SCIENCE ADVICE ON GUIDANCE FOR LIMIT REFERENCE POINTS UNDER THE FISH STOCKS PROVISIONS

Figure 1: Administrative regions of Fisheries and Oceans Canada (DFO).

Context:

Among the 2019 amendments to the Fisheries Act are the Fish Stocks Provisions (FSPs) that introduce legal requirements to promote sustainability, avoid stocks falling below their Limit Reference Point (LRP) and implement rebuilding plans within prescribed time periods for stocks that fall below their LRP, all while considering biology and environmental conditions. According to DFO's Precautionary Approach Policy (DFO 2009a), the LRP represents the stock status below which serious harm (e.g., impaired productivity; Shelton and Rice 2002) may occur to the stock and where there may also be resultant impacts to the ecosystem, associated species and/or a long-term loss of fishing opportunities.

The FSPs apply to major fish stocks prescribed under regulation. When a prescribed major fish stock has declined to, or below its LRP, a requirement for a rebuilding plan is triggered (FSP s 6.2), *highlighting the importance of estimating stock status relative to the LRP. Decisions to prescribe stocks will be informed by a single LRP and single status determination. In some cases, this may mean 'disaggregation' of a single stock with multiple LRPs into multiple stocks with one LRP each, or a single LRP that would apply to a composite of stock subunits*

The Science Sector has identified a need for guidance to address scenarios that presently do not align with the "one stock, one LRP" structure of the FSPs or for which there is no estimated status relative to an LRP. There is also a more general need for guidance on methods to estimate an LRP and report stock status across a spectrum of data and knowledge availability and quality. This advisory process will assist the Department in prescribing major fish stocks under regulation by providing guidance to support the development of LRPs and determination of stock status, and also, by contributing to operational guidelines for the Science Sector. This guidance considers international practices, is supported by Canadian case studies where applicable, and will support fisheries science practitioners in the provision of a nationally consistent approach to providing scientific advice to support sustainable management of Canada's fish stocks.

This Science Advisory Report is from the June 21-23 and June 28-29, 2022 National Peer Review meeting on Science Advice on Guidance for Limit Reference Points under the Fish Stocks Provisions. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule](#) as they become available.

SUMMARY

- The Limit Reference Point (LRP) represents the upper bound of stock states that should be avoided in order to prevent serious harm to the stock and is the boundary between the Critical and Cautious zones of DFO's Precautionary Approach (PA) Policy. Under that Policy and the Fish Stocks Provisions (FSPs), breaching the LRP is a trigger for a rebuilding plan.
- Serious harm is an undesirable state that may be irreversible or only slowly reversible over the long-term. It may be directly or indirectly due to fishing, other human-induced impacts, or natural causes, and occurs at states before extirpation is a concern.
- Loss of stock structure (e.g., depletion of subunits) is not typically included in descriptions of serious harm but can meet the definition of serious harm if it constitutes a loss of stock productivity or resilience.
- A stock can be defined based on the management unit, assessment unit, and/or biological unit. Scale mismatch occurs when there is misalignment in time or space between these units, management or assessment activities, or biological processes. Consequences of scale mismatch can include over- or under-estimation of stock biomass and exploitation rates, as well as impacts to reference points, stock status metrics, and the risk of serial depletion of subunits.
- Best-practice principles are provided to give overarching guidance and recommendations for selecting, estimating and updating indicators, LRPs and stock status metrics under the PA Policy and FSPs. These encompass scenarios ranging from data-rich to data-limited, where more than one indicator or model may be used for advice, where scale mismatch may be occurring or where the perception of stock status has changed between assessments.
- Future revisions to Canadian harvest strategy policy should include default guidance for LRPs based on estimates of unfished biomass.
- Gaps were identified for future work, predominately related to non-stationarity in conditions affecting productivity when defining LRPs, as well as spatial reference points, the impact of climate forcing on scale mismatch, and for situations when it may be desirable to set an LRP that accommodates ecosystem functions.

INTRODUCTION

Context

Canada's *Fisheries Act* (R.S.C., 1985, c. F-14) was revised on June 21, 2019, resulting in new Fish Stocks Provisions (FSPs) that relate to the management of fisheries. The FSPs are being interpreted in the context of existing policies under Fisheries and Oceans Canada's (DFO) Sustainable Fisheries Framework, in particular the *Fishery decision-making framework incorporating the precautionary approach* (PA Policy; DFO 2009a). The FSPs came into force in April 2022 with the prescription of the first batch of *major fish stocks* and associated regulations for rebuilding plan requirements.

The FSPs identify objectives for conservation in light of sustainable use. These include objectives to maintain stocks at or above the "level necessary to promote sustainability of the stock", s 6.1(1); or "above [the limit reference point or LRP]", s 6.1(2); "rebuild [stocks above LRP]", s 6.2(1); as well as "minimizing further [stock] decline" and mitigating "adverse socio-economic or cultural impacts", s 6.1(2) and 6.2(2)). The FSPs also reference management actions (setting LRPs, implementing measures, and developing and implementing rebuilding plans). The LRP represents the upper bound of stock states that should be avoided in order to prevent serious harm to the stock and is the boundary between the Critical and Cautious zones of DFO's PA Policy (DFO 2009a).

Alignment with the FSPs means advice is needed pertaining to:

- A single LRP for each candidate or prescribed major fish stock;
- A single estimate or determination of stock status relative to the LRP (part of the objective for s 6.1(2) that, when breached, triggers a rebuilding plan under s 6.2); and,
- Support for the prescription of major fish stocks that comprise one species, can be defined geographically or by management area, and for which there is a single LRP/stock status.

In Canada, the LRP is intended to help operationalize an objective to prevent *serious harm* to fish stocks, a central objective of the PA Policy (DFO 2009a). The responsibility for setting LRPs (and the estimation of stock status) lies with DFO's Ecosystems and Oceans Science Sector (Science Sector; DFO 2009a). Once an LRP is set, fisheries managers have a leading role in establishing and implementing most aspects of fisheries management objectives and therefore the PA Policy, including most reference points, risk tolerance and timeframes over which objectives are evaluated, and measures to achieve the objectives.

Approach to Guidance

Estimating reference points and stock status in relation to those reference points is a challenge no jurisdiction has entirely resolved, and many approaches may be used. There are multiple reasons for this and for why stocks may not align with the "one stock, one LRP, one status" structure of the FSPs. Consequently, the Science Sector has identified a need for guidance to address such scenarios and support a nationally consistent approach to providing science advice to assist the Department in implementing the FSPs, including the prescription of major fish stocks. The key challenges that the present guidance aims to address as best possible are:

- achieving a common understanding of terms associated with the FSPs, including serious harm, stock, LRP, and status, and their technical challenges (Section 2.1);
- a current lack of LRP or estimated stock status for many stocks, and a need for a consistent approach to evaluating the diversity of options to fill these gaps, from which the most appropriate choice must be made (Sections 2.2, 2.6);

- a need to synthesize multiple indicators or models used to estimate status in some assessments (Section 2.3);
- changes in perceived (versus actual) stock status between assessments, resulting from changes in data, analytical methods, or choice of reference points (Section 2.4); and,
- a mismatch between the spatial and temporal scales at which biological processes, management and assessment activities occur (hereafter termed scale mismatch), which may compromise the efficacy of stock assessment and management systems aiming to avoid serious harm to stocks (Section 2.5).

