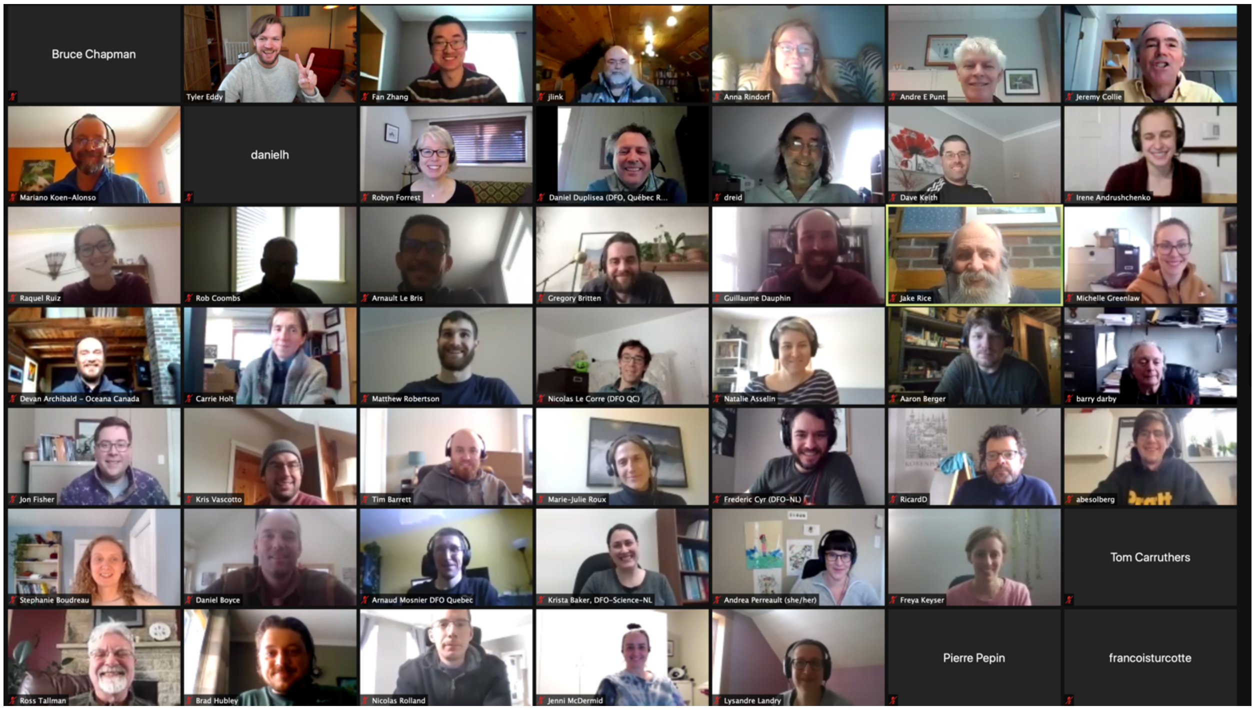
Report on Ocean Frontier Institute (OFI) Workshop on Fisheries Management Reference Points in Highly Dynamic Ecosystems



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SUMMARY

A virtual international workshop on fisheries management reference points in highly dynamic ecosystems was held from January 25-29, 2021. Its purpose was to provide a general overview of the theory and implementation of dynamic reference points to inform fisheries management.

This workshop report includes motivation, background, challenges, workshop objectives, keynote presentation summaries, panel discussion summaries, conclusions, and future steps. The terms of reference, agenda, list of attendees for the meeting, survey questions, and links to keynote presentation videos are appended.

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Motivation

- Systematic and persistent changes of commercially exploited fish and invertebrate populations have been observed in many stocks globally, which affect the efficacy of management.
- There is interest from Fisheries and Oceans Canada (DFO) scientists who are looking for guidance/advice on when/how to alter reference points in response to changing productivity conditions.
- Dynamic ecosystems and changing productivity conditions are widespread phenomena that are important in fisheries science and management globally.

Background

Reference points (RPs) are used in fisheries management to indicate desired and undesired states of fish stocks and fisheries. Biomass and fishing reference points are often used as operational control points to trigger management actions (e.g., reduce fishing mortality in response to declined stock biomass). Reference points are key components of the precautionary approach (PA) which is considered a cornerstone for sustainable fisheries management. PA reference points are usually estimated from models considering historical fish population dynamics and their response to fishing, mediated by environmental conditions and the stock's life-history characteristics. These reference points are mostly estimated from static characterizations of a stock's productivity, assuming equilibrium dynamics (hereafter referred to as static reference points). However, it is well known that a stock's distribution and productivity vary in time both randomly and, often, with trends (Karp et al. 2019), sometimes even showing regime-like characteristics. This means that management decisions based on such static reference points may not reflect a stock's productivity in the future, especially as climate change is already impacting environmental conditions, primary productivity, and fish stocks' distributions (Lotze et al., 2019). This may increase the risk of management decisions that are either unsustainable or overly cautious resulting in foregone yield due to the mismatch between actual productivity and the productivity inherent in a static PA framework.

