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PERSPECTIVE

Closing the feedback loop: on stakeholder participation in management strategy evaluation[1]

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Abstract: Management strategy evaluation (MSE) is a simulation-based approach to examine the efficacy of management options in achieving fishery-, ecosystem-, and socioeconomic-related objectives while integrating over system uncertainties. As a form of structured decision analysis, MSE is amenable to stakeholder involvement, which can reduce implementation barriers associated with nontransparent decision-making procedures. Based on analysis of three MSE processes (Atlantic tunas (*Thunnus* spp.), Atlantic herring (*Clupea harengus*), and eastern oysters (*Crassostrea virginica*)), we provide suggestions for improving stakeholder engagement in MSE. By assembling a workgroup and modeling team with diverse backgrounds, including professional facilitators, communication liaisons, and social scientists, dialogue can be improved and an atmosphere of mutual learning fostered. Communication further benefits from clearly defining roles, responsibilities, and terms of engagement for all involved; explicitly and transparently identifying goals and objectives of the MSE before modeling has begun; and, when appropriate, revisiting goals and objectives throughout the MSE process. Although MSEs are not without limitations, the participatory modeling framework, wherein stakeholders are actively engaged at each stage of MSE development, provides a useful mechanism to support fisheries management.

Résumé : L'évaluation des stratégies de gestion (ESG) est une approche basée sur la simulation utilisée pour examiner l'efficacité de solutions de gestion possibles pour ce qui est d'atteindre des objectifs socioéconomiques et associés à la pêche et à l'écosystème en y intégrant les incertitudes associées au système. En tant qu'approche d'analyse décisionnelle structurée, l'ESG se prête à la participation des parties prenantes, ce qui peut réduire les barrières à la mise en application découlant de procédures décisionnelles non transparentes. À la lumière de l'analyse de trois processus d'ESG (thons de l'Atlantique (*Thunnus* spp.), hareng de l'Atlantique (*Clupea harengus*) et huîtres (*Crassostrea virginica*)), nous présentons des suggestions pour améliorer la participation des parties prenantes aux ESG. La création d'un groupe de travail et d'une équipe de modélisation présentant des expériences variées, dont des facilitateurs professionnels, des agents de liaison chargés des communications et des spécialistes des sciences sociales, il est possible d'améliorer le dialogue et de favoriser une atmosphère d'apprentissage mutuel. La communication bénéficie notamment de la définition, tôt dans le processus, des rôles, responsabilités et mandats de tous les intervenants, de la détermination explicite et transparente des objectifs de l'ESG avant que commence la modélisation et, selon le cas, de la révision des objectifs tout au long du processus de l'ESG. Bien qu'il existe des limites aux ESG, le cadre de modélisation participatif, dans lequel les parties prenantes participent activement à toutes les étapes du développement de l'ESG, constitue un mécanisme utile pour appuyer la gestion des pêches. [Traduit par la Rédaction]

Introduction

A bureaucratic approach to natural resource management has historically been utilized for managing marine fisheries, wherein resource user groups have been regarded as clients to be supervised and controlled to achieve conservation goals (Charles 1995; Decker et al. 1996; Jentoft et al. 1998) and avoid the "tragedy of the commons" (Hardin 1968). However, it has become increasingly recognized that bottom-up approaches to fisheries management that incentivize sustainable development and utilization, as op-

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posed to top-down regulatory approaches, can be more effective for balancing trade-offs between resource use and conservation (Hilborn et al. 2004). Inclusion of resource users in the development of policy through interactive participation often facilitates a feeling of ownership and responsibility for resulting management decisions, which can help improve acceptance of and compliance with regulations (Jentoft et al. 1998; Dankel 2016; Linke and Bruckmeier 2015). The concept of co-management for natural resources was developed with the recognition that the role of policy was not solely to control resource users, but to provide a forum for communication among stakeholders that receive either instrumental (i.e., ecosystem services or socioeconomic benefits) or intrinsic (i.e., from the simple existence of the resource or ecosystem) benefits from a resource (Decker et al. 1996; Smith et al. 1999; Minteer 2001). Similar concerns have developed over the use of scientific models designed and utilized to provide advice on sustainable harvest levels, because models themselves may not be effective tools for management if developed in isolation without consideration of their application within the larger management context (Cooke 1999; Charles 1995; Smith et al. 1999).

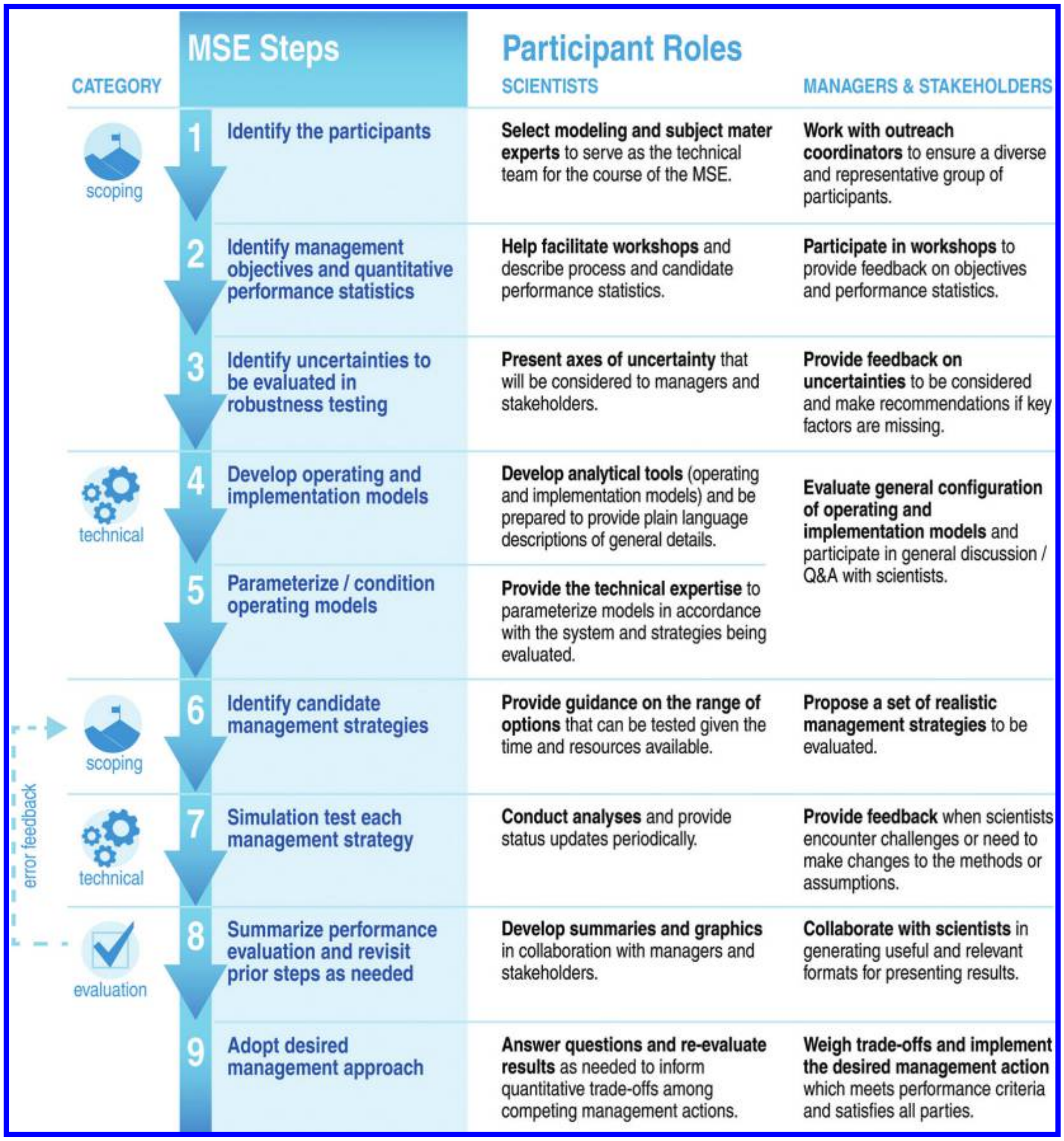
Developing science for policy advice, termed "post-normal" science (Garcia and Charles 2008; Dankel 2016), has led to a movement towards a management-oriented paradigm (de la Mare 1998). In this paradigm for fisheries management, a holistic (or systems) approach to science and policy is taken to better understand how the complete system works (e.g., data collection, stock assessment, harvest policy, and stakeholder response to regulations), rather than focusing on individual components (see Table 1 for definitions of terms used throughout the manuscript; de la Mare 1996; Cooke 1999; Cox and Kronlund 2008). Fisheries management is often based on the stock assessment – total allowable catch (TAC) treadmill, which can elicit combative rather than collaborative stakeholder interactions when decisions are not transparent or there is a lack of understanding as a result of deficient communication (Kell et al. 2006; Cox and Kronlund 2016). This can lead to myopic goals focusing on short-term returns without careful consideration of uncertainty around stock assessment advice or the risk tolerance of managers and stakeholders (Kell et al. 2006; Butterworth 2007; Cox and Kronlund 2008). A critical limitation of the typical scientific approach, as exhibited in fisheries science and stock assessment, is that science alone cannot determine the solution to a biological–sociological–economic problem (i.e., the level of harvest that best balances resource use and conservation objectives). Solving this problem lies within the realm of scientifically informed policy decision-making and requires value judgments to choose acceptable trade-offs (Wilson 2009; Saltelli and Funtowicz 2014). Therefore, the fundamental interaction between science and policy-making may need reconsideration to ensure effective processes are in place (Funtowicz and Ravetz 1993).

