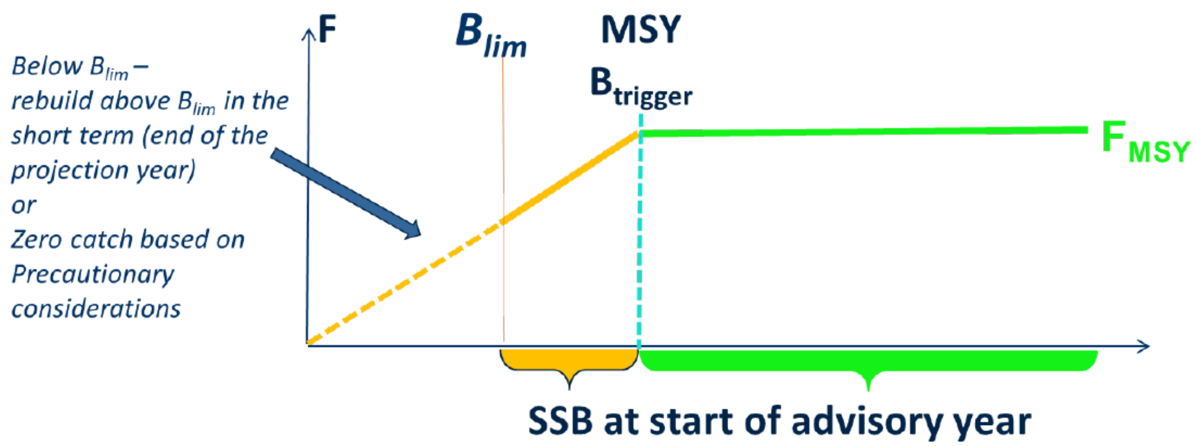

Figure 1. ICES Management framework showing the ICES Advice Rule for data-rich stocks.

F_{MSY} and MSY $B_{trigger}$ are computed using the EqSim program, which performs stochastic simulations. One underlying principle in the system is that reference points are defined under "current fishing patterns and environmental conditions". The reference points are revised (i.e., re-estimated) at each model revision (termed a "benchmark" in the ICES advice system), which typically occurs every 5 years. This means that the reference points are not intended to apply at all stock sizes and environmental conditions, but rather to those expected to apply over the lifespan of the reference points.

ICES will also give advice on the basis of agreed Management Plans (or Management Strategies), subject to two stipulations. First, the plan must have been evaluated by ICES as being precautionary (i.e., with a maximum 5% risk of breaching B_{lim} over a given time period). Second, the plan must be adopted by the managing bodies. The typical process for ICES to adopt such a rule in its advice is for the managing bodies to send a formal request to ICES, which then convenes a review of the proposed Management Plan(s) identifying which variants are assessed to be precautionary. Once the managers agree to adopt a particular Management Plan, ICES will give advice on this basis. Typically, the standard "ICES MSY Advice Rule quota advice" is also included in the advice sheet for comparison, in a section on catch scenarios.

In many cases the agreed-upon Management Plan is a variant of the standard ICES Advice Rule, with typical additions including year-to-year stability constraints on catch variation. However, this is not required, and other forms are in use. One category of rule is applied to short-lived, highly variable fish stocks where an escapement strategy is typically employed. Other forms are possible, for example N.E.A. cod uses a "double hockey stick" Harvest Control Rule with higher fishing at high stock sizes (e.g., if SSB>3Bpa for Northeast Arctic cod, then Ftarget =1.5Fmsy). This system gives a large degree of flexibility to follow management requests which require features outside the standard ICES Advice Rule.

For several stocks including in the Baltic and North Sea the Commission requested ICES to provide plausible values around F_{MSY}. Following that request, ICES introduced so-called F_{MSY} ranges. These ranges are fishing mortalities which allow catches at the level of no less than 95% of MSY, and they are referred to as $F_{MSY\ lower}$ (<F_{MSY}) and $F_{MSY\ upper}$ (>F_{MSY}). Similar to F_{MSY}, advice on $F_{MSY\ upper}$ is constrained by F_{pa} (F_{p05}). The ranges have been used in multiannual management plans for Baltic stocks (cod, herring, and sprat) and demersal stocks in the North Sea and Western Waters. In the developed plans the entire range of F_{MSY} is considered precautionary, but catches above F_{MSY} (but below $F_{MSY\ upper}$) are allowed only under conditions specified in the plan. These conditions may be relevant in case of:

a. mixed fisheries,
b. when intra- or inter-species stock dynamics may cause serious harm to a stock,
c. necessity to limit variations in fishing opportunities to given level.

ICES WKREF2 considered limiting the F to F_{MSY} and excluding $F_{MSY\ upper}$, but also discussed the usefulness of F_{MSY} ranges. ICES WKIRISH (supported by WKREF2) suggested using this flexibility to allow for incorporating more ecosystem realism into advice while relying on the precautionary checks built into the ranges calculated on a single-species basis.

It should be noted that there is a process of revision of the advice basis that is currently ongoing within ICES. There have been a series of meetings, WKREF1 and WKREF2, directly aimed at examining the reference points in the system. There have also been recent Working Groups looking at how to deal with changing environmental conditions (WKRPCHANGE) and producing new guidelines for MSE simulations (WKGMSE2 and WKGMSE3). One key point involves B_{lim}. The current system works well for some stocks, but in other cases it can be difficult to identify a specific value to select for B_{lim}, and there is variability between Working Groups. There is therefore a desire to revise and streamline this system. There is also debate over the F_{msy} and MSY $B_{trigger}$ in the ICES Advice Rule. At present F_{msy} is F_{max} (the maximum of the yield curve) constrained by F_{pa}. There is debate around reducing this to a lower proxy, and if so which proxy should be used. This would allow the constrained F_{max} to become an absolute limit, with a somewhat lower target. There is also debate around the level to set MSY $B_{trigger}$, with concerns that under the current system an uncertain assessment could lead to MSY $B_{trigger}$ being set a long way below B_{msy}, whereas the precautionary principle would seem to suggest setting a higher MSY $B_{trigger}$ in the face of higher uncertainty. There were suggestions to introduce B_0 as a basis for B_{lim} and B_{msy} / MSY $B_{trigger}$. However, these were not well received as, given the long fishing history of many ICES stocks, there typically is considerable data in the B_{lim} - B_{msy} range but very little data on what the level of B_0 is. Although the desire to adapt the system is clear, it is not yet clear what the outcome will be.

A different advice system exists for data-limited stocks within ICES. Where possible, surplus production models are used but results are relative. Methods also involve using length-based indicators such as mean length for F being equal to M.

ii) Canada

Under Canada's precautionary approach, two biomass reference points (Limit Reference Point or LRP and Upper Stock Reference or USR) are defined, which delineate stock statuses of Critical (below the LRP), Cautious (between LRP and USR) and Healthy (above the USR; DFO 2009, Figure 2). A Removal Reference (maximum removal rate) is also set for each of the three stock status zones, and a Target Reference Point (TRP) can also be set. Status relative to the Rem Science sets the LRP as a threshold to stock states below which serious harm is (or is at increased risk of) occurring to the stock, while the USR is set by managers as the level below which removals must be progressively reduced to avoid reaching the LRP, while considering socio-economic factors. Operationalization of reference points, including risk zones and buffers, have previously been reviewed for a broad range of Canadian fish stocks in Marentette et al. (2021a, 2021b). Policy provisional defaults of 0.4 B_{msy} (LRP) and 0.8 B_{msy} (USR) have been widely used (whether estimated directly or based on proxies), although alternatives (e.g., USR = 2*LRP) are also sometimes used. The extent to which TRPs have been implemented is unclear as TRPs have not been tracked. There has been generally less emphasis on the Removal Reference, which is tracked as three separate elements and often considered equivalent to harvest control rules. Work is ongoing to examine operationalization of LRPs in a more in-depth fashion.

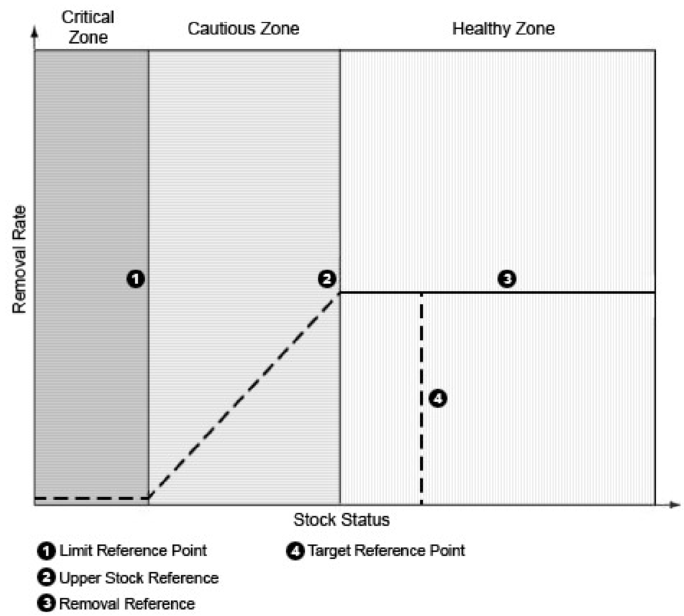

Figure 2. Canada Management framework showing reference points and stock status zones Dashed lines indicate the Target Reference Point (optional) and the Removal Reference which can take different forms below the Upper Stock Reference (DFO 2009).

iii) USA

USA

Under the US MSFCMA, four zones are recognized (NOAA, 2007; Fig. 3):

(i) Overfishing is not occurring, stock is not Overfished;

(ii) Overfishing is occurring, stock is not Overfished;

(iii) Overfishing is occurring, stock is Overfished;

(iv) Overfishing is not occurring, stock is Overfished.