Throughout this report, the term “considerations” refers to factors that should be taken into account when making choices. The terms “guidance and recommendations” refer to advice and suggestions on how to use considerations. The term “best practices” refers to guidance and recommendations that are widely accepted as being most appropriate or effective. Best practices are understood to be defined in part by the community of practice, and will evolve over time (Sainsbury 2008). The term “principle” refers to broad statements that serve as the foundation for more specific guidance and recommendations on a given topic.

The following guidance for LRPs that align with the “one stock, one LRP, one status” structure of the FSPs is derived from a consideration of Canadian practices, Canadian and international policies and guidance, and the peer-reviewed primary literature on reference points. The guidance is based on detailed reviews contained in three documents that were reviewed as part of the advisory process that led to this Science Advisory Report. [1,2,3]

ANALYSIS

Basic Concepts and Issue Identification

Serious Harm

A core objective of the precautionary approach is to prevent serious harm. Definitions of serious harm are generally consistent throughout existing DFO literature but vary somewhat in technical detail (DFO 2004, 2006, 2009a, 2021, Shelton and Rice 2002, Smith et al. 2012). A single, more comprehensive definition of the term was derived for the present Advisory Report.

In the context of fisheries, serious harm is an undesirable state that may be irreversible or only slowly reversible over the long-term. It may be directly or indirectly due to fishing, other human-induced impacts, or other natural causes, and occurs at states before extirpation is a concern. These states can be associated with impaired productivity or reproductive capacity, resulting from changes to biological processes such as recruitment, growth, maturation and survival, and may lead to a loss of resilience, defined as an impaired ability to rebuild, exceed replacement or to recover from perturbation. These states can be associated with an elevated risk of depensation or Allee effect (i.e., negative density dependence, in which the intrinsic rate of increase for a stock decreases, rather than increases, as abundance declines) and are states where population dynamics are generally poorly understood.

[1] Marentette, J.R., Barrett, T.J., Cogliati, K.M., Ings, D.W., Ladell, J., Thiess, M.E. Operationalizing Thresholds to Serious Harm: Existing Guidance and Contemporary Canadian Practices. Working Paper.
[2] Barrett, T.J., Marentette, J.R., Forrest, R.E., Anderson, S.C., Holt, C.A., Ings, D.W., Thiess, M.E. Technical considerations for stock status and limit reference points under the Fish Stocks Provisions. Working Paper.
[3] Ings, D.W., Marentette, J.R., Thiess, M.E., Barrett, T.J. Considerations for stock structure and management scale under the Fish Stocks Provisions. Working Paper.

When a stock is estimated to be at risk of serious harm, there may also be resultant impacts to the broader socio-ecological system, such as the ecosystem, associated or dependent species, or a long-term loss of fishing opportunities. However, economic inefficiencies such as growth overfishing or reduced yield do not in and of themselves constitute serious harm to the stock.

Stock

The term “stock” can be defined based on the management unit, assessment unit, and/or biological unit. A “stock” can be considered as a semi-discrete group of aquatic animals (fish, invertebrate, marine mammals) with some definable attributes in common that are of interest to managers and can be assessed as a unit. Therefore, a stock may be defined with reference to units for the purpose of fisheries management. Alternatively, a biological stock is a population of a given species that forms a reproductive unit and breeds little if at all with other units. The spatial and temporal domains for data collection, analysis and assessment may not be correctly aligned with the spatiotemporal distribution of the biological stock, although the extent of this misalignment may be uncertain. For this reason, the term “stock” is often used in reference to an assessment / management unit even if that unit does not fully encompass a biological stock or if it encompasses more than one biological stock.

Scale and Scale Mismatch

“Scale” can have several definitions and components, but for the purposes of this advice, it is defined as a combination of resolution (i.e., minimum spatiotemporal dimensions over which data collection, management measures, fisheries activities, or biological processes take place) and extent (i.e., maximum dimensions over which these activities collectively occur).

“Scale mismatch” occurs when there is misalignment in time or space between a management unit, assessment unit, and/or biological unit, and the management or assessment activities or biological processes. Spatial resolution mismatches occur where a stock is assumed to be one biological unit when in reality it contains several units with different demographics and dynamics. Spatial extent mismatches occur when a management unit contains only a portion of a biological unit. Temporal mismatches can also occur, for instance when seasonal management measures are not aligned with the biological processes they intend to target.

Stock Status

“Stock status” refers to a determination made about the current, past or future condition of the stock. Stock status is a metric that is often expressed as an indicator (a unit of measurement that provides information on some attribute or characteristic of the stock, e.g., spawning biomass or B) relative to a reference point (a benchmark, such as a limit, target or other threshold, of interest to management against which an indicator is compared). For example, the current estimated spawning biomass may be said to be above or below the spawning biomass associated with maximum sustainable yield (B_{MSY}), at some proportion of unfished spawning biomass (B_0), or some other reference point.

Limit Reference Point (LRP)

LRPs in Canadian policy are typically defined in terms of biomass (particularly spawning stock biomass), abundance, or a proxy for these, but other indicators that represent the reproductive capacity of the stock (e.g., total egg production) may be used. An appropriate measure or metric should best represent the reproductive capacity of the stock and will depend on the nature of the assessment approach and data availability.

Reference points such as LRPs are one component of measurable fisheries management objectives, which also comprise risk tolerance and timeframes. Under the PA Policy and the FSPs, breaching the LRP is a trigger for a rebuilding plan. The LRP may coincide with an inflection point for the removal reference and may be used as an operational control point (point at which management measures change) in harvest strategies. They contribute to but do not ensure fisheries sustainability. The choice of harvest strategies intended to acceptably meet objectives that include reference points will also depend on the choice of risk tolerance for a stock falling below its LRP (or breaching some other reference point) and the timeframes over which risk is evaluated.

Challenges with LRPs and Stock Status

Some challenges with estimating LRPs and stock status include:

- It is difficult to define a point of serious harm until a stock has been observed to fall below that point (Hilborn and Walters 1992).
- Even when serious harm may be occurring to the stock, it may be difficult to detect.
- Defining a threshold for serious harm is challenging both on a theoretical and analytical basis. Consequently, jurisdictions worldwide have adopted proxies or rules of thumb to define LRPs, some of which may result in values that are consistently greater or smaller than those obtained using other options. These differences may have consequences for achieving management objectives in practice depending on how those LRPs are operationalized in harvest strategies (i.e., whether there are also different tolerated risks for breaching LRPs, and associated measures to avoid or rebuild above them).
- Reference points and indicators of stock status such as biomass are generally estimated with a high degree of uncertainty. For instance, reference points such as B_0 may require extrapolation back to periods before data (e.g., biomass index, age-composition) were collected, or may require assumptions about demographic rates affecting productivity of the stock (e.g., growth, natural mortality rate (M), and recruitment) and fishery selectivity (Hilborn 2002).
- Equilibrium reference point calculations assume stationarity in key model productivity parameters such as growth, M, and recruitment and this assumption is frequently violated.
- Insufficient or inaccurate data and information may prevent reliable estimation of reference points or stock status using traditional approaches, resulting in an inability to apply literal interpretations of the PA where uncertainty is very high (Cadrin and Pastoors 2008).