The goal of a systems approach is to treat the scientific and management framework as a single interacting process to develop a holistic understanding of how internal and external factors influence decision-making (de la Mare 1998; Cooke 1999; Garcia and Charles 2008). An essential aspect of a systems approach to fisheries management is that the biological, fishery, stock assessment, socioeconomic, and policy components are modeled simultaneously while incorporating feedback and propagation of uncertainty among all model components. This framework supports the development of resource utilization strategies that are robust to those uncertainties while best achieving the mix of resource use and conservation objectives important to stakeholders (de la Mare 1998; Garcia and Charles 2008; Punt et al. 2016). The systems approach provides a tool for performing post-normal science, but does not guarantee success of the entire science-policy framework. Participatory modeling, wherein relevant stakeholders are included in both framing the policy issue to be resolved and the tools to resolve it, is often required to develop successful and, sometimes more importantly, lasting management solutions (Funtowicz and Ravetz 1993; Kaplan 2000; Kaplan and Kaplan 2003; Wilson 2009).

An increasingly popular tool for performing systems analysis in fisheries is management strategy evaluation (MSE; Smith 1994; Butterworth and Punt 1999; Punt et al. 2016). The MSE process uses closed-loop simulation models to explicitly compare and contrast how the system reacts in terms of trade-offs in objectives across a range of alternative management options or procedures (Butterworth and Punt 1999; Kell et al. 2006; Punt et al. 2016). Ultimately, MSE enables testing the performance of alternative management procedures against uncertainty in biological and socioeconomic processes, data collection methods, stock assessment outputs, and the implementation of management decisions while quantifying how robust particular procedures will be to a range of unknown future system states (Kell et al. 2006). This technique resembles laboratory testing a car's safety system before driving into rush hour traffic. Through incorporation of the science and management aspects of the system in the simulation framework, MSE encourages objective and transparent strategic decision-making and provides a means for scientists to be involved in the management process by informing trade-offs without crossing the line into advocacy (Punt et al. 2016; Cox and Kronlund 2016). However, eliminating value-laden choices within model development may never be completely feasible. Therefore, there may be a role for scientific advocacy in post-normal science, particularly within boundary organizations, which straddle the line between science and policy (e.g., regional fishery management organizations (RFMOs) and academic institutions; Cash et al. 2003; Saltelli and Funtowicz 2014; Guston 2001; Gustafsson and Lidskog 2018).

Perhaps most importantly, MSE is a tool for post-normal science that is amenable to the inclusion of stakeholders throughout the process (Holland 2010; Miller and Shelton 2010; Cox and Kronlund 2016). In fact, stakeholder engagement is fundamental to framing the policy issue to be addressed, providing input on scientific tools developed to address the issue, defining management objectives and performance measures, weighing trade-offs among objectives, and providing input on the desired management strategies (see Fig. 1 for a summary of MSE steps along with the role of both analysts and stakeholders at each phase in MSE development; Smith 1994; Butterworth 2007; Punt et al. 2016). Stakeholders include anyone or any group that has a vested interest in the fishery or resource, including fishery participants, managers, decision-makers, and indirect economic benefactors, along with those who represent social or other interests that may be impacted by a management decision (Decker et al. 1996; Miller et al. 2010). Inclusion in the development of management strategies provides stakeholders the support to transition to long-term strategic decision-making that facilitates sustainable development and away from more contentious short-term tactical (e.g., TAC haggling) decisions, which may have detrimental biological and (or) socioeconomic consequences (Kell et al. 2006; Cox and Kronlund 2016). Furthermore, the inclusion of resource users and conservation interests in the development of management advice can foster a sense of partnership among scientists, managers, and stakeholders from different backgrounds with the primary goal of two-way social learning and integration of novel and transparent approaches to science and management (Reed 2008; Pastoors 2016; Dankel 2016). In practice, the level of stakeholder involvement differs extensively across MSE applications and depends on whether an operational (implemented to provide quantitative management advice for a specific situation) or generic approach (generalized methodology to test the robustness of a given management procedure across different states of nature or population dynamics) is implemented (Kell et al. 2006; Plaganyi et al. 2007; Rademeyer et al. 2007). There is an increasing quantity of operational MSEs being conducted; however,

Fig. 1. The role of each of the main participant groups (i.e., scientists, managers, and stakeholders) at each stage of an operational management strategy evaluation (MSE). Although presented linearly for simplicity, the MSE process often involves revisiting previous steps to explore alternate options or include new complexities. Although managers maintain a duel role in the MSE process as both a representative of the public (i.e., a stakeholder) and a technical expert (i.e., informing policy background), much of their involvement is associated with their role as a stakeholder, and they are presented this way for simplicity in the figure.



many of these applications are purely scientific modeling exercises with limited input from stakeholders (Punt et al. 2016; Dankel and Edwards 2016).

There are distinct benefits from including stakeholders in MSE. Improved communication among user groups and scientists facilitates enhanced understanding of how data are used to inform population models that determine catch allocations. Furthermore, stakeholders may have new data that have not previously been analyzed or can provide perspectives or inform estimates of poorly understood parameters that can improve the MSE operating models. Additionally, having stakeholders explicitly contribute to defining management objectives helps to verbalize needs and promotes reflection upon how the resource could be impacted when all or different sets of objectives are attained. A more comprehensive understanding of the trade-offs associated with how well different management procedures achieve a suite of objectives can often ease tensions among groups with conflicting objectives (Smith et al. 1999; Punt et al. 2016; Jones et al. 2016). When all stakeholders explicitly identify their specific goals, user groups can better understand each other, and the MSE process can help formalize and homogenize the risk portfolio for the implemented management regime (Holland 2010; Punt et al. 2016; Dankel 2016). Ultimately, these benefits can lead to improved acceptance of the final management product by ensuring transparency and stakeholder understanding of how the management procedure determines future harvest levels (Punt and Donovan 2007; Butterworth 2008; Kolody et al. 2008).

