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Addressing Uncertainty in Fisheries Science and Management

NATIONAL AQUARIUM

Preface

The Project

This project was undertaken to advance best practices for addressing the impact of science and management uncertainty on fisheries management systems. The project engaged a panel of experts (the Panel) and the work was facilitated through the examination of a series of case studies. The project used structured approaches to assessing how uncertainty is evaluated, reduced, and managed for in fisheries science and management. The Panel focused on science and management approaches separately, but also probed the implications of work that takes place at the interface of these two fields.

The Expert Panel

This report summarizes the deliberations of an Expert Panel that was assembled in fall 2013 by Eric Schwaab of the National Aquarium with funding provided by the Gordon and Betty Moore Foundation. Panel members included stock assessment scientists and fisheries managers with significant domestic and international experience. They brought diverse perspectives to the project and endeavored to identify best practices and develop innovations to solve uncertainty-related challenges facing fisheries scientists and managers, particularly those in the United States.

The Panel consisted of the following participants:

Dr. Steven Cadrin, Associate Professor of Fisheries Oceanography, School for Marine Science and Technology, University of Massachusetts-Dartmouth, and Education Director, Massachusetts Marine Fisheries Institute

John Henderschedt, Executive Director of the Fisheries Leadership & Sustainability Forum and member of the North Pacific Fishery Management Council

Dr. Pamela Mace, Principal Advisor Fisheries Science, New Zealand Ministry for Primary Industries

Dr. Steven Murawski, Professor, University of South Florida, Director of the Center for Integrated Analysis and Modeling of Gulf Ecosystems (C-IMAGE) and former Director of Scientific Programs and Chief Science Advisor, National Marine Fisheries Service

Dr. Joseph Powers, Professor of Stock Assessment, School of the Coast and Environment, Louisiana State University

Dr. André Punt, Professor and Director, School of Aquatic and Fisheries Sciences, University of Washington

Dr. Victor Restrepo, Vice President, Science, at the International Seafood Sustainability Foundation

Dr. Richard Methot, Science Advisor for Stock Assessments, NOAA Fisheries, served as a consultant to the process.

The Panel was led by Eric Schwaab, Senior Vice President and Chief Conservation Officer, National Aquarium.

The Process

The National Aquarium convened three workshops from January through June 2014 in which the Panel considered various issues surrounding uncertainty in fisheries science and management, refined the focus of this project, and evaluated current approaches to uncertainty. At these meetings, Panel members gained first-hand knowledge from Council members and scientists. The Panel reviewed approaches being used to evaluate, reduce, manage for and communicate uncertainty in fisheries around the world. The Panel also explored innovative approaches that could be developed to be consistent with the current legislative and regulatory framework for U.S. fisheries management. Each workshop concluded with deliberations about critical issues. The Panel identified relevant fisheries case studies, reviewed the current state of uncertainty consideration and discussed approaches to bridge the science/management continuum. Based on these deliberations and through consideration of specific fishery examples, the Panel developed its findings and recommendations.

Acknowledgements

The Panel members are grateful to the invited experts that contributed their understanding and experience to the discussion of various topics related to uncertainty. Many of these professionals joined the meetings to not only present information relevant to the topic but to stimulate deliberations on many of the issues. Many thanks to Drs. Pat Livingston and Anne Hollowed of the National Marine Fisheries Service (NMFS) Alaska Fisheries Science Center, Rick Robins of the Mid-Atlantic Fishery Management Council, Dr. Michael Fogarty of the NMFS Northeast Fisheries Science Center, Drs. Michael Ford and Ned Cyr of the NMFS Office of Science and Technology, and Merrick Burden of the Marine Conservation Alliance. All Panel members also contributed significantly to this project as independent experts presenting their regional and international fisheries work to the Panel. The Panel also depended heavily on professional support provided by Jill Stevenson, fisheries management consultant, and technical and logistical support provided by Holly Fowler of the National Aquarium.

Target Audience

This report is primarily directed toward fisheries scientists, managers, policy makers and other participants in the U.S. fisheries management process. Given the focus on federal policies, practices and case studies, it may be particularly relevant to those who serve on Regional Fishery Management Councils (Councils) and their Science and Statistical Committees (SSCs). Legislative and policy professionals will find this work helpful as they seek to better understand, manage for and respond to uncertainties in the fisheries science and management processes.

Front cover photo, Pacific Sardine, Creative Commons, Allie Caulfield

Photo: Flounder, John McMurray

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More information is available at www.aqua.org/fisheries.

Executive Summary

Understanding uncertainty in fisheries science and management, communicating it, reducing it and accounting for it in our management decisions are critical ongoing functions within the fisheries science and management communities. With the aim of elucidating "best practices" regarding uncertainty, in 2013–2014 an Expert Panel, funded by the Gordon and Betty Moore Foundation and facilitated by Eric Schwaab at the National Aquarium, focused on and developed recommendations in several areas and generally concluded that:

- Uncertainty and risk are difficult to communicate to stakeholders. Ineffective communication often results in mistrust of the fisheries management system and can jeopardize progress made under the current fisheries conservation and management framework.

- Uncertainty is pervasive in fisheries science and management. Reducing it is sometimes possible and cost-effective but we will always need to manage while faced with multiple sources of uncertainty. Circumstances requiring particular attention are those related to large-scale environmental change.

- Failure to effectively account for uncertainty can result in overshooting management targets, failure to rebuild depleted stocks, failure to take advantage of sustainable fishing opportunities, and general mistrust of the management/science system.

- Specifically, failure by fisheries scientists and managers to adapt their models and strategies to understand and account for climate change in science and management decisions may undermine fishery performance and confidence in the management process.

- While fishery "control rules" that specify management actions for given stock status conditions imply the existence of a policy to incorporate risk, establishing explicit risk policies has proven to be an effective management tool in clarifying choices related to difficult management decisions.

The Panel organized its recommendations under four overarching themes:

- Identifying Uncertainty—Better educate and inform stakeholders, managers, scientists and policy-makers concerning the nature, scope and management implications of uncertainty, and enhance communication at the science-policy interface. Better define the roles of various participants in the management process.

- Reducing Uncertainty—Expand and support efforts to reduce uncertainty wherever possible through strategic investments in fisheries-dependent and fisheries-independent data, improved modeling and assessment. Regularly evaluate and communicate the limits to—and costs and benefits of—reducing uncertainty.

- Managing Fisheries in the Context of Environmental Change —Develop new tools to better understand, communicate, reduce and account for uncertainties, particularly those due to ecosystem changes. Place increased emphasis on broader ecosystem trends and their effects on fisheries science and management decisions.

- Managing Risk—Develop and test existing and new methods that prioritize management responses to uncertainty, including Management Strategy Evaluation. Prioritize the use of adaptive management techniques that allow for more regular interaction among scientists, managers and stakeholders to adjust to changes in understanding of fisheries conditions. Incorporate considerations of risk (likelihood and severity of consequences) into management actions and explicitly communicate those risks.

Photo: Science on shore, Ed Roberts, California Dept. of Fish and Wildlife

Summary of Panel Recommendations

Part 1. Identifying Uncertainty

Recommendation #1: Clearly and explicitly communicate sources, treatment and impacts of uncertainty.

Fisheries scientists and managers should clearly and explicitly communicate the sources, treatment and impacts of uncertainty to each other, stakeholders and decision-makers. To integrate the results of stock assessments and accompanying management actions, science and management authorities should develop a structured and transparent method (such as a table or checklist) to identify sources of uncertainty, the consequences of uncertain information on decisions, and specify where those uncertainties are accounted for in the decision-making process. Outstanding concerns or challenges could also be identified in this way.

Recommendation #2: Define stakeholder roles and responsibilities.

Fisheries scientists and managers should work collaboratively to include detailed roles and responsibilities in formal terms of reference for all participants in the fisheries science and management process so that they understand and accept their respective roles, responsibilities and interactions relating to uncertainty. Scientists and managers should develop outreach tools detailing the roles and responsibilities of participants in addressing various sources of uncertainty and outlining effective management responses.

Part 2. Reducing Uncertainty

Recommendation #3: Evaluate and prioritize investments to reduce uncertainty.

Fisheries scientists and managers should consider in advance the requirements for assessment and management to better evaluate benefits and costs of additional research, alternative investments in data, or application of new technologies and methods for stock assessment as they relate to reducing uncertainty in management outcomes. An objective prioritization plan will focus resources strategically to maximize the value of reducing uncertainty and risk. Simulation analyses such as Management Strategy Evaluation (MSE) may be particularly useful in this process.

Recommendation #4: Invest in science needed to support management.

Greater investments in the science needed to achieve management goals should be prioritized and will yield direct benefits to all stakeholders.

Recommendation #5: Prioritize improved catch accounting.

Fisheries scientists should evaluate the costs and benefits of improved catch accounting programs where commercial or recreational catch accounting is incomplete or has other shortcomings. When the benefits outweigh the costs, managers should prioritize improved, accurate catch accounting for all managed fisheries. Special attention should be directed to enhancing direct reporting requirements for for-hire vessels in recreational fisheries.

Recommendation #6: Focus on cooperative research opportunities.

Fishery management plans should evaluate cooperative research opportunities that could yield greater value to future assessments or other management advice. However, managers and policy makers should only divert existing resources to cooperative research in those cases where use of cooperative approaches is cost-neutral or beneficial.

Recommendation #7: Explore new technologies.

Scientists should give specific attention to investment in new technologies or new application of existing technologies where it can provide cost-effective improvements in collection of fisheries-dependent and independent data, including advanced technologies resulting in direct estimates of population abundance (e.g., optical and acoustic methods).

Recommendation #8: Address frequency of stock assessments.

Fisheries scientists and managers should work together to prioritize the frequency of stock assessments to focus limited resources where they are most needed to reduce uncertainty. In cases of less frequent stock assessments, managers should adopt clear checkpoints or sets of indicators that trigger use of new information in advance of a complete new stock assessment. A companion management process should require response to such checkpoints or sets of indicators.

Recommendation #9: Evaluate methodologies for data-poor stocks.

Fisheries scientists and managers should develop new methodologies that provide a generalized approach to managing data-limited stocks. In data-poor situations where a fishery is significant or the stock plays a significant role in the ecosystem and it is deemed cost-effective, managers should support the development of enhanced monitoring programs.

Part 3. Managing Fisheries in the Context of Environmental Change

Recommendation #10: Expand fisheries oceanography research.

Fisheries oceanography research programs should be expanded to further understand the mechanisms of environmental change, current trends, and effects on fisheries. A strengthened strategic program is needed to concentrate efforts to assess, communicate and integrate uncertainty and risk related to large-scale and long-term environmental change.

Recommendation #11: Integrate ecosystem science.

Ecosystem science programs should be more consistently integrated with single-species assessment science to support more comprehensive management advice. Ecosystem scientists should develop explicit criteria for designating an ecosystem shift that should trigger reference point re-evaluation. Ecosystem report cards were identified as a useful practice in support of better understanding of changing conditions.

Recommendation #12: Prepare for environmental shifts.

Fisheries scientists and managers should prepare for a potential environmental shift by educating all participants about the possibility and the potential need to amend reference points and other aspects of control rules or management measures as stock productivity changes.

Photo: Pacific Rockfish, Victor Simon, NOAA

Photo: Fisheries Survey, Creative Commons, Green Fire Productions

Part 4. Risk-Based Management in the Context of Uncertainty

Recommendation #13: Adopt explicit risk policies.

Fisheries managers should adopt explicit risk policies based on stock vulnerability, availability of data and the perspectives of fishery participants (e.g., stability of the fishery from year to year). Risk policies can be applied to harvest control rules, using precautionary buffers between fishery catch targets and overfishing limits and tiered approaches that are responsive to levels of uncertainty and risk. Fisheries management plans or related documents should clearly articulate risk policies. Furthermore, risk policies should incorporate a qualitative consideration of risk into the broader context of the probability and severity of consequences associated with future actions.

