Defining Biological Reference Points in a Dynamic Northeast U.S. Marine Environment

CINAR Workshop

January 8-9, 2024

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Cooperative Institute for the North Atlantic Region

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EXECUTIVE SUMMARY

A workshop entitled *Defining Biological Reference Points in a Dynamic Northeast U.S. Marine Environment* was held in person (New Bedford, MA) and virtually January 8-9, 2024. The 78 participants in the workshop included stock assessment, ecosystem, and social scientists from the NOAA Northeast Fisheries Science Center (NEFSC), staff and Scientific and Statistical Committee (SSC) members from the New England Fisheries Management Council (NEFMC) and Mid-Atlantic Fisheries Management Council (MAFMC), as well as regional experts actively engaged in stock assessment and ecosystem science. This report summarizes the content of the workshop, including contributions from workshop participants and consensus recommendations. Workshop recommendations focused on when and how to revise reference points with specific action items identified as possible next steps to address these issues within the region. Workshop participants recommended identifying both ecosystem-wide and stock-specific changes to inform decisions on when to revise reference points. They emphasized the importance of understanding stock-specific changes in dynamics and their link to environmental drivers, especially for recruitment. Although understanding the mechanism driving changes in stock dynamics was highly desirable, it was not deemed essential for redefining reference points. Participants recommended adoption of alternative methods for defining reference points that are more responsive to a changing environment. These methods include approaches such as dynamic B_0, utilizing dynamic stock-recruit models, updating assumptions for proxy-based reference points (e.g., spawning potential ratio), and adopting temporally stochastic assessment models or models that integrate covariate effects and propagate uncertainty into long-term projections. Additionally, the group discussed considering a fundamental shift in the type of reference points used in the region to only focus on fishing mortality-based reference points, moving away from biomass-based reference points and the goal of rebuilding to a historical stock size. Finally, practical limitations in redefining reference points within a changing ecosystem were also considered. There was an acknowledgment that key questions need to be addressed regarding who is responsible, how the process should unfold, and when reference points should be redefined within the fishery management process.

1. Background

Climate change is fundamentally altering the context of decision-making for fishery management in the Northeast U.S. marine ecosystem, warranting a revised concept of management reference points and rebuilding plans. Biological reference points are the benchmarks by which we determine stock status (i.e., desired and undesired states) and can trigger management actions through integration into harvest control rules. Reference points are typically estimated with an implicit assumption that a stock's productivity is static over time (i.e., stationary), which may not reflect a stock's future productivity under persistent, directional changes in ocean temperature that have impacted the productivity of fish stocks (Pershing et al. 2015) and elicited changes in spatial distribution (Nye et al. 2009, Pinsky et al. 2013). Failure to account for non-stationarity may lead to management decisions that are ineffective at meeting management objectives such as achieving optimum yield, avoiding overfishing, or rebuilding depleted stocks (Szuwalski and Hollowed 2016, Mazur et al. 2023). However, redefinition of reference points can result in a change in the perceived status of the stock and possible management response that may seem non-intuitive (i.e., increased allowable catch) given the health of the resource. This raises the question of how to sustainably manage fisheries when productivity changes over time while not reducing stocks in low productivity states. The redefinition of reference points is one of the key management challenges in the Northeast U.S. and this challenge will become more pervasive with projected accelerated climate change. Recent examples of approaches to integrate temperature impacts on recruitment for stocks such as winter flounder and yellowtail flounder suggest that rebuilding these stocks to historical levels is unlikely, and that integrating climate influences into population dynamics models can provide more realistic short-term forecasts of stock sizes and biological reference point estimates (Miller et al. 2016, Bell et al 2018). How to address non-stationarity in stock productivity in the context of reference points remains an open question and can be controversial among scientists and decision-makers.

The objectives of the workshop were to:

1. Characterize the need to redefine reference points in a changing ecosystem.
2. Review existing approaches to defining biological reference points.
3. Evaluate approaches to defining reference points in other regions of the US and globally.
4. Synthesize recommendations for estimating reference points for stocks in our changing ecosystem.

2. Scope of the Workshop

The workshop included presentations by regional experts that spanned objectives 1-3 with discussion occurring after each talk. Each day ended with a discussion focused on synthesizing presentations and identifying areas of future research and recommendations. Sections 3-5 provide summaries of the presentations given during the workshop, and we provide recommendations coming out of the workshop in section 6.

CINAR workshop Defining Biological Reference Points in a Dynamic Northeast U.S. Marine Environment held in New Bedford, MA and virtually January 8-9. Photo credit: Steve Cadrin

2.1. Database

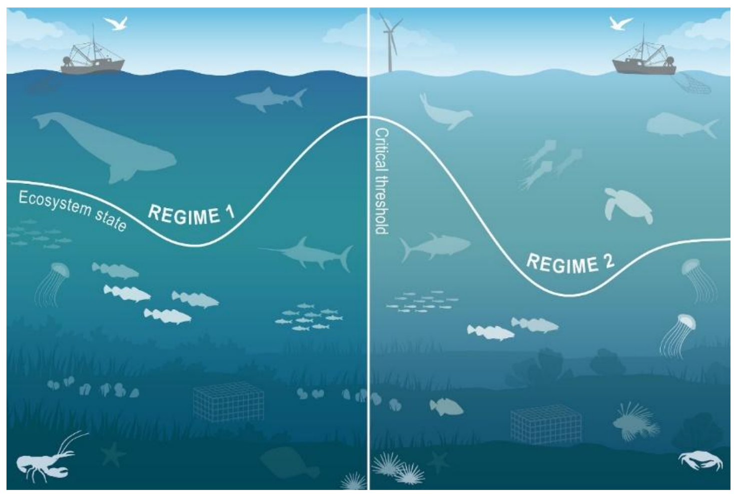
We reviewed the current approaches used to define biological reference points in the context of New England and Mid Atlantic fishery management plans and assembled a database of information related to reference points (LINK TO DATABASE). The information was compiled from available documentation including stock assessment reports, Plan Development Team reports, fisheries management plans, and SSC reports. The data collated include: assessment type (i.e., analytical, empirical), assessment model (e.g., VPA, ASAP, WHAM, index-based), reference point estimation approach (i.e., analytical, empirical), reference point method (e.g. spawner per recruit), recruitment assumptions (i.e., stock-recruit relationship, years that inform reference point estimation), stock status (known, unknown), biomass target (e.g, SSB_{MSY}), fishing mortality threshold (e.g., F_{MSY}, $F_{40\%}$), and the $F_{rebuild}$ definition if relevant. We also included information on the current stock status and frequency the stock was overfished since 2010 and whether the stock is in a rebuilding plan. The harvest control rules were briefly described for each stock/fishery management plan for each Council.

3. Characterizing the Need to Redefine Reference Points in a Changing Ecosystem

Setting the ecosystem context: defining trends, regime shifts, fish productivity change

Scott Large (NEFSC) and Kathy Mills (GMRI)

The Northeast US shelf is experiencing circulation-related environmental changes that percolate throughout the ecosystem. For example, high flow of the Labrador Current during the 1990s enhanced stratification in the region (MERCINA Working Group 2012), and since 2010, the position of the Gulf Stream relative to the shelf slope has changed, leading to subsurface warming and salinity changes (Meyer-Gutbrod et al. 2021). These environmental changes have been associated with changes in phytoplankton productivity, zooplankton composition (MERCINA Working Group 2012, Pershing and Kemberling 2023), fish productivity (Perretti et al. 2017), fish condition (NEFSC 2024), and distribution patterns (Nye et al. 2011). Collectively, these changes in multiple ecosystem components have been identified as regime shifts (Friedland et al. 2020). Distinguishing between ecosystem regimes is important as our social systems have been developed around the expectation of constant and persistent regimes.



A new regime emerges when the ecosystem crosses a critical threshold, resulting in an altered state (from NEFSC 2024).

There are multiple analytical methods to detect trends and regime shifts in ecosystem conditions in the region, ranging from univariate (e.g., changepoint detection) to multivariate (e.g., regime shift detection). Changepoint detection (Friedland et al. 2020) has widely been used to identify situations where the mean or variance of a time series significantly changes between stanzas. Bivariate breakpoint analysis (Möllmann et al. 2021) considers the influence of two variables on a stock or community variable of interest. Finally, regime shifts span multiple components of ecosystems, from physical conditions through lower trophic levels to fish and predators. A classic example of a full ecosystem regime shift is that of the North Pacific, characterized using a Principal Components Analysis of 100 physical and biological time series and tests of differences for specific years of interest (Hare and Mantua 2000).