Issues with Scale Mismatch

Scale mismatches can cause violations of theoretical assumptions implicit in stock assessments (e.g., a closed population, homogenous vital rates, a well-mixed population, equal probability of capture). The consequences of scale mismatches can include both over- and under-estimation of stock biomass and exploitation rates, and therefore impacts on reference points, stock status metrics, and harvest control rules (HCRs) used to manage the stock. For instance, given that the spatial distribution of stocks is often affected by density-dependence, monitoring and assessment activities that concentrate only on core stock areas may underestimate declines in abundance (termed hyperstability), while activities concentrated in marginal stock areas may exaggerate them (termed hyperdepletion). Hyperstability poses an enhanced risk of serious harm, while hyperdepletion may result in an unwarranted reduction in fishing opportunities.

Mis-specifying spatiotemporal structure and connectivity can increase the risk of depletion of population sub-components. Such loss of stock structure is not often considered in conventional descriptions of serious harm, although it can meet the definition of lost resilience or productivity. Serial depletion of population sub-components coupled with mis-specified spatiotemporal structure in assessments can contribute to undetected declines in abundance at the stock level.

Conventional reference points may not be suitable thresholds to serious harm when there are scale mismatches. Furthermore, estimated rebuilding timelines under the FSPs may be inaccurate.

The frequency and severity of scale mismatches may increase in association with climate change. Changes in species distributions are the first predicted response to climate forcing; these distributional shifts may occur due to changes in physical habitats occupied by aquatic animals (via increased temperature, hypoxia and acidification) or connectivity between habitats.

Implications of "One Stock, One LRP, One Status"

It may be challenging to provide consistent advice to estimate one LRP and one stock status per stock across diverse scenarios, given:

- "stocks" are often defined pragmatically as management units which often involve some degree of scale mismatch with biological units, the extent and consequences of which may be very uncertain;
- an objective to prevent serious harm is applied to all stocks with diverse spatiotemporal structures, and it is assumed that status relative to the LRP is informative about whether this objective is being met, regardless of whether the stock contains multiple biological units, one biological unit, or only part of one biological unit;
- widespread difficulties in estimating stock-specific thresholds to serious harm, estimating generic reference points in the absence of stock-specific evidence, and/or status relative to any reference point, given generally high uncertainty resulting from data or information deficiencies; and,
- the existence of numerous options for defining and estimating LRPs and the lack of standard 'rules of thumb' or policy defaults to guide choices.

Defining and estimating LRPs and Stock Status

Common Approaches to Defining LRPs

Considerations and specific technical recommendations for common approaches to defining LRPs in situations that range from data-limited to data-rich are presented in Tables 1–6. Choices should be guided by the following six best-practice principles, which are explained further in Section 2.6:

1. Indicators, LRPs and stock status metrics should be selected based on the best available information for the stock.
2. Indicators, LRPs and stock status metrics should be consistent with an objective to prevent serious harm to the stock.
3. Indicators, LRPs and stock status metrics should be feasible and relevant.
4. Indicators, LRPs and stock status metrics should take into account reliability, plausibility and uncertainty.
5. The rationale for choice of indicator, LRP or stock status metric may change over time.
6. Advice on indicators, LRPs and stock status metrics should be clearly communicated.

In Canada and elsewhere, LRPs are frequently defined in terms of a proportion of B_{MSY} (Table 2) or B_0 (Table 3) or a proxy for these reference points. The provisional default guidance for LRPs in Canada is 0.4 B_{MSY}, and common default LRPs in other jurisdictions that are based on B_0 range from 0.2 (higher productivity stocks) to 0.3 B_0 (lower productivity stocks). The relationship between B_0 and B_{MSY} depends strongly on the resilience of the stock or steepness (h) of the stock recruitment relationship (SRR) and it is important to consider this relationship when a proportion of one reference point is used as a proxy for the other. When the relationship between B_0 and B_{MSY} is uncertain, it is most common to assume that 0.4 B_0 is a proxy for B_{MSY}, but this guidance is sometimes refined further based on the assumed resilience or productivity of the stock. B_{MSY} proxies in the range of 0.35-0.40 B_0 have been demonstrated to maintain yields comparable to B_{MSY}, assuming B_{MSY} is known exactly (Punt et al. 2014). Understanding how B_0 and B_{MSY} are influenced by model assumptions and life-history characteristics can help guide identification of a candidate LRP.

Proxies for B_{MSY} have commonly been used. Theoretical proxies are based on population dynamics theory, while historical proxies are based on estimates of abundance, biomass or fishing mortality for specific time periods in the past, either from models or empirical indicators. For example, a theoretical proxy for the fishing mortality associated with maximum sustainable yield (F_{MSY}) is commonly estimated, and the equilibrium biomass from fishing at the proxy is used as a proxy for B_{MSY} (Table 4). The fishing mortality rate associated with a spawning potential ratio (SPR) of 40% ($F_{40\%SPR}$) is a common proxy for F_{MSY}. However, the choice of the percentage of SPR depends on the resilience of the stock to fishing. Another common proxy for F_{MSY} is some fraction of M. Historical proxies for B_{MSY} include average biomass or abundance (or a corresponding survey index) calculated from previous stock levels considered to have originated from a productive period in the time series (Table 6).

Not all approaches to defining LRPs are based explicitly on the concept of B_0 and B_{MSY}. For instance, the biomass which is expected to produce a predefined percentage (X%) of R_{max}, the maximum predicted recruitment from a SRR, or other assumed thresholds to impaired recruitment, may be used (Table 4). Alternatively, some approaches aim to address the risk of depensation directly and are based on the lowest observed biomass, B_{loss}, or the lowest observed biomass that produced recruitment leading to stock recovery, $B_{recover}$ (Table 5).

An evaluation of multiple candidate LRPs estimated using different methods can provide confidence in selecting an LRP when estimates agree, but can also identify potential risks when estimates do not agree (Mohn and Chouinard 2004). For example, estimates of 0.4 B_{MSY} could occur at a low level of biomass that may be inconsistent with objectives of maintaining resilience, genetic diversity, or avoiding other forms of serious harm.

Less Common Approaches to Estimating Stock Status or Defining LRPs

Some less common approaches to estimating stock status or defining LRPs include:

- Spatial reference points, where candidate LRPs that represent a loss (e.g., of 70–80%) of the area of distribution have been proposed, e.g., for species with limited dispersal of early-life stages.
- The traffic light approach, which uses a system of green, amber, and red “lights” (or analogous concepts) to categorize multiple indicators of the state of the fishery or stock (e.g., ICES 2018). Each indicator has its own threshold or reference point. An overall stock status is determined by integrating across indicators (e.g., weighting the indicators or a simple proportion of “red” indicators below their thresholds). The “LRP” in these cases is defined based on the integrated indicator. These are typically used in, but not limited to, data-limited contexts, and where status is informed by diverse biological information.
- Length-based approaches such as the length-based spawning potential ratio (LBSPR) method, the length-based integrated mixed effects (LIME) method, and length-based proxies of SPR. These can be used where length data are available, and it can be assumed

there is a decline in average length with fishing mortality. The methods assume equilibrium conditions and can be influenced by strong year-classes.