Recommendation #14: Adopt formal procedures to communicate risk.

Fisheries scientists should communicate risk using formal procedures such as decision tables and risk matrices to encourage decision-making that is informed by expected outcomes of various management strategies.

Recommendation #15: Test control rules for robustness to uncertainty.

Fisheries scientists and managers should test current and alternative control rules and associated reference points to determine robustness to predominant sources of uncertainty and responsiveness to the desired characteristics of performance.

Recommendation #16: Promote use of Management Strategy Evaluation.

Fisheries managers and policy leaders should promote the use of explicit risk evaluation frameworks such as MSE and communicate its benefits to stakeholders in the evaluation of risk and the design of robust management approaches. Specifically, they should show how this tool can better engage participants and help inform the decision-making process. Regional managers and authorities should consider new applications of MSE on a pilot basis to evaluate the potential value of adopting the approach more widely.

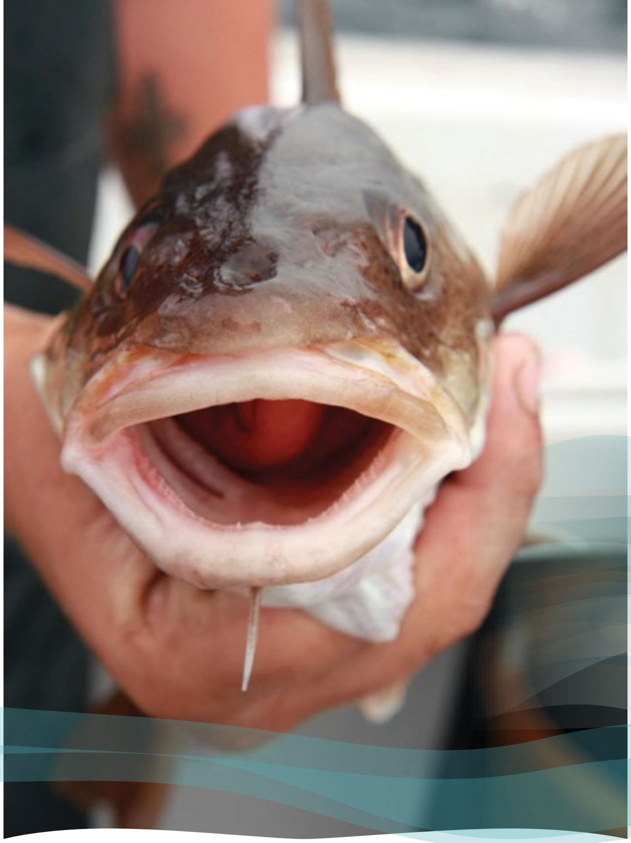


Photo: ICod, Creative Commons, Barney Moss

"Uncertainty is present in every stock assessment. It can form the basis for conservative management decisions, but it can also be misused to avoid management controls in the absence of definitive 'proof' of a detrimental fishery impact. Current legislation reduces this possibility by prescribing that uncertainty be used in a precautionary fashion."

—**Dr. Victor Restrepo**, Vice President, Science, International Seafood Sustainability Foundation

Introduction

***Uncertainty* embodies our incomplete knowledge about states or processes of nature.**

The management of many fisheries is guided by sound scientific stock assessments, which are used as a basis for making management decisions to achieve sustainable harvest and other management goals. But there are many cases where a full stock assessment is not possible, requiring management of fisheries based on other data and trends. In both cases, there are inherent uncertainties in the data, the predictive capabilities of data and assessment models, and the effectiveness of management measures to achieve desired goals. The U.S. fisheries management system has been developed to explicitly focus on using best available science to assess the status of stocks; make quantitative management decisions, including setting quotas and abundance targets; and manage fisheries to achieve sustainable yield goals. The U.S. system is viewed as a model for others to emulate.

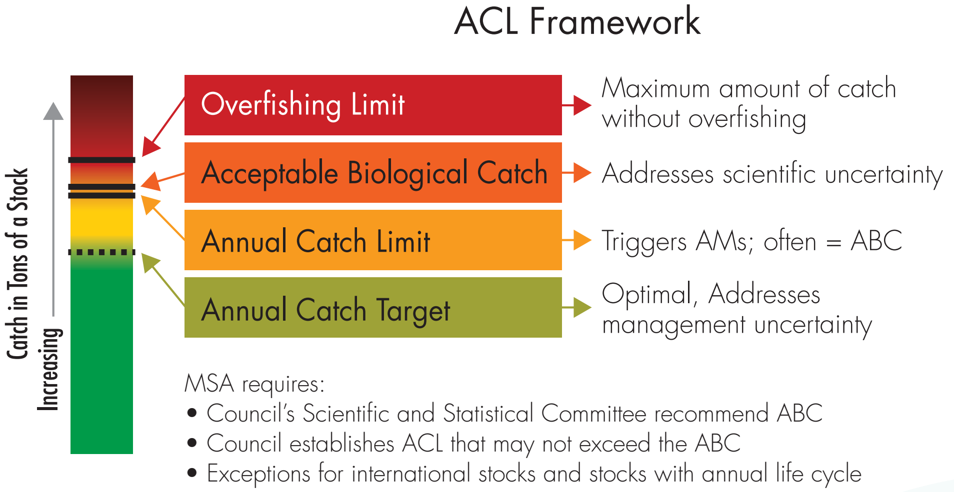


Figure 1. Managing in the context of uncertainty within the current U.S. legislative framework.

The operational guidelines for implementation of the National Standards legislated in the Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act) require scientists and managers to address uncertainty within a management framework in order to attain the stated goal of managing fisheries to achieve Optimum Yield (United States, 2012).

Photo: Recreational, Ralph Kresge NOAA

The Panel focused on four general sources of uncertainty:

- **Data Uncertainty:** Fisheries-dependent and -independent data that are collected and incorporated into assessments or other scientific management advice have sampling variability. Data uncertainty may also include cases referred to as "data-poor" or "data-limited" where there are insufficient data to support comprehensive scientific assessments.

- **Model and Assessment Uncertainty:** These are uncertainties that arise during the modeling and assessment process. They include process and parameter uncertainty, accuracy of assumptions, choice of modeling approach and forecasting-related uncertainties. These and other factors can result in retrospective inconsistencies. This type of uncertainty becomes an acute challenge in data-poor or data-limited situations.

- **Ecosystem or Population Uncertainty:** Ecosystem changes such as long-term oscillations or directional shifts are often beyond the scope of factors currently considered in single-species stock assessments. While they arise explicitly in data, models and assessments, this special set of challenges includes unknown or poorly understood ecosystem relationships and their effects on single-species management advice.

- **Outcome and Implementation Uncertainty:** There are two components of this source of uncertainty. Outcome uncertainty reflects whether the fisheries management system is setting the right target and limit and is affected by the cumulative impact of data, model and ecosystem uncertainty. Implementation uncertainty addresses whether or not the established target is being accurately met. Uncertain performance of management strategies in response to changing behavior of fishermen and other stakeholders operating within the management system can also introduce new uncertainty.

Table 1. General types of uncertainty and management under the current legislative framework. Incorporation of uncertainty into the fisheries management process varies by region.

	Sources of Uncertainty	Examples	Methods to manage for/ Point of response within management process	Methods to reduce
Scientific	**Data: Measurement or sampling—**fishery-dependent and independent data	Accuracy and precision of catch data; quality of biological sampling; survey design and frequency	Use of historical averages; uncertainty buffers; extrapolate observer data; explicit adjustment made in ABC[1]	More intensive sampling; Logbooks; observers; electronic monitoring; improved surveys
	Assessment: Model, structural, forecasting—modeling methods, variables, parameters, generation of catch targets based on best available science	Assumptions of natural mortality; catchability; stock-recruit relationships; age at maturity; Retrospective inconsistencies; lack of contrast; measurement, process, modeling error	Management Strategy Evaluation; buffer between OFL[2] and ABC; buffer between ABC and ACL; explicit adjustment made in ABC	Frequent monitoring and measurement; retrospective model evaluation Long time-series of measurement data; fully calibrated stock size estimates; direct measurement of selectivity; adaptive management
	Ecosystem: Process or population—natural variability and directional change	Natural mortality; growth rates; recruitment	Ensure incorporation into stock assessments; explicit adjustment made in ABC; potentially in ACL[3]	Frequent monitoring and measurement; ensure understanding of modeling processes
Management	**Outcome or Implementation—**Limiting catch at or below desired limit	Catch amounts; catch rates; catch composition; unreported discards; misreporting	ACT set below ACL; explicit adjustment made in ACT[4]	Effort limitation; real-time data collection and processing; in-season quota-based management framework; improved enforcement tools

[1] ABC – Acceptable biological catch is a level of a stock or stock complex's annual catch that accounts for the scientific uncertainty in the estimate of the OFL and any other scientific uncertainty. The ABC is established by the SSC.

[2] Overfishing limit (OFL) means the annual amount of catch that corresponds to the estimate of maximum fishing mortality threshold applied to a stock or stock complex's abundance. The OFL is estimated by the stock assessment author, subjected to peer review, and ultimately approved by a Council's Scientific and Statistical Committee (SSC). It is notable that while uncertainty is not accounted for directly at this point in the fisheries management process (OFL is legislated to be risk-neutral), estimates of OFL necessarily incorporate uncertainty in estimates of biological parameters.

[3] ACL – Annual catch limit is the level of catch of a stock or stock complex that serves as a basis for invoking measures to prevent overfishing (accountability measures). ACLs are recommended by the Councils, but cannot exceed the ABC established by the SSC.

[4] ACT – Annual catch target is the amount of annual catch of a stock or stock complex that is the management target of the fishery, and account for management uncertainty in controlling the catch at or below the ACL. ACTs are recommended by the Councils and cannot exceed the ACL.

Photo: Cod fishing, Creative Commons, Derek Keats

"Fisheries management relies on effective communication between fisheries managers, scientists and stakeholders. Scientists need to describe all sources of uncertainty, and evaluate expected outcomes of management decisions in the context of uncertainty."

—Dr. Steven Cadrin, Associate Professor of Fisheries Oceanography, School for Marine Science and Technology, University of Massachusetts, Dartmouth

Part 1
Identifying Uncertainty

Focus: Better educate and inform stakeholders, managers, scientists and policy-makers about the nature, scope and management implications of uncertainty. Enhance communication at the science-policy interface to support decision-making. Better define the roles of various participants in the management process.

Clearly Identifying Uncertainties in the Management Process

The Panel developed an overview of various sources of uncertainty; identified where the sources are considered in the decision-making process; identified effective tools used to communicate uncertainty (e.g., consequences matrices and decision tables; refer to Part 4); and addressed neutrality and transparency in how uncertainty is considered in stock assessments and the management process. Table 1 identifies the multiple sources of uncertainty and the explicit adjustments through which fisheries scientists and managers address those sources.

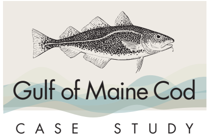
There are approaches to addressing uncertainty specific to each region due to the varying size, scope and operations of fisheries around the nation.

Uncertainties originate from different circumstances and present at different points in the science and management processes. They also present over different time scales (e.g., annual harvest rate vs. long-term policy selection). Because of these differences, uncertainty must be addressed in different ways and at different points in the process (Figure 2).

