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Current approaches for the Provision of Scientific Advice on the Precautionary Approach for Canadian Fish Stocks: Section 8 – Management Strategy Evaluation

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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.

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ABSTRACT

Fisheries management strategies require deliberate design to increase the likelihood that long-term sustainability objectives can be met. Compliance of management strategies with the Precautionary Approach and the DFO PA Framework means that a pre-specified plan should be developed with clear criteria for decision-making. Furthermore, the adopted plan should be evaluated to determine whether it can effectively avoid undesirable outcomes regardless of whether the outcomes relate to conservation or yield objectives. Management strategy evaluation is a simulation-based approach to assessing the relative performance of candidate management procedures under conditions that mimic plausible, though uncertain, stock and fishery dynamics.

The DFO faces increasing pressures to implement the Sustainable Fisheries Framework policy broadly across fisheries in Canada. This policy includes a suite of goals that relate to sustainable resource management, including the development of fishery reference points and harvest decision rules, the incorporation of habitat and eco-system considerations, development of formal measures for rebuilding depleted stocks, and the collaborative development of management procedures with resource users. Furthermore, the development of long-term management strategies, where formal stock assessment advice is updated periodically, has recently been promoted to increase the availability of government Science resources to support comprehensive policy implementation.

Management strategy evaluation is one means of examining the effects of such changes by considering the design of the management procedure used to integrate stock and fishery monitoring data, stock assessment methods, and harvest decision rules. For example, the consequences of adopting multi-year assessment schedules, or revising fishery-independent surveys, can be quantified using simulation outputs. The outputs allow the candidate management procedures to be ranked by how well each performs in relation to satisfying conservation and yield objectives. The approach is not without limitations; management strategy evaluation has been slow to become widely adopted due to lengthy development times and scarce technical resources to support implementation. However, management strategy evaluation is one of the few available methods that provide a consistent approach to informing resource use decisions and by design, demonstrates compliance with the requirements of precautionary fisheries management.

**Approches actuelles de prestation d'avis scientifiques dans le cadre de l'approche de précaution pour la gestion de stocks canadiens :
section 8 – Évaluation des stratégies de gestion**

RÉSUMÉ

Les stratégies de gestion des pêches doivent être conçues délibérément afin d'améliorer la probabilité d'atteinte des résultats de durabilité à long terme. Pour qu'une stratégie de gestion soit conforme à l'approche de précaution (AP) et au cadre du MPO lié à l'AP, il faut qu'un plan prédéterminé soit élaboré selon des critères clairs en ce qui concerne la prise de décisions. De plus, le plan adopté devrait être évalué pour déterminer s'il suffira à éviter de façon efficace les résultats indésirables, qu'il s'agisse d'objectifs de conservation ou de production. L'évaluation des stratégies de gestion est une approche basée sur la simulation qui vise à évaluer le rendement relatif de procédures de gestion envisagées dans des conditions qui imitent des dynamiques plausibles (quoiqu'incertaines) de stocks et de pêches.

Le MPO subit des pressions grandissantes en ce qui concerne son éventuelle mise en œuvre de la politique du Cadre pour la pêche durable dans l'ensemble des pêches du Canada. Cette politique comprend un ensemble de buts relatifs à la gestion durable des ressources, y compris l'établissement de points de référence pour les pêches et de règles de décision en matière de prises, l'incorporation de considérations liées aux habitats et aux écosystèmes, l'élaboration de mesures officielles pour rétablir les stocks épuisés, et la création de procédures de gestion en collaboration avec les utilisateurs des ressources. En outre, l'élaboration de stratégies de gestion à long terme, dans le cadre desquelles des avis officiels sur l'évaluation des stocks sont fournis périodiquement, a récemment été favorisée dans le but d'améliorer la disponibilité de ressources scientifiques gouvernementales à l'appui d'une mise en œuvre approfondie de la politique.

L'évaluation des stratégies de gestion est une façon d'examiner les effets de tels changements en considérant la conception des procédures de gestion utilisées pour intégrer les données de surveillance des stocks et des pêches, les méthodes d'évaluation des stocks, et les règles de décision relatives aux prises. Par exemple, les conséquences de l'adoption de calendriers d'évaluation pluriannuels, ou la révision de relevés indépendants de la pêche, peuvent être quantifiés grâce aux produits d'une simulation. Ces résultats permettent de classer les procédures de gestion envisagées selon leur rendement pour ce qui est de satisfaire aux objectifs de conservation et de production. Cette approche n'est pas sans restrictions. Il a fallu beaucoup de temps pour que se répande l'évaluation des stratégies de gestion en raison des longs délais d'élaboration et du manque de ressources techniques pour appuyer sa mise en œuvre. Toutefois, l'évaluation des stratégies de gestion est l'une des rares méthodes disponibles qui présente une approche cohérente pour informer les décisions relatives à l'utilisation des ressources. De plus, cette méthode, par sa nature même, démontre une conformité aux exigences de la gestion des pêches par précaution.

INTRODUCTION

Management strategy evaluation (MSE) embodies a systematic approach to designing robust resource management systems through extensive computer simulation and iterative stakeholder consultation. The approach is most commonly called management strategy evaluation, but is often called management procedure evaluation (MPE), or infrequently a management-oriented procedure (de la Mare 1998). The MSE method is designed to evaluate the consequences of a range of management procedures and report the results in a way that exposes trade-offs in performance against a suite of objectives. The purpose of MSE is not to provide an optimal strategy or solution, but rather to provide decision-makers with information that can be used to select a procedure that best satisfies the requisite trade-off between objectives and risk tolerance in the context of the overall management system (Smith 1994, Miller and Shelton 2010, Butterworth et al. 2010a).

A management strategy is comprised of stock and fishery objectives and the steps taken to achieve the objectives. The steps define a procedure that includes collection of stock and fishery monitoring data, processing of the data using stock assessment methods, and the provision of advice (e.g., annual catch or effort limits) using a consistent harvest decision rule. A key feature of the approach is prospective evaluation (FAO 1995) of the expected ability of the procedure to achieve stated objectives. The simulation phase of MSE can be conducted in the absence of a consultation phase for the purposes of evaluating the performance of an established or default management system. Ideally, however, responding to changes in: (1) the policy environment, (2) understanding of biological or environmental processes, (3) collateral capture of other species, (4) fish capture technology, or (5) market conditions, requires the periodic revision of objectives in a consultative process between analysts, decision-makers and resource stakeholders.

This paper describes the key elements of MSE and supports use of this methodology as one means of satisfying the requirements of the Precautionary Approach as specified in the DFO Sustainable Fisheries Framework policy and specifically the Decision-making Framework Incorporating the Precautionary Approach, hereafter called the DFO PA Framework. Where appropriate, excerpts from the DFO PA Framework are included using grey text boxes near relevant discussion. Terminology used throughout this paper is described in full in the Glossary.

THE MSE PROCESS

The following are the primary components of the generalized [*DFO Fishery Decision-making*] framework:

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

2. Harvest strategy and harvest decision rules;

3. The need to take into account uncertainty and risk when developing reference points and developing and implementing decision rules.

The MSE method is defined by four components that align with those identified in the DFO PA Framework: (a) measurable management objectives linked to stock status, as well as yield, (b) specific fishery and stock monitoring data and assessment methods, (c) harvest decision rules (or equivalently harvest control rules) that translate estimates of stock status into catch limits, and (d) a prospective evaluation of the entire procedure using simulation. The primary product of the simulation is a set of performance statistics that characterize uncertainty in achieving management objectives (de la Mare 1996). Management objectives reflect national and international policy commitments as well as specific statements by stakeholders, including the civil public, that identify their values and interests for the state of the stock and conduct of the fishery. Objectives must be rendered measurable by specifying a desired outcome or threshold (e.g., a fishery reference point or average catch level), a time frame in which to achieve the outcome, and the desired probability of achieving the outcome (or conversely the risk tolerance for failing to achieve the outcome).