Despite several reviews providing guidance on how to perform the scientific analyses required for MSE (e.g., Butterworth and Punt 1999; Holland 2010; Punt et al. 2016) and the availability of a rich literature on co-management and stakeholder involvement (e.g., Jentoft et al. 1998; Reed 2008; Mackinson et al. 2011; Linke and Bruckmeier 2015), there remains little practical advice on how to initiate and maintain stakeholder engagement throughout the implementation of an operational MSE. In this paper, suggestions and perspectives are provided on ways to engage

Table 1. Definitions of specific terms as interpreted in the context of this manuscript.

Term	Definition
Biological reference point	Metric for defining the status of a resource (Mace 2001).
Boundary organization	An agency that performs work across the science-policy interface and facilitates interactions among scientists and stakeholders (Gustafsson and Lidskog 2018).
Co-management	Decentralized collaborative fisheries management wherein a participatory process among resource user groups and government agencies is utilized for regulatory decision-making (Jentoft et al. 1998).
Decision analysis	An analytical approach (e.g., MSE) for evaluating alternative decisions by weighing gains and losses (i.e., due to conflicting objectives) in various performance measures given uncertainty in the system (Rademeyer et al. 2007).
Digital applications and gaming	Hands-on computer tools for exploring and learning about uncertainty, feedback control, and trade-off decision-making (Walters 1994).
End goal	The final objective of an action acquired through stepwise application of means goals (Luk'yanova 2007).
Extended peer community	The scientists and stakeholders involved in modern participatory modeling exercises, the inclusion of whom is necessary to identify alternative management procedures and the information necessary to implement them for post-normal scientific applications (Dankel 2016).
Feedback control	Utilizing algorithms to adjust management measures (e.g., TACs) based on observations of the resource (e.g., trends in abundance indices; Rademeyer et al. 2007).
Generic MSE	A conceptual MSE (in contrast with operational MSE; see below), which does not necessarily solicit stakeholder feedback, that may be used to test performance of hypothetical management procedures across an array of resource dynamics or situations (Rademeyer et al. 2007).
Harvest control rule (HCR)	Algorithm (often as a component of a management procedure or harvest strategy) for defining management action (e.g., setting a TAC) based on feedback control given observed data or estimated status of the resource (e.g., a biological reference point) from a stock assessment model (Deroba and Bence 2008).
Management objectives	The predefined goals for managing a resource as defined by MSE participants and decision-makers for which management procedure trade-offs are compared (Rademeyer et al. 2007).
Management procedure (MP)	The complete set of algorithms (e.g., HCRs) along with the associated scientific information (e.g., data and (or) stock assessment models) necessary to implement the management action to be undertaken (e.g., the prescribed TAC; Rademeyer et al. 2007).
Management strategy	The complete management framework including both the management procedure and any regulations external to the MP (e.g., closed areas).
Management strategy evaluation (MSE)	Analytical process for implementing the management-oriented paradigm that uses closed-loop simulation models of a fisheries system with feedback control to explicitly compare and contrast how the system reacts in terms of trade-offs in stated objectives across a range of alternative MPs; it forms a framework for structured decision analysis by trial-testing alternative MPs and quantifying how robust particular procedures will be across a range of uncertainties and unknown future system states (Rademeyer et al. 2007).
Management-oriented paradigm (MOP)	A systems analysis approach to resource management that analyzes the system as a whole by accounting for the interactions among each component of the system (e.g., the resource dynamics, data collection methodology, status assessment, and harvest policy) instead of treating them in isolation (i.e., basing management on a stock assessment without accounting for data uncertainty and feedback control; de la Mare 1998).
Means goal	Short-term stepwise goal that eventually leads to a long-term end (results) goal (Luk'yanova 2007).
Mutual learning	Sharing of knowledge between and among user groups and (or) scientists through participatory modeling exercises and co-management (Berkes 2009).
Operating model (OM)	Mathematical model used to represent the resource dynamics (including the feedback control fishery–resource interactions) with prespecified levels of uncertainty and to simulate "observed" data that inform resulting management actions for the system (Rademeyer et al. 2007).
Operational MSE	An MSE that is being developed through a transparent stakeholder engagement process and will be implemented to determine real-world management advice for a specific resource (in contrast with generic MSE; see above; Kell et al. 2006).
Participatory modeling	Incorporation of the extended peer community in the process of scientific model development (Voinov and Bousquet 2010).
Performance measure	A summary statistic that describes how well a given set of management procedures achieve a desired outcome (Rademeyer et al. 2007).
Post-normal science	Issue-driven science developed to inform policy advice using a systems approach, which explicitly addresses the limitations of the analyses due to unaccounted for and unknowable uncertainties and relies on an extended peer community to inform the process (Funtowicz and Ravetz 1993).
Risk tolerance	The probability threshold (i.e., the degree of variability in performance measures) below which a stakeholder is unwilling to accept the potential negative outcomes that may result from system uncertainties (Francis and Shotton 1997).
Robustness	Ability of a tested MP to provide satisfactory performance (e.g., balancing competing performance measures) despite system uncertainty (Rademeyer et al. 2007).
Satisfice	Determining management procedures (often through negotiation within an MSE) that sufficiently or adequately satisfy each resource user groups objectives with the understanding that no stakeholder group will achieve an optimal outcome (i.e., perfectly satisfy all of their objectives; Miller and Shelton 2010).

Table 1 (*concluded*).

Term	Definition
Stakeholder	Anyone who has an interest in the fishery or resource, including fishery participants, managers, decision-makers, and indirect economic benefactors, along with those who represent social or other interests that may be impacted by a management decision and, as such, may participate in the MSE process and contribute to the development of objectives and performance measures (Decker et al. 1996).
Stock assessment	A statistical population model that integrates data from multiple sources to estimate population sizes and fishing mortality rates, which can then be compared with predefined biological reference points to determine stock status (Rademeyer et al. 2007).
Stock assessment – TAC treadmill	The lengthy process of deliberation for determining a TAC based on the estimate of stock status from a stock assessment, which often involves extensive haggling among user groups and scientists over data utilization, model parametrizations, and appropriate biological reference points, all of which affect resulting TACs (these deliberations can be minimized by agreeing to prespecified MPs; Butterworth 2007).
Strategic decision-making	Accounting for long-term benefits of a given management action with the understanding that they may come at the cost of transient, short-term gains (Kell et al. 2006).
Systems analysis	Interdisciplinary approach to understanding how a system works and responds to stimuli by accounting for interactions among all subcomponents (Garcia and Charles 2008).
Tactical decision-making	Myopic focus on short-term objectives (e.g., the TAC in the coming year) with little regard for the long-term impact of associated fishery policy (Kell et al. 2006).
Technical analyst	Participant in an MSE that provides insight on or helps develop models used in the analysis, but is a neutral advisor on decision points (Punt et al. 2016).
Total allowable catch (TAC)	The catch to be removed from the resource in a given time period (Rademeyer et al. 2007).
Trade-off decision-making	See decision analysis.
Uncertainty	Incomplete knowledge regarding the dynamics of a system, including both human error (e.g., measurement error during data collection or implementation error of a management measure due to imperfect enforcement) and unknown states of nature (e.g., error in model parametrization or parameter estimates; Punt et al. 2016).

Note: Citations identify where further explanations of the topic can be found.

stakeholders in the MSE process and maximize stakeholder input and participation. The conclusions and recommendations were determined through expert opinion and a comprehensive review of three practical examples (described in the paper) where stakeholder involvement was, and continues to be, a defining aspect of the MSE.

Methods

We identify attributes that can enhance the effectiveness of stakeholder engagement in MSE. These attributes are based on our collective experiences implementing operational MSEs along with expert opinion obtained from a 3-day, two session MSE symposium and panel discussion at the 2017 American Fisheries Society Annual Meeting, organized by the authors and sponsored by the American Institute of Fishery Research Biologists (AFS 2017). We augment our experiences with a literature review of the primary fisheries, marine policy, and social sciences literature associated with MSE and participatory modeling. Nonetheless, the manuscript is not intended to be a thorough review of the scientific literature on social science methods, participatory modeling, or post-normal science. We note areas where interactive collaborations among scientific disciplines would enhance MSE applications, but cannot claim to provide a thorough review of socioeconomic methods, which we view as outside the purview of this paper and the scope of our collective expertise.