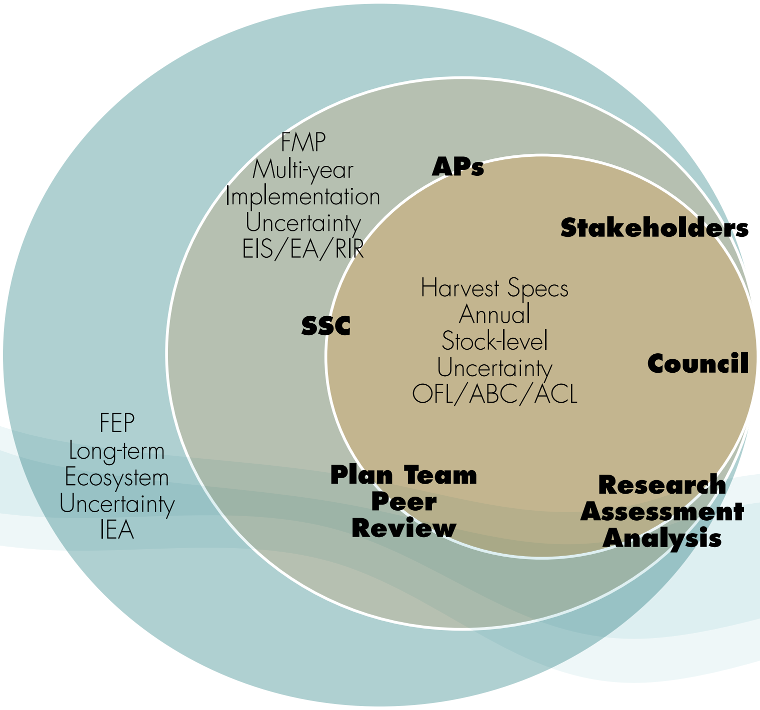
Certain activities fall within the fisheries management plan (FMP) process (e.g., implementation uncertainty) and can be addressed, in many cases, by the participants at that level of the system. Other activities may be addressed in shorter-term processes such as specifying catch limits. At the same time, there are longer-term, larger-scale management challenges (e.g., ecosystem shifts) that may not currently be adequately addressed within the FMP. This challenge needs to be more clearly brought to the fore so that appropriate science and management decisions can be made (refer to Part 3).

Clearly and systematically communicating the various potential sources of uncertainty and where those sources are explicitly accounted for in the management process is critical to clarity and understanding. It can also prevent duplication or omission of certain sources of uncertainty in the decision-making process (Kloprogge et al., 2007).

The management process should be transparent about whose role it is to account for each source of uncertainty, and at which point in the process that occurs. Confirming that the management process identifies all sources of uncertainty and has mechanisms to address and to prevent double-counting uncertainties will build trust in the system.



Consecutive stock assessments of Gulf of Maine cod (2008 and 2011) contained vastly different estimates of spawning biomass, with the 2011 assessment prompting implementation of a stricter rebuilding plan, which also affected fishing for other species. Differences between assessments were unexpected and not easily explained because they were due to uncertainty surrounding several factors, including recruitment estimates, growth estimates and total fish removals. The implications of the new information were significant to stakeholders on many fronts, fomenting mistrust. Fishermen were frustrated and confused about the way that various sources of uncertainty presented in each assessment and were considered in the process. There was a need to communicate science and management uncertainty to participants in more meaningful ways, particularly how and when different sources of uncertainty were accounted for and addressed (refer to Appendices at **www.aqua.org/fisheries** for case study details).



Finding: Stakeholder and decision-maker confusion about how various sources of uncertainty are identified, considered and communicated in the fisheries management process can foster mistrust among stakeholders. In particular, because of the complexity of the current fisheries management process, some stakeholders may feel that uncertainty is being double- or even triple-counted. Not all sources of uncertainty are easily or consistently captured within current structures and processes used to describe and account for uncertainties. Furthermore, much focus remains on such low-level, short-term uncertainties as inaccuracy of catch or survey data or model and assessment-based uncertainties. Comparatively less focus is directed to higher-level and longer-term uncertainties that are potentially much more critical to long-term fisheries sustainability.

Recommendation #1: Fisheries scientists and managers should clearly and explicitly communicate the sources, treatment and impacts of uncertainty to each other, stakeholders and decision-makers. To integrate the results of stock assessments and accompanying management actions, science and management authorities should develop a structured and transparent method (such as a table or checklist) to identify sources of uncertainty, the consequences of uncertain information on decisions, and specify where those uncertainties are accounted for in the decision-making process. Outstanding concerns or challenges could also be identified in this way.

Figure 2. Sources of uncertainty addressed in different spheres of the fisheries management process by different participants. While uncertainty is being addressed in some capacity at all levels, participants are primarily addressing uncertainty at the first level (harvest specifications) at the current time. Communication among participants working in different spheres is critical.

Highlight: Creating Trust Despite Uncertainty: Weather Forecasting

Scientists predicting the weather and those predicting fish abundance develop and utilize multiple data sets and models to predict future events and evaluate risks and consequences for affected populations. Uncertainty is inherent in both weather and fisheries data and the resulting modeling and prediction efforts. In both fields, complex processes have been developed to collect data, develop and run models and account for uncertainty. It is noteworthy that most people understand well that weather forecasts contain uncertainty, yet respond to a stormy prediction by taking along an umbrella. Fisheries stakeholders, however, often respond to "stormy" predictions of reduced fish abundance by calling into question the science and resulting management decisions. Why?

The Panel discussed this disparate treatment as illustrative of several problems. The first relates to familiarity. Weather predictions are a part of daily life and uncertainty in predicted storm tracks is communicated on a daily basis to those interested parties via graphics that have become quite familiar. Uncertainty in fisheries stock assessments, however, is not as well communicated or understood, even by affected participants.

Secondly, weather forecasters are continually evaluating and improving model performance based on the actual track of each predicted storm. Fish stock assessment scientists and those who depend on their work have few such definitive end points. We are generally not able to know actual abundance or distribution of fish in a given year and cannot recalibrate models based on that information. This inability to assess past accuracy is a major challenge in forecasting fish stock abundance in a given year—and a major challenge in building public confidence in predictions over time.

However, modeling approaches have improved greatly over time and fisheries managers would do well to better communicate how efforts to improve calibration of models and assessments are increasing the validity of assessments and projections.

It is notable that fisheries forecasts result in a direct regulatory impact on fishermen. Weather forecasts are predominantly advisory; everyone makes their own choice about whether to venture out in a storm, especially fishermen…

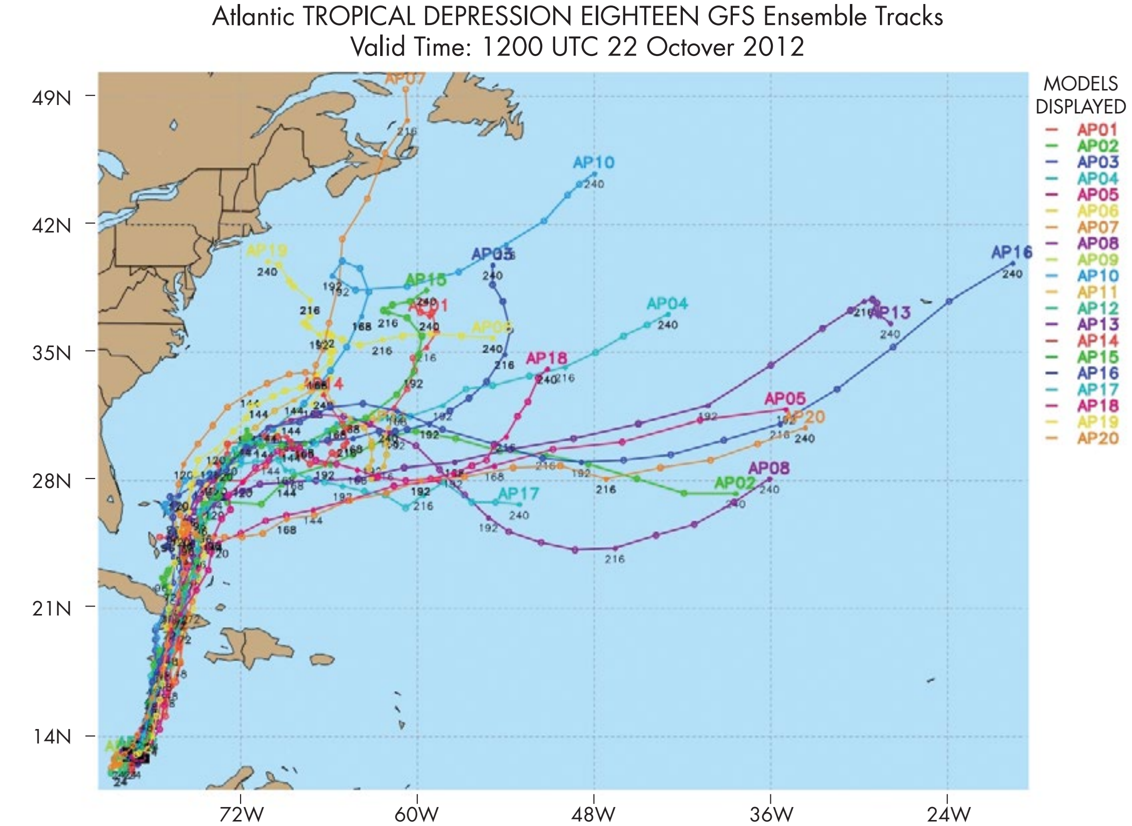


Figure 3. Tropical Depression tracks resulting from 20 weather prediction models. This late-season storm developed into Hurricane Sandy in 2012. This was not the schematic presented to the public, however. Weather models typically are presented in a manner that is easily understood by daily viewers. Image credit: Clark Evans.

Innovative Approach: Transparency in Uncertainty Checklist

The stock assessment process could trigger the SSC or Council to create a table or checklist indicating the major sources of uncertainty for that fishery, how they are addressed and by whom, and at what point in the process they are considered. Such a checklist could also indicate any outstanding challenges identified by scientists and managers. This tool would promote understanding among all participants and would also highlight to all how the system already accounts for certain types of uncertainty and where effort needs to be focused to address concerns.

Identifying and Communicating Roles and Responsibilities

Critical to identifying and communicating sources of uncertainty is a clear understanding of who is responsible and where in the process uncertainty sources are accounted for and addressed. This is also crucial for avoiding real or perceived "double-counting". Lack of clarity and transparency around roles and responsibilities creates opportunities for omission of certain sources of uncertainty in the process. This includes accounting for additional scientific uncertainty outside of the control rule.

Because so much work occurs at the interface of fisheries science and management, those Councils that have outlined the roles and responsibilities of all participants have better promoted information exchange between SSC and Council members, as well as between ecosystem and stock assessment scientists. In the Gulf of Mexico red snapper fishery, roles and responsibilities of scientists on the SSC versus scientists participating in the stock assessment process (SEDAR) have evolved significantly. Prior to the 2007 Magnuson-Stevens Act reauthorization that redefined the role of the SSC, Councils could negotiate the overfishing limit. That limit currently is based on science from the SSC and is non-negotiable. SSC advice is structured to keep stocks below overfishing levels and to account for uncertainty in that advice.

Finding: The Panel concludes that a lack of consistent and clear roles for process participants may be a source of frustration and confusion among stakeholders and participants. A lack of role clarity may be impeding—particularly post-assessment—the appropriate identification, prioritization and response to various sources of uncertainty. All participants would benefit from clarity, both perceptually and substantively.

Recommendation #2: Fisheries scientists and managers should work collaboratively to include detailed roles and responsibilities in formal terms of reference for all participants in the fisheries science and management process so that they understand and accept their respective roles, responsibilities, and interactions relating to uncertainty. Scientists and managers should develop outreach tools detailing the roles and responsibilities of participants in addressing various sources of uncertainty and outlining effective management responses.

Best Practice: Clarify Roles and Responsibilities for All in Terms of Reference

Terms of Reference (TsOR) for stock assessments often include roles and responsibilities for scientists and reviewers, in addition to procedural standards to characterize and present assessment uncertainty. The West Coast Groundfish Assessment Terms of Reference include the responsibilities for the SSC, Advisory Panel, Management Team, Council and NMFS staff, the Stock Assessment Review (STAR) Panel and the Stock Assessment Team. For the STAR Panel, the TsOR indicates how uncertainty should be treated.