Overfishing is defined as F ≥ MFMT (maximum fishing mortality threshold) and Overfished as SSB < MSST (minimum stock size threshold). If a stock is identified as being Overfished, Overfishing has to end within two years. Further, Overfished stocks are subject to a rebuilding plan that will rebuild the stock to SS B_{msy} (or proxy) within a specified period of time, typically not exceeding 10 years. Further, F is required to be adjusted to prevent Overfishing from occurring whenever a stock is identified to be approaching an Overfished condition. MFMT is generally considered to be F_{msy} or a proxy. Therefore, the US MSY-based approach considers F_{msy} as a limit reference point. The MSST is loosely defined as the biomass that is the greater of ½ B_{msy} (or proxy) or the biomass from which the stock can rebuild to B_{msy} within 10 years. In this region, proxies are often used, mainly if a stock-recruitment relationship cannot be estimated or analytical assessments are not possible.

The regions of the US have implemented these guidelines in various ways. The Northeast Region (Maine to North Carolina), which contains two management councils, is the nearest to NAFO waters so will be the focus of this paragraph. In this Region, the MSST is defined as ½ B_{msy} and the MFMT as F_{msy}. F_{msy} is used to set the Overfishing Limit (OFL) and then scientific uncertainty is used to reduce this catch level to the Allowable Biological Catch (ABC).

The two Councils in this region tend to use different methods to set the ABC. For stocks that have analytical assessments, the New England Fishery Management Council generally uses 75% F_{msy} as a target as long as the stock is above the biomass threshold. If the stock is below the threshold, a fishing mortality that allows the stock to rebuild within 10 years is estimated. However, there are those cases when the stock cannot rebuild to B_{msy} in 10 years, even at F = 0. In those cases, the 10 year time period becomes 10 years plus one mean generation. The Mid-Atlantic Council uses a method of projection that is a function based on biomass relative to B_{msy} which changes depending on the uncertainty in the model. The projections are done iteratively to estimate the OFL each year and then use the resulting SSB compared to B_{msy} to reduce the catch to estimate the ABC.

Both Councils use a variety of management measures (Accountability Measures) to ensure that catches either not exceed the ABC or if they do catches in the following year can be potentially adjusted. These include having buffers (10% in the skate fishery) which closes the directed fishery and only have bycatch and having reductions in the following year equivalent to the overage.

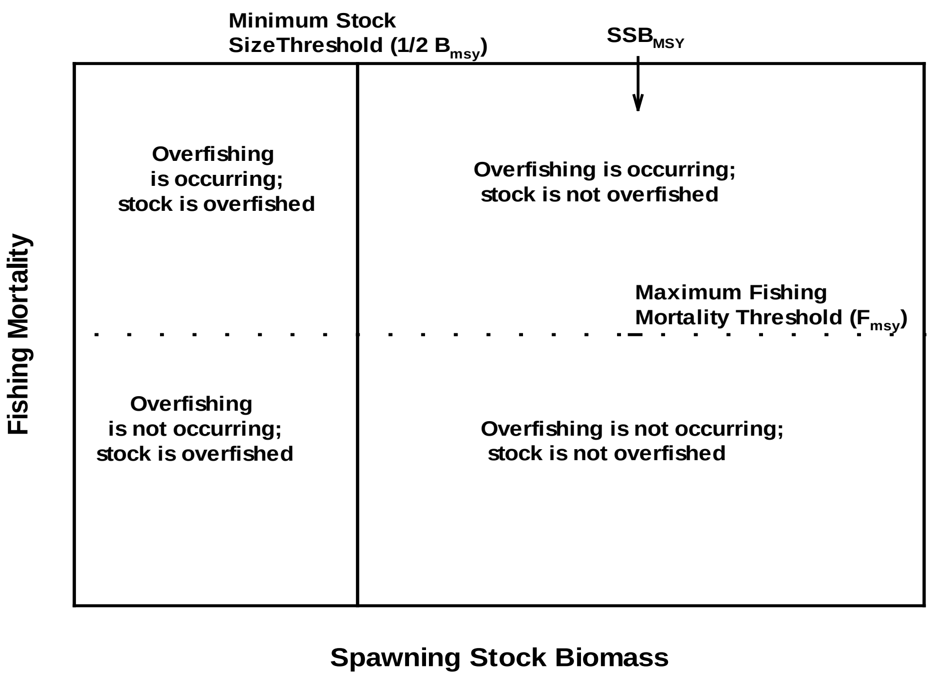

Figure 3. Management framework adopted by the US National Marine Fisheries Service for providing scientific advice under the MSFCMA. The vertical solid line demarcates spawning stock biomass zones (above and below the Minimum Stock Size Threshold, ½ B_{msy}) whereas the horizontal broken line shows fishing mortality zones (above and below the Maximum Fishing Morality Threshold, F_{msy}).

iv) New Zealand

The characteristics of the PA Framework of New Zealand fisheries include:

An MSY-based harvest decision rule and probabilistic determination for achieving targets and not breaching limits.

There are 4 main reference points (Figure 4):

- A target (B_{msy} or 0.4 B_0, around which a stock may fluctuate).
- A soft biomass limit that when breached triggers a rebuilding plan. This is either 0.5 B_{msy} or 0.2 B_0, whichever is higher. If there is a >50% probability that B<soft limit, the stock is considered depleted. A hard biomass limit, whereby if the stock falls to that level, fisheries are considered for closure. This is 0.25 B_{msy} or 0.1 B_0. If there is a >50% probability that B<hard limit, the stock is considered collapsed.
- A maximum removal rate of F_{msy} or its proxies. Overfishing is occurring if $F_{msy}$is exceeded on average for more than 3-5 years.

Management strategies are to be designed such that:

- the probability of achieving the MSY-compatible target or better is at least 50%;
- the probability of breaching the soft limit does not exceed 10%; and,
- the probability of breaching the hard limit does not exceed 2%.

In the absence of evaluating breaches of both soft and hard limits, a probability of breaching the soft limit of no higher than 5% is also considered acceptable (MF 2008). A provisional default harvest control rule similar to Restrepo et al. (1998) is also provided, where a threshold is positioned below the target at 1 – M (natural mortality; Figure 4).

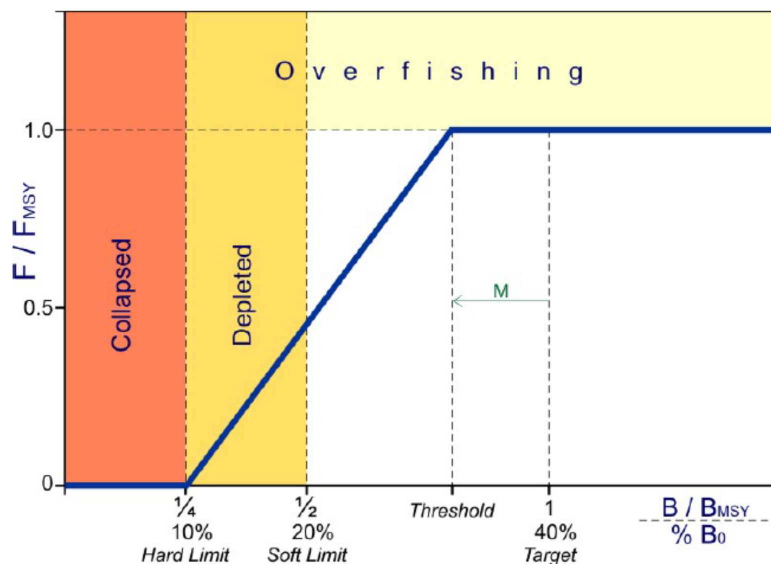

Figure 4. New Zealand Management framework with an illustrative example of a harvest control rule (thick blue line) that might be compatible with this framework (MF 2011).

v) TUNA RFMOs

For several of the tuna RFMOs, specifically ICCAT, IOTC and WCPFC, targets are based on B_{msy} and B_{lim} = 40%Bmsy. For CCSBT and WCPFC stocks, there is a target of 30% B_0 and B_{lim} is 20% B_0. For IATTC stocks, B_{lim} =7% B_0 based on 50% reduction in recruitment.

Advice on achieving or avoiding biomass targets and limits is typically provided in probabilistic sense (i.e., x% probability of exceeding target, y% probability exceeding limit).

vi) International Best Practices

Based on ICES WKREF1, several international best practices for reference points were identified. These were:

- Reference points should use the best available information
- RPs should be updated every 3-5 years
- Fmsy is the maximum acceptable or limit level for fishing. Because it is difficult to estimate, proxies can be used
- Key biological reference points are B_{msy} and B_0.
- Default policy guidance on limit reference points are often some fraction of either B_{msy} or B_0 (based on ICES WKREF1 this fraction can vary widely).

It was noted that since many ICES stocks have such a long history of fishing, it is unknown whether B_0 can be reliably estimated and therefore reference points based on B_0 might not be feasible. This may also be the case with many NAFO stocks. The working group recognized that it was not necessary to have a recruitment function (merely level of recruitment) to estimate this.

Most frameworks examined base their management actions on the probability of exceeding limits and/or achieving targets (Marentette and Kronlund 2020). In NAFO, managers will have to decide whether they want a low risk of going below B_{lim} or a staying near or above a target. Either can be tested, but managers must decide which will be the basis of the TAC.

A review of stock status metrics applied internationally showed that while PA frameworks have generally similar structures, stock status classifications are somewhat arbitrary (Marentette et al. 2021a, Figure 5). New Zealand's Harvest Strategy Standard focuses on stock states representing breached limits in both biomass and fishing mortality, although status relative to targets is also reported (Figure 5d). "Kobe" plots, widely used in many states and Regional Tuna Fisheries Management Organizations, treat both F_{msy} and B_{msy} as limits to undesirable stock states (Figure 5f). The precautionary frameworks of NAFO and ICES, on the other hand, use buffers or precautionary reference points to nuance the range of acceptable stock states (though for NAFO, these have not been implemented). This is done by adding a zone of "caution" or "increased risk" between desirable and undesirable stock states on one or both axes, generally representing the boundary where stocks have greater than 5-20% probability of breaching limits in either the F or B axes (Figure 5c, e). Such zones could be comparable to the Cautious Zone of the Canadian framework where the USR is used as an operational control point at which management measures are adjusted (Figure 5a).