Three applications of operational MSEs are presented: Atlantic tunas (*Thunnus* spp.), Atlantic herring (*Clupea harengus*), and eastern oyster (*Crassostrea virginica*). We identify common successes and failures in stakeholder engagement aspects of each MSE (see Table 2 for a summary of the MSE applications, difficulties encountered, and unique solutions implemented). Collectively, these examples explore three major difficulties for developing co-management frameworks through MSE (i.e., spatial management complexity, ecological complexity, and social complexity; Linke and Bruckmeier 2015). They demonstrate the inherent and unique issues that arise due to complex social, political, management, human, ecological, and climate-related interactions, specifically associated with international transboundary resources (Atlantic tunas), multisector utilization of a forage fish (Atlantic herring), and high dimensionality of interest groups and governing bodies (Chesapeake Bay oysters). We draw on analysis of these three operational applications (see section below on MSE applications) to formulate suggestions for how to establish and organize committees or working groups that facilitate successful implementation of a participatory MSE modeling exercise (see section on Useful composition of MSE workgroups) and identify techniques for maintaining stakeholder engagement throughout the process (see section on Suggested engagement techniques to facilitate stakeholder ownership and acceptance) that were or would have been useful in our experiences with each MSE application.

MSE applications

Atlantic tunas

Fisheries for the five main species of Atlantic tunas — bluefin (*Thunnus thynnus*), albacore (*Thunnus alalunga*), yellowfin (*Thunnus albacares*), bigeye (*Thunnus obesus*), and skipjack (*Katsuwonus pelamis*) — are worth more than $4.5 billion annually at the final point of sale (Galland et al. 2016). The high value of the various Atlantic tuna fisheries has driven overfishing of many of these populations and complicated traditional, consensus-based management of these highly migratory, internationally shared resources. The International Commission for the Conservation of Atlantic Tunas (ICCAT), the RFMO charged with management and science of Atlantic tunas and associated species, has agreed to adopt harvest control rules (HCRs) for eight priority stocks by 2020 (ICCAT 2015). The ICCAT MSE initiatives stem from guidance provided in the United Nations Fish Stocks Agreement and has been motivated by the success of an MSE-based management procedure for southern bluefin tuna (*Thunnus maccoyii*; Hillary et al. 2016), which helped address similar management challenges in that fishery.

To date, an intermediary dialogue group (i.e., the Standing Working Group on Dialogue between Fisheries Scientists and Managers;

Table 2. Description and comparison of the three MSE applications, including key challenges and recommendations for enhancing stakeholder engagement.

	Application		
Attribute	Atlantic tunas	Atlantic herring	Eastern oyster
Spatial context	International waters Ocean basin	Northwest Atlantic (Georges Bank and Gulf of Maine) Continental shelf	Maryland, US state waters Estuarine system
Critical complexity	Spatial management (international boundaries)	Ecological considerations (herring as a forage fish)	Social dimensionality (number of interest groups and governing bodies)
Management strategies evaluated	Harvest control rules (HCRs)	HCR accounting for herring as forage fish	Rotational harvest Enforcement changes Closed areas Oyster seeding Habitat restoration
Time frame	Full management process 5 years for eight stocks Modeling and analysis 2–3 years per stock	Full management process 2 years Modeling and analysis 6 months	Performed external to management with no set time frame Modeling and analysis process 2.5 years
Stakeholder interests	52 governments, each with diverse interests Commercial industry (many gear types, coastal or distant water fleets) Recreational industry NGOs RFMO secretariat staff	Herring fishing industry Lobster industry Recreational and commercial fleets targeting herring predators Federal managers NGOs	Commercial industry Seafood buyers Aquaculturists NGOs State and federal managers
Key performance metrics	Stock status Fishery yield Interannual stability in catch limits	Stock status Fishery yield Predator status Economic stability Transparent decision process	Abundance Fishery yield Economic performance (revenue) Nitrogen removal
Stakeholder process	Formally commissioned scientist–manager workgroup Informal feedback through national representatives	Two open workshops (select performance metrics, review results) Facilitated process to collect range of stakeholder viewpoints	Stakeholder workgroup Nine meetings over 2 years Facilitated voting on MSE inputs–outputs and recommendations
MSE developed prior to stakeholder process?	Yes (e.g., bluefin analysis underway with stakeholder input to be solicited)	No	No
Outcomes	HCR adopted for albacore in 2017 Analysis in progress for bluefin; management procedure to be adopted in 2019 Five stocks yet to start, with completion by 2021	Results used to inform some HCRs considered by managers Final selection in late 2018	Consensus recommendations finalized (submitted to managers May 2018)
Stakeholder challenges	Defining representative stakeholders given diversity and number Formal international political negotiations Language barriers Degree of understanding and support for HCRs Inconsistent approaches and terminology	MSE process new to participants Turnover of participants between meetings Eliciting desired performance metrics Distinguishing long-term performance from short-term	Overcoming previous negative experience with stakeholder processes Maintaining engagement of participants

Table 2 (*concluded*).

	Application		
Attribute	Atlantic tunas	Atlantic herring	Eastern oyster
Recommendations	More open dialogue with stakeholders (informal, stock-specific workgroups) Improved and varied educational opportunities (e.g., interactive tools) Engage stakeholders who are trusted leaders of their constituencies Standardize terminology and format for presentation of results Enlist the guidance of communication and graphic design experts Commit sufficient time and funding to the process	Education regarding MSE process (generally and during) Clear communication (avoid jargon) Use multiple approaches to explain results Maintain transparency Ensure enough time for development and analysis	Ensure support from managers prior to MSE process Careful choice of committed stakeholders Consider reimbursing participants for meeting time Treat everyone in MSE workgroup as equals Include an experienced facilitation team Loose time frames allow addressing unforeseen complexities Include social scientists (e.g., economists) in workgroup

SWGSM) has served as the primary venue for stakeholder dialogue (ICCAT 2013). The SWGSM meets annually, where updates on the MSE process for each priority stock are presented, and there is an opportunity for participants to provide feedback on the modeling effort or input on MSE elements tied to the management domain (e.g., setting management objectives like stock status, fishery yield, and interannual stability in catch limits). However, many managers and stakeholders have voiced frustration with the SWGSM process due to the formal structure of the meetings. For instance, the diversity of languages represented by ICCAT's 52 member nations requires simultaneous interpretation in ICCAT's three official languages and precludes opportunity for constructive dialogue. Several commercial and recreational industry and environmental nongovernmental organizations (NGOs) participate in the SWGSM meetings as observers, but engagement is limited to making comments only if recognized by the meeting chair, and many of those comments receive no response. Therefore, most of the stakeholder dialogue presumably takes place within each member nation. For example, the United States is hoping to enlist its ICCAT Advisory Committee, which includes commercial, recreational, and environmental interests, as the vehicle for stakeholder dialogue on MSE. There is also an effort underway to revise the terms of reference of the SWGSM to incorporate both formal and informal interactions to stimulate more substantive and constructive discussions and be more conducive to providing feedback.

ICCAT's progress on MSE development toward HCR adoption varies by stock. The Commission adopted an interim HCR for northern albacore in 2017, but MSE work is continuing, with agreement to revise the interim HCR into a management procedure in 2020. Development of the MSE for Atlantic bluefin tuna is also mature, with expectations for adoption of a fully specified management procedure in 2020 (ICCAT 2017*a*, 2017*b*). The process for tropical tunas is just beginning, with a preliminary deadline of 2021 for completion of the iterative MSE work plan.

