Technical Guidance for Estimating Status Determination Reference Points and their Proxies in Accordance with the National Standard 1 Guidelines

Prepared for the

National Marine Fisheries Service

By

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EXECUTIVE SUMMARY

National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act (MSA) requires preventing overfishing while achieving, on a continuing basis, optimum yield (OY), from managed U.S. fisheries. OY is limited by the biologically feasible maximum sustainable yield (MSY[1]) which in turn serves as the basis for status determination criteria (SDC) by which NOAA determines when a stock is experiencing overfishing or is overfished. The Maximum Fishing Mortality Threshold (MFMT) is the level of fishing mortality above which overfishing is occurring, and the Minimum Stock Size Threshold (MSST) is the biomass limit below which a stock is considered to be overfished and in need of rebuilding. The NS1 Guidelines have been updated several times (Methot et al, 2013), but technical guidance for their implementation has not been updated since Restrepo et al (1998). In this document, the technical guidance for reference points and status determinations is updated.

Over the past 25 years, there has been substantial research on the scientific basis for reference points and their expected performance in the management of sustainable fisheries, and substantial experience gained from 25 years of stock monitoring and stock assessment implementation. The field has seen:

- Methods for Management Strategy Evaluation maturing to provide a better understanding of the potential performance of and challenges with reference points and control rules;
- Evolution of integrated analysis assessment methods to simultaneously utilize a diversity of data types and statistical methods;
- Development of methods to provide advice for data-limited stocks;
- Movement towards Ecosystem-Based Fishery Management;
- Investigation of changes in productivity due to regime shifts and climate change.

This document is intended to summarize this research and development into updated technical guidance with regard to calculating and evaluating reference points for status determinations. On several topics, the science is still not settled and different approaches have evolved regionally and internationally. The document will describe recommended approaches where feasible to do so, and pros/cons of alternatives where definitive advice is not feasible.

Approaches to Specifying MSY-Related Quantities and SDCs

The calculation and evaluation of MSY-related reference points depend upon the types of data that are available, the length of the time series of data availability, and the history of fishing. We organize the various approaches into three "Tiers" based on the types of data available and types of reference points and SDCs the approach supports. The three Tiers are (1) stocks for which there is an age- or length-structured assessment model, (2) biomass dynamics model (also known as surplus-production or stock-production model), and (3) data-limited situations. The key findings and recommendations under each Tier are summarized below.

Tier 1: Age- or length-structured Models

Age-structured models are the preferred approach for conducting stock assessment and estimation of reference points. The method relies upon life history and fishery characteristics to calculate per recruit

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[1] A Glossary is provided

quantities as a function of fishing mortality level, and a spawner-recruitment relationship (SRR) to calculate recruitment. However, calculating the curvature of the functional form of the SRR over the relevant range of SSB is extraordinarily difficult. If this density-dependent SRR is estimable, then the age-structured model can be used to calculate MSY-based biological reference points (BRPs) directly from the model. If direct estimation is not feasible, then the F_{MSY} can be set to a F_{MSY} proxy. The key advice for direct estimation and proxy approaches include:

Direct Estimation

- Estimate the spawner-recruitment relationship (SRR) simultaneously with the estimation of annual recruitment and all other parameters in the model
- Fixed parameters are ill-advised as this essentially determines reference points a priori and limits the way data can inform MSY estimation
- Expert judgment and information from other stocks can be used in parameter estimation through the use of priors for key parameters such as natural mortality rate and spawner recruitment. Priors help achieve a balance among estimability, bias and variance.
- Seek alignment between the priors used in the assessment and the equivalent SPR proxies used when direct estimation is not attempted
- An investigation of the implications of the SRR functional form should include three-parameter forms to provide a greater range of possible shapes, hence exposing more of the uncertainty in B_{MSY} estimation
- The shape of the spawner-recruitment curve is influenced by a stock's interactions with other species in its ecosystem, hence accelerating movement towards more modeling with multiple species is advised

F_{MSY} and B_{MSY} Proxies

- The recommended F_{MSY} proxy is based on spawning potential ratio (%SPR; see definitions in glossary). $F_{40\%}$-$F_{45\%}$ is the recommended default based on expected performance across a plausible range of SRR
- The current range of F_{MSY} proxies found in FMPs is broader at $F_{30\%}$-$F_{60\%}$ and is considered to have adequate, but dated, technical justification in those FMPs. Updated investigations are recommended.
- Yield-per-recruit based proxies are less advised. In particular, F_{MAX} is regarded as a poor proxy for F_{MSY}, however, $F_{0.1}$ is more precautionary and can be cautiously applied in cases where information on maturity and other factors needed to determine SPR are unavailable
- Proxies for B_{MSY} can be calculated by (1) taking the mean recruitment over a range of years when the stock was reasonably assumed to be near B_{MSY} multiplied by SSB/R associated with the selected $F_{x\%SPR}$ proxy, or (2) some percentage of the unfished biomass (B_0)
- Recalibration of F_{MSY} proxies may be necessary if the units of reproductive potential have changed (e.g., from SSB to egg production).

Tier 2: Surplus Production/Biomass Dynamics Models (BDMs)

Biomass dynamics models (BDMs), also known as surplus production models, are among the simplest types of models to estimate MSY and its associated biomass (B_{MSY}) and fishing mortality rate (F_{MSY}). These models can be employed when there is: (1) time series of total catch, and (2) at least one time series of relative abundance data. There are several pros of BDMs, including (1) minimal data requirements, (2) simple to implement and to communicate, (3) straightforward connection to MSY quantities (having very few estimated parameters and a simple form allows direct estimation of MSY, B_{MSY}, and F_{MSY}). However, there are several caveats of BDMs worth noting, namely that they cannot directly account for age-specific fishery selectivity and age-specific contribution to the SSB, which can bias the reference point estimates, they ignore the lag effect of recruitment contributing to the spawning biomass, and they cannot use age composition data that informs estimates of total mortality rate and recruitment variation.

Tier 3: Data-limited Situations

Data and resource limitations present significant challenges to calculating reference points and using SDC to interpret stocks status to inform fisheries management (Cope et al. in review; Dowling et al. in press). In the 2016 revisions to the National Standard 1 (NMFS 2016), the following statement which relates to these data-limited situations was added in 50 C.F.R. 600.310(e)(2)(ii):

> *"...When data are not available to specify SDCs based on MSY or MSY proxies, alternative types of SDCs that promote sustainability of the stock or stock complex can be used."...*

In this section we describe some of these alternative approaches:

- "Biological composition" methods can be used to compare the current %SPR to the %SPR at the F_{MSY} proxy to make overfishing status determinations. Ancillary information about the approximate stability of the fishery over time may allow comparison of the current %SPR to the %SPR that would correspond to MSST and thus provide an overfished determination
- "Abundance trend" methods are strongest when used to adjust future catch relative to current catch. They are weak at determining overfished status, although the lowest observed value in the index time series is a potential candidate for MSST.
- "Absolute abundance" method starts from a direct measure of the current abundance of the stock. Then if a proxy for F_{MSY} is available, OFL can be calculated. Overfished status cannot be calculated from this approach.
- "Catch-only" methods can only be used to guide the setting of OFL and ACL, and provide information on the overfishing status of the fishery, but not its overfished status

Updating Reference Points and SDCs for Prevailing Conditions

The NS1 Guidelines recognizes the importance of accounting for changes in environmental conditions by defining MSY as "[...] the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological, environmental conditions and fishery technological characteristics (e.g., gear selectivity), and the distribution of catch among fleets". 50 C.F.R. 600.310(e)(1)(i)(A). Then section 600.310(e)(1)(v)(A) states that "*Because MSY is a long-term average, it need not be estimated annually, but it must be based on the best scientific information available (see § 600.315), and should be re-estimated as required by changes in long-term environmental or ecological conditions, fishery technological characteristics, or new scientific information."* Here we provide advice for this re-estimation.

- Fishery characteristics routinely change, so their contribution to reference points should be routinely updated with projection models, trailing averages, or autoregressive methods.

- With changes in biological factor(s), it is important first to determine whether the changes are density-dependent responses (either to reduced abundance from fishing or increased abundance due to extreme recruitment events). If so, the effect should be built into reference point calculations, just as direct estimation routinely takes density-dependent SRR into account.
- If a notable change in environmental conditions has been documented and is expected to persistent, then reference points should be updated
    - Seek knowledge of mechanistic linkages by which environmental change would logically cause the observed biological change. Identified linkages can be used for dynamic reference points.
    - Run simulation studies to understand consequences of changing reference points versus attributing change to density-dependence, especially if the environmental attribution would lead to maintaining high F on a declining stock.
    - Consider setting MSST and control rule inflection biomass based on long-term perspective, and setting F_{MSY}, B_{MSY}, MSY, and rebuilding target on the basis of recent prevailing conditions. Such an approach is untried in practice and thus needs testing before being used.
- When biological factors have fluctuations, but no clear regime shift or density-dependence, then a trailing average approach is advised, rather than a simple average of all years. This is a common situation and can be implemented with dynamic Bzero. However, simplistic application of this approach raises the same concerns about making empirical changes to reference points in situations where density-dependence may be the true cause.

The recommendations and discussions provided in this document are intended to help fishery scientists and managers better define, select, and calculate reference points and determine stock status.

GLOSSARY

- ABC - Acceptable Biological Catch is a level of a stock or stock complex's annual catch, which is based on an ABC control rule that accounts for the scientific uncertainty in the estimate of OFL, any other scientific uncertainty, and the Council's risk policy. 50 CFR 600.310(f)(1)(ii)
- ACL - Annual catch limit is a limit on the total annual catch of a stock or stock complex, which cannot exceed the ABC, that serves as the basis for invoking accountability measures (AMs). An ACL may be divided into sector-ACLs. 50 CFR 600.310(f)(1)(iii)
- B_{MSY} - is the long-term average size of the stock or stock complex, measured in terms of spawning biomass or other appropriate measure of the stock's reproductive potential that would be achieved by fishing at F_{MSY}. 50 CFR 600.310(e)(1)(i)(C)
- B_0 - The expected level of SSB in absence of fishing. Also Bzero, can vary over time as dynamic Bzero.
- Control Rule - is a policy for establishing a limit or target catch level that is based on the best scientific information available and is established by the Council in consultation with its SSC. 50 CFR 600.310(f)(1)(iv)
- F - Annual fishing mortality rate for age(s) that are most selected by the fishery
- F_{MSY} - is the fishing mortality rate that, if applied over the long term, would result in MSY. 50 CFR 600.310(e)(1)(i)(B)
- $F_{\%SPR}$ - Fishing mortality rate that produces a specified level of %SPR. So, $F_{100\%} = 0.0$ and leaves the SSB/R at unfished levels. $F_{40\%}$ is a level of fishing mortality that reduces SSB/R to 40% of unfished levels and is a reasonable proxy for the F that would produce MSY in many cases.
- MGT - Mean Generation Time is the average age of spawners in the absence of fishing mortality.
- MFMT - Maximum fishing mortality threshold means the level of fishing mortality (i.e. F), on an annual basis, above which overfishing is occurring. The MFMT or reasonable proxy may be expressed either as a single number (a fishing mortality rate or F value), or as a function of spawning biomass or other measure of reproductive potential. 50 CFR 600.310(e)(2)(i)(C)
- 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 and fishery technological characteristics (e.g., gear selectivity), and the distribution of catch among fleets. 50 CFR 600.310(e)(1)(i)(A)
- MSST - Minimum stock size threshold means the level of biomass below which the capacity of the stock or stock complex to produce MSY on a continuing basis has been jeopardized. 50 CFR 600.310 (e)(2)(i)(F)
- OFL - Overfishing limit means the annual amount of catch that corresponds to the estimate of MFMT applied to a stock or stock complex's abundance and is expressed in terms of numbers or weight of fish. 50 CFR 600.310(e)(2)(i)(D)
- Prior - Prior distributions are used for some parameters in stock assessment models. The distribution prevents the parameter from taking extreme values and can provide information to guide the estimated parameter value towards a range determined by expert judgment or experience with that parameter for other species.
- R - Recruitment. The number of young fish entering the population each year. Typically referenced to the numbers at age 0 or the numbers at age 1.
- R_{MSY} - is the expected mean recruitment that would result from fishing at F_{MSY}.
- SRR - Spawner recruitment relationship. This is the functional form that relates the mean number of recruits (R) expected to be produced by a given level of SSB.
- SSB - Spawning stock biomass. This is often used as a measure of the stock's reproductive

potential, sometimes referred to as reproductive output. In many cases SSB is measured by the total weight of the mature, female component of the stock, hence the term SSB. However, SSB may include more complete measures of reproductive output such as age-specific fecundity or egg production of the females.

- SSB/R - Spawning stock biomass per recruit. This is the per capita reproductive potential.
- %SPR - Spawning Potential Ratio is the ratio of the spawning stock biomass per recruit (SSB/R) expected to be produced in equilibrium at some level of fishing, relative to the SSB/R if only natural mortality rates were acting on the recruits. This is commonly expressed as a percentage and can be considered as the average portion of the SSB that escapes the fishery.
- YPR (or Y/R) - Yield-per-recruit. The amount of catch (yield) that is attained per recruit.

INTRODUCTION

The U.S. fisheries management system established by the Magnuson-Stevens Fishery Conservation and Management Act (MSA) and further informed by the National Standard 1 (NS1) guidelines is highly dependent on the reliability of various biomass and fishing-mortality based reference points. The MSA requires preventing overfishing while achieving, on a continuing basis, optimum yield (OY) from managed U.S. fisheries. The OY is limited by the biologically feasible maximum sustainable yield (MSY) which in turn serves as the basis for status determination criteria (SDC) by which NOAA determines when a stock is experiencing overfishing or has become overfished. In October 2016, the National Marine Fisheries Service (NMFS) published revisions to the NS1 guidelines (81 FR 71858; October 18, 2016). The guidelines were last revised in 2009, but NMFS has not produced updated technical guidance for the NS1 guidelines since 1998 (Restrepo et. al., 1998). The guidelines have changed significantly since 1998, and there has been substantial research on the scientific basis for reference points and their expected performance in the management of sustainable fisheries since that time.

The field has seen:

- Methods for Management Strategy Evaluation maturing to provide a better understanding of the potential performance of and challenges with reference points and control rules;
- Evolution of integrated analysis assessment methods to simultaneously utilize a diversity of data types and statistical methods;
- Development of methods to provide advice for data-limited stocks;
- Movement towards Ecosystem-Based Fishery Management;
- Investigation of changes in productivity due to regime shifts and climate change.

This document is intended to summarize this research and development into updated technical guidance with regard to calculating and evaluating reference points for status determinations. Its primary purpose is to aid the implementation of the NS1G, but there are many audiences for this document. It can help the entire fishery community understand the technical basis of the calculations driving reference points and limits, it can aid Fishery Management Councils as they amend FMPs, it helps stock assessment practitioners provide consistent, well-supported advice, and it helps the research community see areas where further exploration is needed. In many places, the document presents pros and cons of a particular approach, hence provides guidance on how to build justification that that approach is BSIA. Completely satisfying all audiences is not feasible and we hope that we have achieved a reasonable balance.

The first section of this document focuses on the various approaches for specifying fishing rates or biomass levels associated with MSY or MSY based proxies. At the end of this section we discuss some additional factors to consider when estimating MSY reference points, proxies, and SDCs, which are often overlooked. These include fleet technical characteristics, spatial complexity, age truncation, density-dependence in other life-history factors beyond stock-recruitment, and size-selective fishing. The remaining sections provide guidance or discussion on specific issues: application of the multi-year approach to overfishing determination, making overfished and approaching an overfished determinations, updating reference points for changing environmental conditions, and multispecies considerations. On several topics, the science is still not settled and different approaches have evolved regionally and internationally. This document thus describes recommended approaches where feasible to do so, and pros/cons of alternatives where definitive advice is not feasible. This document is intended to help fishery scientists and managers better define, select, and calculate reference points and determine stock status.

BACKGROUND ON NATIONAL STANDARD 1 AND MSY

National Standard 1 of the MSA states that "*conservation and management measures shall prevent overfishing while achieving on a continuing basis, the optimum yield (OY) from each fishery for the U.S. fishing industry"* (16 U.S.C. 1851(a)(1), MSA sec. 301(a)(1)). The MSA defines "optimum" as the amount of fish which, among other things, is *"prescribed as such on the basis of the maximum sustainable yield [MSY] from the fishery, as reduced by any relevant economic, social, or ecological factor"* and *"taking into account the protection of marine ecosystems"* (16 U.S.C. 1802(33), MSA sec. (3)(33)). The MSA requires that an FMP "assess and specify the present and probable future condition of, and the [MSY] and [OY] from, the fishery, and include a summary of the information utilized in making such specification." 16 U.S.C. 1853(a)(3). According to the NS 1 Guidelines, "*each FMP must include an estimate of MSY for the stock or stock complexes that require conservation and management*" (50 CFR 600.310(e)(1)), and when data is insufficient to estimate MSY directly, Councils "*should adopt other measures of reproductive potential that can serve as reasonable proxies for MSY, FMSY, and BMSY"* (50 CFR 600.310(e)(1)(v)(B)).

