Northwest Atlantic Fisheries Organization

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Achieving NAFO Convention Objectives with a Precautionary Approach Framework

Precautionary Approach Working Group (PA-WG)

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Summary

The Precautionary Approach Working Group (PA-WG) developed recommendations for designing a Precautionary Approach Framework that is expected to meet the objectives of the NAFO Convention. The objectives and general principles of the NAFO Convention can be achieved by a Precautionary Approach Framework in addition to other NAFO processes to minimize bycatch, catch by lost/abandoned gear, pollution and waste from fishing. The PA-WG recommends that the Precautionary Approach Framework should: 1) promote rebuilding of depleted stocks toward the stock biomass associated with maximum sustainable yield (B_{MSY}), 2) account for scientific uncertainty through buffer reference points or other risk-based approaches, 3) develop limit reference points for stock biomass (B_{lim}) and fishing mortality (F_{lim}) that are consistent with each other, 4) B_{lim} should be based on sustainability and reduced productivity where possible, and 5) reference points should be re-evaluated when the available information on productivity substantially changes, there is evidence of a productivity regime shift, or management procedures based on re-evaluated reference points are demonstrated to perform better for meeting NAFO's objectives. All options considered for a revised Precautionary Approach Framework should be simulation tested to determine if management measures set in accordance with the framework are expected to achieve the following objectives: a very low risk of stock depletion (i.e., $B<B_{lim}$), effectively rebuild stocks to B_{MSY}, maintain stocks above B_{MSY} more often than not, and maintain average catches of approximately MSY in the long-term.

Background

In 2015, the NAFO Commission requested the Scientific Council to review the current NAFO Precautionary Approach Framework (PAF; NAFO 2004) and established the Terms of Reference for the review (NAFO 2015). Term of Reference 1 is to clarify the following elements (bold items relevant to mapping deliverable):

a) To confirm/review the NAFO PAF reference points definition on page 3 of NAFO/FC Doc. 04-18 (NAFO 2004).
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.

The mapping deliverable presented in this report involves items ToR 1 a), c), and g) to present conceptual questions that address how the framework can represent NAFO Convention objectives (NAFO 2017). Action 1 of the Precautionary Approach Framework revision is to review ToR 1 items related to mapping objectives, specifically:

i. Compile information on the use of MSY as limit/target in the Precautionary Approach frameworks reviewed by SC PA-WG, as well as other relevant sources (e.g., FAO, other jurisdictions) and summarize these findings identifying the pros and cons of the two conceptual roles (e.g., as a limit or a target) of MSY. The possibility of applying a "weight of evidence" approach (Tao et al 2018), to tabulate the arguments for and against alternative options, should be considered.
ii. Examine how different Precautionary Approach frameworks address (or not) changes in stock/ecosystem productivity over time, focused on long term changes/productivity regimes, and summarize these findings identifying the pros and cons of the different approaches.
iii. Based on the results from the examination above, consider the definitions used in the existing NAFO Precautionary Approach Framework, highlight potential contradictions or inconsistencies, and propose alternative definitions that could address them.
iv. Other relevant matters that may be identified in the process of conducting this work.

In September 2020, the NAFO Commission approved a schedule for conducting the Precautionary Approach Framework review (NAFO 2020b). PA-WG members (Appendix A) met by correspondence in 2021 (26 February, 8 April, 14 May, and 17 August) and presented preliminary recommendations to the NAFO Scientific Council (4 June and 23 September) and the Joint Commission-Scientific Council Working Group on Risk-Based Management Strategies, WG-RBMS (25 August).

Objectives and Principles of the NAFO Convention

The PA-WG reviewed the current Precautionary Approach Framework, identified alternatives that are expected to meet the Objective of the NAFO Convention and its General Principles (NAFO 2017):

Article II – Objective - The objective of this Convention is to ensure the long term conservation and sustainable use of the fishery resources in the Convention Area and, in so doing, to safeguard the marine ecosystems in which these resources are found.

Article III – General Principles - In giving effect to the objective of this Convention, Contracting Parties individually or collectively, as appropriate, shall:

a) promote the optimum utilization and long-term sustainability of fishery resources;
b) adopt measures based on the best scientific advice available to ensure that fishery resources are maintained at or restored to levels capable of producing maximum sustainable yield;
c) apply the precautionary approach in accordance with Article 6 of the 1995 Agreement;
d) take due account of the impact of fishing activities on other species and marine ecosystems and in doing so, adopt measures to minimize harmful impact on living resources and marine ecosystems;
e) take due account of the need to preserve marine biological diversity;
f) prevent or eliminate overfishing and excess fishing capacity, and ensure that levels of fishing effort do not exceed those commensurate with the sustainable use of the fishery resources;
g) ensure that complete and accurate data concerning fishing activities within the Convention Area are collected and shared among them in a timely manner;
h) ensure effective compliance with management measures and that sanctions for any infringements are adequate in severity; and
i) *take due account of the need to minimize pollution and waste originating from fishing vessels as well as minimize discards, catch by lost or abandoned gear, catch of species not subject to a directed fishery and impacts on associated or dependent species, in particular endangered species.*

The NAFO Convention includes three general goals: 1) long-term conservation of the fishery resources, 2) sustainable use of these fishery resources, and 3) safeguarding of the ecosystem in the area. A Precautionary Approach Framework for meeting these objectives needs to limit fisheries to sustainable catch. Unfortunately, the term sustainability is commonly misinterpreted and needs to be precisely defined by population dynamics for determining appropriate limit reference points. Sustainable fisheries harvest within biological limits, and those limits are defined by the fishing mortality expected to cause stock collapse and recruitment failure in the long term (ICES 2000). Maximum sustainable yield (MSY) is expected to be produced at intermediate fishing mortality rates (F_{MSY}) and intermediate stock sizes (B_{MSY}; Figure 1). Contrary to common misperceptions, there are wide ranges of stock sizes less than B_{MSY} and fishing mortalities greater than F_{MSY} that are sustainable (Punt 2000) as evidenced by many long-term fishing histories. Therefore, the determination by FAO (2020) '*when abundance falls below the MSY level, the stock is considered biologically unsustainable*' is technically incorrect. For mapping elements of the Precautionary Approach Framework to the Objective of NAFO Convention, sustainability was defined as harvesting at a rate that is less than the fishing mortality expected to cause stock collapse.

