Technical Guidance for Estimating Reference Points Used for Stock Status Determination in Accordance with the National Standard 1 Guidelines

Prepared for the National Marine Fisheries Service

By

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GLOSSARY

- ABC: Acceptable Biological Catch is a level of a stock or stock complex's annual catch, which is typically based on an ABC control rule that accounts for the scientific uncertainty in the estimate of the overfishing limit, 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, which serves as the basis for invoking accountability measures. An ACL may be divided into sector-ACLs (50 CFR 600.310(f)(1)(iii)).
- ASPM: Age-structured production models.
- BDM: Biomass dynamics models, 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}).
- B_{MSY}: 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_{MSY} is short for SSB_{MSY}.
- B_0: The expected level of SSB in the absence of fishing, also termed B_{zero} and SSB_0, can vary over time as dynamic B_0.
- $\%B_0$: Percentage of the unfished biomass.
- CR: Control Rule, which 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 Scientific and Statistical Committee (50 CFR 600.310(f)(1)(iv)). CRs are commonly defined as a function of SSB and most commonly used to set ABC.
- DLM: Data-limited methods.
- F: Annual fishing mortality rate. F may vary by age (or length) according to the selectivity of the fishery, so F itself is the value for the age with selectivity = 1.0.
- F_{MAX}: Fishing mortality rate that produces the maximum YPR, ignoring the impacts on SSB/R.
- $F_{MSY:}$ 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 percent of unfished levels and is a reasonable proxy for the F that would produce MSY in many cases.
- $F_{0.1}$: Fishing mortality rate at which marginal increase in YPR is 10 percent of that at F = 0. $F_{0.1}$ is always less than F_{MAX}.
- FMP: Fishery management plan. This is a plan containing conservation and management measures for fishery resources and other provisions required by the Magnuson–Stevens Act, developed by fishery management councils or the Secretary of Commerce.
- h: Steepness, which is the parameter that controls the degree to which recruitment is expected to decline as the SSB declines in some spawner–recruitment functions.
- M: Natural mortality is the annual rate at which fish die from natural causes, including predation, disease, and other factors like red tide. It may be age-specific and change over time.
- Mean Generation Time: This is described in the NS1 guidelines as the average length of time between when an individual is born and the birth of its offspring (50 CFR 600.310(j)(3)(i)(B)(2)(i)). In practice, scientists use an equivalent calculation of mean generation time as the average age of spawners weighted by age-specific reproductive output, 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)).

- MMSY: Multispecies MSY is the maximum sustainable yield that can be harvested from a set of interacting species in an ecosystem.
- MSE: Management strategy evaluation. An MSE is a way to test fishery management strategies, which may include alternative regulations or harvest control rules, before implementing them.
- MSY: Maximum sustainable yield is the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological and 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 spawning biomass (or other measure of reproductive potential) 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 toward a range determined by expert judgment or experience with that parameter for other species.
- R: Recruitment is the number of young fish entering the population each year. This is typically referenced to the numbers at age 0 or the numbers at age 1.
- R_0: The equilibrium recruitment expected in an unfished state.
- R_{MSY}: The expected mean recruitment that would result from fishing at F_{MSY}.
- S_{MSY}: MSY spawner abundance is the abundance (numbers) of adult spawners that is expected, on average, to produce MSY. The term S_{MSY} is used by the Pacific Council to manage naturally spawning salmon stocks.
- SDC: Status determination criteria are the measurable and objective factors, MFMT, OFL, and MSST or their proxies that are used to determine if overfishing has occurred or if the stock or stock complex is overfished (50 CFR 600.310(e)(2)(i)(A)).
- SPR_0: SSB/R in an unfished state.
- 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. Some acronyms, like B_{MSY}, simply shorten SSB to B.
- SSB_0: Spawning stock biomass in an unfished state.
- SSB/R: Spawning stock biomass per recruit. This is the per capita reproductive potential.
- %SPR: Spawning potential ratio is the ratio of the 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.
- Stock complex: A stock complex is a tool for the management of a group of stocks within an FMP (50 CFR 600.310(d)(2)). The complex may be considered a single unit with respect to stock

status and may be managed with a single catch limit, or the complex may be managed according to the status of one or more indicator stocks (each of which has SDC and ACLs). The group of stocks should have a similar geographic distribution, life history characteristics, and vulnerabilities to fishing pressure such that the impact of management actions on the stocks is similar.

- Unfished: Refers to the stock's abundance, biomass, and/or age composition in an unfished state. This can be the virgin state (see below) or the theoretically expected state without the impact of fishing. It is typically denoted with the subscript 0.
- Virgin: Refers to the condition of the stock's abundance, biomass, and/or age composition prior to the onset of more than de minimus level of fishing.
- YPR (or Y/R): Yield-per-recruit. The amount of catch (yield) that is attained per recruit.
- Z: Total annual mortality rate ($Z = F + M$).

EXECUTIVE SUMMARY

National Standard 1 (NS1) of the Magnuson–Stevens Fishery Conservation and Management Act requires preventing overfishing while achieving, on a continuing basis, optimum yield (OY) from managed U.S. fisheries. OY cannot exceed the biologically feasible maximum sustainable yield (MSY[1]), which in turn serves as the basis for status determination criteria (SDC) by which the National Oceanic and Atmospheric Administration (NOAA) determines when a stock is experiencing overfishing or is overfished. The primary SDC are the Maximum Fishing Mortality Threshold, which is the level of fishing mortality above which overfishing is occurring, and the Minimum Stock Size Threshold (MSST), which 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 reference points has not been updated since Restrepo et al. (1998).

Over the past 27 years, there has been substantial research on the scientific basis for reference points and their expected performance in the management of sustainable fisheries, and significant experience gained from stock monitoring and stock assessment implementation. The field has seen the:

- Methods for Management Strategy Evaluation (MSE) 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 toward Ecosystem-Based Fishery Management (NOAA Fisheries, 2016).
- Investigation of changes in productivity due to regime shifts in the ecosystem and environment.

This document updates technical guidance for the calculation and application of reference points for status determinations.[2] It is intended to help the entire fishery science and management community understand the technical basis of the calculations driving reference points; Fishery Management Councils and NOAA Fisheries (in the case of Secretarial fishery management plans (FMPs)) amend FMPs; stock assessment practitioners provide consistent, well-supported advice; and the research community explore unsettled topics. It is a guidance document and not a requirements list, and it does not cover other aspects of NS1 guidelines such as control rules and rebuilding plans. It is expected to be consulted as particular assessments seek to demonstrate that they are providing the best scientific information available (BSIA) (see 50 CFR 600.315; NOAA Fisheries, 2019) on reference points. On several topics, the science is still not settled, and different approaches have evolved regionally and internationally. This document describes recommended approaches where feasible to do so and pros/cons of alternatives where definitive advice is not feasible. The approaches and considerations outlined here 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 determined to be the BSIA for the situation to which they are proposed.

[1] A Glossary is provided

[2] The NS1 guidelines at 310(b)(2)(iv) refer to "SDC, MSY, OY, ABC, and ACLs" as "reference points," "collectively." This document focuses only on those reference points pertaining to MSY and SDC.

Approaches to Specifying MSY-Related Quantities and SDCs

The calculation and evaluation of MSY-related reference points (e.g., F_{MSY}, B_{MSY}) 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 used. The three Tiers are (1) stocks for which there is an age- or length-structured assessment model, (2) biomass dynamics model (also known as a surplus-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 provide a strong framework for conducting stock assessments and estimating reference points. The method relies upon life history and fishery characteristics to calculate per recruit quantities as a function of fishing mortality level and may use a spawner–recruitment relationship (SRR) to quantify density dependence in recruitment. If the SRR is estimable, then the age-structured model can be used to calculate MSY-based biological reference points directly inside 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 includes the following:

Direct Estimation

- Estimate, where feasible, the SRR parameters simultaneously with the estimation of annual recruitment and all other parameters in the model.
- Use expert judgment and information from other stocks in parameter estimation through the use of informative priors for key SRR parameters. Priors help achieve a balance among estimability, bias, and variance.
- Use fixed values for SRR parameters only after good investigation of the impacts of that fixed value on reference points and on estimated recruitment trends.
- Note that implementations that involve parameterization with steepness need to carefully account for interactions with time-varying life history parameters.
- Communicate the relationship between the productivity priors used in the assessment and the equivalent spawning potential ratio (%SPR) proxies that would be used when direct estimation is not attempted.
- Future work:
    - New investigations 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 SRR is influenced by a stock's interactions with other species in its ecosystem; hence, more modeling with multiple species is advised.
    - Decades of monitoring fish stock productivity has exposed the frequent occurrence of regime shifts and other temporal changes in productivity. Temporal changes need to be accounted for when estimating SRR.

F_{MSY} and B_{MSY} Proxies

- The most common F_{MSY} proxy is based on %SPR (see the definitions in the Glossary). The current range of %SPR-based proxies found in FMPs is $F_{20\%}$–$F_{60\%}$, with most between $F_{30\%}$ for stocks considered highly productive and $F_{50\%}$ for those considered low productivity stocks. These are based upon studies conducted mostly in the 1990s (see Appendix I) and subsequent technical justification in those FMPs.
- Updated investigations, using MSE, of the expected performance of each FMP's current proxies are suggested, especially if revision of the proxy value is being considered.

- Yield-per-recruit-based proxies are less advised but serve as a stopgap when %SPR may lead to high F. 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 the spawning stock biomass (SSB) per recruit associated with the selected F_{MSY} or suitable proxy or by (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

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) a time series of total catch and (2) at least one time series of relative abundance data. There are several benefits of BDMs, including (1) minimal data requirements, (2) ease of implementation and communication, and (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 worth noting, namely, that historical BDM methods 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. New BDM methods that partially address these shortcomings are now available.

Tier 3: Data-Limited Situations

Data and resource limitations present significant challenges to calculating and using SDC for fisheries management (Cope et al., 2023; Dowling et al., 2023; Macpherson et al., 2022). The 2016 revisions to the National Standard 1 guidelines encouraged the development of suitable methods:

> *"...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"* (50 CFR 600.310(e)(2)(ii)).

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.
- The "absolute abundance" method starts from a direct measure of the current abundance of the stock. Then, if a proxy for F_{MSY} is available, the overfishing limit (OFL) can be calculated. Overfished status cannot be calculated from this approach.

- "Catch-only" methods can be used to guide the setting of OFL and annual catch limit as described in Macpherson et al. (2022) 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 recognize 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 CFR 600.310(e)(1)(i)(A)). Then, section 600.310(e)(1)(v)(A) states that "*[b]ecause 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.

- Time-varying fishery characteristics, adult life history, biology, and recruitment have distinct characteristics that affect how they are updated for reference points.
- Fishery characteristics change frequently, so their contribution to reference points should be routinely updated with projection models, trailing averages, or autoregressive methods. Five-year trailing averages are commonly used and are recommended unless another method is shown to be superior.
- With changes in biological life history factor(s), it is most common to use projection models, trailing averages, or autoregressive methods to track changes in body growth and other life history factors. However, a simplistic application of this approach raises concerns about making empirical changes to reference points in situations where an undetected density dependence may also be causing changes. Time series of biological data should be collected for priority stocks to track changes and to investigate for evidence of density dependence that can be built into reference point calculations, just as direct estimation routinely takes density-dependent SRR into account.
- A stable estimate of prevailing mean recruitment should use the longest time period feasible because of the high inter-annual recruitment fluctuations that routinely occur. Long time series are especially important for calibrating SRR. However, several decades of surveys and assessments have exposed the frequent occurrence of approximately decadal regime shifts in mean recruitment that may warrant the use of a shorter time period to characterize prevailing conditions.
- If a notable change in environmental conditions has been documented and is expected to persist, then reference points should be updated at that change point rather than the simplistic trailing average.
    - An example is using fishing gear regulation as the change point for updating fishery characteristics.
- 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.
- Simplistic updates of reference points to reflect prevailing conditions can have the counter-intuitive effect of maintaining or increasing the F on a declining stock. We recommend further investigation of such updates and alternative approaches that maintain a long-term perspective for

some aspects of SDC and control rules, while updating others to prevailing conditions. For example,

- ○ Prevailing B_{MSY} could be used as the target for rebuilding plans because it is feasible with the current levels of recruitment.
- ○ Long-term B_{MSY} could be used to set the control rule inflection point to ensure that reductions in F will be recommended on declining stocks.
- ○ This approach would benefit from further testing before use, especially regarding the implications for MSST.

Additional sections of this document discuss factors that affect reference point calculations and include recommendations for future investigations. These include the following:

- Use MSE to investigate the expected performance of current F_{MSY} proxies.
- Improve methods to detect regime shifts in productivity.
- Incorporate the effect of size-selective fishing into reference points.
- Investigate the occurrence of density-dependent life history factors and incorporate into reference points.
- Adjust %SPR proxies when hyper-allometric scaling of fecundity is used rather than simple spawning biomass.
- Update assessment models to include consistent approaches (e.g., parameterization and priors) for direct estimation of SRRs, especially with regard to the impact of time-varying biology.
- Update projection software to provide advice on identifying when a stock is approaching an overfished condition.
- Bring research on multispecies reference points into consideration for management. Test cases are needed.
- Note that reference points for spatially structured populations tend to ignore that structure, as well as other spatially explicit dynamics, which may lead to unknown biases and warrant investigation.
- Note that current NS1 guidelines define MSY as conditional on the prevailing mix of fishery technological characteristics. This has discouraged the development of information regarding increases in MSY and B_{MSY} that might be attained with different fishery technological characteristics. Reporting of global MSY associated with perfect selectivity or MSY conditional on the selectivity of the most efficient extant fishery is advised.

1. 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 (50 CFR 600.310) 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 the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA Fisheries) determines when a stock is experiencing overfishing or has declined below the overfished threshold. Technical guidance for calculating reference points was first provided in Restrepo et al. (1998), following a major update of the NS1 guidelines. The MSA and NS1 guidelines have changed significantly since 1998. Most recently, NOAA Fisheries published revisions to the NS1 guidelines in 2016 (81 FR 71858; October 18, 2016) prompting a need to consider updates in the technical guidance. This document updates technical guidance for reference points pertaining to status determination.

Since the technical guidance publication in 1998, there has been substantial research on the scientific basis for reference points and their expected performance in the management of sustainable fisheries. The field has seen the:

- Methods for Management Strategy Evaluation (MSE) 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 toward ecosystem-based fishery management (NOAA Fisheries, 2016).
- Investigation of changes in productivity due to regime shifts and other changes in the environment.

This document is intended to summarize this research and development into updated technical guidance with regard to calculating and evaluating MSY and reference points for status determinations. Although these reference points can be components of control rules and rebuilding plans, this document makes no attempt to provide technical guidance for control rules and rebuilding plans. Section 3 of this document focuses on the various approaches for specifying fishing rates or biomass levels associated with MSY or MSY-based proxies. Sections 4 and 5 address, respectively, making overfishing, overfished, and approaching an overfished condition determinations, and updating reference points for changing environmental conditions. In Section 6, we discuss some additional considerations including fleet technical characteristics, spatial complexity, units of reproductive potential, age truncation, density dependence in other life history factors beyond stock recruitment, size-selective fishing, and multispecies considerations.

This document is intended to help the entire fishery science and management community understand the technical basis of the calculations driving reference points for status determinations; Fishery Management Councils and NOAA Fisheries (in the case of Secretarial fishery management plans (FMPs)) as they amend FMPs; stock assessment practitioners provide consistent, well-supported advice; and the research community explore unsettled topics. On several topics, the science is still not settled, and different approaches have evolved regionally and internationally. This document describes recommended approaches where feasible to do so and the pros and cons of alternatives where definitive advice is not feasible. The approaches and considerations outlined here 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 determined to be the best scientific information available (BSIA) for the situation to which they are proposed.

2. BACKGROUND ON NATIONAL STANDARD 1 AND MSY

NS1 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 that, 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 NS1 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 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}*" (50 CFR 600.310(e)(1)(v)(B)).

The NS1 guidelines also include guidance for other reference points, such as annual catch limits (ACLs), as well as guidance on target control rules, rebuilding plans, and other aspects of NS1. These concepts are not addressed in this document, but some aspects are addressed in other recent technical guidance documents (e.g., control rules with carry-over and phase-in (Holland et al., 2020), and data-limited ACLs (Macpherson et al., 2022)).

The NS1 Guidelines define MSY and MSY-related SDC reference points (F_{MSY} and B_{MSY}) in 50 CFR 600.310(e)(1)(i) as follows:

> "*(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}.*"

The MSA requires that 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 further interpret that each FMP must describe how SDCs will be specified for overfishing as well (50 CFR 600.310(e)(2)(i)(A)). These SDCs are usually based on fishing rates, catch levels, and spawning stock biomass (SSB)[3] levels associated with MSY or MSY proxies (e.g., F_{MSY}, B_{MSY}, or their proxies). These criteria should be accompanied by 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 define MSY relative to the "*<u>prevailing</u> 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)). Prevailing conditions are the conditions existing at the present time and expected to persist in the relevant future. Fluctuations within prevailing conditions are normal and an expected characteristic of stationary[4] conditions. Reference points should be updated to reflect a change in prevailing biological conditions, whether it is an abrupt shift or a slow drift. Reference points also are subject to the influence of changing fishery characteristics, which will be addressed in Section 6.2. Projecting the effects of changing ocean and ecosystem conditions on the productivity of fish stocks is the

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[3] 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 (see Section 6.1: Units of Reproductive Potential/Output).

[4] A stationary process has the property that the mean, variance, and autocorrelation structure do not change over time.

subject of much active research. On shorter time scales, this research seeks to project fluctuations within the current prevailing conditions; on longer time scales, it may portend changes in prevailing conditions. We discuss this topic in Section 5: Updating Reference Points for Changing Environmental Conditions, but we are not yet at a point where definitive technical guidance is feasible.