The revised National Standard 2 Guidelines indicate that fisheries science should be at the "highest level of integrity" and strengthen public confidence in the quality of information. The Guidelines include information about the advisory roles of the SSCs, particularly with respect to the peer review process (78 FR 43066). More consistent use of an approach like that used for the West Coast Groundfish Assessment, defining the roles of the SSCs and other process participants with regard to uncertainty, could build on the Terms of Reference for stock assessments and increase iterative communication between participants in the process. An outreach tool detailing these roles and responsibilities would bolster public trust and would likely result in more informed decision-making.

Photo: NOAA Ship MILLER FREEMAN, David Csepp NOAA

"The ultimate success and credibility of the fishery management process is critically dependent on the quality of stock assessment science producing accurate and timely information supporting decision-making."

—Dr. Steven Murawski, Professor, University of South Florida, Director of the Center for Integrated Analysis and Modeling of Gulf Ecosystems (C-IMAGE) and former Director of Scientific Programs and Chief Science Advisor, National Marine Fisheries Service

Part 2
Reducing Uncertainty

Focus: Expand and support efforts to reduce uncertainty wherever possible through strategic allocation of investments in fisheries-dependent and independent data, modeling and assessment processes. Communicate the limits to, and costs and benefits of, reducing uncertainty.

Prioritizing Projects to Reduce Uncertainty

The success of the fisheries management process is critically dependent on the quality of data and methods used in stock assessments and other science advice. Stock assessment terms of reference include requirements to evaluate both data inputs and methods to model stock behavior. These data are generally characterized as fisheries-dependent (landings and discard estimates submitted by fishermen or dealers) and fisheries-independent (surveys developed by scientists). Modeling methods differ between fisheries and regions but are generally accepted worldwide and are reviewed by independent experts. Yet limited resources continue to preclude increasing data collection efforts and updating modeling advances for every stock assessment. Benefits and costs to management of expanding investment in greater data collection and modeling research should be evaluated (Powers & Restrepo, 1993).

Finding: Complete removal of uncertainty is impossible in fisheries management, however resources are not always utilized strategically when investing in programs that reduce uncertainty.

Recommendation #3: Fisheries scientists and managers should consider in advance the requirements for assessment and management to better evaluate benefits and costs of additional research, alternative investments in data, or application of new technologies and methods for stock assessment as they relate to reducing uncertainty in management outcomes. An objective prioritization plan will focus resources strategically to maximize the value of reducing uncertainty and risk. Simulation analyses such as Management Strategy Evaluation (MSE) may be particularly useful in this process.

Best Practice: Prioritizing Data Requirements for Stock Assessments

NMFS has developed a draft protocol that, when implemented in each region, should prioritize data requirements for stock assessments by identifying a target level for assessment comprehensiveness. High-level assessments will be targeted for stocks with high fishery and ecosystem importance and with biological factors that lead to large natural fluctuations. These will require more information and will provide better forecasts of necessary changes in annual catch limits. Stocks identified as having mid-level management needs will be assessed using methods that require less data. Inevitably, fisheries will also have minor stock components whose assessments require even less information and will not extend beyond baseline monitoring of catch and simple indicators. At all assessment levels, there will be consideration of environmental and ecosystem factors to help distinguish natural from fishery effects on the stocks (*NOAA Fisheries, 2014*). Within a target level, MSE can be used to identify which informational needs are most important in order to achieve management objectives.

Investing to Reduce Uncertainty

Many sources of uncertainty can be reduced in cost-effective ways by acquiring more information or improving data quality. The Panel identified three priority areas where data improvements should be focused: catch accounting, cooperative research and use of new technologies.

The 2007 Magnuson-Stevens Act reauthorization set high standards to end overfishing and rebuild and maintain federally-managed fisheries. The Panel noted that Congress initially increased investment in programs to achieve these goals. In more recent years, however, the budget for programs to help achieve these goals has not grown commensurate with these standards. Of over 500 federally-managed stocks, NMFS tracks 230 of the country's top fish stocks through its Fish Stock Sustainability Index (FSSI). NMFS then reports quarterly on the number of stocks for which there are adequate assessments. Currently, approximately 60% of the FSSI stocks are reported to have adequate assessments (NOAA Fisheries, 2014, Fisheries Assessment Report). A major component of stock assessment (fisheries-independent data collection) depends on ship survey time. NOAA utilizes it own research fleet, in addition to private vessels, to meet its research needs. While NOAA has replaced a number of its aging fleet with modern, acoustically-quiet ships to provide fishery and ecosystem monitoring, the size of the fleet used for fisheries research has decreased in recent years. Currently, NOAA estimates its combined fisheries and protected resource requirements at 9,245 ship days per year (National Weather Service, 2012). In 2014, NOAA reported an estimated 3,673 days at sea on both charter and NOAA vessels combined, only 40% of its validated need (N. Cyr, personal communication, September 5, 2014).

Finding: Investments in the basic data collection supporting the Magnuson-Stevens Act have not risen commensurate with requirements of the 2007 reauthorization. At a time when fishermen and others depend on NMFS and their state, academic and industry partners to produce more science, more quickly, and with greater precision, increased investments in science can reduce uncertainty and yield direct economic benefit.

Recommendation #4: Greater investments in the science needed to achieve management goals should be prioritized and will yield direct benefits to all stakeholders.

Accounting for Catch

Despite significant reporting requirements for commercial fishermen, there remains a lack of complete catch accounting (commercial, recreational, discards, unobserved mortalities), even for many of the nation's important fisheries. There is a significant opportunity to reduce uncertainty associated with catch estimates through improved catch accounting techniques, particularly in the recreational sector.

Significant recreational demand coupled with the fully-exploited state of many marine stocks places increased attention on uncertainty in recreational catch accounting. While the 2007 reauthorization of the Magnuson-Stevens Act directed changes in recreational catch surveys and there has been progress in fulfilling those requirements, there are still questions about the quality and utility of recreational catch data. NMFS continues to focus attention on alternative methods for recreational surveys to increase the reliability of the data and the ability to integrate it into assessments.

Reduced uncertainty in this sector could foster trust between recreational fishermen and fisheries scientists and managers.

Finding: Investments in enhanced fisheries-dependent data collection will generally result in improved stock assessments, more effective fisheries management and increased trust in the system. This is particularly true for recreational catch accounting.

Recommendation #5: Fisheries scientists should evaluate the costs and benefits of improved catch accounting programs where commercial or recreational catch accounting is incomplete or has other shortcomings. When the benefits outweigh the costs, managers should prioritize improved, accurate catch accounting for all managed fisheries. Special attention should be directed to enhancing direct reporting requirements for for-hire vessels in recreational fisheries.

Best Practice: Increased Catch Reporting Required of For-Hire Vessels

High quality position data, mandatory reporting and information derived from observer coverage in commercial sectors have rectified many commercial catch accounting issues. In many areas of the country, recreational fishing on for-hire charter and party boats is counted using methods applied to recreational anglers. Increased direct reporting requirements for all for-hire recreational vessels could efficiently improve the quality of recreational catch data.

Supporting Cooperative Research

A popular and usually cost-effective tool for reducing uncertainty involves engaging fishermen in information collection. Cooperative research can be an effective way to lower the costs of data collection, capitalize on the specialized knowledge of both scientists and fishermen, and increase participation in the fisheries management process. Fishermen are typically knowledgeable about the size and species they catch and often are willing to participate in data collection if they feel the data will be effectively utilized.

Finding: Cooperative research programs are popular with fishermen, and government scientists are often interested in leveraging the knowledge of fishermen. However, three problems generally arise. First and in many cases, there is insufficient strategic alignment among the needs of scientists and the interests of fishermen, managers and policy-makers. Secondly, funding is inadequate to take full advantage of the opportunity available. Thirdly, it is time-consuming for scientists to develop cooperative research projects that ensure data that yield the greatest value to future stock assessments.

Recommendation #6: Fishery management plans should evaluate cooperative research opportunities that could yield greater value to future assessments or other management advice. However, managers and policy makers should only divert existing resources to cooperative research in those cases where use of cooperative approaches is cost-neutral or beneficial.

Photo: Red Snapper, Creative Commons, Jason Beaird

Best Practice: Cost-Effective Cooperative Research

Since 1979, the NMFS Alaska Fisheries Science Center has conducted annual longline surveys to estimate the abundance of sablefish. Initially, these surveys were conducted cooperatively with Japanese vessels. Over time, the surveys transitioned into solely using U.S. vessels. These surveys are unique in that the chartered vessels are able to retain much of the catch after data are collected. The value of landed fish caught during the survey is so high that industry bids to participate in exchange for selling fish ("MESA", n.d.).

Similarly, Research Set-Aside Programs (RSAs) are utilized in the Northeast as a cost-effective way to collect additional data about fishing operations or fish. No federal funds are used to pay for this research. Instead, the Mid-Atlantic and New England Fishery Management Councils set aside quota or days-at-sea to sell and money generated by their sale funds cooperative research. Vessel operators are compensated in the form of direct fish sales (in the commercial fishery) or additional fishing opportunities in the for-hire fishery. Councils establish priorities and projects are selected through a competitive grants process ("Research Set-Aside Programs", n.d.). It should be noted that the current design of the RSA program may make it vulnerable to abuse; underreporting and non-reporting of catch have been documented. Programs should be developed that can pass scientific review and produce data that can be integrated into existing scientific operations. Appropriate monitoring and enforcement programs should also be in place.

Evaluating the Use of Technology

There is promise in using new technologies or novel approaches to existing technologies to support more accurate and precise catch monitoring. Such methods may improve credibility of stock assessments; by reducing uncertainty in catch accounting or by increasing effectiveness of management measures. Fisheries scientists need to evaluate the effectiveness of current programs, as well as novel approaches based on methods associated with technology. For example, rapid technological and social change now make some traditional methods developed to collect recreational data obsolete (e.g., random digit dialing of households). Some traditional methods may also provide increasingly- biased data over time. New technologies such as crowd-sourcing should be evaluated for testing and implementation to provide a rapid indicator of change in fishery behavior.

Such technologies are often themselves associated with inherent assumptions that require "ground-truthing"—and the tasks needed to do this may drive up the costs of implementation significantly. Pilot programs to test new technologies need to be coordinated so that data collected can be incorporated into existing statistical designs and can meet the defined goals for fisheries science projects. Finally, new data collection programs should meet the strategic goals of managers prior to their implementation.

Finding: Technologies such as vessel monitoring systems (VMS) have already demonstrated their potential to reduce implementation uncertainty by increasing enforcement capabilities in commercial fisheries. These and other technological approaches are also available to fisheries scientists who seek to reduce scientific uncertainty through cost-effective collection of more accurate data. Advances in sampling technologies (e.g.,optics and acoustics) make it increasingly feasible to estimate absolute stock size directly from the results of field surveys, instead of or in addition to using indices of abundance in tuning models. New fishery-dependent reporting approaches are also emerging. When described adequately and clearly, these methods tend to engage fishermen and increase trust in the fisheries science process.

Recommendation #7: Scientists should give specific attention to investment in new technologies or application of existing technologies where it can provide cost-effective improvements in collection of fisheries-dependent and independent data, including advanced technologies resulting in direct estimates of population abundance (e.g., optical and acoustic methods).