The technical basis for MSE requires computer simulation to compare the likely consequences of applying candidate management procedures to alternative scenarios regarding the fish stock and fishery (Walters 1986, de la Mare 1986, 1996, 1998, Kirkwood 1997; Punt et al. 2001; Sainsbury et al. 2000). Scenarios represent alternative structural hypotheses about the fish stock and/or fishery dynamics that are not currently resolved by the available data or those that may never be resolved due to lack of resources or non-stationary dynamics. In a single species situation, MSE requires creation of a simulated or true stock and a perceived stock (Figure 1). The true stock is defined by structural hypotheses consistent with the existing data and is described mathematically using an operating model. Candidate management procedures are applied to the perceived stock, and are defined by the combination of (1) observed historical and future data generated by the operating model that represents the true population, and (2) a stock assessment method applied to the observed data, and (3) a harvest decision rule to translate assessment outputs into catch or effort limits. The stock assessment method may take the form of a population dynamics model that attempts a reconstruction of the stock biomass, or may be some direct metric of stock abundance such as an empirical stock index taken from fishery or survey outputs, e.g., an average catch per unit effort or swept-area biomass estimate.

Both the true and perceived stocks are simulated over time; at each time step a harvest decision rule is applied to the perceived stock abundance and its actual effect (i.e., the catch specified by the rule) tracked using the true stock. The performance of candidate management procedures is then evaluated against the true stock (Figure 1). Although this iterative process is more complex than traditional model-fitting stock assessment and stochastic forward projections, it acknowledges that the effectiveness of individual components of a management procedure (i.e., the data collection, stock assessment, and harvest decision rule) cannot be evaluated in isolation. Instead, the effectiveness of the entire procedure must be evaluated in a reasonable facsimile of the full context in which it will be used. This is because the interaction of the stock assessment outputs and harvest control rules cannot be reliably predicted on the basis of the performance of each individual component. It is possible that a management procedure may meet fishery objectives despite shortcomings in one of its components by virtue of design adjustments to other components (de la Mare 1998). For example, the harvest decision could explicitly incorporate a reduction in fishing mortality proportional to the amount of uncertainty in the estimated stock biomass produced by the assessment model. This design change to the rule would help compensate for stock assessment errors that might not be resolvable or may require investment in new data that would take time to accrue.

The process of management strategy evaluation can be conceptualized as the step-wise algorithm described below, or represented schematically as shown in Figure 1. The step-wise algorithm can be stated as follows:

1. Identify a working set of measurable management objectives through consultation with fishery managers and stakeholders with respect to desired outcomes for conservation, catch and inter-annual catch variability (also called stability),

2. Define a range of candidate management procedures by considering combinations of (*i*) data types and data collection procedures (e.g., sample size and frequency), (*ii*) assessment methods, and (*iii*) harvest decision rules,
3. Specify a set of operating models consistent with available data to enable simulation of alternative plausible scenarios for the stock and fishery dynamics, and to provide data generation mechanisms for stock indexing and biological data. Each operating model represents a scenario that reflects a specific hypothesis about the true nature of the stock. In most cases, this step involves fitting the operating model to available data, a process termed conditioning, to determine model parameters consistent with the stock history and the structural assumptions of the scenario. In data-limited situations, model parameters may be taken from the literature or similar species, in which case a wider range of alternative scenarios should be considered. Alternative operating models may be structurally different and/or may vary in their assumptions regarding key parameters,
4. Project stock and fishery status for each management procedure into the future under each alternative scenario that reflects a specific hypothesis about the true nature of the stock. Each iteration of the projection involves the following steps:
    a. generate the data with associated uncertainty that are available for stock assessment using the operating model,
    b. apply the stock assessment method to the data to estimate quantities required by the control rule,
    c. apply the harvest decision rule to generate a catch (or effort) limit, and
    d. apply the catch limit or other management action to the simulated true stock and fishery as represented by the operating model.
5. Calculate a set of quantitative performance statistics that can be used to compare outputs of candidate management procedures against the management objectives. Performance statistics quantify the objectives in terms of desired values and risk tolerances of failing to achieve desired outcomes.

Both scientific uncertainty and uncertainty related to the implementation of a management approach must be explicitly considered and the management decisions taken must be tempered when necessary to give effect to the PA.

Uncertainty in both scientific data and the ability of a management procedure to achieve the desired outcomes are taken into account when identifying a preferred management approach using MSE. A key feature of the evaluation process is that the assessment method applied at each time interval at step (4b) is blind to the workings of the operating model; that is, the assessment is only provided with data that can actually be observed such as survey indices of abundance, catch or catch-at-age. In contrast, the operating model may be informed by assumptions or data not used in the procedure because, for example, some historical data are no longer collected. All simulated data are generated with appropriate statistical uncertainty to account for process and observational errors. The operating model, on the other hand, serves as an omniscient accountant of the true state of the stock and fishery.

The MSE method relies on negative feedback control to provide potential corrective actions in response to declines in stock size or erroneous perceptions about the current status of the resource. Like traditional stock assessments, the MSE approach integrates resource monitoring data into stock assessments and management advice; however, it differs from the traditional approach because it includes a simulation step to test whether application of stock assessment methods and decision rules provide outcomes that are consistent with the fishery objectives identified in step 1. The feedback simulation, sometimes called closed-loop simulation, requires the consistent application of the management procedure into the future using the data collected up to each point in time (de la Mare 1998, Punt et al. 2002a,b,c). Typically, fishery objectives fall within the three broad categories of conservation, catch, and inter-annual stability of catch, i.e., catch volatility. Each category requires specification of a desired outcome, the time period in which to achieve the outcome and acceptable risks of outcomes such as irreversible or economically undesirable stock depletion (Butterworth 2007). Although the order of priority of multiple, conflicting objectives is subject to policy, sustainability objectives generally place priority on conservation (see Shelton and Sinclair 2008). Approaches to prioritizing objectives when selecting a management strategy are described in more detail in Section 4.

Each management strategy component in steps (4a – c) requires a particular set of choices. For example, the data step could involve aggregate survey indices of abundance, or more-detailed age-based indices; the assessment step could involve a simple or complex modeling approach; and the harvest decision rule may make adjustments for perceived risk and uncertainty. More commonly, however, risk tolerances would not be specified in the decision rule, which would instead be adjusted or tuned so that together with the stock assessment the required risk tolerance is achieved. Presenting the effects of these choices, as measured by performance statistics calculated using the status of the true stock in step (5), is the main focus of management strategy evaluation.

It is desirable that scientific uncertainty be quantified to the extent possible and used to assess the probability of achieving a target or of a stock falling to a certain level under a specific management approach.

Performance statistics generated by feedback simulation quantify management procedure performance and uncertainty by producing state, duration, and probabilistic measures based on the status of the operating model. State measures capture the level of the operating model state (e.g., spawning biomass, fishing mortality), at a single point in time which are used to judge performance against pre-specified outcomes such as limit and target reference points. Duration measures quantify how long certain conditions might persist, or the expected time elapsed before a specified state is reached. For example, the expected time to achieve a rebuilding target is a critical performance statistic in planning the restoration of a depleted stock. Both state and duration measures are random variables in the feedback simulations and are calculated based on the status of the operating model. A complete evaluation of the effectiveness of candidate procedures requires specification of a level of probability at which to measure the performance statistics. For example, the stock size relative to the target spawning biomass, B_{TARGET}, is a measure of conservation and economic performance that can be captured as state, duration, and probability measures: (1) the biomass at a given time for some probability, which can be compared to B_{TARGET}; (2) the expected time to achieve B_{TARGET} for some pre-specified probability; or (3) the probability of reaching B_{TARGET} by some pre-specified time.