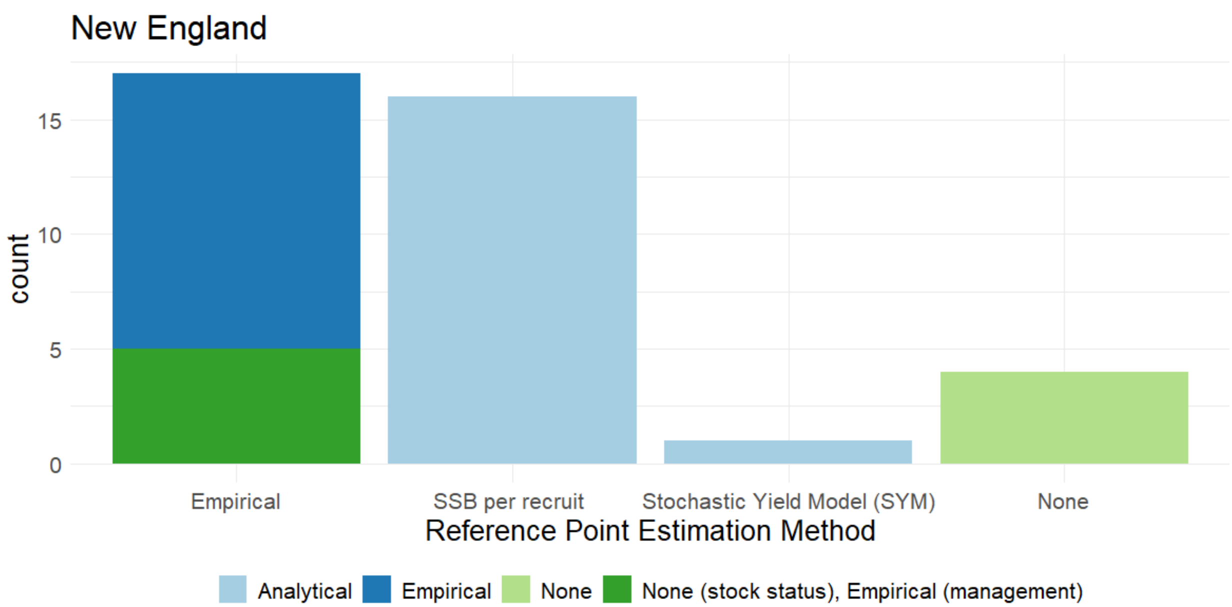
4. Review of Current Challenges in the Estimation and Application of Reference Point Estimation in the Region

Current challenges in the estimation and application of reference point estimation in the region (NEFMC)

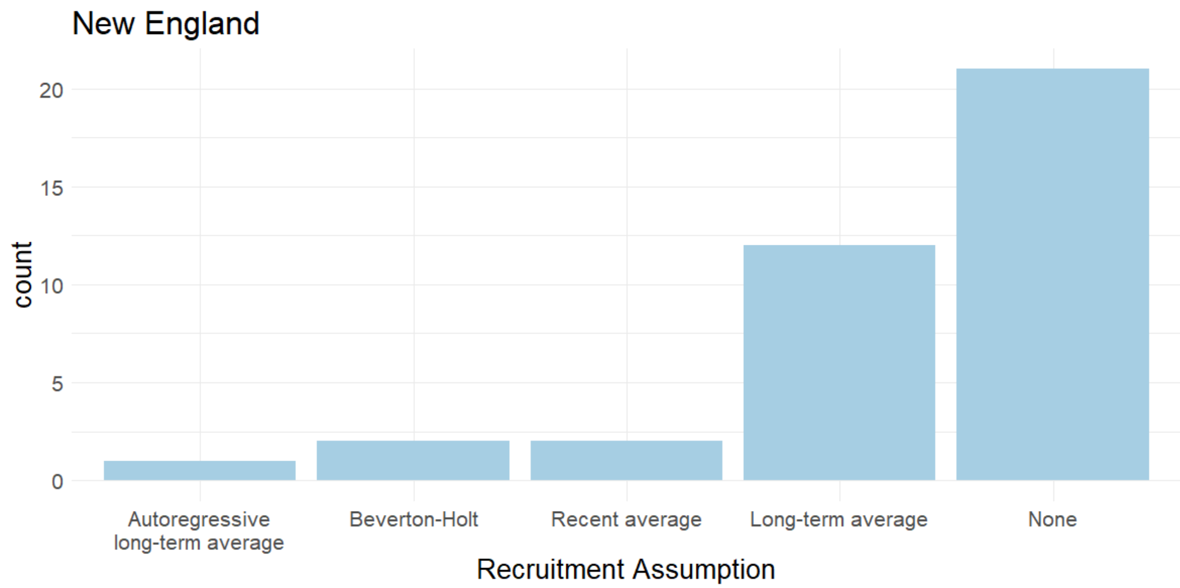
Lisa Kerr (UMaine)

We reviewed the current approaches used to define biological reference points for stocks managed under New England Fishery Management Council's (NEFMC) fishery management plans and assembled a database of information related to reference point estimation settings (LINK TO DATABASE). The information was compiled from available documentation including stock assessment reports, NEFMC Plan Development Team reports, fisheries management plans, and SSC reports. The data collated included details on the assessment type (analytical, empirical), methods of reference point estimation, and the respective harvest control rules used in catch advice setting.

Approximately half of NEFMC stocks utilize analytical approaches in the calculation of reference points, the majority of which estimate proxies for MSY reference points based on spawning stock biomass per recruit and an associated spawning potential ratio (i.e., F_{MSY} proxy $F_{40\%}$ and the biomass target SSB_{MSY} proxy $SSBF_{40\%}$).

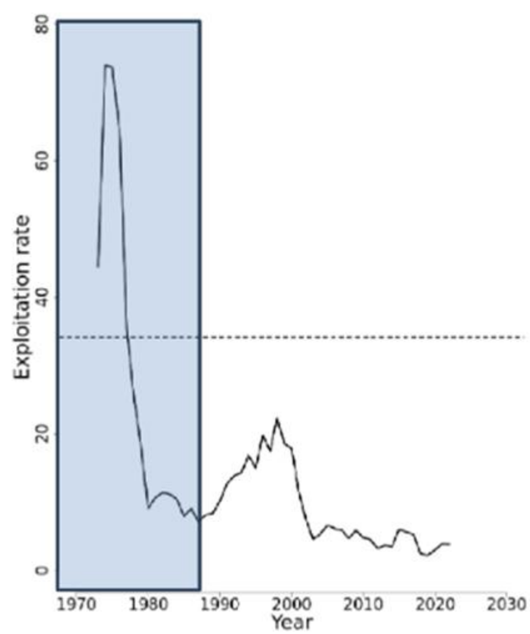


Frequency of reference point methods for New England stocks. Empirical methods are split between reference points used for stock status and reference points used for management only. None are stocks that do not have a reference point for stock status or management.



Frequency of recruitment assumption for New England stocks. The "none" category represents stocks that have empirical or none for estimation methods.

For the majority of these stocks, weight- and maturity-at-age represent recent average conditions in the stock, however, recruitment is typically assumed equivalent to the long-term average. We do have recent examples of revisions to the recruitment assumptions of reference points to account for changes in productivity (e.g., revised recruitment stanzas for SNE/MA winter flounder stock and SNE/MA yellowtail flounder stock). Autocorrelated recruitment was also recently assumed for short-term projections of Atlantic herring and white hake, which maintains short-term recruitment levels regardless of stock size and is viewed as an intermediate between assuming the long-term average or recent recruitment.