- Expert judgement, used to assign a stock status using a weight-of-evidence framework, where judgement is both transparent and repeatable (e.g., Larcombe et al. 2015; Kronlund et al. 2021). Expert judgement can play important roles in advice given under Bayesian frameworks, traffic light approaches or in selection of historical reference points, but expert judgement alone has sometimes been invoked where all other methods appear to be infeasible. Both the experience level of experts and the “true” stock status can both impact the performance of expert judgement-based methods of stock status assignment.
- Assigning a single LRP and status to a collection of stocks or management units, based on the proportion that have status above a given threshold. For instance, LRPs for Pacific Salmon Stock Management Units are defined as a given proportion of Conservation Units that have status above the red zone of a traffic light approach (DFO 2022).

Closed-Loop Simulation

Closed-loop simulation is a process that involves evaluating the performance of alternative management procedures (MPs, algorithms for making management recommendations) through simulation and assessing trade-offs among multiple explicit fishery and conservation objectives (Butterworth and Punt 1999; Punt et al. 2016). It can be used to provide management advice consistent with the PA Policy objectives of avoiding the LRP with a high probability, and can be used as a tool to examine the consequences of alternative MPs aimed at sustainable management or rebuilding depleted stocks. The objective of closed-loop simulation is to identify MPs with acceptable performance relative to management objectives, and not specifically to estimate the stock status relative to the LRP. Closed-loop simulation may also be used to explore the consequences of key uncertainties, such as those resulting from scale mismatches (Kerr and Goethel 2014).

Uncertainty, Reliability, and Plausibility

Estimates of LRPs are inherently uncertain due to imperfect observations (data uncertainty); imprecision or bias around estimates of model parameters (parameter uncertainty); and assumptions about structural forms within the model (structural uncertainty, e.g., form of the SRR, shape of the selectivity ogive, assumptions about whether parameters are age- or time-varying). Uncertainty in stock status includes uncertainty in both the indicator and the LRP. Characterization of the uncertainty in stock status is critical because how that uncertainty is estimated affects conclusions about the indicator relative to reference points and the choice of management measures aimed at meeting objectives related to reference points. Structural uncertainty can be characterized using multiple assessment or operating models and evaluating sensitivity of model outputs to assumptions. A false sense of precision in the estimate of stock status can result when uncertainty is not properly characterized.

Empirical indicators can be influenced by large observation error, which is propagated as high variability in annual estimates of stock status. To account for high annual variability, data smoothing methods may be used to avoid large interannual changes in the perception of stock status.

Indicators and LRPs should be reliably estimated (Principle 4, Section 2.6). The term “reliable estimation” can be interpreted as acceptably robust (considering consistency, variance and bias) to key uncertainties and assumptions in the advice framework. As the “true” values of reference points are always unknown, evaluations of the accuracy and precision (or robustness) of methods used to produce the estimates can be conducted using simulation tests of systems with known values (e.g., using closed-loop simulation). Sensitivity analyses can also be conducted to evaluate the influence of model parameters on reference point estimates.

When multiple candidate LRPs are being considered, the plausibility of the LRP estimates should be taken into account (Principle 4, Section 2.6). The term "plausibility" refers to whether estimates, assumptions or hypotheses are consistent with empirical data, and ecosystem and population dynamics theory. For example, LRP estimates can be compared to past trajectories of stock indicators or productivity in light of fishing pressure and past or expected future environmental conditions.

In the Absence of LRPs or Status Metrics

While every effort should be made to identify an LRP for all stocks, it may not be possible in all cases, and advice for fisheries management may still be provided for stocks without LRPs. Advice may be provided directly, via data-limited methods for developing candidate harvest or fishing mortality rates (e.g., in relation to a generic harvest control rule evaluated with closed-loop simulation); or indirectly, via directional trends in stock and fishery indices. However, there is a need to identify an LRP for each prescribed stock. For stocks where LRPs cannot be identified even with available data-limited methods, advice should be provided for prioritizing further analytical work and/or data collection required to improve the potential for identifying LRPs; the types and amount of data required may vary from stock to stock.

LRPs and Stock Status with Multiple Models

Multiple models may be used to provide advice that accounts for structural uncertainty, and/or where closed-loop simulation or management strategy evaluation are used to evaluate candidate MPs. When a closed-loop simulation framework uses a single operating model (OM) fitted to observed data, it may be appropriate to define a single LRP and single measure of stock status. However, the use of multiple OMs does not lend itself to defining single measures because the OMs are likely to generate different stock dynamics. Furthermore, the OMs may not be equally plausible. Closed-loop simulation may be used in data-limited cases when status cannot be estimated reliably and in some instances there may be an MP that meets conservation and fisheries objectives with a high degree of confidence even if current status is not well estimated.

Ensemble methods (model averaging) that aim to cover a range of structural uncertainties can combine estimates of stock status from multiple models to obtain a single estimate of stock status. Models in an ensemble can be equally weighted, or unequal "plausibility" weights may be assigned, to estimate a weighted mean estimate of stock status. In the absence of model weights, an indicator of stock status can be selected from a single base-case or most pessimistic model with the understanding that information is lost and model uncertainty is not captured (Principle 4, Section 2.6).

If a single best model or averaged stock status cannot be determined (e.g., data-limited scenarios), stock status may be determined using a weight-of-evidence approach (e.g., Kronlund et al. 2021) or using an empirical indicator of stock status outside of the analytical modelling framework (e.g., Stone et al. 2012).

Changes in Understanding or Perception of Stock Status Between Assessments

The perception of stock status can change between assessments as a result of a change in population dynamics ("true" changes), but also because of variability in assessment results (e.g., changes in model fit or degree of misspecification), as well as a change in the assessment methodology. Examples include the addition of new data sources, and a change in the analytical methods or the assumptions made in the application of those methods. Perceived status can also be affected by changes in the choice of status indicator, or in the LRP or other reference point. Changes in perceived status can pose challenges to providing consistent and credible science advice.

Evaluating retrospective patterns in stock assessment is a way of diagnosing impacts of new data and possible structural error in the model. Retrospective patterns are systematic changes in estimates of biomass or other model-estimated quantities that arise with the sequential addition or removal of data for discrete time-steps in the model (e.g., data for a specific year). Incorrectly modelling time-varying population processes (e.g., mortality rates) or data generating processes (e.g., selectivity) as time-invariant is a common cause of retrospective patterns in assessment modelling. Fundamentally, retrospective patterns indicate that the assessment model is mis-specified and reasonable alternative model formulations should be explored to resolve the issue, failing which some assessments have employed ad hoc adjustments to biomass or fishing mortality rate estimates to account for the misspecification in providing advice. Alternatively, closed-loop simulations could be used to evaluate the consequences of the misspecification for the sustainable management of the stock or to identify MPs that are robust to it.