Successful management strategies must, on average, achieve the desired objectives even if the stock assessment component of the procedure is significantly in error. Such a management strategy is deemed robust to assessment uncertainty. The advantage of conducting this evaluation using a representation of the true stock and fishery dynamics generated by the operating model is that the errors due to the stock assessment in the procedure can be diagnosed. Furthermore, attempts can be made to adjust, or tune, either the assessment or the harvest decision rule to provide the desired performance.

One of the advantages of the MSE methodology is that it is a consistent approach, regardless of the context. It can be applied across a wide range of factors such as (1) species, (2) stock condition, and (3) data availability including factors such as survey frequency or the presence of auxiliary oceanographic or biological data. For example, evaluation may focus on questions about the utility of increased levels of data collection, such as the anticipated benefits of more frequent fishery-independent surveys. However, Mace (2001) noted that the accumulation of more, and possibly better quality data, means options for modelling the system and characterizing uncertainty improve, possibly resulting in the identification of greater levels of uncertainty but more informed risk assessment. Regardless of the outcome, MSE can form an appropriate foundation for assessment of risk by generating new resource-monitoring data for each simulation year that incorporates both process and observation errors and consistently applying a management procedure. This feature has the added benefit of allowing feedback effects achieved through continuous updating of trend information to correct for errors in earlier yield recommendations, at least to some degree. In effect, the management procedure benefits from accumulating data with the passage of time, for example by updating the stock-recruit model fit to achieve more precise estimates of key parameters.

SELECTION OF A MANAGEMENT STRATEGY

Within the MSE framework, treatment of uncertainty is accomplished by stating specific operational objectives in probabilistic terms while being equally specific about the time frames over which objectives should be achieved. It is the specification of time frames and probabilities associated with limit, or target, reference points that translate goals into measurable objectives. In the general context of the DFO PA Framework, the relative importance of objectives should be arranged such that conservation-related objectives are given priority, while yield and stability considerations are examined at subsequent stages in the evaluation process. The approach should take into consideration the requirements of fishery managers and stakeholders *a priori*, such that conflicts among objectives are made explicit. Management strategies that fail to meet an objective at any stage are discarded as not being effective at generating desirable outcomes. The approach can be tailored to most situations, but usually requires that specific solutions are developed that recognize the case-specific objectives, data, assessment methodology, and harvest control rules for each fishery.

For example, Cox and Kronlund (2008) applied a hierarchical approach to the selection of a management strategy. Their scheme attempted to simplify the decision environment where value-laden trade-offs between conflicting objectives need to be made. The approach orders fishery management objectives linearly according to their level of priority under a precautionary management policy. Higher level objectives must be met before results related to lower level objectives are considered. Management procedures that fail to meet an objective at any level are eliminated from further consideration. Procedures that survive this hierarchical filtering to the lowest level represent the choices most consistent with the objective; where more than one procedure satisfies the objectives the procedure implemented may be selected on the basis of factors that were not evaluated using MSE.

The selection of a preferred management strategy could also be organized as a two step process, as suggested by Miller and Shelton (2010). In their approach, the first step involves the elimination of management procedures that don’t satisfy imperative performance statistics related primarily to resource conservation issues, e.g., procedures that on average have a greater than 10% probability of falling below the limit reference point are eliminated. In addition to conservation issues, those strategies that don’t satisfy imperative fishery issues (e.g., less than a 20% probability of an annual variation in TAC of greater than 15%) are eliminated. In the second step the trade-offs between less imperative performance statistics are evaluated. For example, having satisfied the imperative objectives, the trade-off between the average catch and variation in catch could be further evaluated across competing management procedures.

WHEN SHOULD MSE BE USED?

Although it will not be practical to apply MSE to all fisheries in Canada due to lack of resources, several situations are described below where application of feedback simulation and consultation within the DFO and/or with external stakeholders could be advantageous. The potential advantages of MSE are well-described in the literature (e.g., de la Mare 1986, Cooke 1999, Butterworth 2007). Most often the benefits are compared relative to the traditional approach of trying to select a best assessment model and relate to avoiding unnecessary variability in assessment approaches from year to year, evaluating the consequences of assessment errors, evaluating the ability to evaluate long-term trade-offs correctly and the provision of a decision-making procedure in years where an assessment cannot be conducted.

Less attention has been paid to the advantages of MSE with respect to determining whether data collection programs are adequately designed or even required. Also, there have been few studies to determine whether a simple assessment model and/or harvest control rule will suffice in a particular context versus more elaborate treatments, although there are suggestions that a simple model might be preferred in terms of robustness and ease of implementation (Parma 2002, Punt 2008, Butterworth et al. 2010). Practical limitations on computing time mean that elaborate assessment models that require many hours to achieve a solution are inherently risky, since their performance cannot be adequately evaluated in a simulation-based facsimile of the management context. Failure to investigate a wide range of alternative hypotheses because the parameters cannot be reliably estimated using currently available data is in conflict with the Precautionary Approach and DFO PA Framework, which require evaluation of uncertainty. The MSE method allows alternative hypotheses to be simulated using the operating model even though the assessment model in the procedure may be much simpler and actually ignore the population and fleet dynamics being investigated.

Lessons learned and techniques for implementing MSE are discussed by various authors including Butterworth and Punt (1999), Punt et al. (2001), and Rademeyer et al. (2007). Rademeyer et al. (2007) provide a useful synthesis of approaches to choosing between candidate management procedures and identify considerations for choosing between data-based and model-based formulations. They also distinguish between scenarios selected for inclusion in primary simulation testing aimed at ranking management procedures and those used to test robustness or sensitivity. This approach helps to reduce the burden of presenting the voluminous results of MSE analyses, which is a major challenge to the communication of advice.

This section focuses on applications of MSE to evolving DFO fisheries management requirements. Applications include consideration of multi-year stock assessment schedules and changes to survey design, rebuilding of depleted stocks, and data-poor fisheries. Extensions of a single gear and fishery perspective to a multi-species ecosystem context are discussed briefly but not developed here.

MULTI-YEAR ASSESSMENT ADVICE

Fisheries and Oceans Canada is taking a new Multi-Year Approach to Fisheries Management based on long-term planning and strategies. This includes the development of multi-year management plans, termed ‘evergreen’ Integrated Fisheries Management Plans (IFMPs), supported by scientific advice that is conditioned on the requirement that the advice must span the period of the management cycle. Where possible, multi-year science advice will complement this new long-term approach via the development of management strategies consistent with the DFO PA Framework. Accordingly, each situation is required to include the establishment of reference points and associated stock status zones, along with harvest decision rules and the management measures associated with each stock status zone. In some cases a multi-year formal advisory process may not be appropriate based on stock biology or for meeting the terms of multi-national agreements. For example, shorter-lived species such as Pacific herring (*Clupea pallasii*) exhibit large year-to-year fluctuations in stock biomass driven by large fluctuations in recruitment (Cleary et al. 2010). Such population dynamics may suggest that more frequent formal updating of stock status is required when compared to longer-lived groundfishes such as rockfishes (*Sebastes* sp.).

Identifying the required frequency to update assessment advice is a natural application of the MSE methodology. For example, MSE can be used to compare the relative performance of management procedures that vary in assessment frequency but utilize the same harvest decision rule. The results of such comparative simulations can help reveal trade-offs between the ability to meet long-term conservation objectives, the costs of stock assessment, and the expected stability of catches (e.g., Kell et al. 1999, ICES 2012). In particular, the costs and benefits of management procedures that require less frequent updating of stock status than existing assessment schedules can be evaluated and successful procedures ranked by anticipated costs. Although a default approach to multi-year management plans could be to set a constant harvest level based on the most recent assessment for the duration of the plan, such an approach may increase risks introduced by lag effects, i.e., persistent harvests at too high or too low a rate. However, the development of a management procedure that includes a harvest decision rule affords the opportunity to adjust catch levels in response to perceived changes in stock abundance in the interim years between stock assessments, possibly based on updated survey results. The latter approach has been shown to perform well within a MSE for many fisheries (e.g., Rademeyer et al. 2007, Cox and Kronlund 2008) and is a significant advantage of the method.