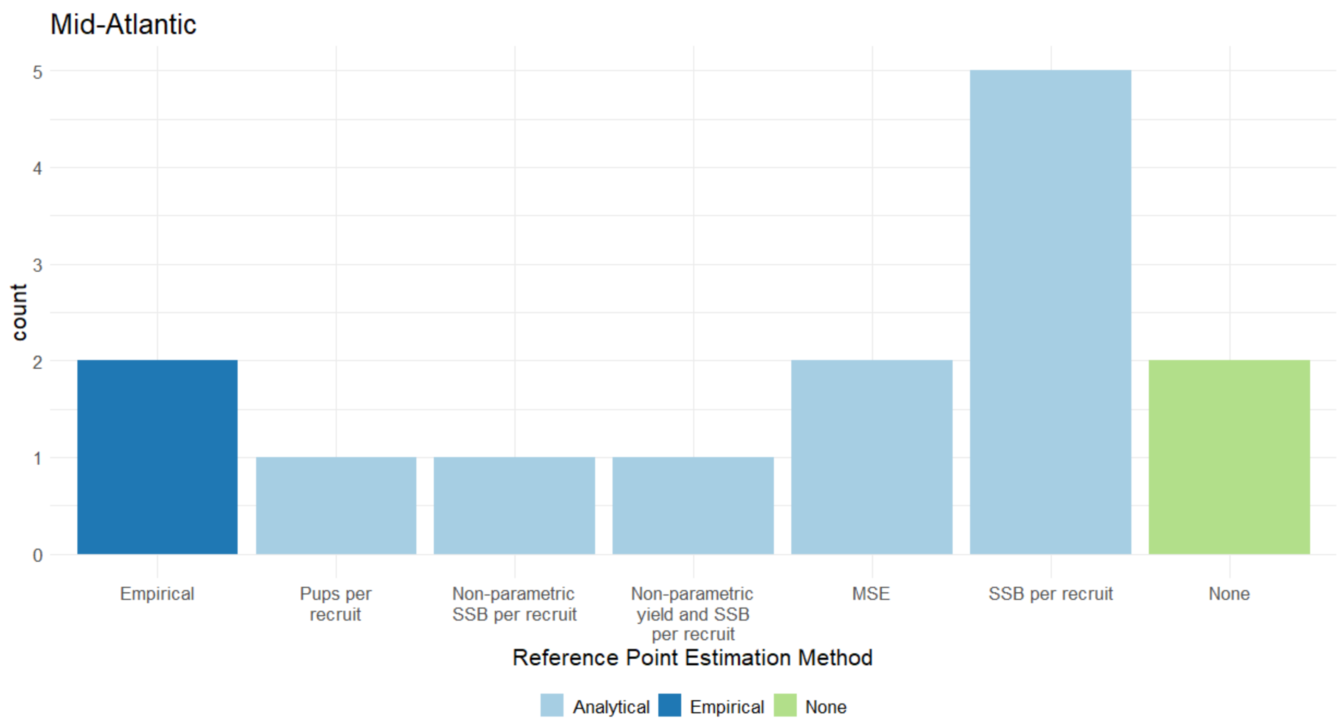
Southern Georges Bank/ Mid-Atlantic Silver hake empirical reference point based on reference period. F_{MSY} proxy (dashed line) is the average exploitation rate from 1973-1982 (approximate blue box) (modified from NEFSC 2020).

Definition of reference points for stocks with empirical approaches also rely on reference time periods for defining exploitation rate or biomass target. There are varied definitions of reference time periods for NEFMC stocks that apply an empirical approach, including a: 1) historical period where a stock was responsive to management, 2) historical period of high, sustained productivity that may approximate MSY conditions, and 3) contemporary period representative of current conditions. The use of historical reference periods assumes conditions for the stock have remained relatively static and will persist into the future. Contemporary reference periods incorporate recent measures of stock productivity which may be appropriate but can lead to changes in stock status and potential increases in catch advice without observable changes in indicators of stock health. Static characterizations of a stock's productivity can lead to unrealistic expectations of future productivity and thoughtful revision of recruitment assumptions is paramount. We need to outline criteria for defining reference periods for analytical and empirical reference points in a dynamic environment.

Current challenges in the estimation and application of reference point estimation in the region (MAFMC)

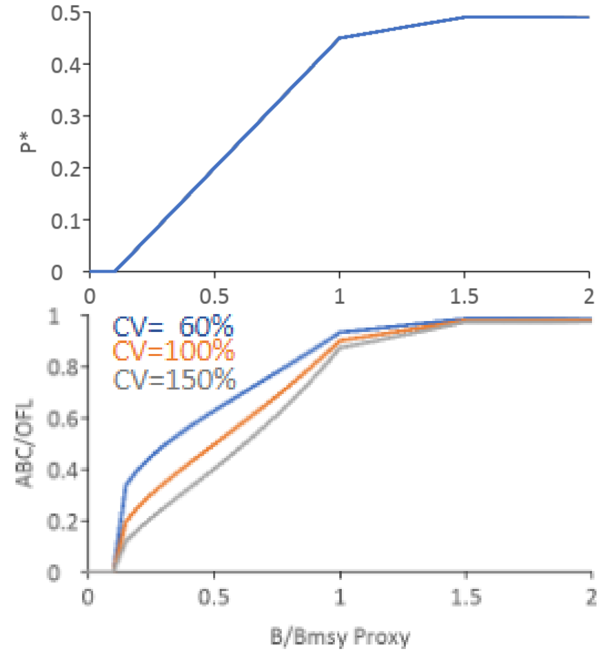
Mike Wilberg (Chesapeake Biological Laboratory UMaryland Center for Env. Sci.)

The Mid-Atlantic Fishery Management Council's approach to setting reference points and catch limits has been changing in recent years to reflect perceived changes in stock dynamics due to environmental change. The Mid-Atlantic Council manages 14 stocks: ten of which have analytic stock assessments, and the remaining four have empirical approaches to set catch limits (LINK TO DATABASE). The majority of the stocks that have analytic assessments use spawning potential ratio proxies to determine fishing mortality rate (F) and spawning stock biomass (SSB) reference points.



Frequency of reference point estimation method for Mid-Atlantic stocks. The "none" category are stocks that do not have a reference point for status determination or management.

The SSC uses a P* (acceptable probability of overfishing) control rule to specify acceptable biological catches (ABCs) in which P* increases with increasing SSB. To date, the SSC has modified aspects of setting ABCs and rebuilding targets for several stocks in response to perceived ecosystem change by modifying the inputs to the reference point calculations or to the ABC calculations. The primary changes to reference point and ABC calculations have been to use truncated recruitment time series to calculate SSB reference points and ABCs (black sea bass, butterfish, summer flounder) and rebuilding trajectories (Atlantic Mackerel). The SSC is developing alternative approaches for responding to environmental change with some important considerations being whether the changes are thought to be potentially reversible, whether they are caused by fishing or the environment, and whether changes in management would cause increases in the probability of overfishing.



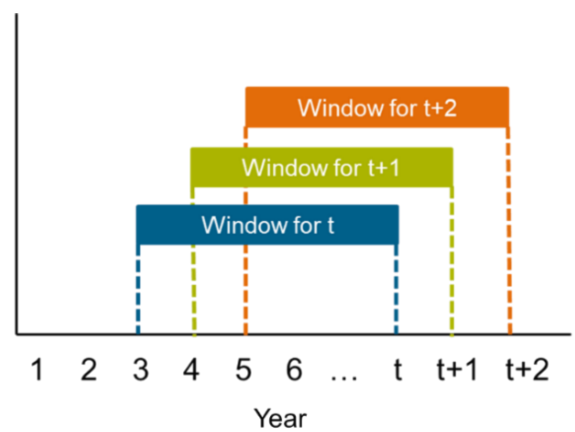
P is the acceptable probability of overfishing. The ABC is closer to the OFL when P* is high and CV is low (M.Wilberg).*

5. Evaluating Approaches to Defining Reference Points Considering Ecosystem Change

Overview of alternative approaches to defining reference points considering ecosystem change

Jerelle Jesse (UMaine)

To sustainably manage fisheries in the context of climate change, reference points must be adaptive to changes in stock productivity, necessitating a reconsideration of traditional methods to account for non-stationary stock dynamics. This review identifies alternative approaches to redefining reference points, particularly in light of ecosystem change, and highlights commonly employed dynamic reference point methods. Dynamic reference points adjust over time to reflect changes in underlying productivity. These methods include truncation approaches for stock productivity data (e.g., recruitment), such as moving windows, which shift with each additional year (e.g., O'Leary et al. 2020), and truncating a time series after detecting an abrupt change to include only years following a regime shift (e.g., Jiao 2009). Other approaches incorporate time-varying productivity or natural mortality, as well as environmentally linked parameters, into stock assessments with various decisions about how to propagate uncertainty and the influence of covariates into reference points (e.g., Miller et al. 2018). Dynamic stock-recruit relationships can allow the stock-recruit relationship to adjust over time to reflect potential changes in the relationship due to environmental fluctuations, climate change, and ecosystem shifts. (Collie et al., 2021). Another adaptive approach to defining reference points is dynamic B_0, which predicts a reference level of unfished biomass under prevailing environmental conditions as a means of accounting for changes in stock productivity over time (MacCall et al., 1985). Additionally, ecosystem model outputs can be used to adjust reference points based on ecosystem indicators (e.g., ecosystem-based fishing mortality reference point, FECO; Howell et al., 2021). Key themes across these methods include: 1) the need for stock-specific approaches to updating reference points in the context of ecosystem change; 2) the usefulness of simulations for selecting methods to redefine reference points and assess their robustness under future climate scenarios; and 3) the importance of supporting evidence (e.g., trends, residual patterns) for redefining reference points. There were varying perspectives on whether a mechanistic understanding of environmental factors influencing time-varying processes is necessary for redefining reference points.