3. APPROACHES TO CALCULATING QUANTITIES RELATED TO MSY

The SDC are defined in terms of fishing mortality rate (F) and reproductive potential (SSB). Surveys and fishery monitoring programs do not measure F directly, nor do fishery-independent surveys measure SSB. The measurements are in the form of catch, age, and length composition, survey trends, and so on. Population (or stock assessment) models use observations to calibrate the models, which, in turn, are informative about F and SSB. The models are a simplified representation of the fish stock and its fisheries. Parameters in the model are adjusted, through external research or internal estimation, to produce a reasonable match to the observed data. The output of the model includes the F and SSB quantities needed for comparison to the SDC. This modeling process is commonly termed integrated analysis (Maunder and Punt, 2013) and allows for analysis of a wide range of data-rich to data-limited situations (Cope, 2024). These techniques have evolved substantially since the previous NS1 technical guidance (Restrepo et al., 1998).

The accuracy and precision of calculated MSY-related reference points depend upon the types of data that are available, the length of the time series of data, the accuracy of the definition of the stock unit, and the history of fishing. We organize the various modeling approaches into three "Tiers": (1) age- or length-structured assessment model (e.g., integrated analysis or statistical catch at age) that provides the greatest detail in modeling the stock and its fishery, (2) biomass dynamics model (also known as surplus-production or stock-production model) that provides a more generalized indication of the effect of fishing on stock abundance, and (3) data-limited approaches where 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 associated SDC, as well as discuss key considerations for applying each approach. We provide a generic flowchart (Figure 1) to help visualize the decision process for choosing the appropriate method for a given situation.

Regardless of the method, reference points 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 the desired probability. Such investigations were called for in Restrepo et al. (1998) and today are commonly referred to as MSE (Walter et al., 2023; Punt et al., 2016). Stock assessment methodologies and fisheries management tools, as well as the research that interfaces these two disciplines, must continue to evolve to meet emerging demands and challenges.

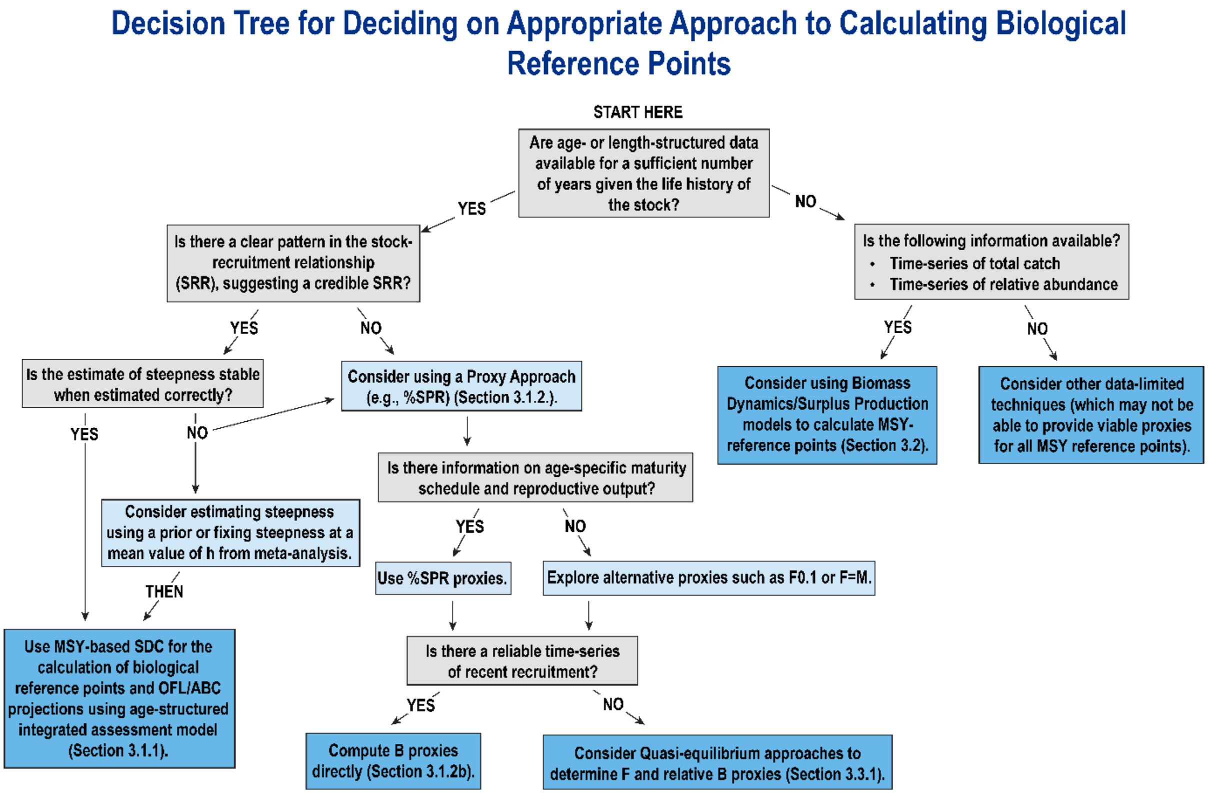

Figure 1*: Decision tree flowchart to help determine the appropriate approach to calculating biological reference based on available data*.

3.1 Tier 1: Age- or Length-Structured Assessment Models

Age (or length-)-structured models for conducting stock assessments and estimating reference points can include age-specific effects that are not feasible to estimate with Tier 2 (biomass dynamics) models. When supported by sufficient data, age (or size)-structured models can:

- Reconstruct the age-structured history of the stock, including annual fluctuations in recruitment of young fish.
- Include realistic life history with age-specific growth, reproductive output, and natural mortality at age/size. Modern assessment models allow for these factors to be time-varying as well as age-varying.
- Account for age-specific patterns of fishing mortality with age (i.e., age selectivity), which can differ by fishing fleet, season, and/or area and change over time. The reference point calculations in age-structured models include these per-capita effects on the yield-per-recruit (YPR) and spawning stock biomass-per-recruit (SSB/R) (see Figure 2 and Section 3.1.2a on Spawning Potential Ratio (%SPR)).
- Provide information on total mortality from the proportion of older fish in the population (i.e., catch curve analysis).

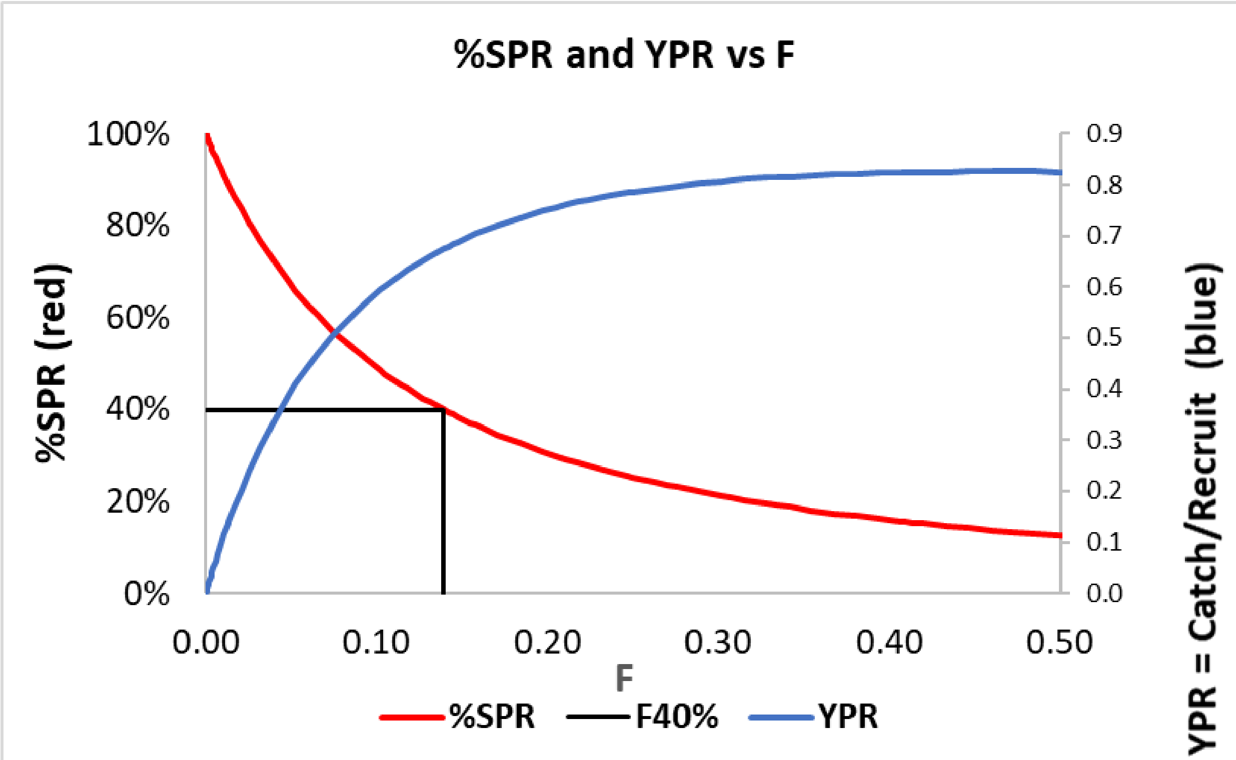

Figure 2: *%SPR is plotted in red versus F. Catch per recruit (i.e., YPR or Y/R) is shown in blue. The level of F that reduces %SPR to 40 percent is denoted with a black line.*

However, the historical reconstruction alone is not sufficient to estimate MSY quantities. Direct estimation of MSY requires that the model also includes a process by which population abundance affects population productivity. This feedback process is often referred to as density dependence. The simple formulation of Tier 2 biomass dynamics models, which will be described later, explicitly includes this feedback in a generic way, so the model can directly estimate the population abundance that produces MSY. Tier 1 models typically implement this feedback as a relationship between the expected level of recruitment and the SSB that produced those recruits (the spawner–recruit relationship, SRR), but other density-dependent life history parameters are also possible. When Tier 1 models include density dependence in the SRR, they are categorized as "direct estimation." Section 3.1.1 below describes some methods and issues regarding direct estimation, including the use of parameter priors based on external information to assist estimation. Then, section 3.1.2 will describe the alternative approach that uses reconstruction without density dependence and switches to the use of proxies for MSY quantities. A caveat is that direct estimation presupposes that the defined stock unit encompasses a biologically self-sustaining population. When knowledge of stock structure is incomplete, then proxy approaches may be less subject to bias than direct estimation. These two sections will include information on the logical connection between MSY proxies and the priors used to assist the direct estimation.

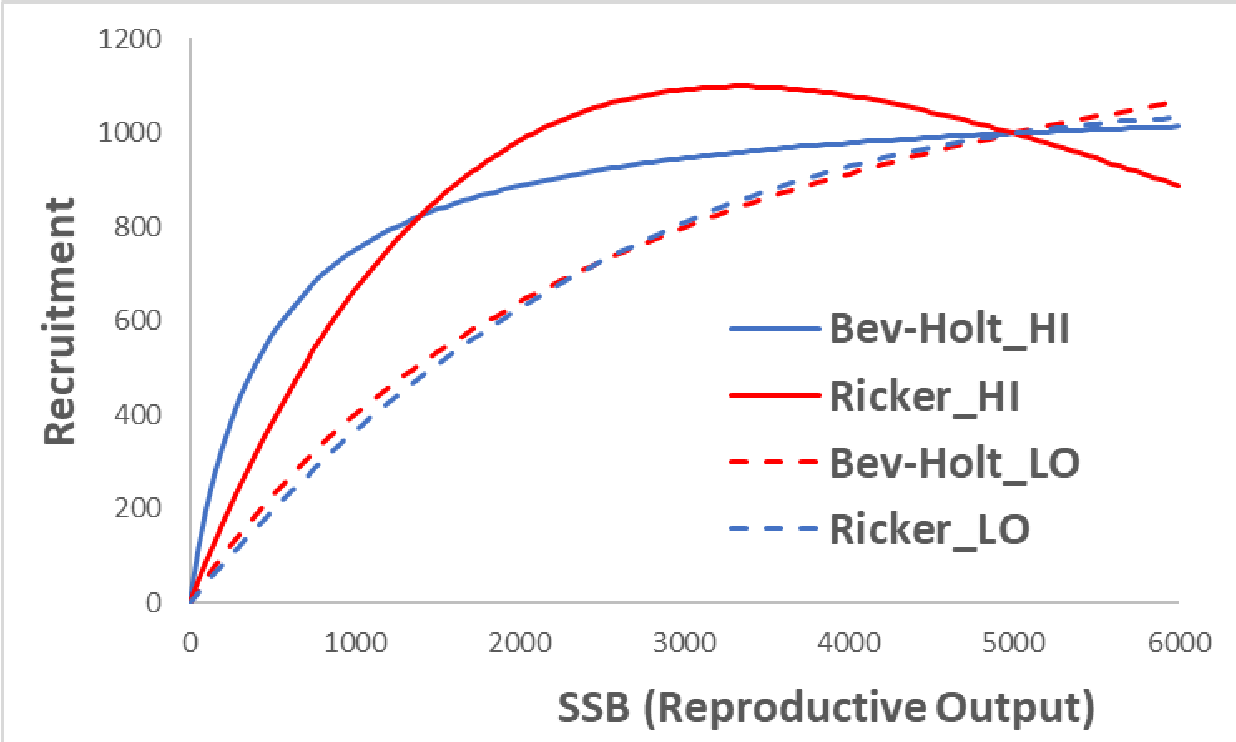

Figure 3. *Spawner–recruitment curves. The Beverton–Holt curve is shown with steepness = 0.75 (HI) and a steepness = 0.40 (LO). Ricker curves have parameter values selected to approximate the Beverton–Holt curves.*

3.1.1 Direct Estimation of MSY Quantities

When the assessment model includes a functional relationship between recruitment and SSB (Figure 3), it becomes feasible to directly calculate the MSY-based reference points (Figure 4). The main issues to be considered in direct estimation of F_{MSY} and B_{MSY} via age-structured methods are as follows:

- Which functional SRR form or range of forms should be used if conducting an ensemble model or MSE.
- Which parameterization of the SRR form should be used.
- Whether to estimate parameters of the SRR from quantities output by the stock assessment or to embed the curve in the assessment for simultaneous estimation.
- Whether the parameters of the SRR can be freely estimated, or whether the estimation needs to be assisted through the use of a prior distribution for one or more of the SRR parameters.
- Whether the SRR parameterization is stationary over time.

3.1.1a SRR Functional Form

A link between recruitment and SSB in a well-defined stock unit seems obvious because the number of young fish recruiting to a population must depend in some way on the parental reproductive output (Mangel et al., 2010). 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 it is

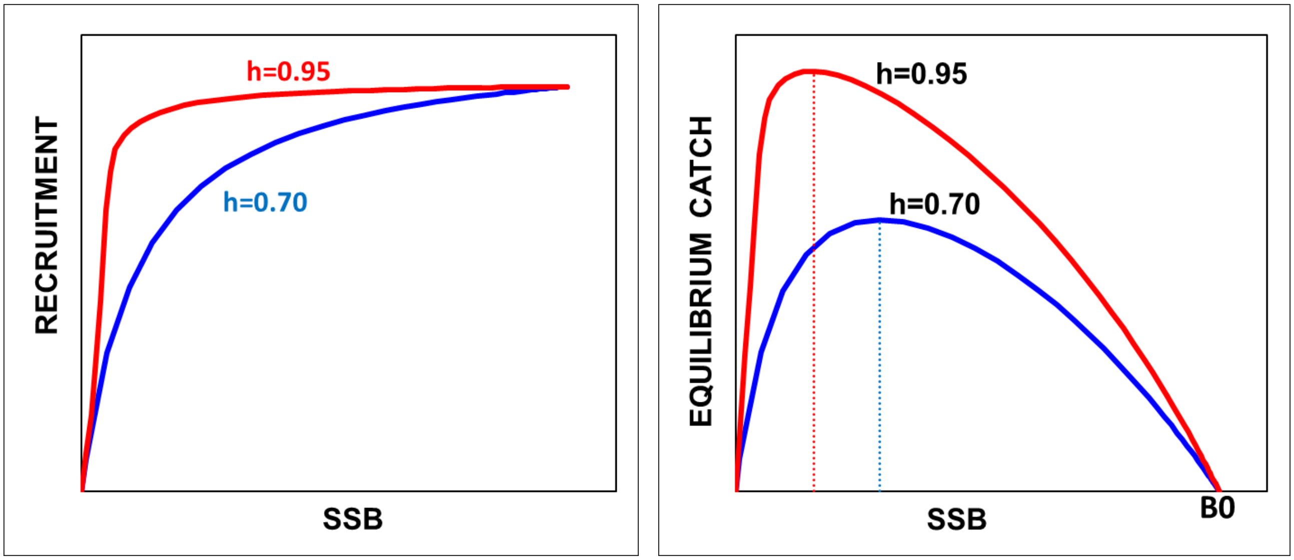

Figure 4: *The left panel displays the relationship between recruitment and SSB at two levels of steepness (the upper curve in red is for h = 0.95, and the lower curve in blue is for h = 0.70). The right panel adds the impact of YPR to calculate the resultant equilibrium catch as a function of SSB. The dotted lines show the respective levels of MSY and BMSY for the two levels of steepness.*

unrealistic to expect this type of information to be available. Instead, several functional forms have been developed to provide a simplified representation of the life history processes that determine average recruitment while also recognizing the substantial impact of environmental and ecosystem factors driving deviations from that average recruitment process. The two most commonly used forms are asymptotic (Beverton and Holt, 1957) and dome-shaped (Ricker, 1975) (Figure 3). The original formulation of the Beverton–Holt curve used two parameters, alpha and beta, to represent density-independent and density-dependent mortality during the pre-recruit stage (i.e., the window from spawning to age at recruitment). An alternative parameterization (Mace and Doonan, 1988) uses R_0, the equilibrium recruitment expected in an unfished state, and steepness (h) as the relative recruitment produced when reproductive output has been reduced to 20 percent of the unfished level of SSB. This transformation is done by including the unfished spawning capacity per recruit, SPR_0, that is calculated from the adult life history parameters. The alternative formulas for the Beverton–Holt SRR are:

$$R = \frac{a * S}{1 + B * S}$$ Beverton and Holt (1957), where S = SSB

$$R = \frac{4 * h * S}{(SPR_0 * (1 - h) + (5 * h - 1) * S)}$$ Mace and Doonan (1988), where SPR_0 is SSB/R at F = 0

The two parameterizations can be interconverted (Myers et al., 1999; Brooks et al., 2010; Mangel et al., 2010) and produce SRR curves with identical shapes. The steepness formulation is popular because it provides an intuitive measure of the dependence of recruitment on SSB that facilitates comparisons between stocks (Dorn, 2002; Punt and Dorn, 2014; Thorson, 2020). We will use the term steepness extensively in this document, sometimes explicitly in reference to this formulation and sometimes generically to represent the degree of resilience that recruitment in a given stock has to declining SSB. In the SRR parameterization section below, we will identify some cautions with regard to the use of the steepness approach.