Challenges

Time-varying (non-stationary) reference points are indicators that can change according to the "prevailing" environmental conditions. For example, time-varying reference points can be calculated by incorporating environmental covariates into models and projections (a "mechanistic approach" including dynamic unfished biomass (B_0), moving time windows or the sequential T-test analysis of regime shift (STARs) approaches to calculating reference points; Punt et al. 2014a). However, there are several challenges with this approach: 1) ecosystem regimes or prevailing conditions are difficult to define and detect, 2) the environmental mechanisms or drivers of stock productivity are often elusive and tend to change over time, 3) forecasting environmental conditions can be highly uncertain, and 4) inclusion of such methods may not lead to substantially better management outcomes. Another option is to use *static reference points* in harvest strategies that are then evaluated for robustness to time-varying productivity by accounting for possible broad scenarios of future dynamics (an "empirical approach"; Punt et al. 2014a). This approach does not require identifying, understanding, or projecting explicit mechanisms affecting fish population dynamics, thereby avoiding the above-mentioned challenges associated with time-varying reference points (Zhang et al., 2020). Nevertheless, implementation of such reference points in harvest strategies may lead to over-exploitation or under-exploitation in periods with poor/good productivity of fish populations, resulting in sub-optimal harvesting in fisheries (Rindorf et al. 2017). Limitations of the use of both time-varying and static reference points in harvest strategies suggest the choice of reference points should be evaluated in the context of specific fisheries and ecosystems, and some general and practical guidance on how to make such choices is warranted (e.g. Holt & Michielsens 2020).

Workshop Objectives

- Discuss whether we need to consider changing management reference points and how this conceptual change may affect our definitions of fisheries' statuses (e.g., healthy, endangered, collapse and recovery).
- Discuss when we should change management reference points, the qualitative and quantitative evidence needed to trigger the change, and the methodologies to test for such evidence.
- Discuss how to change management reference points, the methodologies to implement the change, and the caveats and limitations of these methodologies.

Keynote summary

Prof. Andre Punt: A look in a rearview mirror: 35 years of evolving thoughts on time-varying productivity and reference points in 45 minutes

University of Washington

There are three things that we often assume to be true in fisheries management: 1) All reference points are wrong, but some reference points are useful. In other words, reference points are worthwhile, but both bias and imprecision of reference points can negatively affect fisheries management outcomes. 2) Stationarity (constant mean and variance for observations at different times) is a key premise underpinning passive adaptive management. By assuming that we are managing a stationary system, we expect that the precision of our estimates will improve with increased observation time. 3) We know that estimates of parameters vary over time. For example, stock-recruitment relationships of Pacific salmon (Peterman et al. 2003) and weight-at-age of Alaskan pollock (Ianelli et al. 2020) have been shown to vary over time. Recognizing that parameters vary over time is important because those variations can have direct effects on production and in turn, maximum sustainable yield (MSY), as has been seen for Bristol Bay red king crab (Punt et al. 2014b).

To deal with non-stationarity, fisheries management may refer to the guiding principles from the definition of MSY in the *Magnuson-Stevens Fishery Conservation and Management Act* (1996) which refers to harvest being placed in the context of "prevailing ecological and environmental conditions". Examples of methods that have been used to account for prevailing conditions include basing harvest control rules on environmental covariates (e.g. Pacific sardines and sea surface temperature; Hill et al. 2019) or basing model parameters on "prevailing" ecological conditions (e.g. Bristol Bay red king crab; Punt et al. 2014b). However, identifying "prevailing" environmental conditions can be a substantial challenge. One of the most common solutions to time-varying parameters is to ignore them, which can be justified when data is insufficient, a passive adaptive management protocol is required, or when political challenges make maintaining status-quo measures more reasonable. Methods that actually account for changing environmental conditions include the STARS approach (Punt et al. 2014a), allowing assessment parameters to vary over time (e.g. Moffit et al. 2016), and using dynamic B_0 (e.g. O'Leary et al. 2020).

When defining reference points, it is important to use management strategy evaluation (MSE) to evaluate candidate options, and it is good practice to include climate change and environmental variation in operating models (Punt et al. 2016). During the past 35 years, multiple lessons have been learnt: 1) including environmental covariates when defining reference points is not guaranteed to lead to improved management performance (e.g. Ianelli et al. 2011); 2) results will be sensitive to how (and to what extent) biological parameters change over time (e.g. A'mar et al. 2009); 3) results will be sensitive to choice of model structure; 4) the environment can affect both target fishing mortality and target biomass (e.g. Kell et al. 2005); and 5) the risk of ignoring trends in environmental drivers is not symmetric (e.g. De Oliviera & Butterworth 2005).

Some tentative recommendations are to: 1) develop clear guidelines on when to invoke a regime shift before you apply new reference points, 2) use MSE to test before you adopt a certain management strategy, and 3) consider the plausibility of hypotheses and include uncertainty during the whole process.

Final thoughts on what, why, when, and how to change reference points:

> *What:* modifying the values for biological (and economic) reference points should be a standard part of the assessment and management process (minimally passive adaptive management).
>
> *Why:* management performance deteriorates to a limited extent if allowance is (incorrectly) made for changing reference points but can improve substantially if there are environmental drivers.
>
> *When:* either adopt a consistent approach (e.g. moving window/dynamic B0) or consider a fixed frequency between changes.
>
> *How:* each method has pros and cons, so it is ideal to test methods using MSE.

Prof. Anna Rindorf: Reference points in non-stable Northeast Atlantic stocks

Technical University of Denmark

We live in a world where lots of things are changing all the time. All fisheries management regions use a combination of fishing mortality (F) and biomass (B) reference points. F_{MSY} is the most used F reference point, but definitions of B reference points vary by region. In International Council of the Exploration of the Sea (ICES) countries, the limit and precautionary B reference points (B_{LIM} and B_{PA}) are usually defined from the stock recruitment relationship, where estimates are sensitive to time series length, stock development, and the choice of method (van Deurs et al. 2020). In the US and other countries, B reference points are generally defined as a proportion of B_{MSY}. However, the two definitions of B reference points lead to different results. The B_{R+PA} approach tends to generate higher B reference points than the B_{MSY} approach for pelagic species, and lower B reference points for demersal species (ICES WKMSYREF 2014; Rindorf et al. In prep).