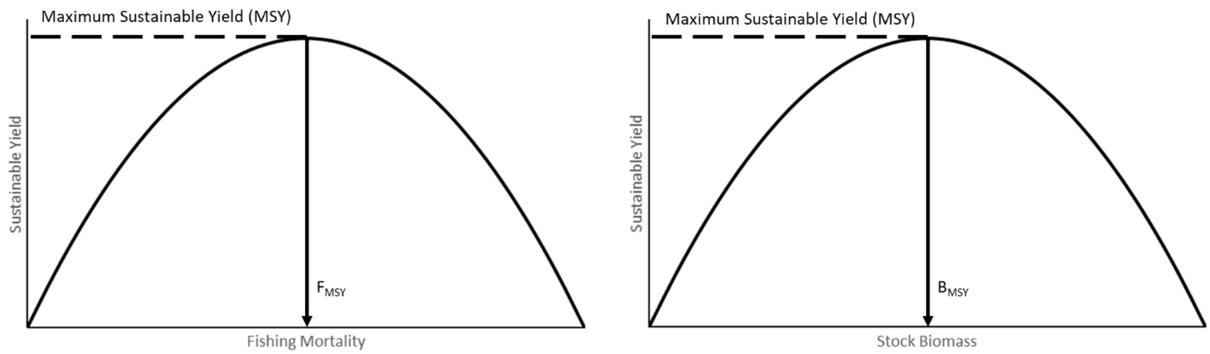

Figure 1. Sustainable yield as a logistic function of fishing mortality and stock biomass, showing the expectation of maximum sustainable yield (MSY) at intermediate fishing mortality (F_{MSY}) and intermediate stock size (B_{MSY}) as well as a range of sustainable fishing mortality rates greater than F_{MSY} and stock sizes less than B_{MSY}. Note that alternative production functions have the same general properties.

The first principle of the convention (a. optimum utilization and long-term sustainability of fishery resources) involves an intermediate trade-off between conservation and utilization. Extreme conservation (i.e., no fishing) or extreme utilization (i.e., unsustainable fishing) do not achieve the balance that is required by the first principle. The second principle (b. maintain fishery resources at levels capable of producing maximum sustainable yield) requires conserving stocks at approximately B_{MSY} and rebuilding depleted stocks to B_{MSY}. However, it may not be possible to maintain all stocks near B_{MSY} at all times with high probability. The Precautionary Approach Framework will be implemented to manage fishing mortality, but stock size is also determined by recent recruitment, natural mortality and ecosystem conditions. Therefore, the framework should be intended to maintain stocks above B_{MSY} more often than not, which implies that fishing mortality should be less than F_{MSY} more often than not.

The third principle (c. a precautionary approach) involves the consideration of uncertainty and refers to Article 6 of UN (1995). However, the specific requirements of UN (1995) have been interpreted differently among international fishery management organizations.

- UN (1995) Article 6: "*Account for uncertainties relating to the size and productivity of the stocks, reference points, stock condition in relation to such reference points, levels and distribution of fishing mortality and the impact of fishing activities on non-target and associated or dependent species, as well as existing and predicted oceanic, environmental and socio-economic conditions*…" This provision has been used to justify fishing mortality targets that are greater than or less than F_{MSY} under different conditions. For example, short-term fishing mortality targets could be greater than F_{MSY} to reduce the socio-economic impacts of a longer-term strategy to reduce fleet capacity. Fishing mortality targets could also be greater than or less than F_{MSY} to account for species interactions (e.g., less fishing on forage fish to promote recovery of predators).

The NAFO convention specifically refers to Article 6, but other sections of UN (1995) provide further guidance on a precautionary approach:

- UN (1995) Annex II.2: "*Limit reference points constrain harvesting within safe biological limits within which the stocks can produce maximum sustainable yield*." This implies that limit reference points for fishing mortality should be based on sustainable limits, which are often greater than F_{MSY}.
- UN (1995) Annex II.7: "*The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points*." This implies that F_{MSY} is a limit reference point.
- UN (1995) Annex II.7: "For overfished stocks, the biomass which would produce maximum sustainable yield can serve as a rebuilding target." This implies that B_{MSY} can be a target reference point for rebuilding. Some fishery management systems define a biomass reference point to determine an overfished stock, and others define a biomass limit reference point (B_{lim}) that is associated with low productivity and sustainability limits, which should be avoided.

NAFO (2004) stated that F_{lim}<=F_{MSY} is a requirement of the Convention, but the Joint Fisheries Commission-Scientific Council Working Group on Risk-Based Management Strategies (WG-RBMS) subsequently concluded that the NAFO Convention does not necessarily prescribe F_{MSY} as a limit (NAFO 2015a), and there are other valid interpretations. An objective of a Precautionary Approach framework should be maintaining low probability of depleting stocks to less than B_{lim} (a stock size associated with low productivity and sustainability limits). Therefore, F_{lim} can be defined as the fishing mortality associated with B_{lim} and a precautionary reference point can be the fishing mortality associated with very low probability of $B<B_{lim}$.