Photo: Recreational, NOAA

Best Practice: Using VMS Data to Support Fisheries Management

VMS data are collected in many fisheries in the United States and constitute highly precise position and effort data from commercial vessels. There has been difficulty in accessing these data, however, to support stock assessment and management because of the existence of proprietary data in the database. The Panel recommends efforts to make these data more generally available for the purposes of fisheries science and management. This should still protect real-time business information by adopting a standard time delay in public reporting (e.g., one year) after which such data would be made public or implementing certain confidentiality restrictions limiting use. Alternatively, when these data are publicly reported, the actual positions could be obscured by moving them in a random direction by a random amount of up to 1 nautical mile, so that exact coordinates are not generally available to others.

Integrating New Information

Fish stock assessments must be updated at some interval in order to provide relevant information on the status of the fish stock and the potential yield that can be taken. Just as the 10th day of a weather forecast has more uncertainty than tomorrow's forecast, the 10th year of a fish forecast has more uncertainty than next year's forecast. While we have a basic understanding of the system being modeled in each case, we do not understand all sources of variation in each system which prevents more accurate long-term forecasts. Monitoring and assessment updates are needed to avoid setting annual catch limits too low, thus preventing access to upticks in stock productivity, or too high, resulting in overfishing.

The optimal interval between assessments depends in part on a stock's biology. It also depends upon available data because overly frequent updates without appropriate data to support them can introduce more noise to the management advice rather than reliably tracking true changes. Assessment frequency should also be influenced by the importance of a stock to the fishery. Most valuable stocks are in need of robust and timely assessments. Because the investment in such a high assessment capability principally benefits fishery participants, cooperative research and monitoring with those participants can help supply the needed information to implement the assessment system (NOAA Fisheries, 2014).

NMFS has developed a draft protocol that, when implemented in each region, will evaluate stocks to set a target assessment frequency and prioritize stock assessments based on how far the assessments are behind schedule (NOAA Fisheries, 2014). Target stock assessment frequency should depend on the stock's intrinsic variability over time as well as its importance to the fishery and ecosystem. MSE also could be used to demonstrate which stocks have the greatest need for updated assessments.

In the late 1990s, there existed no precautionary buffer in Pacific groundfish management plans and delays in updating assessments for these declining stocks meant that fisheries managers were unaware of stock declines and thus could not respond by adjusting target catch levels. Consequently, hindsight often found that overfishing had occurred, thus exacerbating the population decline. There was an acute need to prioritize frequency of stock assessments and address uncertainty relating to inefficiencies in the management process (Ralston, 2014).

Finding: The Panel concludes that there is an expectation of frequent stock assessments in many fisheries, but current resources do not allow for annual updating for most stock assessments, nor is this necessary. The Panel recognizes the time lag between stock assessments that include new data on stock status and implementation of response measures in most fisheries, can be significant and may exacerbate uncertainty. Delays caused by a thorough review of stock assessments and development of management measures also impede a timely response to new information. Even with gaps between stock assessments, new information is generally available to fisheries scientists between assessments, and methodologies should be developed to use this information to determine whether an interim management response might be needed, or an assessment should be considered.

Recommendation #8: Fisheries scientists and managers should work together to prioritize the frequency of stock assessments to focus limited resources where they are most needed to reduce uncertainty. In cases of less frequent stock assessments, managers should adopt clear checkpoints or sets of indicators that trigger use of new information in advance of a complete new stock assessment. A companion management process should require response to such checkpoints or sets of indicators.

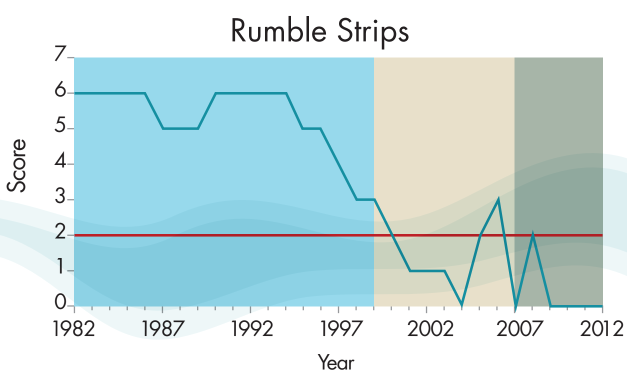


Figure 4. Overall score for summer flounder (blue line) compared to the rumble strip critical score (red line; Mid-Atlantic Fishery Management Council, 2013)

Best Practice: Checkpoints and Indicators for Managing Uncertainty

Councils have responded to the need for timely evaluation and response to fishery and stock changes by "checking-in" between full assessments using simple indicators or control rules. This approach allows for iterative adjustments to management options in order to achieve management goals.

The Mid-Atlantic Fisheries Management Council (MAFMC) has implemented a "rumble-strip" approach in which scientists examine a set of indicators utilizing available data (Figure 4). High score numbers reflect a problem that triggers a consultation between the Council and its SSC. This approach can serve as a warning indicator to fisheries managers of a potential need for future response (new stock assessment or a management response) to changing stock status. The rumble strip approach could be improved by adoption of a companion management trigger that requires fisheries managers to respond to an increased rumble strip score with a management action. While the MAFMC approach is not currently linked to any requirement for action, it does trigger an SSC recommendation for further action.

Data Limited Stocks

Management of data-limited stocks under the current U.S. framework (setting reference points and harvest limits) places demands on stock assessments that sometimes cannot be supported. It is difficult to define a harvest strategy in accordance with National Standard 1 Guidelines without estimates of maximum sustainable yield (MSY), and evaluating risks to fish stocks and the ecosystem is nearly impossible in such data-poor cases. The Panel identified new opportunities to address data-limited stocks.

New methodologies, including those that involve fishermen in data collection, are needed for collecting information and providing insights about data-poor stocks. Cooperative research and new technologies could provide initial monitoring data (catch, effort, and size data) over a large geographic area where no catch data currently exist. These methods, however, must be cost-effective relative to fisheries or ecosystems.

Special Case: Addressing Uncertainty in Data-Limited Fisheries

"Data-limited fisheries" are those fisheries for which available data do not provide sufficient information for assessing the status of the stock or for setting harvest control rules. "Data-poor fisheries" are a subset of data-limited fisheries, namely those small fisheries on target or non-target stocks for which catch or life history data are limited or unavailable and basic or no formal stock assessments have been completed. These data-poor fisheries typically have low productive value; they may be exploratory or developmental fisheries, or may be expanding after stock collapse (*Dowling et al., 2008*).

Finding: The Panel concluded that the National Standard 1 Guidelines fully acknowledge the common need to use proxies where MSY cannot be directly estimated and also acknowledge the need to use data-limited approaches in some situations. However, the Panel also determined that there is a need to focus on implementation of monitoring programs and ongoing development of methodologies to address issues related to managing data-poor stocks. Given the fact that many data-poor fisheries are small and of relatively low value, there is an added challenge of reconciling the costs of these efforts with the net benefits of reducing uncertainty in these fisheries.

Recommendation #9: Fisheries scientists and managers should develop new methodologies that provide a generalized approach to managing data-limited stocks. In data-poor situations where a fishery is significant or the stock plays a significant role in the ecosystem and it is deemed cost-effective, managers should support the development of monitoring programs.

In principle, every ecosystem component stock that is affected by fishing should have some degree of evaluation of the level of fishing impact. Adaptive management strategies, including the use of MSE, could aid in the triage and management of data-limited fish stocks. Triage is a critical first step when evaluating data-poor stocks ("Has the fishing impact been too high, too low, or about right?"). This step drives the performance of most data-poor methods. The second step is to select data-poor methodologies to develop interim strategies for management and to identify data gaps. The methods that have been developed to address data-poor issues (e.g., **O**nly **R**eliable **C**atch **S**tocks method) have been deemed to be, at best, stop-gap measures to create an initial target (Carruthers et al., 2014). They should not be relied upon as a basis for long-term management. MSE can be useful for selecting an appropriate method for implementation (Dowling et al., 2008).

Best Practice: Data-Limited Fisheries Toolkit

The National Resources Defense Council (NRDC) has worked collaboratively to develop a "Data-Limited Fisheries Toolkit" that enables users to apply competing data-limited methods to evaluate which methods provide the most robust results. The Panel finds this toolkit to be useful in comparing methods to evaluate federally managed data-poor fisheries throughout the United States. This resource will be available in the near future from NRDC. It is notable that new methods are being developed and evaluated continuously with a large increase in the number of publications on this topic in the recent past. These evolutions should continue to be monitored (*Carruthers, 2014*).

Quick Reference: Four Steps to Managing Data-Limited Fisheries

1. Triage
2. Use data-limited methodologies to develop interim strategies and identify data gaps
3. Develop appropriate decision-making processes (e.g., control rules, default buffers)
4. Utilize management tools to protect stock

Best Practice: Productivity and Susceptibility Analysis (PSA)

The Panel identified Productivity and Susceptibility Analysis (PSA) as a successful approach to assessing risk for stocks that have not been part of a formal stock assessment. PSA has been used frequently to evaluate risks in many different fisheries and is now recommended as a reasonable approach for determining consequences (*Rosenberg et al., 2009; MRAG Americas, 2009; Patrick et al., 2010; Witherell, 2010*). These scores can be integrated into decision-making, although the priority for high-risk stocks should be to collect the data necessary to carry out stock assessments, in lieu of depending on the PSA.

Best Practice: Default Buffers, Accompanied by a Monitoring Program

In the case of data-poor fisheries when, after a triage approach, there is concern biomass is below or approaching Minimum Stock Size Threshold (MSST) or catch is approaching or exceeding fishing mortality limits, fisheries managers should adopt default data-poor buffers and establish or augment a monitoring program to improve the information base. Default buffers can be applied to data-poor stocks, although it is difficult to predict how well they will perform. Certainly, they provide a precautionary approach when little information is available. They may also serve as motivation for additional data collection and analysis (*Restrepo & Powers, 1999*).

Many common management tools cannot be used to manage data-poor fisheries because monitoring data are scarce. Implementation of “No Take” areas could provide a safety valve in highly uncertain conditions to protect the reproductive potential of a stock while still allowing the fishery to operate. These areas also provide context for future comparisons (e.g., abundance inside closed areas vs. abundance outside).

Looking to the future, it is clear that it will be necessary to continue to evolve scientific and management methods to manage uncertainty in data-limited fisheries. As additional information is gathered about stocks and fisheries that interact with them, the nature of uncertainty will likely change.

Photo: Cast Net, Creative Commons, Flickr, User Barloventomagico

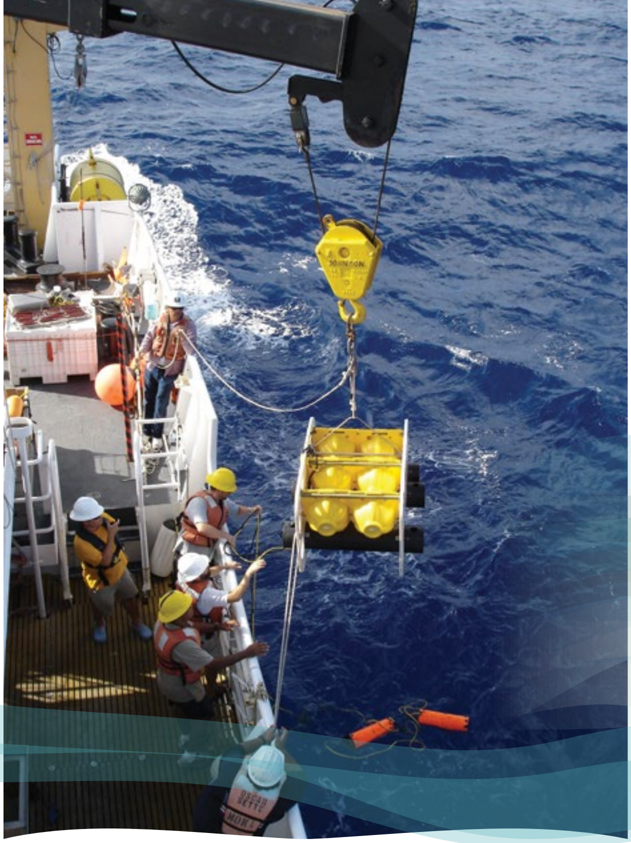


Photo: HARP Buoy, Allen Shimada NOAA

"Uncertainty arising from ecosystem shifts will only grow in scope as Earth's climate changes. Now is the time to plan and account for future ecosystem changes that will affect marine fish stocks. Through the collection of oceanographic information and its integration into stock assessments, we will better react to these changes with new fishery management strategies."