B reference points have a direct impact on the advice for depleted stocks, stocks with decreased productivity, pelagic stocks, and short-lived stocks. Short-lived stocks are managed to leave a specific amount of biomass in the water, making annual F variable according to current productivity. For increasing stocks, stock-recruitment based reference points have been replaced by B_{MSY} based reference points in a few cases (e.g. North Sea plaice; ICES WGNSSK 2020), although B reference points are usually left unchanged. In those cases, stocks are all above the B reference points, so changing B reference points has no impact on management except to draw attention from stakeholders. Much of the controversy comes from declining and low productivity stocks.

In ICES, there are several methods for determining B reference points. There are a range of depleted and decreased productivity stocks where B reference points are mostly addressed based on expert judgement. There are a few cases where assessment model variability can cause scaling issues with biomass over time. When this occurs, assessment outputs are scaled to make biomass relative to a specific year in the past. Despite variability in how B reference points are determined, all these methods have passed external review, suggesting that reviewers may be confused about the best way forward.

For F reference points, there are some common expectations which may not be true: 1) lower productivity will lead to lower F_{MSY}; 2) including ecosystem considerations will reduce F_{MSY}; and 3) precautionary considerations are not relevant if we fish at F_{MSY}. Analysis indicates that F_{MSY} can either increase or decrease when productivity decreases, growth decreases, or natural mortality increases. In the North Sea there is evidence that shows variable natural mortality in empirical data (e.g. Sparholt et al. 2002). Furthermore, studies on the effects of climate change, growth, recruitment and mortality effects on F_{MSY} are frequent (Clausen et al. 2017). In addition to biological impacts on F_{MSY}, time-varying selectivity has been shown to be a common but often ignored issue (Kovalev and Bogstad 2005).

ICES states F_{MSY} should reflect the status of stock productivity until the next update in 5-10 years and an automatic update will occur every 5-10 years (similar to a moving window approach). However, some flexibility exists in adaptive management strategies at shorter time frames. F's for short-lived stocks are based on in-year assessments using the most recent growth, mortality and selectivity combined with surveys of incoming recruitment for annual F's to provide MSY. Barents Sea capelin also adds annual estimates of natural mortality from cod biomass estimates.

In ICES, longer-lived stocks can either implement F-ranges or predefined two step management strategies. The range is often defined by the F's leading to >95% MSY. Some general principles are 1) it's always OK to fish less than F_{MSY}; 2) it's never OK to fish above F_{MSY} when the stock is below the B reference point; and 3) When a stock is above the B reference points, you can use the range to account for interactions between and within species, account for interactions in the fishing process, or stabilize year to year variability in catches. A recent approach for Irish Sea stocks suggests using Ecopath to determine the productivity regime and then adjust within the range accordingly. In general, there is reluctance in the ICES community to base advice on correlations with environmental factors due to their inconsistency over time.

Some general conclusions about density-dependent growth and predation effect F_{MSY}: 1) Fishing on one species will affect others; 2) If much of the time series has low predator stock size, multispecies F_{MSY} (i.e. F_{MSMSY}) > F_{MSY}; and 3) Adding food dependent predator growth increases F_{MSY} (e.g. Gislason 1999). Therefore, you may not want to consider density-dependent growth and predation when stock size is very low because it may increase F_{MSY}. However, even for stocks that are increasing over time, there are concerns about overfishing to cause the stock to return to low stock size. An additional challenge for changing reference points is that changes appear to be shifting baselines on the status of the stock, which can be difficult to explain to stock management outsiders.

In summary, B reference points are not easy to estimate. F reference points are estimated from MSEs and are updated more frequently. Year to year variability is most important in short lived stocks. A decrease in productivity or being short-lived brings precautionary F and F_{MSY} closer to one another. Rapid changes in F_{MSY} occur where recruitment and growth failure coincide with increased natural mortality. We have spent very little time understanding the impacts of selectivity on F_{MSY} and on addressing how we communicate our updates to stakeholders. This is especially important given that many stakeholders seem to expect that incorporating ecosystem and density-dependent effects will work to their advantage, which may not always be the case.

Dr. Jason Link: Moving up one dimension helps in the other four: thoughts, examples, and perspectives on systematic, dynamic reference points in theory and practice

NOAA, United States

Dynamic reference points can help us when perturbations to the ecosystem cannot be explained by fishing alone. To date, fisheries management has mostly focused on using single-species indicators to set reference points (e.g. time-varying parameters, dynamic B_0) . However, research has shown that using environmental and ecosystem covariates to set reference points can lead to better outcomes (e.g. Hill et al. 2019). Despite the recognition that dynamic reference points may lead to better outcomes, there are very few examples of operational use. Part of the problem appears to be a focus on the wrong "dimensions", where the solution may be to emphasize ecosystem indicators that can save time and resources across a variety of stocks.