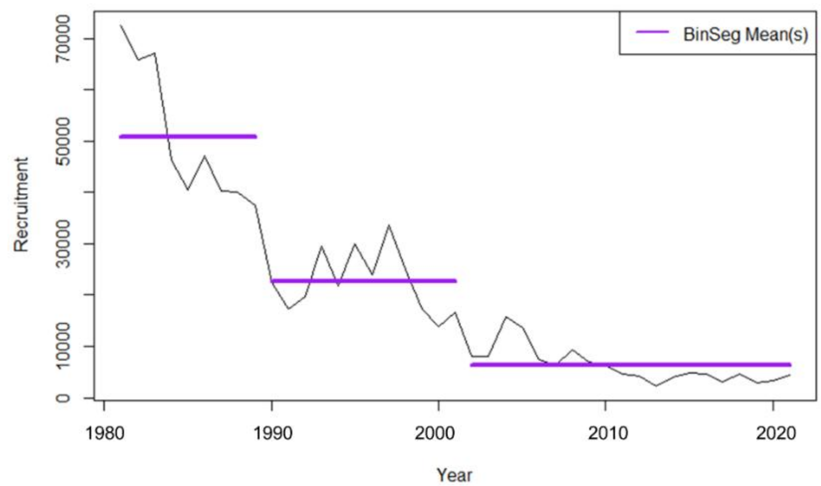
A moving window approach truncates the timeseries to a certain number of years and then shifts for each additional year, e.g. most recent five years of growth data (J.Jesse).

Consideration of regime shifts for management reference points

Steve Cadrin (UMass)

Conventional Maximum Sustainable Yield reference points assume stationary productivity, and US National Standard 1 Guidelines specify that: "*MSY is the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological, environmental conditions...*" However, rapidly changing conditions in the northwest Atlantic ecosystem challenge the estimation of such reference points. Guidance for confronting this challenge is taken from the Northwest Atlantic Fisheries Organization (NAFO 2021) as well as recent attempts to account for changes in recruitment to derive rebuilding targets for New England stocks.

NAFO developed conditions for revising reference points: 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.



Change point analysis found two change points in SNE/MA winter flounder recruitment (from Cadrin 2023).

Recent lessons from New England fisheries suggest that: 1) ideally, reference points should be based on stock-recruit relationships or environmental covariates (e.g., Stock and Miller 2021); 2) regime shifts should be tested with data (rather than model estimates) and time series analyses (e.g., Killick and Eckley 2014); and 3) autocorrelated recruitment offers an intermediate between assuming the long-term distribution of recruitment for deriving reference points and a more recent distribution for projections (Brodziak et al. 1998).

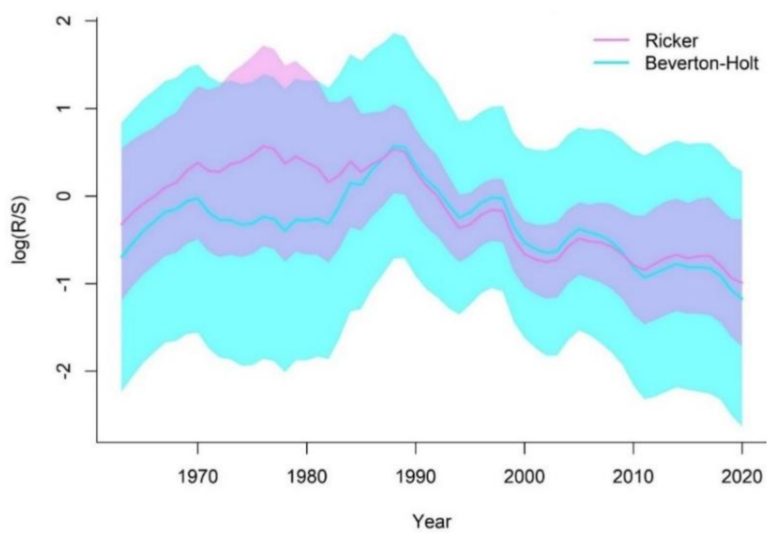
Dynamic recruitment rates in New England fish stocks

Jeremy Collie (URI), Richard Bell (TNC), Cóilín Minto (ATU), Paul Spencer (AFSC) & Rachel Marshall (URI)

Evidence is accumulating that recruitment rates, measured as recruits per spawner, vary on decadal time scales. A consistent approach for modeling and projecting recruitment is needed to resolve inconsistencies between short-term projections and rebuilding targets. We fit dynamic stock-recruitment models to estimate this variability and its associated uncertainty for a suite of New England and Mid-Atlantic fish stocks.

Dynamic stock-recruitment models can improve the accuracy of recruitment projections up to three years in the future (Tableau et al. 2019). Environment-driven recruitment models can modestly improve recruitment forecasts for some stocks. However, for most stocks the mechanisms by which the environment affects recruitment remain unknown.

Changes in recruitment rate imply corresponding changes to biological reference points, both F_{MSY} and B_{MSY}. F_{MSY} proxies such as $F_{40\%}$ fail to account for changes in recruitment rate and can result in fishing rates that are too high when recruitment rate declines. Comparing among life-history parameters, dynamic reference points are more sensitive to changes in recruitment rate than to changes in growth or maturity, which are typically accounted for in stock assessments if the data exist (Collie et al. 2021). We found more variability in fishing mortality reference points than stock size reference points. Dynamic reference points also suggest that time-varying harvest control rules could provide resilience to climate variability.



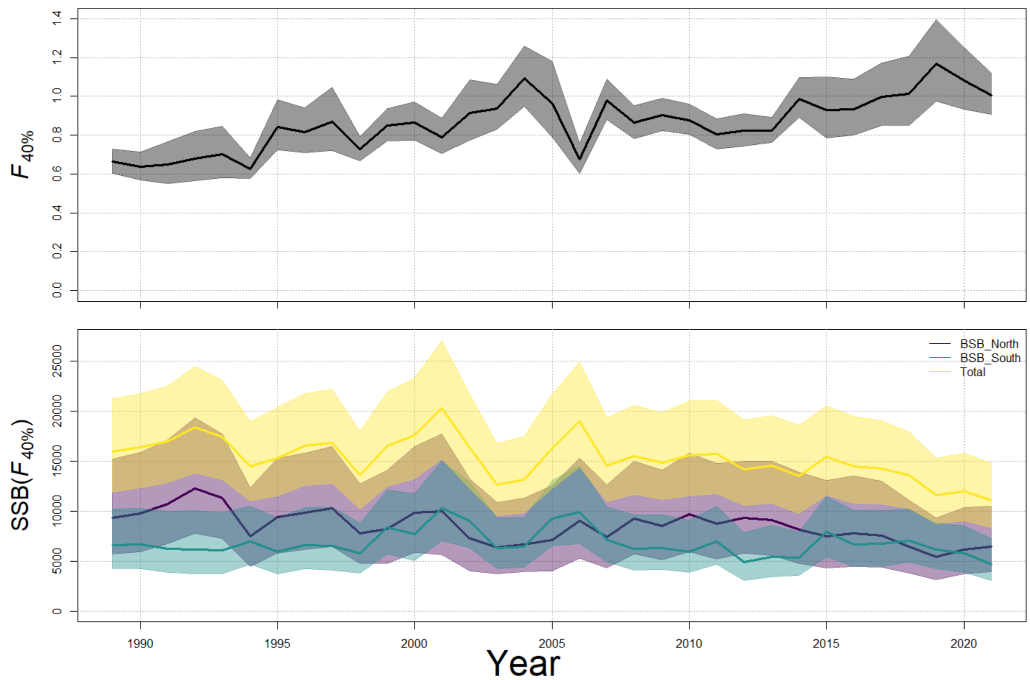
Time-varying productivity for white hake using both Beverton-Holt and Ricker stock recruitment model (from Collie 2023).

Simulations were conducted to compare the performance of time-varying and time-invariant harvest control rules applied to white hake. Preliminary results found that with the decline in stock productivity, none of the harvest control rules could rebuild to the historical, stationary reference points. The time-varying control rule, however, maintained SSB at or above the time-varying SSB reference point particularly during periods of low productivity. Productivity was low for the final two decades of the timeseries and the dynamic harvest control rule maintained SSB above the dynamic SSB_{MSY} reference point resulting in a 'not overfished' stock status. The time-invariant SSB_{MSY} was higher than the dynamic SSB_{MSY} during periods of low productivity and the time-invariant harvest control rule could not rebuild the stock to the reference point resulting in the stock being 'overfished' for the final two decades of the time series. The time-varying harvest control rule tracked with the changes in stock productivity and was better able to meet management objectives.

