Fisheries and Oceans Canada Pêches et Océans Canada
Science Sciences

Canadian Science Advisory Secretariat (CSAS)

Research Document 2013/080

National Capital Region

Current Approaches for the Provision of Scientific Advice on the Precautionary Approach for Canadian Fish Stocks: Harvest Decision Rules

A.R Kronlund[1], K.R. Holt[1], P.A. Shelton[2] and J.C. Rice[3]

[1]Fisheries and Oceans Canada
Pacific Biological Station
Nanaimo, British Columbia V9T 6N7

[2]Fisheries and Oceans Canada
NAFC, P.O. Box 5667
80 East White Hills Road
St. John's, NL A1C 5X1

[3]Fisheries and Oceans Canada
200 Kent Street
Ottawa, ON K1A 0E6

October 2014

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044

Correct citation for this publication:

Kronlund, A.R., K.R. Holt, P.A. Shelton and J.C. Rice. 2014. Current Approaches for the Provision of Scientific Advice on the Precautionary Approach for Canadian Fish Stocks: Harvest Decision Rules. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/080. vi + 29 p.

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ABSTRACT

An essential component of the DFO decision-making framework is the inclusion of a harvest decision rule (or harvest control rule) in a management strategy. The inclusion of a harvest decision rule satisfies a requirement of the Precautionary Approach (FAO 1995) and the DFO decision-making framework to specify in advance actions to be taken when specified deviations from operational targets and constraints are detected. This document is intended as an aid to planning a more comprehensive process for developing harvest decision rule guidelines in Canada. There are two types of rules in the DFO PA Framework:

1) a **status-based rule** where the intended removal rate is a piece-wise function of stock status, and
2) an **acceptable risk-based rule** in which the acceptable probability of stock decline is based on a combination of current stock status and the recent rate of change in stock status (i.e., increasing, stable, or declining).

This document does not contain specific recommendations on the choice of risk tolerance and the relative priority of stock and fishery objectives. The design of a stock-specific harvest decision rule should be considered in the context in which it is to be used. Specific choices are dependent on a collaborative objective-setting process for the stock and fishery that involves assessment analysts, fishery managers, and resource stakeholders.

The design of a harvest decision rule need not explicitly incorporate fishery reference points. This flexibility may be necessary to allow adjustments to fishing mortality over the entire range of stock status so the desired trade-off between conservation and economic performance can be achieved. Complex decision rules should be avoided in favour of the simplest rule that will satisfy the preferred performance trade-offs. Some jurisdictions have promoted the adoption of default, or generic, harvest decision rules that are expected to provide reasonably good performance over a wide range of fisheries. However, there is no assurance that generic harvest decision rules will achieve stock-specific objectives. Finally, harvest decision rules do not necessarily need to be limited to the status of a single target species; multi-species or ecosystem considerations can also be incorporated into rules. However, experience with harvest decision rules that include multi-species or ecosystem considerations is limited in Canada, would require extensive development and testing prior to implementation and may require greater ecosystem level understanding than is currently available.

Approches actuelles de prestation d'avis scientifiques dans le cadre de l'approche de précaution pour la gestion de stocks canadiens :
Règles de décision en matière de prises

RÉSUMÉ

Une composante essentielle du cadre décisionnel du MPO est l'inclusion d'une règle de décision en matière de prises (ou règle de contrôle des prises) dans une stratégie de gestion. L'inclusion d'une règle de décision en matière de prises satisfait une exigence de l'approche de précaution (FAO 1995) et du cadre décisionnel du MPO, qui consiste à préciser à l'avance toute mesure à prendre lorsque certaines déviations des cibles et des contraintes opérationnelles sont détectées. Le présent document se veut un guide pour la planification d'un processus plus détaillé pour l'élaboration de lignes directrices sur les règles de décision en matière de prises au Canada. Il y a deux types de règles dans le cadre du MPO relatif à l'approche de précaution (AP) :

1) une **règle basée sur l'état**, où le taux de prélèvement voulu est une fonction affine par morceaux de l'état du stock, et
2) une **règle basée sur le risque acceptable**, où la probabilité acceptable du déclin du stock est estimée d'après une combinaison de l'état actuel du stock et du récent taux de changement de cet état (c.-à-d. croissance, stabilité ou déclin).

Ce document ne contient aucune recommandation précise sur le choix de tolérance du risque et la priorité relative des objectifs liés à la pêche et au stock. La conception d'une règle de décision relative aux prises pour un stock précis doit être considérée dans le contexte où celle-ci sera appliquée. Les choix particuliers doivent être pris selon un processus collaboratif de détermination des objectifs pour le stock et la pêche, lequel doit inclure des analystes d'évaluation, des gestionnaires des pêches et des intervenants liés à la ressource.

Il n'est pas obligatoire pour une règle de décision en matière de prises d'incorporer de façon explicite des points de référence de pêche. Une telle flexibilité peut être nécessaire pour permettre des ajustements à la mortalité des pêches sur toute la portée de l'état du stock afin que le compromis voulu entre la conservation et le rendement économique puisse être atteint. Il est préférable d'éviter des règles de décision complexes et de favoriser les règles les plus simples qui pourront satisfaire aux compromis de rendement désirés. Certaines instances ont fait la promotion de l'adoption par défaut de règles de décision en matière de prises génériques conçues pour fournir un rendement raisonnablement bon pour une vaste gamme de pêches. Cependant, rien ne garantit que des règles de décision génériques permettront d'atteindre les objectifs propres aux stocks. Enfin, les règles de décision en matière de prises ne doivent pas nécessairement être limitées à l'état d'une seule espèce cible; des considérations multi-espèces ou écosystémiques peuvent y être incorporées. Toutefois, le Canada a peu d'expérience dans les règles de décision en matière de prises qui comprennent de telles considérations. Avant la mise en œuvre, il faudrait procéder à une conception et à des essais de longue durée. De plus, une connaissance plus approfondie des écosystèmes pourrait être nécessaire.

HARVEST DECISION RULES

1 OVERVIEW

The purpose of this working paper is to identify the technical considerations needed to design harvest decision rules that comply with the DFO decision-making framework, hereafter referred to as the DFO PA Framework. Throughout this document excerpts from the DFO PA Framework appear highlighted in grey text boxes to serve as a focus for the related discussion. Notation used throughout this document is defined in Table 1.

An essential component of the DFO PA Framework is the inclusion of a harvest decision rule in a management strategy. The terms harvest decision rule and harvest control rule are used interchangeably in the fisheries management literature and are often taken to mean a set of mathematical relationships for translating the outputs of a stock assessment into an allowable catch or effort recommendation. A key feature of the systematic adoption of this form of harvest decision rule is the application of negative feedback control in a consistent manner over successive years (de la Mare 1996, 1998).

> Actual harvest decision rules should … provide details on the harvest rates and possibly other management procedures that are required in each zone or steps within a zone. The pre-agreed harvest decision rules and management actions should vary in relation to the reference points, and be designed to achieve the desired outcome by affecting the removal rate.

In addition to mathematically expressed decision rules, the DFO PA Framework admits the use of a broad suite of measures in a decision rule that may not *directly* affect the removal rate applied to the stock, such as size limits, in-season or annual spatial closures, gear restrictions, and season length. The inclusion of a harvest decision rule satisfies a requirement of the Precautionary Approach (FAO 1995) and the DFO PA Framework to specify in advance actions to be taken when specified deviations from operational targets and constraints are detected, e.g., a reduction in fishing mortality commensurate with a perceived decline in stock status.

There are two general considerations in the design of harvest decision rules. First, the design of a stock-specific harvest decision rule should be conducted with knowledge of the proposed stock assessment method that provides inputs to the rule. This is because the effect of the decision rule on the overall performance of a management procedure is difficult to predict in isolation of other components, particularly the accompanying stock assessment method. Second, the search for an adequate decision rule should be guided by a collaborative objective-setting process for the stock and fishery that involves assessment analysts, fishery managers and resource stakeholders. Stock and fishery goals will necessarily translate into objectives that are in conflict; therefore it is unlikely that a particular management procedure that includes a harvest decision rule will completely satisfy all objectives simultaneously. Risk tolerances, and the relative priority of objectives determined during consultation, have a large role in specifying the form of a decision rule that leads to a satisfactory trade-off of conservation and yield considerations (de la Mare 1998).

This document is intended as an aid to the development of guidelines for harvest decision rules in Canada. The document does not contain specific recommendations on the choice of risk tolerance and the relative priority of objectives, but does review technical considerations that influence harvest decision rule design in the context of the DFO PA Framework. Over time, accumulating experience with harvest decision rule implementation via simulation-testing and actual practice may help to identify general recommendations that can be tailored to specific stocks and fisheries. There is a growing body of literature internationally that can be consulted for details on the characteristics and implications of rule choice (e.g., see Deroba and Bence 2008, references therein).

The contents of this document support the inclusion of a harvest decision rule in a management strategy and describe the role of Science assessment analysts in providing advice on the design of rules. Two types of mathematical decision rules outlined in the DFO PA Framework are described: (1) a *status-based rule* that relies on negative feedback control, and (2) a *risk-based rule* that integrates risk tolerance into the rule structure and incorporates an additional feed-forward control step. In the case of the status-based rule, the requirement to allow the rule to be independent of the three zones of stock status outlined in the DFO PA Framework is discussed.

Among other things, the Policy is guided by the principle that the fishery is a common property resource to be managed for the benefit of all Canadians, consistent with conservation objectives, the constitutional protection afforded Aboriginal and treaty rights, and the relative contributions that various uses of the resource make to Canadian society, including socio-economic benefits to communities.

This flexibility is needed to ensure that the rule can be designed to achieve acceptable outcomes for conservation and yield. Suggestions are provided for accommodating assessment uncertainty into status-based rules. Issues for discussion in future development of the guidelines are identified, including the need for a generic harvest decision rule to be used when formal simulation-testing is not possible, decision rules for multi-gear contexts, and multi-species and ecosystem considerations.

1.1 The Requirement for Harvest Decision Rules

A harvest rate strategy is the approach taken to manage the harvest of a stock and is a necessary element of any fishery plan. In order to implement the PA in a fishery, pre-agreed harvest decision rules and management actions for each zone, are essential components of a harvest rate strategy.

The pre-agreed harvest decision rules and management actions should vary in relation to the reference points, and be designed to achieve the desired outcome by affecting the removal rate.

The various components of the framework for a fishery (i.e., the reference points, removal references and decision rules) should be explicit enough to allow assessment or evaluation of the performance of the framework.

The DFO PA framework implicitly includes three overarching statements related to decision rules:

1. decision rules are an essential component of a harvest, or management, strategy;
2. decision rules should be designed to achieve the desired outcomes for the stock and fishery;
3. decision rules should be sufficiently well-described to allow evaluation of the performance of management strategies with respect to their ability to satisfy preferred performance trade-offs in achieving operational objectives.

Statement 1 derives from the FAO (1995) Precautionary Approach guidelines where pre-agreed harvest decision rules and management actions were identified as being essential components of a harvest rate strategy. A simple decision rule consistent with this requirement could be designed to change the rate of fishing to avoid limits and achieve targets that represent policy goals for conservation and the desires of fishery managers for yield, respectively. However, decision rules can also include a wider range of management measures in addition to direct adjustments to the removal rate although these might be harder to evaluate through simulation testing. These measures include tactics such as size limits, seasonal or spatial closures related to spawning areas or habitat protection, gear restrictions, or constraints related to the catch of coincidentally caught species. All such tactics are intended to attain some desired operational outcome including stock status with respect to biomass reference points, desired age structure, reductions in discarding, avoidance of non-target species, or reductions in bottom contact. Simulation methods can be used to evaluate the likely effectiveness of many of these tactics (see Kronlund et al. 2014); however, not all methods are easily tested using simulation (e.g., long-term effectiveness of closed areas).