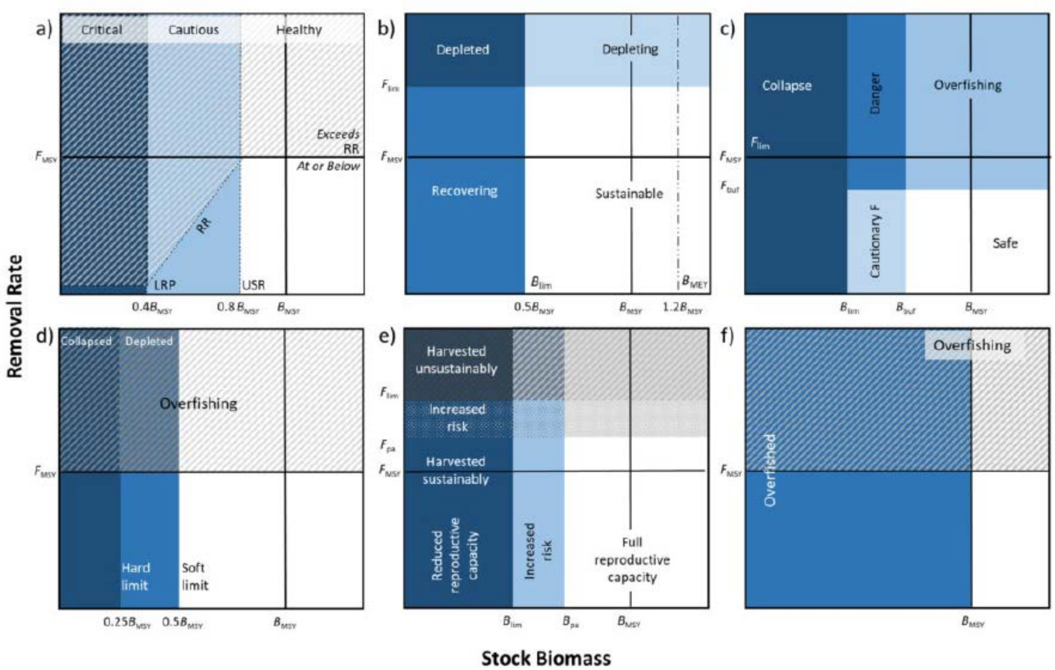

Figure 5. Stock status categories used in precautionary or risk-based fisheries management frameworks for a) Canada, b) Australia, c) NAFO, d) New Zealand, e) ICES, and f) a generalized Kobe plot used in many international contexts. Placement of each jurisdiction's reference points and labels relative to either F_{msy} or B_{msy} (including provisional or default values, where given) are specified. Provisional default values for Canadian reference points (LRP as 0.4 B_{msy}, USR as 0.8 B_{msy}, and three-part RR declining linearly from F_{msy}) are presented in panel a) Other jurisdictions also specify default values of reference points (e.g., a B_{lim} of 0.5 B_{msy} (or 0.2 B_0); Australia, New Zealand and B_{msy} of the generalized Kobe plot) (from Marentette et al 2021a).

The stock status categories used across international jurisdictions reflect a range of objectives and priorities. Some frameworks emphasize achieving maximum sustainable yield, some focus on avoiding states of impaired reproductive capacity, and others attempt some aspect of both. The differences across organizations and jurisdictions are also reflected in varying and sometimes conflicting usage of terms such as "overfished" and "overfishing" that may reflect the values applied to stocks and fisheries. The generalized Kobe plot (Figure 5f) classifies stock status in relation to maximum sustainable yield. The MSST of the US is also defined as a stock size below which the capacity to produce MSY is "jeopardized". Precautionary frameworks in Canada, Australia, New Zealand, ICES and NAFO, however, as well as the Marine Stewardship Council, all define biomass limits based on impaired reproductive capacity. Some, including Canada, also use intermediate/cautionary zones representing states of heightened risk and/or reduced tolerance for further stock decline. Some jurisdictions (ICES) match limits in fishing mortality to limits in biomass, thus treating F_{msy} (or FMEY) as a target. Others (Canada, New Zealand, NAFO) consider F_{msy} as a limit as per the UNFSA (1995). This latter practice simultaneously implies that B_{msy} should be the corresponding biomass limit; however limiting biomass levels are usually indicated to be less than B_{msy} (Marentette et al. 2021a). Based on this analysis, DFO (2021) proposed a generalized precautionary framework to fisheries management that captured key elements found in different harvest strategy policies internationally (Figure 6).

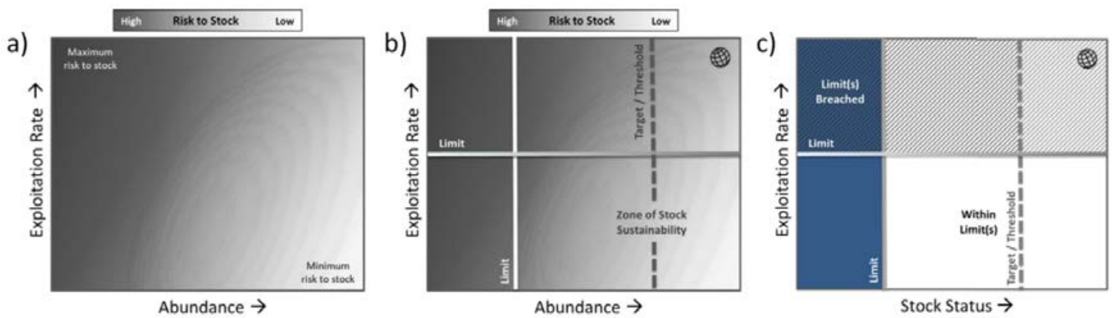

Figure 6. Generalized precautionary approach framework (DFO 2021). a) Conceptual schematic of the gradient of risk of collapse posed to fish stocks as a function of decreasing abundance (biomass, etc.) and increasing exploitation rates (fishing mortality, etc.). b) Conceptual schematic of a precautionary approach to fisheries management operationalized by limits, thresholds, and/or targets that represent outcomes to be avoided or attained, depending on conservation, socio-economic and cultural objectives that vary internationally. c) Stock status metrics are coarsely categorized in relation to reference points as part of performance metrics and monitoring. Names of reference points and stock status zones varies internationally.

2. Compare the current NAFO PAF with the findings of the compilation exercise, identify commonalities and differences, and if appropriate, develop options to optimize/streamline the risk zones/structures in the NAFO PAF.

Different PA frameworks from different organizations/countries have been analyzed. The basic structure (i.e., reference points and definition of stock status metrics) is quite similar between the different frameworks. Acceptably sustainable stock states vary among jurisdictions, where some evaluation frameworks emphasize achieving maximum sustainable yield, or avoiding states of impaired reproductive capacity, and others strive for a mix of both considerations. Another general observation is that based on similar reference points the areas delimited in the NAFO Framework are much more constrained than in the other frameworks. Most of the frameworks analyzed define 2-3 different stock status metrics depending on biomass or fishing mortality levels, as outlined below.

States where limits have been breached. This area in all frameworks is related to unsustainable or unacceptable biomass or fishing mortality levels.

Zones of "caution" or "increased risk". Most of the frameworks have intermediate status zones falling somewhere between limits and targets. These are usually related to threshold, trigger, buffer or precautionary reference points positioned between limits and targets that may also serve as operational control points at which management actions change (i.e., reduce fishing mortality). These reference points may be defined in relation to limits or targets. One of the biggest problems with the current NAFO PA framework is that the

Bbuffer reference points that are reflected in the actual framework were not estimated or used when producing the advice. Normally the management action in this zone is reduce the permitted fishing mortality as biomass declines.

Desirable states. All frameworks define desirable stock states as the zone where biomass levels are above (or fishing mortality levels below) limits, buffers or triggers and these states contain targets, when defined.

3. **Based on the results from the above, examine the reference points being used/considered to define risk zones and/or as triggers for management action, provide a summary of their key features/characteristics, and if appropriate, propose alternative reference points/indices for NAFO that can be suitable proxies for a range of data availability conditions (e.g., stocks with limited data and stocks with rich data).**

Limits: Generally speaking, limits define thresholds to unacceptable outcomes that are to be avoided. These include unacceptably high fishing mortality and unacceptably low biomass or abundance levels. The basis for limit reference points is often in avoiding irreversible, or only slowly reversible harm due to long-term impacts of fishing or other anthropogenic activities (and sometimes to avoid loss in yield). The use of limits that trigger the need for a formal, time-constrained rebuilding plan is quite common (USA, Canada and New Zealand). The use of this soft limit may be interesting since it may allow greater flexibility in management actions (HCR).

To estimate biomass limits, stock/recruitment relationship information or different proxies based on different biological reference points are usually used, and most jurisdictions provide default guidance for this. The most common default guidance used in the frameworks analyzed were to estimate limits as some percentage of B_{msy} (30-50%) and/or some percentage of B_0 (7-20%). In many cases, the choice of limit is recommended to be stock-specific (i.e., depending on the biological characteristics of the stock). The recommended values for the proxies in the NAFO PA are in the lower range of those recommended in other frameworks.

Buffers, Triggers or Precautionary Reference Points: Various non-limit thresholds may be defined in relation to either limits or targets, often serving as operational control points for changes in management action, and are used in multiple jurisdictions. These different management actions are usually related to fishing mortality reference points through an HCR or recovery plans.