The degree of stakeholder engagement also differs depending on the species. The northern albacore industry was very supportive of HCR adoption, in part because it is pursuing sustainable seafood certification by the Marine Stewardship Council, which has an HCR requirement. The HCR was likely even more attractive to industry due to the 20% increase in catch limit it granted for the following 3 years. As a result, there was little stakeholder dialogue during the development phase or discussion on the floor when the Commission adopted the HCR. Unlike northern albacore, the western and eastern stocks of Atlantic bluefin tuna are not confirmed as recovered, so adoption of a management procedure will likely be more controversial and involve more extensive stakeholder dialogue (ICCAT 2017*c*). The stakeholder dialogue has not yet begun, but the robustness of potential management procedures against a suite of performance metrics chosen by the modeling team (i.e., a small group of scientist who are developing the MSE models semi-independently of the SWGSM) has already undergone testing and initial evaluation (Carruthers and Butterworth 2018). It is critical to engage stakeholders on desired management objectives in the near future, so the work can continue with stakeholder buy-in to the process. Owing to the spatial complexity of modeling and managing a transboundary, highly migratory species in addition to the diversity of stakeholder interests, it might be useful to convene a more informal, bluefin tuna-specific dialogue group with stakeholders, managers, and scientists to delve into the process and results more deeply and make recommendations to the SWGSM and Commission. This approach has been successful in the Northwest Atlantic Fisheries Organization (Risk-Based Management Strategies group) and Indian Ocean Tuna Commission (Technical Committee on Management Procedures). With seven more ICCAT stocks scheduled for HCR adoption within the next 3 years, additional opportunities for discussions among scientists, managers, and stakeholders will be necessary. This is especially true for the four stocks of tropical tunas, which are caught in multispecies fisheries targeted by many more gear types and many more nations than ICCAT's temperate tunas.

Transboundary, or straddling, resources present a unique challenge to MSE development, particularly with regard to stakeholder dialogue, because the international political nature, language barriers, and sheer number of participants often impede open communication (Pastoors 2016). Similarly, it can be difficult to define representative stakeholder groups, solicit unbiased input and transparent negotiations from political appointees or industry representatives, and ensure adequate understanding of the MSE process across stakeholder groups (Nakatsuka 2017). However, by opening up new avenues of dialogue that span political, social, and expertise boundaries, the MSE process can lead to important improvements in science, management, and enforcement (e.g., through direct interactions and knowledge sharing among stakeholders and various experts), even if the MSE is not immediately operational (e.g., Kolody et al. 2008).

To help catalyze the MSE process, it is critical to dedicate time and funding to improve the clarity and openness of communications. This can be facilitated by the development of materials that explain the process and results in nontechnical (e.g., The Pew Charitable Trusts 2016) and interactive (e.g., Punt 2017) ways, by standardizing terminology and the presentation of results, and by enlisting the guidance of communication professionals. Another essential component is improving the stakeholder dialogue by providing opportunities for more informal discussions and seeking out participants who are trusted leaders of their constituencies. If ICCAT invests in the MSE process in these ways, it will be much more likely to lead to a product supported by managers and other stakeholders and, thus, have the results translated into management actions in accordance with ICCAT's agreed 5-year timeline.

Gulf of Maine – Georges Bank Atlantic herring

Gulf of Maine – Georges Bank Atlantic herring (hereinafter, herring) along the continental shelf of the northeast US and some inshore areas of Canada has supported a directed fishery for decades and serves as a prey resource for many species in the ecosystem. The stock has been managed without a pre-agreed, long-term control rule, and the role of herring as forage in the ecosystem has not been explicitly incorporated into management decisions. Consequently, the HCR applied in any given year was subject to debate and often changed during each quota-setting process, which took place approximately every 3 years (i.e., the stock assessment – TAC treadmill; Table 1). Some stakeholders expressed interest in evaluating and selecting a long-term HCR based on explicit objectives and performance metrics related to herring's role in the ecosystem as a main source of prey. No analysis was available, however, to evaluate the relative performance for meeting a range of fishery objectives across possible control rule options.

In January 2016, the New England Fishery Management Council (NEFMC), responsible for the management of federal fisheries in the region, elected to conduct an MSE to evaluate the ability of different herring HCRs to achieve various fishery objectives. The entire process from conception to selection of a HCR was expected to take 2 years, with a relatively short amount of time (6 months) allotted to data analysis and modeling (Deroba et al. 2018). The NEFMC anticipated diverse stakeholder interests, including the herring fishing industry, the lobster industry that relies on herring for bait, recreational and commercial fishing interests that target herring predators, and NGOs. The NEFMC, partnering with the National Marine Fisheries Service's Northeast Fisheries Science Center (NEFSC), aimed to use MSE as a collaborative decision-making process involving more upfront public input and technical analysis than usually occur when developing management alternatives. The MSE was also to consider ecosystem and socioeconomic objectives. The MSE steering committee composed of representatives from the NEFMC and NEFSC coordinated two 2-day public workshops. The first introduced the topic of MSE and solicited possible management objectives and quantitative performance metrics from stakeholders. Based on input from the first workshop, NEFSC staff developed the closed-loop simulation portion of the MSE. Time constraints required the development of relatively simple models addressing ecological and economic objectives prior to the second workshop, held 6 months after the first. The second workshop reported preliminary results and allowed the public to voice preferred ranges of performance for the various metrics, all of which were conveyed to the NEFMC to aid in their selection of a HCR. Attendance at each workshop was approximately 65 people, but participation was not consistent, with only half of the attendees at the second workshop also having attended the first. Although inconsistent attendance was inefficient, because of the need to repeat material covered during the first workshop, this aspect was intentional to help ensure that the MSE mirrored the open process used by the NEFMC. The MSE process for herring is ongoing, but the MSE has been used by the NEFMC to select a set of ten possible HCRs, with a final decision expected approximately 3 years after the MSE process was initiated.

Topics covered during the MSE were expected to be controversial, and MSE was new to most stakeholders in the region, so an MSE expert from outside the region facilitated the workshops. The facilitator served as a calming presence and also helped reassure stakeholders of an independent and fair process. The time frame of 1 year for this MSE did not permit more than two formal stakeholder workshops, which was likely insufficient to fully convey the concept of MSE or for most participants to fully comprehend and engage in the process. This challenge was partially overcome by stakeholders contacting subject matter experts from the NEFMC and NEFSC through informal channels (e.g., phone and email) and by providing opportunities for public input at other NEFMC meetings that occurred during the process. These additional opportunities for interactions generally bolstered the positive relationships developed among stakeholders, scientists, and managers that began at the formal workshops. Such interactions would benefit most MSE applications. Some stakeholders also struggled with the concept of evaluating long-term trade-offs in the absence of a consideration of short-term costs and benefits (e.g., What will the quota be next year for each HCR?). Ultimately, 3-year quota-setting projections were conducted for a range of control rules so that some short-term consequences could be considered simultaneously with the long-term trade-offs captured by MSE simulations. More education about MSE in general is needed for scientists and stakeholders alike to increase the capacity for conducting MSEs and so that participants garner the full benefits of the process. Such educational opportunities would ideally be provided outside of a formal MSE process or with time explicitly allotted within a given MSE so that general MSE topics can be presented separately from the management procedures being evaluated.

Oysters in the Choptank River Complex, Maryland, USA

The eastern oyster is a keystone species in the Chesapeake Bay, supporting a valuable fishery and providing a range of ecosystem services. The population has declined to less than 1% of its unfished abundance levels (Wilberg et al. 2011), which has caused substantial interest in restoration and alternative fishery management options. In 2010, the focus of management was on large-scale sanctuaries (i.e., marine protected areas) and increased enforcement of existing regulations. In addition, large-scale restoration efforts have been conducted in some sanctuaries to enhance the population. These changes have caused substantial friction between the fishing and environmental communities. Therefore, analysts proposed to work with a wide range of stakeholders to attempt to develop consensus recommendations for oyster restoration and management using an MSE combined with a consensus solutions approach (e.g., Miller et al. 2010), which was termed OysterFutures. The management agency with jurisdiction over this resource, the Maryland Department of Natural Resources, agreed in advance to consider the recommendations of the workgroup for use in management, which was helpful for getting participants to agree to be involved in the process.