When considering multiple dimensions, we have tended to focus on the temporal dimension (i.e. the dt in dN/dt). Perhaps changing our focus to the taxonomic dimension (i.e. the dN in d/dt) would be beneficial. The taxonomic dimension can be approached using hierarchy theory (Wu 2013), which can address aggregated groups of species simultaneously instead of focusing on individual stocks (Allen & Starr 1982). The benefits of using hierarchy theory to address systemic, taxonomic changes include: detecting major changes earlier, being more robust to lower level dynamics, decreasing the number of details to track in time, and providing an ecosystem context to change. Although there have been a variety of proposed ecosystem level reference points, many of them require a lot of data, complex models, and are not clear about thresholds. There appear to be two consistent ecosystem level reference points that rely on readily available data, simple models, and have clear thresholds: 1) the cumulative trophic curve (cumulative biomass:trophic level and cumulative biomass:cumulative production; Link et al. 2015; Pranovi et al. 2012; Libralato et al. 2014; Libralato et al. 2019; Pranovi et al. 2020) and 2) thresholds for ecosystem overfishing based on trophic transfer efficiency (e.g. Ryther index, Fogarty index; Link and Watson 2019; Stock et al. 2017; Fogarty et al. 2016; Friedland et al. 2012). These ecosystem overfishing thresholds suggest that ~50% of the world's large marine ecosystems are experiencing ecosystem overfishing.

Overall, there is growing evidence for the necessity of dynamic reference points. Despite the evidence, there have been few examples of operational dynamic reference points being used in practice, potentially due to the difficulty in consistently identifying change using commonly used single species indicators. Acting at the ecosystem level can prevent stock and ecosystem overfishing and lead to stable economics since the ecosystem indicators can identify change prior to other indicators. Therefore, using ecosystem indicators to set reference points should begin to be more widely considered.

Dr. Robyn Forrest: Challenges for providing science advice under changing productivity

DFO, Canada

In Canada, the Fish Stocks provisions of the revised *Fisheries Act* (Fisheries Act, RSC 1985, c F-14) explicitly indicate in sections 6.1(1), 6.1(2) and 6.2(1) that management shall "tak[e] into account the biology of the fish and the environmental conditions affecting the stock". This has been interpreted by science to mean that considering changing reference points in response to perceived productivity conditions for the stock is not only allowed but should be encouraged. In addition to the recent changes to the *Fisheries Act*, Fisheries and Oceans Canada (DFO) has initiated a group to promote the ecosystem approach to fisheries management (EAFM). The EAFM group considers that the ecosystem approaches to management should incrementally include ecological and environmental considerations in the development of reference points.

Within the EAFM initiative, there are several case studies in each region, some dealing directly with the issue of altering reference points in relation to environmental and ecological variables (e.g. Pacific salmon; Connors et al. 2020; Debertin et al. 2020; Dorner et al. 2013; Holt & Michielsens 2020; Peterman et al. 2012). Therefore, within DFO there is both a legislative reason and operational incentives to consider changing reference points in relation to productivity changes of stocks. Dynamic reference points are not necessarily a new movement in Canada however, and there are stocks such as harp seals on the east coast and many different stocks of Pacific salmon that have utilized dynamic reference points for many years. Based on these examples, there appear to be two main approaches that have been used to account for time-varying productivity in reference points: 1) allow productivity parameters (e.g. growth, natural mortality) to vary with time in the stock assessment (e.g. MacCall et al. 1985; A'Mar et al. 2009; Haltuch et al. 2009; Punt et al. 2014a; Berger 2019; O'Leary et al. 2020), and 2) add a buffer to the removal rate to allow for greater uncertainty when environmental conditions are known to be changing (i.e. a risk equivalency-based approach to enable *post hoc* adjustment of a harvest control rule (Roux, MJ. personal communication. marie-julie.roux@dfo-mpo.gc.ca).

There are 4 key points to recognize when considering why, when, and how to change reference points for fish stocks in relation to external conditions:

1. Change is happening presently and is always happening.
2. We don't always need to know the dynamics to decide on changing management actions or reference points.
3. Changing reference points changes objectives ... communicating these changes will be key
4. There are existing tools to help guide decisions and communication

Although it is possible and sometimes necessary to change reference points without clear mechanisms linking environmental variables and productivity, lacking a mechanism can make change difficult to justify. Additionally, different sectors of DFO may feel different pressures. For example, there may be times when science feels a reference point change is justified while managers do not feel the same pressure to make a change. We also need to consider that there are different paradigms in management that may be used, namely the fact MSE has become much more common in the past decade. MSE is powerful in the context of dynamic reference points because it can incorporate these changes seamlessly as different operating models. However, MSE presents challenges as a process and adds a level of complication that requires an orderly sequence of events, analysis, and a communications strategy. MSE operating models must be plausible hypotheses about the states of nature, and any simulation studies must be coupled with rigorous data analyses. Further, there must be a well thought-out consultation and communication strategy with all interested parties. The best way to advance the ideas of dynamic reference points is to make sure that all interested parties come together. Whether, when, and how to change reference points are not solely within the purview of science and more work needs to be done to bring together scientists, managers, and stakeholders.

Panel discussion summary:

Under what circumstances should we consider it appropriate to change reference points in response to productivity conditions? Can we develop general guidance that would help us to decide across jurisdictions?

Andre Punt, University of Washington

The default is *status quo*, routinely and systematically evaluating reference points to decide when to change them. A shift in productivity is only one of many reasons to change RPs. We need to move from considering change only under "exceptional circumstances" to considering change as part of the regular assessment process. We should also consider MSE as a method to evaluate dynamic reference points in response to perceived changing productivity for data-limited fisheries.

Anna Rindorf, Technical University of Denmark

The importance of changing reference points depends on the context. It doesn't make a big difference in some cases, but in other cases (e.g., long-lived species, collapsing stocks, and losing/gaining yield situations), it does. On the other hand, institutional inertia may lead to over-reliance on a single model, making us unresponsive to changing productivity.