General principle (f) specifies that overfishing should be prevented with respect to sustainable use, but there is a wide range of fishing mortalities greater than F_{MSY} that are sustainable (i.e., are expected to maintain the stock over the long-term). 'Overfishing' is often defined as fishing mortality greater than F_{MSY}, but according to general principle (f), NAFO could define overfishing as the fishing mortality expected to expected to cause stock collapse and recruitment failure in the long term (ICES 2000, Punt 2000).

Some precautionary approach frameworks implement the requirement for avoiding overfishing by limiting fishing to the annual catch associated with F_{MSY} , defined as the fishing mortality expected to produce maximum long-term average yield (Methot et al. 2014, Garcia and Rice 2020), but MSY can also be sustained in some circumstances even when fishing mortality occasionally exceeds F_{MSY} for a brief period. In other circumstances, such as low productivity conditions, fishing at F_{MSY} may deplete a stock to below B_{lim} (FAO 1996), and catch advice based on an acceptable probability of avoiding B_{lim} in the short-term can be less than catch advice based on F_{MSY} (ICES 2020).

In addition to sustainable fishing for target species, the objective and general principles of the NAFO Convention require the management of sustainable impacts on non-target species (e.g., minimize bycatch, protect endangered species, mitigate mortality from discarded fishing gear), habitat conservation, and limited pollution. Other processes are being developed by to implement a broader ecosystem approach to fishery management (NAFO 2011, 2012, 2019; Koen-Alonso et al. 2019), so the objective of PA-WG is to focus on a single species framework while considering its alignment with the broader ecosystem approach and building possible linkages. For example, the influence of environmental variables and species interactions can be considered for single species reference points. At a minimum, the Precautionary Approach Framework should be compatible with the NAFO Roadmap for an Ecosystem Approach to Fisheries (Koen-Alonso et al. 2019). Similarly, principles (g), (h) and (i) are more relevant to the NAFO Fisheries Commission, but the Precautionary Approach Framework can be compatible with broader management procedures.

Recognizing that there are valid alternative interpretations of the NAFO objectives and principles, and various implementations of a precautionary approach have been successful in other fishery management organizations, simulation testing can determine which options perform well for NAFO stocks. For example, stock-specific Management Strategy Evaluation may be the most effective way to determine the most appropriate options for achieving the NAFO objective and principles through a Precautionary Approach Framework.

Reference Points (ToR 1.a)

NAFO (2004) defines reference points needed for the PA framework (Figure 2):

- *F_{lim} = A fishing mortality rate that should only have a low probability of being exceeded. F_{lim} cannot be greater than FMSY. If FMSY cannot be estimated, then an appropriate surrogate may be used instead.*
- *F_{buf} = A fishing mortality rate below F_{lim} that is required in the absence of analyses of the probability that current or projected fishing mortality exceeds F_{lim}. In the absence of such analyses, F_{buf} should be specified by managers and should satisfy the requirement that there is a low probability that any fishing mortality rate estimated to be below F_{buf} will actually be above F_{lim}. The more uncertain the stock assessment, the greater the buffer zone should be. In all cases, a buffer is required to signify the need for more restrictive measures.*
- *B_{lim} = A biomass level, below which stock productivity is likely to be seriously impaired, that should have a very low probability of being violated.*
- *B_{buf} = A stock biomass level above B_{lim} that is required in the absence of analyses of the probability that current or projected biomass is below B_{lim}. In the absence of such analyses, B_{buf} should be specified by managers and should satisfy the requirement that there is a very low probability that any biomass estimated to be above B_{buf} will actually be below B_{lim}. The more uncertain the stock assessment, the greater the buffer zone should be. In all cases, a buffer is required to signify the need for more restrictive measures.*

According to the PA framework, when the stock is above B_{buf} and fishing mortality is below F_{buf}, a flexible fishing mortality rate will be selected by managers to achieve desired management objectives, subject only to the constraints defined by the limit and buffer reference points. In particular, a target F should be chosen to ensure that there is a low probability that F exceeds F_{lim}, and a very low probability that biomass will decline below B_{lim} within the foreseeable future (e.g., 5-10 years, to be specified by managers). 'Low probability' is approximately 20%, to be specified by managers. 'Very low probability' is approximately 5-10%, to be specified by managers.