As mentioned above, there are two main ways to estimate triggers or buffers, one that consists of estimating it based on some risk of breaching the limit (B_{lim}) (ICES, NAFO) and another that consists of estimating it as a deviation from targets (New Zealand, Canada). In the first case, normally the way to estimate $B_{trigger}$ is the biomass level that has a very low probability (5-10%) of being below B_{lim}, while in the second case, related % of B_{msy} proxies (i.e., where B_{msy} is the target) are usually used.

Targets: Targets, like limits, are fundamental to the precautionary approach (FAO 1995, FAO 1996) and are set to reflect a variety of considerations relevant to decision-makers. Targets are required elements under the United Nations Fish Stocks Agreement (UN 1995), the FAO (1995) Code of Conduct for Responsible Fisheries and the FAO (1996) technical guidelines for implementing the precautionary approach. Although some jurisdictions do not require the identification of a target (e.g., Canada, ICES) targets may be implicit in the estimation of other reference points. The estimation of the biomass target when it exists is usually related to B_{msy}.

Fishing mortality reference points: In all the frameworks analyzed, the maximum accepted fishing mortality is related to F_{msy} and it is this level that determines whether a stock is being overfished (or analogous term) or not. In NAFO is called F_{lim} even in the other cases it can be interpreted as a limit, maximum F allowed although they have no relation to the reference point B_{lim}. Maximum levels of F are allowed when stocks are at desirable levels, but are generally reduced as biomass declines in zones of caution or increased risk. And minimized when stocks have breached biomass limits.

Rebuilding: The use of limits or thresholds that trigger the need for a formal, time-constrained rebuilding plan is common in the frameworks of the US, New Zealand, and Canada. The core objective of a rebuilding plan consists of the rebuilding target, the expected timeframe for rebuilding and a minimum acceptable probability of achieving the rebuilt state, together with a set of management actions that will achieve the desired rebuilt state.

A good idea to link the single species framework with an ecosystem framework that is being implemented in ICES is the use of Feco as a possible Ftarget. In this case, the Feco has a distribution that can be based on the estimation with uncertainty of F_{msy} and depending on the situation of the general ecosystem, the value varies throughout the distribution, being higher when the situation of the ecosystem is good and lower when the ecosystem situation is worse.

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APPENDIX IV. REPORT OF SUBGROUP 2

Subgroup: Steve Cadrin (PA-WG, co-chair), Fernando González (PA-WG co-chair), Jan Horbowy, Daniel Howell, Daniel Duplisea, Kathy Sosebee, Diana Gonzalez-Troncoso

Summary

Approaches to estimating risk, accounting for uncertainty, and data limited approaches vary widely among other fishery management organizations. Uncertainty is typically accounted for in status determination and catch advice. Although estimates of estimation error can be produced by most stock assessments, they do not include some major sources of uncertainty, so best practices for estimating risk involve management strategy evaluation, in which major sources of uncertainty are accounted for in multiple operating models, and risk can be quantified for meeting specific management objectives (e.g., attaining optimum yield, avoiding overfishing, avoiding stock depletion). The risk tolerances specified in the current NAFO precautionary approach framework (20% probability of $F>F_{lim}$, 5-10% probability of $B< B_{lim}$) are generally consistent with other precautionary approach systems. Data-limited stock assessments cannot support the information needed for precautionary status determination or catch advice, but data-limited management procedures can be evaluated to quantify risk for meeting management objectives. PA-WG recommends that the precautionary framework should be implemented using information from stock assessment (e.g., estimation error and stochastic projection), and MSE should be developed for a subset of NAFO managed stocks to test performance of a more general precautionary framework.

Background

The NAFO Precautionary Approach Working Group (PA-WG) was formed in 2016 to reviewing NAFO's Precautionary Approach Framework with these terms of reference, approved by the NAFO Commission in 2015 (NAFO, 2015b):

1. ***To clarify the following elements:***
    a. ***To confirm/review the NAFO PAF reference points definition in page 3 of NAFO/FC Doc. 04-18.***
    b. ***To confirm/review the NAFO Management strategies and courses of action, including risk levels, on page 3 of NAFO/FC Doc. 04-18.***
    c. ***Distinction between MSY (Maximum Sustainable Yield) and limit/target related reference points.***
    d. ***Analysis in support of the development of other reference points (e.g., targets, buffers).***
    e. ***To review the methods for the calculation and interpretation of risk and the quantification and qualification of uncertainties related to them.***
    f. ***For stocks where risk analyses are not possible, provide options on how to establish buffer reference points on a stock-by-stock basis.***
    g. ***Determine the conditions for when/if reference points should change and / or be re-evaluated.***
2. ***Consider how a revised PA can fit within an Ecosystem Approach.***
3. ***In reviewing the NAFO PAF, the WG-PAF will also take into consideration other Precautionary Approach Frameworks with a focus in the North Atlantic.***

In 2020, the SC decided that the review of the PA framework will be approached in a structured and sequential way by addressing conceptual issues first, and second addressing the more operational aspects and classified ToRs 1 into the following categories:

> Mapping objectives. This involves items a), c), and g), where conceptual questions are presented that address how the framework would represent basic convention objectives. Item a) reviews definitions, item c) explores the role of MSY-based reference points as limits and /or targets, and item g) asks about the conditions under which the reference points may need changing (keeping them constant may hinder the ability of the framework to achieve its objectives).

Structural aspects of the framework. This involves items b) and d), which ask about the structure of the framework; which reference points are to be considered, how they are going to be used, and how risk is considered in the design of the framework.

Quantification of uncertainty and risk. This involves items e) and f), which directly address the analytical methods in which risk is estimated and applied, including tiered approaches taking into account data quality/availability. This last point is also related to the structural aspects described under the previous heading. Where probabilities are estimated to inform on risk, these should be based on the statistical estimation of imprecision for the best assessment, or through the development of management procedures within MSE exercises

In November 2020, a Grant Agreement was signed between the European Commission and NAFO to review the NAFO PA Framework. The work undertaken under this grant agreement would contribute directly to address ToR 1 of the NAFO PAF review process. While this revision of the NAFO PAF is intended to retain its single-species focus, whenever appropriate, the proposed solutions will be informed by the ecosystem principles contained in the NAFO Roadmap for an Ecosystem Approach. The actions to be implemented to carry out this revision should proceed along the following plan:

Action 1: Review of and proposal for ToRs related to mapping objectives: ToRs 1a, 1c and 1g. PA-WG addressed Terms of Reference 1a, 1c and 1g by developing recommendations for designing a framework that is expected to meet the objectives of the NAFO Convention (NAFO 2022).

Action 2: Review of and proposal for ToRs related to structural aspects and quantification of uncertainty and risk. Action 2 is related to reference points, uncertainty and risk (Terms of Reference 1b, 1d, 1e and 1f). PA-WG formed two subgroups in January 2022: subgroup 1 to address reference points and risk buffers (Terms of Reference 1b and 1d) and subgroup 2 to address the estimation of uncertainty, risk and data-limited approaches (Terms of Reference 1e and 1f).

This document presents the preliminary results of Subgroup 2 on the estimation of uncertainty, risk and data-limited approaches. Tasks associated with Terms of Reference 1e and 1f are:

- ***Compile information on how uncertainty is calculated and/or risk is considered in the PA frameworks reviewed by SC PA_WG, as well as other relevant sources (e.g., FAO, other jurisdictions). Summarize these findings and highlight the main similarities and difference identifying the pros and cons of the key differences.***
- ***Identify the key methodologies used for the calculation of risk and/or incorporation of uncertainty, including Management Strategy Evaluation (MSE), and evaluate how/when these methods could be used in the revised NAFO PAF as emerging from the above actions, and considering their suitability for a range of data availability conditions (e.g., stocks with limited data and stocks with rich data).***
- ***Based on the results above, propose alternative options to incorporate risk and/or uncertainty within the structure of the emerging NAFO PAF for those stocks where data limitations may prevent the implementation of quantitative approaches to risk and/or uncertainty (e.g., buffers).***

Methods for Estimating Risk

The key methodologies used for the calculation of risk or incorporation of uncertainty, including Management Strategy Evaluation (MSE), were reviewed to consider how these methods could be used in the revised NAFO precautionary framework.

Traditional approaches to evaluating uncertainty and risk are from model estimates of precision (e.g., Smith et al. 1993, Rosenberg and Restrepo 1994, Privitera-Johnson and Punt 2020). These methods of measuring estimation error can be used to evaluate statistical distributions and confidence limits for considering uncertainty in status determination, which can be propagated in stochastic projection for deriving risk-based advice (e.g., Figure 1). Many fisheries management systems apply estimation error or stochastic projection to implement precautionary approaches (see section below on 'Uncertainty and Risk in Other Precautionary Frameworks').