The National Standard 1 Guidelines (NMFS 2016) define MSY and MSY-related SDC reference points (F_{MSY} and B_{MSY}) in 50 CFR 600.310 (e)(1)(i) as:

> *"(A) 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 and fishery technological characteristics (e.g., gear selectivity), and the distribution of catch among fleets.*
>
> *(B) MSY fishing mortality rate (F_{MSY}) is the fishing mortality rate that, if applied over the long term, would result in MSY.*
>
> *(C) MSY stock size (B_{MSY}) means the long-term average size of the stock or stock complex, measured in terms of spawning biomass or other appropriate measure of the stock's reproductive potential that would be achieved by fishing at F_{MSY}."*

An important component of the definition of MSY is the concept of "prevailing conditions". As stated above, the NS1 Guidelines define MSY relative to the "*prevailing ecological, environmental conditions and fishery technological characteristics (e.g., gear selectivity), and the distribution of catch among fleets*". Prevailing conditions are the conditions existing at this time. For the purposes of NS1 implementation, we also expect these conditions to persist for the foreseeable future as current estimates of F_{MSY} are used as the basis for ACLs. Persistence is especially important for rebuilding plan projections. Prevailing conditions are characterized as stationary; that is, the conditions have a predictable mean and stable degree of variability around that mean. If the mean is no longer predictable, or the variance changes, in a way that is expected to persist into the future, then the prevailing conditions have changed. A predictable mean is not necessarily a constant. For example, a model of the system could incorporate time-varying fish growth as a function of changing ocean temperature, but as long as the calibration of that relationship is stable, the system is still in the same prevailing conditions. Non-stationarity occurs when those calibrations break down and the statistical properties of the time-varying process are unpredictable. We revisit this topic in the section: Updating Reference Points for Changing Environmental Conditions.

The Magnuson-Stevens Act also requires that fishery management plans (FMPs) specify "objective and measurable criteria" for determining the status of stocks relative to overfished conditions (16 U.S.C. 1853(a)(10), MSA sec. 303(a)(10)), and the NS1 guidelines extend this requirement for overfishing (*see* 50 C.F.R. 600.310(e)(2)(i)(A)). These Status Determination Criteria (SDC) are often based on fishing rates, catch levels, and spawning biomass (SSB)[2] levels associated with MSY or MSY proxies (e.g., F_{MSY}, B_{MSY} or their proxies). These criteria should be accompanied with an analysis showing how they were determined and the relationship of the criteria to the reproductive potential of stocks of fish in that fishery, hence how they relate to the MSY concept. Below we summarize the SDC reference points defined by the Guidelines in 50 CFR 600.310(e)(2)(i)(A)-(G):

> *(A) Status determination criteria (SDC) means the measurable and objective factors, MFMT, OFL, and MSST, or their proxies, that are used to determine if overfishing has occurred, or if a stock or stock complex is overfished. MSA (section 3(34)) defines both "overfishing" and "overfished" to mean a rate or level of fishing mortality that jeopardizes the capacity of a fishery to produce the MSY on a continuing basis. To avoid confusion, this section clarifies that "overfished" relates to biomass of a stock or stock complex, and "overfishing" pertains to a rate or level of removal of fish from a stock or stock complex.*
>
> *(B) Overfishing occurs whenever a stock or stock complex is subjected to a level of fishing mortality or total catch that jeopardizes the capacity of a stock or stock complex to produce MSY on a continuing basis.*
>
> *(C) Maximum fishing mortality threshold (MFMT) means the level of fishing mortality (i.e., F), on an annual basis, above which overfishing is occurring. […]*
>
> *(D) Overfishing limit (OFL) means the annual amount of catch that corresponds to the estimate of MFMT applied to a stock or stock complex's abundance and is expressed in terms of number or weight of fish.*
>
> *(E) Overfished [refers to a] stock or stock complex…when its biomass has declined below MSST.*
>
> *(F) Minimum stock size threshold (MSST) means the level of biomass [SSB] below which the capacity of the stock or stock complex to produce MSY on a continuing basis has been jeopardized. [MSST should be between 50% and 100% of* B_{MSY}*.]*
>
> *(G) Approaching an overfished condition [occurs] when it is projected that there is more than a 50 percent chance that the biomass of the stock or stock complex will decline below the MSST within two years.*

The NS1 Guidelines also include requirements for other reference points, such as annual catch limits, as well as guidance on target control rules, rebuilding plans, and other aspects of NS1. These concepts are

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[2] Spawning stock biomass (SSB) will be used in this document to indicate a stock's reproductive potential, sometimes referred to as reproductive output. In many cases SSB is measured by the total weight of the mature, female component of the stock, hence the term SSB. However, SSB may include more complete measures of reproductive output such as age-specific fecundity or egg production of the females (this issue is explored in section titled Units of Reproductive Potential).

not addressed in this document, but some aspects are addressed in other recent technical guidance documents (e.g. control rule phase-in[3]; data-limited ACLs[4]).

APPROACHES TO CALCULATING MSY-RELATED QUANTITIES

The calculation and evaluation of MSY-related reference points depend upon the types of data that are available, the length of the time series of data availability, and the history of fishing. We organize the various approaches into three "Tiers" based on the types of data available and types of reference points and SDCs the approach supports. The three Tiers are (1) stocks for which there is an age- or length-structured assessment model (e.g., Statistical Catch at Age type models) that provides usable estimates of current and historical abundance and fishing mortality, (2) stocks for which there is a biomass dynamics model (also known as surplus-production or stock-production model) or an empirical approach based on catch and relative abundance data, and (3) stocks for which there is insufficient data to apply a population dynamics model. Within each Tier we describe the approach taken to estimate MSY reference points (or their proxies) and translate them to their associated SDCs, as well as discuss key considerations for applying each approach.

The SDC are defined in terms of fishing mortality rate (F), and reproductive potential (spawning biomass, SSB). Our surveys and fishery monitoring programs do not measure F and SSB directly, they measure catch, age composition, survey trends, etc. which are affected by F and SSB. The challenge is to translate the observed quantities into units that are informative about F and SSB. The link happens in the population (aka stock assessment) models. The models are a simplified "digital twin" of the population. In the stock assessment process, parameters in the model are set or estimated to produce a reasonable match to the observed data. Then the output of the model includes F and SSB which can be compared to the SDC. This two-stage process allows for a wide range of data-rich to data-limited situations to all produce outputs suitable for comparison to SDC and has enabled great growth of data-limited approaches as will be described here.

The approaches and considerations outlined in the following sections reflect a snapshot of a dynamic and evolving field of research and should not preclude application of any new or modified developments post-publication that are well tested for the situation to which they are proposed. An important consideration for whichever reference point method is proposed is that it should be tested in conjunction with proposed management strategies that involve these reference points, prior to implementation in the FMP to make sure that management objectives are achieved with a desired probability. Such investigations were called for in Restrepo et al. (1998) and today are commonly referred to as Management Strategy Evaluation (MSE). Stock assessment methodologies, fisheries management

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[3] Holland, D., D. Lambert, E. Schnettler, R. Methot, M. Karp, K. Brewster-Geisz, J. Brodziak, S. Crosson, N. Farmer, K. Frens, J. Gasper, J. Hastie, P. Lynch, S. Matson, and E. Thunberg. 2020. National Standard 1 Technical Guidance for Designing, Evaluating, and Implementing Carryover and Phase-in Provisions. NOAA Tech. Memo. NMFS-F/SPO-203, 41 p.

[4] Macpherson, M., J. Cope, P. Lynch, A. Furnish, M. Karp, J. Berkson, D. Lambert, L. Brooks, S. Sagarese, K. Siegfried, E. Dick, C. Tribuzio, and D. Kobayashi. 2022. National Standard 1 Technical Guidance on Managing with ACLs for Data-Limited Stocks: Review and Recommendations for Implementing 50 CFR 600.310(h)(2) Flexibilities for Certain DataLimited Stocks. NOAA Tech. Memo. NMFS-F/SPO-237, 33 p

tools, as well as the research that interfaces these two disciplines, must continue to evolve to meet emerging demands and challenges.

Tier 1: Age- or Length-Structured Assessment Models

Age-structured models are the preferred approach for conducting stock assessment and estimation of reference points for several reasons.

- They provide an explicit and detailed representation of a harvested stock, accounting for age and/or size structure of the modeled population, and age-specific growth, reproductive output, and natural mortality at age/size (termed life history factors).
- They explicitly estimate differences in fishing mortality with age (i.e., age selectivity) from age and/or length composition in the catch data, and can account for differences in selection by fishing fleet, season, and/or area and how selectivity has changed over time.
- They estimate annual recruitment of young fish as a process that can be linked to the SSB and a random process that is implicitly caused by fluctuations in environmental and ecosystem factors. Some implementations allow for explicit linkage of recruitment fluctuations to these external factors.
- Data on changes in the proportion of older fish in the population is directly related to the total level of mortality, so contributes to estimates of the fishing mortality rate and associated population abundance.

When recruitment is linked to SSB it is through a functional form termed a stock recruit curve (also spawner-recruitment relationship (SRR)). A link between recruitment and SSB (Figure 1) seems obvious because the number of young fish recruiting to a population must depend in some way on the maternal reproductive output (Mangel et al 2010). However, calculating the functional form over the entire plausible range of SSB is extraordinarily difficult (Conn et al 2010) as will be discussed here. Despite the operational challenges, utilizing the SRR has the important advantage of enabling straightforward calculations of the MSY-based reference points. The MSY calculations in age-structured models include the effects of fishery selectivity, natural mortality, growth and per-capita reproductive output on the yield-per-recruit (YPR) and spawning biomass-per-recruit (SSB/R) (see Figures 2 and 3).

However, direct estimation is usually not feasible. This has led to evolution of two technical assessment methods:

- One method dispenses with inclusion of the SRR entirely and treats the recruitments as deviations from a mean value. This approach can work well in situations with high data quality regarding fluctuations in recruitment and is used extensively in the North Pacific, Northeast, and Mid-Atlantic regions. In this case, the F_{MSY} will be set to a F_{MSY} proxy as discussed in a subsequent section of this report. Care must be taken to allow the recruitments to be only lightly penalized else they are biased away from declining as SSB declines.
- The other method adopts a hybrid approach that includes a SRR and uses external information to create an expected range (e.g. prior distribution) for the estimated steepness parameter. This approach is used extensively for west coast, Southeast, Pacific Islands, and tuna/billfish assessments. This method will be discussed below, including cautions against biasing the assessment too strongly towards the recruitment trend implied by the steepness prior.

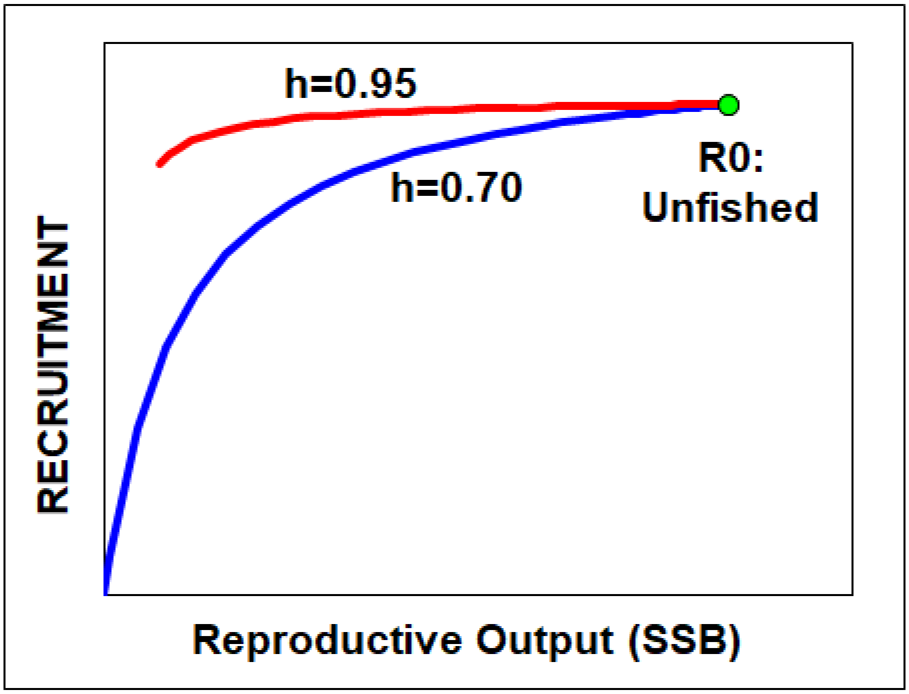

Figure 1: Two spawner-recruitment curves using the Beverton-Holt formulation. The red curve has high steepness (h) such that recruitment declines slowly as reproductive output (SSB) declines from the unfished level. The blue curve has lower steepness, so reductions in SSB cause more immediate declines in average recruitment.

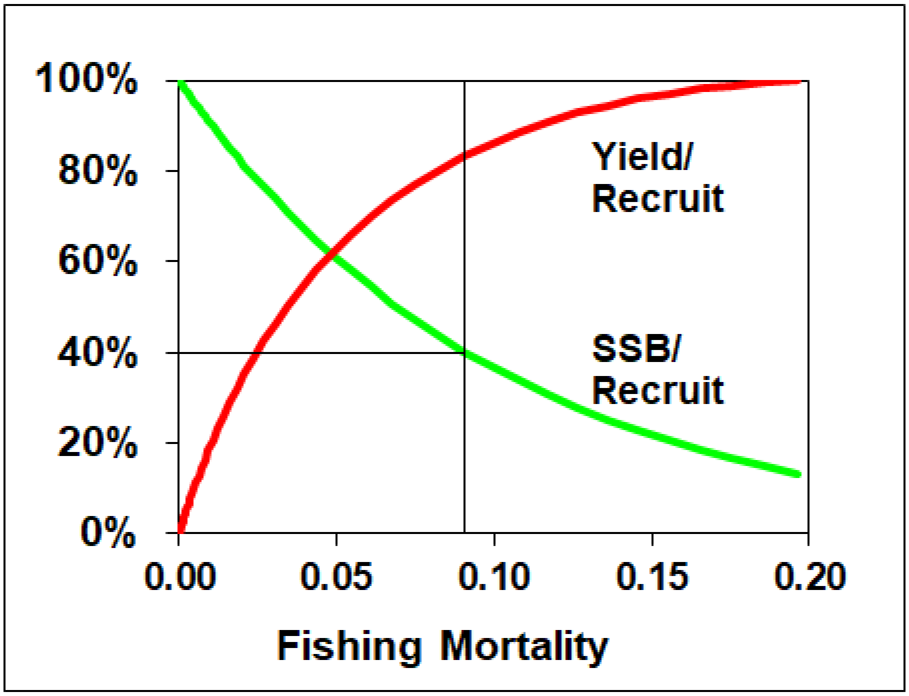

Figure 2: Yield per recruit (YPR) and SSB/R are calculated from life history quantities and fishery characteristics. When F increases, yield increases asymptotically and SSB declines. Here the level of F that reduces SSB/R to 40% of its unfished level is indicated by the intersection of the vertical and horizontal black lines.

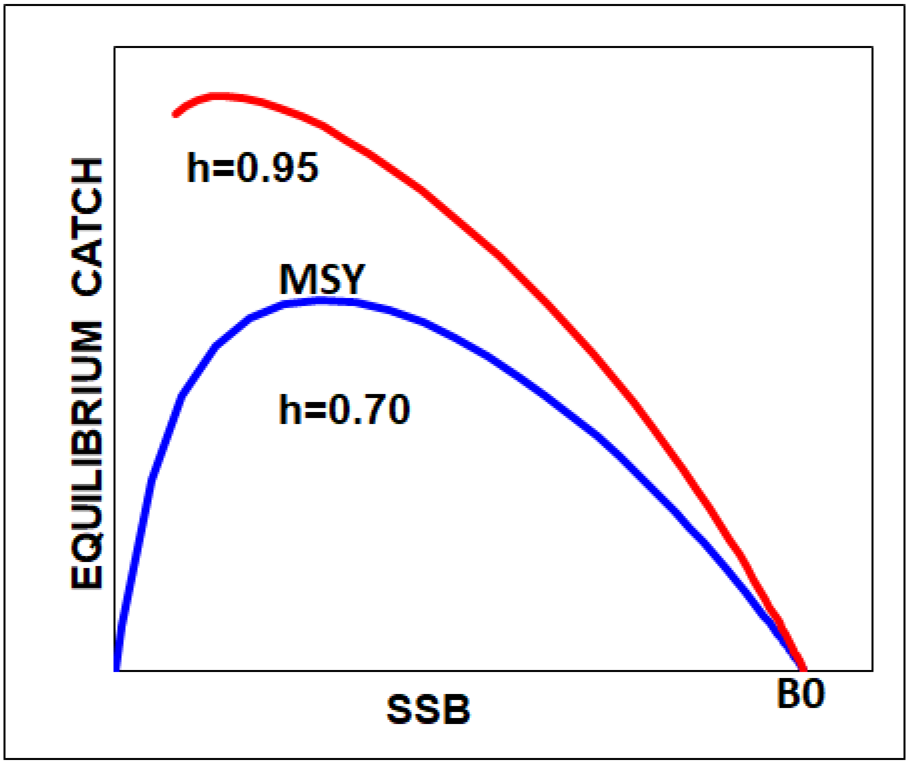

Figure 3: Combining the per recruit information from Figure 2 with the SRR information in Figure 1 produces equilibrium catch as a function of SSB. Each point along the curves is associated with a F level. The peak of each curve is its MSY and is associated with a FMSY and the corresponding BMSY.

1a. Direct Estimation

With direct estimation, the MSY reference points (F_{MSY} and B_{MSY}) and the reference point B_{LIM} (the stock size associated with the MSST) are emergent quantities estimated (or otherwise specified) from parameters estimated within the assessment model. The main issues to be considered in direct estimation of F_{MSY} and B_{MSY} via age-structured methods are:

- Which functional SRR form to use, or range of forms if conducting an ensemble model or MSE?
- Which parameterization of the SRR form to use?
- Whether to estimate parameters of the SR curve based on quantities output by the stock assessment, or to embed the curve in the assessment for simultaneous estimation.
- Has the estimation of the SRR succeeded in a statistical sense and is plausible? Alternatives are to use priors to stabilize estimation of one or more of the SRR parameters; or else a F_{MSY} proxy must be used.
- Whether the SRR parameterization is stationary over time

Which functional form(s) to use?