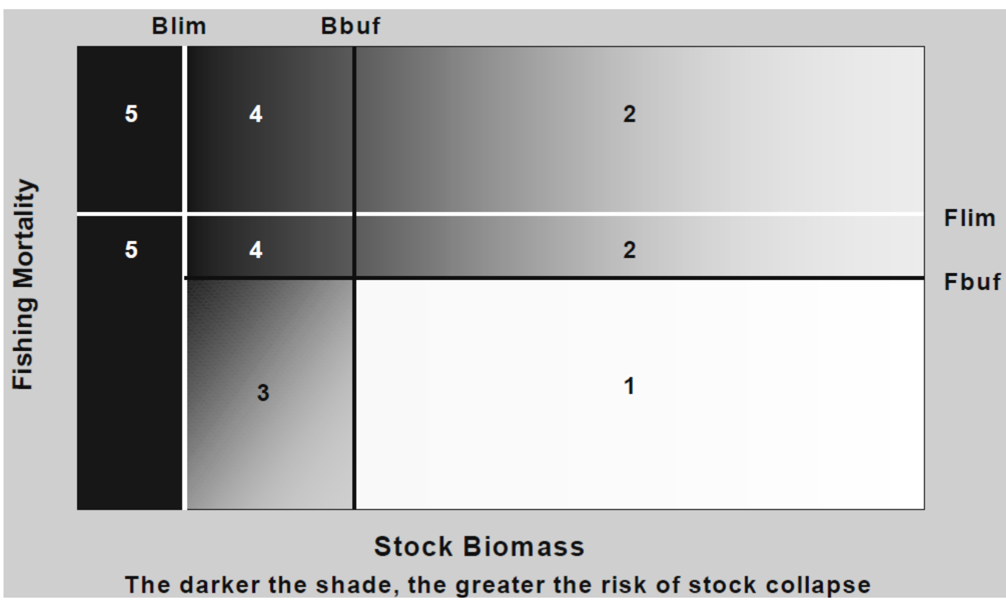

Figure 2. Schematic NAFO Precautionary Approach Framework defining status zones and prescriptive fishery management (from NAFO 2004). In the safe zone (1), fishing mortality should have low probability of exceeding F_{lim}. In the Overfishing Zone (2), fishing mortality should be reduced to below F_{buf}. In the Cautionary F Zone (3), fishing mortality should be less than F_{buf} to ensure very low probability that biomass will decline below B_{lim} in the foreseeable future. In the Danger Zone (4), fishing mortality should be reduced to below F_{buf} to ensure very low probability that biomass will decline below B_{lim} within the foreseeable future. In the Collapse Zone (5), fishing mortality should be set as close to zero as possible.

PA-WG confirms that the precautionary approach should include limit reference points for fishing mortality and stock biomass, and either buffer reference points or other risk-based management procedures to achieve sustainability and optimum yield in the context of uncertainty. However, there are valid alternative options for defining F_{lim} (e.g., either F_{MSY} or the F associated with B_{lim}). There are also valid alternative options for defining B_{lim} (e.g., inflection point of segmented stock-recruit relationship, O'Brien et al. 2003; B_{loss}, lowest observed stock size that the stock has recovered from, Cook 1998; 0.3 B_0, Sainsbury 2008).

Risk tolerance is represented most directly by stochastic buffers (i.e., those associated with a probability of exceeding a limit reference point) but proxy targets (e.g., 75% F_{lim}, Restrepo et al. 1998) can also account for uncertainty if stochastic estimates are not available. Uncertainty in stock assessment (e.g., estimates of current or projected stock size) as well as uncertainty in reference point estimates should be considered in the Precautionary Approach Framework. The nominal uncertainty estimated by many stock assessments are conditional on model assumptions and do not include structural uncertainties, so uncertainty is typically underestimated. The performance of management procedures that involve limit and buffer reference points can be tested with Management Strategy Evaluations that include structural uncertainty using multiple plausible operating models, process error, observation error and implementation error for a more comprehensive consideration of uncertainty.

Distinction of MSY, Limit, and Target Reference Points (ToR1.c)

In the context of uncertainty and natural variability, maximum sustainable yield can be approximately achieved by a variety of alternative management procedures, including multiple options that define limit and target reference points differently. The UN Straddling Stocks Agreement (UN 1995) has been interpreted in various ways to justify F_{MSY} as a limit or a target reference point. The NAFO Convention does not necessarily prescribe F_{MSY} as a limit (NAFO 2015a). The PA-WG concludes that there are other valid options for defining the limit reference point (e.g., fishing mortality limit associated with B_{lim}) that are potentially greater than F_{MSY}.

Conditions for Re-Evaluating Reference Points (ToR1.g)

The NAFO Precautionary Approach Framework involves the definition of biological limits (e.g., F_{lim}, B_{lim}) that represent states to be avoided, and consideration of uncertainty in avoiding limits. General Principles of the NAFO Convention (NAFO 2017) require the management of fishing mortality at approximately F_{MSY}, conserving stocks at approximately B_{MSY}, and avoiding stock collapse (i.e., $B<B_{lim}$) to maintain approximately MSY in the long term. The estimation of MSY reference points relies on information about productivity over a range of stock sizes. When this information is not available, MSY proxy reference points are commonly applied alternatives. Proxy reference points are based on portions of the unfished stock size (B_0), conserving spawning potential ($F_{\%MSP}$), or yield per recruit (F_{max}, $F_{0.1}$; Gabriel and Mace 1999).

Conventional reference points either assume equilibrium (Caddy and Mahon 1995, Williams and Shertzer 2003) or stochastic long-term expectations of productivity (Mace 2001), and some management systems consider reference points to be relatively constant. However, in the context of changing ecosystems and productivity, reference points should be adjusted to meet management objectives (Morgan et al. 2014a, Morgan 2018, Maunder and Thorson 2019, Zhang et al. 2021). For examples, the U.S. management system requires MSY reference points that reflect prevailing ecological, environmental conditions (NMFS 2016), and ICES specifies that F_{MSY} should reflect stock productivity expected over the next five to ten years (Rindorf 2021). For integrated stock assessments, reference point estimates are revised with each update of the stock assessment model, which provides consistent parameter values for estimates of stock size, fishing mortality, projections, reference points, etc., and uncertainties are applied to each (Maunder and Punt 2006, Maunder and Thorson 2019, Punt et al. 2020). In the context of productivity changes, Duplisea and Fréchet (2009) suggest regular, but not too frequent, revaluation of reference points. Stock assessment and fishery management should respond to changes in the fishery system, so revising reference points need not be limited to "exceptional circumstances" (Zhang et al. 2021).