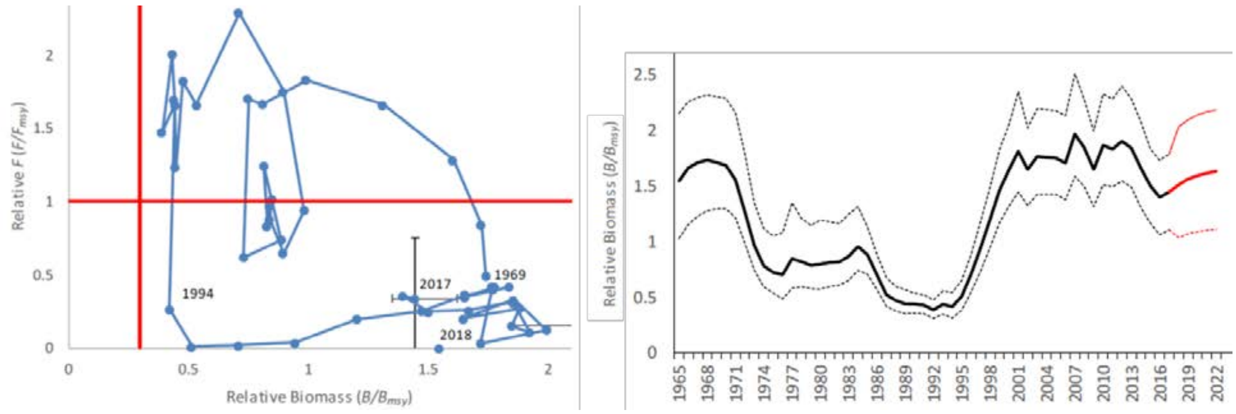

Figure 1. Estimated stock trajectory of yellowtail flounder in NAFO Div. 3LNO from a Bayesian production model, estimates of stock biomass and fishing mortality relative to MSY reference points status with 90% confidence limits for 2017 estimates (left), and stochastic projections assuming status quo fishing mortality (right; from Parsons et al. 2018)

Although stochastic projection is valid for considering estimation error for precautionary advice, the approach implicitly assume that stock assessment models and their assumptions (e.g., natural mortality rate, form of fishery selectivity, stock-recruit relationship) are correct. The precision estimates do not consider sensitivity of status determination or advice to alternative plausible models and assumptions (Ralston et al. 2018, Privitera-Johnson and Punt 2020). This limitation of stochastic projection is demonstrated by retrospective inconsistencies, and updated estimates of stock size or fishing mortality can be outside the confidence interval implied by stochastic projection (Figure 2, ICES 2020b). Stock status and projections can be adjusted for retrospective inconsistency, and management procedures based on retrospective adjustments can perform well for meeting conservation objectives, but often at the expense of foregone yield (e.g., Huynh et al. 2022).

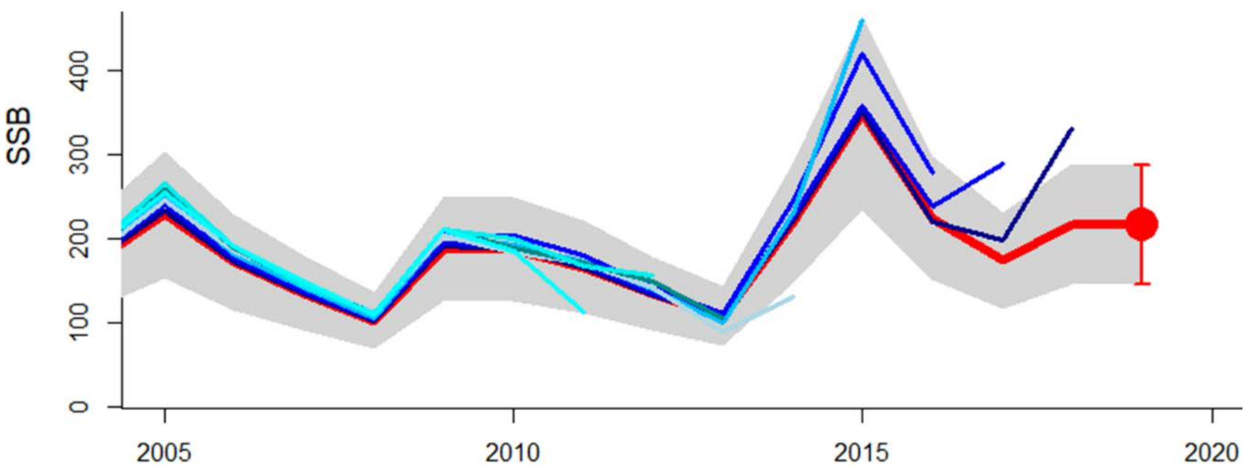

Figure 2. Estimates of North Sea sprat spawning stock biomass (SSB) from the most recent assessment (red) with confidence intervals (grey) and retrospective estimates (shades of blue; from Van Deurs 2020).

Uncertainty in projections can be evaluated by comparing expected values from stochastic projection (e.g., advised catch and fishing mortality, C_{adv} and F_{adv}) with realized catch in the projected year (C_{obs}) and subsequent estimates of F from updated stock assessment for the projected years (F_{obs}; Wiedenmann and Jensen 2017). The F_{adv} is the fishing mortality projected to reach the C_{adv} each year in a short-term projection. Projection error for NAFO stocks with age-structured or surplus production assessment models was derived from annual fishing mortalities and catches compiled since 2014 (Table 1). Advised catch and F, C_{adv} and F_{adv}, were obtained from the NAFO Summary Sheets of each year. The annual F_{obs} and C_{obs} were obtained from stock experts for the last assessment approved by the NAFO Scientific Council.

Table 1. NAFO stocks with age-structured or surplus production assessment models, last approved assessment, assessment periodicity, model and situation of the directed fishery.

Stock	Last Assessment	Periodicity	Assessment Model	Old Assessment Model	Fishery
Cod 3M	2021	1	Bayesian SCCA (2018-2021)	<2018 Bayesian XSA	Open
Redfish 3M	2021	2	XSA		Open
Cod 3NO	2021	3	ADAPT		Moratorium
Yellowtail flounder 3LNO	2021	3	Bayesian Production Model (2018-2021)	<2018 ASPIC	Open
American Plaice 3LNO	2021	3	ADAPT		Moratorium
Witch flounder 3NO	2020	2	Bayesian Production Model (2015-2021)	<2015 Survey trends	Open
Redfish 3LN	2020	2	ASPIC		Open

These advised and updated estimates were used to derive ratios of observed and advised F and catch (Figure 3):

$$Fratio_t = \frac{F_{obs,t}}{F_{adv,t}}$$

$$Cratio_t = \frac{C_{obs,t}}{C_{adv,t}}$$

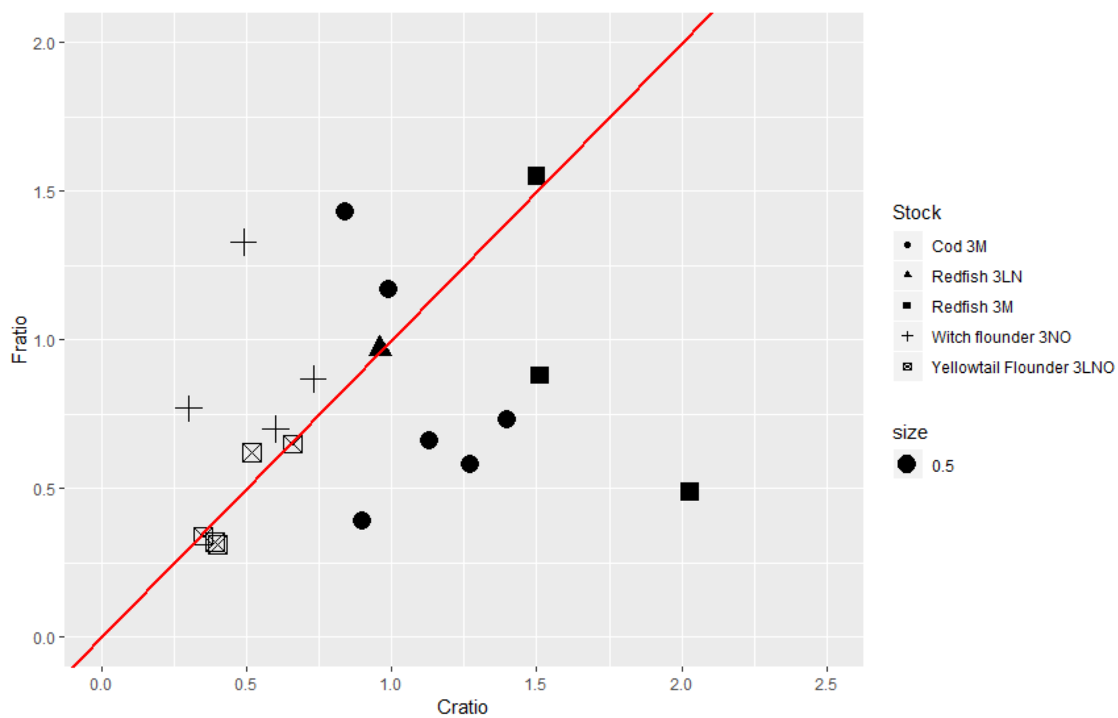

Figure 3. Annual Fratio and Cratio for the NAFO open fishery stocks with age-structured or surplus production assessment models

The projection error is then calculated by adjusting the Fratio for differences between advised catch and realized catch, assuming proportional changes in F in response to changes in catch:

$$Ferror_t = \frac{Fratio_t}{Cratio_t}$$

Values close to 1.0 indicate low scientific uncertainty, because the discrepancies between the observed and target F are largely the result of differences between the realized catch relative to the advised catch. Conversely, values greater than 1 indicate that F was greater than expected, and values less than 1 indicate that F was less than expected by the projections.

Projection error for 3LNO yellowtail (and the one observation for 3LN redfish) were relatively low, and a precautionary uncertainty buffer (e.g., 25%) would have effectively avoided overfishing (Figure 4). By comparison, projection error of 3M cod and 3M redfish was greater, but the frequency of overfishing would still be relatively low. 3NO witch flounder has much greater projection error that would not avoid overfishing, even with conventional uncertainty buffers, because the subsequent estimates of F were greater than the projected F, even after adjusting for realized catch relative to advised catch.