Identifying and communicating the general causes for the change in perceived status is important because it affects the credibility of the assessment. The technical specifications and supporting rationales for the choice of indicator and reference point should be documented (Principle 6, Section 2.6). Changes in either an assumed or estimated model parameter or in how uncertainty in stock status is captured can have significant impacts on the estimated stock status, and this needs to be clearly communicated to avoid possibly confounding with true changes in stock state.

Generally speaking, indicators and LRPs should be re-considered when a new advisory framework (e.g., a new assessment model) or management paradigm (e.g., initiation of a management strategy evaluation framework or closed-loop simulation) are adopted (Principle 5, Section 2.6).

Accounting for and Addressing Scale Mismatch

As noted in Section 2.1, both complex stock structure and the potential for scale mismatch between biological, assessment and management units pose challenges for providing advice LRPs and stock status metrics for management aiming to prevent serious harm at the level of the “stock”.

Best available information may indicate that either the severity of scale mismatch or the level of uncertainty around scale mismatch has important consequences for achieving management outcomes. These consequences can be attenuated at the source by rectifying scale mismatches. This can be achieved, for example, through the collection of new data allowing for accounting for the mismatch as part of stock assessment, or a realignment of assessment or management unit boundaries, either of which may affect choice or estimates of indicator(s), LRP or stock status. However, such changes may not be feasible in many situations.

When there is scale mismatch, some commonly used reference points such as those based on maximum sustainable yield (MSY) may be imprecise or biased, resulting in increased uncertainty which should be taken into account when providing advice. Closed-loop simulations are an approach to qualifying or quantifying the magnitude of the uncertainties, and/or to identify MPs that may be robust to them.

Stocks with multiple biological units for which status is assessed against a single LRP constitute a special case of scale mismatch for which specific approaches have been developed. For instance, the traffic light approach for Pacific salmon explicitly evaluates risks associated with the preservation of stock sub-components, while determining a single stock status metric and LRP. Alternatively, an “index stock” approach (the use of indicators, LRPs and status metrics estimated for one or more well-monitored sub-components within a stock) may be a feasible method of aligning with “one stock, one LRP, one status”. This approach assumes that the dynamics and status of the index sub-component(s) are sufficiently representative of the others and to the stock as a whole. Notably, risks to weaker, unmonitored sub-components should be considered. To prevent serial depletion of sub-components within a larger management unit, lower productivity sub-components within the management unit may require additional management measures.

Best Practice Principles for Indicators, LRPs and Stock Status Metrics

The following represent best-practice principles for indicators, LRPs and stock status metrics derived from existing Canadian and international guidance and informed by Canadian requirements and existing practice. They are intended to help support consistency in how considerations are taken into account when making choices across the wide variety of contexts facing practitioners, including stocks for which there are differing amounts of data or information, of different species, of different assessment and management paradigms, and with different degrees of scale mismatch. These principles may change over time (in keeping with the definition of “best practices” by Sainsbury 2008) as more experience is accrued.

Meeting these principles in providing advice on indicators, LRPs and stock status will help meet the needs of the PA Policy and align with the “one stock, one LRP, one status” structure of the FSPs. Each principle is supported by explanatory sub-bullets, although these considerations are not meant to be exhaustive, nor relevant to all applied cases.

Principle 1: Indicators, LRPs and stock status metrics should be selected based on the best available information for the stock.

- “Best available” should be interpreted as the best of what is available to Science at the time of consideration. The lack of optimal information should not be an impediment to choosing indicators and LRPs.
- Best available information will vary from stock to stock and may change over time.
- Generic provisional policy guidance of 0.4 B_{MSY} should be used if it is both technically feasible and if there is no stock-specific LRP or other rationale upon which to base a different choice.
- Consider alternatives based on proxies (theoretical, historical or empirical), and their assumptions, if the policy guidance is not feasible or appropriate.

Principle 2: Indicators, LRPs and stock status metrics should be consistent with an objective to prevent serious harm to the stock.

- Consistency with an objective to prevent serious harm can be demonstrated by:
    - Indicators and LRPs that are at least conceptually linked to the definition of serious harm.
    - A stock status that is acceptably representative of the entire stock.

- Consider the extent to which assumptions around the relationship between indicators and the stock attributes they are intended to represent (e.g., proportionality) impacts both estimates of LRPs and stock status.
- Loss of stock structure (e.g., depletion of subunits) is not typically included in conventional descriptions of serious harm, although such losses may meet the definition and should be considered where stocks act as management units contain more than one biological unit.

Principle 3: Indicators, LRPs and stock status metrics should be feasible and relevant.

- Consider the role of stock status in the management system:
    - At minimum, it should be feasible (i.e., capable of being done or carried out) to monitor indicators and estimate stock status relative to the LRP on time scales and frequencies relevant to its role as the trigger for a rebuilding plan.
    - Stock status indicators should be relevant to management (i.e., closely connected or appropriate to what is being done or considered), but harvest strategies may also take into account a variety of secondary indicators, including indicators at multiple spatial scales or indicators for the size- or age-composition of the stock, which may assist in avoiding serious harm where scale mismatch occurs between biological and management units.
    - LRPs are often incorporated into harvest control rules, but harvest strategies may have operational control points distinct from reference points.
- Consider whether and how interim indicators should be used to support continuity of stock status advice in between assessments, including whether empirical proxies of stock status should be used to trigger earlier assessments.
- Consider whether indicators, LRPs and stock status are easy to communicate and understand.

Principle 4: Indicators, LRPs and stock status metrics should take into account reliability, plausibility and uncertainty.

- Reliability means estimates should be acceptably robust (considering consistency, variance and bias) to key uncertainties and assumptions in the advice framework.
    - Consider how often estimates will be updated and the sensitivity of stock status to changes in scale of abundance or biomass with new data at each update.
    - Consider whether historical or empirical reference points may provide more reliable or plausible options than theoretical reference points.
    - Consider the quality (reliability and consistency) of data inputs required to estimate indicators, LRPs or stock status.
    - Consider the costs and benefits of smoothing methods to dampen volatile stock status estimates because of high inter-annual variability in indicators.
- Plausibility means estimates should be consistent with empirical data and, where possible, ecosystem and population dynamics theory, taking into account the best available information about the stock.
    - Consider any evidence of serious harm to the stock, other knowledge of the history of the stock, life history information, meta-analyses across stocks, or choices made for analogous stocks.
    - A weight-of-evidence approach can be used to evaluate and select the most plausible LRP or stock status.

  - When applicable, consider the costs, including loss of information, and the benefits of different methods for combining or selecting from equally plausible alternatives for LRPs or for stock status.
- Consider evaluation of risks in light of uncertainty (e.g., with simulation), when requested.

Principle 5: The rationale for choice of indicator, LRP or stock status metric may change over time.

- Consider whether new information accrued for a stock represents a substantial change in the best available information underlying the choice of indicator or LRP rationale used to estimate stock status.
- Reconsider rationales for indicators and LRPs (and re-estimate stock status) when a new advisory framework (e.g., a new assessment model) or management paradigm (e.g., initiation of a management strategy evaluation framework or closed-loop simulation) are undertaken.
- Where uncertainty is high and impactful to LRPs/status, such as in data-limited or emerging fisheries, or where stock structure is complex, consider value of information analyses, prioritizing data collection and establishing timelines to re-evaluate LRP and indicator rationales and stock status once more informative data have accrued.