Estimating dynamic reference points in WHAM

Tim Miller (NEFSC)

The Woods Hole Assessment Model (WHAM) is a state-space age structured stock assessment model that can be configured to treat a variety of sources of stochastic and environmental covariate induced temporal variability in the dynamics of fish stocks (Stock and Miller 2021). WHAM can also produce a variety of biological reference points and associated measures of



WHAM can calculate time-varying reference points and estimate uncertainty using annual inputs, black sea bass (from Miller et al. 2023)

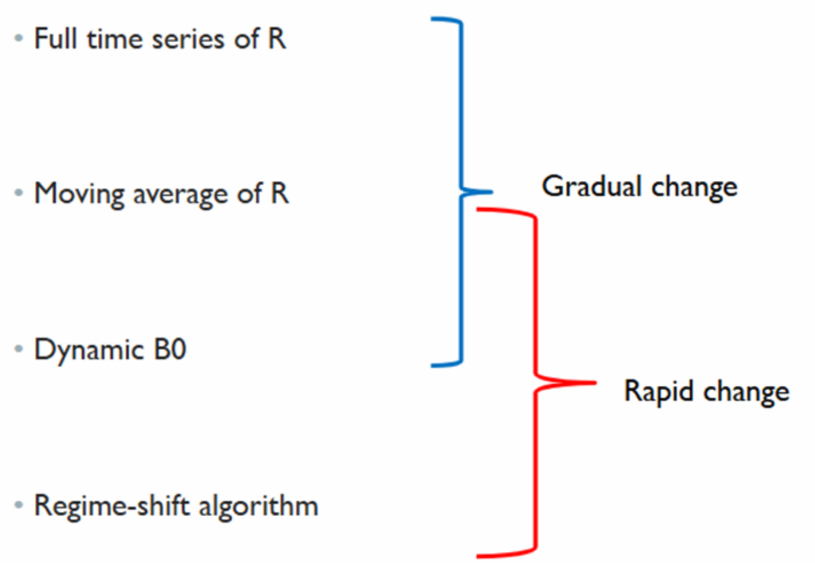
uncertainty that can vary temporally as a consequence of temporal variation in productivity estimated in the assessment model. Whether a covariate should be included in the assessment model should be considered statistically by assessing whether modeling a covariate effect improves the model over one that does not model the effect. Improvement can be assessed by a reduction in residual variation, and better AIC, and whether these improvements are consistent, retrospectively, fitting the model sequentially removing years of observations. Population demographic parameters and productivity can be highly variable from one year to the next, but less variable longer-term changes are presumably what should be targeted for dynamic reference points.

Redefining reference points in the context of control rules

John Wiedenmann (Rutgers University)

Harvest control rules are policies designed to specify catch limits to achieve fisheries management objectives, and many types of harvest control rules have been developed and applied globally. In cases where traditional ("data-rich") biological reference points can be estimated in the U.S., harvest control rules generally aim to achieve a target harvest rate (F), or probability of overfishing (P*), with both approaches aiming to limit the frequency of overfishing on a given stock. In the context of reference points, at a minimum, harvest control rules require an estimate of the F that defines overfishing (F_{MSY}), setting a fixed target F or P* (called a fixed harvest control rule). A more complex harvest control rule adjusts the target F or P* downward as the biomass falls below some threshold (called a threshold-based harvest control rule), and requires a biomass reference point, typically B_{MSY} or SSB_{MSY}. Thus, dynamic reference points can result in dynamic harvest control rules by changing the target *F* or *P** through changes in F_{MSY} and SSB_{MSY}.

The vast majority of stocks in Northeast U.S. rely on the spawning potential ratio (SPR)-based proxy approaches to setting MSY-based reference points, where F_{MSY} is set to the value that reduces the SPR to some fraction of the unfinished level (typically 40%, or $F_{MSY} = F_{40\%}$), and biomass reference point is the spawning biomass that results from fishing at this level ($SSB_{MSY} = SSB_{40\%}$) under some mean recruitment. These reference points are dynamic, changing with each assessment with changes in mean weight-, maturity-, and selectivity-at-age, and changes in the mean level of recruitment used to calculate SSB_{MSY}. Changes in reference point estimates are generally gradual between assessments, but for a few Northeast stocks with prolonged periods of poor recruitment, changes in the reference period used to calculate mean recruitment resulted in large, abrupt decreases in SSB_{MSY}. Such changes impact rebuilding status and projections, and can result in large changes in the prescribed F or P* in a threshold harvest control rule. Approaches that respond more smoothly to changes in recruitment (e.g., the dynamic B_0 approach) can mitigate against abrupt changes in SSB_{MSY} on the harvest control rule. A fixed harvest control rule that does not depend on biomass is another potential approach.



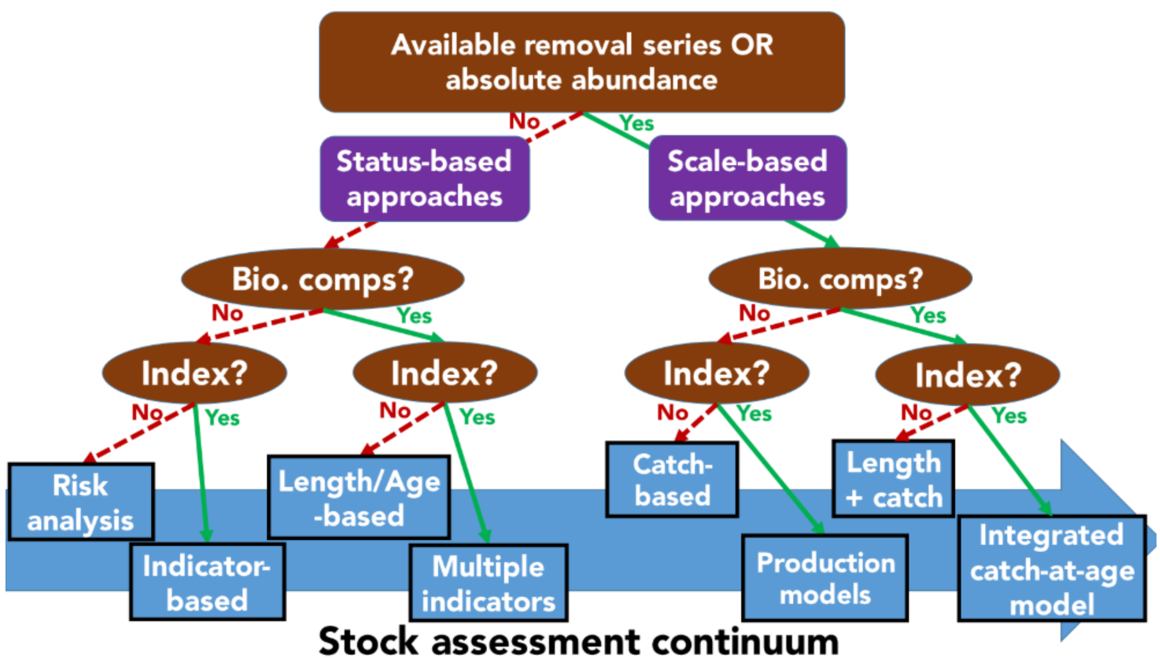
Rapid changes in reference points can result in challenges with threshold harvest control rules, while gradual changes can mitigate these challenges (J. Wiedenmann)

Some data-limited harvest control rules incorporate reference points, but many do not. In the Northeast U.S., a hodgepodge of data-limited harvest control rules are used, with only a few incorporating some type of reference point. Identification of data-limited reference points that are suitable proxies for MSY-based reference points would be an important step forward in data-limited fisheries management, but such proxies have yet to be identified for stocks in the region.

Defining reference points for data and resource limited applications

Jason Cope (NWFSC)

Reference points provide the means to interpret stock assessment output and operationalize management objectives. Reference points can be based on a variety of outputs and meet different management objectives, not just maximum sustainable yield. When data or resources limit the ability to do traditional stock assessments, data and resource limited (DRL) methods have been developed to still provide results to support science-based management decisions. These methods also need to consider how those results are interpreted against reference points. Some DRL methods, such as risk assessments and model-free indicator-based methods, may need method-specific reference points (e.g., vulnerability reference points, indicator-specific reference points). Model-free indicator approaches are particularly varied and thus the interpretation of those approaches rely heavily on the defined reference points that can be either particularly difficult to specify or are highly uncertain. There may also be multiple reference points that will need to be interpreted in an integrated way (e.g., sequential or simultaneous trigger frameworks).



DRL stock assessment methods are based on the available data which influences the type of reference point that can be used (from Cope 2024).