The OysterFutures MSE process began in the winter of 2016. The stakeholder workgroup included six commercial fishers, one seafood buyer, two aquaculturists, five environmental NGO members, and two state and federal agency representatives. Members of the community active in oyster issues were interviewed to identify potential members for the workgroup, and all the potential members were interviewed prior to inviting them to participate. During this process, all the workgroup members were requested to commit to making four meetings during a 1-year period.

The workgroup collaborated with the scientific team to develop a model that forecasted the effects of alternative management and restoration activities on a range of performance measures deemed important by the workgroup. During the first meeting, analysts worked with the group to identify potential management options (i.e., the types of actions the workgroup would like to be able to consider) and performance measures (i.e., the metrics the group would look at to quantify success). The scientific team then used these inputs to begin development of the model. The model included larval transport, habitat heterogeneity, dynamic fishing effort, and production of ecosystem services. The model was iteratively developed with feedback from the workgroup over the course of five meetings. During this time, the scientific team worked extensively to describe how the model operated and frequently showed the data that were used to estimate parameters of the model. Furthermore, data were not available to inform some parts of the model, particularly the economics. The workgroup provided estimates of their costs for fishing activities as well as invaluable information about how the fishery operated that was incorporated into the model. The potential options for fishery regulation and restoration included rotational harvest areas, changes in enforcement, harvest sanctuaries, planting shell or young-of-the year oysters, and habitat restoration. The MSE calculated a range of performance measures to evaluate the degree to which options achieved stakeholder objectives, including oyster abundance, fishery revenue, amount of effort, and ecosystem services such as harvest and water quality improvement.

The process was conducted using a consensus solutions approach developed by a facilitation team that ran the meetings (see Miller et al. (2010) for a description of the consensus approach). All participants agreed to abide by the rules of the meetings, which included respectfully engaging with one another and considering all sides before making a decision. A 75% supermajority of acceptable votes was required for a rating to pass, but ratings for recommendations were not final until the final workgroup meeting. For each rating, members indicated their preference using a show of hands, and members who indicated they had minor or major reservations were prompted to provide their reasons for the reservations. Sometimes, a new proposal would be produced to address the reservations, and the process was repeated. During the fifth meeting, the stakeholders rated all the components of the model as acceptable and began to craft their recommendations package. The subsequent meetings involved the stakeholders revising their options to attempt to balance their goals and interests with those of other members of the workgroup. The workgroup submitted a package of 28 recommendations to the Maryland Department of Natural Resources in May 2018 (for the full package of recommendations see OysterFutures Stakeholder Workgroup 2018), including expanding replenishment programs, enhancing enforcement, changing sanctuary boundaries, considering limited access, and using the OysterFutures approach for other fisheries issues.

The OysterFutures experience highlights several challenges that come when attempting to fully include stakeholders in an MSE. Maintaining engagement of stakeholders can be difficult. There was a high turnover (about 50%) of representatives from the industry during the five project meetings. A lack of initial engagement was partially because the industry participants had to make the choice of potentially sacrificing a day's work to participate in the meetings. The workgroup, therefore, chose to meet on weekends to reduce this conflict, and industry members were compensated for their participation. Furthermore, having a high-level representative from the management agency as part of the stakeholder group was important for convincing many members that it was worth their time to participate in the process. Many of the individuals had either participated in or witnessed processes with stakeholders that they viewed as unsuccessful in the past. The MSE team had to work to convince the group that OysterFutures would be different from other activities in which they had been involved. The degree of success associated with OysterFutures is, in part, because everyone in the workgroup was treated as equals throughout the process. The analysts and modelers spent a substantial amount of time listening to stakeholder ideas and concerns and made many changes to the model based on those concerns. If one wants to engage successfully with stakeholders, one should expect to learn as much as they teach. Lastly, fully integrating stakeholders in an MSE requires a substantial increase in time and effort over a process that does not include them. The OysterFutures project team initially planned for the process to take four meetings over the course of 1–1.5 years. However, OysterFutures has required eight meetings over more than 2 years, partially because of the requests for specific options and inclusion of ecological–economic processes that the workgroup made of the modeling team. Despite these challenges, the stakeholders were extremely positive about their experience in the process and recommended that future stakeholder engagement in Maryland follow a similar process.

Table 3. Example composition of an operational MSE workgroup.

MSE organizer	Stakeholder
MSE and assessment modelers	Commercial fishermen
Technical subject matter experts*	Recreational fishermen
	Subsistence fishermen
Professional facilitator	Other industry representatives (e.g., processors)
Communication specialist	
Graphic artist	Nongovernmental organizations (NGOs)
Outreach coordinator	
Legal expert	Environmental NGOs
	Impacted public
	Fisheries managers

*Technical subject matter experts include oceanographers, ecologists, biologists, economists, and other social scientists.

Improving stakeholder engagement in the MSE process

Useful composition of MSE workgroups

Review of the three operational MSE examples demonstrates that successful applications of MSE, particularly those that result in improvements to and acceptance of harvest rules and regulations, typically involve a broad participant group including a core set of resource users, conservation group representatives, and agencies in charge of fisheries management (i.e., the stakeholders), along with MSE analysts and facilitators (i.e., the MSE organizers). The critical differentiation between stakeholders and organizers is that while the latter actively participate in the analytical development of the MSE, they are neutral advisors on key decision points (Punt et al. 2016). While there is no prescribed or rigidly structured complement of MSE participants, the following composition was identified as desirable (from both the American Fisheries Society panel discussion and analysis of the various MSE processes) for successful MSE applications (see Table 3): a technical modeling team; subject matter experts; management and policy specialists; facilitation, communication, and outreach specialists; and resource interest groups, along with environmental representatives. Optimal participation may not be possible given limited resources, so alternative solutions may need to be considered to ensure sufficient representative input is available to inform the various MSE components. For example, some members of the process could take on multiple roles. We describe the roles and important characteristics of each group below.

Technical modeling team

There needs to be a technical team of scientists leading the analytic development. This team is responsible for implementing the simulation modeling component that forms the technical basis of the MSE process. Model complexity can vary widely across MSE applications, and implementation of an operational MSE often requires a collaborative effort from a team of modelers (although basic performance analyses and simulation tests are considered a form of MSE, they are not at the scale typically described for operational MSEs (see Table 1) in the primary literature and are not the focus of this article). It is the responsibility of the modeling team to develop the analytical approach used to model the system of interest, translate desired management actions into formal HCRs, and synthesize the results of implementing a given management procedure based on requested performance metrics (Smith 1994). Throughout the development of these models, the technical team must work closely with facilitators to communicate with managers, stakeholders, and other scientists about the feasibility and appropriateness of requests to alter or amend the model configuration (Fig. 1; Smith et al. 1999) while ensuring that participants' needs (as agreed upon in the prespecified terms of reference) are being adequately met.

Subject matter experts: economists, social scientists, and ecologists

The development and evaluation of alternative models used for MSE can be a highly technical undertaking. To ensure transparency, build trust, and implement the best use of available science, it is often necessary to bring in subject matter experts to review technical aspects and further the expertise of the workgroup (Punt and Donovan 2007; Kraak et al. 2010). Modeling the human dimension represents a challenge for MSE, but may be the area with the greatest scope for improvement (Edwards and Dankel 2016). While economics and human behavior are widely recognized as an essential component of an MSE operating model, social science experts are oftentimes underrepresented in MSEs, and formal integration of the socioeconomic sciences into MSE has clearly lagged (Holland 2010). Human responses to management, particularly nonrational behavior and noncompliance with implemented regulations, can be one of the greatest sources of uncertainty in an MSE and is often poorly characterized (Salas and Gaertner 2004; Bunnefeld et al. 2011; Punt et al. 2016). For example, noncompliance with sanctuary regulations had the potential to substantially reduce the benefits of restoration efforts for oysters in the Chesapeake Bay during the OysterFutures project, and the inclusion of social scientists helped elucidate how human behavior might mitigate potential benefits of proposed management.