1.2 The Role of Science in the Development of Harvest Decision Rules

> However, it is essential that while socio-economic factors may influence the location of the USR, these factors must not diminish its minimum function in guiding management of the risk of approaching the LRP. In either case, the USR would be developed by fishery managers informed by consultations with the fishery and other interests, with advice and input from Science.
>
> Tailoring the generalized three-zoned decision framework for an individual stock and applying it involves a number of steps, as outlined in this paper, from the determination by Science of reference points and stock status in relation to these points, to the development by fisheries management, in collaboration with fishery interests, of a harvest rate strategy including pre-agreed decision rules for each zone of the framework.
>
> Footnote 10: Specific values for individual stock harvest strategies are to be provided through science assessments. The development of decision rules is a Management responsibility and Science's role is to provide advice in support of their development.

The role of Science in the design of decision rules relates directly to the requirement to evaluate the feasibility and reliability of a management procedure to avoid undesirable outcomes and to attain desired outcomes for the stock and fishery. This process was termed prospective evaluation in the Precautionary Approach to fisheries guidelines (FAO 1995, clauses 35-38). When a management procedure is determined to be inadequate to achieve all objectives in prospective evaluation, the role of Science may include provision of advice on how to re-design components of the procedure, e.g., the harvest decision rule, such that an acceptable trade-off in satisfying objectives can be identified by decision-makers. One means of conducting the prospective evaluation is through simulation-based management strategy evaluation (Kronlund et al. 2014) which is designed to describe the trade-offs that determine how much has to be postponed relative to some set of objectives in order to fully achieve others. As decision-makers refine the nature of the desired conservation-yield trade-off, Science can help to identify what harvest decision rule design choices are consistent with the policy choice. Such evaluation should attempt to determine whether the harvest decision rule, in conjunction with the stock assessment method, is robust to uncertainties related to stock dynamics, environmental variability, abundance, model error, statistical error, and implementation error (FAO 1995). Therefore, Science analysts have a role to play in proposing options for how policies are rendered operational because the objectives used to judge policy success will depend on scientific data and methods (de la Mare 1998).

2 HARVEST DECISION RULES

2.1 Reference Points and Rules

The following are the primary components of the generalized framework:

1. Reference points and stock status zones (Healthy, Cautious and Critical).

2. Harvest strategy and harvest decision rules.

The primary components of the DFO decision-making framework are (1) reference points that define stock status zones, and (2) harvest decision rules that are tactics used to achieve the desired stock and fishery objectives. Reference points have their genesis in conceptual criteria that capture in broad terms the management aspirations for the fishery; implementation of the conceptual criteria requires conversion to operational outcomes that can be calculated on the basis of biological (i.e., fishery reference points) or economic attributes of the stock and fishery (Caddy and Mahon 1995). The DFO PA Framework requires the specification of limit and upper stock status reference points denoted (B_{LRP}, B_{USR}) that are typically presented in terms of (spawning) stock biomass (Figure 1a). These reference points delineate the Critical, Cautious and Healthy zones of stock status. An additional status-based target reference point, B_{TARGET}, is also required, where $B_{\mathrm{TARGET}} \geq B_{\mathrm{USR}}$. Limit reference points represent thesholds that should be avoided with high probability, while target reference points represent desirable outcomes for the stock and fishery that should be met with high probability. Objectives are made measureable by defining a time horizon for achieving the outcome and the certainty, probability or risk, with which the outcome is to be achieved (de la Mare 1998). For example, a conservation objective might be stated as "... *the probability of spawning stock biomass breaching a limit reference point* B_{LRP} *should be less than 5% in each of the next 20 years*". A target reference point should typically be achieved with at least 50% certainty over a specified time frame.

The Removal reference is the maximum acceptable removal rate for the stock. It is normally expressed in terms of fishing mortality (F) or harvest rate. It could be described in ways other than F or harvest rate but it always must be described in terms of fishery-related pressure that affects the overall stock. The Removal reference includes all mortality from all types of fishing. To comply with the UNFA, the Removal reference must be less than or equal to the removal rate associated with maximum sustainable yield.

Reference points related to fishing mortality are also specified in the DFO PA Framework. The removal reference, F_{REF}, is the maximum acceptable removal rate for the stock (i.e., a limit reference point) and includes removals from all sources of fishing. The UNFSA (1995) states "*The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points.*" In particular, the constraint that the instantaneous fishing mortality rate satisfies $F < F_{\mathrm{MSY}}$ implies some value $B_{\mathrm{TARGET}} > B_{\mathrm{MSY}}$ as a target reference point.

In contrast to reference points, harvest decision rules are tactics that when consistently applied in conjunction with a stock assessment method are intended to produce the desired management outcomes. The DFO PA Framework describes two types of decision rules that can be expressed as mathematical functions to translate the outputs of monitoring data and assessments into removals from the stock. First, a status-based rule is described where the intended removal rate is determined using a piece-wise function of estimated stock status. The control mechanism provided by this type of rule depends only on the application of negative feedback. Second, a risk-based rule is described where the acceptable probability of future stock decline is based on a combination of current stock status and the recent rate of change in stock status (i.e., increasing, stable, or declining). This rule differs from a status-based rule in two ways: (1) the risk-based rule relies on a control mechanism that includes a feed-forward step to assess the probability of future stock decline, and (2) the tolerances for decline in stock status must be explicitly specified in the risk-based rule, instead of being stated as separate measurable objectives for subsequent evaluation using performance statistics.

2.2 Status-based and Risk-based Harvest Decision Rules

A simple status-based rule such as that depicted in Figure 1b takes as input the perceived stock status (shown on the *x*-axis), usually obtained through fitting a population dynamics model to historical data, and outputs a removal rate (shown on the *y*-axis). The intended removal rate is a piece-wise function of stock status where the maximum reference removal rate is set to $\max(F_{\mathrm{REM}})$ when the spawning stock biomass is thought to be above some upper bound, $\mathrm{B}_{\mathrm{upper}}$. The removal rate decreases in some fashion until a lower bound, $\mathrm{B}_{\mathrm{lower}}$, is reached, whereupon the removal rate is reduced to some minimum level, including possibly zero. Although the realized removal rate on the stock is uncertain and can only be estimated, the intended removal rate specified in the rule must be set so that $\max(F_{\mathrm{REM}}) \leq F_{\mathrm{REF}}$. The status-based rule is presented in the DFO PA Framework as the special case where the rule bounds coincide with the reference points that delineate the stock status zones, i.e., $\mathrm{B}_{\mathrm{lower}} = B_{\mathrm{LRP}}$ and $\mathrm{B}_{\mathrm{upper}} = B_{\mathrm{USR}}$, and $\max(F_{\mathrm{REM}}) = F_{\mathrm{REF}}$ and the functional form is piece-wise linear (Figure 1b). Other, equally acceptable cases could have different rule bounds that do not coincide with reference points, or indeed, no rule bounds at all. The DFO PA Framework provides an provisional status-based rule interpretation that uses values of $\mathrm{B}_{\mathrm{lower}} = 0.4B_{\mathrm{MSY}}$ and $\mathrm{B}_{\mathrm{upper}} = 0.8B_{\mathrm{MSY}}$, and $\max(\mathrm{F}_{\mathrm{REM}}) < F_{\mathrm{MSY}}$ that can be used in contexts that permit estimation of maximum sustained yield (MSY) based reference points. The equations for this rule are given in Table 2. Similar examples of a status-based decision rule can be found in the fisheries policies for New Zealand (Ministry of Fisheries 2008), Australia (AFMA 2007), and the United States (NMFS 2009). The status-based approach has been evaluated for various fisheries in Canada including Pacific Herring (*Clupea pallasii*; Cleary et al. 2010), Greenland Halibut (*Reinhardtius hippoglossoides*; Shelton and Miller 2009), Sockeye Salmon (*Oncorhynchus nerka*; Pestal et al. 2008), and Sablefish (*Anoplopoma fimbria*; Cox and Kronlund 2008).

In contrast, the risk-based rule is based on a combination of (1) current stock status, (2) the recent rate of change in stock status (i.e., increasing, stable, or declining), and (3) the projected probability of future decline subject to a specified harvest level. The harvest level specified by the rule is that amount where the projected probability of future decline does not exceed the acceptable probability of stock decline. In this document, the term *acceptable decline* is adopted instead of *preventable decline* as in the DFO PA Framework to restrict meaning to the tolerance for future stock decline rather than to consider the implications of whether the decline is preventable. This decision rule is outlined in Table 1 of the DFO PA Framework, reproduced here as Table 3. Table 4 contains a 7-level qualitative categorization of risk tolerance for decline reproduced from Annex 2, Table B of the DFO PA Framework. This categorization is used in Table 3 to supply the quantitative ranges for the probability of stock decline. Note that the DFO PA Framework does not identify which risk values corresponding to each qualitative category are optimal under a given stock condition.

At a minimum, Table 3 defines a 9-zone harvest decision rule produced by the three states of recent stock trend and three stock status zones. For each combination of recent stock trend and stock status zone, the acceptable probability of future stock decline must be specified as a function of estimated stock status. Figure 3 shows examples of the relationships between acceptable probability (risk) of stock decline and stock status for each trend type based on interpretation of the categories in Table 3 and risk tolerance ranges provided for each category in Table 4. In contrast to the status-based rule, where control is based solely on negative feedback, the acceptable risk-based rule includes a feed-forward step where the target fishing mortality is a function of projected future catches over some pre-specified time-frame, as well as recent trend and current stock status (S.P. Cox, pers.comm.). In practice, the predicted probability of future stock decline for several alternative levels of catch (or harvest rate, escapement, etc.) must be determined using stochastic stock projections. These predicted probabilities are then compared to the acceptable probability of decline relationship in Table 3 to identify the appropriate level of catch, i.e., the level that maximizes catch at the estimated stock status while ensuring that the acceptable probability of future stock decline is not exceeded.

Management actions should promote stock growth to the Healthy Zone within a reasonable time frame. Risk tolerance for preventable decline – **low to moderate** (if high in zone).

Management actions must encourage stock growth in the short term. Risk tolerance for preventable decline – **low to moderate** (if high in zone).

Management actions should react to a declining trend that approaches the cautious boundary. Risk tolerance for preventable decline – **moderate** (if low in zone) to neutral.

As stated above, the combination of increasing, stable, and decreasing recent stock trends and three stock status zones creates a 9-zone harvest decision rule (Table 3). However, the acceptable risk-based approach outlined in the DFO PA Framework allows scope for further adjustment of the decline tolerance depending on the estimated stock status within the Cautious Zone (Table 3). This elaboration potentially creates a 12-zone rule. The conditions that would produce equivalent performance of status-based and acceptable risk-based rules have not been evaluated. Therefore general guidance on the appropriate choice of risk tolerance values corresponding to the qualitative categories in Table 3 is not provided here. It is likely that stock-specific solutions will be required for implementing an acceptable risk-based rule, with risk tolerance values determined by consultation with managers and stakeholders. Furthermore, simulation-based prospective evaluation of expected management procedure performance will be required to demonstrate that the desired trade-off performance between conservation and catch is likely to be achieved.