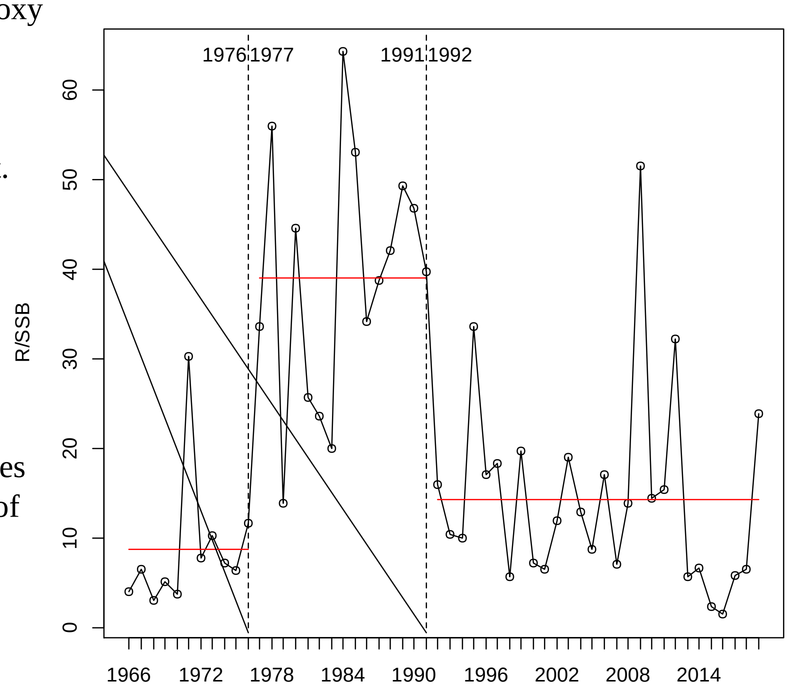
DRL methods that use underlying population dynamics models often have similar metrics to more traditional assessments and can thus borrow reference points established in more data-rich assessments. Biological reference points are highly determined by life history values, and thus uncertainty in life history traits may provide an additional source of uncertainty, in addition to the higher uncertainty associated with DRL assessments, when determining buffers on catch limits. There are also instances where data do not support the articulation of weight or number based catch limits, thus rate (e.g., fishing mortality) based limits are instead needed, and therefore rate-based reference points would also need to be defined.

A major simplifying assumption of many DRL methods and associated reference points are equilibrium dynamics or static life history. Given the link between biological reference points and life history traits, heightened consideration is needed when incorporating this uncertainty into either defining reference points or buffer calculations based on the interpretation of model output relative to reference points in dynamic or changing environmental conditions. These same considerations are often needed in traditional stock assessments as well, so similar reasoning can be developed from those examples.

Application: Atlantic herring case study

Jon Deroba (NEFSC)

Atlantic herring have experienced an unprecedented series of poor recruitment for approximately a decade. These poor recruitments led to a reconsideration of the time stanza of recruitments used to define the biomass MSY proxy reference point (i.e., $B_{40\%}$) and the recruitment assumptions used for short-term projections during the 2022 management track assessment. Previously, the reference point and short-term projections used random draws from the entire time series of estimated recruitments, which no longer seemed appropriate.



Atlantic herring recruits per spawner changepoints from the 2022 management track assessment. The most recent recruitment stanza (1992-2019) used in reference points (J.Deroba).

A change-point analysis of the recruits per spawner (R/S) time series was conducted to test for evidence of temporal shifts in production that may be environmentally driven. A significant change-point was identified beginning in 1992 that demonstrated a reduction to the average R/S relative to previous years. This decline in production was inconsistent with a compensatory response from a stock-recruit relationship, which suggested an environmental driver. Consequently, $B_{40\%}$ was calculated using the estimated recruitment time series from 1992-2019 (the most recent two years were not included due to high imprecision in the estimates).

Short-term projections were conducted using an autoregressive (AR1) model so that projected recruitments would remain relatively low and help avoid overly optimistic projections. The change to the calculation of the biomass reference point had the effect of improving our perception of stock status and permitting an increase in target fishing mortality based on the harvest control rule used for herring, even though the absolute condition of the population had not improved (i.e., estimated biomass in the terminal year was still low). This counterintuitive outcome has occurred in other stock assessments and is worthy of additional research.

Novel approaches being explored by MAFMC

Paul Rago (MA SSC)

Biological reference points are complex scalar functions that integrate observable biological data, derived parameters from stock assessment models, and policy to define desired rates of harvest and biomass levels. As assessment models are updated with new data, reference points are revised, but tools for isolating the effects of data and model-based changes are not commonly used. Several practical methods for disentangling these effects are proposed.

Recruitment in nearly all Northeast assessments is assumed to be a density-independent stochastic process with variations about some mean whose parameters are defined by a subset of model-based estimates. One way of monitoring the efficacy of management or progress towards rebuilding targets is to compare observed catches or derived biomass estimates with what would have been possible under optimal management given the realized set of recruitment estimates. In other words, how well have we played the hand we have been dealt?

Methods are proposed to evaluate this counterfactual scenario for several Mid-Atlantic stocks. Results illustrate the success of management measures albeit at a pace slower than implementation of optimal harvest rates defined by the reference point. Further refinement of the methodology would include incorporation of annual estimates of average weights and maturity, rather than recent values, into the scenarios. Large changes in reference points are frequently reported but seldom analyzed with respect to the underlying changes in weights at age, fishery selectivity, maturation and so forth. A methodology borrowed from demography (Horiuchi et al. 2008) can be used to decompose the total differential of reference points into their component factors. The methodology was illustrated for Georges Bank haddock. Between 2005 and 2019 large changes in average weights at age have been the primary factors contributing to reduced MSY. F_{MSY} has increased two-fold, but this is misleading, since the selectivity has shifted toward older fish. Decomposition analyses reveal the increase in F_{MSY} to be almost entirely offset by the changes in selectivity at age. Reductions in estimated average recruitment have been the other primary factor reducing reference points for haddock. The Horiuchi method holds promise for analyzing the factors underlying the timing and magnitude of changes in biological reference points, and potentially the ability to link such changes to ecosystem factors.

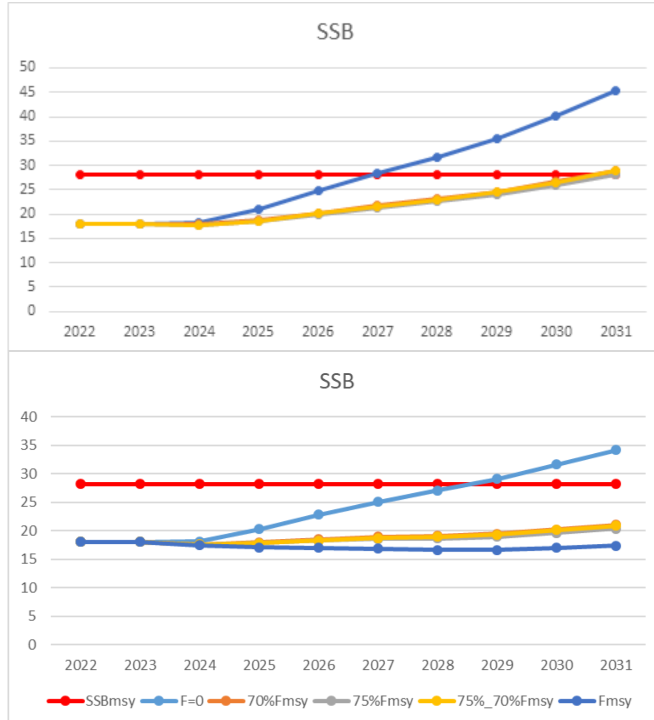
Changes in F40%, average recruitment, SSB, and MSY for Georges Bank Haddock by stock assessment year. Each axis is ratio of reported estimate to 2001 GARM I (P.Rago).

Finally, the potential utility of odds ratios and randomization tests for diagnosing evidence for stock recruitment relationships is described. Contingency tables can be used to compute the odds of recruitment above the given stock biomass above its median value. Randomization tests can be used to compare the probability of observed patterns of recruitment, SSB and R/SSB for recent stanza vs earlier periods. These methods are illustrated for Atlantic mackerel.

Management implications and challenges of stationary and dynamic reference points

Cate O'Keefe (NEFMC)

The New England Fishery Management Council manages ten Fishery Management Plans including species ranging from Maine to North Carolina within US federal waters of the Gulf of Maine, Georges Bank, and the Mid-Atlantic Bight. Currently, several stocks are characterized as overfished, but few are experiencing overfishing. The majority of overfished stocks do not have defined biological reference points and are assessed with empirical approaches. For overfished stocks that have reference points, rebuilding efforts have been largely unsuccessful due to climate change and other external factors limiting ability to rebuild to historical reference points. Management challenges associated with stationary assumptions include 1) unknown stock status, which prevents managing to specific targets and thresholds; 2) unrealistic rebuilding targets, which have forced substantial reductions in fishing effort due to failure to rebuild within specific timeframes; and 3) constrained ability to target healthy stocks, which has resulted in negative economic impacts. Stationary assumptions have resulted in inconsistent approaches for setting catch advice, deviations from the Council's Risk Policy and harvest control rules, inconsistent recruitment assumptions between reference points and projections, and ignoring effects of climate drivers.