Principle 6: Advice on indicators, LRPs and stock status metrics should be clearly communicated.

- Avoid tentative language for the LRP and stock status in final advice such as “suggested,” “recommended,” “interim” or “proxy”. It should be clear whether the stock has an LRP and stock status determination in order to align with the structure of the FSPs.
- Technical specifications (e.g., model equations) and supporting rationales should be documented for the choice of indicator and reference point.
- Formal analyses, such as sensitivity analyses, or other explanations should be provided when some information available for the stock is not included from “best available information” on which choices were based.
- Key uncertainties and assumptions, in stock status indicators, LRPs and stock status should be documented and communicated, where applicable, including those related to scale mismatch.
- Stock status should be communicated as a ratio of indicator to the LRP (or to B_{MSY}, B_0, etc.) instead of absolute estimates especially where estimated stock status is sensitive to changes in scale in successive assessments.
- Differentiate between the effects of new information accrued for a stock (e.g., longer time series), and other changes (e.g., a new assessment model), when estimated stock status changes because of a new advisory framework or management paradigm.

Key Gaps For Future Work

Provisional Default Policy Guidance on Fractions of B_0 and Historical Proxies

The provisional default policy guidance for LRPs in Canada is 0.4 B_{MSY}. In some situations, e.g., when h or M is highly uncertain, B_{MSY} estimates will be unreliable. Other jurisdictions have set minimum LRPs in terms of B_0 instead of or in addition to B_{MSY} for this reason. Given that reference points based on B_0 are commonly used in Canada, the addition of default policy guidance for LRPs based on B_0 is recommended for future consideration in Canadian harvest strategy policies.

The PA Policy also provides for the use of historical reference points. There is some variation in practices for selecting periods for defining these which could also be re-evaluated in any future consideration for Canadian harvest strategy policies.

Non-Stationarity, Environmental Conditions

Equilibrium reference points, including those defined based on B_0 and B_{MSY}, are influenced by non-stationarity or regime shifts in key model productivity parameters such as *M*, growth, and recruitment. Equilibrium assumptions also underlie many historical or empirical reference points. Management decisions based on static equilibrium reference points may not reflect stock dynamics in the future, including in situations of mismatch between biological and management units. Dynamic reference points have been proposed as one solution to address temporal changes in productivity parameters. A dynamic B_0 can be defined as the biomass at any point in time that would have resulted if no fishing had occurred and can be estimated using the parameters of a stock assessment model and projecting the population forward over the same time period with $F = 0$ (Berger 2019). The estimation of a dynamic B_0 makes an implicit assumption that temporal changes in biological parameters (e.g., *M*, weight-at-age, maturity-at-age, and recruitment anomalies) are independent of fishing (e.g., environmentally driven) and are not density-dependent. These assumptions may be tenuous and a decrease in reference points over time due to a change in productivity seems in conflict with the objective of the LRP to avoid states of serious harm.

Consideration of environmental conditions in fisheries assessment and management is complex and impacts entire harvest strategies, not just the LRP. This includes *F*-based reference points (DFO 2013), which can be fine-tuned to account for changes in environmental drivers (ICES 2021b, Duplisea et al. 2020).

Currently the PA Policy recommends using “as long as a time series as possible” in estimating reference points and to avoid using low productivity periods alone unless there is no expectation of improved conditions in future. Guidance with respect to how to account for non-stationarity and time-varying environmental conditions in PA harvest strategies is needed, but was not in scope for this advisory process.

Spatial Reference Points and Serious Harm

A threshold for serious harm could potentially be defined as a spatial reference point (i.e., a decrease in area of distribution), based on the assumption that the range of a population will covary with population density as a function of habitat selection (MacCall 1990). Range contraction has been measured by several spatial metrics for many populations in decline. Spatial thresholds to substantial declines in spawning stock biomass (SSB) have been explored (Reuchlin-Hugenholtz et al. 2016), but this was based on a limited number of species. Also, there has been little research on expansion of population range as depleted populations recover and whether a threshold to serious harm is appropriate during periods of population contraction and periods of expansion.

Climate Impacts on Scale Mismatch

Climate change may impact the physical habitats occupied by marine and freshwater organisms and connectivity between them. Distributional changes, perhaps the first response to climate forcing, may potentially increase the frequency and severity of scale mismatch between biological and management units. This risk is usually studied in light of changing water temperature, however a range of physical and biological processes important to the scale of biological processes may be impacted by climate forcing.

Accommodating Ecosystem Considerations

Some policies allow for LRPs to include additional considerations beyond serious harm, such as DFO's Forage Fish Policy (DFO 2009b; part of DFO's Sustainable Fisheries Framework), which considers the LRP to be a threshold to serious harm experienced by both target and ecologically dependent species. Advice here focused on the PA Policy guidance for LRPs that addresses serious harm only to target stocks. Ecosystem approaches to fisheries management may invoke objectives related to the preservation of ecosystem function and, like consideration of environmental conditions above, impacts entire harvest strategies, not just the LRP. Consideration of serious harm to ecosystem functions in status and LRP determination was beyond the scope of this process.

Sources of Uncertainty

At present, the need for alignment with the FSPs with respect to LRPs is interpreted in the context of the *Fishery Decision-Making Framework Incorporating the Precautionary Approach* (PA Policy, DFO 2009a). Thus, recommendations for the Science Sector here do not account for future regulations, policies, and/or clarification of requirements of the revised *Fisheries Act* via other processes. Best scientific practices are also expected to evolve over time, such as with the development of guidance and experience.

CONCLUSIONS AND ADVICE

This Science Advisory Report identifies considerations, guidance and recommendations for the Science Sector in providing advice on LRPs in support of the implementation of the FSPs in the revised *Fisheries Act* (DFO 2021). The advice takes into account Canadian and international practices and is aimed to:

- address scenarios that do not align with the "one stock, one LRP, one status" structure of the FSPs, due to use of multiple models or scale mismatch;
- support LRP and stock status determination for situations ranging from data-limited to rich; and,
- help to accelerate the development of LRPs and prescription of major fish stocks by regulation.

More generally, the advice aims to help to provide a nationally consistent approach to providing scientific advice on LRPs and stock status to support sustainable management of Canada's fish stocks. However, reference points such as LRPs, are only one component of measurable fisheries management objectives and harvest strategies, and contribute to, but do not ensure fisheries sustainability.

Table 1: Considerations and specific recommendations for LRPs based on proportions of B_{MSY}. h = steepness of stock-recruitment relationship (SRR). M = natural mortality.