Many fishery management organizations routinely update reference point estimates as part of the operational stock assessment process by applying previously developed approaches and methods, so that reference point estimates are consistent with current conditions (e.g., size and maturity at age, fishery selectivity, natural mortality, etc.). Beyond these operational updates, there are also valid justifications for occasionally reconsidering the general approach or basis of reference points. Justifications include changes in the information available, evidence of productivity regime shifts, or performance evaluations of current reference points relative to alternatives.

Changes in Available Information for Re-Evaluating Reference Points

The information available on stock productivity varies among stocks and among the series of assessments for the same stock. Data-rich assessments may have sufficient information to reliably estimate MSY reference points from a well-defined stock-recruit relationship to accurately predict average recruitment for a wide range of stock size (Williams and Shertzer 2003) or an informative series of catch and relative biomass indices to accurately predict productivity for a wide range of stock sizes (Hilborn and Walters 1992, Prager et al. 1996). However, the information provided by many stock assessments are insufficient to estimate MSY reference points, so proxies are commonly applied (Gabriel and Mace 1999, Punt et al. 2014b). Proxy reference points can perform relatively well for achieving nearly MSY (Clark 1991, 1993), but in some situations, management based on proxy reference points performs poorly for achieving MSY objectives (Haltuch et al. 2008, Rothschild and Jiao 2013, Morgan et al. 2014a). As a result of parabolic or dome-shaped production functions, even uncertain estimates of F_{MSY} can perform well for producing near MSY (Simmonds 2013). Therefore, direct estimation of MSY reference points should be attempted with the available data.

The available data and quality of assessments change over time, so the decision to estimate F_{MSY} or a proxy and its uncertainty should be reconsidered when the quality of information changes. Estimates of MSY reference points depend on the choice of stock assessment model (DFO 2013), and model choice can change as assessments advance. The understanding or perception of a stock's productivity can also change over time. Periods of depletion, rebuilding and stability can improve the perception of productivity, and the possibility to estimate MSY reference points like F_{MSY} (Hilborn and Walters 1992, Prager et al. 1996, DFO 2013).

Re-Evaluating Reference Points to Account for Regime Shifts

Reference points are typically based on long-term expectations (e.g., F_{MSY} is defined as the fishing mortality expected to produce MSY in the long term; fishing at $F_{40\%}$ over an entire generation of the target species is expected to conserve 40% of the maximum spawning potential). These reference points assume long-term stationarity in productivity (e.g., a constant natural mortality and growth rates, constant stock-recruit relationship). However, each component of productivity (i.e., rates of growth, natural mortality, reproduction) commonly varies over time because of environmental influences (Williams and Shertzer 2003, Brander 2010, Morgan et al. 2014b, Punt et al. 2014b, Morgan 2018, Maunder and Thorson 2019, Zhang et al. 2021). In many cases such temporal variability results in minor changes to reference point values, but in other cases the changes in productivity and reference points are substantial (e.g., NAFO stocks 3NO cod and 3LNO American plaice; Morgan et al. 2014a, 2014b; Zhang et al. 2021). In cases where productivity greatly decreases, management based on long-term productivity and F_{MSY} can lead to suboptimal yield (Haltuch and Punt 2011, Rindorf et al. 2017), poor performance of harvest control rules (A'Mar et al. 2009, Brunel et al. 2010), and failure to achieve rebuilding targets that assume long-term productivity (e.g., B_{MSY}; Szuwalski and Punt 2013, Punt et al. 2014b, Bell et al. 2018, Maunder and Thorson 2019). Reference points can be routinely updated with each updated stock assessment to reflect recent recruitment, and environmental regime shifts can be reflected in the reference point assumptions (e.g., Haltuch et al. 2009, Jiao 2009).

A climate regime shift is a transition between multiple ecological states (Möllman et al. 2009, Lindegren et al. 2012, Litzow et al. 2013). Klaer et al. (2015) defined a productivity shift as a change in the biological characteristics of a stock that lead to a change in reference points. An example of an environmental regime shift that substantially affects fishery productivity is the El Niño–Southern Oscillation, in which strong El Niño events impact several small pelagic species (Jiao 2009, Bertrand et al. 2020). In the NAFO region, Buren et al. (2013) identified a regime shift in the marine ecosystem off Newfoundland and Labrador in the early 1990s when the ecosystem structure changed abruptly, has not returned to its previous structure, and has impacted capelin biomass and spawning season. A meta-analysis of 230 assessed stocks from around the world suggested that productivity was primarily related to environmental regime for 39% of the stocks, primarily related to stock size for 18% of stocks, related to both regime and stock size for 30% of stocks, and random for the remaining 13% (Vert-pre et al. 2013).

Detection of productivity regime shifts can be challenging, because many stock assessment time series are short relative to the species generation time (DFO 2013, Karp et al. 2019, Schijn and Pauly 2021). Jiao (2009) reviewed methods to define and identify regime shifts. Simulation analyses suggest that conventional stock assessment methods tend to incorrectly detect recruitment regime shifts (i.e., type I statistical error) because of the coincident effects of stock depletion from fishing, but such errors can be minimized by choosing appropriate recruitment assumptions in the assessment and reference points (Haltuch and Punt 2011). Multivariate analysis of a suite of biotic and abiotic variables were used to identify regime shifts in the Baltic (Möllman et al. 2009) and North Pacific (Litzow et al. 2013). Evidence for a productivity regime shift is stronger when based on multiple species in the ecosystem (DFO 2013, Perretti et al. 2017). Meta-analysis of multiple vital rates can also help to detect changes in productivity (Zhang et a. 2021). Klaer et al. (2015) propose a weight-of-evidence approach to accepting a productivity shift that scores a range of attributes, including observed change in a productivity indicator, understanding of the structural assumptions in the stock assessment model, and explanatory hypotheses. Several statistical methods have been developed for early detection of regime shifts (e.g., Rodionov 2004, Lindegren et al. 2012). The processes proposed for the NAFO Roadmap for an Ecosystem Approach to Fisheries (e.g., Tier 1 Ecosystem State Assessment and Tier 2 Multispecies Assessment, Koen-Alonso et al. 2019) can help to detect regime shifts in the NAFO area.