Rebuilding timelines to SSB_{MSY} (red line) across a range of F values, in which the SSB estimates assumes 1963-2019 recruitment, and projections either assume the same recruitment (top) or 1995-2019 recruitment (bottom) (C.O'Keefe)

Dynamic reference points may better reflect prevailing conditions and provide a more realistic basis for stock status determination. However, there are associated management challenges with the use of dynamic reference points, including 1) lack of formal guidance of how to incorporate dynamic approaches in management; 2) reluctance to onboard new approaches in the management arena; and 3) implications for implementation which may impact individual or fleet allocations. To move forward with dynamic approaches, both scientific and management challenges need to be considered, and processes for integrating alternative approaches to estimating reference points should be developed.

6. Recommendations

When to Revise Reference Points?

Workshop participants discussed and made recommendations on when reference points should be revised in the context of ecosystem change, emphasizing the need to identify both system-wide and stock-specific changes to guide decision-making on revising reference points. Regime shifts and ecosystem trends reflect broader system-wide changes, so evidence of such changes should be observed across multiple ecosystem components, such as different species or trophic levels. Thus, adopting multi-species approaches can help determine when it is appropriate to redefine reference points. In addition, various analytical methods, such as change point analysis, can be used to detect trends and regime shifts in ecosystem conditions.

Evidence of changes across multiple ecosystem components was considered crucial to assess whether a new regime or trend is likely to persist or revert to previous conditions. Indicators of system-wide change are included in the State of the Ecosystem Report (e.g., NEFSC 2023), and the group supported increasing efforts to formally identify regime shifts in the region. Strong evidence of a regime shift was seen as solid supporting evidence for revising reference points. The group discussed ongoing work in the region to address a possible regime shift around 2010 and further synthesis on this topic is anticipated in future State of the Ecosystem Reports.

Identification and understanding of stock-specific changes in dynamics, particularly in recruitment, was deemed important to the decision of when to redefine reference points. There is a recognized need for a directive to look for changes in the dynamics (e.g., growth, maturity, recruitment, R/SSB, natural mortality) of stocks or stock complexes in the region. This work can be done outside or inside of a stock assessment. Stock-specific ecosystem profiles conducted as part of efforts to address Term of Reference (TOR) 1 in research track assessments can synthesize existing literature on this topic (generic TOR1: "*Identify relevant ecosystem and climate influences on the stock. Characterize the uncertainty in the relevant sources of data and their link to stock dynamics. Consider findings, as appropriate, in addressing other TORs. Report how the findings were considered under impacted TORs*.").

Although identifying the mechanism of changes in stock dynamics is highly desired there was open discussion on whether it is required for redefining reference points. Identifying a mechanism or driver of changes in stock dynamics can be difficult because a combination of factors may be driving change. Oftentimes management decisions need to be made before mechanisms have been identified, but there are methods of incorporating time-varying parameters in reference points that can be implemented without understanding the mechanism and existing knowledge and expert judgment can be used in the meantime. However, low recruitment due to low stock size should be considered as an explanation before assuming ecosystem drivers are responsible.

How to Revise Reference Points?

Workshop participants provided recommendations for revising reference points in the context of ecosystem change, recognizing the need for both short-term and long-term solutions. In the short term, the focus should be on characterizing patterns of change in recruitment. Recruitment variation should be evaluated across multiple indicators, such as recruits, recruits per spawner, and egg production, to identify trends, non-stationary patterns, or potential change points that could signal regime shifts. Special attention should be given to the mechanisms behind these changes, particularly whether they are driven by environmental factors or spawning stock size, as this would influence the approach for accounting for time-varying recruitment. Stock-recruit relationships should be routinely reexamined in stock assessments to determine if they are sufficient for use in stock assessments as these relationships could offer MSY-based reference points without relying on proxies. The criteria for determining a "well-determined" stock-recruit relationship need to be reconsidered, along with a standardized process for rejecting inadequate relationships.

The commonly applied proxy-based reference point $F_{40\%}$ and associated SSB reference point can incorporate changes in stock productivity, however, this comes with known challenges. In cases when a decline in recruitment productivity is recognized, a different recruitment stanza can be used to reflect this change. When a lower recruitment assumption is used, the SSB reference point will decline, however the calculation of $F_{40\%}$ does not account for changes in recruitment and can result in fishing rates remaining static. This is a known problem of using SPR-based proxies like $F_{40\%}$ and can result in maintaining the target F at lower stock sizes. Furthermore, changing the biomass-based reference point may result in an abrupt stock status change, such as an overfished stock no longer being overfished. This change in status could result in different target F (e.g., shift from $F_{rebuild}$ to 75%F_{MSY}) and allowable catch could be increased even when the stock health remains unchanged. This disconnect introduces the risk of maintaining higher fishing mortality rates on a stock already in low productivity regimes. If productivity declines, both the F and biomass-based reference points may need to be lowered to protect the stock. This necessitates ad-hoc adjustments to proxy reference points and criteria should be developed for this process. Truncation methods for stock productivity can offer short-term solutions; however, it is important to consider whether the change is gradual or abrupt, as well as the likelihood of a regime shift. In cases for which changing recruitment assumptions informing long-term projections is not well supported, adoption of autocorrelated recruitment in short-term projections can provide an intermediate approach between assuming a long-term average and using recent recruitment data (as illustrated by the white hake example).

Adoption of alternative methods for defining reference points that are more responsive to a changing environment should be considered. This could include approaches such as dynamic B_0 or utilizing dynamic stock-recruitment models. Participants also recommended the transition of stock assessments to model platforms (e.g., WHAM) that can account for time-varying dynamics (e.g., natural mortality) or directly incorporate important environmental covariates into the assessment when indicated and propagate uncertainty into long-term projections. The group also discussed considering a fundamental shift in the type of reference points used in the region. One approach is to move away from management based on biomass targets (e.g., a target F expected to rebuild the stock to B_{MSY} within 10 years) and shift toward management focused solely on F limits and precautionary targets (i.e., an F level that minimizes the risk of exceeding the F limit). This approach may be suitable when rebuilding is unlikely for stocks whose productivity is affected by environmental changes rather than fishing pressure. It is crucial to prioritize thinking beyond the conventional MSY and equilibrium models, as current methods may not be effective in the face of ecosystem change (i.e., if we had to start from scratch on defining reference points, how would we do this?). Reference points should be considered in the broader context of the entire management procedure, including the harvest control rule, precautionary targets, and threshold biomass levels. Furthermore, more guidance is needed on how to approach redefining empirical reference points in the context of ecosystem change. A comprehensive evaluation of the diversity of empirical methods currently in use should be conducted, and standard criteria for their application should be developed. For each recommended approach, it is important to better understand the potential risks and benefits before implementation. It is recommended to assess both current and revised approaches to reference points through management strategy evaluation.

Practical Limitations

The group discussed practical limitations with redefining reference points in a changing ecosystem. There was acknowledgement that key questions have to be answered about who, how, and when to redefine reference points within the fishery management process. This is further complicated as some stocks have reference points defined and updated through assessments, and other stocks have a mixed approach with some reference points defined through the assessment and others via the fishery management plan. For stocks with reference points prescribed within their fishery management plan, revisions would likely take a Council action (e.g., fishery management plan amendment). The discussion centered around possible limitations and benefits of redefining reference points at different stages of the fishery management process (e.g., revision within the research track, management track, at the SSC, or within a revision to a fishery management plan). There was a recognized need to develop guidance for incorporating these recommendations into the management system given the diverse pathways through which reference points are defined for federally management fisheries resources.

Outlining and prioritizing how and where recommendations could be used within the stock assessment and management processes would be beneficial. This guidance could include what methods could be employed now and for which stocks, as well as defining an on-ramp and identifying barriers for any new approaches that may be utilized in the future. Additionally, there was discussion around how modified or new reference points could merge with the legal requirements of fisheries management (i.e., what would overfishing mean when we move away from an equilibrium view of reference points?). Lastly, there was general consensus that collaboration between science and management is needed to find meaningful solutions and there is a lot of interesting work that can be done outside of formal processes.

6.1. Synthesis of Recommendations

Our synthesis of recommendations and corresponding action items reflects the discussions of participants during the workshop and are intended to help guide regional work in these focal research areas. Our goal is to foster collaboration and shared progress across the scientific community.