The functional form of the SRR is important because it influences the estimates of MSY and associated biological reference points and the level of SSB that produces MSY (Myers et al., 1995; Brodziak, 2002). 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 some salmon, and therefore, most stock assessments use the asymptotic Beverton–Holt function (Gilbert, 1997). Several alternative forms have been developed, for example, a form explicitly for low fecundity species, particularly sharks (Taylor et al., 2013). Other investigations have explored depensation at low SSB levels.

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). New investigations 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. A very similar issue occurs for biomass dynamics models that typically use a two-parameter parabolic function (discussed in Section 3.2: Tier 2 Surplus Production/Biomass Dynamics Models) rather than the more flexible three-parameter production functions. Selecting a two-parameter form simplifies the modeling challenge at the expense of potentially misspecifying the true productivity of the stock. Before settling on any particular functional form, due consideration should be given to the species' biology and ecological setting that may support or rule out other potential candidates.

3.1.1b SRR Parameterization

If life history parameters are assumed to be constant across time, which is a common situation for data-limited and data-moderate assessments, then the alpha, beta, and R_0, h formulations of the Beverton–Holt SRR provide identical results. However, when adult life history parameters used to calculate SPR_0 vary through time, then the steepness formulation has an ambiguity as to which year's value of SPR_0 should be used (Miller and Brooks, 2021), with potential consequences for the calculation of reference points and the measurement of the degree of stock depletion. This sensitivity to SPR_0 also can influence the meta-analysis of h across species (Thorson, 2020; Miller and Brooks, 2021). Consequently, Miller and Brooks (2021) advocate using the SRR in its original alpha, beta parameterization rather than the R_0, h parameterization. With the alpha, beta parameterization, the SRR is just used for predicting recruits from spawners, and the choice of which year's values to use for calculating reference points is a separate, transparent decision. Assessment models that use R_0, h can achieve the same transparency by clearly identifying how the SPR_0 is calculated and keeping it separate from the SSB/R used for MSY calculations. The biology for SSB/R and Y/R in MSY calculations should be based on recent, that is, prevailing life history values as will be discussed in Section 5 on environmental effects. There are potential vulnerabilities in current R_0, h applications:

- If the assessment has annual life history data (particularly weight-at-age used in spawning biomass calculations) that is noisy, then the selection of the first year as basis for SPR_0 is vulnerable to this noise. A vector based on an average of a few years seems reasonable.
- If there is time-varying biology, then assessment software may need additional controls to allow the software to use the first year SSB/R for the spawner-recruitment calculations and contemporary SSB/R for MSY. Such controls were introduced in Stock Synthesis in 2025 with version 3.30.24 (https://nmfs-ost.github.io/ss3-website/).
- If the SRR itself has changed over time (i.e., regime shift in R_0 or h has changed) and life history also is time-varying, then the appropriate value of SPR_0 that should be used to update the time-varying SRR is not clear. Assessment software needs to be prepared to deal with this situation.

3.1.1c External Estimation of SRR Parameters

Along with selecting among candidate SRRs, analysts must decide whether to estimate the SRR simultaneously with other parameters within the assessment model or to estimate the SRR parameters externally using the time series of estimates of annual R and SSB produced by the assessment model. External estimation is necessary for assessment methods that cannot embed the SRR into the assessment model, particularly virtual population analyses and some older types of statistical catch at age. However, this incorrectly treats the time series of R and SSB, which are model-based estimates, as though they are 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 use a contemporary assessment package (Dichmont et al., 2016; Li et al., 2021) that is capable of estimating the SRR parameters simultaneously with the estimation of annual recruitment in the assessment model.

3.1.1d Fixed Values for SRR Parameters

In some cases, one or more SRR parameters, particularly steepness, 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). The fixed steepness value also limits the flexibility with which the assessment can estimate the trend in recruitments and the resultant degree of decline in SSB. Brooks et al. (2010) note that fixing the steepness parameter at a single value is essentially the same as using a %SPR proxy but with less transparency and a false sense of precision in the reference points. Conducting sensitivity analyses to explore the impacts of different steepness assumptions is therefore recommended when fixing steepness.

3.1.1e Using Priors for One or More of the SRR Parameters

Within the simultaneous estimation models, there is another decision point regarding potential constraints or priors on values of the SRR parameters. When estimation of the SRR parameters, in either a frequentist or Bayesian framework, does not penalize the values the parameters may take beyond the imposition of reasonable bounds, alternative candidates for the SRR can be fairly compared within the model framework itself. However, reliable calculation of the SRR parameters is hampered by the high year-to-year fluctuations in R due to environmental influences and the narrow domain over which SSB has been observed, especially where historical fishing reduced SSB well below its pre-fishery level before age-structured data collection began (Conn et al., 2010). In these cases, parameter values can end up on extreme bounds, and updated assessments can produce unacceptably large changes in SRR parameters and resultant MSY quantities, especially when the SRR is shallow (low steepness). A prior provides a middle ground between freely estimating and fixing parameters. With the use of a prior, the assessment model will estimate the MSY quantities from parameter values that are a balance between the strength of the prior and the stock-specific information in the model data. Strong priors produce high consistency, which can be biased for some stocks. Weak (diffuse) or non-existent priors allow for noisy data to produce variable or implausible results.

The priors can be based on life history information and statistically based meta-analysis across numerous similar stocks. Thorson (2020) found differences in steepness predictable by life history and classification (order) with typical values near 0.63 to 0.76. This approach is used extensively for West Coast (Thorson et al., 2019), Southeast, Pacific Islands, and tuna/billfish assessments. However, Miller and Brooks (2021) note that if the prior for h has come from a species with much different life history, then the prior could be biased for the subject species because SSB/R at F = 0 differs.

Priors for spawner–recruitment parameters may imply an F_{MSY} value that differs from the %SPR-based value for the F_{MSY} proxy that would be used as the alternative to direct estimation. For a given SRR functional form, there will be a steepness parameter value that corresponds to the FMP's F_{MSY} proxy expressed in terms of %SPR. This approach to create a steepness prior is just reverse engineering the way in which the %SPR proxies were originally derived in the 1990s (see Section 3.1.2a on Proxies for F_{MSY} and Appendix I). Those early studies investigated the impact of fishing at a range of possible %SPR levels while recruitment was simulated to follow a range of plausible SRR forms and steepness levels. They found a good performing level of %SPR that could be used as a proxy for F_{MSY}. That %SPR value has a corresponding value for steepness, which can be used as a prior in direct estimation to provide consistency between the direct estimation approach and the proxy approach. However, Section 3.1.1.g below identifies a consequence associated with the use of SRR parameter priors.

3.1.1f Current SRR Estimation Approaches

Assessment meta-data extracted from Stock SMART in early 2024 showed that 14 stocks had F_{MSY} based on estimated steepness and that 35 had fixed steepness (Figure 5A and C and Appendix II). Over 140 stocks used a %SPR proxy, and this is discussed in Section in 3.1.2a on current %SPR levels. The estimated steepness approach was most common in the Atlantic highly migratory species stocks. Fixed steepness was used in several regions with a high value (0.8 to 0.9) being most common and lower values occurring mostly for sharks. Note that the data in Stock SMART do not show if a prior was used in the estimation. The data also do not show which assessments use an SRR for the assessment while using a %SPR for the reference point. The regionality to the current SRR estimation approaches (Figure 5B) seems ripe for consideration by a cross-regional working group that is beyond the scope of this NS1 Technical Guidance Group.

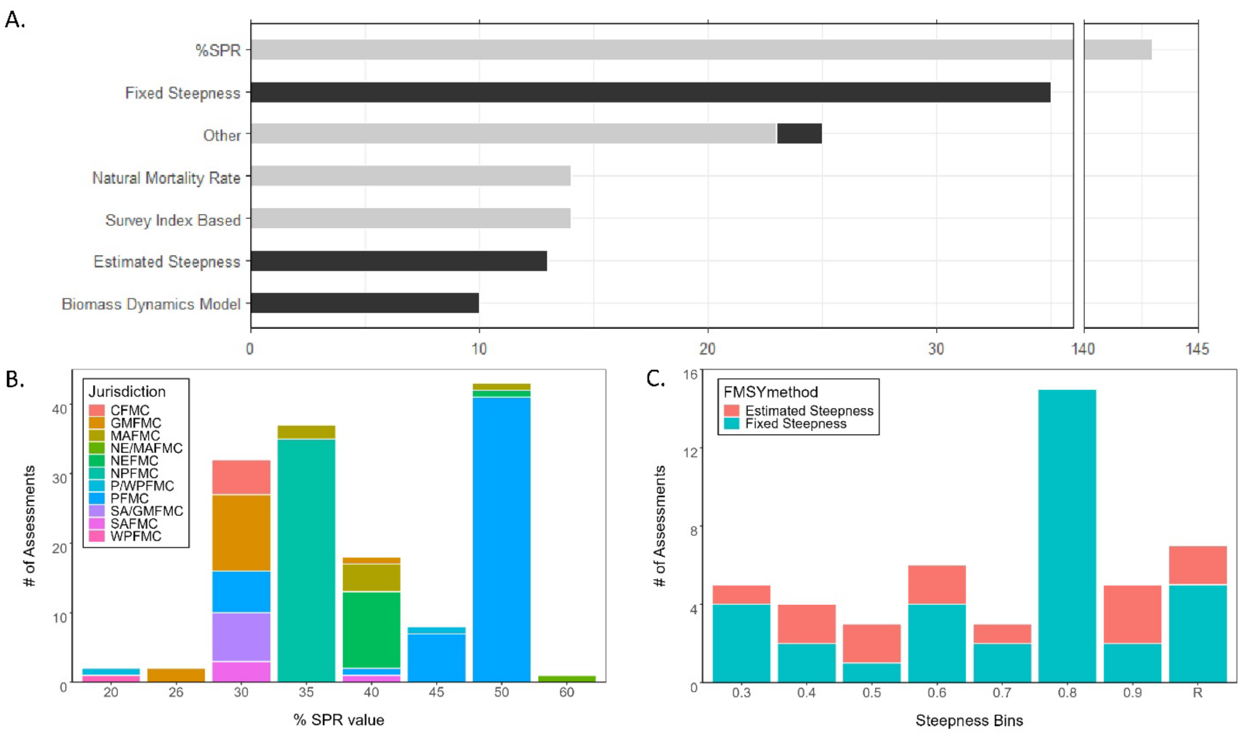

Figure 5: *(A) Overview of the F_{MSY} method by the number of assessments. The dark color bars are "direct estimation" approaches, and the light gray bars are "proxy" approaches. (B) Distribution of %SPR-based F_{MSY} proxy values by Fishery Management Council jurisdictions. (C) Distribution of estimated and fixed steepness values binned into ranges of 0.1 so that the range labeled 0.3 represents steepness values of 0.30 to 0.399. The column labeled R indicates that the assessment used a range of values. Results for all assessments completed as of 2024.*

3.1.1g Effect of SRR on Estimated Recruitments

When recruitments are estimated as deviations from an SRR, the penalty on those deviations draws the resultant time series of estimated recruitments in the assessment toward that SRR. This is a benefit for data-limited assessments attempting to model stock productivity for years without age data, and several data-limited assessment approaches (e.g., stochastic stock reduction analysis; Walters et al., 2006) are based on this principle. Although very precise age composition data and recruitment surveys can overwhelm the penalty, for many data-moderate assessments, it is a balancing act, and the SRR deviation penalty can influence the assessment result. The recruitment trend becomes biased toward the trend expected from the SRR. Thus, the form of the SRR, the strength of its priors, and the degree of penalty on recruitment deviations should be considered as a set of related factors (Methot and Taylor, 2011). Hence, fixed or highly informative SRR parameter priors should be used with caution. The same is true for assessments that use a null SRR (i.e., just a mean) because recruitments penalized too strongly as deviations from a mean are penalized toward not having a downtrend as SSB declines, especially near the end of the time series.

State-space methods, which treat recruitments as random effects, have been shown to provide improved estimation of SRR parameters and the degree to which an individual year's recruitment deviates from the SRR (de Valpine and Hastings, 2002; Peterman et al., 2003). State-space models are the best framework in which to use parameter priors. These methods provide a natural way of distinguishing stochastic processes for the population from observation error (noise) (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). However, most assessments are still done using the penalized likelihood approach in which the appropriate strength of the penalty on the prior is less objective, so care to achieve good transparency should be applied.

3.1.1h 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, 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 SRR? Second, even if the relationship is considered long-term stationary, are there recent patterns in the annual deviations from this relationship such that the prevailing mean deviation needs to be taken into account when using the curve for projections? Accordingly, it is important to consider the evidence suggesting that the SRR may have changed over the time frames relevant to management. This is discussed extensively in Section 5 on Updating Reference Points for Changing Environmental Conditions.

3.1.1i Direct Estimation Summary

- The functional form of the SRR should be chosen with cognizance of the ecology of the species. The most common form is the asymptotic Beverton–Holt SRR, but it is not mandated. Some species like salmon are prone to overcompensation that supports a dome-shaped Ricker SRR. Special forms have been developed for low fecundity species like sharks.

- Direct estimation within assessment models spans a range of approaches from freely estimated SRR parameters to fixed parameters. An intermediate approach that uses prior information to guide parameter estimation is also used, but the value and strength of the prior needs to be carefully considered. State–space models are an improved method for the use of priors.

- If the SRR steepness is fixed (or the prior is very strong/tight), this influences the estimated time series of recruitment and the resultant degree of stock decline. In these situations, a weaker penalty on recruitment deviations will allow the estimation of the recruitment time series to be less constrained by the steepness prior.

- A logical inconsistency occurs if the SRR parameter prior is set at a value that is inconsistent with the %SPR used as the F_{MSY} proxy. Therefore, it is important to consider the value of the prior used in the stock assessment relative to the %SPR proxy value and the perceived productivity of the stock.

- Directly estimated MSY reference points will have inflated precision whenever the SRR parameters or any assessment parameters become more tightly constrained by priors or fixed values.
- Some SRR parameterizations depend upon values calculated from adult life history, which, if time-varying, can be challenging to accommodate.
- Regime shifts and temporal trends in recruitment and life history are increasingly recognized as a fact-of-nature, whereas direct estimation of SRR parameters is tied to the assertion of stationarity. Methods that can discern temporal patterns from density-dependent changes (i.e., SRR forms) are needed, as are robust approaches for advice when these two sources cannot be disentangled.

3.1.2 Proxies for MSY Quantities

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, inaccuracy regarding stock structure, or temporal changes in other factors that affect productivity. In the typical proxy approach, the measure of reproductive potential remains the same (typically spawning biomass), but an alternative (i.e., proxy) approach to calculating reference points replaces direct estimation. The proxies 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, and discuss the close relationship between MSY proxies and SRR parameter priors. Proxies for use in data-limited situations will be covered in Section 3.3, Tier 3: Data-Limited Approaches.

3.1.2a Proxies for F_{MSY}

Spawning Potential Ratio (%SPR)

The recommended F_{MSY} proxy approach is based on the spawning potential ratio (%SPR; Goodyear, 1993). It is labeled as spawning potential ratio because of the long and common usage of spawning biomass as a proxy for reproductive potential, but in all usages here, the term spawning biomass is used to mean reproductive potential. Percent SPR is the ratio of the 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 (Figure 2). It is favored as a proxy because it is directly responsive to the effect of fishing on the reproductive potential of the stock. 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 noted here as $F_{xx\%SPR}$. For example, $F_{45\%}$ means to fish at a rate such that the SSB/R would be 45 percent of its unfished level. Another way to think of this is that %SPR is the long-term average escapement from the fishery. For a given %SPR, calculating the corresponding $F_{xx\%SPR}$ requires age-specific reproductive output, natural mortality, and fishery selectivity from a selected range of years. Complications arise when there are multiple fleets, discarding, spatial stock structure, and time-variation in any of the input quantities, but the principle remains the same. The direct estimation section above (Section 3.1.1) noted that the biology for SSB/R and Y/R should be based on recent, that is, prevailing, life history values as will be discussed in Section 5 on environmental effects. Section 3.1.1 also noted that steepness is expected to be less than 1.0, so a decline in SSB is expected to cause some decline in R. Thus, a %SPR of 40 percent is expected to result in SSB being somewhat less than 40 percent of SSB_0.

The key question when using a %SPR proxy is selecting the level that will approximate MSY for a particular stock or stocks. Selection of a %SPR proxy implies that the stock's true but unknown SRR parameters are similar to those used in the development of the proxy. Like MSY, the selection of the %SPR proxy is expected to be based on the BSIA regarding the productivity of the stock and not on additional economic factors associated with OY. Over the last 30 or more years, researchers have used comparisons with other species, meta-analytic approaches, 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 I for a 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 percent of MSY). Clark did this by simulating MSY using a range of SRR parameter values with both the Beverton–Holt and Ricker curves. This and other studies contributed to Restrepo et al. (1998), stating technical guidance as follows:

> "It is recommended that fishing mortality rates in the range $F_{30\%}$ to $F_{60\%}$ be used as general default proxies for F_{MSY}, when the latter cannot be reliably estimated. In the absence of data and analyses that can be used to justify alternative approaches, it is recommended that $F_{30\%}$ be used for stocks believed to have relatively high resilience, $F_{40\%}$ for stocks believed to have low to moderate resilience, and $F_{35\%}$ for stocks with "average" resilience (Mace and Sissenwine 1993). For stocks with very low productivity (such as rockfish and most elasmobranchs), fishing mortality rates in the range $F_{50\%}$ to $F_{60\%}$ are recommended as proxies for F_{MSY}."

Subsequent work has modified the scientific advice but not invalidated the general conclusions. When recruitment variability was taken into account, 40%SPR resulted in a better approximation to F_{MSY}. Later studies considered a wider range of steepness, SRRs, and life history and found that the range of %SPR needed to approximate F_{MSY} increased 40 percent–70 percent depending on the life history of the species (see Dorn, 2002; Clark, 2002; Harford et al., 2019). Considering the range of possible SRRs and life history parameters, the use of a "one-size-fits-all" %SPR is not advised, and the life history of the subject species should be considered when selecting within this range.