There is little Canadian experience or experience elsewhere with implementation of risk-based rules as described in the DFO PA Framework. For the Greenland Halibut management strategy (Shelton and Miller 2009) the harvest decision rule responds to the recent trend in the stock indices, but was tuned through management strategy evaluation to meet the risk tolerances specified by managers for a number of conditions, i.e., the risk tolerances were not part of the harvest decision rule but were incorporated into the performance statistics. A risk-based harvest decision rule was identified as a desirable management tool for a Canadian Lingcod (*Ophiodon elongatus*) stock by a multi-stakeholder management committee (Logan et al. 2005). In this case, the maximum acceptable probability of stock decline projected 10 years ahead was defined as a piece-wise function of the current proportion of unexploited spawning biomass; however, there was no attempt to accommodate the recent stock trend. This rule was not tested using prospective evaluation and has yet to be directly applied to set allowable catches for this stock.

At this time, it is not clear that risk-based harvest decision rules have any advantage over simpler feedback harvest control rules. Disadvantages relative to simpler feedback decision rules numerous. They are much harder to evaluate through simulation testing and, in general, will require substantial annual computation. Moreover, they are much more difficult to explain to stakeholders and get agreement on their exact formulation. Rather than attempt to incorporate acceptable probabilities into the harvest decision rule, it is more common, practical and efficient to include these probabilities as performance statistics that a management procedure has to meet in order to be considered an acceptable candidate for implementation.

2.3 Separating the Harvest Decision Rule from Reference Points

The pre-agreed harvest decision rules and management actions should vary in relation to the reference points, and be designed to achieve the desired outcome by affecting the removal rate.

The DFO PA Framework includes a three zone, status-based harvest decision rule as shown in Figure 1b. The depiction of the status-based rule in the DFO PA Framework shows the special case of a piece-wise linear decision rule with bounds (B_{lower}, B_{upper}) that coincide with the limit and upper stock reference points (B_{LRP}, B_{USR}), respectively. However, that particular choice of rule configuration is not guaranteed to achieve the desired trade-off performance determined by the relative priorities assigned to conservation and yield objectives, possibly constrained by imperative performance outcomes (see Section 3.5, Miller and Shelton 2010). Other design choices for the harvest decision rule (Figure 1c,d), where the rule bounds do not align with reference points or are entirely independent of reference points, may provide decision-makers with options that can achieve a more satisfactory trade-off result. For example, the rule shown in panel (c) is likely to result in reduced conservation risk and more stock growth relative to the rule in panel (b) since the rule bounds are set to higher levels of estimated biomass and the removal rate is always lower than F_{REF}. In contrast, the rule shown in panel (d) is likely to provide higher average yield and increased yield stability, albeit at the expense of conservation performance by virtue of lowering the biomass level at which the removal rate is reduced. This illustrates the ever-present trade-off that must be made between short-term fishery performance and long-term conservation objectives and the importance of setting explicit probability thresholds that have to be met within prescribed time horizons in order for the harvest decision rule to be considered a candidate for implementation.

Furthermore, changes to the rule configuration in an attempt to achieve the desired trade-off performance should not redefine the reference points. For example, in response to a greater priority on conservation outcomes, rule options where $B_{lower} > B_{LRP}$ could be evaluated to determine if this change results in an acceptably higher probability of avoiding the limit reference point, while maintaining acceptable yields. This rule design change should not result in a redefinition of B_{LRP}. The choice of B_{LRP} must reflect the status level where recruitment is impaired, and the biomass associated with impaired recruitment is determined by the population dynamics of the stock. Impairment is considered to occur when the rate of loss of expected recruits is accelerated relative to the rate of loss of spawning stock biomass, and surplus production is compromised (FAO 1995).

Deferring management action until the estimated stock size reaches the biomass associated with impaired recruitment, i.e., the B_{LRP}, poses more than a small risk of impaired recruitment due to uncertainty in stock dynamics, assessment estimates, or management effectiveness. Consequently, a precautionary approach requires actions to reduce harvest rate and increase the likelihood of stock growth before the B_{LRP} is reached. For any specified level of risk aversion, the mitigation actions must commence sooner, as the uncertainty in assessments, stock dynamics, or management effectiveness increases. One way to achieve this approach is to use a variable removal rate decision rule that commences reduction of the intended removal rate from the reference removal rate at some biomass $B_{upper} > B_{LRP}$. Depending on the level of risk aversion, and assessment and implementation errors, the constraint $B_{lower} > B_{LRP}$ might be required to ensure the likelihood of breaching the limit reference point is not undesirably high. Policy and management may take social and economic considerations into account in specifying the level of risk aversion and time horizon to be applied relative to B_{LRP}, but once the level of risk aversion is specified, B_{upper} is set by the uncertainties outlined above.

Although the role of B_{USR} as a biologically-based reference point is not clear in the DFO PA Framework, other jurisdictions have proposed a biological rationale. For example, the New

Zealand operational guidelines (Ministry of Fisheries 2011) includes a reference point equivalent to B_{USR}, called the threshold, where the threshold equals $(1-M)B_{\mathrm{MSY}}$ where M is the estimated natural mortality rate for the species and B_{MSY} is the minimum target reference point. The basis for this choice relates to the correlation of natural mortality with fluctuations in abundance when fished stocks are fished at F_{MSY}; stocks with higher M tend to have fewer year classes and, therefore, recruitment variations tend to introduce larger fluctuations, and possibly a greater rebuilding rate in comparison to stocks with low natural mortality rates (Restrepo et al. 1988).

One possible interpretation of the DFO PA Framework is that B_{USR} is simply a point (say $\mathrm{B}_{\mathrm{upper}}$) at which to adjust the harvest rate to avoid the limit reference point and encourage stock growth towards a target reference point, subject to the desired time frame and trade-off performance of conservation and yield considerations. Science advice may also be needed to identify the target state that the stock must achieve to meet policy and management goals for harvest, expressed as profit, employment or other societal benefits. This target state must be greater than the point at which precautionary measures should commence, and possibly well above that level as uncertainty increases, if management is to simultaneously provide the desired level of protection from impaired recruitment and have an acceptable likelihood of meeting the desired socio-economic objectives. While it may be challenging to achieve both these outcomes at once, design of the harvest decision rule, and other elements of the management procedure, should provide options for decision-makers for trade-offs between risk to the stock and provision of benefits to users in both the short and long-terms. The ability to provide these options may require flexible specification of ($\mathrm{B}_{\mathrm{lower}}$, $\mathrm{B}_{\mathrm{upper}}$) and F_{REM} independently of (B_{LRP}, B_{USR}) and F_{REF}, or the implementation of a feedback harvest decision rule that does not relate directly to perceived biomass states or fishing mortality rates. For example, a data-based procedure could include a harvest decision rule that adjusts the TAC based on the current survey value or trend in the survey series. The role of Science is to identify design options for management procedures that: (1) achieve desired outcomes with the specified probability over defined time horizons, (2) meet the trade-offs between fishing benefits and risk to stock productivity, and (3) are fully transparent to the decision-makers.

3 RULE DESIGN

3.1 Design of a Status-based Feedback Rule

The provisional harvest rule is as follows (linear decrease in F to zero between 80%B_{MSY} and 40%B_{MSY}).

In the Cautious zone, the adjustment of the Removal reference does not have to follow a linear relationship as shown in the diagram, but a progressive reduction in removals is required.

The DFO PA Framework describes a provisional status-based rule in which $\mathrm{B}_{\mathrm{lower}} = 0.4B_{\mathrm{MSY}}$, $\mathrm{B}_{\mathrm{upper}} = 0.8B_{\mathrm{MSY}}$, and $\max(F_{\mathrm{REM}}) = F_{\mathrm{REF}} < F_{\mathrm{MSY}}$. Implementation of this provisional B_{MSY}-based rule requires estimation of three quantities:

1. Current spawning stock biomass, B_{T} (or a one-year ahead projected biomass, $B_{\mathrm{T+1}}$),
2. B_{MSY} which serves to scale rule bounds ($\mathrm{B}_{\mathrm{lower}} = 0.4B_{\mathrm{MSY}}$, $\mathrm{B}_{\mathrm{upper}} = 0.8B_{\mathrm{MSY}}$), and
3. A maximum reference removal rate $F_{\mathrm{REF}} < F_{\mathrm{MSY}}$.

The relationship between the removal rate and stock status is typically presented as piece-wise linear as shown in Figure 1b, however, curvi-linear relationships are not excluded from consideration. This flexibility permits rules that very gradually reduce the removal rate below

B_{upper} and approach the minimum removal rate abruptly as estimated stock status approaches B_{lower}. This type of rule would approximate the decision rule applied to Pacific Herring (Cleary et al. 2010) that sets $B_{upper} < B_{USR}$ in comparison to the provisional status-based rule where $B_{upper} = B_{USR} = 0.8B_{MSY}$.

Footnote 13: However, the development of harvest decision **rules** should also include defining growth criteria for the stock when it is in the Cautious zone.

The rate at which the stock grows in the Cautious zone can be influenced by altering objectives related to specified targets and making appropriate changes to rule design. For example, the objectives for stock growth can be specified by identifying the time horizon and the desired certainty of achieving a particular status target, such as attain at least B_{TARGET} with 50% certainty within 10 years. Only management procedures that achieve this outcome on average during simulation testing should merit further consideration. If more rapid stock growth is required, the constraint imposed by the objective could be made stronger by stipulating a shorter time horizon (e.g., 7 years) or a higher probability of exceeding B_{TARGET}, such as 70%. Any change in objectives may require changes to the choice of the harvest decision rule bounds and removal rate, since the positions of rule bounds or adjustments to max(F_{REM}) directly affect the intended removal rate at a given stock level (Figure 1c,d). Changes to the shape of the harvest decision rule may also be required. For example, a harvest decision rule with a concave shape that increases the intended removal rate gradually over the range from B_{lower} to B_{upper}, before rapidly increasing the removal rate to max(F_{REM}) as the upper rule bound is approached could produce more rapid stock growth than a straight-line function. However, changes in the rate of stock growth can only be expected on average if management actions are directly informed by these objectives.

Stocks that are not managed on the basis of biomass and/or harvest rate controls should adapt the concepts in the reference points and harvest rules below to their particular circumstance, while respecting the basic tenants of the PA as set out in the general framework.

For many targeted species, available data enables stock status to be defined in terms of spawning stock biomass, either through direct use of survey estimates or by application of population dynamics model estimates. However, in some cases estimates of stock status in terms of spawning stock biomass units may not be available or may not be appropriate: escapement counts for salmon, the catch rate of egg-bearing female prawns (Boutillier and Bond 2000), or commercial catch per unit effort for data-poor stocks, are alternatives that have been applied in Canada. A harvest decision rule can be data-based (or empirical), rather than model-based, and catches can be altered using a rule that increases or decreases catch in response to changes in the fishery or survey-based stock index (Starr et al. 1997, Schnute and Haigh 2006, Cox and Kronlund 2008, Shelton and Miller 2009, Miller and Shelton 2010, Dichmont and Brown 2010). The choice of approach may not depend on the ability to develop a population dynamics model for a stock, because data-based rules may, in some cases, be shown to out-perform model-based rules. The aforementioned distinction between reference points and the bounds of the harvest decision rule becomes clear when considering these situations, since the rule bounds could be expressed in terms of catch rate values but the measurable objectives of the management strategy can remain stated relative to MSY, stock depletion-based, or other alternative reference points (e.g., Starr et al. 1997, Cox and Kronlund 2008, see also Section 5).