When to Revise Reference Points?

- Consider both ecosystem-wide and stock-specific indicators of change to assess whether it is appropriate to revise reference points.
  - *Action Item:* Integrate a review of indicators into research and management track stock assessment processes.
- Identify regime shifts in the region using multiple system components and indicators to support decision making regarding revision of reference points.
  - *Action Item:* Expand the NEFSC's State of the Ecosystem Report to include more emerging research on regime shifts in the region.
- Characterize stability of prevailing ocean conditions and expectations of future change to support decision making regarding revision of reference points.
  - *Action Item:* Include likelihood statements (i.e., National Climate Assessment) based on best available science in the State of the Ecosystem Report regarding probability of stability of current and future states of ocean conditions.
- Characterize non-stationarity in stock dynamics and linkages to environmental drivers to support the decision to revise reference points.
  - *Action Item:* Examine stock dynamics (growth, maturity, recruitment, etc.) for stationary and non-stationary patterns to determine if stock productivity has changed.
  - *Action Item:* Evaluate relationships between environmental drivers and each aspect of stock dynamics. Understanding of mechanisms is highly desired but should not be a limitation to revision of reference points.

How to Revise Reference Points?

- Prioritize focus on characterizing non-stationarity in and the influence of environmental drivers on recruitment to inform reference points.
  - *Action item:* Characterize non-stationary patterns and whether there are definitive change points in recruitment indices using multiple indicators when available (e.g., recruits per spawner, stock-recruit relationship).

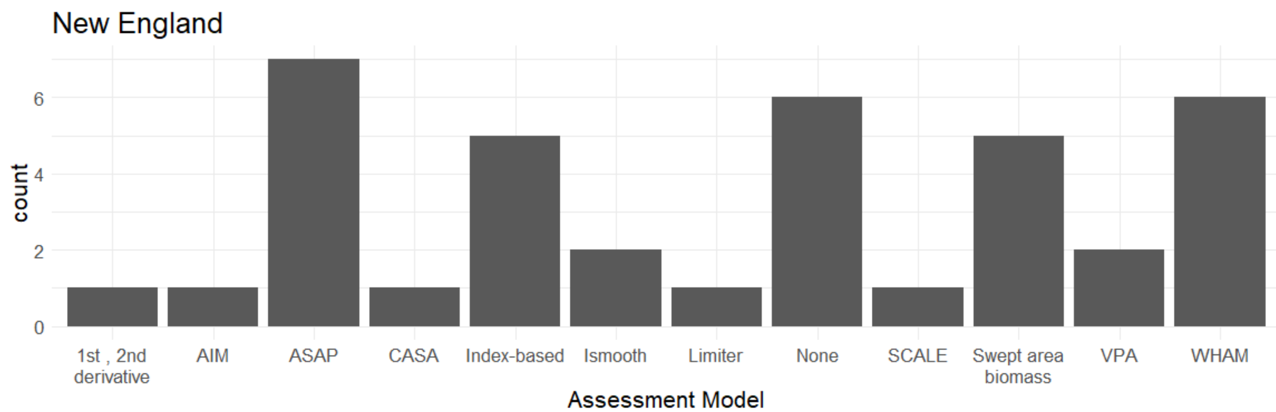
- Stock recruitment functions should be routinely examined and not assumed to be insufficient for use in stock assessments.
    - *Action item:* Explore fitting of stock-recruit relationships within the assessment model and with environmental covariates. Criteria should be developed for defining a "well-determined" relationship and for rejecting a stock-recruit relationship.
- Adopt assessment models (e.g. WHAM) that can account for time-varying stock dynamics and can integrate environmental covariates and can propagate uncertainty into projections.
    - *Action item:* Provide more explicit guidance on reference points TOR in the research track process regarding definition under dynamic conditions.
    - *Action item:* Consider the consistency in assumptions between short-term projections and reference points. There is a recently formed NOAA research track stock assessment working group focused on projection and the Research Track Steering Committee recommended integration of thinking on topics (e.g., non-stationarity) across short-term projections and definition of reference points.
- For stocks using analytical approaches to determine reference points, re-examine assumptions and specifications of status quo reference points.
    - *Action item:* Evaluate stability of recruitment, weight-at-age, maturity-at-age, and selectivity-at-age in recent years to inform assumptions regarding prevailing conditions.
- For stocks using empirical approaches to determine reference points, there is a need to characterize the responsiveness of alternative approaches to environmental change.
    - *Action Item:* Cross-stock evaluation of how we are defining empirical reference points and when they are used in status determination or catch advice setting. Evaluate the diversity of empirical methods for determining reference points and provide guidance for defining in a dynamic environment.
- Consider alternative methods for defining reference points that are more responsive to a changing environment.
    - *Action Item:* Consider a broad range of dynamic reference points as suggested by the circumstances (e.g., dynamic B_0, utilizing dynamic stock-recruit models, updating assumptions for proxy-based reference points (e.g., spawning potential ratio), and adopting temporally stochastic assessment models or models that integrate covariate effects and propagate uncertainty into long-term projections). This guidance could be made more explicit in research track TORs.
- Consider fundamental shifts in the use of reference points in the region.

- *Action Item:* Focus on estimating a sustainable F target rather than rebuilding to a historical stock size. Consider reference points in the context of the whole management system.

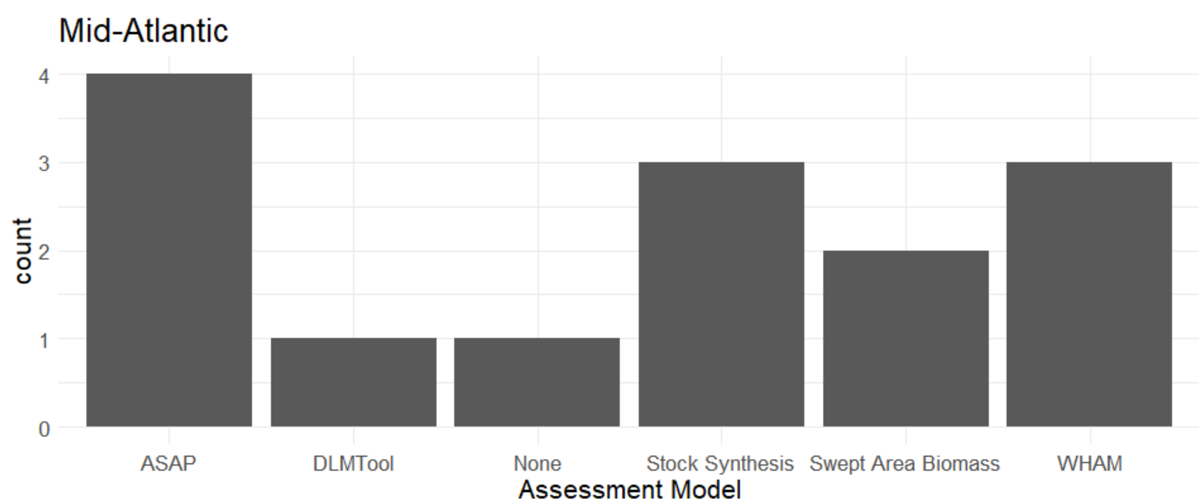
- Evaluate risks of current and alternative approaches to define reference points
    - *Action Item:* Use management strategy evaluation to simulation test risks of status quo approaches and performance of alternative approaches to define reference points under climate change scenarios.

- Address key questions in the fishery management process regarding who, how, and when to redefine reference points within the fishery management process.
    - *Action Item:* Establish joint management-science (including expertise on stock assessment and ecosystem change) working group on this topic. Consider adoption of more flexible descriptions of reference points in FMP such that they can be modified without Council action.

7. Additional Figures



Frequency of assessment model type for New England stocks.



Frequency of assessment model type for Mid-Atlantic stocks.

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Glossary

B_0: Unfished biomass

B_{MSY}: The stock biomass level at which the fishery is able to achieve the maximum sustainable yield

Dynamic B_0: Dynamic unfished biomass

F_{MSY}: The fishing mortality rate which provides the maximum sustainable yield.

$F_{X\%}$: The fishing mortality rate that results in x% equilibrium spawning potential ratio

MSY: The maximum yield (catch) that can be taken on average from the fishery in the long term without impacting the reproductive potential of the stock.

MSY proxies: Analytical proxies for B_{MSY}, F_{MSY} and MSY are quantitative surrogates that can be used if direct estimation is not possible, or the estimates are not considered reliable.

Additional Glossary Resource on Reference Points:

https://www.pewtrusts.org/~/media/assets/2016/09/referencepts_brief_v6.pdf