LRP	Proportion of B_{MSY}
Definition	B_{MSY} is the average stock biomass that results from fishing at F_{MSY} (fishing mortality rate that provides MSY) over the long-term under equilibrium conditions. It is often expressed in terms of spawning stock biomass, but may also be expressed as recruited or vulnerable biomass.
Estimation	Data-rich methods (analytical assessments supported by age-structured, size-structured, or surplus production models): ● Age- or size-structured models: estimated using the SRR, growth, maturity, *M*, and fishery selectivity data. ● Delay-difference model: same equations as for age-structured models, with the advantage that the models can be fit without size- or age-composition data ● Surplus production model: estimated directly from model parameter estimates. Data-limited methods: ● Catch-only methods can produce estimates of biomass relative to B_{MSY} but should be used with caution ● LRPs based on B_{MSY} can be defined in operating models within closed-loop simulation frameworks.
Link(s) to Serious Harm	Loss of surplus production; Proxy for relative depletion (proportion of B_0) and thus for recruitment overfishing
Pros	DFO provisional PA Policy default LRP (0.4 B_{MSY})
Cons	May be difficult to estimate; sensitive to uncertainty in selectivity, *M* and *h* of the SRR; May correspond to very low biomass where stock dynamics are uncertain (e.g., validity of compensatory assumptions) or other sources of serious harm may become important (e.g., Allee effects).

LRP	Proportion of B_{MSY}
Other Considerations	B_{MSY} estimates (and the ratio B_{MSY}/B_0) are strongly influenced by *h*, but also influenced by *M* and the relationship between selectivity-at-age and maturity-at-age. Policy defaults in other jurisdictions range from 0.3 to 0.5 B_{MSY} For a symmetrical Schaefer surplus production model, 0.5 B_{MSY} occurs at 75% of MSY. DFO's PA Policy provisional default LRP of 0.4 B_{MSY} is equivalent to 0.2 B_0 and occurs at 64% of MSY. Catch-only methods assume that trends in catch are indicative of trends in abundance or biomass, have generally been used to assess the global status of unassessed stocks, and have been shown to produce biased and imprecise estimates of stock status, especially for stocks that are lightly exploited.
Specific Recommendations	When the functional form of the SRR and/or estimates of *h* (resilience) are highly uncertain, consider defining a metric of stock status based on a proxy for B_{MSY} or an ensemble composed of multiple models that capture model (structural) uncertainty. When *h* is assumed to be high, LRPs based on a proportion of B_{MSY} may be below the minimum observed historical biomass or below a threshold for other sources of serious harm. In these cases, consider other LRPs such as relative depletion (proportion of B_0) or $B_{recover}$. LRPs based on B_{MSY} can be defined in operating models used in closed-loop simulation frameworks. Closed-loop simulation provides the basis for evaluating the performance of management procedures against objectives that embed reference points. Robustness of a management procedure is assessed by examining performance over a range of hypotheses for stock and fishery dynamics represented by operating models. Closed loop simulation can be applied to data-rich to data-limited stocks to provide sustainable catch advice consistent with the PA Policy that meets the legal obligations of the FSP.

Table 2: Considerations and specific recommendations for LRPs based on fractions of B_0. h = steepness of stock-recruitment relationship (SRR). M = natural mortality.

LRP	Proportion of B_0
Definition	B_0 is the mean long-term equilibrium biomass of the stock in the absence of fishing.
Estimation	Data-rich methods (analytical assessments supported by age-structured, size-structured, or surplus production models): ● Age- or size-structured model: the product of unfished SSB-per-recruit (influenced by *M*-at age, maturity-at-age, and weight-at-age) and R_0, the equilibrium or average unfinished recruitment estimated by the model. ● Surplus production model: the population carrying capacity *K*, can be interpreted as B_0. Data-limited methods: ● Catch-only methods can produce estimates of biomass relative to B_0. ● LRPs based on B_0 can be defined in closed-loop simulation frameworks.
Link(s) to Serious Harm	Proxy for recruitment overfishing; Proxy for Allee effects, Proportions of B_0 may be a proxy for B_{MSY}
Pros	B_0 may be more reliably estimated than B_{MSY}
Cons	No explicit DFO PA policy provisional default for the proportion to choose; B_0 may be difficult to estimate; Sensitive to uncertainty in model assumptions (e.g., *M*); If used as a proxy for 0.4 B_{MSY}, the ratio B_{MSY} / B_0 depends strongly on the productivity of the stock (e.g., *h*, which is often poorly estimated), as well as the relationship between maturity-at-age and fishery selectivity-at-age.

LRP	Proportion of B_0
Other Considerations	A common assumption in other jurisdictions is that 0.4 B_0 is an acceptable proxy for B_{MSY} but various proportions in the range of 0.3-0.6 of B_0 have been used for B_{MSY} with higher ratios applied for less resilient species. 0.2 B_0 is a common rule of thumb for a threshold for recruitment overfishing (Myers et al. 1994). For a symmetrical Schaefer surplus production model, DFO's PA Policy provisional default LRP of 0.4 B_{MSY} is equivalent to 0.2 B_0. LRPs used in other jurisdictions where generic policy defaults or best practice recommendations for LRPs range from 0.2 to 0.3 B_0 (e.g., higher proportions for lower productivity stocks), and 0.1 B_0 in the case of New Zealand Harvest Strategy hard limits (below which fishery closures are considered). Considerations for catch-only methods and closed-loop simulation in Table 1 also apply.
Specific Recommendations	None.

Table 3: Considerations and specific recommendations for LRPs based on theoretical proxies for B_{MSY}. F = fishing mortality rate. SSB = spawning stock biomass.

LRP	Proportion of theoretical proxies for B_{MSY}
Definition	Per-recruit or “dynamic pool” reference points are estimates of the lifetime expectation of the contributions of a single recruit to various metrics such as yield, biomass (or SSB), or egg production: • The spawning potential ratio (SPR) is defined as the ratio of SSB-per-recruit (φ) at a given constant, long-term F and the φ at long-term F = 0 (φ_0). $F_{X\%SPR}$ is the fishing mortality rate associated with an SPR of X%. • F_{max} is the F that maximizes yield-per-recruit. $F_{0.1}$ is the F where the slope of the yield-per-recruit curve is 10% of the slope at the origin. • $F = M$ is the F equal to the natural mortality rate (M).
Estimation	F-based reference points can be interpreted in terms of biomass-based reference points as the equilibrium biomass resulting from long-term fishing at the constant specified F.
Link(s) to Serious Harm	Loss of reproductive potential; Proxy for B_{MSY}
Pros	Requires fewer assumptions and data (e.g., no SRR); $F_{X\%SPR}$ and others can be a proxy for F_{MSY}, and therefore can be used to estimate a proxy for B_{MSY}, with X = 40 commonly used.
Cons	X depends on stock productivity and $F_{X\%SPR}$ is sensitive to M; A per-recruit estimate does not account for lower recruitment at low biomass; An estimate of equilibrium recruitment is needed to estimate the equilibrium biomass at $F_{X\%SPR}$
Other Considerations	$F_{X\%SPR}$ is a proxy for F_{MSY}, and therefore can be used to estimate a proxy for B_{MSY}; Other jurisdictions or best practice recommendations advise X ranging from 30 to 50 depending on stock productivity or resilience, where X is higher for lower productivity stocks. $F_{0.1}$, which DFO’s PA Policy suggests can be a possible proxy for F_{MSY}, can exceed F_{MSY} in some cases. Another general rule of thumb has been to assume that F_{MSY} is approximately equal to M, or a proportion of M for some stocks.