Fundamentally, decisions regarding the selected value of %SPR should be based on scientific determinations of what percentage would be the closest approximation to F_{MSY}. However, the F that would produce a given %SPR is also influenced by the fishery's technological characteristics (e.g., allocation between fleets that catch small versus larger fish, degree of discarding, etc.). This complicates the separation of MSY from OY, which takes into account economic, ecological, and other considerations. We will return to this topic in Section 6.2 on Fishery Technological Characteristics. Identification of the best %SPR for a given group of species is best done by a MSE designed specifically for the biology of the species involved and the nature of that fishery.

Current %SPR Levels

The distribution of %SPR across all U.S. stocks is presented in Figure 5B and Appendix II. It is common practice for FMPs to use the same %SPR for all of its stocks, although a few FMPs use a few different %SPR levels based on the biology of a set of species in the FMP (Appendix II). Lower %SPR levels (i.e., higher F) have been used for high productivity stocks, while stocks with slower growth or maturation (i.e., longer generation times like elasmobranchs and rockfishes) usually have a %SPR value greater than 50 percent. %SPR values <30 percent provide less protection to the reproductive potential of the stock. The chosen %SPR varies by region: 30 percent is most commonly used in the Southeast and for Pacific Coast flatfish; 35 percent is used in the North Pacific in combination with a more conservative 40%SPR for their Acceptable Biological Catch (ABC) target; 40 percent is commonest in the Northeast and Mid-Atlantic; and 45 percent is used for Pacific Coast groundfish and 50 percent for Pacific Coast rockfish. We document this range of %SPR approaches but are not investigating their historical rationales in the respective FMPs. We note that for a given life history, a lower %SPR leads to fishing harder on a smaller, younger stock in order to get close to MSY, whereas a higher %SPR leads to fishing less hard on a larger, older stock. The FMP amendments in which these %SPR proxies were established are typically 20+ years old, and we encourage an updated investigation of their performance using MSE. Later in Section 4 on Approaches to Status Determinations, we will describe how once the principle of a %SPR approach and an agreed range is established in an FMP, then technical updating of the value used for each stock can be based on biological and fishery information in assessments.

When a proxy is used for F_{MSY}, the assessments often dispense with inclusion of the SRR entirely and treat 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, care must be taken to allow the recruitments to be only lightly penalized; otherwise, they will be biased away from declining as SSB declines. Similarly, an assessment that uses a fixed steepness will pull the estimated recruitment trend toward the trend expected from that steepness level. Whenever a proxy is used for F_{MSY} over an extended time period, those performing assessments should look out for evidence of declines in recruitment following declines in SSB levels. Such declines may warrant consideration of a direct estimation of F_{MSY}.

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 YPR, 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, YPR-based proxies were commonly used. However, 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 YPR curve where the rate of increase in YPR achieves 10 percent 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 (steepness = 1) and generally higher otherwise (Mace, 1994). In this sense, F_{MAX} is the theoretical upper bound of F_{MSY}, but we emphasize that estimates where steepness = 1 are mostly due to limitations in the data rather than reflecting populations where recruitment is independent of spawners. Therefore, F_{MAX} is not expected to be appropriate for any stock. The $F_{0.1}$ was developed as a precautionary proxy for F_{MSY}, being considerably lower than F_{MAX}. Despite $F_{0.1}$ being more precautionary than F_{MAX}, both suffer from the conceptual shortcoming that they do not directly address the protection of the reproductive potential of the stock, as expected under the NS1 guidelines. $F_{0.1}$ is still used today, mostly outside the United States, but is much less than %SPR proxies. $F_{0.1}$ can be cautiously applied in cases where information on maturity and other factors needed to determine %SPR is unavailable and as a backstop for fish that mature at much younger ages before entering the fishery.

3.1.2b Proxies for B_{MSY}

B_{MSY} is a direct output of the biomass dynamics models and of age-structured models that include an SRR, whether or not that SRR is directly estimated or informed by a prior or constant. When B_{MSY} cannot be calculated directly, it must be either replaced with a reasonable proxy or recorded as unknown. The most common proxy approaches are to (a) set B_{MSY} to a fraction of B_0 if B_0 can be estimated and (b) set $B_{MSY} = R_{MSY} \cdot SSB/R$ when F is at F_{MSY} if recruitment at MSY can be estimated.

B_{MSY} as Percent of Unfished Biomass

If the unfished, virgin biomass can be more reliably estimated than biomass at MSY, then B_{MSY} can be based on a specified percentage of the unfished biomass (%B_0). This can occur if historical fishing levels have been low enough such that the SSB at the onset of data collection is not much below B_0 and the data are informative about B_0. This situation is much more common on the West Coast and Alaska versus in New England with its long history of fishing. The logic for this approach is that the shapes 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 the selection of an $F_{\%SPR}$ proxy for F_{MSY}. Currently in the United States, only the Mid-Atlantic Fishery Management Council and Pacific Fishery Management Council (PFMC) use this method to estimate a B_{MSY} proxy (see Appendix II). 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 Fishery Management 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 (Goodyear, 1993). For a typical Beverton–Holt curve, fishing at $F_{40\%SPR}$ will produce SSB that is approximately 35 percent 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

This approach takes the average recruitment over some time period as a proxy for the prevailing R_{MSY}, then multiplies it by the SSB/R associated with F_{MSY} or a suitable proxy to produce an estimate of B_{MSY}. The approach is preferable to simply taking average SSB over that period because SSB is more affected by the historical fishing level. This R-based approach presupposes either (a) that SSB was not too far from B_{MSY} during that time period or (b) that steepness is high so that the mean R will be a reasonable estimate of R_{MSY}. If SSB is suspected to be far from B_{MSY} and the unknown steepness level is suspected to be low, then the management system should be prepared to update the R_{MSY} and B_{MSY} over the next several years as the stock gets fished at the recommended F level based on a %SPR based proxy, which should allow the stock abundance to move toward B_{MSY}. The time period should be recent enough to confidently be the prevailing R_{MSY} but long enough to provide a stable estimate, so probably longer than the time period of recruitment used in short-term projections of OFL, short-term projections of approaching an overfished condition, and medium-term projections in the evaluation of rebuilding plans. Even though the use of very recent years seems relevant for OFL projections, the most recent years of an assessment are typically not well informed by data and are influenced by model assumptions and priors. Therefore, they are not well suited for use in mean recruitment for R_{MSY}. It also may be reasonable to exclude some range of early years if there is evidence that a regime change has happened. For example, the North Pacific Fishery Management Council (NPFMC) excludes recruitments prior to the 1977 regime shift in their reference point calculations. Section 5.1.2 has more discussion of the use of trailing averages in reference point calculations.

Unknown B_{MSY} Estimate

If it is not possible to develop a reliable value for B_{MSY}, short-term catch limits can still be set using a control rule based on a %SPR proxy for F_{MSY} and projected abundance using recent recruitments based on the concept that the best predictor of the near future is the recent past. 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 biomass response toward 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 as follows: high environmentally driven variability or trends in recruitment are masking the expected response to the controlling F, or the stock was already at a biomass level consistent with the %SPR. For this former case, a reliable estimate of B_{MSY} may not be attainable in the near term.

3.2 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) a time series of total catch and (2) at least one time series of relative abundance or effort data to indicate population trends. Software like ASPIC (Prager, 1994) made BDMs more accessible. BDMs pool the effects of growth, recruitment, and mortality into a single process representing population growth, ignoring the age or size structure and thus treating a stock as undifferentiated biomass. The simplest versions only require the estimation of two parameters, the intrinsic rate of population growth (r) and the unfished biomass (B_0). Their simple form allows for direct estimation of MSY, B_{MSY}, and F_{MSY}. The generalized approach by Pella and Tomlinson (1969) relaxes the shape of the production curve through the introduction of a shape parameter that allows B_{MSY}/B_0 to have a wider range more similar to the range of B_{MSY}/B_0 that occurs with age-structured models using a spawner–recruitment function.

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 3.1) but are ignored in historical 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. Today, some BDM approaches like JABBA-select can address fishery selectivity to some degree (Winker et al., 2020). 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.

One milestone in the evolution of BDMs was the implementation of state–space models that allow productivity to be stochastic and deviate from the deterministic expectation while simultaneously estimating the observation error (Francis et al., 2003; Meyer and Miller, 1999; Winker et al., 2018). Process error can account for the 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. Stochastic BDMs are demonstrating good performance in more applications (Nesslage and Wilberg, 2019) and are recommended over the historical deterministic forms.

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. This echoes the caveats on direct estimation of the SRR in age-structured models. In some circumstances, this uncertainty is reduced by adding information from other sources or other similarly assessed stocks. For example, one might assert that tuna species with similar life history 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 for a tuna species where there was little contrast. Also, tools such as FishLife (Thorson, 2020) can be used to obtain life history-based estimates of key population dynamic parameters (e.g., r) that can be incorporated in BDMs.

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

- Have minimal data requirements; do not require explicit information on life history (growth, reproduction, natural mortality).
- Are simple to implement and to communicate.
- Have new generation BDMs that can incorporate random effects in productivity and can naturally adapt to changing conditions.
- Have a straightforward connection to MSY quantities. Both F_{MSY} and B_{MSY} are model outputs.

The cons are that they:

- Cannot account for age-specific fishery selectivity and age-specific contribution to the SSB, which can bias the reference point estimates, although progress on this is occurring.
- Ignore the lag effect of recruitment contributing to the spawning biomass.
- Cannot use age composition data that inform 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 utilize age-structured life history information (growth, natural mortality, and maturity) but do not require age-structured catch or indices. ASPM are simply age-structured assessment models that do not estimate annual recruitment values (although some variants may treat annual recruitment as a random effect), 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. The 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 (Tier 1), specifying the SRR parameters determines the corresponding reference points, similar to how they are determined with a BDM. The default "one-size-fits-many" SPR range of 40–45 percent could be a starting point to derive the SRR parameterization, unless life history characteristics align with %SPR rates higher than this default range.

ASPM provides a bridge to data-rich age-structured models as more data become available. If life history information is available, then ASPM is a viable approach, especially if implemented with recruitment as a random effect. If life history information is not available, then Bayesian biomass dynamics models (e.g., JABBA; Winker et al., 2018) are a good approach to calculating MSY-based reference points from time series of catch and abundance data. Recent developments include the ability to address fishery selectivity (Winker et al., 2020).

3.3 Tier 3: Data-Limited Approaches

Data limitations (e.g., quality, quantity, coverage) present significant challenges to calculating reference points. The 2016 National Standard Guidelines addressed this limitation by adding the following statement 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. For example, SDC could be based on recent average catch, fish densities derived from visual census surveys, length/weight frequencies, or other methods. In specifying SDC, a Council must provide an analysis of how the SDC were chosen and how they relate to reproductive potential of stocks of fish within the fishery. If alternative types of SDCs are used, the Council should explain how the approach will promote sustainability of the stock or stock complex on a long term basis.*"

There has been a proliferation of data-limited methods (DLM) to address the spectrum of situations (Bentley, 2015; Porch et al., 2014; Chrysafi and Kuparinen, 2016), with no single approach applicable in all data-limited situations (Dowling et al., 2019; Cope, 2024). 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; Cope, 2024). In general, the reduction of data leads to a 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; Cope, 2024) that is more capable of providing outputs in terms of estimated SSB, %SPR, and F. However, when only one of the three data types is available, there is not enough information to produce all these quantities. Some DLM can provide relative indicators of increasing or decreasing F or SSB, but they are difficult to compare to the units of the SDC. 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 calculating either a reference point or the metric to compare to a reference point. A recent NOAA Technical Memorandum (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 collecting more information to bring the assessment at least up to "data-moderate" standards and to acknowledge the higher uncertainty associated with DLM.

3.3.1 Biological Composition Methods

Biological composition methods, also called catch curve analysis, can be used when the only available information is recent fishery-dependent length observations and basic life history parameters. This method is based on the fact that the current population's age and length composition has been influenced by the history of fishing; therefore, a 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 that overfishing determinations are feasible. In addition, ancillary knowledge about the approximate stability of the fishery over time may allow for a comparison of the current %SPR to the %SPR that would correspond to minimum stock size threshold (MSST).

Catch curve analysis measures the total mortality rate, Z, using the age (or length) 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 occurring. 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). However, even if the catch is not known, the approach still produces a measure of recent Z, SSB/R, and %SPR. With the 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 regard 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, for example:

- LIME (Rudd and Thorson, 2018).
- SS-LO (Cope, 2020; 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/).

3.3.1a Overfishing SDC and Status from Age/Length DLM

The overfishing SDC (MFMT) for composition-based DLM typically uses the same %SPR proxy indicated in the FMP under 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) describe how this approach can be used to develop rate-based ACLs.

3.3.1b 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, here termed F_{MSST}. If the current stock and fishery have been relatively stable for at least a generation time, then the recently obtained

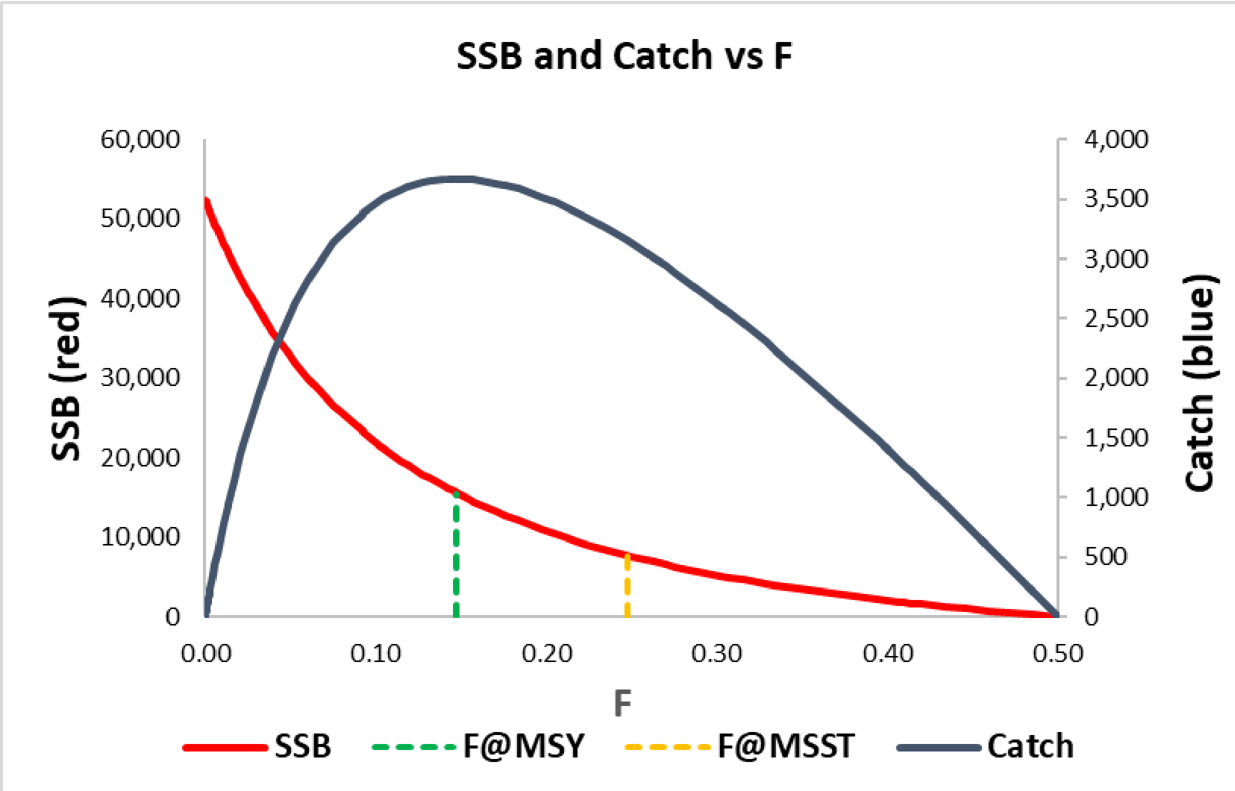

Figure 6: *SSB and catch plotted versus F while accounting for the effect of a SRR. The vertical green line shows F for MSY, and the vertical orange line shows F that reduces biomass to 50% of SSB at MSY, that is, MSST.*

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 F_{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 follows:

- MSST is normally specified as a fraction of SSB_{MSY} (or its proxy) or percentage of SSB_0. That same fraction, typically 0.5, can be used to calculate MSST in terms of %SPR. If the FMP's $F_{\%SPR}$ proxy is $F_{45\%}$, then 0.5 × 45 percent = 22.5 percent is an upper limit on an equivalent MSST (Figure 6).

- 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.

- Theoretically, if there is no relationship between spawners and recruits (steepness near 1 in the Beverton–Holt model), then the per-recruit and absolute biomass ratios will be identical. Realistically, steepness is <1. Therefore, to the degree that the recent average recruitment has

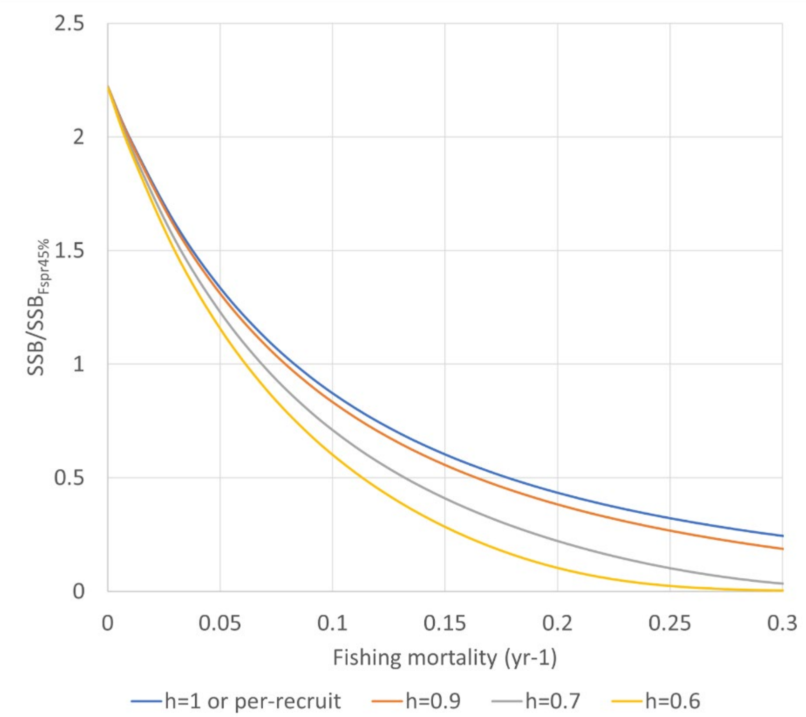

Figure 7: *Biomass ratios under a range of fishing mortalities, at 4 different steepness (h) levels. Note that per-recruit biomass ratios are identical to absolute ratios when h = 1 (blue line). The biomass reference point ($SSB_{Fspr45\%}$) is the spawning biomass at F resulting in an SPR of 45%, calculated using a steepness of 1.*

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 (SSB/MSST) (Figure 7). It is recommended to take this into consideration when specifying SDC for per-recruit overfished status by making them more conservative in accordance with the 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.