Regime shifts in recruitment can be accounted for in fishery management by applying reference points that are 1) informed by an environmental covariate, 2) dynamic reference points, or 3) regime-based reference points and harvest control rules (Maunder and Thorson 2019). To account for changing environments in the California Current system, Jacobson and MacCall (1995) estimated MSY reference points for Pacific sardine that were conditional on temperature, but environmental effects and predictors of recruitment changed over time (Jacobson and McClatchie 2013). Zhang et al. (2021) showed that correctly accounting for non-stationary population dynamics is needed for estimating MSY reference points. Modifying reference points with environmental covariates can improve management performance for achieving yield and conservation objectives for some stocks (Holsman et al. 2016, Miller et al. 2016), but Basson (1999) showed that advantages depend on the ability to predict environmental conditions in the near term.

The assumption of stationarity (i.e., constant productivity) can also be relaxed with dynamic reference points that do not require an environmental predictor. The conventional reference point B_0 (the long-term equilibrium biomass expected from no fishing) assumes a stationary stock-recruit relationship, but it can also be derived as a dynamic reference point. Dynamic B_0 is the biomass expected each year that would have resulted if fishing had not occurred based on population parameters estimated by the stock assessment (MacCall et al. 1985). An alternative dynamic approach to reference points is estimating the components of productivity using information from 'moving windows', or periods within the assessment series, for deriving dynamic B_{MSY} (Punt et al. 2014a). Variability in components of productivity can also be modeled as process error, which can contribute to estimates of uncertainty in reference points (DFO 2013, Miller et al. 2016, Maunder and Thorson 2019). Although dynamic reference points are sensitive to changes in productivity and can improve the achievement of optimum yield, management based on dynamic reference points performs best when changes in productivity are accurately identified and directional rather than bidirectional (Haltuch et al. 2009, Ianelli et al. 2011, Berger 2019, O'Leary et al. 2020, Zhang et al. 2021). Among the alternative approaches to accounting for environmental regime shifts, Maunder and Thorson (2019) recommend dynamic reference points, particularly for biomass reference points.

A more discrete form of dynamic reference points is to define reference points that are conditional on the current environmental regime. Hurtado-Ferro et al. (2010) demonstrated that F_{lim} can be modified to account for environmental regime shifts based on an environmental threshold. However, accounting for regime shifts in simulated management procedures did not improve performance in some situations (A'Mar et al. 2009). King et al. (2015) reviewed attempts to consider productivity regime shifts in stock assessments and fishery management, concluded that they have had limited success, and proposed that best practice is to supplement conventional reference point estimates with dynamic reference points

Dynamic reference points are mostly affected by recruitment variability, but all components of production can be influenced by a changing environment (Morgan et al. 2014b, Morgan 2018). If the rate of natural mortality appears to have changed, Legault and Palmer (2015) recommend that there should be strong evidence to support the change, and the trade-offs between risk of overfishing and forgone yield should be considered for revising reference points. Similarly, Swain (2013) explained that reference points should not be revised when the source of increased natural mortality is a 'predator pit' (predator-driven depensation). DFO (2013) suggested that revising reference points is most justified by changes in density-dependent production (e.g., carrying capacity or asymptotic recruitment, R_0) rather than density-independent components of production (e.g., the intrinsic per-capita rate of increase or steepness of the stock-recruit function).

Canada has a legislative mandate and some operational incentives to consider changing reference points that account for productivity changes (Zhang et al. 2021). The Canadian Fisheries Act specifies that management shall "take into account the biology of the fish and the environmental conditions affecting the stock" (RSC 1985). A Canadian initiative to promote an ecosystem approach to fisheries management proposes that environmental considerations should be incrementally considered in the estimation of reference points (Forrest 2021). Understanding the mechanism of productivity regime shifts, which involves investigating each component of productivity, helps to justify revised reference points, but it may also be necessary to change reference points without such understanding (Zhang et al. 2021).

A concern about re-evaluating reference points to account for productivity regime shifts is that managing fisheries using revised reference points may prevent stocks from achieving historical productivity (Jackson et al. 2001, DFO 2013). The Canadian precautionary approach policy states that "*as a general rule the only circumstances when reference points should be estimated using only information from a period of low productivity is when there is no expectation that the conditions consistent with higher productivity will ever recur naturally or be achievable through management*" (DFO 2013). Swain (2013) clarified that reference points should not be changed if the change in productivity is entirely a function of a change in stock size but can be reconsidered if the change in productivity reflects a regime shift caused by external factors, depending on which component of productivity is affected. For two Canadian stocks with a historically productive period and a recent unproductive period (4VsW cod and 4X haddock), Mohn (2013) developed criteria for maintaining reference points from the earlier period if the viability of the stock was otherwise compromised, a return to the earlier productivity was probable, and the return could be facilitated by conservation; he found that 4X haddock did not meet the criteria for maintaining the long-term reference points, because the stock was viable and a return to higher growth was unlikely in the near term. Rice (2013) proposed similar criteria for changing reference points to account for productivity changes, including identifying the nature of productivity shift (changes in density-dependent or density-independent vital rates, and for what life stages), persistence of the new productivity for several years, and sufficient data to revise reference points for the new regime; noting that these criteria are rarely met. Duration for the persistence criterion was suggested as five years of a more productive regime and 25 years for a less productive regime, and occasional dominant year-classes do not represent a persistent change in productivity (DFO 2013). Considering that components of productivity are expected to have maximum rates at low densities, hypotheses about productivity can be tested at low stock sizes, and the potential for a shift back to greater productivity can be monitored using the same methods used to detect the shift to low productivity.