The functional form of the SRR influences the estimates of MSY and associated biological reference points (Myers et al. 1995, Brodziak 2002). In principle, a non-parametric SRR could be calculated from a series of direct observations of spawners and recruits collected over a sufficient range of spawning levels, but this type of information is seldom available. Instead, a parametric form of the SRR is used, with the two most common forms being an asymptotic form termed Beverton-Holt, and a dome-shaped form termed Ricker. Reference points based on the Beverton-Holt function tend to be more precautionary than those based on the Ricker function (e.g. Williams and Shertzer 2003, Horbowy and Luzenczyk 2012), and some simulation studies (Clark, 1991) have included both forms in recognition of this difference. Additionally, mechanistic hypotheses that support the overcompensatory response of the Ricker function are few except for salmon, and therefore most stock assessments assume the asymptotic two-parameter Beverton-Holt function as a default SRR (Gilbert, 1997).

While the default is to use the two-parameter forms of SRR, including a third parameter in the SRR (e.g., Shepherd, 1982) introduces more flexibility regarding where B_{MSY} occurs relative to an unfished level of SSB and the level of F that will produce MSY (PFMC, 2017; Punt and Cope, 2019). An example of such a three-parameter form of the SRR has been designed explicitly for low fecundity species (Taylor et al 2013). An investigation of the implications of the SRR functional form should include three-parameter forms to provide a greater range of possible shapes, hence exposing more of the uncertainty in B_{MSY} estimation. Of course, direct estimation of a value for the third parameter will be even more uncertain and more in need of priors than the estimate for the second parameter (e.g. steepness or intrinsic rate of increase). The point of including the third parameter is only to more clearly represent the uncertainty in the B_{MSY} estimate. A very similar issue occurs for biomass dynamics models that typically use a 2 parameter Schaefer function (discussed in section: Tier 2 Surplus Production) rather than more flexible 3 parameter production functions. Selecting a two-parameter form simplifies the modeling challenge at the expense of potentially misspecifying the true productivity of the stock. Accordingly, before settling on any particular functional form, due consideration should be given to process studies or empirical evidence outside the assessment model that may support, or rule out, other potential candidates.

Which parameterization of the SRR form to use?

How the SRR is parameterized can affect estimation performance in assessments and, when there are time-varying life history parameters, cause problems for reference point calculations. It has become common in the stock assessment community to use SRR parameterized using steepness (termed h) defined as the relative recruitment when spawning capacity has been reduced to 20% of the unfished level of SSB, termed B_0 (Mace and Doonan 1988). Steepness formulations are popular because they provide an intuitive measure of the dependence of recruitment on SSB that facilitates comparisons between stocks. In the case of the two-parameter Beverton-Holt and Ricker SRR functions, steepness has been shown to be an explicit function of pre-recruit mortality and unfished spawning capacity (Myers et al. 1999, Brooks et al. 2010, Mangel et al. 2010). However, use of the steepness formulations implicitly assumes that growth, natural mortality and fecundity-at-age are constant over time. However, these biological factors can change over time resulting in biased estimates of steepness (Miller and Brooks, 2021). This issue is moot if data to inform time-varying biology are lacking and biology is assumed constant over time. The problem manifests in some assessment packages, notably Stock Synthesis (Methot and Wetzel, 2013), when there is time-varying biology and the user must choose a range of years to be used for averaging the biology to represent unfished conditions. Miller and Brooks (2021) advocate for using the SRR in its original parameterization rather than the R0, steepness (h) parameterization. Implied steepness and R0 can still be reported as derived quantities and used in meta-analyses. As with data rich applications, the estimated SRR incorporates the important density-dependent response, and makes it explicit and transparent what values were assumed for unexploited conditions when calculating (or updating) reference points. We recommend that assessment groups accustomed to using the R0, h approach explore the alternative.

Estimating SRR Parameters

Along with selecting among candidate SRRs, analysts should determine how to estimate the parameters of each candidate SRR. Estimating the SRR parameters using the time series of assessment estimates of annual R and SSB (e.g., outputs from the assessment model approach) is necessary for assessment methods that cannot embed the SRR into the assessment model. This is the case for virtual population analyses (VPA) and some older types of Statistical Catch at Age (SCAA), however, it is not otherwise recommended. This approach incorrectly treats the time series of spawners and recruitments, which are model based estimates, as if known perfectly (Brooks and Deroba 2015). This approach also creates a logical inconsistency where the implicit SRR (or lack of an SRR) underlying the estimates of recruitment from the assessment may differ from that predicted by the externally fit SRR. Therefore, the better approach is to estimate the SRR simultaneously with estimation of the time series of R and SSB. Most contemporary assessment packages (Dichmont et al 2016, Li et al 2021) are capable of estimating the SRR parameters simultaneously with the estimation of annual recruitment in the assessment model. Within the simultaneous estimation models there is another decision point regarding potential constraints on values of the SRR parameters.

Freely estimated SRR parameters

Ideally, estimation of the SRR parameters, in either a frequentist or Bayesian framework, would proceed without penalizing the values the parameters may take beyond the imposition of reasonable bounds. This allows alternative candidates for the SRR to be fairly compared within the model framework itself. State-space methods, which treat recruitments as random effects, have been shown to provide improved estimation of SRR parameters (de Valpine and Hastings 2002; Peterman et al. 2003). These methods have also been applied to the entire population model and provide a natural way of distinguishing stochastic processes for the population and associated observations (Mendelssohn 1988; Sullivan 1992; Gudmundsson 1994; Schnute 1994; de Valpine 2002). Integrated state-space age-structured models that can estimate traditional assessment model parameters, including SRR parameters, as well as variances for separate population processes and/or observations are becoming more commonly used for management (Nielsen and Berg 2014, Cadigan 2016, Stock and Miller 2021).

Using Priors for one or more of the SRR parameters

In practice, however, the precision of SRR parameter estimates tends to be low, especially when year-to-year fluctuations in recruitment are high, the time series is short, or other elements of the assessment model have been mis-specified. For instance, Conn et al. (2010) show that without good data from both high and low SSB eras, steepness is poorly estimated or is estimated at its upper bound of 1.0 for Beverton-Holt SRR (implying recruitment does not decrease as SSB decreases). In these situations, it usually is necessary to use priors for one or more of the SRR parameters to improve their estimation.

Priors essentially tell the model that some values of the parameter being estimated are more likely than others so the final parameter estimates are a balance between the strength of the prior and the stock-specific information in the model data. The advantage of using priors is that it directly estimates all the MSY quantities and provides a middle ground between either freely estimating and fixing parameters. The priors can be based on life history information or statistically based meta-analysis across numerous similar stocks, under the assumption that a particular stock's productivity is not too different from the productivity of other stocks considered to be similar. This approach has been used for some Pacific coast species (Thorson, Dorn and Hamel, 2019).

In some cases, one or more SRR parameters are assigned a constant value. This should be done with caution and thorough investigation as this essentially determines reference points *a priori* and limits the way data can inform the estimation of reference points (Mangel et al. 2013). Brooks et al. (2010) note that fixing the steepness parameter at a single value is essentially the same as using an SPR proxy, but with less transparency and a false sense of precision in the reference points. For these reasons, fixing steepness is not recommended. Further, setting the steepness parameter to a fixed value can bend the estimated population trend to conform to the trend implied by that fixed steepness value.

The use of priors for the SRR is a compromise between freely estimated vs fixed parameter values. Direct estimation of reference points is often not possible without the use of priors, and we conclude that precision and stability of SRR and MSY estimates can be improved through the specification of informative priors. Below are several important considerations to keep in mind when using priors:

- The SRR will have an inflated precision as the SRR parameter becomes more tightly constrained by the prior.
- The time series of estimated recruitments is somewhat drawn towards the form and level of the simultaneously estimated SRR parameters. This is a benefit for data-limited assessments attempting to model stock productivity for years without age data, and for rebuilding plans seeking to model the rate at which stocks will approach the rebuilding target. However, all recruitment estimates (including those in projections) are somewhat drawn towards the SRR, so are influenced, e.g. biased, by the chosen SRR form. Hence fixed or highly informative SRR parameters should be used with caution.
- The resultant MSY quantities are influenced by the SRR parameter priors, so the selection of the priors is essentially equivalent to selecting the proxy. This is essentially the same as using a comparable range of SRR parameter priors in a MSE in order to derive a $F_{\%SPR}$ proxy (see section XXX). A proxy %SPR level is selected under the assumption that stocks incapable of direct estimation have a productivity (e.g. range of steepness levels) such that the $F_{\%SPR}$ proxy has a good chance of producing MSY. For a given SRR functional form, there will be a steepness parameter value that corresponds to the FMP's default %SPR. If this value is used as a prior for the steepness parameter when estimating the SRR of each stock, then all the estimated SRR's will be pulled towards this steepness value unless the stock-specific information is sufficient to produce a different stock specific value. Therefore it is important to ensure that the choice of %SPR value and the prior used for the steepness in the stock assessment are both consistent with each other and the perceived productivity of the stock.

Non-stationarity in SRR parameters

The direct estimation approach is based on the assertion that the parameters of the SRR relationship are stable over the decades of observed spawner and recruitment levels, that is it implicitly assumed that the SRR is stationary. However, a number of studies (Perretti et al 2017, Vert-Pre et al. 2013, Szuwalski et al. 2015) have shown that this is often not the case and that regime shifts are often the most prominent feature of a recruitment time series.

This leads to two questions. First, can the SRR be reasonably assumed to be stationary over a long time period such that all data can be used to calibrate the curve, or are some older years no longer relevant for calculating the prevailing spawner-recruitment relationship? Second, even if the relationship is considered long-term stationary, are there patterns in the annual deviations from this relationship such that the prevailing mean deviation needs to be taken into account when using the curve? Accordingly, it is important to consider the evidence suggesting the SRR may have changed over the timeframes relevant to management. This is discussed extensively in the section on Updating Reference Points for Changing Environmental Conditions.

1b. Proxies for MSY

The NS1 Guidelines expressly allow for the use of proxies when data are unavailable or unreliable to estimate MSY based quantities directly (Gabriel and Mace 1999). Specifically in 50 CFR 600.310(e)(1)(v)(B), the guidelines state that "*When data are insufficient to estimate MSY directly, Councils should adopt other measures of reproductive potential that can serve as reasonable proxies for MSY, F_{MSY}, and B_{MSY}*". Such situations arise when the time series of recruitments may not be sufficient for estimating the SRR due to insufficient contrast in the available time-series data, high variability, or temporal changes in other factors that affect productivity. The previous section discussed using priors within the assessment model to deal with these situations. That is not always possible and bypassing the assessment based SRR estimation and using a proxy may actually be more credible than the stock or species-specific estimates. These proxies are quantitative surrogates that can be used to provide reasonable approximations of the MSY reference points themselves. They are often based on theoretical modeling studies or meta-analyses of estimates from high-information stocks or groups of stocks. Here we discuss the supported proxies for F_{MSY} and B_{MSY} under data-moderate situations, where age- and/or size- data exist. The section also will address the fact that SRR parameter priors can be aligned with MSY proxies.

Proxies for F_{MSY}

Spawning Potential Ratio (%SPR)

The primary F_{MSY} proxy approach recommended for use today is based on the spawning potential ratio (SPR). Percent SPR is the ratio of the spawning biomass per recruit (SSB/R) expected to be produced in equilibrium at some level of fishing, relative to the SSB/R if only natural mortality rates were acting on the recruits (Goodyear 1993). The SSB/R does not require information on the SRR, making it straightforward to calculate from life history rates. The fishing rate associated with a SPR value is notated here as $F_{xx\%}$. For example, $F_{45\%}$ means to fish at a rate such that the SPR would eventually equilibrate to 45% (i.e., SSB/R would equilibrate to 45% of the unfished level). For a given SPR, calculating the corresponding $F_{xx\%}$ requires an ogive of fishery selectivity, and if fishery selectivity is changing over time (and potentially changing amongst user groups) then one must be explicit about the time period chosen to represent selectivity.

A key question when using the SPR proxy is determining the level that will approximate MSY for a particular stock. Selection of a SPR proxy implies that the stock's true, but unknown, SRR parameters are in a range of plausible SRR parameters as determined by the study that created the proxy recommendation. Given the lack of identifiability of the SRR in the stock assessment, recruitment is often modeled as a process with estimated mean and annual deviations. Although functionally this looks like recruitment is independent of SSB, it is irrefutable that spawners are necessary to the production of recruits. Consequently, F_{MAX} (discussed further below) which assumes steepness of 1, is not an recommended SPR proxy. Over the last 30 or more years, researchers have used comparison with other species, meta-analytic approaches and simulations and MSE to investigate the potential performance of a range of SPR levels against possible states of nature, particularly alternative SRR and life history parameterizations (see Appendix 1 for more detailed discussion of this history).

Early studies (Clark, 1991) looked to find SPR which would prevent recruitment overfishing while achieving "pretty-good yield" (75% of MSY). Clark 1991 did this by examining a range of SRR parameter values using both the Beverton Holt and Ricker curves. These studies found 35%SPR accomplished this for most stocks, however when recruitment variability was taken into account a more conservative 40%SPR was recommended. Later studies considered a wider range of steepness and stock-recruitment relationships representing a more realistic resilience and productivity for certain stocks, such as rockfish, and found a much higher, more conservative SPR level in the range of 40-70% was needed. Considering the range of possible stock recruitment relationships and life-history parameters the existence of a "one-size-fits-all" %SPR is not possible, but a "one-size-fits-many" is more attainable. The collective experience, as documented in Appendix I, points to a value between 40-45% SPR as a reasonable default for an F_{MSY} proxy when the productivity of the stock is uncertain. However, stocks with slower growth or maturation (i.e. longer generation times) may need a higher %SPR value (50% or greater), and the most vulnerable life histories such as elasmobranchs may require even higher %SPR rates of 60% or greater. There is little justification for %SPR values < 30% as that provides little protection to the reproductive potential of the stock. We conclude therefore, that the current range of proxies (nearly all between $F_{30\%}$ and $F_{60\%}$) (see table in Appendix I) are reasonable, especially given the performance of fisheries that have been managed with this range of proxies for 20+ years. However, their justifications are often decades old and updated investigation is advised.

Yield-Per-Recruit Based F_{MSY} Proxies (F_{max} and $F_{0.1}$)

Before the development of SPR-based proxies, the typical proxy was based on the yield per recruit, which is the amount of catch (usually in weight) expected over the lifetime of an average recruit. When Restrepo et. al. (1998) published their technical guidance in 1998, yield-per-recruit analysis ($F_{0.1}$ and F_{MAX}) was commonly used. But consistent with the advice in Restrepo et al. (1998) YPR-based reference points have become a much less recommended approach. As for SPR, the calculation of YPR does not require any knowledge of the SRR, only growth, natural mortality, and selectivity. The two most common YPR-based reference points are the fishing mortality rate that maximizes YPR over the long term (F_{MAX}) and the fishing mortality rate that corresponds to the point on the yield-per-recruit curve where the rate of increase in YPR achieves 10% of the maximum rate of increase (at the origin) ($F_{0.1}$). F_{MAX} is today regarded as a poor proxy for F_{MSY}, being exactly equivalent only in the special case where recruitment is independent of spawning potential, and generally higher otherwise (Mace 1994). In the case of the Beverton-Holt SRR, for example, F_{MAX} always exceeds F_{MSY} except in the limiting case of steepness = 1. In this sense, F_{MAX} is the theoretical upper bound of F_{MSY}. The $F_{0.1}$ was developed as a precautionary proxy for F_{MSY}, being considerably lower than F_{MAX}, and is still used today mostly outside the U.S. and much less than %SPR proxies. However, despite $F_{0.1}$ being more precautionary than F_{MAX}, both suffer from the conceptual shortcoming of the YPR based proxies in that they do not directly address the degree to which they protect the reproductive potential of the stock, as expected under the NS1 Guidelines. On the other hand, $F_{0.1}$ can be cautiously applied in cases where information on maturity and other factors needed to determine SPR are unavailable.

Proxies for B_{MSY}

B_{MSY} is a direct output of the biomass dynamics models, and of age-structured models that include a SRR, whether or not that SRR is directly estimated or informed by a prior. In particular, $B_{MSY} = R_{MSY} *$ SSB/R when F is at F_{MSY}. However, when a proxy is used for F_{MSY}, there needs to be an alternative approach to obtaining a proxy for B_{MSY} directly, or a proxy for R_{MSY} such that B_{MSY} can be calculated.

B_{MSY} as Percent of Unfished Biomass

If the unfished, virgin biomass can be more reliably estimated than biomass at B_{MSY}, then B_{MSY} can be based on a specified percentage of the unfished biomass (%B_0). The logic for this approach is that the shape of the common SRR curves all result in B_{MSY} / B_0 in the approximate range of 0.25 to 0.50. The level chosen for a particular stock depends on the same stock productivity considerations that underlie selection of a $F_{\%SPR}$ proxy for F_{MSY}. It is uncommon however, for B_0 to be better estimated than B_{MSY}. Currently in the U.S., only the Mid-Atlantic and Pacific Fishery Management Councils (PFMC) use this method to estimate a B_{MSY} proxy. In the California Current Ecosystem, the PFMC uses 40%B_0 for a default B_{MSY} proxy for all groundfish except flatfish which uses 25%B_0. The Mid-Atlantic Council uses 50%B_0 for a B_{MSY} proxy for ocean quahog. Care should be taken to elucidate the logical linkage between the $F_{\%SPR}$ proxy and the B_{MSY} proxy. This is because the percent reduction in equilibrium spawning biomass from fishing at a given %SPR from unfished biomass may be more or less than the SPR percentage depending on the stock-recruitment curve (i.e., Goodyear 1993). For a typical Beverton-Holt curve, fishing at $F_{40\%SPR}$ will produce SSB that is approximately 35% of B_0. The B_{MSY} proxy and the F_{MSY} proxy should be selected based upon the same logic regarding expected productivity and SRR conditions.