Simple feedback harvest decision rules that respond directly to an empirical, or data-based, index of stock abundance can have practical application and have been implemented for Sablefish (Cox and Kronlund 2008), the western component of Pollock (*Pollachius virens*) in Atlantic Canada (DF0 2011) and on an Regional Fisheries Management Organization managed straddling Greenland Halibut stock off Newfoundland (Shelton 2011). See also the treatment by Schnute and Haigh (2006). In these cases simple feedback rules were applied that responded directly to survey data. Little et al. (2011) developed a fishery-based catch rate harvest decision rule for scalefish and shark fisheries in Australia to apply where there are insufficient data to conduct a statistical catch-at-age assessment. They used feedback simulation to evaluate the performance of the decision rule and proposed some approaches to resolving the sensitivity of their method to the assumption that catch rates are proportional to abundance.

3.2 Adjusting the Status-based Feedback Rule for Assessment Uncertainty

> 2. The need to take into account uncertainty and risk when developing reference points and developing and implementing decision rules.
>
> In this framework, scientific uncertainty about stock status and/or stock trajectory must be explicitly considered when establishing decision **rules** and management actions.

The DFO PA Framework suggests that, under circumstances when assessment error is high, the removal rate for the status-based rule should also be adjusted downwards to favour stock conservation. One means of accommodating assessment uncertainty is to adjust the estimate of stock status that is input to the harvest decision rule, rather than adjust the rule. This approach is illustrated in Figure 2 where the estimate of stock biomass input to the rule is reduced by a factor proportional to the assessment error around the projected stock biomass for the upcoming fishing year. Equation T.3 of Table 2 shows the form of an adjustment for projected biomass based on the uncertainty of the estimate. A similar means of adjusting for uncertainty was used by the International Whaling Commission in the development of their Revised Management Procedure. In that case the harvest decision rule was used to output a distribution of possible catch recommendations by calculating an approximation to the Bayes posterior distribution (de la Mare 1996, Cooke 1999). A precautionary adjustment was achieved by taking the 41st percentile of the marginal posterior catch distribution; a value selected through prospective evaluation of the management procedure, i.e., the 41st percentile was selected as the most suitable from a set of alternative choices. In the case of the Whaling Commission work, the selected percentile was one that led to the most satisfactory trade-off performance related to stock and fishery objectives.

3.3 Design of an Acceptable Risk-based Feed-forward Rule

> Footnote 8: Table 1 provides generalized management actions to apply this decision framework to the management of key harvested stocks. Actual harvest decision **rules** should be more precise and provide details on the harvest rates and possibly other management procedures that are required in each zone or steps within a zone.

An acceptable risk-based rule represented by the combination of Table 3 and acceptable probability of decline (APD) values is an example of a decision rule that explicitly programs risk tolerance into the rule. The following discussion applies to cases where stock biomass can be estimated and the decision rule bounds coincide with fishery reference points (B_{LRP}, B_{USR}). One approach to the technical implementation of an acceptable risk-based rule is described by the following algorithm (S.P. Cox, pers. comm.):

1. Specify the functional form of the relationships between perceived stock status and the acceptable probability of decline (ADP) for increasing, stable, and decreasing states subject to the following constraints:
    a. the tolerance for future decline must be reduced as stock status decreases,

   b. the relationship must increase emphasis on conservation as the recent stock trend transitions from increasing to decreasing, and
   c. the selected ADP values are stock-specific, but consultation could begin with the draft ranges provided in the DFO PA Framework (Table 4).
2. Estimate current stock biomass using a stock assessment method,
3. Classify the recent rate of stock decline as increasing, stable or decreasing, and
4. Use stochastic simulation to project stock status forward over a range of different catch levels and then determine the maximum removals by identifying the catch level that maximizes catch while ensuring that the acceptable probability of decline is not exceeded.

Figure 4 shows a graphical example implementation of Steps 1-4. This example is based on a closed-loop simulation using an operating model similar to that described by Cleary et al. (2010) and a simple statistical catch-at-age model as the stock assessment method in the management procedure. The approach described here relies on samples from the joint posterior distribution of model parameters to integrate over the uncertainty in stock assessment parameters for both trend evaluation in Step 3 and for the projection of future stock status in Step 4. For each of the trend states (increasing, stable, or declining), the stock-specific relationships between the acceptable probability of decline and stock status required by Step 1 are piece-wise linear with bounds that coincide with fishery reference points ($\mathrm{B}_{\mathrm{lower}} = B_{\mathrm{LRP}}$, $\mathrm{B}_{\mathrm{upper}} = B_{\mathrm{USR}}$) (Figure 4a-c). In this example, the probability values were obtained by linear interpolation of the ranges provided in Table 4 based on interpretation of the text in Table 3. For example, Table 3 suggests that when the recent stock trend is decreasing, the probability of acceptable stock decline should be (1) *very low* (i.e., 0.05) if the stock is in the Cautious Zone but near the limit reference point, and (2) *moderate* (i.e., 0.5) if the stock is in the Healthy Zone near the upper stock reference point.

Steps 2 and 3 require application of a stock assessment method that provides a reconstruction of historical (spawning) biomass to allow determination of current stock biomass and recent stock trend. Trend evaluation requires three elements: a method of trend determination, the number of years to include in the trend assessment, and criteria for discriminating among the increasing, stable or decreasing states. For example, Figure 4d shows the distribution of slopes obtained from 10,000 draws from the marginal posterior distribution of exponential slopes approximated using the Markov Chain Monte Carlo (MCMC) method (Hastings 1970). These slopes were based on the most recent 3 year trend of spawning biomass estimates from an assessment model. In this case, the recent stock trend was classified as decreasing by determining the position of a slope of 0 relative to the 10th and 90th percentiles of the distribution of slopes, i.e., a slope ≥ 0 is unlikely for this case (<10% probability). Actual application of this algorithm to assessments will require simulation chain of much greater length to ensure convergence of the MCMC method.

The recent stock trend determines which of the three relationships between APD values and stock status to use in catch determination (Figure 4a-c). Based on the assignment of a decreasing state, an acceptable probability of stock decline value of 0.384 was obtained by applying the current stock depletion, $\hat{B}_T \big/ \hat{B}_0$, of 0.515 from the assessment model to the relationship shown in Figure 4c. The expected probability of stock decline is obtained by projecting into the future a given number of years at a range of catch levels based on draws from the joint posterior distribution of stock assessment model parameters. For each projection obtained from a posterior draw, the estimated current stock biomass at time T is compared to future estimated stock biomass p years ahead, $\hat{B}_{T+p}$ to determine if the stock declined. The proportion of stock declines at each catch level is used to determine the relationship between the expected probabilities of stock decline and catch levels (Figure 4e). The catch output by the rule corresponds to the level of removals where the probability that projected biomass is less than current biomass, $\Pr\left(\hat{B}_{T+p} < \hat{B}_{T}\right)$, does not exceed the acceptable probability of decline.

The example shown in Figure 4e is based on 10,000 draws from the posterior distribution of biomass projected over 10 years at catch levels ranging from 0.5 to 5 (000s t) in increments of 0.5, i.e., 10 catch levels with the catch held at a given level in each year of the projection. The acceptable probability of decline from the risk tolerances determined in Step 1 was 0.384 from Figure 4c. Inverting the relationship between expected probability of decline and the range of catch levels gives an interpolated catch of about 3,000 t for this example (Figure 4e).

A large number of decisions about rule design must be made prior to application of an acceptable risk-based rule (Figure 4f). These include the APD values (21 risk probabilities for a piece-wise relationship based on two rule bounds), trend evaluation (3 numbers, and selection of trend evaluation method), projection period (1 number), catch levels (10 in the example), and the number of draws from the joint posterior distribution. While the probability of acceptable decline values specify the desired level of risk tolerance and are therefore part of operational objectives, the evaluation of recent trend and length of the projection period represents a means of tuning the performance of the harvest decision rule to achieve the desired trade-off relationship between conflicting objectives. These choices are dependent on the stock and fishery monitoring data, and the method of stock assessment, i.e., the expected performance of the entire management procedure must be evaluated as a whole.

3.4 Differences Between the Status-based and Acceptable Risk-based Rules

Implementing an acceptable-risk based rule requires a significantly larger number of *a priori* choices, and a far greater computational burden than for a status-based rule. In particular, acceptable-risk rules require a more complicated assignment of risk tolerance from fishery managers and stakeholders, since the risks depend on both the perceived recent trajectory of the stock and the projected short-term trajectory. The assignment of acceptable decline probabilities, trend evaluation parameters, and forward projection parameters means, in the example presented here, that more than 25 quantities need to be pre-specified before the decision rule can be applied. Furthermore, it is unlikely that the conservation versus yield trade-off behaviour of an acceptable risk-based rule could be anticipated in the absence of a prospective evaluation of the entire management procedure using closed-loop simulation. For example, the risk-based rule does not apply an intended removal rate; it is possible that a particular choice of risk tolerance values will result in removal rates much greater than the maximum removal reference rate, F_{REF}. The acceptable risk-based rule also imposes a significantly greater computational burden, which is exacerbated in a feedback simulation context by the combinations stock and fishery scenarios, harvest decision rule tunings, and the number of time steps in the projection period. Like a status-based rule, the overall performance of a management procedure that includes an acceptable risk-based rule is subject to the effects of assessment errors. However, the requirement to estimate recent trend introduces an additional assessment error to the risk-based approach, namely the potential to misclassify the recent trend, e.g., the trend is estimated to be increasing when it is actually decreasing. This misclassification may introduce additional noise into catch recommendations as a result of applying the incorrect acceptable risk tolerances over time.

Although the development of a status-based rule also requires a potentially challenging consultation step during the objective-setting phase of the fishery management process, a simple status-based rule only requires estimation of current B_T or projected spawning stock biomass, B_{T+1}, and the rule bounds (B_{lower}, B_{upper}) and reference removal rate. For example, only three quantities need to be determined for application of the DFO provisional MSY-based rule which scales the rule bounds to B_{MSY}, i.e., $0.4B_{MSY}$ and $0.8B_{MSY}$, and constrains the reference removal rate to the fishing mortality at MSY, F_{MSY}. This comparison with the acceptable risk-based rule is slightly unfair, since the latter also explicitly programs part of the stock and fishery objectives into the rule design while measurable objectives are stated externally to status-based rules. Regardless, application of the provisional status-based rule, without prospective evaluation via feedback simulation, will not ensure that the desired risk tolerances for avoiding limits or attaining targets can be met. Similarly, while the explicit programming of future decline tolerance into the risk-based rule might address that aspect of operational objectives, the corresponding effects on yield and yield stability are difficult to predict without a prospective evaluation step.

3.5 Tuning a Decision Rule to Objectives using Prospective Evaluation

The pre-agreed harvest decision rules and management actions should vary in relation to the reference points, and be designed to achieve the desired outcome by affecting the removal rate.

The various components of the framework for a fishery (i.e., the reference points, removal references and decision rules) should be explicit enough to allow assessment or evaluation of the performance of the framework.

The attainment of sustainable fisheries management requires some demonstration of the robustness of the management procedure against alternative scenarios for a stock and fishery due to model, process, observation, and implementation errors (FAO 1995). However, the success of a management procedure in attaining the desired trade-off of conservation and yield considerations cannot be reliably predicted on the basis of the performance of each individual component (i.e., the data collection, assessment method, and harvest decision rule). For example, an assessment method that consistently over-or under-estimates stock status may provide acceptable management performance when paired with a harvest decision rule that compensates for bias. Therefore, the expected performance of a management procedure should be evaluated as a whole using prospective evaluation rather than as individual components (FAO 1995, clauses 35-38).