There are several published recommendations for considering when reference points should account for productivity regime shifts. Perspectives on best practice appear to have evolved over recent decades as climate impacts increased in frequency and extent. For example, a Canadian workshop in 2013 concluded that there are rare conditions that justify the adjustment of reference points to a new productivity regime (DFO 2013), but a more recent Canadian workshop suggests that environmental change should be regularly considered in the derivation of reference points (Zhang et al. 2021). Holt and Michielsens (2020) adapted the best practices developed by DFO (2013) for reevaluating reference points based on productivity regime shifts:

1. document evidence for productivity shift from variation in recruits per spawner or regime detection algorithms,
2. identify the underlying mechanisms causing the change in productivity,
3. demonstrate that the change in productivity will persist long enough for revised reference points to meet management needs,
4. compare revised reference points with conventional reference points that assume long-term productivity,
5. estimate uncertainty in reference points, and
6. communicate the relative risks of current and revised reference points for stock assessment and fishery management (e.g., simulation testing).

Karp et al. (2019) recommended a similar sequence of detecting shifts, understanding the associated mechanisms, and evaluating risks and priorities before proceeding with revised stock assessments or fishery management decisions. Zhang et al. (2021) concluded that reference points should be revised when the risks of negative consequences for the stock and fishery from implementing current reference points are greater than the risks of revising them, and these tradeoffs vary among fisheries.

Performance of Management based on Re-Evaluated Reference Points

Many model-based management procedures rely on reference point estimates, and Management Strategy Evaluation can be used to determine the performance of such management procedures for achieving management objectives (Punt et al. 2016, Sainsbury et al. 2000). Although harvest control rules based on conventional reference points are expected to generally perform well for a range of fisheries, reference point alternatives (e.g., MSY reference points, MSY proxies, dynamic reference points, empirical management procedures) may perform better for specific fisheries (A'Mar et al. 2009; Haltuch et al. 2008, 2009; Punt et al. 2014a). Results from such evaluations that demonstrate substantially improved performance of alternative reference points justify adoption of the revised reference points.

Recommended Conditions for Re-Evaluating Reference Points

The basis of reference points should be reconsidered when 1) the available information on productivity substantially changes, 2) there is evidence of a productivity regime shift, or 3) alternative management procedures based on revised reference points are demonstrated to perform better for meeting NAFO's objectives.

1. The decision to estimate either F_{MSY} or a proxy should be reconsidered when the content and quality of information substantially changes. For examples, a) new information can change the ability to estimate a stock-recruit relationship; b) additional periods of depletion, rebuilding or stability can change the perception of productivity or the ability to reliably estimate MSY reference points; and c) the quality of an assessment can improve or deteriorate, changing the uncertainty of reference points and the ability to estimate MSY reference points. In these situations of new information about productivity, the basis of reference points (e.g., MSY or MSY proxies) should be re-considered.
2. 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. If recent productivity is assumed in revised reference points, operational stock assessments should routinely test productivity shift hypotheses and the potential for a shift back to previous productivity.

3. When performance evaluation indicates that the management procedure based on current reference points does not perform well for meeting the objectives and principles of the NAFO convention, or alternative management procedures are evaluated to perform better for meeting objectives, reference points should be re-considered.

PA Framework Requirements and Options to Implement the NAFO Convention

The objective and general principles in the NAFO Convention are not precisely defined and can be achieved by a variety of technical approaches for the Precautionary Approach Framework. For example, similar objectives have been met differently among fishery organizations, and performance of alternative management procedures varies by fishery. Valid options were identified for defining F_{lim} and B_{lim}, and each option has strengths and weaknesses. However, there is no definitive weight of evidence among options, the decision among valid options involves policy decisions that are more suited to the NAFO Commission (e.g., acceptable risk tolerance), and the most appropriate options may be specific to each stock or fishery. Therefore, the Precautionary Approach Framework should provide operational guidelines that maintain the objectives and principles of the NAFO Convention while allowing for stock-specific flexibility.

Objective - The objective of this Convention is to ensure the long term conservation and sustainable use of the fishery resources in the Convention Area and, in so doing, to safeguard the marine ecosystems in which these resources are found.

The objective for long term sustainability requires limiting fisheries to sustainable yield as well as additional conservation of marine ecosystems. In addition to limiting fisheries to sustainable yield, the Precautionary Approach Framework needs to be compatible with other processes that have been developed by NAFO for a broader ecosystem approach to fishery management (described by NAFO 2011, 2012, 2019; Koen-Alonso et al. 2019). The NAFO Convention objective includes three explicit overarching goals: long-term conservation of the fishery resources, sustainable use of these fishery resources, and safeguarding of the ecosystem in the area. The Precautionary Approach Framework should maintain low probability of depleting stocks to less than B_{lim} (a stock size associated with low productivity and sustainability limits) by accounting for uncertainty.