B_{MSY} based on Expected Mean Recruitment

A common approach is to take the average recruitment over some time period as a proxy for R_{MSY} with which to scale the SSB/R associated with the %SPR proxy. There are several factors that influence the choice of time period to use and whether further adjustments are necessary. For one, recruitment fluctuates annually, so it is good to include many years to get an accurate mean. This approach is easy and most logical when the stock is thought to have been near B_{MSY} through a long portion of the observed time series. However, if the stock has only been observed while far from B_{MSY}, observed recruitment may need adjustment before used as a proxy for R_{MSY}.

Use of the mean of the entire estimated recruitment time series is reasonable where there is a noisy scatter of recruitment estimates with little trend. However, recruitment can also change over longer time scales in response to climate and ecosystem regimes, so not including early years may be relevant. Additionally, the most recent recruitments are based on little data so are most imprecise and/or affected by model assumptions. It seems important to use a time series that is at least as long as a generation time for moderately long-lived species. Short-lived (2-5 years) species probably need alternative consideration. If trends are apparent in the time series of recruitment, one should examine the estimates of spawning biomass to determine if there is a corresponding trend and whether it preceded or followed that observed in recruitment and whether these trends support SRR estimation. Perhaps most relevant in this situation is if the trend occurs at the end of the time series. An understanding of whether it was environmentally induced or the result of a SRR can help refine selection of an appropriate time period for estimating R_{MSY}. If a recent increase in catch is thought to have reduced spawning biomass and driven down recruitment, then one should select a range of years that preceded the increased catch; conversely, if a recent reduction in catch lead to increased spawning biomass and recruits then one should consider defining R_{MSY} from that recent window of recruitment estimates. A more challenging case is when recruitment and spawning biomass are both low today, environmental changes have been noted, and no contemporaneous change in catch (or discarding) has been noted. Again, a useful diagnostic in this situation is the timing of low recruitment relative to the biomass trend. A downward trend in biomass followed by a downward trend in recruitment, is consistent with a depleted stock being the problem with recruitment. Alternatively, a downward trend in recruitment leading to a downward trend in biomass is consistent with a regime shift. In these situations, we recommend a scenario analysis that considers both possibilities. For instance, analysis can be conducted to evaluate how average recruitment differs across a wide range of time scales to try to understand the influence of the choice of time window on subsequent biomass reference points. See additional discussion on this topic in the section of Updating Reference Points for Changing Environmental Conditions.

If a recent period of recruitment is to be used to calculate a R_{MSY} proxy, an important consideration is the effect of fishing on recent recruitment; that is, whether the stock has recently been at low, moderate or at a high biomass level. If it has been at moderate levels, then its biomass is probably close to the probable, but inestimable, B_{MSY} so the recruitment period should reflect the expected recruitment at B_{MSY}. However, if the stock is currently depleted, then recent mean recruitment probably underestimates recruitment at B_{MSY}. It might be used as a provisional estimate, but this estimate should be updated as the stock rebuilds. Conversely, if the stock is currently lightly exploited and at high biomass levels, the recent mean recruitment will be close to unfished recruitment levels, which is a common reason for not being able to detect a spawner-recruitment curve. In this situation it seems advisable to not use this high recruitment period for a proxy for recruitment at B_{MSY}. Instead, the calculations could be done with recent mean recruitment as an estimate of unfished recruitment and a prior for steepness used to diminish this recruitment level to a level expected at B_{MSY}. That prior could come from meta-analysis across other stocks, or from the value corresponding to the FMP's %SPR proxy. If the stock is subsequently fished down to near this level, then attempts to estimate the spawner-recruitment steepness should be made or the new recent average used directly as mean recruitment at B_{MSY}.

Deferred B_{MSY} Estimate

If it is not possible to develop a reliable value for B_{MSY}, then management can still use the %SPR proxy approach to controlling F. After the stock has been fished at this F for several years, reanalysis should evaluate if the biomass has responded in the expected direction (increase or decrease, depending on the controlling F relative to recent F). With low recruitment variability, a generation time should be sufficient to witness a response to imposed F. If there is a biomass response, it should come towards an average biomass level near B_{MSY} and updated estimates of B_{MSY} can be produced by the recent average approach. If there is no detectable response, possible explanations are: variability in recruitment is high and masking the expected response to controlling F; the %SPR proxy is misspecified; there has been a regime change, and the %SPR proxy is no longer appropriate for the new regime. If recruitment variability is low but no response is observed, revisiting the justification for the SPR proxy and evaluating environmental data for evidence of recent change are recommended. For this latter case, a reliable estimate of B_{MSY} may not be attainable in the near term.

Tier 2: Surplus Production / Biomass Dynamics Models

Biomass dynamics models (BDMs), also known as surplus production models, are the oldest and simplest types of models to estimate MSY and its associated biomass (B_{MSY}) and fishing mortality rate (F_{MSY}). These models can be employed when there is: (1) time series of total catch, and (2) at least one time series of relative abundance data, but age- or size-structured data is insufficient to apply an age-structured assessment approach as described above (Prager, 1994). BDMs pool the effects of growth, recruitment, and mortality into a single production model, ignoring the age or size structure and thus treating a stock as undifferentiated biomass. Having very few estimated parameters and a simple form allows direct estimation of MSY, B_{MSY}, and F_{MSY}. The widely used Schaefer and Fox production functions only require the estimation of two parameters, the intrinsic rate of population growth r and the unfished biomass B_0. Because of the simplicity of the 2-parameter production function the ratio of biomass B_{MSY}/B_0 is fixed at 0.5. The generalized Pella-Tomlinson relaxes this implicit assumption about the shape of the production curve through the introduction of a shape parameter that allows B_{MSY}/B_0 to have a wider range.

Originally, BDMs were based on a deterministic (equilibrium) population model. However, the use of BDMs for management has become more flexible over time. One milestone in the evolution of BDMs was the implementation of state-space models that allow biomass to be stochastic and deviate from the deterministic expectation, while simultaneously estimating the observation error. Process error can account for natural variability of stock biomass due to stochasticity in recruitment, natural mortality or growth, whereas observation error determines the uncertainty in the observed abundance index due to measurement error, reporting error and other unaccounted variations in catchability (Francis et al., 2003; Meyer and Miller, 1999; Winker et al., 2018).

The application of BDMs is appealing due to the low data requirements and ease of communicating the concepts of deriving stock status results relative to the reference points B_{MSY} and F_{MSY}. In fact, the very concept of MSY in the MSA is based on a BDM view of the world. The adequate performance of BDMs is conditional on the degree to which the simplicity of its assumptions represent reality. One simplification is the treatment of all catch and indices as non-age structured, therefore the effect of varying age-dependent fishing mortality cannot be explicitly accounted for by conventional BDMs. In reality, it is common for fisheries to differ with regard to the age range of fish they commonly capture. These differences, termed selectivity, are dealt with explicitly in age-structured models (described in Section II.B.3), but are ignored in BDMs. The inability to separate between the biomass that is vulnerable to the fishery and the spawning biomass can result in biased stock status estimates. A second caveat that arises from ignoring age-structure is the inability to account for the lag effect of recruitment contributing to the spawning biomass.

The successful performance of BDMs is conditional on the degree of contrast in the time series of data. A high contrast situation would be one in which periods of high catches were followed by declines in the stock index and periods of low catches were followed by an increasing stock index. In the absence of contrast in the catches and indices, the estimates of model parameters, and of resultant reference points, will have high uncertainty. In some circumstances, this uncertainty is reduced by adding information from other sources or other similarly assessed stocks. For example, one might assert that all tuna have similar productivity, so the average productivity parameter from well-informed tuna assessments could be used as a statistical prior in the estimation of the productivity parameter in a BDM of a particular tuna for which there was little contrast. Also, tools such as FishLife (Thorson, 2020) can be used to obtain estimates of key population dynamic parameters (e.g., r) estimated or assumed for other similar stocks or species that can be incorporated in BDMs.

There are pros and cons to using the BDM approach for estimation of biological reference points. In summary the pros of BDMs are:

- Minimal data requirements
- Simple to implement and to communicate
- Straightforward connection to MSY quantities. Both F_{MSY} and B_{MSY} are model outputs.

And the cons are:

- Cannot account for age-specific fishery selectivity and age-specific contribution to the SSB, which can bias the reference point estimates
- Ignores the lag effect of recruitment contributing to the spawning biomass
- Cannot use age composition data that informs estimates of total mortality rate and recruitment variation

Some of the cons of BDMs may be addressed through the use of age-structured production models (ASPM) (Hilborn 1990) which are age-structured and can be implemented with only life history information (growth, natural mortality and maturity). ASPM are simply age-structured assessment models that do not estimate annual recruitment values, so are useful for determining if the changes in stock abundance over time can be attributed principally to changes caused by fishing (Minte-Vera et al 2017) or if fluctuations in recruitment are an important driver. Internally, the ASPM calculates numbers at age and these are summed by year for comparison with the age-aggregated data that are available. Numbers of recruits each year are calculated from the SRR, which requires the analyst to specify the form and curvature (steepness) parameters. As noted in the data rich tier above, specifying the SRR parameters determines the corresponding reference points, similar to how they get determined with a BDM. The default "one-size-fits-many" SPR range of 40-45% could be a starting point to derive the SRR parameterization, unless life history characteristics align with SPR rates higher than this default range.

These models provide a bridge to data-rich age-structured models as more data becomes available. Therefore, even when age-structured data are not available, age-structured models are a viable approach. Another class of models that provide a viable intermediate approach between simple biomass dynamics and ASPM are Bayesian biomass dynamics models (e.g. JABBA; Winker et al 2018). We recommend that if the assessment data are insufficient to implement a complete age-structured model, then either ASPM or JABBA be considered.

Tier 3: Data-limited Approaches

Data (e.g., quality, quantity, coverage) and resource (e.g., time, money, technical capacity) limitations present significant challenges to calculating reference points and using SDC to interpret stocks status to inform fisheries management (Cope et al. in review; Dowling et al. in press). In the 2016 National Standard Guidelines, the following statement which relates to these data-limited situations was added in 50 CFR 600.310(e)(2)(ii):

> *"[...] when data are not available to specify SDCs based on MSY or MSY proxies, alternative types of SDCs that promote sustainability of the stock or stock complex can be used".*

There has been a proliferation of methods to address the spectrum of data-limited situations (Bently 2015; Porch et al. 2014; Chrysafi and Kuparinen 2015), with no single approach applicable in all situations (Dowling et al. 2019). The goal is a metric that can be used as the SDC to indicate stock status, and/or be associated with catch advice (Carruthers et al. 2016). The metrics depend upon data availability and can be grouped into the following broad categories: catch-based (i.e., "catch-only"), index-based (either relative or absolute biomass), and length/age-based methods (i.e., biological composition or quasi-equilibrium methods). These methods represent three basic types of data commonly used in stock assessments (catches, indices of abundance, and biological compositions) that can also be combined in a variety of ways to approximate more data-rich stock assessment methods (Cope 2013; Harford et al. 2021). In general, the reduction of data leads to the greater reliance on assumptions, which should be recognized, tracked, and evaluated when applying each method. When more than one of the three data types mentioned above is available, it is generally preferable to use an integrated analysis approach (Cope, 2013; Methot and Wetzel 2013) that is capable of providing outputs in terms of estimated SSB, %SPR and F. However, in data-limited situations, only one of the three data types may be available, and thus there is not enough information to produce all these quantities. Some data-limited methods (DLM) can provide outputs in the same units as some of these familiar quantities, others can provide an indicator related to these quantities but require that the SDC be re-stated in terms of quantities they can measure. Some DLM are better for supporting an overfishing SDC and some are better used with an overfished SDC. In this section we provide an overview of these broad DLM categories as they pertain to either calculating a reference point or the metric to compare to a reference point. A recent NOAA Technical Memo (Macpherson et al. 2022) provides a more detailed discussion on data-limited approaches to setting ACLs. We note that while data-limited approaches, as we describe below, exist and can be used to manage stocks, priority should be given to bringing the knowledge base at least up to "data-moderate" standards.

Biological Composition Methods

In some cases, the only available information may be recent fishery-dependent length observations, basic life history parameters, and some highly uncertain estimates of catch, thus precluding the ability to estimate recent fluctuations in recruitment and the current SSB. Biological composition methods, also called catch curve analysis, are based on the fact that the current population composition has been influenced by the history of fishing, so comparison of this composition to the expected composition of an unfished population provides a measure of the recent level of F without knowing the catch that caused that F. This measure of F can be translated into the same %SPR units as typical overfishing SDC, so overfishing determinations are feasible. In addition, ancillary knowledge about the approximate stability of the fishery over time may allow comparison of the current %SPR to the %SPR that would correspond to MSST.

Catch curve analysis measures the total mortality rate, Z, using the age composition of the catch under specific assumptions about the selectivity pattern of the gear used to acquire the sample. The principle is simple: with life history information it is possible to calculate the expected proportion of fish at one age surviving to the next age if only natural mortality (M) is occuring. Comparison of the observed proportions at age to the unfished proportions gives a measure of how much fishing mortality (F) has increased total mortality ($Z = M + F$) above natural mortality. Additional calculations from the same information produce a measure of the fished SSB/R, which is the building block for %SPR. If catch is also known, as it is for the data-moderate assessments, then it is possible to calculate how large the recruitment, R, must have been, on average, to produce a stock abundance (SSB) large enough to support the observed catch and observed Z (Rudd et al. 2021). But even if the catch is not known, the approach still produces a measure of recent Z, SSB/R and %SPR. With use of a growth curve, the catch curve concept can be applied to length/size composition data. Furthermore, if it is reasonable to assume that recent conditions have persisted for many years, then we discuss below a protocol for also determining the overfished status of data-limited stocks.

If multiple years of length data are available, it is possible to relax the quasi-equilibrium assumption in regards to F by using dynamic length-based models. A mean length estimator of total mortality (Z) based on von Bertalanffy growth curve parameters was initially developed by Beverton-Holt (1956) under equilibrium conditions. This model was subsequently expanded by Gedamke and Hoenig (2006) to include transitional estimates of Z. This specifically relaxes the assumption that the population is in an equilibrium state under constant mortality. Nonequilibrium estimates of Z account for changes in mortality due to fishing if M and recruitment can be assumed constant, and thus used to track changes in F. This approach has subsequently been modified to allow for the inclusion of recruitment (Gedamke et al. 2008), abundance (Huynh et al. 2017), and effort (Then et al. 2018) indices, and increase the resolution of Z estimates from groups of years to yearly changes. While general trends in mortality may be tractable with the non-equilibrium methods (Huynh et al. 2019), the absolute value of F remains difficult to capture in these methods and is still sensitive to the many assumptions, but does provide an alternative to constant mortality rates.

The data-limited length-based methods have been implemented in several assessment software packages. These include (at least):

- LIME (Rudd and Thorson 2018);

- SS-LO (Cope, 2021 (https://github.com/shcaba/SS-DL-tool));
- LBSPR (Hordyk et al. 2015 (http://barefootecologist.com.au/lbspr.html));
- DLMTool (Carruthers et al 2018; https://www.datalimitedtoolkit.org/

Overfishing SDC and Status from Age/length DLM

The overfishing SDC (MFMT) for composition based DLM typically uses the %SPR proxy indicated in the FMP under higher data-moderate Tiers. The SDC units can be in terms of the %SPR itself, say 45%SPR, or in terms of the F that would produce that SPR level. It is preferable to keep it in terms of the %SPR which allows the F associated with it to be updated as life history information is updated with new assessments. The overfishing status determination is then made with no special modifications for it being from a DLM. Macpherson et al. (2022) describes how this approach can be used to develop rate-based ACLs.

Overfished SDC and Status from Age/length DLM

The B_{MSY} and overfished SDC (MSST) are more difficult to develop than the overfishing SDC because the basic data are not in terms of SSB or trends in SSB. However, the biological composition data, do directly relate to the degree to which the relative abundance of older fish has been reduced below a reference level. This is sufficient to develop an alternative MSST. If the current stock and fishery have been relatively stable for at least a generation time, then the recently obtained measure of %SPR has probably been the %SPR for several years. So, this %SPR is both a measure of the recent F that created this stock condition, AND a measure of the current condition of the spawning stock relative to what the stock would have been if unfished. The MSST can be expressed in units of %SPR to enable comparison to the current measure of %SPR.

The logic that supports this approach is as follow:

- MSST is normally created as a level of SSB relative to SSB_{MSY} (or its proxy). That same adjustment ratio, typically 0.5, can be used to create a MSST in terms of SPR. If the FMP's $F_{\%SPR}$ proxy is $F_{45\%}$, then 0.5 * 45% = 22.5% is an upper limit on an equivalent MSST.
- It is an upper limit because the measured %SPR is only a measure of the degree to which SSB/R has been reduced by fishing; it is not informative about how much that reduction in SSB/R has already reduced R because of the SRR.
- If the steepness is near 1, then the per-recruit and absolute biomass ratios will be identical. However, to the degree that the recent average recruitment has already been reduced below the unfished recruitment level as a cumulative effect of fishing and steepness<1, the $(SSB/R)_{CURR}$ / $(SSB/R)_{MSST}$ will overestimate the ratio (SS*B*/*MSST*) (Figure 4). It is recommended to take this into consideration when specifying SDC for per-recruit overfished status by making them more conservative in accord with expected degree of density-dependence.

- If the stock's current %SPR has fallen below this rate-based MSST, then there is a very high probability that it is overfished. Even if the current %SPR is slightly above the rate-based MSST, there is a chance that it is below the true MSST because of the effect of steepness on recruitment.