Jason Link, NOAA, United States

It is essential to monitor ecosystem changes to decide when to change RPs. Changes in ecosystem dynamics may affect stock productivity, trophic linkages, and the appropriate reference points under such circumstances. Meta-analysis of multiple traits (e.g., weight-at-age, life-history traits) can help to detect changes in productivity. Hence, a meta-analysis of dynamic RPs and ecosystem changes can assist in developing guidelines.

Robyn Forrest, DFO

We need a systematic procedure to determine changes in RPs and when to change them. Testing the decision to change and how to change will be necessary before we can comfortably adopt dynamic RPs in response to changes in productivity. Finally, a retrospective analysis of management procedures is necessary to evaluate their effectiveness.

General discussion

Understanding the mechanisms underlying productivity changes is critical, as management strategies are different depending on the mechanisms. By default, the best action should probably be maintaining the established management strategies. However, when the situation changes such that the risk of negative consequences (for stock health and yield) of the *status quo* are greater than the risk of modifying them, then the reference points should be changed. There is a tradeoff between management stability and management performance – sometimes, it may be better to have slightly less performance to maintain stability. It remains to be defined how that change should be calculated and how to set the management performance. Finally, we could be informed by existing work of guidelines and do a meta-analysis to advise a set of valuable guidelines grounded in data/evidence.

Could we develop guidelines to describe which dynamic reference point approaches and methods could be applied under different circumstances or stocks?

Anna Rindorf, Technical University of Denmark
Guidelines should not be too general but neither too specific to ensure they are valid over various circumstances. Reference points can have multiple uses, and it's not only used to make management decisions (e.g., MSC certification, sustainability checklist). If we are going to consider dynamic RPs, we need to consider their multiple uses.

Jason Link, NOAA, United States
It is important to attribute causes of changes in stock productivity (e.g., bottom-up, top-down). Climate change will modify multiple aspects of the ecosystem, including spatial distribution, physical environment, trophic interactions, etc. We need to start thinking about migration and adaptation.

Robyn Forrest, DFO
Dealing with changing productivity is not entirely mapped to changing reference points (e.g., a different management procedure may deal with changing productivity). Dynamic RPs is just one tool in the toolbox for dealing with changing productivity.

Andre Punt, University of Washington
When making the guidelines of dynamic RPs, it is crucial to focus on the objectives, outcomes, and ultimate goals (i.e., good management).

General discussion
We should focus on outcomes rather than purely guidelines which may turn out to be bureaucratic. Nevertheless, guidelines are often necessary to avoid decisions that appear to be arbitrary. Some of the barriers for developing guidelines reside in the objectives (ecological, economic or social) to be achieved, as goals do not necessarily align with each other. This may contribute to increased institutional inertia, because changing one objective could have unforeseen consequences on the others. There is an appetite for adaptive management with changing PRs, but there needs to be a performance evaluation process to adjust on a relatively short time scale.

Are our legislative and policy environments sufficiently flexible to handle the idea of adjusting reference points to changing productivity? If not, what single operational change could potentially offer the best first step forward?

Robyn Forrest, DFO
Canada and most other countries with well-developed legislative and policy environments allow for changes of RPs. Developing guidelines is the first step forward.

Jason Link, NOAA, United States
US legislative and policy environments allow for changes of RPs, but not necessarily required. Making guidelines is also a key step forward.

Andre Punt, University of Washington
Communicating and explaining why adjusting reference points is a crucial step forward. Also, try not to change objectives too frequently as this may complicate implementation.

Anna Rindorf, Technical University of Denmark
It is important to maintain the credibility of the regulator when talking about adjusting reference points. Note that the credibility of scientists and managers could be different.

General discussion:
Not all reference points are the same in how difficult they are to change. Some RPs may have socio-economic components built-in, while others may be purely biological. It is an open question about how to deal with these multidimensional RPs during the decision-making process. Canadian policy is capable of dealing with biological RPs, but may have limited capacity to include socio-economic components even if legislation may permit it.

General thoughts

To Change or Not to Change

The idea that reference points are frequently changing is not under question, even if they are often treated as static points in F vs SSB space. Not only are reference points subject to model and estimation errors, but they also vary in time with external conditions. We have, however, usually considered these variations to be stochastic and have considered this stochasticity in management strategies as part of uncertainty. Over the past 30 years, there has been an increasing awareness of the non-random nature of some of these variations akin to regime-like behaviour, where mean stock productivity and associated reference points may be considerably different between time periods (Jiao 2009). Recognizing the non-random variations in productivity and consequently changing reference points demands that we adjust our management accordingly or face the distinct possibility that we could be developing advice and management that is mismatched to a stock's capacity to support an advised fishery, thus leading to dangerous over-exploitation or foregone yield through under-exploitation.

Thus, because of large changes in productivity of many fish stocks and fisheries over the past 30 years and the recognition that we are currently in a period of rapid climate and ecosystem change, it is no longer an option to consider that fisheries reference points are constant or just vary randomly in time. With this acceptance that reference points are dynamic because of non-random variation in a stock's productivity, the question turns to when and how to change reference points. Furthermore, we need to consider what are appropriate recovery targets and interim milestones for recovery of collapsed stocks. The consequences for not doing this and continuing the status quo are that we are more likely than not to produce advice mis-specified for the actual environmental conditions, and it will become more difficult to make appropriate management decisions.