—**Eric Schwaab**, former Director, National Marine Fisheries Service, current Chief Conservation Officer, National Aquarium

Part 3
Managing Fisheries in the Context of Environmental Change

Focus: Collecting oceanographic information to identify a shift in conditions that might affect fisheries, integrating that information into stock assessment models to predict outcomes, and preparing a management response to support sustainable fisheries

The Panel dedicated significant attention to challenges associated with long-term ecosystem-driven changes. These include both long-term oscillations and new directional signals. While historically occurring, they are increasingly introducing new, significant and challenging uncertainties into the management process. Such changes complicate stock assessments, may broaden the geographic scope of management areas, and require alternative survey, assessment or management approaches. As climate-driven changes and environmental variability become more significant, there is an increased need to better understand and incorporate ecosystem changes.

Identifying a Shift in Environmental Conditions

There is an increasing need for short- and long-term oceanographic research programs. Information is needed to support stock assessments in the near-term but it is also needed to help identify environmental shifts over a longer time span. In the past, fisheries scientists and managers have often identified a shift five to ten years later than it occurred, which made it difficult to prepare for a management response (e.g., northern cod). Both short-term fisheries performance and long-term fisheries sustainability will benefit if these shifts are identified sooner and managers are prepared to respond accordingly.

Finding: In order to identify shifts in environmental conditions that affect fish stocks, there is a need to increase strategic collection of oceanographic information and conduct studies of important physical and ecological processes. While new programs were developed to address this need, current funding for fisheries oceanography and ecosystem research is not sufficient to understand stock dynamics within an ecosystem context. Funding for oceanographic information collection and synthesis is decreasing just as the need to develop more complex ecological models increases in the face of climate-related and other large scale changes.

Recommendation #10: Fisheries oceanography research programs should be expanded to further understand the mechanisms of environmental change, current trends, and effects on fisheries. A strengthened strategic program is needed to concentrate efforts to assess, communicate, and integrate uncertainty and risk related to large-scale and long-term environmental change.

At-A-Glance: The Need for Fisheries Oceanographic Information

- NMFS is responsible for over 500 fish stocks.
- Each year, approximately 80–90 stock assessments are updated.
- It is increasingly apparent that many of these stocks are sensitive enough to environmental perturbations to require incorporation of that environmental information into the stock assessment process.
- It could be roughly estimated that 50 stock assessments each year would need to incorporate environmental information for optimum accuracy.
- The current program, Fisheries and the Environment (FATE), supports an average of 10 projects per year.

(M. Ford, NMFS, Personal Communication, June 18, 2014)

Best Practice: Comprehensive Fisheries Oceanography Program

To further understand oceanic systems and the mechanistic processes that affect fisheries management decisions, the GLOBEC (Global Ocean Ecosystem Dynamics) and CAMEO (Comparative Analysis of Marine Ecosystem Organization) programs operated as comprehensive fisheries oceanography research programs. CAMEO, a joint NOAA-NSF program, successfully funded two rounds of proposals including 16 projects with 71 investigators from 35 institutions. A budget reduction created conditions that prevented continuation of the program. The GLOBEC program progressed from concept through field campaign to the final synthesis phase (in 2011). However, the momentum created by GLOBEC is still felt today by fisheries oceanographers. The partnerships that developed as a result of these programs were very successful.

NMFS currently operates Fisheries and the Environment (FATE), a very limited program ($1.5 million) that funds research directly supporting stock assessments. In order to guide sustained and coordinated fundamental research, a larger program is best developed in a national context with enhanced collaboration among multiple agencies and research institutions.

Integrating Environmental Information into Assessment Models to Predict Outcomes

Scientists and managers have an imperfect understanding of how best to integrate environmental data into single-species stock assessments to be able to predict the effects of an environmental shift. In addition to improved understanding of ecosystem change, research is needed to improve models that capture ecosystem processes and predict their effects. Historical assumptions about resource productivity and distribution may not be valid in the future and scientists and managers will need to collaborate to respond to new paradigms.

Finding: The Panel concludes that while the United States appears to be advanced in consideration of environmental variables as they relate to fisheries management, stock assessments formally integrating ecosystem and climate effects are rare. Scientists and managers alike are in need of new ways to model systems, integrate information and respond to uncertainties that emerge with ecosystem changes. Precautionary measures that assume stationarity have not been sufficiently updated regarding emerging environmental shifts.

Recommendation #11: Ecosystem science programs should be more consistently integrated with single-species assessment science to support more comprehensive management advice. Ecosystem scientists should develop explicit criteria for designating an ecosystem shift that should trigger reference point re-evaluation. Ecosystem report cards were identified as a useful practice in support of better understanding of changing conditions.

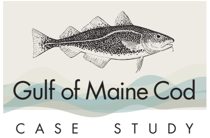
Photo: Catch Sorting, NOAA OMAO

Best Practice: Ecosystem Considerations Reports

The North Pacific Fishery Management Council (NPFMC) has developed and utilized Ecosystem Considerations Reports as a tool to begin to incorporate qualitative and quantitative data related to multi-species interactions (e.g., foraging conditions and predator biomass), sea surface temperatures, and other current environmental conditions and ecosystem markers. These reports include information about trends in various indicators but do not provide direct input into control rules. The indicators have been developed to directly address ecosystem-level processes and are used to inform fisheries management advice. This "Ecosystem Report Card" is presented to the Plan Teams in its draft form and to the SSC and the Council prior to setting annual quotas. The information is then used by the SSC to consider ad hoc adjustments to ABCs. This work is important because it allows managers to view trends in indicators and provides scientists a framework with which to develop criteria to designate an ecosystem shift. The next evolutionary step would be to use this information to prepare participants for the future need for changes in reference points and other aspects of control rules and resulting management schemes.

Preparing a Management Response

Uncertainty exists even within a relatively static marine ecosystem, as there are many variables which we cannot completely understand, quantify, or predict. To the extent that environmental drivers (including the effects of climate change) result in changes to stock population dynamics, interactions between species, function and resilience of key habitat, and impacts of anthropogenic activities, the scope and scale of uncertainty has the potential to increase.



Climate change, a general warming trend over recent decades and changes in stock status have caused substantial shifts in the geographic distribution of fisheries resources in the northeast U.S., generally northward and deeper. Such shifts have profound implications for the northeast U.S. shelf ecosystem and also have considerable implications for fisheries management. In the Gulf of Maine cod fishery, environmental factors affecting recruitment were not considered during preparation of the 2008 stock assessment. When the subsequent 2011 assessment results were released, stakeholders were shocked and mistrustful of the conclusions and recommendations for necessary restrictive management measures. Scientists have since concluded that changes in the environment were one of several factors affecting the more recent and less optimistic assessment results regarding the health of the stock. The New England Fisheries Management Council (NEFMC) is now developing an Ecosystem-Based Fishery Management Plan to establish a formal process to incorporate possible effects of environmental information into management decisions.

Finding: Councils that have more explicit processes and tools in place to explore and incorporate larger system uncertainties have been more proactive in considering and responding to longer-term challenges such as ecosystem variability.

Recommendation #12: Fisheries scientists and managers should prepare for a potential environmental shifts by educating all participants about the possibility and the potential need to amend reference points and other aspects of control rules or management measures as stock productivity changes.

Best Practice: Maximum Allowable Biological Catch Reference Point

Stock assessment scientists incorporate uncertainty considerations into the Bering Sea pollock fisheries assessment and generate a maximum ABC. This fishery has been classified as "Tier 1" in a series of tiers based on availability of information. In this Tier 1 fishery, the continuum for considering uncertainty is sufficiently broad to allow the fishery to incorporate uncertainty at the broadest level and take into account possible environmental factors as well as management uncertainty.

Taking advantage of this capability, in 2006, the SSC recommended an ABC for pollock below the maximum because zooplankton forage for juvenile pollock was reduced, predator abundance was increasing, and recruitment estimates for several consecutive years were poor (NPFMC SSC, 2006). Similar considerations were also used the following year (NPFMC SSC, 2007). This is a good example of how the Ecosystem Report Card, described above, has been used—and could be used in other regions—when the relevant environmental information is available.

Best Practice: Harvest Control Rules that Incorporate Environmental Change

Developing criteria for designating an ecosystem shift will allow reevaluation of biomass targets while supporting the goals of the current fisheries management process. Once such a shift has been determined, scientists, managers and stakeholders will need to be prepared with a change to reference points or other aspects of control-rule response, for example, addressing environmental-related variation in biomass through the harvest control rule (Pacific Fishery Management Council, 1998).

United States Pacific sardine managers have responded to uncertainties related to environmental variability by developing harvest control rules that consider the effects of biomass and environmental variability on recruitment. Implementation of an MSE aided in selecting strategies that were robust to this source of uncertainty (refer to Appendices at **www.aqua.org/fisheries** for case study details).

Additional modifications to management schemes may be necessary to address environmental changes. Uncertainty related to shifts in distribution, for example, affects governance of many fish stocks and demands early detection and response by fishery managers, particularly if management areas expand as a result of such shifts. Summer flounder offers a typical example of a mid-Atlantic stock that has demonstrated a distributional shift and resulting management challenges. Uncertainty related to environmental change has caused governance issues in this fishery due to a distributional shift in the population. In the context of geographic shifts, allocations based on catch histories present fisheries and management problems. The mis-match between state allocations and local availability of summer flounder is presenting considerable challenges for fisheries participants and fisheries managers. Commercial fishermen in southern states continue to land their quotas. However, they are generally travelling further north to do so due to the shift in the concentration of the resource and the turtle excluder device requirements in the southern range of the fishery. Northern state fisheries are shutting down early due to lack of quota. It is more difficult for most recreational anglers to shift effort, further challenging fishery managers (refer to Appendices at **www.aqua.org/fisheries** for case study details).

Photo: Boats, Ralph Kresge NOAA

Best Practice: Allocation of Fishery Resources Based on Physical Distribution of Target Stocks

State, regional and national fisheries allocations based on historical catch patterns are a common practice in fisheries management. Alternatives to allocations based on catch history are those based on fisheries resource distribution. For example, the U.S.-Canada Transboundary Guidance Committee developed a sharing agreement for national catch allocations that transitioned from catch histories to resource distributions (Gavaris and Murawski, 2004). The U.S.-Canada sharing agreement is a weighted average of proportional catch histories by each country and proportional resource distributions in each country's jurisdiction. In the first year of the agreement, the weighted average was based on 60% resource distribution and 40% catch history, and the weighting of resource distribution transitioned to 90% resource distribution and 10% catch history in annual increments over seven years. This combined approach offers catch allocations based on traditional fishery development and is responsive to geographic shifts in resource distribution resulting from environmental change (The Transboundary Management Guidance Committee, 2002; Gavaris and Murawski, 2004).

"Achieving outcomes that are responsive to uncertainty and risk requires a transparent and iterative process between scientists and managers supported by clearly communicated goals and objectives and a shared understanding of potential consequences."

—**John Henderschedt**, Director, Fisheries Sustainability and Leadership Forum and Member, North Pacific Fishery Management Council

Part 4

Risk-Based Management in the Context of Uncertainty

"Fishery scientists, managers and stakeholders can benefit from delving more deeply into the very uncertainty that causes so much consternation. Better shared management outcomes will result by articulating clear goals, probing the nature of uncertainties, testing results, and doing so much more regularly."