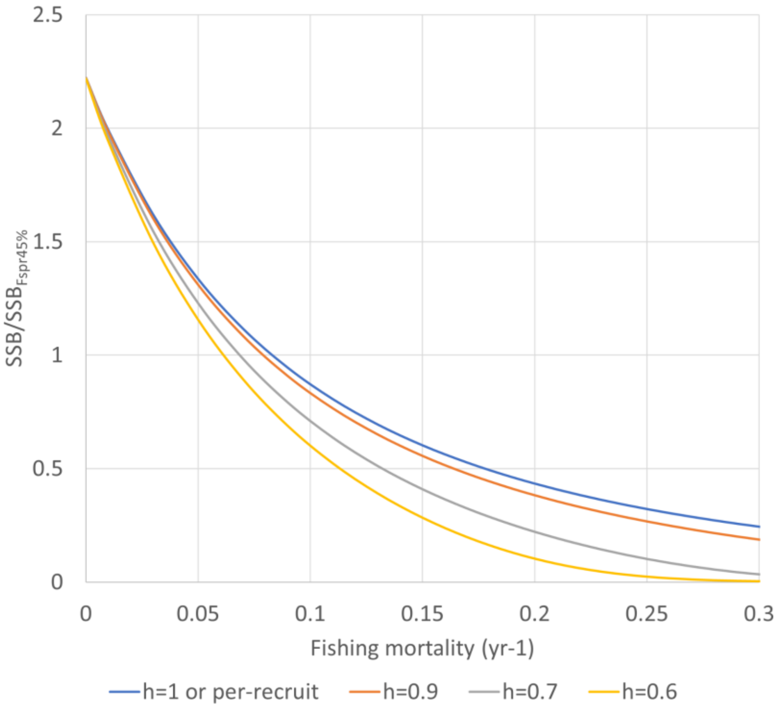

Fig. 4. Caption - Biomass ratios under a range of fishing mortalities, at 4 different steepness (*h*) levels. Note that per-recruit biomass ratios are identical to absolute ratios when *h*=1 (blue line). The biomass reference point ($SSB_{Fspr45\%}$) is the spawning biomass at *F* resulting in an SPR of 45%, calculated using a steepness of 1.

Previously, NMFS has not supported use of SPR based measurements to support overfished SDC. This occurred first in the early 1990s as SPR measures were first being developed and in 1999, NMFS rejected the Western Pacific Council's proposed overfished definitions which were based on SPR (e.g., MSST = SPR of 20 to 30 %). NMFS noted that: "SPR is not an appropriate proxy for [biomass associated with] MSY, because it does not provide a measure of stock biomass as required by the MSA to determine the status of each stock" (64 FR 19067; April 19, 1999). Subsequently Nadon (2017) proposed an approach similar to that described here, but it was not used to recommend overfished determinations because stock status must be based on SDC contained in the FMP. Recent revisions to the NS1G (2016) recognize the need for alternatives for SDC when conventional approaches cannot be applied (50 CFR 600.310(e)(2)(ii)), including consideration of rate-based alternatives to Annual Catch Limits (Macpherson et al. 2023). We recommend that the approach described here can be used to make an overfished status determination, in situations where %SPR can be measured by recent population age or length composition and a reasonable assumption of population and fishery stability can be made. We note that the quantity *biomass* in even the most data-rich situations is a product of the assessment model. The model analyzes data that are related to biomass, but biomass itself is not directly measured and the model generated values of biomass are typically evaluated as a ratio to B_0 or B_{MSY}. Here with this data-limited application, the model uses available data to estimate the ratio directly. The accuracy of the data-limited overfished determination cannot be well determined because of the necessary assumptions. Nevertheless, the method certainly can provide an indication of whether the stock is close to being overfished.

One situation that per-recruit overfished SDC is ill-suited for is when recruitment has a trend due to environmental changes (e.g., climate trends, habitat degradation). In this situation, it is possible for the per-recruit biomass ratio to be biased as a biomass index (Mace et al., 1996). For example, if recruitment is decreasing due to a long-term trend in water temperature, the absolute biomass, SSB, will also trend downward because of the reduced recruitment, while the ratio, SSB/R, is less affected. Mace (1996) makes the distinction that while a stock may not be "overfished" when its SPR is below a given threshold, the stock may become "depleted" by lowered recruitment levels that are environmentally induced and not related to historical fishing levels (the opposite situation can also be true).

Abundance-Based Methods

One abundance-based method uses a time series index of stock abundance (trend) to make an overfished determination. The other uses a measure of absolute fish abundance which can be combined with current catch to calculate the current exploitation rate, to make an overfishing determination. These methods are considered as data-limited because they do not model population dynamics explicitly.

Overfished SDC from Trends in CPUE or Relative Abundance

Trend based methods have only a relative indicator of the population trend so can only show how much of a percentage decline a stock has experienced over the observed time series. They lack catch data and a population production function, so cannot provide MSY reference points or overfishing status determinations. However, if both trend and catch data are available, then one is in a higher data Tier and can consider using Surplus Production Models that incorporate a production function as described in Tier 2.

One possible approach is to use the lowest observed index in a time series as an indicator of undesirably low biomass beyond which management seeks to avoid (ICES 2017). This level is set as the MSST proxy and enables overfished status determinations to be made. The quality of this proxy is dependent on the length of the index time series relative to the fishing history of the stock. Availability of multiple, high quality fisheries-independent indices is more likely to provide confidence in abundance indices reflecting population trends and associated SDCs than a situation with only limited fishery-dependent time series where changes in gear(s) and spatial distribution of effort may have occurred.

Another approach is to use the percentage change over time as an indicator of whether the stock has declined excessively. The MSST proxy is expressed not in units of SSB, instead it is expressed as the expected ratio of MSST to either B_0 or B_{MSY}. For example, if the stock was believed to be lightly fished in years leading up to the beginning of the index time series, then a 50% decline in the index would indicate that the stock may be near B_{MSY} and a 75% decline would put the stock near MSST. But if substantial fishing had already occurred by the time of the start of the time series, then the stock may have been near B_{MSY} at the beginning and a 50% decline would put the stock near MSST. These greatly simplified scenarios demonstrate the biggest challenge to applying this approach (Fischer et al. 2021; Harford et al. 2021; NEFSC 2023; Legault et al. 2023). In addition, such an approach can be biased if selectivity or catchability changes over time. Given the reliance of overfished status determination on assumptions of initial depletion, some robustness can be achieved by calculating what initial value of assumed depletion ("$d_{critical}$") would result in the stock being below MSST and then evaluate the plausibility that the stock could have been at or below $d_{critical}$ at the start of the time series (Cortés and Brooks, 2018). If the collective knowledge about the fishery suggests low plausibility for $d_{critical}$, then the conclusion of being above MSST is more robust to this specification.

Overfishing SDC from Absolute Abundance

This approach is designed to set the overfishing SDC in terms of the exploitation rate, which is the ratio of catch to a direct (absolute) measure of population abundance. The simplest option is to relate this exploitation rate (E) to the natural mortality rate, such as E=0.75*M (Gulland, long time ago), but if more complete life history information is available, then a $F_{\%SPR}$ should be used. The absolute abundance approach is considered to be in the data-limited category because it does not produce information about the population trend or MSY, although the absolute abundance survey itself is quite data-rich.

The absolute abundance approach relies upon the population survey covering the range of the stock and having information on the catchability of the survey gear so that the survey result can be scaled to an estimate of total population in the surveyed area. Estimates of catchability are derived from field experiments and gear studies. This approach is used for some acoustic surveys and for the lower tiered assessments in the North Pacific by using swept-area biomass estimates from the bottom trawl survey, and in the Northeast using catchability estimates from field experiments (primarily flat fish and highly demersal stocks). Similarly, it has been used in Pacific Islands and elsewhere using swept-area abundance estimates from SCUBA surveys. Other absolute abundance possibilities are tag-recapture, including new genetics-based approaches using a technique termed close-kin mark-recapture (CKMR).

Absolute abundance could conceivably be compared to an MSST to determine an overfished stock status, but this requires the MSST to be determined by a previous absolute abundance estimate or through expert opinion. It is conceivable that an overfished determination could also be made if there was knowledge indicating that the current situation regarding overfishing had persisted for a long time; just as biological composition approach can allow both overfishing and overfished determination if the current condition has persisted for a long time. Generally, the absolute abundance method has only been used for defining an overfishing SDC rather than comparing it to an overfished SDC.

Note that an absolute abundance survey probably provides a measure of population length or age composition, so the biological composition method for overfishing status probably can be applied in addition to the absolute abundance approach. Finally, current integrated population models generally can use absolute abundance information in combination with all other typical data types, so it generally is preferable to use this approach to status determination rather than using just one source of information.

Overfishing SDC from Catch Only Methods

Catch only methods assert that the existence of the historical time series of catches is evidence that the population was at least large enough and productive enough to support those catches. This method has no data on stock trends, so variations in methods tend to depend upon assumptions regarding the degree to which the population declined, or not, while those catches occurred (i.e., require as an input an assumption of relative stock status). This method can be used to guide setting an OFL and an ACL as fractions of historical or recent catch, but does not provide information on overfished stock status as that is typically an assumed input to these methods.

Catch only methods use, at minimum, a time series of total removals (landings plus dead discards) to determine a sustainable catch level. These approaches rely on defining population scale through the catches, then assuming stock status at a given catch level. Average catch multiplied by a buffer is one of the simplest approaches (MacCall, 2009; Restrepo et al. 1998). Later, the Only Reliable Catch Stocks (ORCS; Berkson et al. 2011; Free et al. 2017) approach added expert opinion on stock life history (to adjust productivity expectations) and status to better define the use of average catch. Methods have greatly expanded to incorporate more complete time series of catches linked to population dynamics models, specific life history values and strong assumptions of stock status (e.g., Dick and MacCall, 2011). Because assumed stock status is an input into these methods, they should not be considered as providing a measure of relative stock status, only the overfishing (OFL) reference point.

Additional Considerations for Reference Point Calculations

MSY, B_{MSY}, F_{MSY} and their proxies can be influenced by a number of additional factors, many of which may not be routinely considered during estimation of reference points. The units of reproductive potential section illustrates a correctable bias that arises when historical proxies are used and assessments move from simple spawning biomass basis to fecundity-based measures of reproductive potential. Fleet complexity and spatial complexity highlight the challenges of doing reference point calculations in real world situations. Sections on age truncation, and density-dependent life history describe additional impacts of fishing that are not routinely taken into account in status determinations based solely on preservation of reproductive potential.

Units of Reproductive Potential

In principle and in accord with ecological literature, reproductive potential should be in terms of viable offspring. This is difficult to measure and the most commonly used proxy is the mature female biomass of the stock, commonly termed spawning biomass. The use of spawning biomass as a proxy for stock reproductive potential assumes that reproductive output increases isometrically with size (Hixon et al. 2014, Barnache et al. 2018, Minte-Vera et al. 2019). Recent research indicates that spawning stock biomass alone may be an incomplete index of spawning potential (Scott et al. 1999, Murawski et al. 2000, Hixon et al. 2014). For many species it is now typically observed that older spawners produce more eggs of higher quality per unit of biomass compared with younger spawners (Scott et al. 1999, Sogard et al. 2008, Hixon et al. 2014, Barnache et al. 2018). Barnache et al. (2018) found that 140 of 177 species included in a meta-analysis presented hyper-allometric mass scaling with fecundity, with a mean scaling exponent of 1.29.

The units with which reproductive output is measured will interact with estimation of the spawner-recruitment steepness. When a species has hyper-allometric fecundity, it will appear to be more depleted in units of fecundity-based reproductive output than the degree of depletion measured in terms of mature female biomass (Minte-Vera et al. 2019), but the level of recruitment has not changed so the estimate of steepness will be slightly higher to explain that recruitment stayed high as the fecundity-based SSB declined more than the previous measure of SSB.

For situations that use a proxy for FMSY, a small bias can arise when the assessment transitions to fecundity-based SSB. Previous investigations of MSY proxies were all done in units of mature female biomass and led to conclusions such as $F_{40\%SPR}$ as a reasonable proxy for F_{MSY}. These proxies are somewhat biased if a stock's reproductive output is now measured in terms of population fecundity. The issue is that the F that produces 40%SPR in terms of biomass is a slightly larger F than the F that produces 40%SPR in terms of fecundity. Thus, switching to the fecundity-based SSB will cause the MFMT to shift to a slightly lower value. Alternatively, the %SPR proxy could be recalibrated for stocks with hyper-allometric fecundity.

Fishery Technological Characteristics

The NS1G defines MSY with reference to, among other things: *fishery technological characteristics (e.g., gear selectivity), and the distribution of catch among fleets.* 50 CFR 600.310 (e)(1)(i). By inference, F_{MSY} and SDC also take these characteristics into account. MSY and associated reference points are influenced by the fleet selectivity (i.e., the relative distribution of age-based F for a given fleet that combines gear contact selectivity and availability of each age-class to the gear) and relative effort among fleets with different selectivity patterns (Beverton and Holt 1957; Maunder 2002; Powers 2005; Guillen et al. 2013). However, the true MSY (i.e., the largest potential yield), also termed global MSY, relies on an idealized selectivity pattern, which would harvest all fish over a certain age (i.e., 'knife-edge') and is determined solely by the species' life history (Goethel et al. 2018). It is not feasible to manage fisheries to attain the idealized knife-edge selectivity pattern associated with global MSY. Therefore, traditional MSY calculations are conditional on the extant selectivity patterns and associated fleet allocations of catch or effort (i.e., as enforced by policy or realized through harvest patterns). For example, when multiple gears or sectors target a species (e.g., an offshore bottom longline fishery that catches primarily older fish and a near shore recreational fishery that catches primarily younger fish), then the distribution of effort among gear types will directly influence the conditional MSY level that can be achieved due to each sector harvesting different segments of the population. Currently, global MSY is not commonly computed, but reporting global MSY values can be a useful and informative tool to help managers and stakeholders to better understand how fleet allocations and associated differences in gear selectivity may influence resulting MSY.

A further complication to computing conditional MSY is that there are multiple assumptions that could be utilized to scale or allocate effort among fleets or gear types in projection models, and the approach utilized will directly influence the value of the conditional MSY (Goethel et al., 2018). Moreover, certain fleets (e.g., bycatch and discard) often are not proportionally scalable to target fisheries. For instance, as the effort associated with achieving a SDC increases for a target fishery, it may not be reasonable to assume a similar proportional increase in a non-target fishery. In fact, common treatments of non-target fisheries (e.g., assuming fixed discard levels regardless of target fishery effort) can lead to non-conservative estimates of conditional MSY. Goethel et al. (2018) recommend an alternate approach to computing conditional MSY when multiple fisheries are present, particularly non-target fisheries, which uses the inherently sustainable level of spawning biomass associated with the global MSY as the biomass SDC. The primary rationale for this approach is that the SPR associated with global MSY will be achievable in the long-term given the appropriate management (i.e., gear- or fleet-specific yield streams) regardless of fleet dynamics (even though global MSY is not inherently achievable due to extant selectivity patterns for each fishery). Because global MSY (and the associated spawning biomass) relies only on life history factors, using the SPR associated with global MSY as an SDC provides a more stable and conservative reference point compared to using the biomass associated with any of the conditional MSY values. Additionally, when the yield streams required to achieve the SPR associated with global MSY are calculated based on extant fleet allocations, selectivity patterns, discard levels, and bycatch rates, the framework can be employed without disruption to the various fisheries.

A related issue is that a single F does not exist and cannot be computed, except in surplus production models (see Tier 2 below) that lack age structure. F typically differs by fleet, age, size, sex, spatial region, and season. In addition, the relative F among all those factors changes over time. Condensing that complexity into a single metric of fishing intensity is complex and obscures those details. There are two basic approaches to creating a simpler index of fishing intensity, here termed F'. One approach creates F' as an average of the F's across some range of ages that have the highest age-specific F (after summing age-specific F across fleets if necessary). Then the fleet-specific and age-specific F used in reference point calculations is calculated relative to F'. This allows assessment software to search for the F' that produces MSY, or a particular SPR, conditional on the allocation of that F' to all the individual F components as the software calculates catch, SSB and SPR. The other approach goes through all the same calculations, then reports the %SPR that results from fishing at that level of multi-dimensional F in equilibrium, so the F metric is the resultant %SPR. Because %SPR goes down as F goes up, it is convenient to report the metric as 1-%SPR. An important distinction between F' and 1-%SPR is that they have a curvilinear relationship to each other. As F goes to high levels, 1-%SPR will asymptote at some level < 1.0 when some of the SSB is from ages that are younger than the age range that experiences substantial F. For this reason, it seems valuable to report both F' and 1-%SPR to provide a fuller accounting of the consequences of fishing.

As a final note of caution regarding the consequences of F complexity, assessments should clearly report the prevailing F pattern used in calculation of reference points as well as the F pattern used when doing projections, as these may differ. Indeed, projection of social and economic factors driving changes in the F pattern is an area for potential improvement in reference points and projections (Chan et al 2022)

Spatial Complexity

Spatial population structure is widely recognized as an important driver of productivity and population resilience (Lowerre-Barbieri et al. 2017). Awareness of the spatial structure within and between fish populations is improving due to an increasing array of high resolution data sources that can identify population structure (e.g., 'omics) or movement and distribution (e.g., electronic tagging, GPS, habitat, and oceanography data). Simulation studies have demonstrated that ignoring population structure or connectivity among population units often results in incorrect status determinations and increased potential for overharvesting (or underharvesting) or misdiagnosing productivity, which may result in localized depletion if stock structure is ignored in management advice or sedentary life stages are targeted by the fishery (Fu and Fanning 2004; Kerr et al. 2014; de Moor and Butterworth 2015; Kerr et al., 2017).