REQUIREMENT FOR REBUILDING PLANS

When a stock has reached 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.

The primary objective of the Canadian Species at Risk Act (SARA) is to prevent Canadian species from becoming extinct and to ensure the necessary actions for species recovery. Currently, when the Government of Canada has accepted a determination by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) that a species is at risk of extinction, a Recovery Potential Assessment (RPA) is required before the species is listed under the SARA. In some cases, DFO may conduct an RPA on the basis of the COSEWIC determination alone to inform the Government decision on acceptance of the determination. A requirement of the DFO RPA process (DFO 2007) is the recommendation of population and distributional objectives and the identification of threats (e.g., fishing). Mitigating measures must be identified for each threat via recovery scenarios. The MSE process is an ideal tool for application in RPA development to evaluate the probability of recovery in relation to proposed population and distributional objectives over specified time frames (e.g., Shelton et al. 2007). For example, a 5-year review of the effectiveness of proposed mitigations is required under Section 46 of the SARA. Many of the assessment tasks required as part of a RPA would also benefit from an MSE approach, such as the requirement to "*assess the probability that the recovery targets can be achieved under current rates of population dynamics parameters, and how that probability would vary with different mortality (especially lower) and productivity (especially higher) parameters.*" (DFO 2007, page 2). The development of a management procedure that specifies actions across the entire range of stock depletion to provide reasonable assurance that conservation objectives are met, actually meets the requirements of a rebuilding plan without the necessity for a separate process. This is because mitigating measures are pre-specified in the design of a management procedure developed using MSE that anticipates the possibility that stock status approaches or breaches a limit reference point.

Regardless of the requirement for a recovery potential assessment, MSE can help to illustrate the consequences of alternative management measures aimed at rebuilding depleted stocks. The advantages of this approach for designing and evaluating rebuilding plans have been demonstrated in several fishery jurisdictions, including Europe (Bastardie et al. 2010) eastern Canada via the Northwest Atlantic Fisheries Organization (Miller and Shelton 2010), and the United States (Punt and Ralston 2007). Performance statistics that show the expected trade-off relationships between recovery-focused performance statistics, such as the time to reach recovery targets, and the costs of rebuilding over multiple scenarios about uncertain stock and fishery dynamics can help decision-makers make informed choices about which rebuilding strategy best meets specific rebuilding objectives. For example, performance statistics computed from feedback simulations and used to evaluate rebuilding plans in other jurisdictions include:

1. the probability of reaching the recovery target biomass within a specified number of years,
2. the number of years until biomass exceeds the recovery target biomass,
3. the average ratio of fishing mortality to fishing mortality at MSY, i.e., the average of (F_t/F_{MSY}), over the rebuilding time period,
4. the average annual catch, and average annual variation in catch over the rebuilding time period, and
5. the average age of fish.

Depleted species subject to rebuilding plans often have patchy distributions leading to high survey variability; maintenance of the same precision of survey abundance estimates may require more survey effort (i.e., greater survey costs) than when the species was at a healthy level of abundance. Application of MSE can help to determine how much more survey effort might be expected to assure that recovery objectives can be met and allow a return to the target biomass and a more profitable level of harvesting. Uncertain stock dynamics have also been considered when evaluating the robustness of rebuilding plans including examination of factors such as the shape of the spawner-recruitment curve, productivity, the natural mortality rate, recruitment depensation at low stock sizes, and the impact of climatic regimes on recruitment (Punt and Ralston 2007, Bastardie et al. 2010, Miller et al. 2008, Punt 2011).

STOCK ASSESSMENT SURVEY DATA EVALUATION

Long-term resource management time-series are integral to the implementation of the DFO Sustainable Fisheries Framework policy because they serve as a basis for establishing biological reference points and are a key input for stock assessments that estimate current stock status relative to reference points. Fisheries and Oceans Canada requires a methodology for evaluating how changes to resource surveys affect scientific advice in support of fisheries management. Surveys are frequently important determinants of fisheries management decisions and typically represent a large percentage of the overall cost of the management system. Long-term survey time-series are utilized by agencies other than DFO. For example, survey data are frequently used by COSEWIC to evaluate the risk of extinction of marine species. Furthermore, involving the fishing industry and other stakeholders (e.g., First Nations, recreational sector) in the collection of monitoring data serves Sustainable Fisheries Framework (SFF) requirements for consultation; stakeholders may have suitable expertise, vessels and gear to conduct the work, and a keen interest in supporting surveys because of their direct connection with the resource. For example, on the west coast of Canada, Sablefish (*Anoplopoma fimbria*) research surveys are undertaken jointly with the Canadian Sablefish Association (NRC 2004) and an extensive multi-species bottom trawl survey program is conducted in collaboration with the Canadian Groundfish Research and Conservation Society (Olsen et al. 2007 a-d). On the east coast of Canada, numerous research surveys have been conducted in collaboration with industry, operated under the auspices of the Groundfish Sentinel Program (NRC 2004). These include: the Scotian Shelf and Southern Grand Banks Survey, a longline survey targeting halibut (DFO 2002) and the 4VsW Sentinel Survey, a longline survey targeting Atlantic Cod (*Gadus morhua*) (NRC 2004). These collaborations are further supported by the Fishermen and Scientist Research Society, a non-profit organization created to promote interactions and understanding between industry and DFO in the Maritimes region.

In the course of such collaborative undertakings, the question of how much to invest in stock and fishery monitoring data naturally arises. Government and stakeholders must assess the trade-offs between objectives related to conservation and sustainable yield, which includes assessing the ability to satisfy the requirements for precautionary fisheries management as specified in the DFO PA Framework. The Government of Canada has a responsibility to ensure that fisheries management systems meet Canada's commitments to a suite of international agreements and statements of national policy (Shelton and Sinclair 2008), while stakeholders may see opportunities for increased certainty in management decisions, a reduction of risk to the resource, or enhancements to the amount and timing of harvests by virtue of investment in information. However it is not always possible to determine *a priori* whether enhanced survey effort in the form of the number of sampling sites, the level of biological sampling for size and age, or increased spatial and temporal coverage, will result in appreciable benefits with respect to achieving stock and fishery objectives. This uncertainty arises because surveys are not usually the sole input that determines whether conservation or sustainable use objectives are met. Other considerations unrelated to the outputs of a survey can affect the decision-making process such as the quality of fishery and biological data, the properties of the stock assessment methodology, the characteristics of the harvest decision rule, socio-economic factors, and how well the management system is able to adhere to harvest recommendations, i.e., implementation uncertainty.

Application of MSE, in which all components of the fishery system are evaluated simultaneously, can help assess the relative importance of the above factors by informing a cost-benefit analysis of survey programs. For example, MSE could be used to determine how much more survey effort (e.g., increased sample size, frequency, or spatial coverage) might be required to assure that a given management procedure is meeting conservation objectives. Conversely, the approach could also be used to examine the consequences of reducing survey effort in the face of budget constraints to determine if conservation objectives could be achieved without unacceptable reductions in fishing opportunities.

Blanchard et al. (2008) noted the increasing use of large-scale surveys for more than one purpose. For example, estimates of abundance may be required for more than one species as well as information on their spatial distribution, age or size-structure, and associated biological measurements. Large-scale bottom trawl surveys on the west coast of Canada (Fargo et al. 1990, Sinclair et al. 2003, Olsen et al. 2007 a-d, Workman et al. 2007, Workman et al. 2008) provide information for over 250 different populations, only some of which are commercially valuable while all could be of potential interest for COSEWIC review and consequently have implications under the SARA. Additional demand for large-scale survey data is created in Canada by SFF requirements to develop an ecosystem approach to fisheries management (see Section 4.6).