An assessment or evaluation should be considered on a regular basis and it would normally take place after there is sufficient experience with the framework to conduct a proper evaluation of its performance (a period of 6 -10 years might provide enough time to gain appropriate experience with the framework).

The DFO PA Framework requires that the various components of the framework for a fishery (i.e., the reference points, removal references and decision rules) should be explicit enough to allow assessment or evaluation of the performance of the framework. It requires that such an assessment or evaluation should be considered on a regular basis and would normally take place after there is sufficient experience with the framework to conduct a proper evaluation of its performance. It considers a period of 6 to 10 years might provide enough time to gain appropriate experience with the framework in order to conduct such an evaluation, i.e., retrospective rather than prospective evaluation (FAO 1995).

Although prospective evaluation is not a requirement before implementation of a management strategy, the DFO PA framework does identify the need to (1) to alter the design of a harvest decision rule to achieve desired outcomes, and (2) to state the harvest decision rule such that performance can be evaluated. These requirements are consistent with the FAO Precautionary

Approach requirements for prospective evaluation, which additionally specifies that a management plan should not be accepted until it has been shown to perform effectively in terms of its ability to avoid undesirable outcomes. One means of accomplishing prospective evaluation is through a reasonable facsimile of the real management system based in simulation (Kronlund et al. 2014). In contrast, the need to consider regular retrospective empirical evaluation of the management strategy after implementation under the DFO PA framework, including the harvest decision rule, is not specific on the nature of the evaluation. Evaluation after a period of 6 to 10 years is suggested, however, the time frame should be selected based on the perceived stock status, life history considerations, and the constraints imposed by existing management strategies such as the precedence of a rebuilding plan for a species at risk.

Prospective evaluation of a harvest decision rule can apply to both status-based and acceptable-risk based rules, and may lead to adjustments to the rule parameters in order to improve performance relative to achieving a preferred trade-off result. In the case of status-based rules, tuning parameters include the bounds ($\mathrm{B}_{\mathrm{lower}}$, $\mathrm{B}_{\mathrm{upper}}$), and the value of max($F_{\mathrm{REM}}$). For example, $\mathrm{B}_{\mathrm{upper}}$ could be shifted to smaller values of stock status in order to stabilize average catches in the vicinity of the target reference point, albeit at the expense of conservation performance. Similarly, the value of max(F_{REM}) above $\mathrm{B}_{\mathrm{upper}}$ could be decreased from the reference removal rate F_{REF}. Such a design choice might accommodate a desire to achieve a higher probability of stock growth above a minimum target level, with the possible benefits of higher catch rates and improvements to fishery profitability (e.g., Figure 1c,d).

In the case of acceptable-risk based rules, tuning parameters include adjustments to the number of years included in the evaluation of recent trend and the criteria for classifying the recent trend as increasing, stable or decreasing. It could also be argued that the time horizon of the feed-forward step to evaluate the expected probability of future stock decline is part of objective setting, in a manner similar to the specification of risk tolerances for stock decline. However, given the difficulty of specifying and explaining an acceptable risk-based rule, it is worthwhile evaluating whether a relatively simple status-based rule could be found that met the specific risk tolerances measured by performance statistics output from feedback simulations. Tuning procedures have been applied to status-based feedback rules in Canada (e.g., Sablefish, Greenland Halibut); however, there is limited experience with tuning to specified risk tolerances (e.g., Greenland Halibut). The lack of experience in tuning acceptable risk-based rules as described in the DFO PA Framework is likely because the computational demands of such an exercise would be exceedingly intensive given the need for stochastic projections over a range of catch levels within each year of each simulation trial.

Examples of two types of performance statistics related to tuning a decision rule have been considered in Canada for Greenland Halibut: satisficing and trade-off statistics (Miller and Shelton 2010). Satisficing, a portmanteau of satisfy and suffice, is defined as "*... a decision-making strategy that attempts to meet criteria for adequacy, rather than to identify an optimal solution*" (Wikipedia: The Free Encyclopedia, 2009). Satisficing statistics require identification of thresholds and risk tolerances that have to be met for a management strategy to be considered adequate. Thresholds refer to specific performance statistic values to be met and risk tolerances refer to the likelihood of this happening (i.e., the percentage of stochastic simulations where this occurs). If any threshold is breached with a probability that exceeds the risk tolerance, then the management procedure is judged inadequate. For example, consider an objective where the maximum acceptable probability of breaching a limit reference point is less than 5%, i.e, $\Pr(B_t < B_{\mathrm{LRP}}) < 0\ .05$. In this case, any management procedures that generate a performance statistic indicating greater than a 5% chance of falling below B_{LRP} over a specific time period would be discarded. Threshold values and risk tolerances for satisficing statistics should be set by decision-makers, in consultation with a broad range of stakeholders, including the fishing industry, as well as recreational and environmental interest groups. Trade-off statistics on the other hand typically evaluate the trade-off between achieving fishing and conservation outcomes. The harvest decision rule can be tuned based on the desires of managers to meet objectives provided the criteria for adequacy defined in the satisficing statistics are still being met.

4 OUTSTANDING ISSUES

4.1 Harvest Decision Rules for Multi-Gear Fisheries

The DFO PA Framework is based on a single-fishery context where annual fishing mortality rates can be compared against a reference removal rate such as F_{MSY} to estimate whether over-fishing is occurring relative to the intended fishing rate. However, for many Canadian fisheries more than one gear type intercepts a species. The Integrated Groundfish fishery in Pacific Region is one such example of a multi-gear (and multi-species) fishery where longline hook, longline trap, and trawl gears intercept approximately 30 commercially important species and over 300 species in total. Comparisons of fishing rates against a reference rate cannot easily be made in the multi-gear context, because exploitation rates are gear-specific, and there is no single selected biomass because each gear type has a different selectivity. Implementation guidelines for this problem have not been developed for Canadian fisheries. However, the New Zealand operational guidelines suggest one approach to resolving this problem using the concept of fishing intensity, which maps the fishing mortality rate of multiple gears to a single measure of the fishing rate, where higher values correspond to greater effort and higher fishing mortality rates (Ministry of Fisheries 2011).

4.2 Multi-species and ecosystem considerations

This framework provides guidance on developing reference points and harvest decision rules for key harvested targets stocks. However, the application of the harvest decision rules in a fishery may need to be tempered to limit effects on other stocks.

Most if not all aspects of ecosystem approaches result in management strategies that are more conservative than those developed for single-stock approaches, whether based on MSY or other foundations. In other words, they generally result in fishing mortality rates that are considerably lower than F_{MSY} in order to ensure conservation of stocks with low productivity or already depleted conditions within the suite of capture species (Mace 2001). Decision rules that include measures other than adjustments to removal rates have been implemented. For example, habitat protection measures can be introduced into decision rules using spatial controls and protocols to restrict areas subject to bottom contact, establish so-called move away rules when vulnerable marine ecosystems are encountered, and implement controls in areas most impacted by fishing (Penney et al. 2009). In general, however, the policy applicable to ecosystem approaches is not specified in the DFO PA Framework and is beyond the scope of this document.

4.3 Should There Be a Default Status-based Rule?

In the absence of a pre-agreed harvest rule developed in the context of the precautionary approach, a provisional removal reference or fishing mortality (say F_{p}) could be used to guide management and to assess harvest in relation to sustainability. The provisional harvest rule is as follows (linear decrease in F to zero between 80%B_{MSY} and 40%B_{MSY}).

Some jurisdictions have promoted the adoption of default, or generic, harvest decision rules that are expected to provide reasonably good performance over a wide range of fisheries. This choice was, in part, motivated by the need to implement harvest decision rules consistently, and for situations where limited resources prevent the formal development of stock-specific rules for each fishery. In many cases, these default rules are supported by legislation that enshrines maximum sustained yield as a target reference point (e.g., New Zealand, Australia, United States) and decision rule bounds are aligned with fishery reference points. However, generic rules are not guaranteed to work in any specific context; it is not clear whether a generic decision rule can provide an acceptable trade-off result that is broadly applicable unless priority is given to, for example, conservation considerations. In contrast, the DFO PA Framework identifies required features of a harvest decision rule and recommends provisional reference points to be used as part of the decision rule. These provisional reference points include alternatives for approximating MSY-based reference points to serve as rule bounds when available data cannot support reliable estimation of B_{MSY} or F_{MSY}, (Annex 1B of the DFO PA Framework). However, the DFO PA Framework does not specify a generic rule. In this section, examples of key design elements used to develop default, or generic, harvest decision rules in other jurisdictions are reviewed for consideration in subsequent development of guidelines for harvest decision rules in Canada.

An example of a default MSY-based rule designed to mitigate assessment and implementation errors can be found in the New Zealand harvest strategy (Figure 5, Ministry of Fisheries 2008). The New Zealand default harvest rule is presented as a status-based piece-wise linear 3-zone rule similar to that found in the DFO decision-making framework. The lower bound of the rule is aligned with the larger of $0.25B_{\mathrm{MSY}}$ or $0.1B_0$ and is analogous to the DFO limit reference point. A *threshold* bound analogous to the DFO upper stock reference point is suggested at the target biomass, less a buffer proportional to the natural mortality rate of the species. The target biomass, which determines the location of the threshold bound on the decision rule, is set to the larger of B_{MSY} or $0.4B_0$. In addition, the New Zealand generic rule has an action point called the *soft limit* at the larger of $0.5B_{\mathrm{MSY}}$ or $0.2B_0$ where increased management control can be applied to encourage stock rebuilding towards the target based on the advice of Restrepo et al. (1998). The fishing mortality at maximum sustained yield is regarded as a limit fishing mortality rate.

The New Zealand generic rule differs from the provisional rule suggested within the DFO PA Framework because measurable objectives are provided relative to the reference points. In particular, the following statements of certainty accompany outcomes related to the hard limit, soft limit, and target reference points:

1. When the probability that stock biomass is below the hard limit is greater than 50% the hard limit will be considered breached,
2. When the hard limit has been breached, the fishery will not be re-opened until there is at least a 70% probability that the soft limit has been exceeded,
3. When the probability that the stock biomass is below the soft limit exceeds 50% the soft limit will be considered breached, and
4. A stock will be considered rebuilt when there is at least a 70% probability that the stock has exceeded the target reference point, and at least a 50% probability that the stock is above the soft limit (the 70% probability is adopted to avoid abandoning rebuilding plans to soon due to uncertainty and to acknowledge that age structure may need to be rehabilitated).

In addition, the New Zealand harvest strategy standard provides a rebuilding time of T_{min} to $2T_{\mathrm{min}}$, where T_{min} is the minimum number of years that the stock can achieve the rebuilding target in the absence of fishing. This may present advantages in comparison to using time frames based on generation time, since T_{min} takes into account life history considerations, current stock depletion and assessment uncertainty.

Another example of a generic rule was recently proposed for application in European fisheries in response to a call from the European Commission to produce new long-term fisheries management plans (Froese et al. 2011). The rules, which have not been adopted, are designed to meet international fisheries agreements, are based on MSY, and set rule bounds to correspond to B_{MSY}-scaled reference points. In particular, the generic rules:

1. Set the upper rule bound (coinciding with B_{USR}) to the estimated value of B_{MSY},
2. Set the lower rule bound (coinciding with B_{LRP}) to $0.5B_{MSY}$,
3. Set the maximum total allowable catch above the B_{upper} to 0.91 of MSY, or 0.75 of MSY for forage fish and sensitive species when using a Schaefer production function, and
4. Reduce the catch linearly from the maximum level at B_{upper} to 0 at B_{lower}.