Additionally, not accounting for the spatial dynamics of the fishery can result in overharvesting (Fahrig 1993; Benson et al. 2015; Hoshino et al. 2014) or underharvesting when effort is not efficiently allocated between spatial units (Tuck and Possingham 1994). Shifting distributions due to environmental effects further complicate determination of stock status within spatially dynamic populations (Link et al. 2011). To ensure appropriate status determinations, it is necessary to first understand and adequately define stock boundaries or population units of management concern using myriad stock identification approaches (Cadrin, 2020). Misaligning or misdiagnosing stock boundaries with biological units will impede the ability to identify stock status regardless of the population structure (Berger et al., 2021). Changes in fish distribution can be accounted for through fitting a temperature-dependent catchability within the stock assessment (e.g., Wilderbuer et al., 2011), and spatially explicit models could also be explored to account for dynamic spatial stock structure and can directly account for changing spatial distributions of a stock. However, although methods exist for estimating stock status for complex spatial population structure (e.g., Goethel and Berger 2017; Kapur et al. 2021; see Goethel et al. 2016 for a review of spatial reference point approaches), assumptions of stationarity can be problematic given the dynamic nature of movement and dispersal across all life history stages. There is also increasing evidence that population structure and spawning potential can vary over much smaller spatial scales than typically considered in an assessment (Marteinsdottir et al. 2000, Grewe et al 2015), making the aggregate measures of reproductive capacity misleading. The importance of directly accounting for spatial dynamics in status determination criteria is context dependent and often depends on the population structure of the species, the level of connectivity among population components, and the spatial distribution of fishing effort. No strong guidelines currently exist for implementing spatially explicit status determination criteria, given that spatial dynamics are infrequently accounted for within stock assessment models used as the basis of management advice (Berger et al., 2017). Langseth and Schueller (2017) demonstrate well the complexity of population-wide F when there are unequal F rates across multiple spatial areas and only slow mixing of the stock among those areas. The extreme being marine protected areas in which all the F occurs outside those areas (Field et al, 2006).

Given the complexities of accounting for spatial dynamics in reference point models, continued exploration of alternative approaches to developing harvest strategies and defining sustainable biomass targets that account for spatial processes is warranted. Empirically driven, spatially-explicit reference points (e.g., spatial distribution metrics) represent a promising approach that could be utilized in tandem with conventional BRPs (Reuchlin-Hugenholtz et al. 2015, 2016). Application of data-conditioned management strategy evaluation using spatial operating models is recommended as current best practice for determining robust spatially explicit status determination criteria and spatiotemporal management that is likely to provide sustainable harvest levels for a given stock or interconnected population complex (Goethel et al. 2016; Berger et al. 2017; Punt et al. 2017).

Age Truncation

The protection of SSB is focused only on the total reproductive potential. The degree to which the age composition of the SSB gets compressed into a few young age groups is not routinely presented as a consequence of fishing, nor have standards been set. Concerns are that a compressed age composition leads to higher stock fluctuations due to recruitment, especially if regime shifts cause long intervals between strong recruitment events (Botsford et al. 2014). Concerns also have been raised about needing multiple age classes of spawners to assure continuity in spawning aggregations. High variability in recruitment makes for a non-smooth population age composition, hence it is difficult to develop standard metrics. Restrepo et al (1998) recognized that with an overly compressed age composition, a single, large year class could rebuild the stock to the SSB target without providing good stock resilience.

Size-Selective Fishing: Declining Size-at-Age

Fisheries tend to capture larger fish. This means that for a given cohort of fish, the faster-growing members of the cohort enter the fishery at a younger age and experience higher cumulative fishing mortality over their lifetimes. This reduces the realized mean size-at-age of older fish when fishing pressure is high, thus reducing the reproductive potential below that of a population that is not fished by size-selective means. If fish growth is a heritable trait, then such selection could also have evolutionary consequences. There are complicating and ameliorating factors, such as some fisheries having dome-shaped selectivity, but in general this “Rosa Lee’s phenomenon” has been known for over a century, but not integrated into routine assessment methods. Where long-term declines in mean fish size-at-age have been observed, investigation of size-selective fishing should be considered. Some assessment software packages, such as Stock Synthesis (Methot and Wetzel, 2013), have the capability to account for the impact of size-selective fishing on reference points, but this feature cannot be employed in all situations.

Density-Dependent Life History Factors

A commonly overlooked issue in age-structured assessments is that all density-dependence is assigned to the spawner-recruitment function. Most software in use today limits this choice to either the planktonic stage (age 0) or the first year of life (Li et al. 2021). This ignores the possibility that there is compensatory density-dependence in growth, maturation, natural mortality, fecundity, range-expansion, or other factors (Rose et al 2001). Biomass-dynamics models implicitly admit that density-dependence is inclusive of all such possibilities, but provide no pathway for investigation of particular mechanisms. If young fish continue experiencing mortality after they enter the fishery, then calculations of stock status and surplus production will be biased if it is not considered (Brooks and Powers 2007). Accordingly, the decision to adopt any particular SRR, and the reference points it implies, should consider whether it adequately captures the age classes affected by density dependence. Although changing life history factors are taken into account as recent average values when updating reference points, it is possible that some of these changes are density-dependent, hence linked to the level of fishing and hence are potentially reversible. Numerous instances of potential density-dependence can be found in the scientific literature. For example, Rindorf et al (2022) found evidence of density-dependent reductions in growth for a high fraction of stocks in ICES waters. In principle, such density-dependent changes could become an integral component of the estimation of the F level that produced MSY. Improved monitoring and investigation of density-dependent life-history changes is advised so they can become a component of reference points in the future.

APPROACHES TO STATUS DETERMINATIONS

Overfishing Determinations

MFMT vs OFL Approach

The NS1G provide two alternative methods to making the overfishing status determination:

- Maximum fishing mortality threshold (MFMT) means the level of fishing mortality (i.e. F), on an annual basis, above which overfishing is occurring. The MFMT or reasonable proxy may be expressed either as a single number (a fishing mortality rate or F value), or as a function of spawning biomass or other measure of reproductive potential (50 C.F.R. 600.310(e)(2)(i)(C)). This is usually set to correspond to the F_{MSY} or its proxy.
- Overfishing limit (OFL) means the annual amount of catch that corresponds to the estimate of MFMT applied to a stock or stock complex's abundance and is expressed in terms of numbers or weight of fish. 50 C.F.R. 600.310(e)(2)(i)(D).

There are pros and cons to these two approaches depending on the timeliness and precision with which each can be calculated. When assessment is done in year T, there is a terminal year, typically T-1 but not always, for which catch has been measured, thus F can be calculated for that year and the MFMT method can be applied to that year. The assessment also typically will be able to project the expected fishable abundance to year T+1 and beyond and calculate the OFL for each year. If the assessment is not updated every year, the MFMT method cannot be applied to the most recent fishing year because there was no assessment to calculate F. The OFL method can be applied as soon as annual catch is measured, but if that OFL is carried forward, or projected from an older assessment, then it may be inaccurate relative to the true OFL, especially for short-lived stocks with high recruitment variability. Thus, status determinations made by the OFL method might look incorrect when subsequent assessments look back at the F that resulted in those years.

The advantages of using OFL as the SDC are that catch can be easily understood by constituents, a determination can be made as soon as catch totals are available, and there is no retrospective problem with setting the SDC itself. The OFL method doesn't depend on having an assessment for the most recent year; only that the most recent assessment can project the fishable abundance to the most recent year with reasonable accuracy. The ability to project fishable abundance to the relevant year is the shortcoming of the OFL method because with high recruitment variability and/or long projections, the calculated OFL in increasing composed of model-based recruitments that are not well-represented in the data. The OFL will also be sensitive to assumed weight at age in the projections, and this would be exacerbated if those values have exhibited strong recent trends.

The MFMT approach to determine if overfishing is occurring is using the stock assessment to look back at the past performance of the fishery. This means that the MFMT method is less sensitive than the OFL method to recent fluctuations in recruitment. However, F cannot be calculated until an assessment has been updated, which may lag the fishery by several years. Therefore, a status determination based on MFMT could be less current than a determination based on OFL and catch, and reflects past, rather than current, fishery performance. Also, if there is a retrospective pattern in the assessment, then the hindsight estimate of F for a particular year used for the SDC will be different than the forecast estimate of stock condition used when setting target catch levels and management measures for that same year. This mismatch can lead to an awkward situation in which catch is controlled below the ACL but the F is subsequently determined to be above MFMT.

Multi-Year Approaches to Overfishing Stock Status Determinations

Overfishing status determinations are typically made based on the most recent year for which there is information. However, when utilizing the MFMT (F Based) approach, the estimate of F for the most recent year for which there is data is often more uncertain than the estimates of F in prior years (NRC 1998). In contrast, as time goes on, sources of such uncertainty (e.g., catch misreporting, model misspecification, etc.) are identified and corrected, resulting in more certainty in data points from prior years. Uncertainty in the data from the most recent year can cause fluctuations and inconsistencies in a stock's overfishing status (i.e., "subject to overfishing" and "not subject to overfishing"). In addition, the extent to which the effort or catch exceeded the threshold for overfishing has not traditionally been considered when determining whether the stock was subject to overfishing. Small amounts of excess effort or catch in a single year may not jeopardize a stocks' ability to produce MSY over the long term, thus an overfishing stock status determination based on that single year's reference point may not be the most appropriate characterization of stock status. To ensure accuracy and consistency in overfishing status determinations and more stability to fisheries, the 2016 NS1 guidelines included a new provision that allows overfishing status determinations, in certain circumstances, to be based on a period of no more than 3 consecutive years of past data. *See* 50 C.F.R. 600.310(e)(2)(ii)(A)(*3*). This multi-year approach allows managers to utilize relatively certain data from prior years when the most recent data point is uncertain. The specific circumstances in which the multi-year approach is appropriate and will be used for a particular stock needs to be described in an FMP or FMP amendment. While a multi-year approach can be used for determining and reporting on stock status (*see* MSA sections 303(a)(10) (SDC in FMP) and 304(e)(1)-(2) and 50 C.F.R. 600.310(j)(1) (report to Congress and status determinations), it cannot be used as a basis to specify future annual catch limits (ACLs) at levels that would result in overfishing. The MSA requires—and the NS1 guidelines reiterate—that ACLs must be set to prevent overfishing each year. Further background on the multi-year overfishing stock status determination provision is provided on pages 2791–2792 of the proposed rule (See 80 FR 2791–2792, January 20, 2015).

A multi-year approach is used to determine overfishing status (3-year average of F compared to MFMT) for some South Atlantic and Gulf of Mexico stocks. The 3-year average approach is not explicitly specified in their FMPs, but is used when endorsed by the respective Council SSCs. For example, South Atlantic golden tilefish was assessed in 2021, using data through 2018. The stock assessment supported a determination that golden tilefish is not subject to overfishing because $F_{2016\text{-}2018}$ (0.2671) was less than the MFMT (0.282). For another example, the South Atlantic gag was assessed in 2021, using data through 2019. The stock assessment supported a determination that gag is subject to overfishing because $F_{2017\text{-}2019}$ (0.79) was greater than the MFMT (0.37).

Overfished Determinations

The reference point for overfished determination is referred to as the minimum stock size threshold (MSST), and defined in the NS1 guidelines as "*the level of biomass* [SSB] *below which the capacity of the stock or stock complex to produce MSY on a continuing basis has been jeopardized.*" The 2016 revision to the Guidelines updated the requirements for MSST to be: "*The MSST or reasonable proxy must be expressed in terms of spawning biomass or other measure of reproductive potential. MSST should be between 1/2* B_{MSY} *and* B_{MSY}*, and could be informed by the life history of the stock, the natural fluctuations in biomass associated with fishing at MFMT over the long-term, the requirements of internationally-managed stocks, or other considerations.*" 50 C.F.R. 600.310(e)(2)(ii)(B). However, little guidance currently exists for how to determine where in that range between ½ B_{MSY} and B_{MSY} MSST should lie for individual stocks. Subsequent to the 1998 Tech Guidance, the range of MSST approaches included a predominance of 0.5*B_{MSY} in the Northeast, a predominance of (1-M)*B_{MSY} in the Southeast, simulation study approach in Alaska, and 25% of Bzero for Pacific Coast groundfish with 40% Bzero as the B_{MSY} proxy. Simulation studies and MSE are advised to improve understanding of the expected performance of MSST.

We note that the U.S. approach to overfished determinations is intermediate between the ICES (2022) approach in which their B_{LIM} is set at a low SSB level that is not explicitly coupled to B_{MSY}, and the FAO (1995) guidance for a precautionary approach by which many RFMOs for highly migratory species treat B_{MSY} as the overfished limit. Recent workshops in ICES (2022) have explored and advocated for defining B_{LIM} as a fraction of B_{MSY} or B_0.

Approaching an Overfished Condition

Additionally, Section 304(e)(1) of the MSA requires that stock status be reported for stocks that are approaching an overfished condition, which the Act defines as follows: *A fishery shall be classified as approaching a condition of being overfished if, based on trends in fishing effort, fishery resource size, and other appropriate factors, the Secretary estimates that the fishery will become overfished within two years*. The NS 1 guidelines further clarify that stocks approaching an overfished condition are projected to have more than a 50 percent chance that the biomass will decline below the minimum stock size threshold (MSST or Blimit) within two years (50 CFR 600.310(e)(2)(i)(G)). Making an approaching overfished determination typically requires the use of future stock projections.

The 1998 Tech Guidance did not address the topic of "approaching an overfished condition", and it has received only limited attention in FMPs (see FMP for Gulf of Alaska Groundfish: https://www.npfmc.org/wp-content/PDFdocuments/fmp/GOA/GOAfmp.pdf). Here we provide an updated set of recommendations for MSST and the related issue of approaching an overfished condition.

A. MSST: Most FMPs use ½ B_{MSY} as the MSST. However, few FMPs seem to have done simulation studies to determine the relationship between that level and the probability distribution of natural fluctuations in SSB associated with fishing at MFMT. It is possible that some stocks would rarely get that low through natural fluctuations. Other stocks, particularly short-lived stocks with high recruitment variability, would routinely fluctuate to that level or lower through natural factors unrelated to overfishing. If a Council is contemplating a change to its MSST definition, we recommend simulation studies to determine the frequency with which typical stocks in a FMP would be expected to fluctuate below MSST. That same simulation approach can be configured to determine how long a stock would be expected to take to rebuild from MSST to B_{MSY} at MFMT. Conducting these simulations at F_{ABC} and at typical F levels could be useful to have readily available if the stock approaches MSST and a rebuilding plan is needed.

B. Approaching Overfished: Assessments already routinely provide projections of at least one year while fishing at F_{ABC} in order to provide information for setting ABC and then ACL levels. It should be straightforward for any assessment software package to be configured to also produce two year projections in order to determine the probability that the stock will fall below MSST within two years. The NS1G are silent regarding the exact conditions under which such a two year projection be conducted. It is logical that this two year projection be conducted at F_{ABC} (e.g. using the ABC Control Rule) to provide a conservative calculation of the probability of falling below MSST because F cannot intentionally be greater than F_{ABC}. It also seems reasonable to conduct a second projection at the F level expected to prevail over those two years (i.e., prevailing F) because there are many fishery situations in which the realized F is less than F_{ABC}.

a. The projection using prevailing F is recommended because many recent factors that are expected to prevail for upcoming two years could result in F being less than F_{ABC}. If the projection using prevailing F gives the stock at least a 50% chance of falling below MSST within two years, then it supports a determination that the stock is approaching an overfished condition.

b. If the projection using the ABC Control Rule shows that the stock has at least a 50% chance of being above MSST but below B_{MSY} (or proxy) within two years, then it is recommended that projections out to ten years or one generation time be conducted to provide a longer term perspective on expected stock trends.

   i. If a projection using the ABC Control Rule projects that the stock has at least a 50% chance of being above B_{MSY} (or proxy) within 10 years or one generation time, whichever is greater, the stock is not approaching an overfished condition and is generally near B_{MSY}.

   ii. If the probability of being above B_{MSY} (or proxy) is <50%, then it is advised that the performance of the ABC Control Rule be investigated because fishing at the ABC Control Rule, which is less than MFMT, should produce an average stock abundance above B_{MSY}. Consideration should be given to whether or not there has been a shift in prevailing environmental conditions.

   iii. Both scenarios (i) and (ii) are contingent on the accuracy of projections. However, for a time frame of 10 years or one generation time, the projected stock is likely to be almost entirely composed of cohorts that were generated by the projection algorithms rather than estimated from observations in the assessment. A sobering analysis by Brooks and Legault (2016) demonstrated poor projection performance beyond a couple of years, and we recommend analyses that evaluate recent projection accuracy before basing final determination on these longer projections.

UPDATING REFERENCE POINTS FOR CHANGING ENVIRONMENTAL CONDITIONS

The NS1 guidelines state at 50 CFR 600.310(e)(1)(v)(A): "*Because MSY is a long-term average, it need not be estimated annually, but it must be based on the best scientific information available (see § 600.315), and should be re-estimated as required by changes in long-term environmental or ecological conditions, fishery technological characteristics, or new scientific information".* The guidelines do not define a time-frame for "*long-term*", nor any other conditions for re-estimation. Fishery technical characteristics and fish population dynamics (e.g., life history, recruitment) change on a range of time scales – short (annual), medium (3–10 years), and long (multi-decadal) – so determining what is a persistent change and which are fluctuations within the current prevailing conditions is not always clear-cut. However, it is important to differentiate the patterns of variation (e.g. high-frequency white-noise variation versus low-frequency regime-like variation) because the effects on stock productivity, distribution, and corresponding reference points depend on the time scale. This section will describe some current practices for updating reference points and will identify some challenges that are encountered.