Social scientists are trained to solicit unbiased samples (perspectives or opinions) from humans, which can provide insights on social or cultural motivations that may not be obvious to fisheries scientists or managers, and may help elucidate stakeholder objectives and concerns (Crosson 2011). Additionally, social scientists have different perspectives on how fishery management works. Therefore, incorporating social scientists in MSEs allows exploration of alternate performance metrics and management strategies (e.g., Pascoe et al. 2010) and can improve how MSEs parameterize human behavior and fleet dynamics (Holland 2008) through development of bioeconomics models or elucidating human responses to management actions in comparable systems (Holland 2010; Dichmont et al 2016; Holland et al. 2017). Including social scientists in the OysterFutures project improved the bioeconomic model and permitted stakeholders to consider performance measures better tailored to their individual operations (Table 2).

Ecosystem scientists and physical oceanographers should also be included in the MSE process (e.g., Gaichas et al. 2016*a*, 2016*b*), particularly as the scope of MSEs extends beyond single species applications. They can inform pertinent trophic interactions, habitat- or climate-related hypotheses, processes that govern stock dynamics, and can provide tools necessary to develop operating models with ecosystem-level dynamics. In the herring example, inclusion of ecosystem scientists enabled explicit modeling of multispecies interactions to account for the role of herring as a forage fish (Table 2).

In general, the specified management objectives and hypotheses about alternative states of the system being modeled provide the landscape for identifying subject matter experts across a diverse array of disciplines needed to better inform the underlying models. Although MSE remains a largely fisheries science-centric endeavor (Smith et al. 1999; Degnbol et al. 2006; Benson and Stephenson 2018), as the three MSE applications illustrated, the incorporation of various scientific fields within the MSE process are continuously evolving. However, there remains an urgent need for better collaboration and communication among scientific disciplines to improve on the use of MSE initiatives in fisheries management.

Facilitation, communication, and outreach specialists

Eliciting stakeholder involvement and input is just as critical as the technical modeling when conducting an MSE. Given the complexity, novelty, and uniqueness of each MSE, workgroups benefit from professional, neutral facilitation (Reed 2008). As demonstrated in both the herring and oyster MSEs, professional facilitators were crucial for success as they are trained to foster communication and develop dialogue among all vested groups, maintain discussions on relevant topics, resolve conflicts, oversee negotiations in a fair and unbiased manner, and cultivate group decisions (Table 2; Davis 2008; Jones et al. 2016; Oates and Dodds 2017). Unlike subject matter scientists who may not necessarily have the skills or natural inclination to operate in this role, trained facilitators have the experience necessary to ensure that meetings run smoothly and knowledge and information are adequately disseminated. Facilitators can also help to open lines of dialogue among scientists and stakeholders by simplifying scientific terminology and eliciting the necessary inputs from stakeholders that are required for scientists to develop a useful modeling framework.

However, facilitators need to understand the MSE process. In most cases, bridging the scientist–stakeholder communication divide will require that the facilitators and the MSE lead analysts work together closely to ensure facilitators understand the model development process so that they can determine the best ways to engage with stakeholders. When time and funding permit, graphic design and communication specialists can also be helpful for developing unique communication and presentation techniques that can convey complex scientific concepts in formats more suited to the particular learning styles of the stakeholders involved (Rademeyer et al. 2007; Punt et al. 2016; Voinov et al. 2016; Levontin et al. 2017; Lynham et al. 2017).

Outreach efforts are necessary before initializing MSE development to ensure that the public is informed about the process and to engage key participants (Thompson et al. 2017*b*). Outreach coordinators are valuable for identifying the extended peer community that should be included in the MSE (i.e., the potential stakeholder groups; Dankel 2016) and to spread the word about the opportunity to be directly involved in the management decision-making process (Chuenpagdee and Jentoft 2007). It is important that the process is accessible to all stakeholder groups whether as individuals or through representation and that stakeholders are aware that the process is taking place (Mackinson et al. 2011; Punt et al. 2016).

Management and policy specialists

Fishery managers should be consulted to ensure management options being evaluated are permissible under current rules, regulations, or law. However, legislative restrictions can limit the ability to explore new or unique management approaches, and lack of flexibility may hamper management performance. Therefore, exploring management measures that do not align with existing laws may be beneficial, and policy experts can provide a clear understanding of the process for (and likelihood of) amending existing statutes and regulations. Participation of fishery man-

Table 4. Four broad categories of stakeholder characteristics that can help ensure the long-term success of MSE recommendations.

Informed process	Interactive process	Results widely disseminated	Negotiations supported
Previous training	Open to participatory modeling initiatives	Broad peer base	Esteemed by peers
Knowledgeable about management	Effective listener	Willing to explain MSE process	Industry or community leader
Derives active or passive value from resource	Willing to devote time to participate	Communicates constructively	Nominated by peers
	Actively participates		Willing to represent a group
	Supportive of collaborative solutions		

Note: These basic traits were identified through analysis of the example MSE processes for Atlantic tunas, Atlantic herring, and eastern oyster and were supplemented by similar suggestions from the participatory modeling literature (e.g., Reed 2008; Duggan et al. 2013; Thompson et al. 2017*a*; Jordan et al. 2018). Not all stakeholders will possess each characteristic, and many will be learned or improved during the MSE process (through associated education and experience). A successful MSE will incorporate stakeholders with a diversity of opinions, but who are open to attempting a participatory modeling initiative.

agers is often critical to ensure management options are practical, because they are typically responsible for implementing and monitoring the final management framework (Kolody et al. 2008). Moreover, fishery managers can function as both legal advisors (e.g., providing background on the history and legality of regulations) and as stakeholders (i.e., representing the interests of the general public; Mikalsen and Jentoft 2001). Involving managers throughout the process as direct voting stakeholders promotes buy-in from a regulation and enforcement perspective and increases the chance that the agreed upon outcome will be feasible in practice (Smith et al. 1999). Developing MSEs within the context of RFMOs (i.e., as was done with herring and is being done with Atlantic tunas) provides an additional layer of support for the process, ensuring that resultant advice is feasible while demonstrating to stakeholders that their participation will be productive and the results of the MSE implemented. Incorporating management representatives directly in the MSE workgroup for oysters was identified by other stakeholders as a main incentive to participate, because they felt that the results would directly impact future management (Table 2).

Stakeholder representatives

Obtaining an adequate group of scientists is often more straightforward than assembling a representative, yet tractable (in the sense of running efficient meetings), set of stakeholders (Davis 2008). Once the primary constituent groups are identified, selecting individuals to be representatives for each stakeholder group is an important, yet challenging, next step. Constituents are likely to listen to sector leaders or representatives more so than a counterpart, but care must be taken that the chosen representative actively reflects the goals of the larger group or else acceptance of the results will be greatly diminished (Yates 2014; Jordan et al. 2018). Therefore, soliciting nominations from stakeholder sectors is advisable given that nominees are likely to be prominent members that maintain the respect of their group. For more diverse or less organized sectors, it can also be useful to analyze social networks (Reed 2008) or use evidence-based clustering (e.g., Hartley 2010; Duggan et al. 2013) by exploring existing management group membership, performing telephone or dockside polls, or identifying active and top-grossing fishermen (e.g., highliners). However, because no single group is likely to achieve all of its individual goals, individual representation may not be as important as ensuring that all broad-scale stakeholder groups are represented so that no single group can monopolize discussions and negotiations (Pascoe et al. 2009; Pascoe and Dichmont 2017).