This design, proposed by Froese et al (2011), aligns the rule bounds with thresholds and targets identified for stock and fishery objectives:

1. Achieve a low probability of falling below a minimum target biomass of B_{MSY} over the specified time frame, or alternately a low probability of exceeding the fishing mortality limit reference point, F_{MSY},
2. Avoid breaching the limit reference point of $0.5B_{MSY}$ with high probability within the specified time frame, and
3. Account for uncertainty in the estimate of B_{MSY} by setting a target biomass of 1.3 B_{MSY} (1.5 B_{MSY} for forage and sensitive species), corresponding to an average long-term yield of 0.91 MSY (0.75 MSY for forage and sensitive species).

As noted above, a generic rule has no guarantee of satisfactorily meeting a context-specific suite of objectives. On the other hand, it is unlikely resources will be available to provide context-specific harvest decision rules for each stock in Canada, at least in the short-term given resource constraints. While the DFO PA Framework is quasi-specific about a conservation objective, i.e., avoid breaching the limit reference point with high probability over some time frame, there are no general objectives related to target reference points that can be used in the absence of a collaborative objective-setting consultation process.

Footnote17: The scientific information available may vary substantially from one stock to another. Accordingly, different approaches must be used for calculating LRPs and defining harvest **rules** that take into account the information currently available for a given stock.

Generic harvest decision rules will not apply to all data situations. The DFO PA Framework recognizes that the choice of rule for a given stock will depend on the type of information available from the stock assessment. Available information can vary both in terms of the metric used to define stock status (i.e., a survey or fishery catch rate index rather than an absolute estimate of spawning stock biomass) and in the frequency of new information being collected (e.g., annually or multi-year updates). To a certain extent, the time required to conduct simulation-based prospective evaluations of management procedures given case-specific data availability could be reduced through the development of standardized software tools. Generic software that can approximate typical fishery contexts may be useful in supporting decision-making where formal context-specific evaluation cannot be conducted. For example, a comparison of an existing harvest decision rule used for Pacific Herring stocks to the DFO provisional MSY-based rule was recently conducted using closed-loop simulations by Cleary et al. (2010). The Pacific Herring rule is a hybrid constant harvest/minimum escapement rule defined relative to unfished spawning biomass, B_0. Both rules provided similar performance under situations where the policy parameters were known without error, with the existing herring rule delivering slightly better conservation performance. Nevertheless, both rules failed to meet the conservation objectives under low productivity scenarios, a result that would likely be exacerbated if values of B_{MSY} or B_0 were estimated using accumulating data in the forward projection. Although the analysis only approximated the application of the Pacific Herring management procedure, it suggested that an existing rule might outperform the provisional rule based on B_{MSY}. Similar simulation approaches could be developed to allow evaluation of a suite of questions related to the interacting effects of alternative survey schedules, multi-year assessments, and harvest decision rules, and for identifying when case-specific modifications are needed based on data availability.

5 SUMMARY

The DFO PA Framework stipulates that (1) harvest decision rules are an essential component of a PA Framework (management strategy), (2) harvest decision rules should be designed to achieve the desired outcomes for the stock and fishery, and (3) harvest decision rules should be sufficiently well-described to allow evaluation of the performance of management strategies with respect to their ability to satisfy conservation and yield objectives. Key issues to consider in the development of guidelines for harvest decision rules in Canada are listed below:

- Primary components of the DFO PA Framework include: (1) reference points that, when coupled with time frames and desired risk tolerances, translate policy goals into operational objectives for the stock and fishery, and (2) harvest decision rules that describe management actions in response to stock status in order to achieve a satisfactory trade-off between conservation and yield objectives. Such objectives relate to the desire to avoid breaching the point of serious harm and to achieve economic yield aspirations.
- The role of Science in the development of decision rules relates directly to the requirements to (1) design harvest decision rules to achieve conservation and yield objectives and (2) to assess or evaluate the performance of a management procedure. Science is involved in identifying conservation objectives and has a role in proposing options for how policies are rendered operational because the evaluation of policy success will depend on scientific data and methods. This role includes assisting in the evaluation of the ability of a harvest decision rule, combined with the stock assessment method, to avoid undesirable outcomes and attain desired outcomes. This requirement was termed prospective evaluation in the FAO Precautionary Approach to fisheries guidelines (FAO 1995).
- The design of a stock-specific harvest decision rule should be considered in the context in which it is to be used. This means evaluating the interaction of the harvest decision rule with other components of the management procedure, i.e., the data and stock assessment method.
- The specific design of a harvest decision rule is dependent on an inclusive objective-setting process for the stock and fishery that involves assessment analysts, fishery managers, and resource stakeholders.
- There are two types of rules in the DFO decision-making framework: (1) a status-based rule where the intended removal rate is 3-zone, piece-wise function of estimated stock status, and (2) an acceptable risk-based rule in which the acceptable probability of stock decline is based on a combination of current stock status and the recent rate of change in stock status. The former is a feedback decision rule which is not equivalent to the acceptable risk-

based rule; the latter rule does not specify a reference removal rate and also incorporates a feed-forward step.

- Complex decision rules should be avoided in favour of the simplest rule that will best satisfy the conservation and yield objectives. For example, the quantitative evaluation of acceptable risk-based rules requires a significantly larger number of *a priori* decisions and a far greater computational burden than for status-based rules. Status-based rules require far fewer design choices in comparison to an acceptable risk-based rule, making them easier to develop and explain to stakeholders. Simple status-based harvest decision rules that do not rely on an estimate of current spawning stock biomass, but respond directly to an empirical index of stock abundance, have been implemented for several fisheries in Canada under a Management Strategy Evaluation framework. These include Sablefish in the Pacific Region, the western component of Pollock in Atlantic Canada, and the Greenland Halibut stock off Newfoundland. Performance statistics that capture the risk of stock decline can be included in the evaluation of simple status-based rules without the need to specify acceptable decline risk in the rule definition.
- The choice of the rule bounds should not be restricted to exactly match the fishery reference points, although such alignment is one option. This flexibility allows the form of the harvest decision rule (a tactic) to be adjusted for stock-specific applications so that a desired trade-off between conservation and economic performance can be achieved. Choices of rule bounds other than the fishery reference points that define stock status zones may result in a more desirable trade-off between conservation and yield objectives. For example, the lower bound of the rule may be set higher than the limit reference point, or the removal rate at some value lower than the reference removal rate, to emphasize conservation or rebuilding outcomes. Similarly, the upper stock status bound of the rule may be set at some value near the target reference point to encourage higher biomass levels and potentially higher profitability through improved catch rates.
- Some jurisdictions have promoted the adoption of default, or generic, harvest decision rules that are expected to provide reasonably good performance over a wide range of fisheries. However, there is no assurance that generic harvest decision rules will achieve stock-specific objectives. If DFO wishes to develop a generic harvest decision rule, simulation testing of several possible rules over a reference set of life history and stock configurations should be undertaken, as has been done in some other jurisdictions.
- Harvest decision rules do not necessarily need to be limited to the status of a single target species. Multi-species or ecosystem considerations can also be incorporated into rules, but this often adds substantial complexity and would require extensive development and testing prior to implementation.

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Table 1. Notation used for harvest decision rules.

Symbol	Description
Indices	
t	Time (year) from t=1,…,T
States	
B_t	Stock biomass in year t, e.g., spawning stock biomass. Estimated quantities are denoted $\hat{B}_t$.
Reference Points	
B_{TARGET}	Biomass-based Target reference point, e.g., B_{MSY}, the spawning stock biomass at maximum sustained yield.
B_{USR}	Biomass-based Upper Stock Reference point
B_{LRP}	Biomass-based Limit Reference Point
F_{REF}	Reference (maximum) removal rate, e.g., F_{MSY}, the fishing mortality at maximum sustained yield.
Harvest Decision Rule	
B_{lower}	Lower bound, e.g., $\text{B}_{\text{lower}}=0.4B_{\text{MSY}}$
B_{upper}	Upper bound, e.g., $\text{B}_{\text{upper}}=0.8B_{\text{MSY}}$
F_{REM}	Removal rate, $F_{\text{REM}} \leq F_{\text{REF}}$
max (F_{REM})	The value of F_{REM} applied when $\hat{B}_t > \text{B}_{\text{upper}}$
DFO Provisional MSY-based Rule	
$\hat{B}_{\text{MSY}}$	Estimated biomass at maximum sustained yield
$\hat{F}_{\text{MSY}}$	Estimated instantaneous fishing mortality at maximum sustained yield
$\hat{F}_{T+1}$	Harvest control rule (instantaneous) removal rate
M	Instantaneous natural mortality rate
$\hat{Q}_{T+1}$	Total allowable catch in year T+1
σ_B^2	Variance of estimated stock biomass in year T+1

Table 2. Provisional MSY- and status-based harvest decision rule.

Equation	Notation
T1	$\Theta = \left(\hat{B}_{T+1}, \hat{F}_{\text{MSY}}, \hat{B}_{\text{MSY}}, \sigma_B^2\right)$
T2	$F_{T+1}^{*} = \begin{cases} 0 & \hat{B}_{T+1} < 0.4\hat{B}_{MSY} \\ \hat{F}_{\text{MSY}}\left(\dfrac{\hat{B}_{T+1} - 0.4\hat{B}_{MSY}}{0.4\hat{B}_{\text{MSY}}}\right) & 0.4\hat{B}_{MSY} \leq \hat{B}_{T+1} < 0.8\hat{B}_{\text{MSY}} \\ \hat{F}_{\text{MSY}} & \hat{B}_{T+1} \geq 0.8\hat{B}_{\text{MSY}} \end{cases}$
T3	$\hat{Q}_{T+1} = \dfrac{F_{T+1}^{*}}{M + F_{T+1}^{*}}\left(1 - e^{-M-F_{T+1}^{*}}\right)\hat{B}_{T+1}e^{-\sigma_B^2/2}$

Table 3. DFO PA Framework with criteria for management actions for key harvested stocks.

		Stock Status		
		Critical	**Cautious**	**Healthy**
General Approach		Conservation considerations prevail. Management actions cannot be inconsistent with secure recovery	Socio-economic and conservation considerations should be balanced in a manner that reflects location in zone and trajectory	Socio-economic considerations prevail. Conservation measures consistent with sustainable use apply.
Harvest rate strategy		Harvest rate (taking into account all sources of removals) kept to an absolute minimum.	Harvest rate (taking into account all sources of removals) should progressively decrease from the established maximum and should promote stock rebuilding to the Healthy Zone.	Harvest rate (taking into account all sources of removals) not to exceed established maximum.
Recent Stock Trajectory	**Increasing**	Management actions must promote stock growth. Removals from all sources must be kept to the lowest possible level until the stock has cleared the Critical Zone. A rebuilding plan must be in place with the aim of having a high probability of the stock growing out of the Critical zone within a reasonable timeframe. This plan must be associated with appropriate monitoring and assessment of the condition of the stock to confirm the success of rebuilding. The plan must also include additional restrictions on catches, and a provision that application of the measures is mandatory if the evaluation fails to find clear evidence that rebuilding is occurring.	Management actions should promote stock growth to the Healthy Zone within a reasonable time frame. Risk tolerance for preventable decline – **low to moderate** (if high in zone)	Management actions should be tolerant of normal stock fluctuations. Risk tolerance for preventable decline – **high**
	Stable		Management actions must encourage stock growth in the short term. Risk tolerance for preventable decline – **low to moderate** (if high in zone)	
	Declining		Management actions must arrest declines in the short term or immediately if low in the zone. Risk tolerance for preventable decline – **very low / low**. Development of a rebuilding plan is ready to come into effect if the stock declines further and reaches the critical zone.	Management actions should react to a declining trend that approaches the cautious boundary. Risk tolerance for preventable decline – **moderate** (if low in zone) to neutral

Table 4. Probability of acceptable decline ranges corresponding to categories of risk ranges identified in Table 1. Ranges are reproduced from Annex 2, Table B of the DFO PA Framework.