Optimization of a multi-objective survey is by necessity a compromise that means the best results for a specific species are achieved at the expense of other target species. The primary impediment to resolving this conflict may be a lack of objectives for situations where simultaneous maximization of multiple species is impossible (e.g., Butterworth and Punt 1999). However, designing multi-species management systems is possible if objectives are explicitly stated and the tradeoffs between attaining specific-species objectives are evaluated.

COLLABORATIVE STAKEHOLDER ENVIRONMENT

To be successful, the utilization of this decision making framework generally and its application to the specific fisheries needs to be done in concert with the fishing participants, to which it is applied, and with engagement of others with an interest, including Provinces, Territories, Aboriginal people, wildlife management boards (as authorized under a land claims agreement), processors and others. If effectively implemented in this way, this approach will facilitate the stable and predictable business environment in the fishery that participants seek, while at the same time contributing to sustainability. In fact, decision rules we are seeking to establish are only likely to hold if they are developed in concert with its participants.

Stakeholder engagement is necessary to the implementation of the DFO PA Framework. Fisheries and Oceans Canada consults with First Nations, stakeholders and the civil public to improve departmental decision-making processes, promote understanding of fisheries, oceans and marine transport issues, and strengthen relationships. The MSE approach can serve as a useful tool for engaging stakeholders in the process of developing a management procedure where resources are available and the stakeholder climate is amenable to iterative consultation. Stakeholder participation can occur throughout the MSE process, including: (1) the development of measureable stock and fishery objectives, (2) the identification of candidate management procedures, (3) the identification of key uncertainties to be considered, (4) participation in debates about acceptable performance tradeoffs across conflicting objectives, and (5) the provision of analytical expertise not available within the management agency. Experience with the Canadian Sablefish fishery has shown that the inclusion of stakeholders into the MSE process in this way can lead to practical management procedures that are acceptable to industry participants while ensuring that conservation objectives are met (Cox and Kronlund 2008). Additional benefits of stakeholder participation in MSE include improved communication of management objectives arising from different stakeholder interests, a clearer understanding of key trade-off decisions, and increased support among stakeholder participants for the selected management strategy (Butterworth and Punt 1999, Smith et al. 1999, Mapstone et al. 2008, NAFO SC 2008). In most cases, consultations with the fishing industry and other stakeholders in Canada are focused on the development of Integrated Fisheries Management Plans (IFMPs) with the short-term objective of setting annual harvest levels. The MSE framework can help to identify management procedures that are precautionary in the face of uncertainty and that also serve the economic and social interests of all stakeholders over the long-term.

Links between MSE and eco-certification requirements may also provide an added incentive for stakeholders to participate in, and support the outcomes of, an MSE process. For example, scoring criteria for performance indicators used by the Marine Stewardship Council (MSC) reward the testing or evaluation of harvest strategies, harvest control rules, and the assessment of stock status. Within the criteria definitions used by the MSC, MSE is listed as an appropriate tool to conduct such evaluations for some fisheries (Marine Stewardship Council 2009). While MSE can play an important role in facilitating stakeholder involvement in the development of decision rules, there are also several challenges that must be considered before committing to the analysis (see Section 6).

DATA-POOR SITUATIONS

The MSE approach has most often been applied to data-rich situations, however, arguments have been made for the benefits of MSE in data-poor cases (e.g., Smith et al. 2009, Dichmont and Brown 2010) and as an alternative to expert-judgment alone (Butterworth et al. 2010b). High uncertainty about population parameters, current stock status, and the reliability of available data can be addressed by testing candidate management procedures over a wide range of scenarios about population dynamics, observation error, and the possibility that observed stock index data are not proportional to true stock status. Simulation testing of candidate management procedures to determine the most acceptable trade-off relationship over all plausible scenarios can lead to robust management choices even in data-poor situations. In addition, MSE can be used to help determine the extent to which additional data collection would improve management performance for data-poor fisheries (Butterworth et al. 2010b).

MULTI-SPECIES AND ECOSYSTEM APPLICATIONS

This decision framework is one part of an overall Sustainable Fisheries Framework for Canadian fisheries, which includes a number of other policies and initiatives, completed or being developed, such as a Forage Species policy and a Sensitive Benthic Areas policy that together will provide a more rigorous and comprehensive approach to managing Canada's fisheries, factoring in ecosystem considerations and precaution.

Management actions related to other ecosystem elements may also be considered when using the decision-making framework based on available information.

Canadian fisheries policy establishes the expectation that environmental and ecosystem impacts should be accounted for in the selection of a management strategy, despite the lack of well-established mechanisms for determining the effects of environmental change on marine resources and in most cases an adequate level of ecosystem understanding. Management strategy evaluation has been applied in the context of the Gulf of Alaska Walleye Pollock (*Theragra chalcogramma*) fishery to evaluate the effects of changing predator-prey relationships on the selection of a management strategy (A'mar et al. 2010), as well as the effect of changing climatic regimes (A'mar et al. 2009). The effects of climatic changes on the performance of management strategies has also been investigated using MSE for Pacific salmon (Dorner et al. 2009) and U.S. West coast groundfish stocks (Punt 2011).

However, in many cases the forcing mechanisms of changing environmental conditions are not well understood and in particular their impacts on fish stocks are uncertain. Therefore a management procedure developed with the knowledge that non-stationary effects cannot be accurately predicted or even reliably detected until they are well advanced offers significant advantages. Since there is no imperative that the management procedure match the stock and fishery dynamics of the operating model, a procedure can be tested for robustness against environmental or climate change factors simulated by the operating model. A significant advantage of MSE is that the procedure can be blind to these effects and need not explicitly account for the underlying dynamics or even require inputs related to non-stationary effects (de la Mare 1998).

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. Management actions related to other ecosystem elements may also be considered when using the decision-making framework based on available information.

The DFO PA Framework does not consider multi-species fisheries explicitly; the harvest strategy policy is in general developed for a single species, single gear fishery context. However, both the DFO PA Framework and the umbrella Sustainable Fisheries Framework expand requirements for Science advice to environmental or habitat considerations, and to fishery impacts on co-harvested stocks. These kinds of requirements have been investigated elsewhere using MSE; the performance of the management procedure for an Australian multi-species trawl fishery was evaluated against specific objectives using MSE by Punt et al. (2002a-c). Their operating model allowed for discarding due to fish size, lack of quota, and because of mismatches in the total allowable catches set independently for each species.

However, the scientific literature to date suggests that MSY cannot be achieved for a mixture of harvested species simultaneously (Beddington and Cooke 1982) so that a management strategy needs to be applied that takes into account the tradeoffs in yields between interacting species in an ecosystem. As an example, Walters et al. (2005) used a simulation with constant catch set to MSY from single species assessments to show that MSY is unattainable for several species, with top predator populations most often declining in abundance. Dichmont et al (2006) used MSE to demonstrate that multiple prawn species cannot be sustainably harvested at individual effort rates at MSY where they are caught simultaneously. They developed a five-stock, two species operating model for the Australian Northern Prawn Fishery that included stock-specific recruitment relationships and was conditioned using fishery logbook time-series and research data. Key uncertainties tested were changes in gear efficiency over time and management procedure implementation error. Simulation testing of a range of management procedures showed that one of the species could not be maintained at or above the spawner level corresponding to maximum sustained yield, S_{MSY}, because the two species (*Paneus esculentus* and *P. semisulcatus*) are caught simultaneously in an effort controlled fishery. The management procedure that best maintained both species near S_{MSY} was found to be one that set more precautionary effort targets for *P. esculentus* and shifted the timing of the fishing season to direct effort away from *P. esculentus*.