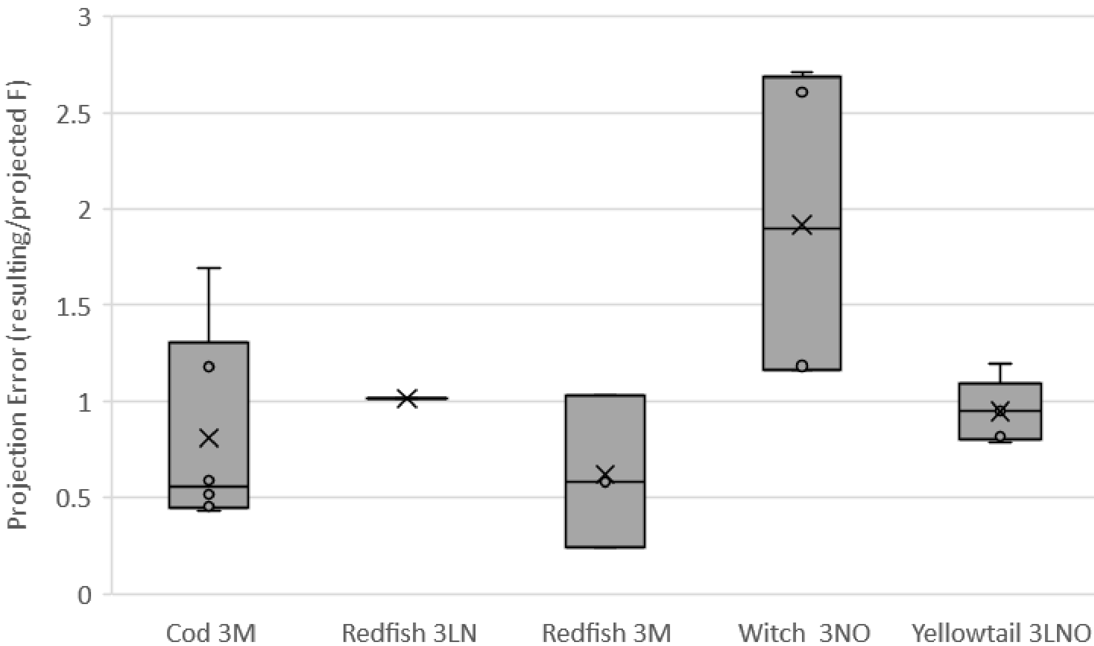

Figure 4. Annual projection errors for the NAFO open fishery stocks with age-structured or surplus production assessment models. Values of 1 indicate low scientific uncertainty, and values deviating from 1 are a measure of scientific uncertainty.

Management Strategy Evaluation (MSE) offers an approach to consider all major sources of uncertainty for risk-based fishery management (Punt et al. 2014) and has been proposed as a valid alternative to meet the needs of the NAFO precautionary approach framework (NAFO 2020). Objectives and performance metrics for evaluating alternative management procedures would need to be consistent with the NAFO Convention. The PA-WG mapping deliverable identified that management procedures would need to achieve a low risk of stock depletion (i.e., $B<B_{lim}$), rebuild stocks to B_{msy}, maintain stocks above B_{msy} more often than not, and maintain approximately MSY in the long-term (PA-WG 2021).

Uncertainty related to assessment model assumptions and sensitivity to alternative plausible models and assumptions can be addressed in MSE by developing multiple plausible operating models. One operating model is usually conditioned on the current stock assessment, with consistent model assumptions and perceptions of stock productivity, but several alternative plausible operating models should also be developed to account for structural uncertainty among plausible models (NAFO 2020). The information typically available for a specific assessment is simulated from the operating model, used to support a candidate management procedure that involves a harvest control rule in which target catch is determined by the results of a stock assessment model or directly from the data. The resulting fishery management action is imposed on the operating model in the next time step of the analysis. The analytical process is iterated to simulate implementation of the management procedure over several years, and results from the operating model are used to derive performance statistics.

NAFO has applied MSE to several stocks. A management strategy was evaluated for Greenland halibut in NAFO Subarea 2+3LMNO in 2010 (Figure 5; Miller et al. 2008, Miller and Shelton 2010) and 2017 (NAFO, 2017). The first management procedure for this stock was approved by the Fisheries Commission in 2010 and was applied to set 2011-2107 TACs (NAFO 2020). In 2017, a new MSE and HCR were tested and approved, and the HCR has been used to establish the TACs from 2018 to the present. In 2014 an MSE for redfish in NAFO Subarea 3LN was tested and approved by NAFO Fisheries Commission (Dauphin et al. 2014, NAFO 2020). These two MSE (Greenland halibut 2+3LMNO and redfish 3LN) are currently under review by the SC. A third MSE was tested to cod in NAFO Division 3M cod. A first component was completed in 2015 (González-Costas et al. 2014) and the second attempt was presented in 2019 but NAFO WG-RBMS could not recommend any of the candidate harvest control rules since the results show that none of the HCRs tested meets the accepted risk levels for SSB being below B_{lim} and F being above F_{lim}. These HCRs need a reformulation and a much deeper study, both in their formulation and the values of the parameters. (NAFO 2015a, 2019a).

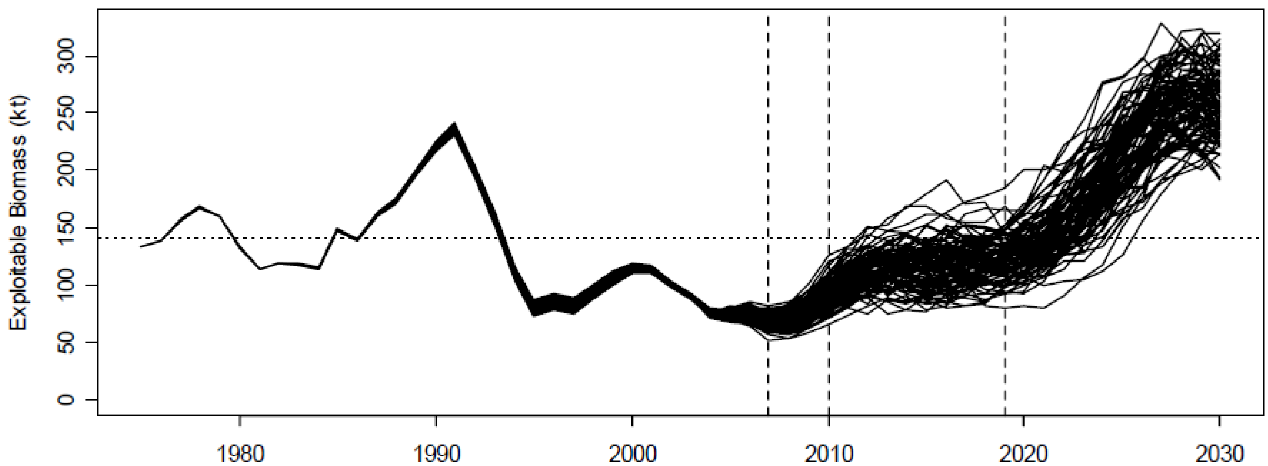

Figure 5. Stock trajectories from individual replicates (n=100) of stochastic simulations of the PA Management Strategy for Greenland halibut (from Miller et al. 2008).

MSE is a rigorous and transparent option for developing precautionary management procedures, providing detailed simulations that can be tailored to a particular species in manner. However, considerable human, technical and informational resources are required to implement MSE for given stock and resources must be committed on an ongoing basis to periodically test or revise the management procedure. Therefore, MSE may not be feasible for all NAFO stocks. There is also some disagreement on the specifics of MSE specifications (e.g. ICES 2020a). PA-WG recommends that the precautionary framework should be implemented using information from stock assessment (e.g., estimation error and stochastic projection), and MSE should be developed for a subset of NAFO managed stocks to test performance of a more general precautionary framework. Development of MSE for this purpose is beyond the scope and schedule of the current PA-WG terms of reference.

Uncertainty and Risk in Other Precautionary Frameworks

Several precautionary approach frameworks were reviewed to compile information on how uncertainty is calculated and how risk is considered. These findings highlight the main similarities, pros and cons, and key differences. Methods to calculate uncertainty include defaults based on expert judgement, stock assessment estimation error, stochastic projection, and MSE. McIlgorm (2013) concluded that 50% probability of achieving a target, and 10% probability of exceeding a limit were international best practice, but risk tolerance varies widely among management systems (Marentette and Kronlund 2020, Marentette et al. 2021b). The current NAFO precautionary approach framework includes specific risk tolerances of 20% probability of $F>F_{lim}$ and 5-10% probability of $B< B_{lim}$ (NAFO 2004), and some of the MSEs tested by NAFO had 30% risk tolerance for $F>F_{msy}$ (e.g., González-Costas et al. 2014).

<u>ICES</u>

The technical basis for ICES advice involves precautionary reference points for fisheries with data-rich stock assessments, with explicit definitions of risk, using estimation error from stock assessment models to measure uncertainty. ICES categorizes stocks according to data availability, utility of stock assessments for advice and magnitude of catch (ICES 2012a):

1. **Data-rich stocks with quantitative assessments**
2. **Stocks with analytical assessments and forecasts that provide qualitative advice**
3. **Stocks for which survey-based assessments indicate trends**
4. **Stocks for which only reliable catch data are available**
5. **Data-poor stocks**
6. **Stocks with negligible landings or minor bycatch**

Precautionary reference points for category-1 and category-2 stocks are based on defining a limit biomass (B_{lim}) from stock-recruitment relationships, a limit fishing mortality (F_{lim}) from stochastic simulation or equilibrium expectations. ICES considers a management plan to be precautionary if management strategy evaluation determines <5% risk of the stock declining below B_{lim} in each and every year of the plan (Marentette and Kronlund 2020).

Precautionary reference points for biomass and fishing mortality are derived from estimation error of spawning stock biomass (SSB) and fishing mortality (F) in the last year of the stock assessment (ICES 2021a, see PA-WG subgroup 1 report):

- **B_{lim} is the stock size below which a stock is considered to have reduced reproductive capacity, estimated from the stock-recruit relationship as the biomass below which recruitment reduces.**
- **$B_{pa} = B_{lim} \times e^{(1.645 \times \sigma)}$, where σ is estimated from the assessment uncertainty in SSB in the terminal year. If σ is unknown, $B_{pa} = B_{lim} \times 1.4$ (assuming $\sigma = 0.2$).**
- **F_{lim} is derived from B_{lim}. The preferred method derived F_{lim} as the fishing mortality that has a 50% probability of long-term SSB>B_{lim}, assuming a segmented regression stock-recruit relationship in which the point of inflection is B_{lim}. As an alternative method, F_{lim} is derived as F_{SPR} from spawner-per-recruit analysis that provides replacement for R/SSB at B_{lim} (Figure 6)**
- **F_{pa} is the fishing mortality that has 5% probability of SSB<B_{lim} (also known as F_{p05}).**

The definitions of B_{pa} and F_{pa} are explicitly based on a 5% risk tolerance for F>F_{lim} or B<B_{lim}. These probabilities are derived from long-term stochastic projection.