Previously, NOAA Fisheries has not supported the use of %SPR-based measurements to support overfished SDC. This occurred first in the early 1990s as %SPR measures were first being developed. In 1999, NOAA Fisheries rejected the Western Pacific Fishery Management Council's proposed overfished definitions that were based on %SPR (e.g., MSST = SPR of 20 to 30 percent). The notice of agency decision stated that "SPR is not an appropriate proxy for 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 of the agency's practice of not using %SPR for determining overfished status. Further, the MSA (Section 304(e)(1); 16 U.S.C. 1854(e)(1)) requires that NOAA Fisheries make stock status determinations based on criteria specified in the FMP, and the assessment applied different criteria than those specified in the Hawaii Archipelago Fishery Ecosystem Plan. The 2016 revisions to the NS1 guidelines (81 FR 71858; October 18, 2016) recognized the need for alternative types of SDC when data are not available to apply conventional approaches (50 CFR 600.310(e)(2)(ii)). For example, this might include the consideration of rate-based alternatives to ACLs (Macpherson et al., 2022). We recommend that the approach described here be used to make an overfished status determination in situations where %SPR can be measured by recent population age or length composition and where 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 derived quantity in the assessment model. The model analyzes data that are related to biomass, but absolute 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}. With this data-limited application here, the model uses available data to estimate the ratio directly. The accuracy of the data-limited overfished determination is dependent upon the accuracy of model assumptions. Nevertheless, the method certainly can provide an indication of whether the stock is close to being overfished.

The %SPR approach to overfished SDC will be biased if there is a trend in recruitment due to environmental changes (e.g., climate trends, habitat degradation; Mace et al., 1996). For example, if recruitment is decreasing due to a long-term trend in environmental conditions, the absolute biomass, SSB, will also trend downward because of the reduced recruitment, while the ratio, SSB/R, is less affected. Because this method is being applied in a data-limited situation, there is little direct information to evaluate the no-trend assumption. Available ancillary information should be consulted to support the conclusion that there has been little trend in recruitment. The implementation of the method can also gain support from simulation studies illustrating the degree of bias that would result from hypothetical trends in recruitment.

3.3.2 Abundance-Based Methods

There are two broad categories of abundance-based methods. One approach uses a time series index of stock abundance (trend) to make an overfished determination. The other approach uses a measure of absolute fish abundance that can be combined with current catch to calculate the current exploitation rate, which can then be used to make an overfishing determination. These methods are considered data-limited because they do not model population dynamics explicitly. Trend-based methods are also applicable when attempts to apply age-structured population dynamics methods encounter substantial problems such as retrospective bias (Legault et al., 2023).

3.3.2a Overfished SDC from Trends in CPUE or Relative Abundance

Trend-based methods have only a relative indicator of the population trend, so they 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 they cannot provide MSY reference points or overfishing status determinations. However, if both trend and catch data are available, then this corresponds to a higher data Tier, and one can consider using surplus production models that incorporate a production function as described in Tier 2.

One possible approach to calculating an MSST is to use the lowest observed index in a time series as an indicator of undesirably low biomass to be avoided (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 and the measurement uncertainty on each year of the index. The 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 to specifying SDC is to use the percentage change over time as an indicator of whether the stock has declined excessively. The MSST proxy is not expressed 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 the years leading up to the beginning of the index time series, then a 50 percent decline in the index would indicate that the stock may be near B_{MSY}, and a 75 percent decline would put the stock near MSST. However, if substantial fishing had already occurred by the start of the time series, then the stock may have been near B_{MSY} at the beginning, and a 50 percent 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 evaluating 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. An additional consideration is the fact that some potential measures of stock trend have high measurement uncertainty and are noisy. This can be addressed by smoothing the index by averaging observations over a suitable time period, typically about three years.

3.3.2b 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 $E = 0.75 \cdot M$ (Gulland, 1983), but if more complete life history information is available, then an $F_{\%SPR}$ could 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 flatfish and highly demersal stocks). Similarly, it has been used in the 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; Bravington et al., 2016).

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 evidence that the current overfishing situation had persisted for a long time (similar to the way that the 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 defining an overfished SDC.

Note that an absolute abundance survey may provide 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; thus, it generally is preferable to use this approach for making status determinations rather than using just one source of information.

3.3.3 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). A period of stable catches could, for example, be interpreted as sustainable, but it is not in and of itself an indication of MSY or stock status relative to B_{MSY}. Accordingly, 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 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 (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. Ideally, such methods would use total catch but typically use only landed catch due to the lack of discard data. 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.

4. APPROACHES TO STATUS DETERMINATIONS

Here, we describe the NS1 guidance for the specification of overfishing and overfished SDCs, highlight some common practices, and provide ideas for evaluating if a stock is approaching an overfished condition. As described in the Introduction, the MSA requires that Councils (and NOAA Fisheries in the case of Secretarial FMPs) specify in their FMPs "*objective and measurable criteria for identifying when a fishery to which the plan applies is overfished*" (MSA section 303(a)(10); 16 U.S.C. 1853(a)(1)). The NS1 guidelines explain that FMPs should describe how objective and measurable SDC will be specified to determine both overfishing and overfished status (50 CFR 600.310(b)(1)(ii)). Applying the SDC set forth in an FMP, the Secretary of Commerce determines if overfishing is occurring and if the stock or stock complex is overfished or approaching an overfished condition (MSA section 304(e)(1); 16 U.S.C. 1854(e)(1)). The NS1 guidelines emphasize that "*[i]n specifying SDC, a Council* *must provide an analysis of how the SDC were chosen and how they relate to reproductive potential of stocks of fish within the fishery*" (50 CFR 600.310(e)(2)(ii)). In the case of internationally managed stocks, the NS1 guidelines explain that Councils may decide to use the SDCs defined by the relevant international body (50 CFR 600.310(e)(2)(ii)).

The NS1 guidelines state that "*a Council should consider a process that allows SDCs to be quickly updated to reflect the best scientific information available*" (50 CFR 600.310(e)(2)(ii)). Councils (and NOAA Fisheries in the case of Secretarial FMPs) may wish to revise their SDC as new information (e.g., stock assessments) becomes available. Stock assessment peer review panels are often charged with evaluating the technical merits of potential revisions to SDC. The Council Scientific and Statistical Committees (SSCs) play a critical role in reviewing assessment results as well. NOAA Fisheries recently published a white paper (NOAA Fisheries, 2024) outlining how SDC can be structured in a flexible way so that new reference levels, determined to be BSIA, can be quickly adopted without an FMP amendment to enable more timely stock status determinations.

4.1 Overfishing Determinations

4.1.1 MFMT versus OFL Approach

The NS1 guidelines provide two alternative methods to determine overfishing status:

- "*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 CFR 600.310(e)(2)(i)(C)). MFMT 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 CFR 600.310(e)(2)(i)(D)).
- While data-limited proxies for MFMT and OFL are addressed elsewhere in this document, here we contrast MFMT and OFL as commonly implemented for Tier 1 and Tier 2.

There are pros and cons to these two approaches depending on the timeliness and precision with which each can be calculated. The OFL method can be applied as soon as catch is measured for a year, but the MFMT method cannot be applied to that year until the assessment includes that year. When an assessment is done in year T, there is a previous year, often T-1, for which observed catch allows calculating F for that year and applying the MFMT method. The assessment also typically will be able to project the expected fishable abundance to at least year T+1 and calculate the OFL for each year. If the assessment is not conducted 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 and stocks with large changes in body weight. Thus, even though the OFL was not exceeded on a year-to-year basis, a retrospective analysis might show that the F time series sometimes exceeded the F that was used to create those annual OFL values. These uncertainties in applying either the MFMT or OFL approach are among the uncertainties that should be considered when developing control rules that prevent overfishing.

The advantages of using OFL as the SDC are that catch can be easily understood by constituents and that a determination can be made as soon as catch totals are available. This same logic led to the development of the requirement for ACLs. The OFL method does not depend on having an assessment for the most recent year; only that the most recent assessment can project the OFL for that year or that the DLM being used can provide that OFL value. One drawback is that projected OFLs become increasingly uncertain with time as the calculation is increasingly composed of model-derived recruitments that are not yet 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 uses the stock assessment to look back at the past performance of the fishery. This means that the MFMT method is less vulnerable 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 F > MFMT could be less current than a determination based on catch > OFL and reflect 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 from 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 OFL, but the F is subsequently determined to be above MFMT.

4.1.2 Multi-Year Approaches

Overfishing status determinations are typically made based on the most recent year for which there is information. Multi-year approaches are designed to address situations where that most recent year has high uncertainty. The estimate of F for the most recent year depends upon the uncertain estimate of population abundance in that year and is often more uncertain than the estimates of F in prior years (National Research Council, 1998). The OFL method is subject to uncertainty when catch is not from a fish ticket census. This uncertainty occurs when a substantial percentage of the catch is from recreational fisheries where catch is measured from samples, not a census, and from fisheries in which a substantial percentage of the catch is discarded and the discards are measured from low levels of observer coverage. Some OFL approaches only use landed catch to support overfishing determinations, so this could potentially create additional uncertainty, as landed catch does not capture discard mortality. Uncertainty in the most recent year's catch or F can cause fluctuations and inconsistencies in a stock's overfishing status. In addition, the extent to which the F or catch exceeded the threshold for overfishing in a single year is not a criterion in the NS1 guidelines when determining whether the stock was subject to overfishing. However, exceeding the overfishing limit in a single year may not jeopardize a stocks' ability to produce MSY over the long term, thus a determination that a stock is subject to overfishing based on that single year's value may not be the most appropriate characterization of stock status.

To ensure accuracy and consistency in overfishing status determinations and bring 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 three consecutive years of past data (see 50 CFR 600.310(e)(2)(ii)(A)(3)). This multi-year approach allows managers to reduce fluctuations in overfishing status determinations by using a more stable basis. The downside of such an approach is that it is less responsive to real changes if F, so it should be used only where justified. The specific circumstances in which the multi-year approach is appropriate and will be used for a particular stock should be described in an FMP or FMP amendment. A multi-year approach has been used to determine overfishing status for some South Atlantic and Gulf of America (formally the Gulf of Mexico) stocks. While a multi-year approach can be used for determining and reporting on stock status, it cannot be used as a basis to specify future ACLs at levels that would result in overfishing. Further background on the multi-year overfishing stock status determination provision is provided in the 2015 proposed rule to revise the NS1 guidelines (See 80 FR 2791–2792, January 20, 2015).

4.2 Overfished Determinations

The reference point for an overfished determination is referred to as the 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*" (50 CFR 600.310(e)(i)(F)). The 2016 revision to the NS1 guidelines updated the requirements for MSST to be as follows: "*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 CFR 600.310(e)(2)(ii)(B)). Subsequent to Restrepo et al. (1998), the range of MSST approaches included a predominance of $0.5{\cdot}B_{MSY}$ in the Northeast; a predominance of $0.5{\cdot}B_{MSY}$, $0.75{\cdot}B_{MSY}$, and $(1\text{-}M){\cdot}B_{MSY}$ in the Southeast; a simulation approach in Alaska; and 25 percent of B_0 for some Pacific Coast groundfish with 40 percent B_0 as the B_{MSY} proxy. Recently, management bodies in the Southeast have shifted away from (1-M) because the low M associated with long-lived species produced an unacceptably narrow buffer between MSST and B_{MSY}. Now, most of their MSST levels are between $0.5{\cdot}B_{MSY}$ and $0.75{\cdot}B_{MSY}$. Simulation studies and MSE are advised to improve understanding to determine the relationship between the MSST and the probability distribution of natural fluctuations in SSB associated with fishing at MFMT. Some unpublished studies have shown that many stocks would rarely get that low through natural fluctuations. Other stocks, particularly short-lived stocks with high recruitment variability, may 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 an 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.

We note that the U.S. approach to overfished determinations is intermediate between the International Council for the Exploration of the Sea (ICES) approach in which their B_{LIM} (conceptually like MSST) 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 regional fisheries management organizations for highly migratory species treat B_{MSY} as the overfished limit. An ICES workshop explored and advocated for defining B_{LIM} as a fraction of B_{MSY} or B_0 (ICES, 2022).

In some cases, a multi-year approach has been used to make the overfished status determination. For example, in the PFMC's Pacific salmon FMP, the SDC used to determine the overfished status reads, "A stock will be considered overfished if the three-year geometric mean of annual spawning escapements falls below the MSST, where MSST is generally defined as $0.5S_{MSY}$ or $0.75S_{MSY}$, although there are some exceptions" (PFMC, 2024). A stock is considered rebuilt once the three-year geometric mean escapement exceeds S_{MSY} (or other criteria established on a case-specific basis). Since many Chinook salmon primarily return at one of three main age classes, this window has some biological linkage to the strength of a particular cohort (though this logic does not apply as well for coho salmon). The geometric mean also smooths over inter-annual variability attributable to both the highly dynamic nature of salmon populations and errors in estimating annual escapements. This approach therefore reduces the risk that a single year of low estimated escapement triggers overfished status and the development of a rebuilding plan that may be obsolete by the time it is completed if escapement is high enough the next year, and a single year of low escapement does not necessarily create substantial risk of long-term depletion. A single year of low escapement may not even produce a weak future cohort for a stock with sufficiently diverse age structure. However, a year of very low escapement will affect the geometric mean for multiple years. Thus, while it may be harder to trigger overfished status in the first place, it may prove very difficult to meet the criteria for rebuilt status until the year of low escapement is no longer included in the running mean since geometric means are particularly affected by low values.

4.3 Approaching an Overfished Condition

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*" (16 U.S.C. 1854(e)(1)). The NS1 guidelines further clarify that this determination should be made if the stock has more than a 50 percent chance that its SSB will decline below the MSST within two years (50 CFR 600.310(e)(2)(i)(G)). Restrepo et al. (1998) did not address the topic of "approaching an overfished condition," and it has received only limited attention in FMPs (e.g., see the FMP for Gulf of Alaska groundfish: https://www.npfmc.org/wp-content/PDFdocuments/fmp/GOA/GOAfmp.pdf and Pacific salmon). Making an approaching overfished determination typically requires the use of stock projections beyond one year. Here, we provide an updated set of recommendations for MSST and the related issue of approaching an overfished condition.

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 NS1 guidelines 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} (i.e., 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., recent average 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 the 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 percent 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 percent chance of being above MSST but below B_{MSY} (or proxy) within two years, then it is recommended that projections out to 10 years or one generation time be conducted to provide a long-term perspective on expected stock trends.

   a. If a projection using the ABC control rule projects that the stock has at least a 50 percent 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}.

   b. If the probability of being above B_{MSY} (or proxy) is <50 percent, 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.

   c. Both scenarios (a) and (b) are contingent on the accuracy of projections. However, for each progressive year of a projection, the stock will be composed of an increasing fraction of cohorts that were generated by the projection algorithms rather than being estimated from observations in the assessment. A sobering analysis by Brooks and Legault (2016) demonstrated poor projection performance beyond a couple of years. We recommend that the level of projection precision be clearly communicated.

5. UPDATING REFERENCE POINTS FOR CHANGING ENVIRONMENTAL CONDITIONS

The NS1 guidelines state the following 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*" or any other conditions for re-estimation. According to the NS1 guidelines definition of MSY, the prevailing conditions that impact MSY can be broken down into fleet characteristics, biological (life history) factors, and recruitment. All these factors change on a range of time scales, short (1-2 years), medium (3–10 years), and long (multi-decadal), so determining what is a long-term change and which are fluctuations within the current prevailing conditions is not always clear-cut. Prevailing conditions for OFL and ABC control rule projections may benefit from a shorter time horizon than is relevant for reference points. However, even for reference points, the most recent conditions may be the best predictor of which conditions will prevail in the near future. This section will describe some current practices for updating reference points and will identify some challenges that are encountered. Sections 5.2 and 5.3 identify situations that may indicate a need to review reference points and recommendations for doing so.

- *Prevailing fishery characteristics:* Reference points are conditional on the prevailing fleet characteristics, which often change in response to management actions (such as reallocation of quotas between sectors, increases or decreases in size limits, and gear modifications and seasonal changes in the fishery) and/or drift over time in response to various factors. Fishery economic and market considerations may also influence the propensity for the fishery to target larger versus smaller fish. Environmental conditions may alter life history characteristics, movement, and distribution, which could affect availability/catchability. The resultant age/length selectivity of each fleet and the allocation of F among fleets affect the F_{MSY} and MSY, and to a lesser degree the B_{MSY}.

- *Prevailing biological characteristics:* Each component of a stock's life history (growth, maturity, fecundity, natural mortality, movement) 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, but others like natural mortality are very difficult to measure and partially depend on the stock’s interaction with other species. A core challenge is that many of the biological factors can be density-dependent as well as environmentally affected (see Section 6.6 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. We typically do not have enough knowledge to determine the relative contribution of the environment versus density dependence to the change. We emphasize the importance of collecting biological data with sufficient temporal frequency such that reference points can track changes, and we can detect density dependence from long-term patterns.

- *Prevailing recruitment:* The situation is more challenging for recruitment because of the high fluctuations that occur from year-to-year. This means that many years must be averaged in order to have a stable mean. A shorter time span of trailing average recruitment makes sense for short-term projections but will fluctuate too much for a stable reference point. Some regions use the entire time series to characterize the prevailing mean recruitment, and others have seen enough change over time to support restricting to a shorter time period. This challenge was described previously in Section 3.1.2b, which discussed the year range for mean recruitment to be used in B_{MSY} calculations.