Unless objectives are adjusted to accommodate minimizing the risk of any one species falling below a conservation threshold, some stocks will inevitably be overharvested to enable prosecution of a multi-species fishery. The New Zealand operational guidelines, which are based on MSY concepts, acknowledge the problem of closures of fishing on one stock in a mixed-species fishery causing closure of the entire fishery, or at least significant costs to implement rebuilding measures. In response to this possibility, the operational guidelines advocate taking corrective action well in advance of a limit reference point breach (Ministry of Fisheries 2011). These issues are particularly exacerbated in highly integrated, multi-gear fisheries such as the commercial groundfish fishery in the Pacific Region. This fishery intercepts over 38 species important to the various participating longline hook, trap, and trawl gear sectors by virtue of quota limitations or conservation concerns, and an additional 250 species are intercepted. Challenges to implementing SFF goals for ecosystem-based management in such a context are considerable. However, Mace (2001) suggested that adopting F_{MSY} as a limit reference point, coupled with the implementation of management procedures that assure the probability of exceeding the MSY fishing rate is low, could be an effective means of making the goals of ecosystem-based management operational. Sainsbury et al. (2000) discuss approaches to using MSE for decision-making in the context of benthic habitat management, fish community composition, and coincidental catch of species at risk.

WHEN RESOURCES DO NOT ALLOW CASE-SPECIFIC MSE

Management strategy evaluation is resource intensive and it is unlikely that it can be applied on a stock-specific basis for all cases. However, other jurisdictions such as Australia (AMFA 2007) advocate simulation testing of generic stock and fishery scenarios to identify management procedures that can be applied in the absence of a stock-specific evaluation. This approach may be particularly important when information is incomplete and/or uncertain, and when the harvest decision rule is complex. Application in Australia allows the adoption of management procedures where the components are generally believed to have acceptable performance characteristics and possibly provides an interim strategy when it is not feasible to immediately develop full MSE analyses on a stock-specific basis. For example, the situation of depleted fish stocks in European seas under the jurisdiction of the European Commission resulted in the proposal of a generic harvest control rule founded on objectives related to maximum sustained yield, avoidance of discarding, bycatch considerations, and multi-species harvests (Froese et al. 2011, Kronlund et al. 2013).

In contrast, Butterworth and Punt (1999) concluded against the development of generic decision rules as an approach. They cited the International Whaling Commission's pursuit of a generic management strategy that eventually required the evaluation of case-specific options to deal with multi-stock considerations for which a generic rule was not robust (IWC 1994). Butterworth and Punt (1999) concluded that despite valuable insights gained by the IWC's testing of general strategies, little analysis time was saved because of the requirement to condition the operating model on case-specific data already available. However, the lack of capacity to implement unique management strategies for all fisheries in Canada should not support the status-quo where harvest decision rules have not been implemented. Management strategies that include generic assessment and decision rule components tested under broad simulation conditions could be considered in the absence of stock-specific solutions (see Froese et al 2011, Butterworth et al 2010a, Deroba and Bence 2008).

CONSISTENCY OF MSE WITH THE DFO PA FRAMEWORK

Development and evaluation of management strategies using a feedback simulation approach addresses the requirements of the precautionary approach to fisheries management as well as other aspects of DFO's fishery decision-making framework. In particular, the approach is able to:

1. consider alternative data collection and stock assessment approaches for characterizing stock status,
2. evaluate alternative forms of decision rules that specify how harvest levels should be adjusted based on differences between stock status and operational targets,
3. demonstrate, via computer simulation, whether whole management strategies are likely to meet fishery objectives while avoiding undesirable outcomes,
4. take into account model (structural) uncertainty where the choice among competing models that represent different plausible hypotheses cannot be resolved,
5. include process error that represents variability not captured in the model, and
6. include observation error.

Footnote 6. This decision framework is consistent with the 1995 FAO Code of Conduct for Responsible Fisheries and the 1996 FAO Technical Guidelines for Responsible Fisheries: Precautionary Approach to Capture Fisheries and Species Introductions.

Management strategy evaluation changes the focus of advice from the selection of a best assessment to the identification of a preferred procedure. The preferred procedure is one that satisfies most closely the desired objectives over a wide range of plausible scenarios about the resource and fishery processes (Smith 1994, de la Mare 1998, Miller and Shelton 2010). The MSE method is compatible with the Precautionary Approach as specified in FAO (1995) and the DFO PA Framework because it demonstrates robustness in the face of uncertainty by testing the performance of candidate management procedures against a range of stock and fishery scenarios. This is one of the most significant advantages of MSE; it serves as one means of demonstrating due diligence that a management system has a reasonable expectation of meeting the agreed-upon conservation and yield objectives. Without consideration of the management strategy as a whole, it is nearly impossible to predict its behaviour across a variety of plausible scenarios for the stock and fishery. For example, Table 1 provides a summary of how choices required during implementation of the DFO PA Framework (i.e., management procedure design choices) could be organized into a MSE process. All of the choices identified in Table 1 are required in order to implement the DFO PA Framework, regardless of whether or not these choices are based on simulation testing. This list is not comprehensive, but already creates a large number of possible combinations of the various choices. This complexity suggests that the performance of a procedure relative to stock and fishery objectives is difficult to anticipate unless it is tested under known (simulated) conditions.

The outcome of selecting a management procedure is guidance to decision makers in the form of a total allowable catch, effort, or some other control variable such as fishing season, or size limits, etc. The selected management procedure may not include MSY- or depletion-based reference points explicitly. However, this does not mean that the approach is inconsistent with the DFO PA Framework because the prospective evaluation of the procedure can include performance statistics based on the true reference points derived from the population simulated by the operating model, such as B_{MSY}, F_{MSY}, or MSY. In cases where there are insufficient data to reliably estimate MSY-based reference points, or even approximations (proxies), a simple management procedure could utilize changes in a survey index to adjust annual total allowable catch (Shelton and Miller 2009, Miller and Shelton 2010, Cox and Kronlund 2008). Such a management procedure that does not explicitly include reference points can be tuned to achieve the desired stock and fishery outcomes relative to the true limit and target reference points derived from the status of the operating model.

LIMITATIONS OF MSE

Widespread acceptance and implementation of the MSE approach has been slow despite its attractiveness from a scientific and precautionary point-of-view (Smith et al. 1999; Butterworth 2007). Extensive work has been conducted in South Africa, Australia, and New Zealand where MSE has found application (Butterworth and Punt 1999; Smith et al. 1999; Starr et al. 1997, Punt and Smith 1999, Dichmont and Brown 2010 [Australian crab fishery]). Difficulties in adopting formal management strategies have been well-documented (e.g., Butterworth and Punt 1999, Butterworth 2007, Rochet and Rice 2009, Butterworth et al. 2010a), and appear to derive from several causes, among them:

1. a lengthy development time and the requirement for a high level of quantitative skills to implement MSE means that applications often require an analytical team rather than a single individual, i.e., resource intensive,
2. a lack of stakeholder and management confidence in following a procedure that is derived in a more complicated way than a typical stock assessment,

3. a lack of stakeholder ownership of the process, sometimes due to poor management of resources allocated between the technical aspects of the simulation exercise and the requirement for meaningful iterative consultation (Rochet and Rice 2009),
4. difficulty determining the relative credibility of alternative operating models, i.e., selecting the so-called reference set, and establishing the plausibility weighting of each scenario (e.g., Butterworth and Punt 1999, Miller and Shelton 2010, Shelton 2011),
5. insufficient attention to uncertainty, including underestimation of uncertainty and difficulties in estimating the extremes of the distributions of key parameters, can lead to false confidence in predicted outcomes (Rochet and Rice 2009),
6. lack of guidance regarding the appropriate trade-offs between objectives (e.g., maximizing catch, reducing inter-annual variation in catches, minimizing the risk of serious stock depletion),
7. the perception by all parties that decision-making has been handed over to an automated process with no chance for intervention,
8. reluctance to accept advice that provides a single catch or effort recommendation as a result of applying the selected management procedure, i.e., a perception of lack of flexibility, and
9. uncertainty over the future availability of data used by the management procedure or the lack of data.