When to Change

Despite wide agreement that we should consider changing reference points in dynamic ecosystems, there has been no consensus on when these changes should be triggered. Changing environmental and ecosystem conditions, e.g. climate change, productivity change, trophic structure variation, etc., are important factors that may help to decide when to change management reference points. Long-term ecological monitoring programs are important to detect, understand, and predict systematic ecosystem changes. Reference points may be changed when there is “strong evidence” of ecosystem change, but the definition of “strong evidence” may vary among ecosystems and management jurisdictions. It is challenging to come up with consistent and objective criteria to define “strong evidence”. Therefore, a certain degree of subjectivity may be inevitable when making decisions about changing reference points in response to changing ecosystem conditions.

It should also be noted that ecological data may not be available for many fisheries, and, in such cases, we would have very limited knowledge about the dynamics of these ecosystems. In such cases, we may still consider changing reference points if there is strong evidence of systematic changes of population vital rates (e.g. recruitment, natural mortality, maturation, growth, etc.). However, for data-limited fisheries where the population dynamics are poorly understood, it may not be feasible to consider changing reference points.

Of course, management considerations are also important when deciding when to change reference points. There is a trade-off between management stability and performance. Frequently changing reference points may improve management performance, but the loss of management stability could impair the credibility of managers. In such cases, management may prefer to sacrifice a bit of performance to gain more stability. It is a common practice to consider a fixed frequency between changes of reference points. However, the optimal frequency may differ among species (e.g. long-lived versus short-lived). Additionally, management may have different pressures to change reference points depending on the fish stock status (increase, stable or decrease) and the socio-economic context. For example, there is often more pressure to change reference points when stock is declining and there are strong socio-economic values of the stock.

In summary, the decision point on when to change reference points may differ among fisheries depending on the ecological, biological and socio-economic context. Even within a fishery, the criteria may differ among scientists and managers, because they could have different priorities and considerations. To reduce arbitrary decisions about when to change reference points, it is useful to have guidelines that can be consistently applied to various fisheries. It is important to solicit and integrate perspectives from multiple stakeholders (e.g., scientists, managers, the fishing industry, indigenous groups, etc.) when developing the guidelines. Additionally, simulation tests can be used to gauge the effect of changing reference points in relation to achieving management objectives before making the change, and MSE is a useful tool that can be applied for this purpose.

How to Change

How to change management reference points is as much of a policy question as a scientific question, and there is no clear consensus for implementing these changes. Science can advise about changes in ecosystem and stock productivity when sufficient data is available, however there are important tradeoffs to consider when changing reference points. For example, industry may value management stability more highly than optimality of management. Internal obstacles also may be a hindrance to changing reference points, as managers may be skeptical of new methods and changes. Based on discussions within the workshop, communication among stakeholders, managers, and scientists is crucial to ensure there is a mutual understanding of changing stock and ecosystem productivity and how to address it.

There are several methods that have been proposed to change reference points, most of which are reflections of the variable productivity of marine ecosystems, and some of which are more dynamic than others. Among workshop participants who responded to our survey, the most common responses for *how* to change reference points were to (1) account for variable productivity in the assessment, (2) utilize a dynamic B_0, (3) use ecosystem models, (4) use time-varying natural mortality, and (5) regime-based methods. Accounting for variable productivity in the assessment could include accounting for changes in ecosystem productivity and how much primary production is made available to higher trophic levels, or it could account for the changing productivity of the fished stock in question. The second most frequent response, dynamic B_0, refers to changes of unfished biomass. This method accounts for changing baselines of a species, which may be related to changes in productivity of the ecosystem, the stock itself or due to changes in trophic dynamics. Ecosystem models, as summarized by Andre Punt in his keynote lecture, can be a tool to compliment stock assessments to provide knowledge of ecosystem-level productivity. Many respondents also suggested using time-varying natural mortality (M). Many single species stock assessments assume constant M, which may lead to bias in estimates if trophic dynamics have changed within an ecosystem. Finally, regime-based methods, which account for changes in ecosystem state that would affect stock productivity and its unfished biomass level were also recommended. There were a number of methods that were suggested at a lower frequency, including dynamic linear modelling, moving time window (not using the entire time series and instead using a more recent section of it – e.g. rolling 10 year average), variable temperature, dynamic stock recruitment, buffering harvest control rules, and the statistical method STARS.

Not every method above will be useful for every stock and ecosystem, as there are data and information requirements associated with each. Most of these methods require a strong understanding of system dynamics to detect shifts in productivity, so these situations are usually more applicable in data rich systems. These methods will be limited when data is insufficient, if there is uncertainty about changes in productivity or system dynamics, and when fishing alters biological parameters.

Conclusions

The precautionary principle is operationalized in fisheries through the precautionary approach that involves setting reference points that reflect a stock's productivity and define the sustainable operating space for fisheries. Reference points are estimated for the specifics of individual stocks and populations based on models and/or observations of stock production and responses to fisheries removals. The implicit assumption in estimating reference points this way is that past stock productivity conditions will properly reflect present and future conditions. This, however, is not always the case and presently the productivity conditions of many fish stocks globally are changing in response to rapid climate and ecosystem changes. Thus, static reference points appear to be mismatched to the actual productivity conditions of stocks more frequently. An alternative to static reference points is to try to adjust reference points to actual productivity conditions such as considering productivity regimes or fully dynamic conditions. Though this may seem a 'no-brainer', it comes with steep costs: older data may need to be rejected, uncertainty increased, and we may not know when or how to alter reference points. Hence, dynamic reference points, if not calculated and implemented wisely, may not provide better outcomes than the static ones.