Category	**Probability of Acceptable Decline**
Very low	< 0.05
Low	0.05 to 0.25
Moderately low	0.25 to 0.5
Neutral	0.5
Moderately high	0.5 to 0.75
High	0.75 to 0.95
Very high	> 0.95

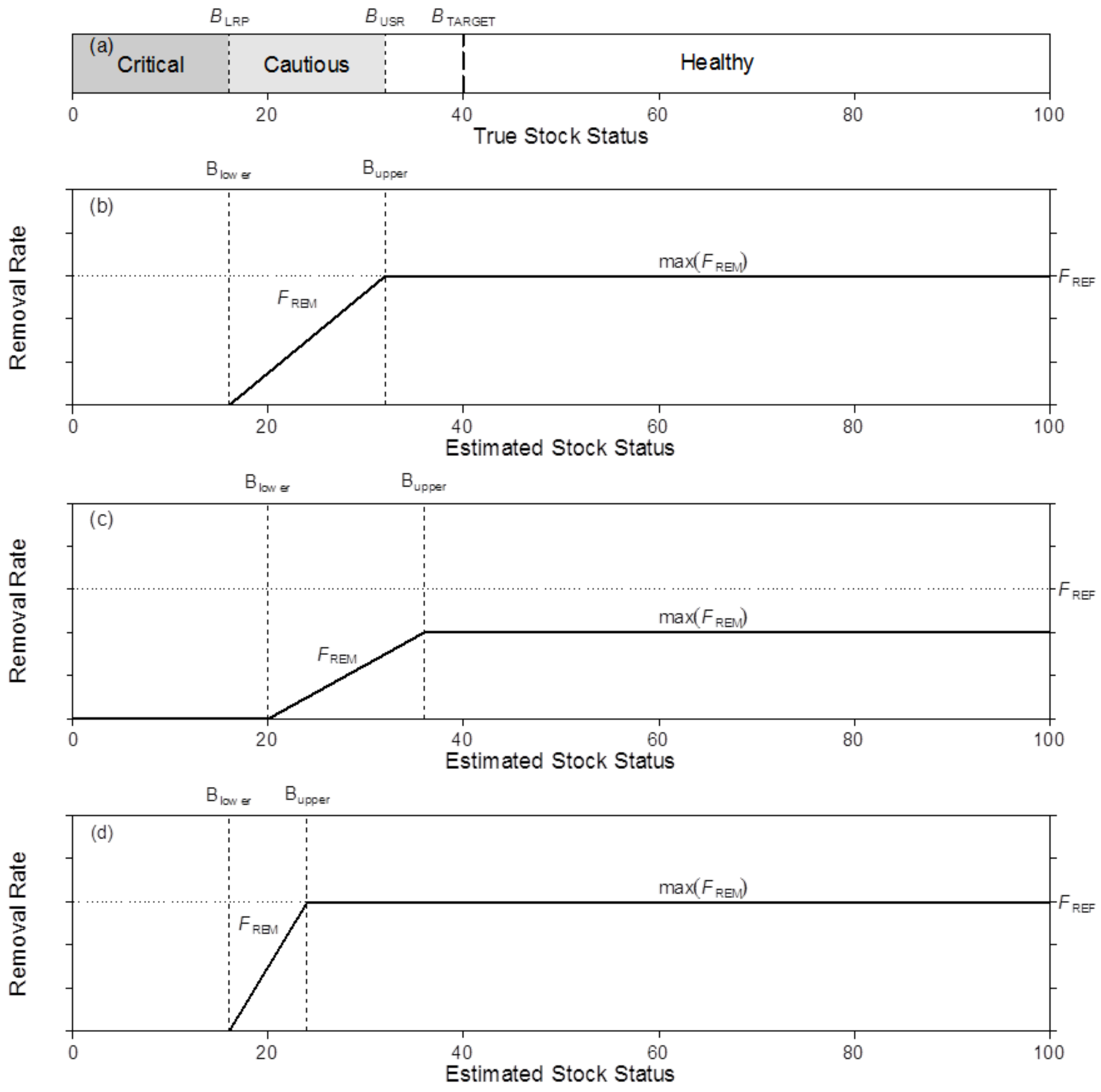


Figure 1. Characterization of stock status into Critical, Cautious and Healthy Zones zones using biomass limit (B_{LRP}) and upper stock (B_{USR}) reference points (panel a). A target reference point, $B_{TARGET} > B_{USR,}$ represents a desired outcome. Lower panels (b-d) show three possible harvest decision rules in which the removal rate F_{REM} (solid line) is dependent on estimated stock status relative to bounds (B_{lower}, B_{upper}). The choicees of bounds and the maximum removal rate, max(F_{REM}), applied above B_{upper} depend on the time frame and desired probabilities of avoiding B_{LRP}, achieving B_{TARGET}.and satisfying yield stability objectives. The value of max(F_{REM}) may be equal to the reference removal rate, F_{REF} (dashed horizontal line), for the stock (panel b) or less than F_{REF} (panel c). Note in panel (b) that the rule bounds do not coincide with reference points (B_{LRP}, B_{USR}). The rule shown in panel (c) is likely to result in reduced conservation risk and more stock growth relative to the rule in panel (b): the rule bounds are set to higher estimated biomass levels and the removal rate is always lower than F_{REF}. In contrast, the rule shown in panel (d) is likely to provide higher average yield and increased yield stability, albeit at the expense of conservation performance.

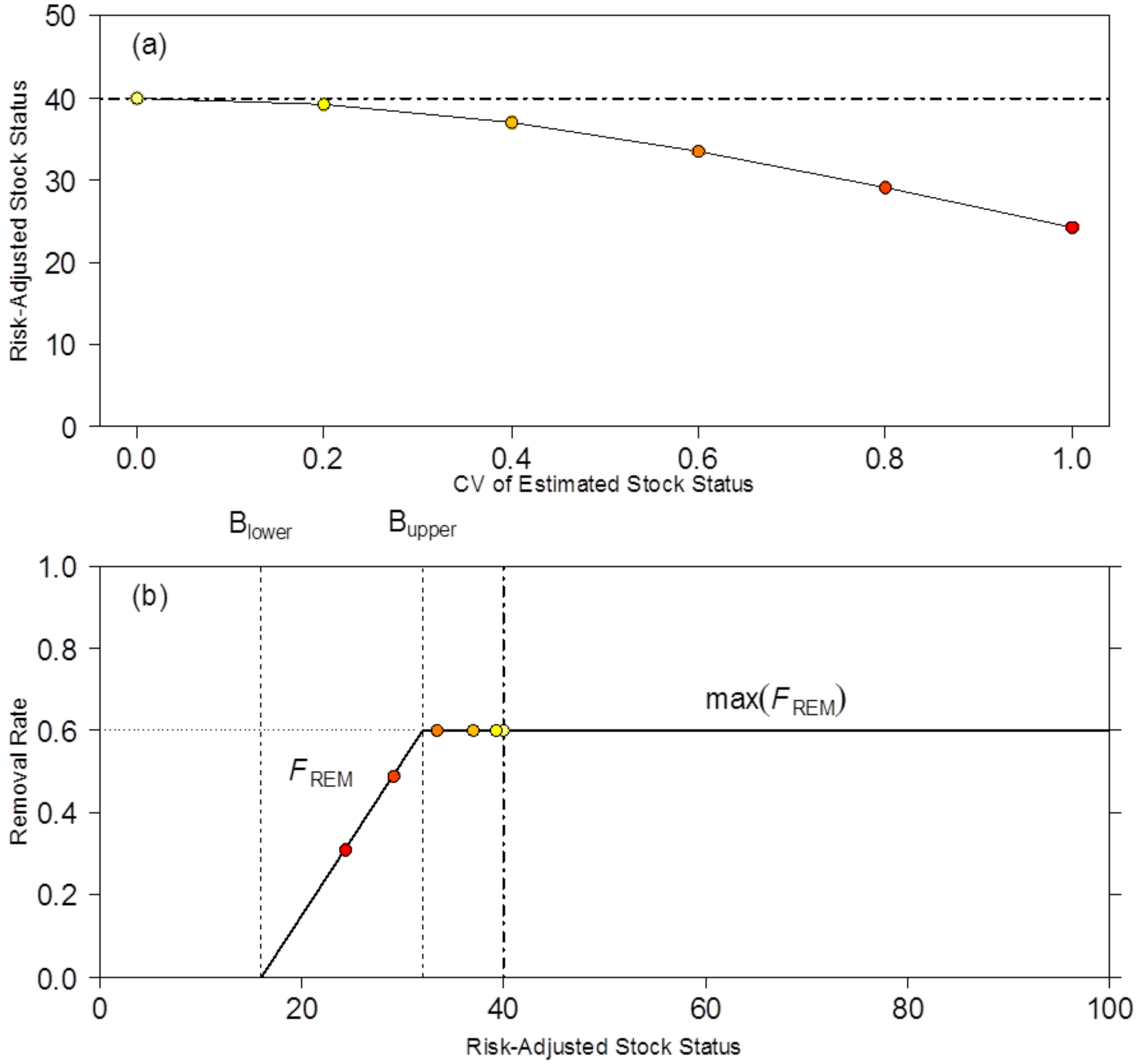


Figure 2. An illustration of adjusting the status-based harvest decision rule to uncertainty in the estimated stock status. The estimated stock status value input to the harvest control rule (dot-dash line) is reduced from perfect information by a factor related to the coefficient of variation (CV) as shown by the relationship in panel (a). The corresponding effects of the risk-adjusted estimates of stock status on the removal rates output by the harvest decision rule are shown in panel (b). The effects of adjusting for uncertainty in the stock status estimate are reductions in the removal rate from the perfect information level (vertical dot-dash line). Note that corresponding points (filled circles) in panels (a,b) are shaded similarly.