In summary, limitations primarily relate to an increased requirement for analytical resources, significant development times, coordination of an environment conducive to consultation, and a misconception that all the problems faced in the best fit model approach to fishery stock assessments are eliminated. Based on review of experience in the International Whaling Commission and in South Africa, Butterworth (2007) suggested necessary precursors for successful MSE implementation include:

1. agreement on data quality and availability for the management procedure,
2. agreement on the conditions under which a management procedure might be changed or brought forward for review,
3. organizational processes for regular interaction among scientists, managers and stakeholders during development of the management procedure to encourage buy-in to the outcome, and
4. adherence to strict deadlines for completion of the sequential steps of preparing historical data and the operating models for use in simulation testing.

The MSE process is time-consuming and the complexity of implementing the simulation framework requires high level skills in stock assessment and modelling, and is computationally intense. Where MSE processes are undertaken it is critical to provide adequate resources, which may entail the formation of assessment teams comprised of subject-matter experts from government, academia and the private sector.

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. Such 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 requirement for prospective evaluation was included in the Precautionary Approach to fisheries (FAO 1995) to mitigate against negative effects on the stock and fishery. The MSE method is designed to allow proposed management plans to be tested in simulation where the real stock is not at risk. The assumption is that procedures that do not perform satisfactorily in simulated conditions are unlikely to perform well in the real world. Furthermore, stock-specific life history attributes and current stock depletion levels relative to fishing effects may mean that a 6-10 year lapse prior to empirical evaluation is risk-prone. For example, Northern Cod (*Gadus morhua*) collapsed within 5 years of altering the $F_{0.1}$ harvest rate policy to favour yield stability considerations (Shelton 2007). Various authors have proposed an interval of 2-5 years for updating an MSE analysis (e.g., Butterworth 2007) where the management procedures have been pre-tested for robustness against structural and statistical uncertainties. In practice, a newly introduced MSE analysis may require frequent updating, e.g., a 2-year lifespan, early in its development as stakeholders learn how to articulate measurable objectives and experience is gained. This is one reason why savings in analytical resources for use on other stock assessment and management problems may not be realized while a MSE is maturing.

For fisheries where *a priori* simulation testing of proposed management strategies cannot be completed, empirical testing of management strategies is supported under the policy. The management strategy to be empirically tested should incorporate the following components:

1. pre-specified measurable objectives and acceptable risks to conservation and yield outcomes, and the selection of a testing period commensurate with species life-history and prevailing opinion on the current degree of depletion,
2. consistently collected fishery and stock monitoring data to be utilized over the proposed testing period,
3. an assessment methodology consistently applied over the proposed testing period,
4. an explicitly stated harvest decision rule as described in Kronlund et al. 2013, and
5. agreed-upon performance measures that relate directly to the stock and fishery objectives.

Where possible, the choices of strategy components should be guided by good practice identified in general simulation testing of management strategies (see for example Deroba and Bence 2008, Froese 2011), successful practices identified in the primary literature and stock assessment documents, and empirical evidence from other similar fisheries contexts. This approach does not guarantee that a procedure will meet stock-specific conservation and yield objectives but is consistent with FAO (1995, clause 37) for small fisheries. Improved risk-management for all fisheries can be achieved by developing procedures that have been evaluated to at least some degree by taking into account stock specific characteristics. It may be possible to mitigate risks pending a formal MSE by using an interim approach that uses feedback simulation to approximately mimic the stock-specific context and test a proposed procedure against at least the major uncertainties of concern to scientists, fishery managers and stakeholders.

SUMMARY

Management strategy evaluation (MSE) is the systematic determination of the ability of a pre-specified management system to satisfy a set of measurable objectives. A management strategy is defined as a combination of management objectives, fishery and stock monitoring data, stock assessment, and harvest decision rules. In other words, it is the set of steps whereby scientific information is collected, processed, and used to provide advice in setting fishery management measures, e.g., annual catch or effort limits. Management strategy evaluation uses a combination of computer simulation and iterative stakeholder consultation to evaluate the consequences of a range of management procedures, and reports the results in a way that exposes trade-offs in performance against a suite of conflicting objectives. Ideally this prospective evaluation (FAO 1995) of a procedure is conducted prior to implementation, however, existing management systems can benefit from MSE analyses conducted in response to revised objectives, new policy considerations, and the accumulation of stock and fishery data. Key considerations for the application of MSE are listed below:

- For each management strategy considered, a mathematical-statistical model is used to project the simulated true fishery system forward in time. Observed monitoring data with measurement error is generated from the “true” fish population, and an estimate of population status (i.e., the perceived population) is developed by applying an assessment method to the observed data. Simulated management decisions throughout the projection time period are made based on the perceived state of the stock, which leads to management actions (e.g., catch) that affect the true population. Performance measures are calculated based on the state of the true population, and characterize uncertainty in achieving stated management objectives.
- The purpose of MSE is not to provide an optimal strategy or solution, but rather to provide decision-makers with information that can be used to select a procedure that best satisfies the requisite trade-off among objectives and risk tolerance in the context of the overall management system. In addition, it allows the robustness of candidate management procedures to be considered, where robustness represents the ability of a management procedure to produce acceptable trade-off relationships over a range of scenarios representing plausible hypotheses about uncertain stock and fishery dynamics.
- The MSE methodology is compatible with the Precautionary Approach, as specified in FAO (1995), as well as other aspects of the DFO fishery decision-making framework because it demonstrates robustness in the face of possibly irresolvable uncertainty by testing the performance of candidate management strategies against a range of stock and fishery scenarios. Specifically, the approach is able to:
    1. consider alternative data collection and stock assessment approaches for characterizing stock status,
    2. evaluate alternative forms of decision rules that specify how harvest levels should be adjusted based on differences between stock status and operational targets,
    3. demonstrate, via computer simulation, whether management strategies are likely to meet fishery objectives while avoiding undesirable outcomes,
    4. take into account model (structural) uncertainty where the choice among competing models that represent different plausible hypotheses cannot be resolved,
    5. include process error that represents variability not captured in the model, and
    6. include observation error.

- Stakeholder participation is an important aspect of MSE applications, and can occur throughout the process, including (1) the development of measureable fishery objectives, (2) the identification of candidate management procedures, (3) the identification of key uncertainties to be considered, and (4) participation in trade-off debates about acceptable performance across conflicting objectives. Experience has shown that the inclusion of stakeholders into the MSE process in this way can lead to practical management strategies that are acceptable to diverse sets of stakeholder groups while ensuring that conservation objectives are met.
- Although it will not be practical to conduct MSEs for all fisheries in Canada, several situations exist in Canadian fisheries management where application of feedback simulation and consultation within the management agency, and/or with external stakeholders, could be advantageous. These situations include:
    1. evaluation of the properties of <u>survey programs</u> (e.g., How do the expected benefits of increasing sample size or spatial coverage compare to the associated costs, and vice versa? How will reductions in survey frequency affect the ability of a management strategy to achieve conservation objectives?),
    2. evaluation of <u>multi-year stock assessment</u> advice by comparing trade-offs between the ability to meet long-term conservation goals, the costs of stock assessment, and the expected stability of catches,
    3. evaluation of the expected performance of alternative monitoring and management measures aimed at <u>rebuilding depleted stocks</u>,
    4. as an alternative to relying on expert-judgment alone for the management of <u>data-poor fisheries</u>. High uncertainty about population parameters, current stock status, and the reliability of available data can be addressed by testing candidate management strategies over a wide range of scenarios about population dynamics, observation error, and the possibility that observed stock index data are not proportional to true stock status, and
    5. exploration of <u>ecosystem considerations</u>, such as environmental impacts and/ or predator prey dynamics, on the performance of management strategies.
- Given that case-specific MSE applications may not be feasible for all Canadian fisheries, simulation testing of management strategies supported by the DFO PA Framework over a range of generic stock and fishery scenarios would help identify interim strategies that are expected to perform well for most species. For example, the performance of the 3-zone harvest decision rule based on the provisional limit reference point, upper stock reference,, and removal reference rate identified in the DFO PA Framework could be evaluated for a wide range of stock and fishery dynamics and levels of uncertainty.
- Despite the apparent advantages of adopting an MSE approach, experience has shown that several challenges also exist. Difficulties in adopting formal and mathematically explicit management strategies appear to derive from several causes, among them lengthy development time, high development costs, reluctance to accept advice that provides a single catch or effort recommendation as a result of applying the selected management procedure (i.e., a perception of lack of flexibility), and a lack of guidance regarding the appropriate trade-offs among objectives.