For data-limited fisheries, ICES advice is based on MSY proxies, but advice is not based on precaution, uncertainty or risk (ICES 2018, see section on 'data-limited approaches' below). For short-lived species, B_{lim} is derived as above, but B_{pa} may not be defined and stock status can be based on the distribution of SSB relative to B_{lim}. (ICES 2021a). ICES does not use F reference points to determine exploitation status for short-lived species.

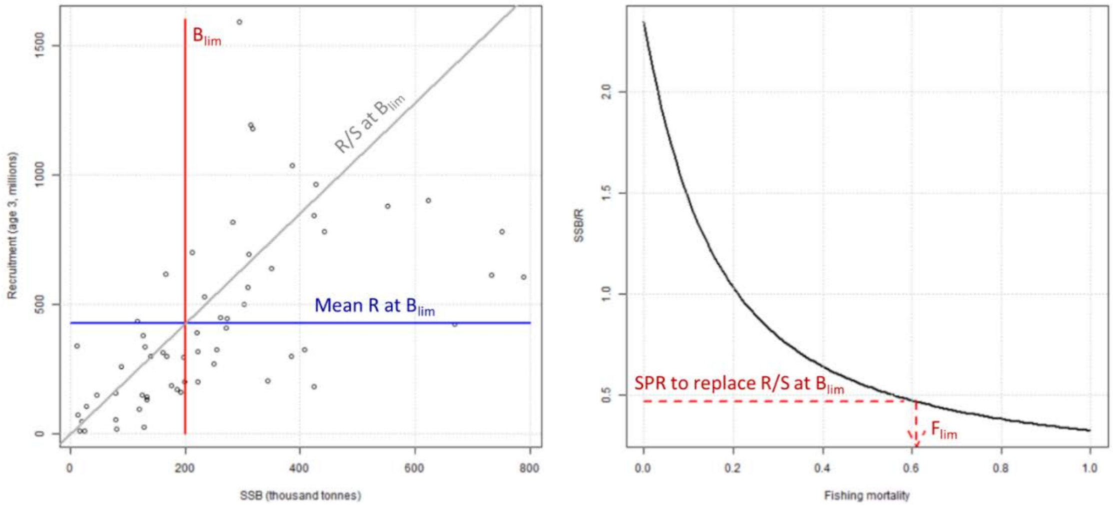

Figure 6. Example stock–recruitment relationship (left), with B_{lim} (red line), mean recruitment at B_{lim} (blue line), and R/S at B_{lim} (gray line); and spawner-per-recruit as a function of fishing mortality (right), with SPR that would replace R/S at B_{lim} and associated F_{lim} (dashed red line, from ICES 2017).

Tuna Regional Fishery Management Organizations

The first global summit of the five tuna RFMOs (Regional Fisheries Management Organizations) developed standards for status determination, science-based management decisions, and application of the precautionary approach (tRFMOs 2007), and the standards have been refined (tRFMOs 2009, 2011) and implemented to various extents among organizations (DeBruyn et al. 2013, Merino et al. 2020, Ogwa et al. 2021). Stock status is deterministic, based on stock biomass relative to B_{msy} and fishing mortality relative to F_{msy} (or proxy reference points, e.g., B_0; Sharma 2022), and catch limits are evaluated based on the probability of exceeding F_{msy} and the probability of maintaining or rebuilding to B_{msy} over various time frames based on stochastic projection (Figure 7; tRFMOs 2009, DeBruyn et al. 2013). Specific risk tolerance varies among organizations, stocks, and specific TAC decisions. Tuna RFMOs have also promoted MSE and implemented management procedures based on MSE (tRFMOs 2018).

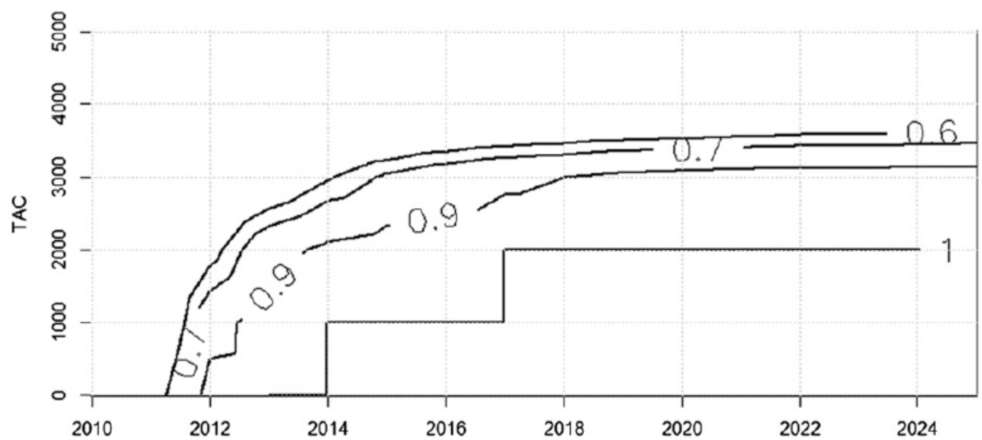

Figure 7. Probabilities of a tuna stock being greater than B_{msy} while being fished at $F<F_{msy}$, for specific TACs. Isopleths show the probability of $B> B_{msy}$ for a given year and TAC (e.g., all values above the 0.6 isopleth will have <60% chance of $B> B_{msy}$; from DeBruyn et al. 2013).

Canada

Canada's *Fisheries Act* was revised in 2019, and technical guidelines are being developed to support Canadian Precautionary Approach Policy (Marentette et al. 2021a, 2021b, ICES 2022). The guidelines stipulate that uncertainty should be considered for stock status determination and reference points. Default policy guidance is for an upper stock reference point to control the risk of approaching limit reference point. Risk aversion can be incorporated into risk-based harvest control rules (Marentette et al. 2021a). There are no prescriptive risk tolerances, but the policy suggests that the acceptable risk of exceeding a limit is 5-25% (Marentette et al. 2021b).

US

The fishery management system considers uncertainty and risk in the implementation of annual catch limits, in which acceptable catch has a low probability of $F>F_{msy}$ based on stochastic projection or proxies (Methot 2022). Risk tolerance (defined as P*, Prager and Shertzer 2010) is defined in acceptable catch control rules and varies among fisheries. For example, P*=0.25 for Atlantic scallop, P* ranges from 0.1 to 0.45 as a function of stock assessment quality and stock size for Mid Atlantic fisheries (Witherell 2010). For fisheries with unreliable projections, acceptable catch is based on default uncertainty buffers (e.g., 75%F_{msy} for New England groundfish; Witherell 2010). Risk policies vary among fisheries and regional fishery management councils, several consider a wider array of risks beyond probability of $F>F_{msy}$ and are being tested with MSE (e.g., Dorn and Zader 2020).

Australia

The Australian Fisheries Management Act has the explicit objective of maximizing economic efficiency, which is implemented by a fishing mortality target based on maximum economic yield, MEY (Dichmont et al. 2010). Stock status is based on B_{MEY} (defined as 1.2 B_{msy}) and B_{lim} (defined as 0.5 B_{msy} or 0.2 B_0). The Management should maintain $B>B_{lim}$ at least 90% of the time (Haddon 2016). Therefore, risk tolerance for $B<B_{lim}$ is 10% or less (e.g., once in a 10-year period; Marentette et al. 2021b).

New Zealand

The harvest strategy standard for New Zealand fisheries is based on specific risk tolerance for achieving the targets and not breaching limits (ICES 2022). Stock status is based a target of B_{msy}, a 'soft limit' threshold (the greater of 0.5 B_{msy} or 0.2 B_0) at which rebuilding plans are triggered, and a hard limit (the greater of 0.2 B_{msy} or 0.1 B_0) at which closures may be considered, and >50% probability that the stock estimate is greater than the reference point. MSE is used to test harvest control rules to confirm that the probability of maintaining $B> B_{msy}$ is at least 50%, the probability of biomass being depleted to the 'soft' biomass threshold does not exceed 10%, and the probability of biomass being depleted to the 'hard' biomass limit does not exceed 2%.

Data-Limited Approaches

Data-limited stock assessments cannot support some elements of a risk-based precautionary framework, but several fisheries management systems have developed data-limited approaches to quantitative catch advice. MSE is being applied to the development of empirical management procedures to meet management objectives and desired risk tolerance (Carruthers et al. 2014, Geromont and Butterworth 2014). Several initiatives to provide quantitative advice for data-limited stocks have promoted the development of alternative approaches that do not require information from conventional stock assessment (e.g., Newman et al. 2015, ICES 2020).

ICES

In response to a European Commission mandate for quantitative catch advice for all fisheries, ICES expanded the scope of its advice and conducted data-limited assessments, increasing the number of stocks assessed from 78 to 146 in 2012 (ICES 2012c) and now provides advice on more than 260 stocks (ICES 2017, 2021b). Precautionary reference points for the relatively data-rich stocks and assessments (categories 1 and 2) are based on stock-recruitment relationships and stochastic projections (see above). For data-limited stocks (categories 3 and 4), four methods are used to calculate MSY reference points (length-based indicators, mean length mortality estimates, length-based spawner per recruit, or production models), but advice is not based on precaution, uncertainty, or risk (ICES 2018).