LRP	Proportion of theoretical proxies for B_{MSY}
Specific Recommendations	F_{max} meets or exceeds F_{MSY} and is not a precautionary proxy for F_{MSY}. $F_{0.1}$ should not be used as a proxy for F_{MSY} without understanding how well it relates to F_{MSY}.

Table 4: Considerations and specific recommendations for LRPs based on X% R_{max} or other thresholds to impaired recruitment. B = biomass. F = fishing mortality. SSB = spawning stock biomass. SRR = stock-recruitment relationship.

LRP	Biomass at X% R_{max} or other thresholds to impaired recruitment
Definition	Biomass at X% R_{max} is the biomass associated with X% reduction from maximum recruitment (R_{max}) estimated from the SRR. B_{rep} is the SSB that results from fishing at F_{rep} (where the median replacement line intersects the SRR curve) over the long-term under equilibrium assumptions. Breakpoints may be used, below which recruitment declines.
Estimation	Various parametric (e.g., Beverton-Holt, Ricker models) or non-parametric approaches (e.g., segmented regression, smooth hockey stick, replacement *F*-based approaches) to estimating stock-recruitment relationships (SRR) are available
Link(s) to Serious Harm	Loss of recruitment; R_{max} estimated from a Ricker SRR or B_{rep} is sometimes used as a proxy for B_{MSY}
Pros	Easy to interpret; Stock specific thresholds are possible
Cons	Dependent on SRR (including data on recruitment at low stock sizes); May occur at a very low level of depletion for stocks with high *h*
Other Considerations	None.
Specific Recommendations	None.

Table 5: Considerations and specific recommendations for historical LRPs based on $B_{recover}$ and related reference points.

LRP	$B_{recover}$ (including B_{loss} and B_{min})
Definition	B_{loss} is the lowest observed biomass $B_{recover}$ is the lowest observed biomass that produced recruitment that led to stock recovery B_{min} is the lowest observed biomass from which a recovery to average has been observed or other minimum biomass that produced “good” recruitment
Estimation	From time series estimates of biomass or abundance
Link(s) to Serious Harm	Proxy for recruitment overfishing, reflecting high uncertainty in population dynamics at low stock sizes
Pros	Easy to understand and communicate; Not influenced as strongly by model assumptions; Recommended for stocks with occasional large year classes (spasmodic recruitment)
Cons	Values may not “scale” with stock size or life history; Assumption of possible recovery in future depends on prevailing conditions; Recovery must also be defined and no consistent practice has emerged for what constitutes recovery. Variation in practices for selecting year(s) used in defining these reference points.
Other Considerations	Definition of recovery or large recruitment requires expert judgement
Specific Recommendations	Not suitable for stocks where recruitment appears to increase with stock size, nor stocks with narrow ranges of estimated biomasses; If used, the reference point should not be taken from recent years if the stock is declining

Table 6: Considerations and specific recommendations for other historical LRPs. B = biomass.

LRP	Historical LRPs including proxies for B_{MSY} or B_0
Definition	Historical LRPs are thresholds set from estimates of abundance, biomass, or fishing mortality (harvest rate) for a specific period of time in the past. These involve model-based estimates or empirical indicators such as catch, catch per unit effort (CPUE), or survey indices.
Estimation	A historical proxy for B_{MSY} can be estimated as the mean or median value of an indicator or model estimate over a historical time period when the indicator is high (and assumed recruitment is stable) and catches are high; or the mean or median value of an indicator over a productive period. A historical proxy for B_0 can be estimated as the mean/median indicator or model estimate over a historical time period reflecting the beginning of exploitation, or the maximum value of the indicator if the stock has a history of exploitation.
Link(s) to Serious Harm	Often employed as proxies for other reference points such as B_{MSY}, B_0, or $B_{recover}$, although other thresholds to serious harm may be considered (e.g., agreed-upon undesirable states to avoid).
Pros	Easy to understand and communicate; Can be applied to data-limited stocks; LRPs derived from empirical indicators are based on observable quantities that do not rely on assessment model assumptions; A provisional proxy for B_{MSY} is 50% of the maximum estimated population size as suggested by the PA Policy
Cons	May be harder to link to desired management outcomes in some cases; When based on empirical indicators, relies on assumptions of the relationship between the indicator and stock attribute it represents. Wide variation in practice for selecting historical time periods, and thus may be variation in suitability for approximating B_{MSY} or B_0.
Other Considerations	Determination of an appropriate time period requires expert judgement, including whether the beginning of the time series represents an unfished stock state.

LRP	Historical LRPs including proxies for B_{MSY} or B_0
Specific Recommendations	If a reference period is used to approximate B_{MSY} from fishery-dependent indices such as CPUE, catches or landings indicators, there should be no evidence that abundance was declining during that time (both CPUE and catches should have been high and CPUE is considered proportional to stock size)

LIST OF MEETING PARTICIPANTS

Name	Affiliation
Sean Anderson	DFO Science, Pacific Region
Tim Barrett	DFO Science, Maritimes Region
Hugues Benoit	DFO Science, Quebec Region
Melissa Brochu	DFO Fisheries and Harbour Management, National Capital Region
Vanessa Byrne	Government of Newfoundland and Labrador
Noel Cadigan	Memorial University of Newfoundland
Marc Clemens	DFO, Strategic Policy
Karen Cogliati	DFO Science, National Capital Region
Adam Cook	DFO Science, Maritimes Region
Daniel Duplisea	DFO Science Quebec Region
Robyn Forrest	DFO Science, Pacific Region
Colin Gallagher	DFO Science, Ontario and Prairies Region
Carrie Holt	DFO Science, Pacific Region
Kendra Holt	DFO Science, Pacific Region
Quang Huynh	Blue Matter Science Ltd.
Danny W Ings	DFO Science, Newfoundland and Labrador Region
Roger Kanno	DFO Fisheries Management, Pacific Region
Adam Keizer	DFO Science, Pacific Region
Martha Krohn	DFO Science, National Capital Region
Allen (Robert) Kronlund	Interface Fisheries Consultants
Jason Ladell	DFO Science, National Capital Region
Amy Lebeau	DFO Strategic Policy, National Capital Region
Keith Lewis	DFO Science, Newfoundland and Labrador Region
Julie Marentette	DFO Science, National Capital Region
Jenni McDermid	DFO Science, Gulf Region
Darrell R Mullowney	DFO Science, Newfoundland and Labrador Region
Melissa Olmstead	DFO Science, National Capital Region
Paul Regular	DFO Science, Newfoundland and Labrador Region
David Rodger	DFO Strategic Policy, National Capital Region
Rebecca Schijns	Oceana Canada
Lisa Setterington	DFO Science, National Capital Region
Ross Tallman	DFO Science, Ontario and Prairies Region
Mary Thiess	DFO Science, National Capital Region
Alex Tuen	DFO Science, National Capital Region
François Turcotte	DFO Science, Gulf Region
Elisabeth Van Beveren	DFO Science, Quebec Region
Kris Vascotto	Atlantic Groundfish Council
Xinhua Zhu	DFO Science, Ontario and Prairies Region

SOURCES OF INFORMATION

This Science Advisory Report is from the June 21-23 and June28-29, 2022 National Peer Review meeting on Science Advice on Guidance for Limit Reference Points under the Fish Stocks Provisions. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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