5.1 Overview of Approaches

5.1.1 Entire Time Series

It is recognized that all factors change over time, but if these changes are not measured, as often is the case for life history data, or if the fluctuations have high variability and are without obvious trend, as often is the case for recruitment, then the use of the entire time series of observations is a reasonable approach to determining the prevailing conditions. In the special case of direct estimation of the SRR, the intention is to use all years of spawner and recruitment information to estimate the relationship. While this default long-term perspective may be appropriate for reference points, it also is recognized that short-term projections with control rules generally are better if based on recent, not long-term, information. It also is true that several decades of surveys and stock assessments have disclosed the common occurrence of approximately decadal scale shifts in recruitment that explain the recruitment time series better than an SRR.

5.1.2 Trailing Average

The trailing average approach is based on the concept that the recent years are a reasonable indicator of the conditions that will prevail in the future. The trailing average is the mean of a fixed number of recent years to provide gradual updating of reference points to adapt to changing biological and fishery conditions. For example, in the Northeast, where life history parameters show sustained directional trends, the default has been to update reference points with a recent five-year average for fishery selectivity and fish life history. 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 have a stable basis for comparison. We support the recent average approach for life history and fishery characteristics and suggest that time windows for these updates could be framed in relation to the mean generation time of the stock when unfished or as five years, whichever is greater. A tradeoff to consider is that consistent trends are more closely tracked by a shorter window of years, whereas a longer window can be better where there are noisy year-to-year fluctuations without trend. Shorter time frames will be more strongly influenced by between-cohort variation (van Deurs et al., 2021), especially for short-lived species. We note that time windows on the order of a generation time would allow for the characterization of prevailing environmental conditions on the variability in life history parameters. A shortcoming of the trailing average approach is that it provides no direct examination of long-term trends or consequences, so may miss density-dependent effects and blur distinct regime changes.

Trailing average is the simplest approach to tracking changes, but more advanced statistical approaches that link to covariates or that use autoregressive techniques are viable and can be used if their performance is demonstrated to be superior to trailing average. Some assessments are already doing this to model changes in fish growth over time.

A five-year or generation time trailing average approach may not be well suited for recruitment because high inter-annual fluctuations in recruitment require a longer set of years to establish a stable estimate of the mean for SDC. It is possible that a trailing average over more years could be demonstrated to be useful for calculating the prevailing recruitment, but more common are approaches that seek to identify distinct regime shifts and/or SRRs.

5.1.3 Regime Shifts

If there is an abrupt change in ecosystem or 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. While the use of trailing averages over a fixed time period is straightforward to implement, it could blur distinct changes in the reference points, particularly with regard to recruitment. In addition, time blocks are sometimes used with fishery characteristics when there is a distinct intervention, for example, a change in regulated gear size or a dramatic change in quotas leading to a change in fishery behavior. Such intervention-based changes are essentially regime shifts and should have precedence over a strict trailing average.

It is now recognized that environmental shifts are common features in time series of recruitment and will lead to biased SRR estimates and to biased estimates of mean recruitment if they are not accounted for. For example, for Bering Sea tanner crab, the determination of B_{MSY} ($B_{35\%}$) depends on the selection of an appropriate time period over which to calculate average recruitment. Following a discussion in 2012 and 2013, the SSC endorsed (and continues to do so) an averaging period of 1982+. Starting the average recruitment period in 1982 is consistent with a five- to six-year recruitment lag from 1976/77, when a well-known climate regime shift occurred in the Eastern Bering Sea (Rodionov and Overland, 2005) that may have affected stock productivity (see Stockhausen, 2022).

The preferred approach for identifying regime shifts 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; Perälä and Kuparinen, 2015; Porch and Lauretta, 2016; Perälä 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., El Niño-Southern Oscillation) time series as corroboration for the change point. 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, including identified changes in ecological relationships through climate indices (i.e., Cai et al., 2015; Litzow 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 SRR. 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).

The general conclusion from recent workshops on reference points (DFO, 2013; Klaer et al., 2015; ICES, 2019; ICES, 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 unresponsive to changes in fishing pressure over the time period or existing strong correlation can be accounted for with the change in environmental conditions
- Strong/justified reason to believe that conditions are not going to return to previous conditions/reverse trend in the period leading up to the next benchmark assessment

5.1.4 Dynamic B_0

A special case of trailing average is the dynamic B_0 approach (MacCall et al., 1985; Berger, 2019; Bessell-Browne, 2022) that takes into account time varying fishery, biology, and recruitment. Dynamic B_0 is a method to determine relative stock status that compares current biomass (i.e., SSB) to the biomass that would have been present if fishing had never occurred (so-called "unfished" biomass (B_0)) in any given year or set of years. This is in contrast to defining B_0 as a single, static value based on historical, pre-fishing conditions that assume steady state population dynamics across the time series.

Dynamic B_0 does not require specifying a range of years over which to average recruitment. Instead, the dynamic B_0 value for a particular year is composed of surviving biomass coming from all prior recruitments. The prior year that contributes the most will be the year for which the numbers of fish multiplied by their fecundity are at a maximum. Younger ages contribute less because they have low body weight and fecundity; older ages contribute less because their numbers have declined. 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. 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 B_0 approach is an estimated product from a 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. Miller and Brooks (2021) note that some assumptions built into the dynamic B_0 approach may be violated when the SRR is parameterized using steepness and there is time-varying life history. As noted above (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.

Another method capable of addressing dynamic productivity is the Peterson Productivity Method (Peterman et al., 2000) which was recently re-investigated by Silvar-Viladomiu et al. (2022). This method allows for time-variation in the spawner–recruitment parameters and could be considered as new models seek improved approaches for direct estimation of reference points.

5.1.5 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, Pacific decadal oscillation), 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 SRR (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 (National Research Council, 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).

5.2 Whether to Change Reference Points

As mentioned above, the NS1 guidelines describe that MSY "*should be re-estimated as required by changes in long-term environmental or ecological conditions, fishery technological conditions, or new scientific information*" (50 CFR 600.310(e)(v)(A)). Further, "*[i]f environmental, ecosystem, or habitat changes affect the long-term reproductive potential of the stock or stock complex, one or more components of the SDC must be respecified*" (50 CFR 600.310(e)(2)(iii)(B)). This puts a high burden on the separation of fishery-induced changes from environmentally induced changes in the stock's recruitment, natural mortality, body growth, and other factors affecting productivity. The most common situation is one in which a decline in recruitment has been observed, and there is uncertainty regarding whether this is (a) fishery-induced consequence of the SRR (hence reversible by adjusting the level of the fishery), (b) caused by a short-term environmental effect that might be accommodated by a more robust control rule, and/or (c) a semi-permanent shift in the environment that will persist long enough to warrant a change to the reference points.

5.2.1 Type I versus Type II Error

The problem of identifying environmental causality can be considered in terms of hypothesis testing. A Type I error occurs when one identifies an environmentally induced change in productivity when one has not occurred, or a Type II error occurs 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 of more concern, 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 by reducing the SSB. Here, we agree with the recommendation in Restrepo et al. (1998) that the presumption be that fishing caused a decline and that the "burden of proof" should rest on demonstrating that the environment caused a change that would require the reference points to be modified. Recent international workshops (DFO, 2013; ICES, 2021) express similar cautions about too easily adjusting reference points due to recruitment changes. Hence, trailing average approaches, which inherently are constantly invoking a dominant environmental influence, should be mindful of the possibility of a Type I error.

5.2.2 Interaction Between Biomass Reference Points and Control Rules

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 control rules 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 biomass reference points.

Adjusting biomass reference points (MSST and B_{MSY}) down in response to perceived deteriorating environmental conditions will reduce the chance of triggering rebuilding plans designed to help stocks recover more quickly than would occur by preventing overfishing alone. A series of consecutive low recruitments will cause a stock to decline in abundance. However, if that is interpreted as a regime shift and biomass reference points are likewise scaled downward, then stock status relative to the lower reference point will not be as bad, and target fishing mortality rates would not be reduced as much as they would have been if the reference point was not changed. Conversely, adjusting reference points upward in response to perceived improving conditions could decrease current stock status relative to the higher reference point and increase the chance of imposing rebuilding plans unnecessarily. Szuwalski et al. (2023) explored an approach that maintains a long-term perspective for calculation of the SSB level for the control rule's inflection point, while SDC reference points are updated to reflect prevailing conditions. An approach like this is also mentioned in ICES (2021) but, to our knowledge, is untried in practice. It would be inappropriate to attempt to state technical guidance for this approach at this time. However, its broad characteristics can be outlined as follows:

- MFMT (F_{MSY} or proxy) depends on prevailing biological and fishery technical characteristics and density dependence in recruitment and biology. It would be routinely updated to reflect prevailing conditions.
- MSY and B_{MSY} depend on these same factors plus recruitment. They would 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 with current levels of recruitment.
    - Long-term B_{MSY} could be used to set the control rule inflection point to ensure that reductions in F will be recommended on declining stocks.
- 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 below MFMT whether or not the stock is considered to be below the MSST (calculated based on the prevailing conditions).
- 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.
- Simulation studies and MSE to investigate the performance of such a system are needed.

5.3 Recommendations Regarding Updating Reference Points

The table below summarizes our recommendations for updating factors used in reference point calculations. A column for projections is included for comparison.

	Reference Points	Projections
Fishery Characteristics	Use projection model, mean since last change point, or trailing average. Trailing average at least as long as trailing average for projections.	Projection model or short-term trailing average
Life History (Post-Recruitment Biology)	Use projection model, mean since last change point, or	Projection model or short-term trailing average

	trailing average. Be watchful for density-dependent effects.	
Recruitment	Use SRR (possibly environmentally informed) when available, otherwise use a long-term mean. Invoke a discrete change point only with strong supporting evidence. Also consider the trade-offs in Section 5.2.2.	Projection model (e.g., autoregressive or environmentally linked recruitment models) or short-term trailing average

Rationale:

- The time frame for updating prevailing conditions for changes in fishery characteristics and adult life history parameters is commonly shorter than the process for recruitment. This is logical and due to the high year-to-year fluctuations in recruitment and the predominant recognition of density dependence in recruitment.

- Fishery characteristics and adult (i.e., post-recruitment) life history should be routinely updated with projection models, trailing average, or autoregressive calculations. Distinct shifts due to management changes or environmental influences should supersede rigid trailing average time frames. Trailing average time frames of approximately one generation time or five years, whichever is greater, seem rational, but a time frame tailored to the degree of change and level of data quality is better. Longer time frames will be less responsive to changing conditions but will buffer the degree of change with each update. These characteristics are also routinely updated for use in ABC control rule projections where a high responsiveness is desirable. Therefore, a shorter averaging time frame may be useful for projections.

- Trailing averages will simply track long-term changes, so separate attention is necessary to detect and incorporate density dependence in fishery and life history factors.

- With routine updating of fishery and biological factors in reference points using trailing average calculations, it is useful to build this update into the stock assessment technical process and not the FMP amendment process.

- For recruitment, the recommended approach is either to maintain a long-term perspective, including by calibrating an SRR, or to adopt an approach that is designed to achieve biomass proxies implicitly. A regime shift should not be invoked unless it is well supported by corroborating evidence to avoid a Type I error (i.e., invoking a regime when one is not present; Haines et al., 2025).

- When %SPR or other proxies are used with prevailing recruitment without invoking a regime shift, the corresponding B_{MSY} and MSY proxies should be annotated as transitional until their estimates have stabilized over several assessment cycles (see Section 3.1.2b).

- Long-term recruitment changes may manifest as tracking slow drift in environmental and ecosystem conditions, rather than an abrupt regime shift. In this case, the dynamic B_0 approach may be useful to explore, but the caution about avoiding Type I error still applies.

- When changing reference points, highlight and investigate situations leading to maintaining high F on a declining stock. Recent studies, described above, have explored the benefits of setting the control rule inflection point for biomass based on a long-term perspective such that the target F for ABC would be reduced at low biomass even when the decline was due to an environmental influence.

6. 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 an estimation of reference points. The units of reproductive potential section (Section 6.1) illustrate a correctable bias that arises when historical proxies are used and assessments move from a simple spawning biomass basis to fecundity-based measures of reproductive potential. Fleet complexity (Section 6.2) and spatial complexity (Section 6.3) highlight the challenges of doing reference point calculations in real world situations. Section 6.4 on age truncation and Section 6.6 on density-dependent life history describe additional impacts of fishing that are not routinely taken into account in status determinations based solely on the preservation of reproductive potential.

6.1 Units of Reproductive Potential/Output

In principle and in accordance with ecological literature, reproductive potential should be in terms of viable offspring. This is difficult and costly to measure, and the closest we have come is to measure egg production and spawning frequency. Most assessments simply continue to use the mature female biomass of the stock, commonly termed spawning biomass. Further complications arise for hermaphroditic species for which the male contribution is important or for sharks where the units are in pups and gestation time matters. The use of spawning biomass as a proxy for a stock's reproductive potential assumes that reproductive output increases isometrically with size (Hixon et al., 2014; Barneche et al., 2018; Minte-Vera et al., 2019). For many species, it is observed that older spawners produce more eggs of higher quality per unit of biomass than younger spawners (Scott et al., 1999; Sogard et al., 2008; Murawski et al., 2001; Hixon et al., 2014; Barneche et al., 2018). Barneche 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. Subsequent work by Marshall, et al. (2021) found an exponent of 1.18 but still well above 1.0. In some situations, hierarchical approaches can provide information for assessment models in the absence of species-specific data. For example, the terms of reference for groundfish stock assessments adopted by the PFMC recommend the use of the results of a meta-analysis of size-dependent fecundity in stock assessments of rockfish along the U.S. West Coast (Dick et al., 2017).

The units with which reproductive output is measured will interact with the 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 annual estimates of recruitment do not change.

Consequently, the estimate of steepness will be higher to explain that recruitment stayed high as the fecundity-based SSB declined more than the weight-based measure of SSB. This interaction between the unit of reproductive potential and resulting steepness estimate has been found to have a canceling effect on a relative scale (i.e., SSB/SSB_{MSY}) such that estimated stock status is similar (Brooks, 2023).

For cases where a %SPR proxy is used for F_{MSY} and the assessment transitions to fecundity-based SSB, we recommend re-evaluating the level of the %SPR. 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}. The issue is that the F that produces 40%SPR in terms of biomass tends to be larger than the F that reduces fecundity to 40 percent of the unfished level. Thus, switching to the fecundity-based SSB will cause the MFMT to shift to a slightly lower value so that the equivalent %SPR proxy could be recalibrated for stocks with hyper-allometric fecundity (Minte-Vera et al., 2019).

Our guidance includes the following:

a. Continue to use the weight-based measure where direct fecundity-based measures are not available but consider sensitivity analyses to evaluate the magnitude of impact if fecundity is not isometric with weight (Brooks, 2023).
b. Use a fecundity-based measure of reproductive output where feasible but evaluate through simulation what recommended %SPR proxies should be for a range of hyper-allometric exponents, along the lines of the original studies by Clark (1993, 2002).

6.2 Fishery Technological Characteristics

The NS1 guidelines define 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 this definition, MSY and the associated reference points are influenced by fleet selectivity (i.e., the relative distribution of age-based F for a given fleet that combines gear contact selectivity and the 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). The optimal age to harvest is where the ratio of reproductive value to harvest value is the smallest (Brooks, 2002); hence, the choice of reproductive unit can be impactful for yield as well. It is not feasible to manage fisheries to attain the idealized knife-edge selectivity pattern associated with global MSY. Therefore, MSY calculations in practice 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) as explored recently by Stewart et al. (2021). 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 and reporting the MSY associated with each fishery can inform managers and stakeholders 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 fishing effort associated with achieving an 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 use the inherently sustainable level of spawning biomass associated with the global MSY to determine the target SPR. The primary rationale for this approach is that the %SPR associated with global MSY will be achievable in the long-term given 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′ values across some contiguous range of ages that have high 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 decreases as F increases, 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 increases 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 the calculation of reference points as well as the F pattern used when doing projections, as these may differ. Indeed, the projection of social and economic factors driving changes in the F pattern is an area for potential improvement in reference points (Chan et al., 2022).

6.3 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; Karp et al., 2019).

To ensure appropriate status determinations, it is necessary to understand biological stock boundaries relative to management boundaries using available stock identification approaches (Cadrin, 2020). Misaligning or misdiagnosing these boundaries will impede the ability to identify stock status regardless of the population structure (Berger et al., 2021). For example, changes in fish distribution can be accounted for through fitting 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, 2000; Grewe et al., 2015), making the aggregate measures of reproductive capacity misleading. The importance of directly accounting for spatial dynamics in SDC 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. Spatial dynamics are infrequently accounted for within stock assessment models used as the basis for 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 case 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 biological reference points (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 SDC 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).

6.4 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 fluctuations in 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. We recommend that assessments characterize the age composition of SSB routinely so that the number of year classes and their proportion contributing to spawning are part of the assessment report.

6.5 Size-Selective Fishing: Declining Size-at-Age

Some fisheries tend to target 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, known as “Rosa Lee’s phenomena.” Additionally, there is a considerable body of literature that shows that fish growth and other life history characteristics are heritable traits and that therefore size-selective fishing could have evolutionary consequences (Heino et al., 2013; Heino et al., 2015). 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, despite several recent papers pointing to the value and feasibility of doing so (Kraak et al., 2019; McGarvey et al., 2024). 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, although this feature cannot be employed in all situations.

6.6 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 the investigation of particular mechanisms.

If young fish continue experiencing density-dependent 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 are potentially reversible. Numerous instances of potential density dependence can be found in 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 are advised so that they can become a component of reference points in the future.