Length-Based Indicators

The mean length indicator used within ICES is mean length of fish (L_{mean}) but a few others are also defined, e.g. $L_{95\%}$, $L_{25\%}$, L_{maxy} (length with maximum biomass in the catch), $L_{max5\%}$ (mean length of largest 5% fish). L_{mean} and L_{maxy} are used as indicators in relation to MSY and optimal yield; others are used as conservation indicators.

For each indicator a reference point has been defined, e.g. as F_{msy} proxy for L_{mean} mean length at fishing mortality equal to natural mortality ($L_{F=M}$) is used. It is approximated as

$$L_{F=M} = 0.75L_c + 0.25L_{inf} \quad (1)$$

where L_c and L_{inf} are length at first capture (50% selectivity) and asymptotic length, respectively.

Mean length (L_{mean}) values lower than $L_{F=M}$ indicate overfishing with respect to F_{msy}. In practice, to evaluate stock status the ratio $L_{mean}/L_{F=M}$ is used (ratio<1 means overfishing). There are a few strong assumptions made when deriving this indicator:

- **Natural mortality is good proxy for F_{msy}**
- **Recruitment and fishing mortality have been constant**
- **Selectivity follows a logistic curve**
- **The M/K ratio equals 1.5.**

Indicator (1) may be extended to more general form as

$$L_{F=aM,K=bM} = \frac{bL_{inf}+L_c(a+1)}{a+b+1} \quad (2)$$

where a, b are positive parameters (Jardim et al., 2015). This form allows for setting F_{msy} proxy at some product of M and the M/K ratio is not constrained by 1.5. However, that form of indicator has seldom been used by ICES.

The use of indicator (1) should be applied with caution as M is in general not good proxy for F_{msy}. F_{msy} is often lower than M as indicated by Patterson (1992), Thompson (1993), Mace (1994), Walters & Martell (2002) or Zhou et al. (2012). Similarly, Horbowy & Hommik (2022) showed that for low steepness values (up to 0.6) the F_{msy} may be markedly lower than M.

For reasonable comparison of mean length with its reference points assumptions of constant (or modest, random variability) recruitment has been made, so the LBI may be applied to stock which fulfil such assumptions (ICES, 2018, Guidelines for stocks categories 3-4). Another problem is that contrast between length-based indicators for unfished stocks and stocks near limit or trigger reference points may be low (Cope & Punt, 2009; Horbowy & Hommik, 2022). Punt et al. (2001) examined mean length as an indicator of the stock status of broadbill swordfish off eastern Australia and found that there was no direct relationship between decreases observed in indicators and changes in biomass.

Another reference point for mean length accepted in ICES is L_{opt} but it has rarely been used. L_{opt} is defined as length for which cohort gets maximum biomass at no exploitation (Cope & Punt, 2009; ICES, 2012b) and is approximated as $2/3L_{inf}$ for M/K=1.5.

Horbowy & Hommik (2022) developed length-based reference point for F_{msy} as mean length in the catch estimated at F_{msy} at equilibrium (L_{msy}). L_{msy} was linearly related to life history traits (M, K, t0, age at 50% and 95% maturity, age at 50% and 95% selectivity) including steepness. In addition, it appeared that linear model without steepness also may approximate L_{msy} (96% of L_{msy} variance was explained) and the difference between L_{msy} estimates from both models was mostly within +/-10%, so the estimate of L_{msy} from without steepness model could be used in data-limited situations. However, Horbowy & Hommik (2022) found that sensitivity of mean length to changes in fishing mortality was relatively low (especially for species with a high growth rate) and it could be relatively high probability (20-40%) that mean length at fishing mortality 20% higher than F_{msy} was higher than L_{msy}, so the stock could be incorrectly evaluated in relation to F_{msy} (L_{msy}).

Above findings suggest that the use of mean length as an indicator of state of stock should be done with caution. The current mean length is an effect of usually variable recruitment and exploitation in several previous years. For stocks with strong changes in recruitment, e.g., when a strong year class is followed by a sequence of a few week or average year classes, the recruitment effect on mean length will be high. In such a case, it may be difficult to distinguish the mean length effects of high fishing mortality and year class strength.

Mean Length Mortality Estimates

A Length based estimator for total mortality is:

$$Z = \frac{K(L_{inf} - L_{mean})}{L_{mean} - L_c} \qquad (3)$$

where L_c is length of full capture, and L_{mean} is mean length (Beverton & Holt, 1957). It may be used to evaluate current F (as Z-M) in relation to reference fishing mortality resulting from SPiCT or LBSPR. However, the estimator assumes equilibrium conditions, including constant total mortality, which is not often the case for real fisheries. Gedamke & Hoening (2006) extended Beverton & Holt estimator to cover situations when Z changes from one level to another. They modelled transition of mean length from one equilibrium period with given Z to the next, characterised by another total mortality. Gedamke & Hoening also generalised the method to cover multiple periods with different (but constant within period) Z. The method was further extended by Then et al. (2018). They included fishing effort (f) into the model, and modelled Z as qf+M, which coupled with series of yearly mean lengths enabled to estimate natural mortality, catchability (q), and next fishing mortality in years covered by fishing effort.

Length-Based Spawner per Recruit

Length based spawner per recruit (LBSPR) or spawning potential ratio (SPR) (Hordyk et al., 2015) enables estimation of F_{msy} proxy and/or F_{lim} proxy on the basis of length distribution in the exploited population, given M/K ratio, L_{inf} and CV of L_{inf}. F_{msy} proxy is given usually as fishing mortality which reduces length-based SPR to 30-40%; the F_{lim} proxy may be assumed as F producing SPR at 20% or lower. The method assumes equilibrium conditions and has been seldom used to evaluate stock status in ICES advice. An example of its use is advice for cod in Subarea 2 between 62°N and 67°N (Norwegian Sea), southern Norwegian coastal cod.

Production Modeling

SPiCT is stock-production model formulated as a state-space model with random-effects (includes process error and fishing mortality is treated as random walk), based on Pella and Tomlinson biomass equation (Pedersen and Berg, 2017). It uses catch/landings data and indices of stock size (survey or commercial). The model provides absolute estimates of stock size, fishing mortality and MSY parameters (B_{msy}, F_{msy} and MSY itself), all with 95% confidence intervals. In ICES for data-limited stocks SPiCT estimates are often presented in relative terms, i.e. B/ B_{msy} and F/F_{msy}, as such ratios are believed to have lower uncertainty than absolute estimates. The model may be also used for catch and biomass predictions under specified fishing mortality scenarios.

Sparholt et al. (2021) fit SPiCT to about 50 data-rich stocks in Northeast Atlantic and estimated F_{msy} claiming that such F_{msy} is more relevant than the one estimated in standard ICES procedure as production models take density dependent effects into account while standard ICES approach considers only density dependence in recruitment. Estimated F_{msy} were on average higher than the ICES estimates.

<u>US</u>

In 2006, the US Fishery Conservation and Management Act required annual catch limits for all stocks so that overfishing would not occur. For data-rich stocks, catch limits are based on low risk of F>F_{MSY} (see above), but data-limited stock assessments cannot support the estimation of reference points or reliable stochastic projection. Therefore, alternative methods are needed for data-limited stocks (Sabater and Dalzell 2016). Data-moderate stock assessments can support MSY proxies (e.g., F_{SPR}, $F_{0.1}$), default uncertainty buffers (e.g., 75% F_{MSY}, Restrepo et al. 1998), and empirical targets (e.g., average exploitation ratios, catch/survey). Many more assessments could not provide reliable catch projections. Only 30% of 2015 catch limits were based on data rich assessments, 11% were based on data-moderate approaches, and the remaining 59% of US catch limits were based on data-limited methods (Newman et al. 2015). Data-poor approaches include depletion-based stock-reduction analysis (Dick and MacCall 2011) and Depletion-corrected average catch (MacCall 2009). Recent recommendations are to test data-limited methods with MSE to confirm that they achieve management objectives (e.g., low frequency of F>F_{MSY} or B<0.5 B_{msy}; DeVore and Gilden 2019).

Australia

The number of assessed Australian stocks has substantially increased since 2014 from the development of data-limited approaches. Methods include the 'Robin Hood' approach (i.e., Bayesian priors from data-rich stocks) and managing multispecies groups according to assessments of data-rich species in the group (Smith et al., 2009). More recently, performance of data-poor assessment methods has been tested with MSE (Haddon 2016).

New Zealand

The number of New Zealand stocks with an estimated overfishing threshold also substantially increased by developing data-limited approaches that include catch-only methods, length-based estimators, non-parametric or time-series models, swept-area methods, and deterministic production models (Edwards 2015).

Options for Considering Risk in the NAFO Precautionary Framework

The NAFO precautionary framework should be implemented using information from stock assessment (e.g., estimation error and stochastic projection), and MSE should be developed for a subset of NAFO managed stocks to test performance of a more general precautionary framework. Development of MSE for this purpose is beyond the scope and schedule of the current PA-WG terms of reference.

The risk tolerances specified in the current NAFO precautionary approach framework (20% probability of $F > F_{lim}$, 5-10% probability of $B < B_{lim}$) and applied in MSE of NAFO stocks (e.g., 30% probability of $F > F_{MSY}$ in the MSE for 3M cod) are generally consistent with other precautionary approach systems in which risk tolerance varies in association to the reference point it is associated with (e.g., lower risk of irreversible harm than suboptimal outcomes). However, extreme probabilities (e.g., 5%, 95%) are relatively difficult to estimate, and are more moderate probabilities (e.g., 10%, 90%) are commonly applied in stock assessment. The Joint Commission-Scientific Council Working Group on Risk-Based Management Strategies would be the appropriate group to confirm or revise these risk tolerances. If low risk tolerances are

Data-limited stock assessments cannot support the information needed for precautionary status determination or catch advice, but data-limited management procedures can be evaluated to quantify risk for meeting management objectives using MSE.

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