Dynamic reference points can be applied at both the species and/or the ecosystem level. Identifying when to change reference points is challenging and has been approached with a variety of single-species and ecosystem methods. These methods need to be capable of identifying changes in ecosystem dynamics. Shifts in ecosystem dynamics may affect stock productivity, trophic linkages, and in turn the appropriate biomass and fishing reference points. Hence, reference points need to be routinely and systematically re-evaluated and re-defined in the context of the prevailing environmental conditions. However, it is important to remember that different stakeholders will have different considerations related to changing reference points. Scientists, managers, and industry all operate under different mandates, and will all be impacted by dynamic reference points differently. Understanding these differences and identifying and highlighting shared goals that can be achieved with dynamic reference points will be essential to future operationalization. Similarly, institutional inertia can be a large obstacle to implementing dynamic reference points. Changing reference points is both a scientific and a political question, and for these reasons, it is important that scientists develop clear messaging around dynamic reference points, and that we build a "culture-of-change" in order to build institutional support for these vital, but relatively new approaches.

Finally, we need to work across sectors to develop a set of collectively reviewed and agreed-upon guidelines, or guiding questions, that set the basis for reference point approaches and methods that could be applied under different circumstances or stocks. During this workshop, the only consistent recommendation was to test dynamic reference points in a MSE framework before applying them.

Future steps

Here, we have identified several steps that merit further research, and would be helpful in establishing guidelines and demonstrating when and how reference points should be changed. Going forward, meta-analyses of cases where changing ecosystems, and changing reference points, lead to better (or worse or neutral) management decisions *vis-à-vis* static reference points will be an important step towards establishing feasibility, and highlighting when and how reference points can be changed in practice. This will also help to highlight situations in which reference points should *not* have been changed.

We have a second workshop planned, which we hope to hold in-person. In preparation, we recommend a series of workshops and simulation exercises based on empirical case studies to test dynamic reference points and proposed guidelines. These workshops may also include ecosystem models, which could be brought in as operating models.

Finally, it is important to include a diverse group of participants and perspectives (e.g. managers, stakeholders, First Nations, etc.), so that we can achieve a better consensus on operationalizing dynamic reference points. As introducing dynamic reference points to a fishery could potentially be a significant departure from standard practice, including all relevant stakeholders is essential to understand obstacles to implementation and to develop clear messaging around the *what, why and how* of dynamic reference points. While there is no one-size-fits-all approach to changing reference points, these steps will allow us to develop and improve existing guidelines for changing reference points.

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We sincerely thank the keynote speakers for their presentations as well as all participants for their questions, insight, and discussion. We also thank participants who filled out the survey. We thank the Ocean Frontier Institute (OFI) for funding this and future workshops on Fisheries Management Reference Points in Highly Dynamic Ecosystems. We thank Dr. Julie Marentette (DFO) for providing useful comments on this report.

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Appendices

1. Terms of Reference
2. Agenda
3. Participant list
4. Survey questions
5. Links to the keynote presentations

Appendix 1: Terms of Reference

1. Participation in online survey prior to workshop Part 1 indicating experience with dynamic reference points with examples.

2. Overview of experience and ideas from keynote speakers about management reference points in dynamic ecosystems, and provide basis for discussions.

3. Discuss whether we need to consider changing management reference points, the conceptual change of fisheries management from single equilibrium assumption to multiple states assumption, and the implications to our definitions of fisheries status (e.g. healthy, endangered, etc.), collapse and recovery.

4. Discuss when we should change management reference points, the qualitative and quantitative evidence that needed to trigger the change, and the methodologies to test for such evidence.

5. Discuss how to change management reference points, the methodologies to implement the change, and the caveats and limitations of these methodologies.

Appendix 2: Workshop Agenda

January 25th
12:30-12:45 Welcome and introduction (Fan Zhang, Tyler Eddy and Daniel Duplisea)
12:45-1:30 Keynote talk: A look in a rearview mirror: 35 years of evolving thoughts on time-varying productivity and reference points in 45 minutes. (Andre Punt, University of Washington, US)
1:30-1:40 Break
1:40-2:30 Q&A and general discussions

January 26th
12:30-1:15 Keynote talk: Reference points in non-stable Northeast Atlantic stocks (Anna Rindorf, Technical University of Denmark)
1:15-1:30 Q&A
1:30-1:40 Break
1:40-2:30 Q&A and general discussions

January 27th
12:30-1:15 Keynote talk: Moving up one dimension helps in the other four: thoughts, examples, and perspectives on systematic, dynamic reference points in theory and practice. (Jason Link, NOAA, US)
1:15-1:30 Q&A
1:30-1:40 Break
1:40-2:30 Q&A and general discussions

January 28th
12:30-1:15 Keynote talk: Challenges for providing science advice under changing productivity (Robyn Forrest, DFO, Canada)
1:15-1:30 Q&A
1:30-1:40 Break
1:40-2:30 Q&A and general discussions

January 29th
12:30-1:00 Survey results and analysis (Fan Zhang, Tyler Eddy and Daniel Duplisea)
1:00-1:15 Q&A
1:15-1:25 Break
1:25-2:15 Panel discussion (Andrea Punt, Anna Rindorf and Robyn Forrest)
2:15-2:30 Next steps and concluding remarks (Fan Zhang, Tyler Eddy and Daniel Duplisea)