6.7 Multispecies Interactions

The NS1 guidelines recognizes that "*[t]he 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*" (§600.310(e)(1)(v)(C)). 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 when fishing on one species generates fishing mortality on other species, such as 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. 3(2); 16 U.S.C. 1802(2)) in another fishery. Technical interactions are mostly accounted for in the process of setting ACLs, monitoring catch from all sources, and applying accountability measures, which prevent ACLs from being exceeded and correct or mitigate overages of the ACL if they occur. See 50 CFR 600.310(g)(1). Thus, technical interactions are not typically considered as part of reference points and status determinations, although the section on fishery technological characteristics recognizes the difficulty caused by the total catch of a species coming from a variety of fisheries. One result of accounting for technical interactions is that the F for some target species will need to be maintained below their optimum F level because that level of F in a multispecies fishery causes overfishing for other species that can only sustain a lower F, for example, vulnerable bycatch species or species on rebuilding plans. This "under-fishing" has been described by McQuaw and Hilborn (2020).
- Biological interactions are predator–prey interactions or competition between species. 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., 2016). Predator abundance changes over time and, therefore, causes time-varying natural mortality (M) for the prey species, which will

affect its reference points. This can be estimated using a multispecies model (Collie et al., 2016; Holsman et al., 2016).

Both types of interactions 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 (i.e., human caused versus biological). Additionally, with both mixed-stock fisheries and multispecies biological interactions there are trade-offs in terms of the yield achievable across the different stocks involved. If the predator is also fished, then its target level of fishing will have an impact on prey abundance and M, so the search for F_{MSY} becomes a multispecies issue. It may not be possible to achieve the global 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. Although single species approaches take current interactions into account, they do not do so simultaneously for all interacting species and thus do not provide comprehensive guidance regarding the situation. Karp et al. (2023) provide recommendations on how to increase the uptake of multispecies modeling in fisheries management. Here, we discuss approaches to account for such technical and biological interactions in specifying reference points.

Several approaches exist to aid in managing multiple species within a mixed-stock fishery. One approach the authors recommend that could be explored is to estimate the F associated with MSST (F_{MSST}) for each species, taking into account equilibrium per recruit dynamics and the SRR (or proxy approach for MSY reference points). The F_{MSST} can be used to gauge whether a stock is being fished at a level that would result in a 50 percent chance or greater of it dropping below its MSST. For data-limited situations, F_{MSST} can be used as a rate-based approach to making overfished status determinations if certain conditions are true as explained earlier in the data-limited section of this document (Section 3.3). We recommend that these calculations and reports be routinely available in stock assessment software so that they can be used in situations that warrant consideration.

Another set of approaches involves taking more of a system approach and determining targets for multiple species and/or the system simultaneously using a combination of single and multispecies models. These approaches involve decisions regarding trade-offs between different objectives. One approach is to calculate the $F_{xx\%SPR}$ for each species using multispecies model projection such that each species equilibrates at $p \cdot B_0$, 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 (Chagaris et al., 2020). 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.

Another approach is 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 an analysis leads to the conclusion to "eliminate the predator, to harvest the prey" (Moffitt et al., 2016), which is not in line with the dual requirements of MSA of preventing overfishing while achieving OY on a continuous basis. 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 $p \cdot B_0$ (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 (Moffitt 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 is 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 the precautionary management of all stocks in the system.

As multispecies considerations inherently include trade-offs between different management actions and objectives, this analysis lends itself nicely to inclusion as operating models in MSEs. MSEs are one recommended pathway to move toward more multispecies management and trade-off decision making under current authorities (see Karp et al., 2023). 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 the New England FMC (NEFMC)). Additionally, to help encourage the fisheries science and management process to address these broader issues we emphasize the recommendation from Karp et al. (2023) that stock assessment terms of reference include the need to consider predator–prey interactions and ecosystem trends (e.g., system productivity) and evaluate scenarios.

7. CONCLUDING REMARKS

This document updates technical guidance for implementation of reference points used in 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 these reference points versus the 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. This document provides an overview of current F_{MSY} proxies and advocates for the use of MSE as a technique to investigate the performance of existing proxies with decades-old justifications. We do caution that the scope of this suggested MSE to investigate the performance of alternative control rules given current reference points is much narrower than an MSE to investigate the best levels for reference points themselves.

This 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 NS1 guidelines 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, for example, 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 SRR 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.

Environmental variability creates a challenging 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 or prevent it rebuilding if favorable conditions return. This conundrum is discussed but not resolved. Another conundrum is that separation of environmental 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 discussion on species interactions. This includes both biological interactions, especially predator–prey interactions, and technical interactions such as the fact that fishing on one targeted species may impact 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 for relative to 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 jurisdictions.

In the end, many points remain difficult to clarify for several reasons. First, the past 27 years of monitoring fish populations and their ecosystems 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 environmental variability, 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 that equivalent but different approaches have evolved and are challenging to gather into a holistic approach.

Despite these challenges and differences, the NS1 guidelines system of reference points has been highly effective in providing a scientific approach to the implementation of the MSA's mandate to prevent overfishing and to 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 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 those used 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; Clark, 1993). Goodyear (1990) recommended an SPR of 20 percent, whereas Mace and Sissenwine (1993) suggested 30 percent would be more appropriate for most stocks with 20 percent 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 SRRs typical of demersal fish (groundfish), SPR 35 percent would usually achieve pretty good yields (e.g., 75 percent 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 temporally correlated 40%SPR was more appropriate as a default proxy to protect against the stock dropping below the 20 percent 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 (Public Law 104-297 §§ 109(e), 102, 108(a) (October 11, 1996)). Subsequently, in 1998, NOAA Fisheries amended the NS1 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 600.310(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 that debate about the most appropriate %SPR persisted. However, studies began to consider the impacts of fishing at certain $F_{xx\%SPR}$ on biomass levels. Work in the 2000s recognized that the search for the "most appropriate" %SPR depended on the stocks considered and suggested that more conservative proxies are appropriate for most stocks (Brodziak, 2002; Clark, 2002; Dorn, 2002; Brooks et al., 2010; Cortés and Brooks, 2018; Harford et al., 2019). For instance, when a wider range of steepness and SRRs were considered, representing more realistic levels of resilience and productivity for certain types of stocks (e.g., rockfish), the %SPR increases to between 40 percent and 70 percent (see Dorn, 2002; Clark, 2002; Harford et al., 2019). The desired levels of unfished biomass maintained from a given fishing rate was also found to be an important consideration when selecting an appropriate $F_{xx\%SPR}$. 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 $F_{40\%}$ was only 20–30 percent of unfished biomass for more resilient stocks and that the biomass resulting from fishing at the same level ($F_{40\%}$) drops if stock resilience is assumed to be lower. A higher SPR value of $F_{50\%}$–$F_{60\%}$ on the other hand would achieve 40–50 percent of unfished biomass (Clark, 2002).

Furthermore, Brooks et al. (2010) derived the analytical relationship between steepness of the SRR 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[5] (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 SRRs 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

[5] Registry of Research Data Repositories. re3data.org. [Available at http://doi.org/10.17616/R34D2X]

or response to extrinsic factors such as changes in habitat quality. Changes in life history parameters directly impact 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 Sections 3.1.1h and 5.

APPENDIX II: TABLE OF REFERENCE POINT METHODS AND VALUES BY STOCK

Information for this table was compiled through a query of the NOAA Species Information System (SIS) for all stock assessments completed as of February 2024. Unassessed stocks and salmon were removed from the table, resulting in 270 stocks.

Jurisdiction	FMP	Stock	F_{MSY}			B_{MSY}		
			Category	Method	Value	Category	Method	Value
CFMC[6]	Puerto Rico Fishery Management Plan	Caribbean spiny lobster - Puerto Rico	Proxy	%SPR	30	Proxy	%SPR	30
	Puerto Rico Fishery Management Plan	Puerto Rico Triggerfishes Complex	Proxy	%SPR	30	Proxy	%SPR	30
	St. Croix Fishery Management Plan	Caribbean spiny lobster - St. Croix	Proxy	%SPR	30	Proxy	%SPR	30
	St. Thomas and St. John Fishery Management Plan	Caribbean spiny lobster - St. Thomas/ St. John	Proxy	%SPR	30	Proxy	%SPR	30
		St. Thomas/ St. John Triggerfish Complex	Proxy	%SPR	30	Proxy	%SPR	30
GFMC[7]	Red Drum Fishery of the Gulf of Mexico	Red drum - Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
	Reef Fish Resources of the Gulf of Mexico	Gray snapper - Gulf of Mexico	Proxy	%SPR	26	Proxy	%SPR	26

[6] Caribbean Fishery Management Council
[7] Gulf Fishery Management Council

		Red snapper - Gulf of Mexico	Proxy	%SPR	26	Proxy	%SPR	26
		Gray triggerfish - Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		Greater amberjack - Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		Gulf of Mexico Shallow Water Grouper Complex	Proxy	%SPR	30	Proxy	%SPR	30
		Gulf of Mexico Tilefishes Complex	Proxy	%SPR	30	Proxy	%SPR	30
		Hogfish - Eastern Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		Lane snapper - Gulf of Mexico	Proxy	%SPR	30	Unavailable	-	-
		Red grouper - Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		Tilefish - Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		Vermilion snapper - Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		Yellowedge grouper - Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		Gag - Gulf of Mexico	Proxy	%SPR	40	Proxy	%SPR	40
	Shrimp Fishery of	Brown shrimp -	Direct Estimate	Estimated Steepness	0.99	Direct Estimate	Estimated Steepness	0.99

	the Gulf of Mexico	Gulf of Mexico						
		Pink shrimp - Gulf of Mexico	Direct Estimate	Estimated Steepness	0.99	Direct Estimate	Estimated Steepness	0.99
		White shrimp - Gulf of Mexico	Direct Estimate	Estimated Steepness	0.99	Direct Estimate	Estimated Steepness	0.99
		Royal red shrimp - Gulf of Mexico	Proxy	Reference Catch	337000	Unavailable	-	-
HMS	Consolidated Atlantic Highly Migratory Species	Bluefin tuna - Western Atlantic	Proxy	%YPR	10	Unavailable	-	-
		Albacore - North Atlantic	Direct Estimate	Biomass Dynamics Model	Fox	Direct Estimate	Biomass Dynamics Model	Fox
		Scalloped hammerhead - Atlantic	Direct Estimate	Biomass Dynamics Model	Fox	Direct Estimate	Biomass Dynamics Model	Fox
		Blacknose shark - Atlantic	Direct Estimate	Estimated Steepness	0.36	Direct Estimate	Estimated Steepness	0.36
		Porbeagle - Northwestern Atlantic	Direct Estimate	Estimated Steepness	0.45	Direct Estimate	Estimated Steepness	0.45
		Blacktip shark - Gulf of Mexico	Direct Estimate	Estimated Steepness	0.47	Direct Estimate	Estimated Steepness	0.47
		Atlantic sharpnose shark - Atlantic	Direct Estimate	Estimated Steepness	0.57	Direct Estimate	Estimated Steepness	0.57
		Atlantic sharpnose shark - Gulf of Mexico	Direct Estimate	Estimated Steepness	0.57	Direct Estimate	Estimated Steepness	0.57
		Sailfish - Western Atlantic	Direct Estimate	Estimated Steepness	0.75	Direct Estimate	Estimated Steepness	0.75
		White marlin - Atlantic	Direct Estimate	Estimated Steepness	0.557–0.617	Direct Estimate	Estimated Steepness	0.557–0.617

		Dusky shark - Atlantic and Gulf of Mexico	Direct Estimate	Estimated Steepness	0.25–0.71	Direct Estimate	Estimated Steepness	0.25–0.71
		Sandbar shark - Atlantic and Gulf of Mexico	Direct Estimate	Fixed Steepness	0.3	Direct Estimate	Fixed Steepness	0.3
		Shortfin mako - North Atlantic	Direct Estimate	Fixed Steepness	0.345	Direct Estimate	Fixed Steepness	0.345
		Blacktip shark - Atlantic	Direct Estimate	Fixed Steepness	0.4	Direct Estimate	Fixed Steepness	0.4
		Smooth dogfish - Atlantic	Direct Estimate	Fixed Steepness	0.54	Direct Estimate	Fixed Steepness	0.54
		Bigeye tuna - Atlantic	Direct Estimate	Fixed Steepness	0.8	Direct Estimate	Fixed Steepness	0.8
		Skipjack tuna - Western Atlantic	Direct Estimate	Fixed Steepness	0.8	Direct Estimate	Fixed Steepness	0.8
		Yellowfin tuna - Atlantic	Direct Estimate	Fixed Steepness	0.8	Direct Estimate	Fixed Steepness	0.8
		Blue shark - North Atlantic	Direct Estimate	Fixed Steepness	0.86	Direct Estimate	Fixed Steepness	0.86
		Swordfish - North Atlantic	Direct Estimate	Fixed Steepness	0.88	Direct Estimate	Fixed Steepness	0.88
		Blue marlin - Atlantic	Direct Estimate	Fixed Steepness	-	Direct Estimate	Fixed Steepness	-
		Finetooth shark - Atlantic and Gulf of Mexico	Proxy	Replacement Yield	0.03	Proxy	%Carrying Capacity	50
		Gulf Smoothhound Complex	Proxy	Replacement Yield	0.106	Proxy	%Carrying Capacity	50

MAFMC	Atlantic Surfclam and Ocean Quahog	Atlantic surfclam - Mid-Atlantic Coast	Proxy	F Threshold	-	Proxy	B Threshold	-
	Atlantic Surfclam and Ocean Quahog	Ocean quahog - Atlantic Coast	Proxy	F Threshold	-	Proxy	F Threshold	-
	Bluefish	Bluefish - Atlantic Coast	Proxy	%SPR	35	Proxy	%SPR	35
	Mackerel, Squid, and Butterfish	Longfin inshore squid - Georges Bank/Cape Hatteras	None	-	-	Proxy	K/2	-
		Atlantic mackerel - Gulf of Maine/Cape Hatteras	Proxy	%SPR	40	Proxy	%SPR	40
		Butterfish - Gulf of Maine/Cape Hatteras	Proxy	%SPR	50	Proxy	%SPR	50
	Summer Flounder, Scup, and Black Sea Bass	Summer flounder - Mid-Atlantic Coast	Proxy	%SPR	35	Proxy	%SPR	35
		Black sea bass - Mid-Atlantic Coast	Proxy	%SPR	40	Proxy	%SPR	40
		Scup - Atlantic Coast	Proxy	%SPR	40	Proxy	%SPR	40
	Tilefish	Blueline tilefish - Mid-Atlantic Coast	None	-	-	None	-	-
		Tilefish - Mid-Atlantic Coast	Proxy	%SPR	40	Proxy	%SPR	40

NE/MAFMC	Monkfish	Goosefish - Gulf of Maine/Northern Georges Bank	None	-	-	None	-	-
		Goosefish - Southern Georges Bank/Mid-Atlantic	None	-	-	None	-	-
	Spiny Dogfish	Spiny dogfish - Atlantic Coast	Proxy	%SPR	60	Proxy	%SPR	60
NEFMC	Atlantic Herring	Atlantic herring - Northwestern Atlantic Coast	Proxy	%SPR	40	Direct Estimate	Assessment Model	Long-term stochastic projection
	Atlantic Salmon	Atlantic salmon - Gulf of Maine	None	-	-	None	-	-
	Atlantic Sea Scallop	Sea scallop - Northwestern Atlantic Coast	Direct Estimate	Biomass Dynamics Model	SYM[8] Model	Direct Estimate	Biomass Dynamics Model	SYM Model
	Deep-Sea Red Crab	Red deep-sea crab - Northwestern Atlantic	None	-	-	None	-	-
	Northeast Multispecies	Atlantic halibut - Northwestern Atlantic Coast	None	-	-	None	-	-
		Red hake - Gulf of Maine/Northern	None	-	-	None	-	-

[8] Surplus Yield Model

		Georges Bank						
		Red hake - Southern Georges Bank/Mid-Atlantic	None	-	-	None	-	-
		Witch flounder - Northwestern Atlantic Coast	None	-	-	None	-	-
		Winter flounder - Georges Bank	Proxy	%F	40	Proxy	%F	40
		Winter flounder - Southern New England/ Mid-Atlantic	Proxy	%F	40	Proxy	%F	40
		Yellowtail flounder - Cape Cod/Gulf of Maine	Proxy	%F	40	Proxy	%F	40
		Yellowtail flounder - Southern New England/ Mid-Atlantic	Proxy	%F	40	Proxy	%F	40
		American plaice - Gulf of Maine/Georges Bank	Proxy	%SPR	40	Proxy	%SPR	40

		Atlantic cod - Southern New England	Proxy	%SPR	40	Proxy	%SPR	40
		Atlantic cod - Western Gulf of Maine	Proxy	%SPR	40	Proxy	%SPR	40
		Atlantic cod - Georges Bank	Proxy	%SPR	40	Proxy	%SPR	40
		Atlantic cod - Eastern Gulf of Maine	Proxy	%SPR	40	Proxy	%SPR	40
		Atlantic wolffish - Gulf of Maine/Georges Bank	Proxy	%SPR	40	Proxy	%SPR	40
		Haddock - Georges Bank	Proxy	%SPR	40	Proxy	%SPR	40
		Haddock - Gulf of Maine	Proxy	%SPR	40	Proxy	%SPR	40
		Pollock - Gulf of Maine/Georges Bank	Proxy	%SPR	40	Proxy	%SPR	40
		White hake - Gulf of Maine/Georges Bank	Proxy	%SPR	40	Proxy	%SPR	40
		Acadian redfish - Gulf of Maine/Georges Bank	Proxy	%SPR	50	Proxy	%SPR	50
		Window pane - Gulf of Maine/Georges Bank	Proxy	None	-	None	-	-

		Yellowtail flounder - Georges Bank	Proxy	Survey Exploitation Rate	7	None	-	-
		Winter flounder - Gulf of Maine	Proxy	Survey Exploitation Rate	40	None	-	-
		Ocean pout - Northwestern Atlantic Coast	Proxy	Survey Exploitation Rate	-	Proxy	Median Survey Biomass	-
		Silver hake - Gulf of Maine/Northern Georges Bank	Proxy	Survey Exploitation Rate	-	Proxy	Survey Exploitation Rate	-
		Silver hake - Southern Georges Bank/Mid-Atlantic	Proxy	Survey Exploitation Rate	-	Proxy	Survey Exploitation Rate	-
		Window pane - Southern New England/Mid-Atlantic	Proxy	Survey Exploitation Rate	-	Proxy	Survey Exploitation Rate	-
	Northeast Skate Complex	Rosette skate - Southern New England/Mid-Atlantic	Proxy	Percent Survey Abundance Change	–60	Proxy	% Long-Term Survey Biomass Distribution	75
		Clearnose skate - Southern New England/Mid-Atlantic	Proxy	Percent Survey Abundance Change	–40	Proxy	% Long-Term Survey Biomass Distribution	75