—**Dr. André Punt**, Professor and Director, School of Aquatic and Fisheries Sciences, University of Washington

Focus: Incorporating considerations of risk (likelihood and severity of consequences) and communicating those risks. Using Management Strategy Evaluation to evaluate and choose management options robust to inherent sources of uncertainty, to allow for more regular interaction among scientists, managers and stakeholders and to allow for adjustments to changing understanding of fisheries conditions.

Definition: Risk is the likelihood and the severity of adverse consequences of an action.

Risk assessment requires considering:

- the possible results of the action;
- the probability that each result will occur; and
- the set of possible consequences from each result and their probabilities.

Incorporating Considerations of Risk

The Panel reviewed and discussed the relationship between uncertainty and risk. Specifically, the Panel considered how scientific and management uncertainty translates into risk in final decisions and the likely consequences associated with that risk. Without considering the consequences as well as their likelihood, it is difficult to identify which sources of uncertainty pose the greatest risk at the species or ecosystem level. Panel members recognize that uncertainty around the likelihood and consequences of overfishing makes decisions about risk significantly more complicated in fisheries operating close to legislatively mandated sustainability targets, because they need to be managed

Figure 5. Management authorities should develop an explicit risk policy that applies to ABC setting and other management actions. Assessing and communicating risks support the appropriate choice of management response.

At-A-Glance: Roles and Responsibilities for Setting ABCs

National Standard 2 Guidelines indicate explicit roles and responsibilities for setting ABCs.

1. The Council indicates the acceptable level of risk for overfishing;
2. Stock assessment scientists determine the level of scientific uncertainty in an assessment, assess risks, and communicate them to the Council; and
3. The SSC then recommends the ABC that takes into account assessment uncertainty and any other relevant information about uncertainties and stock status.

more carefully. Developing and adopting an effective risk policy and assessing and communicating risks associated with a set of management actions will promote selection of a management strategy that benefits the resource as well as the stakeholders.

In addition to establishing ABC Control Rules (where risk consideration is implied), Councils can establish explicit risk policies. These risk policies articulate a Council's tolerance for risk, given certain criteria. The risk policy and control rules are very closely related elements of a broader decision-making process—the ABC control rule is an articulation of a harvest limit that reflects, or is responsive to, a particular harvest strategy. Perhaps the best example of this is an estimate of p* (percent likelihood of overfishing) as an expression of risk policy, with the ABC control rule generating the ABC that reflects that tolerance for risk. If the Council fails to articulate a risk policy, scientists have no management guidance to inform their process of setting catch limits (MAFMC, n.d.).

Processes for assessing risk within the ABC process abound. Within the ABC process, scientists and managers frequently utilize tiered approaches for classifying stocks, although these are not without disadvantages. In many regions, scientists group most managed stocks into only one or two tiers because of a lack of information.

ABC buffers are used to respond to risk by accounting, in a precautionary way, for uncertainties that arise in the management process (Table 1). They are reflective of two very distinct dynamics: how uncertainty is quantified and accounted for (scientific determination) and the tolerance of risk of overfishing (policy determination). Adverse consequences are often more severe in the case of overfished stocks.

Gulf of Maine Cod
CASE STUDY

While development of a control rule implies that a risk policy has been adopted, the NEFMC lacked an explicit statement of their risk policy that left them struggling to develop an adequate response to two significantly different stock assessment outcomes for Gulf of Maine cod (2008 and 2011). The NEFMC currently is developing a risk policy that will help decision-makers address uncertainty in a methodical and transparent manner.

Finding: Despite the implication that adoption of harvest control rule reflects a risk policy, the Panel concludes that most Councils lack an explicit statement of risk policy which complicates the process of setting catch limits. Fisheries scientists and managers have a very developed notion of the purpose and need of a risk strategy as it applies to setting ABC, but tend to assess and confront other risks in the fisheries management system in a much more ad hoc manner. In most cases, ABC buffers are a useful precautionary tool to account for uncertainty and respond to risk within the specifications process. Outside of that process, Councils usually address risks in an ad hoc manner and may be in need of tools to respond to risks.

Recommendation #13: Fisheries managers should adopt explicit risk policies based on stock vulnerability, availability of data, and the perspectives of fishery participants (e.g., stability of the fishery from year to year). Risk policies can be applied to harvest control rules, such as precautionary buffers between fishery catch targets and overfishing limits and tiered approaches that are responsive to levels of uncertainty and risk. Fishery management plans or related documents should clearly articulate those policies. Furthermore, risk policies should incorporate a qualitative consideration of risk into the broader context of the probability and severity of consequences associated with future actions.

Quick Reference: Nine Characteristics of a Successful Risk Policy

- Reflective of unique regional management context
- Considers short-term/long-term tradeoffs
- Iterative and performance-based
- Comprehensive and holistic
- Provides direction for improvement
- Responsive to availability of information and reaction time
- Resilient in the face of change (including environmental change)
- Transparent and objective with clear roles and responsibilities
- Balances structure and flexibility

(Adapted from Fisheries Leadership and Sustainability Forum, 2012)

Best Practice: Tiered Approach for Risk Assessment Based on Availability of Data

To support the process of setting ABC, the NPFMC assigns stocks to different tiers based on availability of data (groundfish are in Tier 1). The Council then adopts and applies harvest control rules to account for scientific uncertainty. The control rule is structured explicitly in terms of the type of information available, which is related qualitatively to the amount of scientific uncertainty. A buffer is then established based on the amount of scientific uncertainty. In Tier 1 (more data; lower uncertainty), the size of the buffer between $maxF_{ABC}$ of the ABC control rule and F_{OFL} of the OFL control rule varies directly with the amount of scientific uncertainty. In other tiers, the amount of scientific uncertainty is harder to quantify, so buffers of fixed sizes are used instead (NPFMC, 2014).

The MAFMC has adopted a similar approach with four levels (tiers) of overall assessment uncertainty defined by characteristics of the stock assessment and a determination by the SSC that the uncertainty in the probability distribution of OFL (probability density function-"pdf") adequately represents the best available science. The procedure applied to determine ABCs is different for each tier. The SSC assigns a stock assessment to a tier when setting ABC specifications and a justification for that assignment is provided with the ABC recommendation. The ABC recommendations should be more precautionary as an assessment moves from Level 1 to Level 4 (MAFMC, n.d.). It is notable that implementation of a tier system does not necessarily reflect species-specific levels of uncertainty, particularly if most species in a region fall into one or two tiers.

Innovative Approach: Development of Structured Ways to Respond to Risk Outside of the ABC Process

Regarding stock structure, a Council might work with its scientific and technical advisors to develop a policy for responding to indications of diverse stock structure. At some threshold of risk (indication that stock structure exists and that fishing patterns may threaten a certain component of that structure), the Council would respond by establishing catch limits for separate components of the stock. Similar policies could be developed for bycatch management, habitat interactions, and other management issues where the likelihood and potential consequences of fishing should be considered in the development and implementation of management measures.

Table 2. 2014 Preliminary Decision Table from the International Pacific Halibut Commission, with the probabilities of various risks (columns) given alternative harvest levels (*"Preliminary Staff Harvest Advice", 2013*).

				Stock Trend				Stock Status				Fishery Trend				Fishery Status
				Spawning biomass				Spawning biomass				Fishery CEY from the harvest policy				Harvest rate
				in 2015		in 2017		in 2015		in 2017		in 2015		in 2017		in 2014
2014 Alternative	Total removals (M lb)	Fishery CEY (M lb)	Harvest rate	is less than 2014	is 5% less than 2014	is less than 2014	is 5% less than 2014	is less than 30%	is less than 20%	is less than 30%	is less than 20%	is less than 2014	is 10% less than 2014	is less than 2014	is 10% less than 2014	is above target
No removals	0.0	0.0	0.0%	5/100	<1/100	23/100	4/100	3/100	<1/100	1/100	<1/100	0/100	0/100	0/100	0/100	0/100
FCEY = 0	11.4	0.0	5.0%	31/100	<1/100	32/100	18/100	3/100	<1/100	2/100	<1/100	0/100	0/100	0/100	0/100	<1/100
	20.0	8.5	10.1%	33/100	<1/100	37/100	24/100	4/100	<1/100	3/100	<1/100	<1/100	<1/100	<1/100	<1/100	<1/100
	30	18.2	15.9%	39/100	<1/100	66/100	41/100	4/100	<1/100	5/100	<1/100	5/100	2/100	8/100	4/100	7/100
Blue Line	36.4	24.5	19.7%	56/100	1/100	82/100	63/100	5/100	<1/100	6/100	1/100	43/100	20/100	74/100	47/100	50/100
	40.0	28.0	21.8%	68/100	1/100	87/100	73/100	5/100	<1/100	8/100	1/100	85/100	52/100	96/100	84/100	92/100
	45.0	32.8	24.7%	82/100	4/100	93/100	83/100	6/100	1/100	10/100	1/100	>99/100	>99/100	>99/100	>99/100	>99/100
status quo	48.5	36.1	26.7%	88/100	8/100	95/100	87/100	6/100	1/100	13/100	1/100	>99/100	>99/100	>99/100	>99/100	>99/100
	55.0	42.6	30.5%	95/100	23/100	98/100	94/100	6/100	1/100	19/100	2/100	>99/100	>99/100	>99/100	>99/100	>99/100
	60.0	47.5	33.5%	98/100	38/100	99/100	97/100	7/100	1/100	26/100	2/100	>99/100	>99/100	>99/100	>99/100	>99/100
				a	b	c	d	e	f	g	h	i	j	k	l	m

Communicating Risk

If stakeholders have greater difficulty understanding probability density functions or probabilities as they relate to risk, they will be unable to understand the potential consequences of various management actions. Low probability/high impact events could be catastrophic for vulnerable fish stocks and participants in associated fisheries.

Finding: Risk experts separate the probability and severity components of a risk, but many managers and stakeholders often do not, leading to an under-appreciation of low probability/ high impact events. Councils and other fisheries management organizations are currently using decision tables and risk matrices to communicate risk in order to facilitate appropriate decision-making.

Recommendation #14: Fisheries scientists should communicate risk using formal procedures such as decision tables and risk matrices to encourage decision-making that is informed by expected outcomes of various management strategies.

Best Practice: Decision Tables to Communicate Risk

The International Pacific Halibut Commission utilizes a risk-based precautionary approach to evaluate current and potential harvest strategies. As a communication tool, scientists have developed a decision table to demonstrate risk, prompting managers to take action based on the probabilities of risks and benefits of particular harvest choices (Table 2).

Photo: Purse Seine, Creative Commons, Tom Clifton

Biological Reference Points

An additional opportunity to examine the robustness to uncertainty of fisheries management protocols occurs after data are integrated; in the scientific modeling realm of the process, where estimations of various reference points can significantly affect management outcomes. There is variation in the way that uncertainty in reference points is conveyed in different assessments. In some cases, uncertainty in reference points is not conveyed at all and a point estimate of the reference point is used. Estimates of current biomass and fishing mortality are usually represented by a probability distribution that represents the uncertainty, and these are often compared to the point estimates of the reference points. However, estimates of the reference points themselves are uncertain —so these should generally also be represented by a probability distribution, and the two probability distributions should be compared.

Finding: The Panel finds that some Councils use deterministic estimates of reference points such as MSY or B_{MSY} or F_{MSY}, while others use more conservative proxies such as 40% B_0 and $F_{40\%}$, in their control rules. The shape of the rules themselves also differs substantially.

Recommendation #15: Fisheries scientists and managers should test current and alternative control rules and associated reference points to determine robustness to predominant sources of uncertainty and responsiveness to the desired characteristics of performance.