Per the NS1G definition of MSY, the prevailing conditions which impact MSY can be broken down into fleet characteristics and biological factors.

- *Prevailing fleet technical characteristics*

  Reference points and control rules are based on the prevailing fleet characteristics. These characteristics will change in response to management actions (such as reallocation of quotas between sectors, increases or decreases in size limits, gear modifications and seasonal changes in the fishery and/or environmental conditions), and/or environmental conditions that alter life-history characteristics, movement and distribution which could affect availability/catchability. Fishery economic and market considerations may also influence the propensity for the fishery to target larger vs smaller fish. The resultant age-selectivity of each fleet and the allocation of F among fleets affects the F_{MSY} and MSY, and to a less degree the B_{MSY}.

- *Prevailing biological conditions:*

  Each component of a stock's productivity (growth, maturity, fecundity, natural mortality, recruitment) commonly varies over time in response to changes in the underlying ecological or environmental conditions. Some of these factors (particularly growth) are commonly measured on an annual basis, others like natural mortality are very difficult to measure and partially depends on the stock's interaction with other species, and some like recruitment can vary widely from year-to-year.

  A core challenge is that many of the biological factors (recruitment, growth, natural mortality, etc.) can be density-dependent as well as environmentally affected (see section Density-Dependent Life History Factors for further discussion; Helser and Brodziak 1998, Brodziak et al. 2008, Rindorf et al. 2022). If the change is due to density-dependence, then fishing, which changes the abundance of the stock, is partly the cause and this effect can be built into the reference point calculations. Calculations like this are routinely done when recruitment is linked to a spawner-recruitment relationship. We typically do not have enough knowledge to determine the relative contribution of the environment vs density-dependence to the change. Therefore, it is important that ascribing long-term biological changes to environmental causes be well-supported such that the basis for reference points is not eroded erroneously.

Overview of Approaches

Use Empirical Estimate: "Moving window" / "Trailing average" approach

The principal approach in use today is regular updating of SDC to adapt to changing biological and fishery conditions gradually over time. For example, in the Northeast, where life history parameters show sustained directional trends, the default has been to update reference points with a recent 5 year average for fishery selectivity and fish life history and to use either the entire or subset of the time series to characterize mean recruitment, with reference point updates occurring when stock assessments are updated. In the ICES system (ICES, 2021) reference points are generally updated every 5-10 years, hence they expect that reference points should be designed to be relevant for the upcoming 5-10 year period such that assessments during that time period can calculate status relative to the established reference points.

We suggest that time windows for these updates could be framed in relation to the mean generation time of the stock when unfished. This allows for consideration of a set of population cohorts in the estimation process, noting that shorter time frames may be too strongly influenced by between-cohort variation (van Deurs et al. 2021), especially for short-lived species. While no specific guidance can be provided because the situation will be species-specific, we note that short time windows on the order of one to two mean generation times would allow for the characterization of prevailing environmental conditions on the variability in life history parameters. However, this empirical adaptation approach provides no direct examination of long-term trends or consequences, which will be discussed later.

Dynamic Bzero

A special case of trailing average is the dynamic Bzero approach (MacCall et al. 1985; Berger 2018; Bessell-Browne 2022). Dynamic Bzero is a method to determine relative stock status that compares current biomass (e.g., SSB) to the biomass that would have been present if fishing had never occurred (so-called 'unfished' biomass) in any given year or set of years. This is in contrast to defining Bzero as a single, static value based on historical, pre-fishing conditions that assume steady state population dynamics across the time series. In application, the unfished biomass time series can be used to understand general (typically not mechanistic) changes in stock productivity, assumptions about equilibrium population conditions, and therefore applicable time periods over which prevailing conditions may have changed and thus reference points redefined. This information, along with species-specific life histories such as generation times, can be used to support the definition of a time window over which the trailing average (or related measure) is calculated.

The unfished biomass time series used in the dynamic Bzero approach is an estimated product from stock assessment, and thus has model assumptions associated with it. In particular, calculations assume that stock biology is not influenced by the level of fishing pressure (i.e., not an additional source of density dependence), which may be a strong assumption in some cases. As noted below (the four criteria for identifying a credible productivity change), careful consideration is also warranted when interpreting changes in productivity from unfished biomass time series. It is good practice to examine the risks and options (next section) associated with changing management benchmarks.

The Dynamic Bzero approach was intended principally to deal with the effect of variability in recruitment over time. However, its implementation and usage in common assessment packages (Methot and Wetzel, 2013) also applies to time-varying life history. Thus, when it gets used with a SRR parameterized in terms of steepness, an internal inconsistency results (Miller and Brooks, 2021). Updating of assessment packages to address this inconsistency is recommended.

Regime Specific Averages

While the use of trailing averages over a fixed time period is straightforward to implement, it could miss or blur important changes in the reference point factors. If there is an abrupt change in ecosystem/environmental state (i.e., regime shift), then it could be beneficial to detect and implement when that shift occurred as the year from which prevailing conditions are calculated.

The preferred approach is to use time series analysis, such as STARS (Vert-Pre et al. 2013, Szuwalski et al. 2015) and other change-point analyses (Brodziak and O'Brien 2005, Perala and Kuparinen 2014, Porch and Lauretta 2016, Perala et al. 2020, Möllmann et al. 2021), to determine the time window over which a new productivity regime or otherwise applicable period should be defined to update SDC. Additionally, it would be prudent to consider oceanographic (e.g., ENSO) and biological (generation time) cycles that may be useful for defining a relevant time window. Time windows should be selected to represent the 'prevailing environmental conditions' or the time horizon when a stock's productivity is thought to have 'shifted' from one productivity state to another as well as possible changes in ecological relationship with climate indices (e.g., Cai et al. 2015, Lizow et al. 2020). Truncating the time series window to this new regime is making a strong assumption that the historical data carry no information for the current or foreseeable future. Truncation may make it harder to accurately estimate the stock-recruitment relationship. Before deciding to truncate the time series, it is important to consider (1) the relative magnitude of change in the productivity regime, with larger changes giving more support for considering only the most recent years in the time series and (2) the amount of data left available after truncating to the new productivity regime and if it is sufficient for the methods being applied (DFO 2013).

Truncating the time series should only be considered if change is unlikely to reverse in short-to-medium term, and thus the selection of truncated data should be a hypothesis driven process (DFO 2013).

The general conclusion from recent workshops on reference points (DFO 2013, Klaer et al. 2015, ICES 2019, 2021) is that there are several key criteria that should be met before an environmentally-driven regime shift should be considered a credible explanation for a change in productivity. These criteria included the following:

- Consistent evidence of environmental change
- Change observed across multiple stocks
- Stock size largely not responsive to changes in fishing pressure over the time period, or no strong correlation exists that cannot be accounted for with the change in environmental conditions
- Strong/justified reason to believe conditions are not going to return to previous conditions/reverse trend in the period leading up to the next benchmark assessment.

Direct Linkage to Drivers within Models

The ideal situation is one in which we have a sufficiently sophisticated observation system and model such that future changes in fish productivity, distributions, and fishery activities can be linked to environmental drivers and those drivers can be projected into the future. If there is a clear mechanistic relationship between a life-history parameter (e.g., growth, recruitment, natural mortality), or stock distribution, and some measurable time series of an environmental factor (e.g., temperature, dissolved oxygen, PDO, etc.), then it may be possible to use that relationship directly in the stock assessment model and thus dynamically account for changes in these environmental factors in the calculation of MSY. An example of this approach to account for changing productivity would be fitting a temperature-dependent stock recruitment relationship (e.g., Hare et al. 2010). Such an approach would allow for estimation of biological reference points with more precision, as well as for projections of levels of population abundance and sustainable harvest under assumed future temperature conditions (Nat Academies 2014). However, while it is most preferable for mechanistic relationships to be directly associated with the stock of interest and directly incorporated into tactical models (ICES, 2021), establishing these mechanistic relationships remains a challenge for most stocks today (Haltuch et al. 2019).

Dynamic/Responsive Harvest Control Rules

Another approach is to account for the changing conditions outside of the assessment model by designing a dynamic or responsive Harvest Control Rule. An example of this is the management model used for Pacific Sardine, where F_{MSY} is adjusted based on measurements of sea surface temperature, where a higher F_{MSY} is allowed when ocean conditions are conducive for sardine recruitment and F_{MSY} is reduced when conditions are poor (Jacobson and MacCall 1995, Hill et al. 2011, Haltuch et al. 2018). A similar concept can be applied to account for changing stock distributions using a location of biomass cutoff in the HCR which could reduce the fishing rate in an area in proportion to the percent of a stocks total biomass which has shifted out of an area (see Link et al. 2021).

Implications of Changing Reference Points

The NS1G state that the reference points must be updated if conditions have changed. This puts a high burden on determining that a change has actually occurred. Otherwise, changes caused by the fishery on the stock could be overlooked.

Type I vs Type II error

There is often substantial uncertainty around whether a drop in a stock biomass is a result of normal fluctuations, excessive fishing, or a regime shift to a lower level of productivity. This leads to concerns about potentially making a Type I error, where one identifies an environmentally-induced change in productivity when one has not occurred, or a Type II error when one fails to identify an environmental impact on productivity when there is one (Haltuch and Punt 2011, Wayte 2013). Generally, a Type I error is more concerning, especially when the stock is erroneously thought to be experiencing a lower productivity resulting in lower recovery targets, when in fact fishing, not the environment, has caused the low productivity. Here we agree with Restrepo et al (1998)'s recommendation that the "burden of proof" should initially rest on demonstrating that the environment (as opposed to fishing) caused the decline, and that, therefore, the reference points should be modified. Recent international workshops (DFO 2013; ICES 2021) express similar cautions about too easily adjusting reference points.

Current state of the stock

If the stock is already in a poor state, then adjusting biomass reference points (MSST and B_{MSY}) down would increase the risk that the stock will remain in a low biomass state or decrease even further. This is because the new, lower estimates will adjust the relative status of the stock upwards, potentially indicating that there may be a less-pressing need for management action (e.g., rebuilding plans) or need to allocate surplus production to growth rather than fishing. Both of these situations may lead to the stock being less likely to take advantage of future, higher productivity conditions. In a similar vein, a series of consecutive low recruitment will cause a stock to decline in abundance. But if that is interpreted as a regime shift and biomass reference points are likewise scaled downwards, then target fishing mortality rates would be maintained at full levels.

To address concerns that adapting to lower abundance regimes might perpetuate excessive fishing pressure on declining stocks, Restrepo et al. (1998) suggested that "it may be therefore necessary to design control rules that conserve spawning stock abundance during prolonged periods of poor recruitment to preserve a stock's capability to produce higher recruitment when environmental conditions improve". Today, commonly used harvest control rules (HCR) typically reduce the target F rate when the SSB declines below an inflection level, typically set at B_{MSY} (or proxy), thus they provide protection to the stock at low biomass levels. However, it also is common practice to adjust this inflection point along with the reference points. This adjustment can have the counter-intuitive impact of maintaining the full target F even as the stock is declining so does not achieve the degree of protection envisioned in Restrepo et al. (1998). What is needed is an approach that maintains a long-term average approach for calculation of the HCR's inflection point, while SDC reference points are updated to reflect prevailing conditions. An approach like this is mentioned in ICES (2021) and Holsman et al (2020), but is untried in practice to our knowledge.

It would be inappropriate for this hybrid approach to be designed and recommended in this technical guidance document. However, its broad characteristics can be outlined:

- MFMT (F_{MSY} or proxy) depends on prevailing biological and fishery technical characteristics and density-dependence in recruitment and biology. It can be routinely updated to reflect prevailing conditions;
- MSY and B_{MSY} depend on these same factors and can be calculated from both a short-term, prevailing perspective, and a long-term perspective.
    - Prevailing B_{MSY} could be used as the target for rebuilding plans because it is feasible in the current regime;
    - Long-term B_{MSY} could be used to set the HCR inflection point to ensure that reductions in F will be recommended on declining stocks;
- This approach requires the simultaneous consideration of reference points and HCRs.
- Simulation studies and MSE to investigate the performance of such a system are needed.
- This approach would reduce F on stocks when biomass declines whether the decline is from fishing or from environmental change. In such situations, the F rate will be reduced whether or not the stock is considered to be below the MSST.
- As the time series gets longer, the new prevailing years will outweigh the older conditions in the long-term. Clearly, there is no prescriptive, one size-fits-all solution. The point here is that these interactions need to be brought into consideration whenever a shift in prevailing conditions is considered.

Recommendations Regarding Updating Reference Points

These recommendations are provisional because there is little experience to date with how adjusting reference points will perform in the long-term. They do reflect the collective judgement of scientists working in several systems around the world and are based on a growing number of simulation studies.

- Fishery characteristics routinely change, so their contribution to reference points should be routinely updated with projection, trailing average, or autoregressive calculations. To the extent feasible, SDC for the upcoming management era should utilize expected changes in fishery characteristics due to management changes, economic and environmental conditions.
- With changes in biological factor(s), the main objective is to determine whether it has changed because fishing has reduced the abundance of the stock or extreme recruitment events have increased abundance such that resources limitation may occur (i.e. density-dependence). If so, the effect should be built into reference point calculations, so it becomes a dynamic component of direct estimation
- If a notable change in environmental conditions has been documented and is expected to persist, then reference points should be updated
    - Seek knowledge of mechanistic linkages by which environmental change would logically cause the observed biological change.
    - Be wary of invoking an environmental explanation for a stock decline that could have been due to historical fishing and density-dependence.
    - Run simulation studies to understand consequences of changing reference points versus attributing change to density-dependence; document the risks of Type I and Type II errors.
    - Highlight and investigate situations leading to maintaining high F on a declining stock. Consider setting control rule inflection biomass based on long-term perspective, and setting F_{MSY}, B_{MSY}, MSY, and rebuilding target on the basis of more recently prevailing conditions. Such an approach needs simulation testing before being used.
- When biological factors have fluctuations, but no clear regime shift or density-dependence, then a trailing average approach is advised over a simple average of all years. This is a common situation. Simplistic application of this approach raises the same concerns about making empirical changes to reference points in situations where density-dependence may be the true cause.
- If invoking a regime shift in productivity, and using a %SPR for the proxy reference points, it is recommended to not only change the time period of recruitment used in the model, but to also re-evaluate the choice of %SPR proxy used to ensure it is still consistent with the new perception of the stock's productivity
- If invoking regime shifts, the assessment should routinely test the productivity shift hypothesis and the potential for a shift back to previous productivity state.
- If environmental drivers are identified, explore ways to directly incorporate them into the assessment model and resultant SDC reference point updates, but still be cautious of situations that could increase F on a declining stock.

MULTISPECIES INTERACTIONS AND REFERENCE POINTS

The NS1 Guidelines recognizes that the MSY for a stock or stock complex is influenced by its interactions with other stocks in its ecosystem and that these interactions may shift as multiple stocks in an ecosystem are fished. The Guidelines state that this "[e]cological and environmental information should be taken into account, to the extent practicable, when assessing stocks and specifying MSY…" (§600.310(e)(1)(v)(C)).

There are two types of interactions between species: technical interactions (e.g., mixed-stock fisheries, bycatch) and biological interactions. Technical interactions occur where species are caught together in the same gear at the same time, whereas biological interactions is used to refer to interactions between stocks, such as predator-prey interactions or competition. These two concepts are similar in that they both take account of multiple fish stocks and recognize that taking management action for one stock will have potential consequences for others in the system; however, they differ in the underlying processes governing the interactions (e.g., human caused vs. biological). Additionally, with both mixed-stock fisheries and multispecies interactions there are trade-offs in terms of yield achievable across the different stocks involved, as it is often not possible to achieve the MSY for all stocks simultaneously (Restrepo et al. 1998) because fishing targeted on one stock may cause bycatch of other stocks, and because the abundance of one stock could suppress another stock from achieving its MSY. Here we discuss approaches to account for such technical and biological interactions in specifying reference points.

Technical Interactions: Mixed Stock Fishery

Technical interactions occur when fishing on one species generates fishing mortality on other species. This occurs when multiple species are harvested together as in a mixed-fishery, or in situations where one species is incidentally caught or is bycatch (defined in MSA sec. 2(2)) in another fishery. Technical interactions are mostly accounted for in the process of setting ACLs and through accountability measures, which prevent ACLs from being exceeded and correct or mitigate overages of the ACL if they occur. *See* 50 C.F.R. 600.310(g)(1). Thus technical interactions are not typically considered as part of reference points and status determinations. The typical result of accounting for technical interactions is that the catch of some target species is below their MSY because more catch of that target species would incur excessive incidental catch or bycatch of more vulnerable species, including species on rebuilding plans with low allowable F levels. This "under-fishing" has been described by McQuaw and Hilborn (2011). Here we discuss some considerations and recommendations for establishing reference points to sustainably manage stocks with such technical interactions.

One approach to consider is a systems view of the multispecies reference points and to solve for system wide multispecies MSY (MMSY). This is similar to the provision in the NS1 Guidelines that allows the estimation of MSY for an aggregate group of stocks (50 CFR § 600.310(e)(1)(iv)). The idea here is to find the level of fishing across key stocks in the system that results in the greatest yield being obtained. However, often such analysis leads to the conclusion to "eliminate the predator, to harvest the prey" (Moffit et al. 2016), which is not in line with the dual requirements of MSA of preventing overfishing while achieving on a continuing basis OY. Therefore, biomass thresholds need to be added to this analysis. This can be done through constraining the MMSY optimization so that no stocks are predicted to drop below p^*B_0 (where the proportion, p, can be set to result in the B_{MSY} target, MSST threshold level of biomass, or somewhere in between) during the projection (Moffit et al. 2016). Therefore, the maximum yield that can be taken from the system while still ensuring the sustainability of each individual stock can be determined. It's important to note that the system level MMSY is often lower than the sum of individual single species MSYs (Holsman et al. 2016) and therefore if aggregate MSY is to be used, it should be calculated from multispecies models, or by a reduction from the sum of individual MSYs, not from simply summing individual MSYs, to ensure precautionary management of all stocks in the system.