		Barndoor skate - Georges Bank/Southern New England	Proxy	Percent Survey Abundance Change	–30	Proxy	% Long-Term Survey Biomass Distribution	75
		Smooth skate - Gulf of Maine	Proxy	Percent Survey Abundance Change	–30	Proxy	% Long-Term Survey Biomass Distribution	75
		Little skate - Georges Bank/Southern New England	Proxy	Percent Survey Abundance Change	–20	Proxy	% Long-Term Survey Biomass Distribution	75
		Thorny skate - Gulf of Maine	Proxy	Percent Survey Abundance Change	–20	Proxy	% Long-Term Survey Biomass Distribution	75
		Winter skate - Georges Bank/Southern New England	Proxy	Percent Survey Abundance Change	–20	Proxy	% Long-Term Survey Biomass Distribution	75
NPFMC	Bering Sea/Aleutian Islands King and Tanner Crabs	Indicator stock - Golden king crab - Eastern Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35
		Indicator stock - Golden king crab - Western Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35
		Red king crab - Bristol Bay	Proxy	%SPR	35			
		Snow crab -	Proxy	%SPR	35	Proxy	%SPR	35

		Bering Sea						
		Southern Tanner crab - Bering Sea	Proxy	%SPR	35	Proxy	%SPR	35
		Blue king crab - Pribilof Islands	Proxy	Average Bycatch Mortality	1.16	Proxy	Average Survey Biomass from Reference Period	-
		Blue king crab - Saint Matthew Island	Proxy	Average Bycatch Mortality	48	Proxy	Average Survey Biomass from Reference Period	-
		Red king crab - Pribilof Islands	Proxy	Natural Mortality Rate	0.18	Proxy	% MMB[9] Estimated from Reference Period	35
		Red king crab - Norton Sound	Proxy	Natural Mortality Rate	0.68	Proxy	Average Estimated MMB	-
	Groundfish of the Bering Sea and Aleutian Islands Management Area	Alaska plaice - Bering Sea/Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35
		Arrowtooth flounder - Bering Sea/Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35
		Atka mackerel - Bering Sea/Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35

[9] Mature male biomass

		Bering Sea/Aleutian Islands Blackspotted and Rougheye Rockfish Complex	Proxy	%SPR	35	Proxy	%SPR	35
		Greenland halibut - Bering Sea/Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35
		Indicator stock - Alaska skate - Bering Sea/Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35
		Indicator stock - Flathead sole - Bering Sea/Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35
		Indicator stock - Northern rock sole - Bering Sea/Aleutian Islands	Proxy	%SPR	35	Direct Estimate	Biomass Dynamics Model	Ricker Model
		Kamchatka flounder - Bering Sea/Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35
		Northern rockfish - Bering Sea/Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35
		Pacific cod -	Proxy	%SPR	35	Proxy	%SPR	35

		Aleutian Islands						
		Pacific cod - Bering Sea	Proxy	%SPR	35	Proxy	%SPR	35
		Pacific ocean perch - Bering Sea/Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35
		Walleye pollock - Aleutian Islands	Proxy	%SPR	35	Proxy	%SPR	35
		Yellowfin sole - Bering Sea/Aleutian Islands	Direct Estimate	Biomass Dynamics Model	Ricker SRR	Direct Estimate	Biomass Dynamics Model	Ricker SRR
		Indicator stock - Giant octopus - Bering Sea/Aleutian Islands	Proxy	Consumption Estimate	-	None	-	-
		Walleye pollock - Eastern Bering Sea	Direct Estimate	Estimated Steepness	0.6	Direct Estimate	Estimated Steepness	0.6
		Shortraker rockfish - Bering Sea/Aleutian Islands	Proxy	Natural Mortality Rate	0.03	None	-	-
		Bering Sea/Aleutian Islands Other Rockfish Complex	Proxy	Natural Mortality Rate	0.032	None	-	-

		Bering Sea/Aleutian Islands Other Flatfish Complex	Proxy	Natural Mortality Rate	0.156	None	-	-
		Walleye pollock – Bogoslof Island	Proxy	Natural Mortality Rate	0.3	None	-	-
		Pacific sleeper shark - Bering Sea/Aleutian Islands	Proxy	Reference Catch	689	None	-	-
		Sablefish - Eastern Bering Sea/Aleutian Islands/Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Arrowtooth flounder - Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Dusky rockfish - Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Flathead sole - Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Geographic subunit - Rex sole - Eastern Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Geographic subunit - Rex sole - Western/Central Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35

		Gulf of Alaska Blackspotted and Rougheye Rockfish Complex	Proxy	%SPR	35	Proxy	%SPR	35
		Indicator stock - Dover sole - Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Indicator stock - Northern rock sole - Central Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Indicator stock - Northern rock sole - Western Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Indicator stock - Rock sole - Central Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Indicator stock - Rock sole - Western Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Northern rockfish - Western/ Central Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Pacific cod - Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35

		Pacific Ocean perch - Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Walleye pollock - Western/ Central/ West Yakutat Gulf of Alaska	Proxy	%SPR	35	Proxy	%SPR	35
		Indicator stock - Shortspine thornyhead - Gulf of Alaska	Proxy	Natural Mortality Rate	0.03	None	-	-
		Shortraker rockfish - Gulf of Alaska	Proxy	Natural Mortality Rate	0.03	None	-	-
		Indicator stock - Yelloweye rockfish - Gulf of Alaska	Proxy	Natural Mortality Rate	0.032	None	-	-
		Gulf of Alaska Other Rockfish Complex	Proxy	Natural Mortality Rate	0.07	None	-	-
		Big skate - Gulf of Alaska	Proxy	Natural Mortality Rate	0.1	None	-	-
		Gulf of Alaska Other Skate Complex	Proxy	Natural Mortality Rate	0.1	None	-	-
		Longnose skate - Gulf of Alaska	Proxy	Natural Mortality Rate	0.1	None	-	-
		Walleye pollock - Southeast Gulf of Alaska	Proxy	Natural Mortality Rate	0.3	None	-	-

		Spiny dogfish - Gulf of Alaska	Proxy	Survey Exploitation Rate	0.04	None	-	-
	Scallop Fishery off Alaska	Weathervane scallop - Alaska	Proxy	Reference Catch	1284000	None	-	-
P/WPFMC	U.S. West Coast Fisheries for Highly Migratory Species/Pacific Pelagic Fisheries of the Western Pacific Region Ecosystem	Pacific bluefin tuna - Pacific	Proxy	%SPR	20	Proxy	%SPR	20
		Thresher shark - North Pacific	Proxy	%SPR	45	Direct Estimate	Fixed Steepness	0.74
		Skipjack tuna - Eastern Pacific	Proxy	%Virgin Biomass	30	Proxy	%Virgin Biomass	30
		Bigeye thresher - Pacific	Direct Estimate	Biomass Dynamics Model	Bayesian state-spaced	Unavailable	-	-
		Swordfish - Eastern Pacific	Direct Estimate	Biomass Dynamics Model	Bayesian state-spaced	Direct Estimate	Biomass Dynamics Model	Bayesian state-spaced
		Shortfin mako - North Pacific	Direct Estimate	Fixed Steepness	0.317	Direct Estimate	Fixed Steepness	0.317
		Blue shark - North Pacific	Direct Estimate	Fixed Steepness	0.67	Direct Estimate	Fixed Steepness	0.67
		Skipjack tuna - Western and Central Pacific	Direct Estimate	Fixed Steepness	0.8	Proxy	%SPR	50
		Yellowfin tuna - Western and Central Pacific	Direct Estimate	Fixed Steepness	0.8	Direct Estimate	Fixed Steepness	0.8
		Striped marlin - Western and Central North Pacific	Direct Estimate	Fixed Steepness	0.87	Direct Estimate	Fixed Steepness	0.87

		Albacore - North Pacific	Direct Estimate	Fixed Steepness	0.9	Direct Estimate	Fixed Steepness	0.9
		Swordfish - Western and Central North Pacific	Direct Estimate	Fixed Steepness	0.9	Direct Estimate	Fixed Steepness	0.9
		Bigeye tuna - Western and Central Pacific	Direct Estimate	Fixed Steepness	0.65–0.95	Direct Estimate	Fixed Steepness	0.65–0.95
		Yellowfin tuna - Eastern Pacific	Direct Estimate	Fixed Steepness	0.7–1.0	Direct Estimate	Fixed Steepness	0.7–1.0
		Bigeye tuna - Eastern Pacific	Direct Estimate	Fixed Steepness	0.8–1.0	Direct Estimate	Fixed Steepness	0.8–1.0
		Striped marlin - Eastern Pacific	Direct Estimate	Multiple Models		Direct Estimate	Multiple Models	
PFMC	Coastal Pelagic Species	Pacific sardine - Pacific Coast	Proxy	Allowable Harvest Rate	0.25	Unavailable	-	-
		Pacific chub mackerel - Pacific Coast	Proxy	Allowable Harvest Rate	0.3	Unavailable	-	-
		Northern anchovy - Southern Pacific Coast	Direct Estimate	Fixed Steepness	0.6	Unavailable	-	-
	Pacific Coast Groundfish	Indicator stock - Starry flounder - Northern Pacific Coast	Unavailable	-	-	Unavailable	-	-

		Indicator stock - Starry flounder - Southern Pacific Coast	Unavailable	-	-	Unavailable	-	-
		Pacific sanddab - Pacific Coast	Unavailable	-	-	Unavailable	-	-
		Stripetail rockfish - Pacific Coast	Unavailable	-	-	Unavailable	-	-
		Arrowtooth flounder - Pacific Coast	Proxy	%SPR	30	Proxy	% Unfished Spawning Biomass	25
		Dover sole - Pacific Coast	Proxy	%SPR	30	Proxy	% Unfished Spawning Biomass	25
		English sole - Pacific Coast	Proxy	%SPR	30	Proxy	% Unfished Spawning Biomass	25
		Northern California Gopher/ Black-and-Yellow Rockfish Complex	Proxy	%SPR	30	Proxy	% Unfished Spawning Biomass	40
		Petrale sole - Pacific Coast	Proxy	%SPR	30	Proxy	% Unfished Spawning Biomass	25
		Rex sole - Pacific Coast	Proxy	%SPR	30	Proxy	% Unfished Spawning Biomass	25
		Pacific hake - Pacific Coast	Proxy	%SPR	40	Proxy	% Unfished Spawning Biomass	40
		Cabezon - Oregon	Proxy	%SPR	45	Proxy	% Unfished Spawning Biomass	40

		Indicator stock - Cabezon - Northern California	Proxy	%SPR	45	Proxy	% Unfished Spawning Biomass	40
		Indicator stock - Cabezon - Southern California	Proxy	%SPR	45	Proxy	% Unfished Spawning Biomass	40
		Kelp greenling - Oregon	Proxy	%SPR	45	Proxy	% Unfished Spawning Biomass	40
		Lingcod - Northern Pacific Coast	Proxy	%SPR	45	Proxy	% Unfished Spawning Biomass	40
		Lingcod - Southern Pacific Coast	Proxy	%SPR	45	Proxy	% Unfished Spawning Biomass	40
		Sablefish - Pacific Coast	Proxy	%SPR	45	Proxy	% Unfished Spawning Biomass	40
		Assessed unit - Copper rockfish - Northern California	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Assessed unit - Copper rockfish - Oregon	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Assessed unit - Copper rockfish - Southern California	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Assessed unit - Copper rockfish -	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40

		Washington						
		Assessed Unit - Vermilion and Sunset rockfish - Northern California	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Assessed Unit - Vermilion and Sunset rockfish - Southern California	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Assessed Unit - Vermilion rockfish - Oregon	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Assessed Unit - Vermilion rockfish - Washington	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Aurora rockfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Big skate - Pacific coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Black rockfish - Point Conception/Oregon Border	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Black rockfish - South of Point Conception	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40

		Black rockfish - Oregon	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Black rockfish - Washington	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Blackgill rockfish - Southern California	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Bocaccio - Southern Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Brown rockfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		California Blue and Deacon Rockfish Complex	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		California scorpionfish - Southern California	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Canary rockfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Chilipepper - Southern Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		China rockfish - Central Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		China rockfish - Northern Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40

		China rockfish - Southern Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Cowcod - Southern California	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Darkblotched rockfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Greenspotted rockfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Greenstriped rockfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Longnose skate - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Longspine thornyhead - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Oregon Blue and Deacon Rockfish Complex	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Pacific Coast Blackspotted and Rougheye Rockfish Complex	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Pacific Ocean perch - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40

		Sharpchin rockfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Shortbelly rockfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Shortspine thornyhead - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Spiny dogfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Splitnose rockfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Widow rockfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Yelloweye rockfish - Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
		Yellowtail rockfish - Northern Pacific Coast	Proxy	%SPR	50	Proxy	% Unfished Spawning Biomass	40
SA/GMFMC	Coastal Migratory Pelagic Resources of the Gulf of Mexico and South Atlantic	Cobia - Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		King mackerel - Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		King mackerel - Southern Atlantic Coast	Proxy	%SPR	30	Proxy	%SPR	30

		Spanish mackerel - Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		Spanish mackerel - Southern Atlantic Coast	Direct Estimate	Fixed Steepness	0.75	Direct Estimate	Fixed Steepness	0.75
	Snapper-Grouper Fishery of the South Atlantic Region/Reef Fish Resources of the Gulf of Mexico	Black grouper - Southern Atlantic Coast/Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		Mutton snapper - Southern Atlantic Coast/Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
		Yellowtail snapper - Southern Atlantic Coast/Gulf of Mexico	Proxy	%SPR	30	Proxy	%SPR	30
SAFMC	Golden Crab Fishery of the South Atlantic Region	Golden deepsea crab - Southern Atlantic Coast	Proxy	Trap Hauls	19000	Proxy	% Carrying Capacity	50
	Shrimp Fishery of the South Atlantic Region	Pink shrimp - Southern Atlantic Coast	Proxy	Pound of tails (FMP specified)	1800000	Unavailable	-	-
		Brown shrimp - Southern Atlantic Coast	Proxy	Pound of tails (FMP specified)	9200000	Unavailable	-	-
		White shrimp - Southern Atlantic Coast	Proxy	Pound of tails (FMP specified)	14500000	Unavailable	-	-

		Brown rock shrimp - Southern Atlantic Coast	Proxy	Pound of tails (FMP specified)	14687775	Unavailable	-	-
	Snapper-Grouper Fishery of the South Atlantic Region	Hogfish - Southeast Florida	Proxy	%SPR	30	Proxy	%SPR	30
		Red snapper - Southern Atlantic Coast	Proxy	%SPR	30	Proxy	%SPR	30
		Speckled hind - Southern Atlantic Coast	Proxy	%SPR	30	Unavailable	-	-
		Scamp - Southern Atlantic Coast	Proxy	%SPR	40	Proxy	%SPR	40
		Vermilion snapper - Southern Atlantic Coast	Direct Estimate	Estimated Steepness	0.69	Direct Estimate	Estimated Steepness	0.69
		Red porgy - Southern Atlantic Coast	Direct Estimate	Fixed Steepness	0.38	Proxy	%SPR	30
		Black sea bass - Southern Atlantic Coast	Direct Estimate	Fixed Steepness	0.64	Direct Estimate	Fixed Steepness	0.64
		Wreckfish - Southern Atlantic Coast	Direct Estimate	Fixed Steepness	0.75	Direct Estimate	Estimated Steepness	0.75
		Blueline tilefish - Southern Atlantic Coast	Direct Estimate	Fixed Steepness	0.836	Direct Estimate	Fixed Steepness	0.836
		Gag - Southern Atlantic Coast	Direct Estimate	Fixed Steepness	0.84	Direct Estimate	Fixed Steepness	0.84

		Snowy grouper - Southern Atlantic Coast	Direct Estimate	Fixed Steepness	0.84	Direct Estimate	Fixed Steepness	0.84
		Tilefish - Southern Atlantic Coast	Direct Estimate	Fixed Steepness	0.84	Direct Estimate	Fixed Steepness	0.84
		Greater amberjack - Southern Atlantic Coast	Direct Estimate	Fixed Steepness	0.87	Direct Estimate	Fixed Steepness	0.87
		Red grouper - Southern Atlantic Coast	Direct Estimate	Fixed Steepness	0.87	Direct Estimate	Fixed Steepness	0.87
WPFMC	American Samoa Archipelago Ecosystem	Longtail red snapper and Ruby snapper Complex - American Samoa	Direct Estimate	Fixed Steepness	0.64	Direct Estimate	Fixed Steepness	0.64
	Hawaii Archipelago Ecosystem	Main Hawaiian Islands Deep 7 Bottomfish Multispecies Complex	Direct Estimate	Biomass Dynamics Model	Surplus Production Model	Direct Estimate	Biomass Dynamics Model	Surplus Production Model
		Spanner crab - Main Hawaiian Islands	Direct Estimate	Biomass Dynamics Model	Surplus Production Model	Direct Estimate	Biomass Dynamics Model	Surplus Production Model
		Green Jobfish - Main Hawaiian Islands	Direct Estimate	Fixed Steepness	0.81	Direct Estimate	Fixed Steepness	0.81
	Mariana Archipelago Ecosystem	Guam Bottomfish Multispecies Complex	Direct Estimate	Biomass Dynamics Model	Surplus Production Model	Direct Estimate	Biomass Dynamics Model	Surplus Production Model

		Northern Mariana Islands Bottomfish Multispecies Complex	Direct Estimate	Biomass Dynamics Model	Surplus Production Model	Direct Estimate	Biomass Dynamics Model	Surplus Production Model
	Pacific Pelagic Fisheries of the Western Pacific Region Ecosystem	Albacore - South Pacific	Proxy	%SPR	20	Proxy	%SPR	20
		Silky shark - Western and Central Pacific	Direct Estimate	Estimated Beta	2.69	Direct Estimate	Estimated Beta	2.69
		Oceanic whitetip shark - Western and Central Pacific	Direct Estimate	Fixed Steepness	0.409	Direct Estimate	Fixed Steepness	0.409
		Blue marlin - Pacific	Direct Estimate	Fixed Steepness	0.65–0.95	Direct Estimate	Fixed Steepness	0.65–0.95