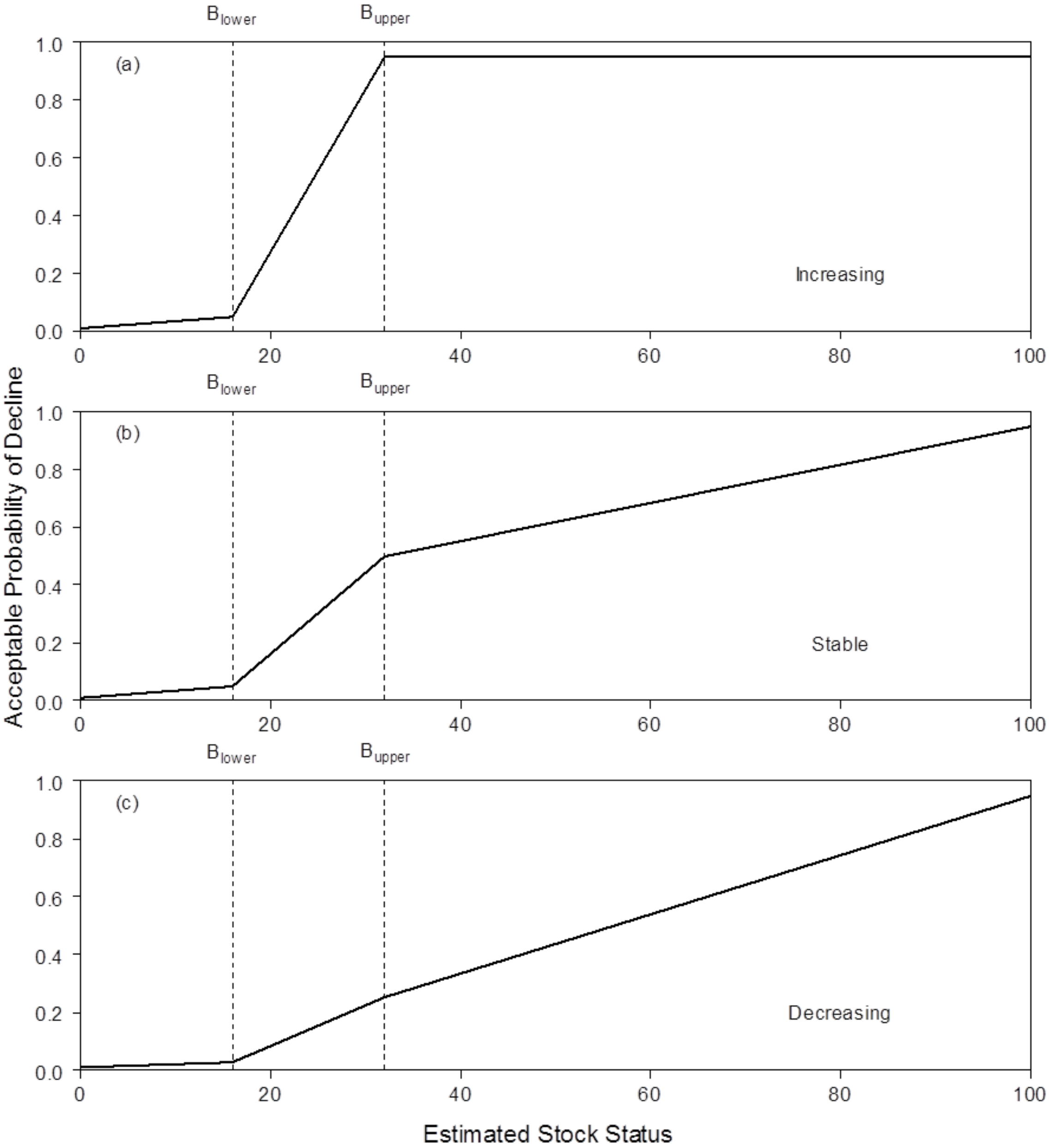
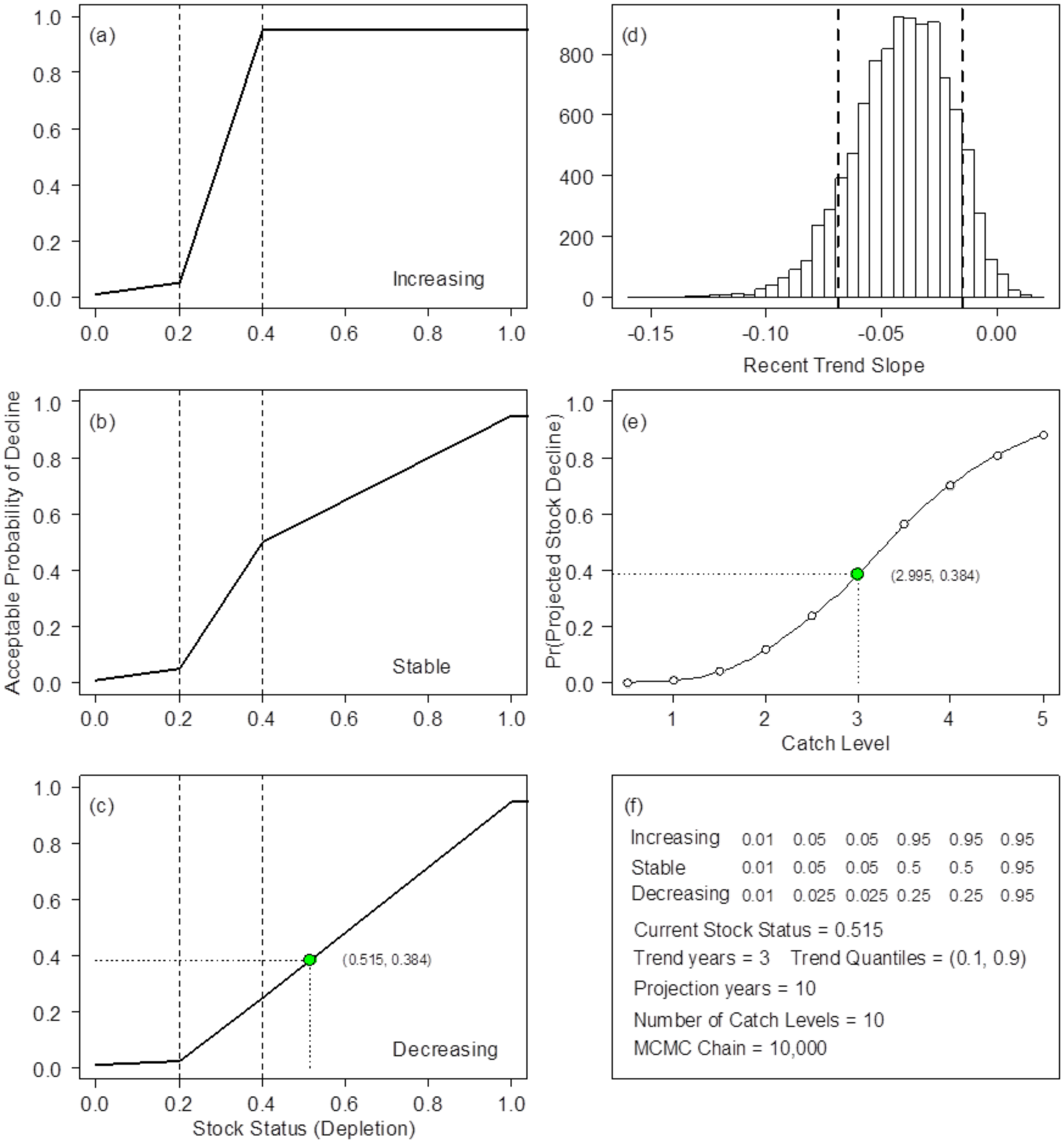


Figure 3. Acceptable probability of future stock decline as a function of estimated stock status for increasing (a), stable (b) and decreasing (c) stock trajectories. Acceptable probabilities were derived from linear interpolation of Table 4. Rule bounds (B_{lower}, B_{upper}) may coincide with fishery reference points (B_{LRP}, B_{USR}) but may also be considered tuning parameters of the acceptable risk-based harvest decision rule.



Increasing	0.01	0.05	0.05	0.95	0.95	0.95
Stable	0.01	0.05	0.05	0.5	0.5	0.95
Decreasing	0.01	0.025	0.025	0.25	0.25	0.95

Current Stock Status = 0.515
Trend years = 3   Trend Quantiles = (0.1, 0.9)
Projection years = 10
Number of Catch Levels = 10
MCMC Chain = 10,000

Figure 4. Example of how a catch is determined using a risk-based decision rule. Panels (a-c) show the relationship between the acceptable probability of stock decline and stock status for increasing, stable and decreasing recent trends. Recent trend is assigned using Bayesian estimation; the distribution of recent trend statistics obtained from a sample of the Bayes posterior distribution from a statistical catch-at-age model indicates a decreasing trend. The acceptable rate of stock decline (0.384) is computed from the estimate of current depletion (0.515) in panel (c). Stochastic projections over a range of catch levels are used to estimate the relationship between catch and the expected probability of projected stock decline (panel e). The acceptable rate of stock decline from panel (c) is then compared to the curve in panel (e) to identify an allowable catch level. Application of the rule for this example results in a catch recommendation of approximately 3,000 t. Panel (f) summarizes the values that need to be pre-specified for implementation of an acceptable risk rule.

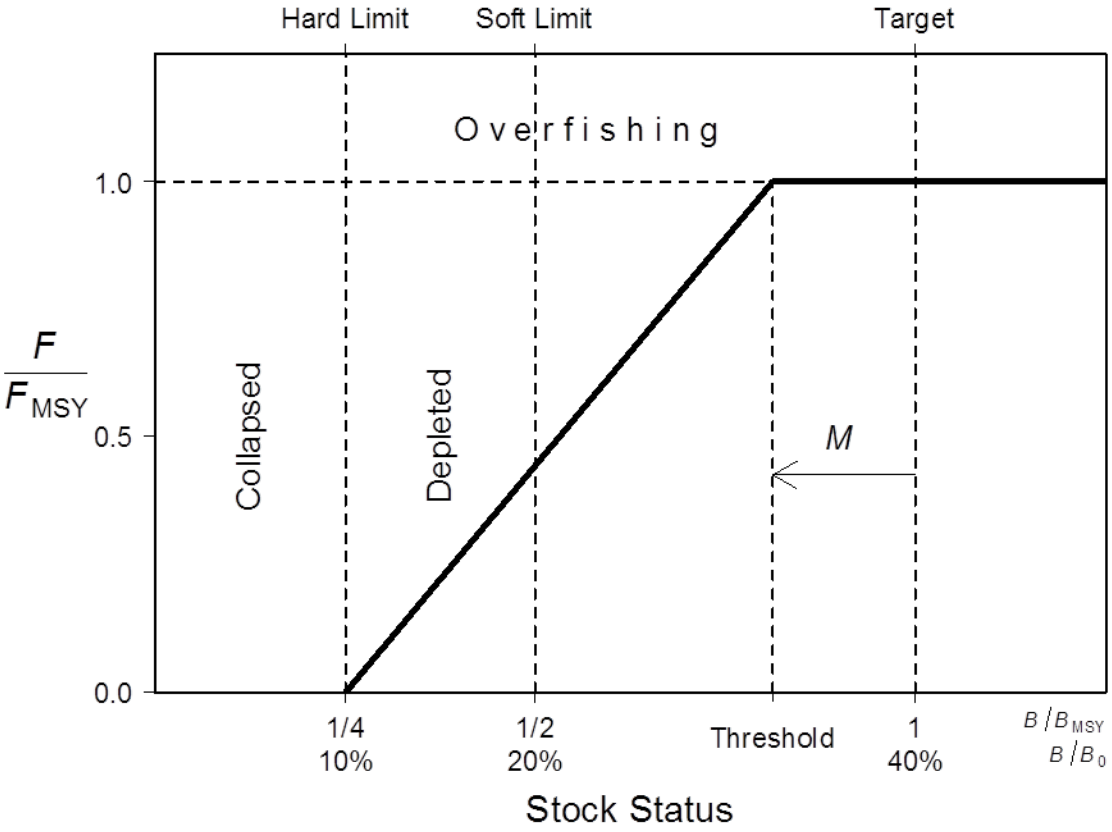


Figure 5. An example of a harvest decision rule used in the New Zealand harvest strategy standard (adapted from Ministry of Fisheries 2008).