General Principle (a) promote the optimum utilization and long-term sustainability of fishery resources;

General Principle (b) adopt measures based on the best scientific advice available to ensure that fishery resources are maintained at or restored to levels capable of producing maximum sustainable yield;

These principles involve achieving average catches of approximately MSY in the long term by conserving stocks at an average of approximately B_{MSY} over time. In addition to the long-term sustainability objective, optimum yield requires further managing fishing mortality at approximately F_{MSY}. Reference points associated with optimum yield require information on productivity over a range of stock sizes (e.g., the stock-recruitment relationship). When this information is not available, MSY proxy reference points are alternatives. Proxy reference points are based on portions of unfished stocks size (B_0), conserving spawning potential ($F_{\%MSP}$), or yield per recruit (F_{max}, $F_{0.1}$). A requirement of achieving MSY is maintaining stocks at approximately B_{MSY}, avoid depleting stocks to the point of low productivity (i.e., $B<B_{lim}$), and rebuilding depleted stocks toward B_{MSY}.

General Principle (c) apply the precautionary approach in accordance with Article 6 of the 1995 Agreement;

This principle requires the consideration of scientific uncertainty. The precautionary approach involves the definition of biological limits (e.g., F_{lim}, B_{lim}) that represent states to be avoided, and consideration of uncertainty for effectively avoiding limits. Uncertainty can be considered through target reference points, precautionary reference points (e.g., F_{buf}, B_{buf}) or other risk-based evaluations like Management Strategy Evaluation. A wide range of management procedures can be tested with Management Strategy Evaluation, including empirical harvest control rules, but performance of each candidate management procedure can be evaluated in relation to the objective and principles of the NAFO Convention. Target reference points can be precautionary, having low probability of exceeding a limit reference point (similar to buffer reference points) or based on the other considerations of optimum yield specified in Article 6 of UN (1995) *"… the impact of fishing activities on non-target and associated or dependent species, as well as existing and predicted oceanic, environmental and socio-economic conditions…"*. For example, targets can be based on economics (e.g., F_{MEY}, Dichmont et al. 2010) or bycatch in mixed-stock fisheries.

General Principle (d) take due account of the impact of fishing activities on other species and marine ecosystems and in doing so, adopt measures to minimize harmful impact on living resources and marine ecosystems;

General Principle (e) take due account of the need to preserve marine biological diversity;

In addition to limiting fisheries to sustainable yield, the Precautionary Approach Framework needs to be compatible with other processes being developed by NAFO to implement a broader ecosystem approach to fishery management (described in NAFO 2011, 2012, 2019; Koen-Alonso et al. 2019).

General Principle (f) prevent or eliminate overfishing and excess fishing capacity, and ensure that levels of fishing effort do not exceed those commensurate with the sustainable use of the fishery resources;

Achieving optimum yield requires that overfishing should be avoided. Overfishing can be defined as $F>F_{lim}$ within the Precautionary Approach Framework, so that uncertainty can be accounted for in avoiding overfishing. As described above F_{lim} can be defined as F_{MSY}, or the F associated with B_{lim}.

General Principle (g) ensure that complete and accurate data concerning fishing activities within the Convention Area are collected and shared among them in a timely manner;

This principle is more relevant to the NAFO Commission but implementing the Precautionary Approach Framework requires data from fishery monitoring and other information to be available for regular stock assessments and associated reference point estimates.

General Principle (h) ensure effective compliance with management measures and that sanctions for any infringements are adequate in severity; and

This principle is also more relevant to the NAFO Commission, but the Precautionary Approach Framework implicitly assumes effective implementation of advice and management decisions. Some implementation error can be included in management strategy evaluation, but management procedures are not expected to perform well without compliance, and exceptional circumstances to the framework can be defined for infractions.

General Principle (i) take due account of the need to minimize pollution and waste originating from fishing vessels as well as minimize discards, catch by lost or abandoned gear, catch of species not subject to a directed fishery and impacts on associated or dependent species, in particular endangered species.

In addition to limiting fisheries to sustainable yield, the Precautionary Approach Framework needs to be compatible with other processes being developed by the NAFO Commission that implement a broader ecosystem approach to fishery management (described in NAFO 2011, 2012, 2019; Koen-Alonso et al. 2019). Bycatch can be considered in the Precautionary Approach Framework in the form of management targets, which is consistent with Article 6 of UN (1995).

Conclusions

All options for the NAFO Precautionary Approach Framework, including the existing framework (NAFO 2004) require full implementation to achieve objectives (NAFO 2020b). 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, but stock assessments are often complicated by important environmental factors that influence Precautionary Approach reference points.

Maintaining all stocks at B_{MSY} at all times with high probability may not be possible 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. Accordingly, all options considered for a revised Precautionary Approach Framework should be performance tested with respect to whether management measures set in accordance with the framework can achieve the following objectives:

- 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 average catches of approximately MSY in the long-term.

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APPENDIX I. PA-WG Members

Name	Affiliation
Ricardo Alpoim	EU
Tom Blasdale	NAFO Secretariat
Tanja Buch	Greenland
AnnDorte Burmeister	Greenland
Steven Cadrin	co-Chair, external expert
Daniel Duplisea	Canada
Karen Dwyer	SC Chair, Canada
Carmen Fernandez	EU
Jan Horbowy	external expert
Daniel Howell	external expert
Carsten Hvingel	Norway
Fernando Gonzalez-Costas	WG-RBMS co-Chair, EU
Diana Gonzalez-Troncoso	STACREC Chair, EU
Mariano Koen-Alonso	Canada
Martha Krohn	Canada
Julie Marentette	Canada
Adolfo Merino Buisac	EU
Adriana Nogueira	Greenland
Pierre Pepin	Canada
Rick Rideout	STACPUB Chair, Canada
Mark Simpson	STACFIS Chair, Canada
Katherine Sosebee	USA