Choosing a Management Response

Management Strategy Evaluation is a simulation tool used to evaluate the potential performance of alternative management options in relation to stated objectives. It is based upon a range of potential inputs, including current stock assessments. MSE can be used in a variety of ways: from clearly articulating the real potential performance of the current system, to investigating the effect of changing data collection methods or levels, to allowing a full investigation of alternative management options. The ability of an MSE to facilitate fisheries decision-making depends on: 1) clear goal setting and prioritization of desired outcomes; 2) how well uncertainty is represented; and 3) how effectively the results of analyses are communicated to fisheries managers.

Quick Reference: What is Management Strategy Evaluation?

It is a quantitative modeling tool involving the following steps:

- Determination of objectives and definition of desired outcomes (via workshops)
- Development of possible management strategies
- Testing of management strategies
- Evaluation of management effectiveness of various tested strategies against stated objectives and desired outcomes
- Periodic review of the overall management program

By identifying outcomes resulting from implementation of various management scenarios, MSE can be used as a decision or optimization tool. It can help managers evaluate recovery strategies for overexploited stocks, consider multiple sources of uncertainty, including environmental variability, and improve communication and understanding of how uncertainty is addressed in fisheries management decisions. Finally, MSE can also help guide risk and investment choices for fisheries managers. MSE integrates multiple sources of uncertainty and can prioritize management options in light of risks and their anticipated consequences (Punt et al., submitted).

Because MSE forces decision-makers to clearly articulate their long-term goals and performance measures and prioritize among them, it requires participants to specifically define their objectives and consider the trade-offs that emerge amid competing goals. An effective MSE can quantify the extent to which various uncertainties are likely to complicate attempts to achieve management goals. Another benefit of MSE is that it can improve understanding of the implications of specific uncertainties through simulations. As a result, smarter choices about investment of limited data and science resources can be made in advance.

Finding: The Panel concludes that MSE is not used routinely in management applications in most regions of the United States, despite the active development of MSEs both within NMFS and with collaborators.

Recommendation #16: Fisheries managers and policy leaders should promote the use of explicit risk evaluation frameworks such as MSE and communicate its benefits to stakeholders in the evaluation of risk and the design of robust management approaches. Specifically, they should show how this tool can better engage participants and help inform the decision-making process. Regional managers and authorities should consider new applications of MSE on a "pilot" basis to evaluate the potential value of adopting the approach more widely.

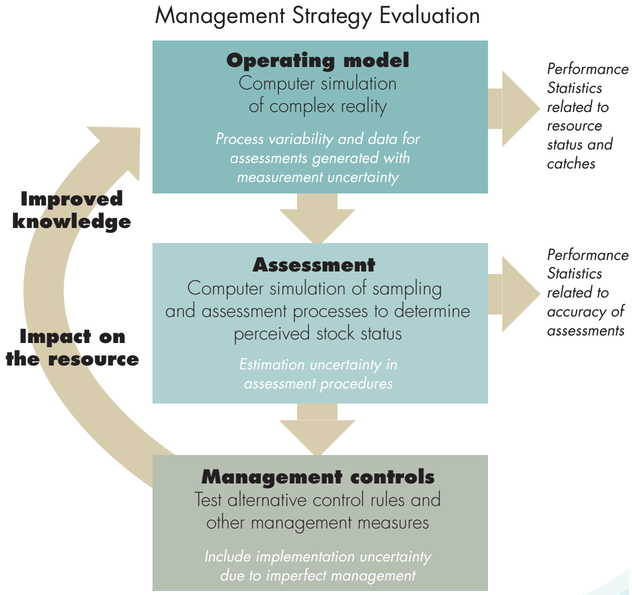


Figure 6. Schematic representation of the Management Strategy Evaluation process.

Best Practice: MSE Workshops to Engage Stakeholders and Promote Communication

MSE workshops provide a platform to improve communication about science and management uncertainty to different categories of participants in more meaningful ways, particularly how and when different sources of uncertainty are accounted for and addressed.

The MSE enables managers to fully assess the consequences of various management strategies and select a suitable strategy that achieves stated goals and objectives but minimizes impacts on stakeholders. In an effective MSE, stakeholder engagement is critical to setting objectives and characterizing uncertainty (and associated plausibility). Scientists work together with fisheries managers to interpret and implement the results of the MSE, which include the quantitative evaluation of various sources of uncertainty and its effects on outcomes (Punt et al., submitted). MSE workshops convened to solicit stakeholder input bolster trust in the management system and serve to educate all participants—scientists, managers, and the public—about the nature, scope, and management implications of uncertainty. They also enhance the science-policy interface.

The Panel considered the Pacific sardine MSE to develop awareness of the challenges of conducting an MSE as well as the advantages of an adaptive management program that is robust to uncertainty. Development of an initial set of possible management strategies for the Pacific sardine fishery resulted from a 2013 workshop and an MSE was conducted, in iterative fashion, based on input from all parties, including fishermen, scientists, conservation organizations, and Council advisors and members. The MSE enabled scientists and managers to select which uncertainties to consider, including how environmental change should be modeled, and which management strategies were most robust to uncertainty. (Hurtado & Punt, 2014). The MSE of the U.S. Pacific sardine fishery has been successful and the outcomes are consistent with all applicable laws and regulatory structures.

Conclusions

To accomplish fisheries conservation and management in a sustainable way, the United States has legislated a rigorous and detailed system for managing our nation's fisheries based on quantitative analyses, catch accounting, rebuilding timeframes, accountability measures and the precautionary approach. This system depends on a great deal of information that is utilized to set fishery reference points and make other important management decisions.

Even with substantial investment, innovative data collection techniques and sophisticated modeling, uncertainty is an inherent characteristic of any fisheries management process. This does not mean that the goals and implementation of the current management system are in any way invalid or unachievable. It simply requires continued work to develop ways to better manage in the context of the uncertainty that remains. This project was undertaken to assist in guiding that important work.

The Panel recommends the following actions be taken to address outstanding challenges associated with uncertainty:

- Better identify sources of uncertainty and educate and inform stakeholders, managers, scientists and policy makers about the nature, scope and management implications of uncertainty. Explicitly identify roles and responsibilities of process participants in addressing uncertainty.

- Work to reduce uncertainty, where possible and cost-effective, using existing and new tools, technologies and approaches.

- Place increased emphasis on understanding and incorporating environmental variability into fisheries science and management decisions.

- Incorporate explicit risk calculations and preliminary evaluation of uncertainty using tools such as Management Strategy Evaluation as a means to understand and prioritize management responses to uncertainty and make effective resource allocation decisions.

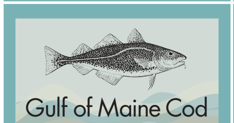
Creating and sustaining an effective fisheries management process requires support and communication among all the participants, especially in the face of uncertainty. The recommendations and best practices set forth in this report are offered as building blocks with which to engage stakeholders, promote understanding and transparency of the fisheries management process, and tackle large issues in support sustainable fisheries.

Communicating uncertainty clearly and systematically will build trust among stakeholders, fisheries scientists and fishery managers. This will significantly affect attitudes of fishermen and participants in the management process and their response to conclusions about uncertainty that is pervasive in assessment and management decisions (Kloprogge et al., 2007).

Scientists and managers have developed successful approaches to manage fisheries in the context of uncertainty. Best practices that have been implemented in some regions could be extended to other regions of the country. By focusing on these recommendations and on increased utilization of best practices, scientists, managers, stakeholders and policy makers can continue to achieve great results for fishery resources and fishing communities.

Summary of Case Studies

Table 3. Summary of Case Studies

Fishery	Challenges	Lessons Learned
 Mid-late 1990s	Data-poor; Lack of precaution; Management not able to respond in an iterative way to new information; Environmental factors affecting recruitment were unknown.	Prioritize frequency of stock assessments; Address uncertainty relating to inefficiencies in the management process; Need to incorporate environmental information into stock assessments and management
	Environmental uncertainty; Data uncertainty due to multiple management entities; Lack of coordination among management entities	Collaborative monitoring needed; Dialogue under way concerning governance
	Combined stocks; Multiple stocks with overlapping distributions; Widely varying recruitment, in response to environmental drivers; Lack of data from southern catches; Environmental change uncertainty; How to choose a management strategy?	MSE workshops improve communication about uncertainty; MSE can reduce impacts to stakeholders, consider effects of environmental change, select preferred management option; Harvest control rule to incorporate environmental effects
 2011–present	Lack of precaution; Management not able to respond in an iterative way to new information; Environmental factors affecting recruitment were unknown; Lack of explicit risk policy; Mistrust by stakeholders of how uncertainty was considered in process	Precautionary adaptive management rebuilding plan implemented; Ecosystem management plan and risk policy in development; Stakeholder workshops held to solicit/disseminate information
 1996–present	Data limited (Significant recreational component; Significant bycatch in shrimp fishery); Governance issues; Allocation issues; Environmental drivers affecting recruitment (natural + oil spills)	Reducing uncertainty increases credibility; Adaptive management is useful because of changing uncertainties over time

Five case studies taken as snapshots in time illustrate the diversity of issues related to uncertainty. Although actions have been taken to address challenges these fisheries present(ed), in some cases concerns remain and additional action is required to fully reduce, and/or manage in the context of uncertainty. *Refer to* **www.aqua.org/fisheries** *for Appendices for detailed evaluations of these fisheries.*

List of Acronyms

ABC	Acceptable Biological Catch
ACL	Annual Catch Limit
ACT	Annual Catch Target
AP	Advisory Panel
CAMEO	Comparative Analysis of Marine Ecosystem Organization
EA	Environmental Assessment
EIS	Environmental Impact Statement
FATE	Fisheries and the Environment Program
FEP	Fisheries Ecosystem Plan
FMP	Fishery Management Plan
FSSI	Fish Stock Sustainability Index
GLOBEC	Global Ocean Ecosystem Dynamics
IEA	Integrated Ecosystem Assessment
MAFMC	Mid-Atlantic Fishery Management Council
MSE	Management Strategy Evaluation
MSST	Minimum Stock Size Threshold
MSY	Maximum Sustainable Yield
NEFMC	Northeast Fishery Management Council
NFSC	NMFS Northeast Fisheries Science Center
NMFS	National Marine Fisheries Service
NPFMC	North Pacific Fishery Management Council
OFL	Overfishing Limit
PSA	Productivity and Susceptibility Analysis
pdf	probability density function
RIR	Regulatory Impact Review
RSA	Research set-aside
SSC	Science and Statistical Committee
STAR Panel	Stock Assessment Review Panel
VMS	vessel monitoring system

Glossary of Fishery Science and Management Terms

ABC	Annual catch level that is recommended by a Council's SSC to address scientific uncertainty
ABC Control Rule	This is established by the Council and used to calculate ABC for a stock, considering stock size, overfishing, and other factors. The ABC control rule should always take into account the Council's acceptable level of risk of overfishing.
ACL	Acceptable catch limit triggers accountability measures; often the same as annual catch target
ACT	Acceptable catch target; optional; addresses management uncertainty
MSE	A simulation tool to evaluate the potential performance of alternative management options in relation to stated objectives. Management Strategy Evaluation is an analytical tool that enables the user to assess the consequences of a range of management options. It evaluates the robustness of strategies to uncertainty and error.
OFL	Maximum amount of a fish stock that can be caught in a year without overfishing
pdf	Probability density function is the probability that the true OFL is equal to the estimated OFL. Broader pdf's imply more uncertainty.
RSA	Research set-aside programs in the Northeast and Mid-Atlantic promote cooperative (and cost-effective) research by prioritizing data collection goals, setting aside quota/days at sea in applicable fisheries, and allowing fishermen to bid on those allocations in return for selling landed fish caught during a cooperative research project. These projects are also sometimes available in the recreational and for-hire sectors, with different incentives for participants.

Appendices, including additional information about best practices and case studies and a library of useful references on uncertainty in fisheries science and management, can be found online at **www.aqua.org/fisheries**.

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