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GLOSSARY

Feedback control: Rules or algorithms based directly or indirectly on trends in observations of stock indices, which adjust the values of management measures such as TACs in directions intended to avoid undesirable outcomes and towards target levels.

Harvest decision rule (HDR): a set of well-defined rules used for determining a management action in the form of a TAC or allowable fishing effort given input from a stock assessment model or directly from data. Also called a **harvest control rule**.

Management strategy: the combination of pre-defined data, together with a method for assessing stock status and a harvest control rule that translates the outputs of the assessment into a total allowable catch (TAC) or an effort control measure. Additional rules may be included, for example to spread a TAC spatially to acknowledge uncertainty about stock structure. Also called a **management procedure**. Two types of management strategies may be distinguished:

> **Empirical**: A strategy where monitoring data (such as survey estimates of abundance) are input directly into a formula that generates a control measure such as a TAC without an intermediate (typically population-model based) estimator.
>
> **Model-based**: A strategy where the process used to generate a control measure such as a TAC is a combination of a stock assessment model estimator and a HDR.

Operating model (OM): a mathematical–statistical model used to describe the actual stock and fishery dynamics in simulation trials and to generate resource monitoring data when projecting forward in time.

Performance statistics: Statistics that summarize different aspects of the results of a simulation trial used to evaluate how well a specific management strategy achieves some or all of the pre-specified objectives for management.

Replicate: One realization of a specific scenario of population and survey dynamics projected forward in time for a specified period, under controls specified within a management strategy. A large number of replicates will typically be conducted to capture stochastic effects.

Risk: Strictly defined as having two primary dimensions: the probability that an event occurs and the impact of that event in terms of a cost. Some definitions however focus only on the probability of an event occurring.

Scenario: A specific hypothesis concerning resource status and dynamics, represented mathematically as an operating model.

Trade-offs: Comparisons of gains in some performance statistics against losses in others when selecting among competing management strategies; these trade-offs arise because some objectives for management conflict (e.g., maximizing catch versus minimizing risk of stock depletion).

Table 1. Design choices for the implementation of a management strategy. This list is not comprehensive, but suggests that the many possible combinations of choices among elements means the performance of a procedure relative to stated objectives is difficult to anticipate unless simulation tested.

Component	Element	Design Choice	Example Choices
Objectives	Reference points	Method of reference point calculation	MSY-based Depletion-based Alternative (e.g., a MSY "proxy") Empirical reference points?
		Identification of LRP, USR, and Target reference points	Provisional MSY-based LRP, USR and Target from decision-making framework versus other options
		Frequency of reference point update	Fixed, estimate annually, every 2 years, 3 years, 10 years, etc.
		Adjust for climate change or other non-stationary processes?	See TESA workshop, December 2011 See DFO 2013
	Risk levels	Shape of acceptable probability of decline relationship in each zone	See draft risk choices cited in Table B of Annex 1b of the DFO decision-making framework
Data	Survey	Frequency of survey Effort (sample size)	Annual, every 2 years, 3 years, etc. Number of sets
	Biological data	Frequency of collection Source	Ages or lengths every year? Independent survey and/or fishery samples?
Assessment	Method	Assessment model	Model-based options (e.g., VPA, Statistical catch-at-age model, production models) vs. data-based options (e.g., fishery-independent survey catch rates, etc.)
		Frequency	Annual or multi-year assessment
		Estimation method	Maximum-likelihood, MCMC, Importance sampling, etc.
Harvest Decision Rule	Status-based DFO rule	Risk levels external to HDR	DFO "3 Zone" (See Kronlund et al. 2013)
		Rule form	Piece-wise linear or curvi-linear relationship between removal rates and stock status?
		Tuning of control points, removal rate	Match rule bounds to reference points (See Kronlund et al. 2013)? Reduction of removal rate from reference removal rate?
		Stability control	Limits on percent change in catch among years via a smoother or hard limits?
	Acceptable Risk-based rule	Risk levels programmed into HCR	Table 1 of the DFO decision-making framework
		Calculation of recent trend for Table 1	Linear trend? Number of years to include in recent trend?
		Projection period for evaluation of future decline over a range of possible removals for Table 1	Related to life history? 10 years?

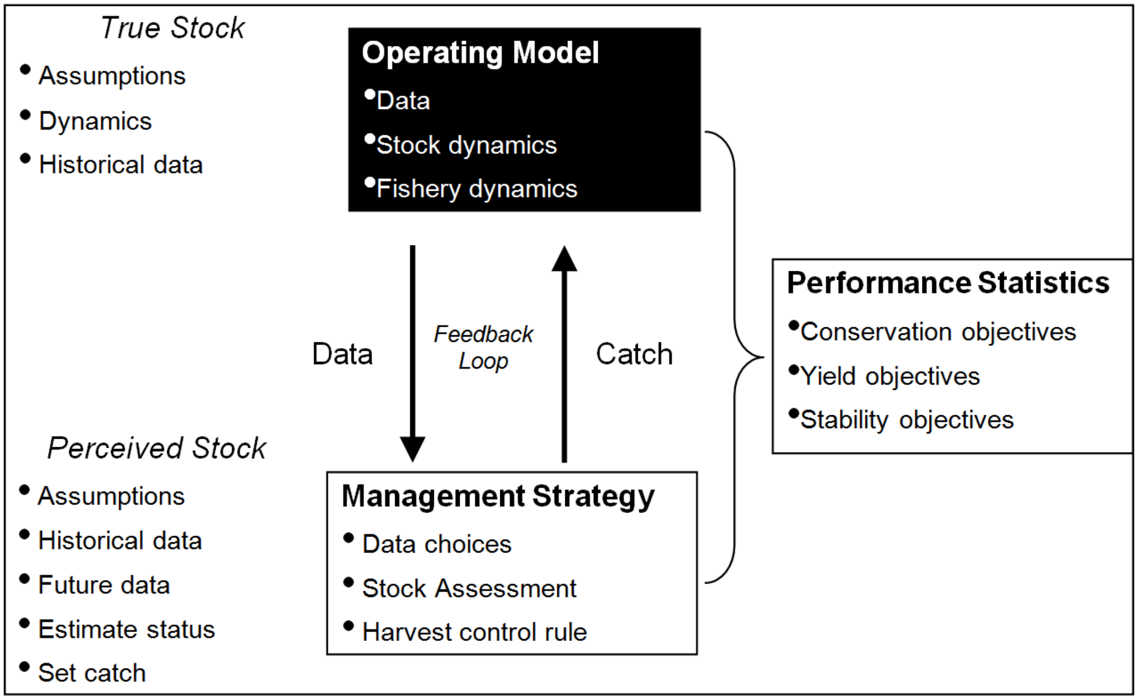

Figure 1. Schematic representation of the closed-loop feedback simulation for evaluating a management strategy within an MSE process.