To further aid in managing multiple species within a mixed-stock fishery we recommend that the F associated with MSST (F_{MSST}) be calculated for each species, taking into account equilibrium per recruit dynamics and the spawner-recruitment relationship (or proxy approach for MSY reference points). The F_{MSST} can be used to ensure that no stock is being fished at a level that would result in a 50% chance or greater of it dropping below its MSST in the long-term. With this additional metric (reference point) it may be possible to allow small amounts of overfishing to occur on some stocks (i.e., fish certain stocks above their F_{MSY}), while ensuring that they are not fished above their F_{MSST}, and thus still meeting the NS1 requirements that limits F on all stocks to a level that will not lead to the stock becoming overfished in the long term. We recommend that these calculations and reports be routinely available in stock assessment software so they can be used in situations that warrant consideration.

A related issue is that some fleets may catch a species only incidentally or may discard it entirely, and/or the species may be managed by a different FMP. Attempting to manage the amount of this bycatch or discards can be extremely difficult (Diamond 2004). In such instances, it is imperative that projections of BRPs and the yield required to attain them account for these sources of non-directed incidental catch and bycatch. Some software packages for projections are capable of dealing with these issues, but it is a complex and often confusing topic.

Biological (Ecological) Interactions

As mentioned previously, the main multispecies interaction is trophic (predator-prey) interactions. Predation is known to be an important process structuring fish communities, both bottom-up (prey abundance) and top-down (predator abundance). Bottom-up controls include the influence of prey-abundance on predator growth rates, and top-down controls include the influence of predator abundance on prey natural mortality rates (Collie et al. 2014). Here we explore various approaches to account for both these bottom up or top down controls.

Estimating Predation Mortality

One approach to account for top-down impacts of predators on prey in setting reference points, is to estimate natural mortality (M) for the prey species using a long time series of stomach content data for the predator species. With this approach the prey stock-recruitment relationship will be based on temporally variable estimates of natural mortality, that is conditioned on predator abundance and feeding habits. Estimating predation mortality requires information on predator and prey abundance and predator diet composition. A multispecies model can be used to integrate the stomach content data with the abundance estimates from the stock assessment (Collie et al. 2014). The time-varying predation mortality will have a greater influence on SPR based biological reference points compared with directly estimated F_{MSY} (Collie et al. 2014). Additionally, it is important to use SPR based reference points with caution for prey species, as these types of BRPs increase in a risky direction as M increases (Collie et al. 2014).

Simultaneously estimating targets for multiple species

Another approach involves modeling both species and the determination of targets for both species simultaneously using a combination of single and multispecies models. These approaches involve decisions regarding trade-offs between different objectives. One approach is to calculate each species Fx% using multispecies model projection such that each species equilibrates at p*B0, when F for all other species is fixed at average F or zero. This is similar to the process by which Ecological Reference Points (ERPs) for Atlantic menhaden were established to account for its role as prey for striped bass. For Atlantic menhaden an ERP target was specified to be the maximum F on menhaden that sustains striped bass at their B target when striped bass are fished at their F target, and the ERP threshold was the max F on menhaden that sustains striped bass at their B threshold when striped bass are fished at their F target. To obtain the F values, the NWACS-MICE model was run to provide the long-term, equilibrium values of F that met the ERP target and threshold criteria, and then that F was used in projections from the single-species assessment to provide the total allowable catch.

Lastly, as multispecies considerations inherently include trade-offs between different management actions and objectives, this analysis lends itself nicely to include as operating models in MSEs. There are several examples of MSEs already being used to help evaluate and provide advice within a multispecies management context (e.g, Herring MSE in NEFMC).

CONCLUDING REMARKS

This document strived to update technical guidance for implementation of reference points and status determinations under NS1. It is based on deliberations among knowledgeable experts that spanned several years. The document describes the issues related to direct estimation of reference points versus use of proxies. That section also describes how modern techniques can unify proxies with estimation through the use of parameter priors. Those same concepts help extend estimation to more data-limited situations. The document provides an overview of current F_{MSY} proxies and advocates for use of management strategy evaluation as a technique to investigate some existing proxies with decades-old justifications. We do caution that the scope of a MSE to investigate the performance of alternative control rules given current reference points is much narrower than a MSE to investigate the best levels for reference points themselves.

The document addresses some new issues. It provides a description of protocols to follow to provide advice on identifying if a stock is approaching an overfished condition, and it provides a rationale for situations in which a data-limited approach using a measurement of the current SPR can support both an overfishing and an overfished determination. It addresses how the shift from measuring SSB simply as biomass to a more complete measure of reproductive potential should be accompanied by a recalibration of the SPR proxy for F_{msy}.

Much of the current implementations of NS1G focus solely on the impact of fishing on the SSB of a stock. This misses other aspects of the impact of fishing on the reproductive potential of the stock. One is age truncation, e.g. the reduction in occurrence of older fish and the possible ecological consequences that are currently unmeasured. Another is the impact of size-selective fishing on the biology of the population that becomes increasingly dominated by slow-growing fish. Third is that the singular focus on the spawner-recruitment relationship is ignoring the possibility that other life history factors (growth, natural mortality, maturation) can also be density-dependent and affect the MSY-based reference points.

Climate change creates a wicked problem for reference points. Reference points can and should evolve with changing conditions, but reference points also need to establish a long-term perspective such that fishing does not perpetuate or exacerbate declines in a naturally declining stock. This conundrum is discussed, but not resolved. Another conundrum is that separation of climate impacts on fish productivity from density-dependent impacts is difficult to discern. Knowledge of both is derived from the same few decades of system monitoring.

The document concludes with a section on species interactions. This includes both biological interactions, especially predator-prey interactions, and technical interactions such as fishing on one targeted species does not occur in isolation of other species. Biological interactions mean that the reference points for one species will need to take into account the reference points for other species. Technical interactions have less impact on reference points, but they do create much complexity for the monitoring of all the sources of F that need to be accounted towards a species' reference points. For both biological and technical interactions, the challenge is compounded by the fact that the interacting species may be in different FMPs or even different management jusisdictions.

In the end, many points remain difficult to clarify for several reasons. First, the past 25 years of monitoring fish populations and their ecosystem has demonstrated the wonderful complexity of those fishery systems. Collapsing that richness into a single value for a reference point is challenging. Second, it is increasingly clear that reference points must shift over time in response to biological and ecosystem changes induced by climate change, but we need to guard against allowing the reference points to shift too readily. Third, the data situation varies tremendously across the 500+ stocks in fishery management plans so there is no one size-fits-all solution to several issues. Finally regional assessment teams and Council SSC's have evolved approaches to dealing with regional situations without a high level of inter-regional coordination and communication. Consequently, today we find equivalent, but different, approaches have evolved and are challenging to gather into a holistic approach.

Despite these challenges and differences, the NS1G system of reference points has been highly effective in providing a scientific approach to implementation of the Magnuson-Stevens Act's mandate to prevent overfishing and rebuild overfished fisheries.

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APPENDIX I: EARLY HISTORY OF SPR PROXY

A key question when using the SPR proxy is determining the SPR level that will approximate F_{MSY} for a stock or group of stocks. Over the last 30 or more years researchers have used comparison with other species, meta-analytic approaches and simulations to investigate the potential performance of a range of SPR levels against possible states of nature to help make this determination (Table 1).

In the early 1990s, the Magnuson Fishery Conservation and Management Act (renamed MSA in 1996) had different criteria for managing stocks compared to today, with an emphasis on avoiding recruitment overfishing and achieving MSY with little emphasis on the biomass levels associated with fishing at the recommended SPR levels. In that context, early studies sought to identify a common level of %SPR to calculate an F_{MSY} proxy that would work for all (or most) stocks to guard against recruitment overfishing and still achieve good yield (Goodyear 1990, Mace and Sissenwine 1993, Clark 1991, 1993). Goodyear (1990) recommended an SPR of 20%, whereas Mace and Sissenwine (1993) suggested 30% would be more appropriate for most stocks with 20% only sustainable for the most resilient of stocks. Clark (1991) proposed a min-max approach to optimize catch when faced with uncertainty in recruitment dynamics, which has become one of the most often cited methods for defining SPR proxies. Using this approach he demonstrated that for a wide array of life history and stock-recruitment relationships typical of demersal fish (groundfish), SPR 35% would usually achieve pretty-good yield (e.g., 75% of MSY). In a follow-up study Clark (1993) considered the impact of recruitment variability on the estimate of the optimal SPR level, and concluded that when recruitment variability is correlated 40%SPR was more appropriate as a default proxy to protect against the stock dropping below the 20% unfished biomass threshold, which has generally been considered worrisome for stock resilience. This recommended default was also supported by Mace (1994).

The 1996 Sustainable Fisheries Act amended the MSA to, among other things, add rebuilding requirements, amend the optimum yield definition to include rebuilding an overfished fishery to a level consistent with producing MSY, and require that FMPs have objective and measurable criteria for identifying when a fishery is overfished with analysis of how the criteria related to the reproductive potential of stocks of fish in the fishery. Pub. L. 104-297 §§ 109(e), 102, 108(a) (October 11, 1996). Subsequently, in 1998, NMFS amended the National Standard 1 Guidelines to require MSST and provide guidance on rebuilding requirements, noting that if a stock or stock complex is overfished, the purpose of management action is to rebuild the stock or stock complex to the MSY level. 84 FR 24212, 24230-24231 (May 1, 1998) (600.310(d)(2) (status determination criteria) and (e) (ending overfishing and rebuilding overfished stocks)). This change in the MSA did not change the search for SPR reference points. Challenges fitting stock-recruit curves still meant that many stocks used proxy reference points, and debate about the most appropriate %SPR persisted. However, studies began to consider the impacts of fishing at certain Fx%SPRs on biomass levels. Work in the 2000s recognized that the search for the "most appropriate" SPR depended on the stocks considered and suggest more conservative proxies are appropriate for most stocks (Brodziak 2002, Clark 2002, Dorn 2002, Brooks et al. 2010, Cortes and Brooks 2018, Harford et al. 2018). For instance, when a wider range of steepness and stock-recruitment relationships were considered, representing more realistic levels of resilience and productivity for certain types of stocks (e.g. rockfish), the optimum SPR increases to between 40%-70% (see Dorn 2002, Clark 2002, Harford et al. 2018). The desired levels of unfished biomass maintained from a given fishing rate was also found to be an important consideration when selecting an appropriate Fx%SPR. Clark (2002)

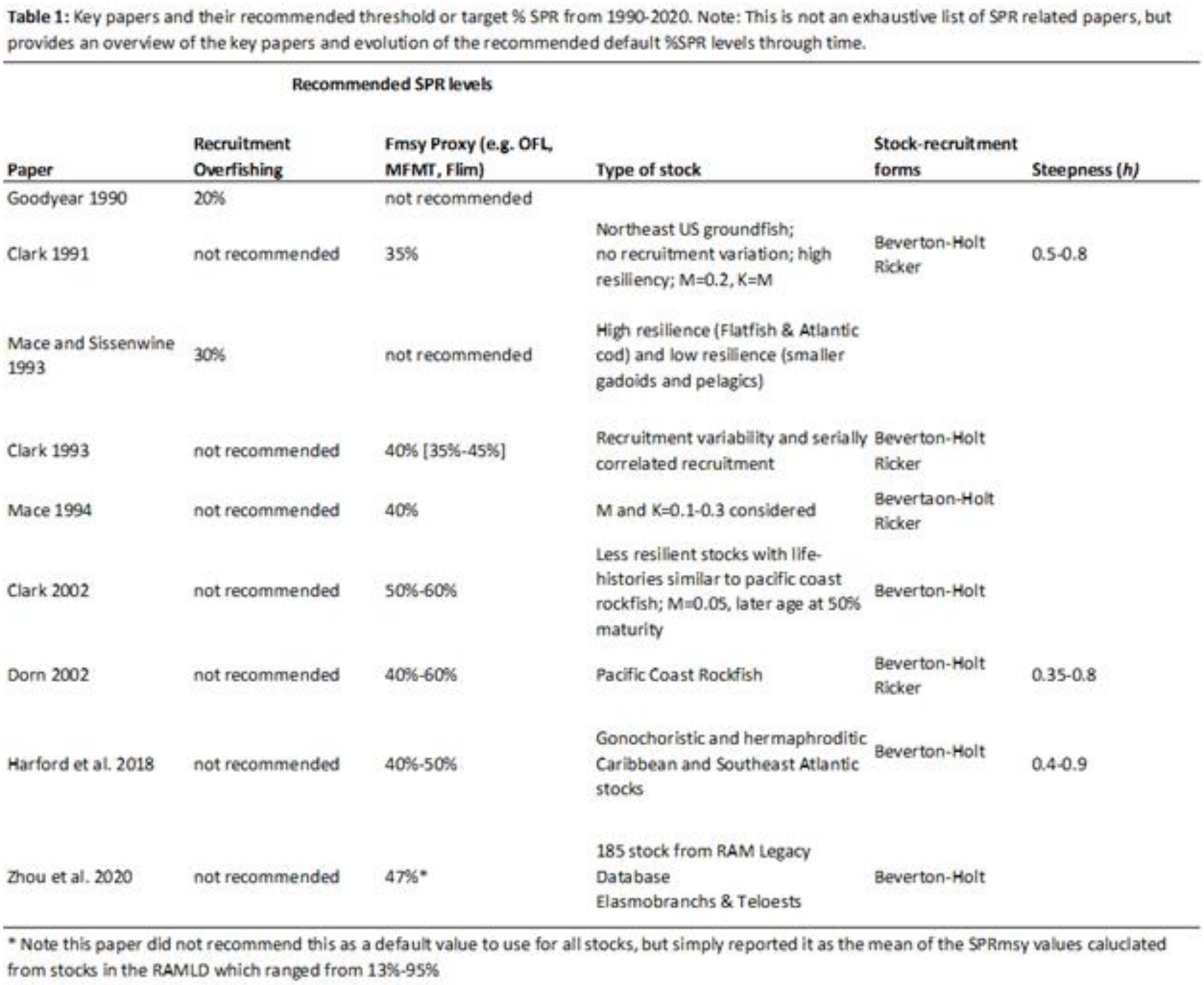

Table 1: Key papers and their recommended threshold or target % SPR from 1990-2020. Note: This is not an exhaustive list of SPR related papers, but provides an overview of the key papers and evolution of the recommended default %SPR levels through time.

	Recommended SPR levels				
Paper	**Recruitment Overfishing**	**Fmsy Proxy (e.g. OFL, MFMT, Flim)**	**Type of stock**	**Stock-recruitment forms**	**Steepness (*h*)**
Goodyear 1990	20%	not recommended			
Clark 1991	not recommended	35%	Northeast US groundfish; no recruitment variation; high resiliency; M=0.2, K=M	Beverton-Holt Ricker	0.5-0.8
Mace and Sissenwine 1993	30%	not recommended	High resilience (Flatfish & Atlantic cod) and low resilience (smaller gadoids and pelagics)		
Clark 1993	not recommended	40% [35%-45%]	Recruitment variability and serially correlated recruitment	Beverton-Holt Ricker	
Mace 1994	not recommended	40%	M and K=0.1-0.3 considered	Bevertaon-Holt Ricker	
Clark 2002	not recommended	50%-60%	Less resilient stocks with life-histories similar to pacific coast rockfish; M=0.05, later age at 50% maturity	Beverton-Holt	
Dorn 2002	not recommended	40%-60%	Pacific Coast Rockfish	Beverton-Holt Ricker	0.35-0.8
Harford et al. 2018	not recommended	40%-50%	Gonochoristic and hermaphroditic Caribbean and Southeast Atlantic stocks	Beverton-Holt	0.4-0.9
Zhou et al. 2020	not recommended	47%*	185 stock from RAM Legacy Database Elasmobranchs & Teloests	Beverton-Holt	

* Note this paper did not recommend this as a default value to use for all stocks, but simply reported it as the mean of the SPRmsy values caluclated from stocks in the RAMLD which ranged from 13%-95%

found that the equilibrium biomass resulting from fishing at a $F_{40\%}$ was only 20-30% of unfished biomass for more resilient stocks and the biomass resulting from fishing at the same level ($F_{40\%}$) drops if stock resilience is assumed to be lower. A more conservative, higher SPR value, of $F_{50\%}$-$F_{60\%}$ on the other hand would achieve 40-50% of unfished biomass (Clark 2002).

Furthermore, Brooks et al. (2010) derived the analytical relationship between steepness of the stock recruit relationship and life history parameters, directly linking a stock's steepness to its own appropriate %SPR and demonstrating that there is no "one-size fits all" %SPR. Their results suggest that the appropriate %SPR should be determined for each stock depending on its life-history parameters and productivity. Much work has also sought to approach the quest for appropriate %SPR through meta-analysis (Zhou et al. 2020) with the goal of strengthening inference by considering multiple similar stocks together. This work has often relied on the RAM Legacy Database (ref... Ricard or something like that?, Zhou et al. 2020). A comprehensive analysis that attempts to estimate global steepness relationships across species from data is undesirable because such relationships based on assessment model outputs could be biased by those models (Brooks and Deroba 2015). The steepness formulation of stock recruitment relationships and the calculation of %SPR rely on life history parameters such as natural mortality, maturity, and weight at age, which can vary through time--reflecting individual variation or response to extrinsic factors such as changes in habitat quality. Changes in life history parameters directly impacts SPR reference points and stock recruitment parameterization, and this variability should be reflected in the overall uncertainty of advice (Brooks 2013). Persistent changes over time are discussed in the section X.X.