Appendix 3: Participant list

Name	Institution
Aaron Adamack	DFO-NL
Aaron Berger	NOAA/NMFS
Aaron MacNeil	Dalhousie University
Abe Solberg	MUN
Adam Cook	DFO-Maritimes
Andre Punt	UW
Andrea Buchholz	Dalhousie University
Andrea Perreault	MUN
Andres Beita-Jimenez	MUN
Andy Edwards	DFO-Pacific
Ann-Marie Huang	DFO-Pacific
Anna Rindorf	DTU
Arnaud Mosnier	DFO-QUE
Arnault LeBris	MUN
Aura Barria	UQAR
Barry Darby	n/a
Boris Worm	Dalhousie University
Brad Hubley	DFO-MAR
Brendan Connors	DFO-Pacific
Brianne Kelly	WWF Canada
Brittany Beauchamp	DFO-Newfoundland
Brooke Davis	DFO-Pacific
Bruce Chapman	GEAC
Cameron Freshwater	DFO-Pacific
Carey Bonnell	OCI
Carrie Holt	DFO-Pacific
Christine Penney	Clearwater
Cody Szuwalski	NOAA-seattle
Courtney D'Aoust	DFO-Ottawa
Dan Ricard	DFO-Gulf
Daniel Boyce	Dalhousie University
Daniel Duplisea	DFO-Quebec
Daniel Howell	IMR-Norway
Dave Reid	Marine Institute, Ireland
David Deslauriers	UQAR
David Keith	DFO-Mar
Deborah Austin	DFO-Ottawa
Derek Butler	ASP

Devan Archibald	Oceana Canada
Divya Varkey	DFO-NL
Doug Swain	DFO-Gulf
Elisabeth Van Beveren	DFO-QUE
Eric Pedersen	Concordia University
Erin Carruthers	FFAW
Fan Zhang	MUN
Fatemeh Hatefi	MUN
Francois Turcott	DFO-Gulf
Freya Keyser	DFO-MAR
Gregory Britten	MIT
Guillaume Dauphin	DFO-Gulf
Hanbyeol Jang	UBC
Hannah Murphy	DFO-NL
Heather Bowlby	DFO-MAR
Hsiao-Yun Chang	University of Maine
Hugo Bourdages	DFO-QUE
Irene Andrushenko	DFO-MAR
Jake Rice	DFO-Ottawa
Jason Link	NOAA
Jenni McDermid	DFO-Gulf
Jeremy Collie	University of Rode Island
Jessica Sameoto	DFO-MAR
Jin Gao	MUN
John Couture	UINR
Jonathan Fisher	MUN
Jonn Schmidt	ICES
Julie Marentette	DFO-Ottawa
Karen Cogliati	NCR
Karen Dwyer	DFO-NL
Karen Hunter	DFO-Pacific
Karl Sullivan	Barry Group
Katie Schleit	Oceans North
Kris Vascotto	AGFC
Krista Baker	DFO-Newfoundland
Laura Wheeland	DFO-NL
Lauren Bottke	DFO-Ottawa
Lingbo Li	DFO-Pacific
Luke Warkentin	DFO-Pacific
Lysande Landry	DFO-Gulf
Mackenzie Mazur	Gulf of Maine Research Institute

Mariano Koen-Alonso	DFO-Newfoundland
Marie-Andree Giroux	DFO-Gulf
Marie-Julie Roux	DFO-Quebec
Mark Dickey-Collas	ICES
Mark Simpson	DFO-NL
Matthew Robertson	Memorial University
Michelle Greenlaw	DFO-MAR
Mike Frisk	Stony Brook Univ
Natalie Asselin	DFO-Gulf
Nicolas Le Corre	DFO-NL
Nicolas Rolland	DFO-Gulf
Nis Sand Jacobsen	DTU-Aqua
Noah Khalsa	University of Maine
Noel Cadigan	MUN
Paul Regular	DFO-NL
Pierre Pepin	DFO-Newfoundland
Raquel Ruiz	MUN
Renae Butler	ASP
Rob Coombs	Innu
Rob Kronlund	DFO-Ottawa
Robyn Forrest	DFO-Pacific
Robyn Morris	DFO-NL
Roger Wysocki	DFO-Ottawa
Ross Tallman	DFO-C&A
Shelley Dwyer	DFO-NL
Stephanie Boudreau	DFO-Gulf
Steve Alexander	DFO-NCR
Steve Devitt	AGFC
Tim Barrett	DFO-StAnd
Tyler Eddy	MUN
Vanessa Trijoulet	DTU-Aqua
Victoria Neville	WWF
Xinhua Zhu	DFO-C&A

Appendix 4: Survey questions

1. What is your province/state and country of residence?
2. What sector do you work in?
3. Does your work involve providing management reference points?
4. Number of years experience providing reference points?
5. Countries where reference points have been provided?
6. Fisheries where reference points have been provided?
7. Is changing ecosystem or fisheries productivity an issue in your experience?
8. Should reference points be changed each time an assessment is updated?
9. What is/are the criterion/criteria to change management reference points?
10. Should reference points change, how often, and if so, what do you think would be the best process that leads to change?
11. How often do you see implementation of dynamic refence points in management practices?
12. If you have seen implementation of dynamic reference points, for which fisheries are they applied?
13. If you think dynamic reference points are important, but not yet implemented, why aren't they?
14. Please identify method(s) to address dynamic reference points that you are familiar with (including references)
15. Has/have this/these method(s) been applied? If so, please provide examples
16. Where are these methods useful?
17. Where are these methods limited?
18. Data situation where this/these method(s) is/are applicable or not

Appendix 5: Links to keynote presentations

Prof. Andre Punt – University of Washington, US
Prof. Anna Rindorf – Technical University of Denmark
Dr. Jason Link – NOAA, US
Dr. Robyn Forrest – DFO, Canada