Different stakeholders will join the process with different viewpoints, goals, and interests, but all will require skills in listening to others' perspectives, understanding others' needs, and negotiating through conflicting objectives (Smith et al. 1999; Reed 2008). Characteristics of stakeholders that can help ensure the long-term success of an MSE and resultant advice can be broken down into four broad categories (Table 4): an individual is informed (e.g., regarding fisheries regulations and management); an individual is willing to interact with others and actively participate in the MSE process; an individual is willing to disseminate results to constituents; and an individual has the support of his or her peers such that MSE negotiations will be better received by the broader impacted community. By including MSE participants that are active members of the fishing or conservation community, there will be increased opportunities for stakeholders to better understand how the resource is managed and, thus, provide new (and feasible) perspectives on alternative management options. Similarly, representatives that have a broad peer base or are trusted leaders can often more readily negotiate on behalf of a stakeholder group, which can help ensure support of the final MSE product (Duggan et al. 2013; Thompson et al. 2017*a*; Jordan et al. 2018).

If MSE participants do not maintain at least some of the traits outlined in Table 4, the results of the MSE may encounter resistance among individuals or groups who were not directly involved in the MSE process (Smith et al. 1999; Jordan et al. 2018). The inclination to actively engage in a participatory MSE, however, should not be confused with the need for every participant to wholeheartedly support the concept of MSE. A successful MSE process often requires a willingness by participants to collaborate, including providing critique and skepticism, which are essential components of scientific advancement. On the other hand, if participants are not willing to listen to one another and openly explore alternative ideas and management options, then the chance for successful engagement can lessen considerably. As mentioned previously, fisheries managers participate in a duel role as both policy specialists and stakeholder representatives of the general public. In their role as stakeholders, it is important that managers possess the same traits and open-mindedness as other MSE participants to ensure a fruitful MSE process.

The OysterFutures project utilized interviews to identify and select community members who were actively involved with issues related to oyster harvesting and conservation, open to active participation in an MSE initiative, and whose stature would be advantageous to disseminate the potential benefits of the recommendations submitted by the MSE workgroup. Even with the small spatial scale of the OysterFutures project (only two state counties), it was necessary to select among hundreds of potential industry participants. For herring and Atlantic tuna, the broader geographic scale of management issues caused inherent difficulty in narrowing participation while still maintaining an open and transparent process, which demonstrated that limiting participation is not always feasible or recommended. However, as MSE group size increased, it became even more imperative for professional facilitation that aided clear and open communication along

Table 5. Suggested communication and education tools that can help improve stakeholder interactions and enhance understanding of the MSE process.

Communication	Education	Forum
Ensure dialogue	Everyday examples of trade-off decision-making	Informal (e.g., boat shows)
Flexible interactions	Explore MSE success stories	Formal (e.g., meetings)
Transparent decision-making	Develop interactive exercises	At-home (e.g., remote access)
Equal opportunities to speak	Digital applications and hands-on learning	Educational (e.g., learning workshops)
Engage stakeholders	Emphasize mutual learning	One-on-one (e.g., phone or email)
Avoid jargon	Summary pamphlets and educational materials	
Easily understood summary graphics		
Repetition		
Peer-to-peer conversations		

Note: Example meeting forums are given that provide differential exchanges among scientists and the myriad stakeholder groups involved in the development of an operational MSE. These suggestions were identified through analysis of the example MSE processes for Atlantic tunas, Atlantic herring, and eastern oyster and were supplemented by similar suggestions from the participatory modeling and MSE literature (e.g., Kolody et al. 2008; Reed 2008; Punt et al. 2016; Cox and Kronlund 2016; Oates and Dodds 2017; Sampedro et al. 2017). Figure 2 demonstrates how these tools can be used synergistically to optimize participation of all stakeholders in the MSE process.

with constructive interactions among all members of the workgroup.

Suggested engagement techniques to facilitate stakeholder ownership and acceptance

The MSE process is relatively new to a majority of fishery stakeholders (including managers and analysts; Punt et al. 2016; Nakatsuka 2017). Because human nature is often resistant to change, particularly when changes are associated with a lack of understanding about how they may come about (e.g., implementing new policy based on a poorly understood MSE process), it is important that continuous and direct participatory engagement of stakeholders is undertaken from the outset of any natural resource management initiative (Kaplan 2000; Kaplan and Kaplan 2003). Therefore, hands-on education and clear two-way communication about the MSE process are critical first steps to facilitate full stakeholder participation, ownership, and, ultimately, support for MSE outcomes (Kolody et al. 2008; Cox and Kronlund 2016). We highlight several facets of education and communication within a given participatory modeling project (e.g., an operational MSE) that can support a successful outcome (Table 5) and address major challenges to stakeholder engagement in MSE (Table 6).

Utilize adaptable and diverse education and communication techniques

Stakeholders come from myriad backgrounds, which often span variable scientific understanding, and each utilizes different techniques for assimilating new information. Thus, education and communication approaches that are ideal for one stakeholder sector may not resonate with another. Similarly, scientists have varying communication skill sets resulting in differential interactions among scientists and stakeholders depending on the forum. Therefore, communication techniques and educational tools should be adaptive to meet the needs of the various participants (Reed 2008). For instance, representatives of NGOs are often comfortable in formal meeting settings, whereas fishermen may communicate more openly in informal arenas (e.g., boat shows or harbor cafes; Yates 2014; Lynham et al. 2017; Oates and Dodds 2017). Exploring diverse meeting locations along with communication and educational tools (see Table 5) while determining the most effective mixture for each stakeholder sector (Fig. 2; Smith et al. 1999; Sampedro et al. 2017) will help the array of MSE participants better understand the MSE process and the decisions being explored. Developing alternate informal channels of communication (e.g., one-on-one conversations via phone and email) can also be useful to break down communication barriers, which was cited as a main benefit and reason for success in the herring example. The lack of open communication channels was noted as a main detriment in the development of MSEs for Atlantic tunas (Table 2).

Utilizing assorted education tools (Table 5), such as hands-on learning, interactive exercises, and digital applications (e.g., Punt 2017), that allow stakeholders to explore how the fishery interacts with potential management options gives participants a chance to understand the basics of MSE in an environment best suited to their personal learning style. These types of instructional aids can provide insight into the MSE process by exploring hypothetical impacts based on particular interests and can give stakeholders a sense of how the modeling works, what the uncertainties are, how decisions translate into outcomes, and how alternative management options translate into trade-offs among management objectives (Walters 1994; Cochrane et al. 1998; Punt et al. 2016). Real-world examples are another useful education tool that can demonstrate MSE success stories that have led to improved management, greater transparency, or other positive outcomes. Direct engagement of stakeholders through peer-to-peer learning exercises can be helpful for convincing participants why the substantial investment of their time and energy in an MSE can be worthwhile (e.g., typically several day-long meetings per year over the course of multiple years for a thorough MSE process such as OysterFutures). Analysis of the Atlantic tuna example suggested that improved educational tools, especially dissemination of summary pamphlets and digital applications to stakeholders that describe the basics of MSE, would be useful for improving stakeholder understanding of the MSE process and increase future participation (Table 2).

General education about MSE should ideally be separated from an immediate decision-making context or a particular MSE application, so that stakeholders can become comfortable with the steps involved in the process without the pressure of decisions that potentially affect livelihoods (Table 6; Jenkins et al. 2017). The herring example highlighted that improved education about MSE concepts external to the MSE process would have been extremely useful, especially given the limited time frame available to organize and implement the MSE (Table 2). Basic education can often be done in a broader context than any specific project, which helps prepare the extended peer group for involvement in participatory modeling initiatives. Fortunately, education and capacity building is underway in many RFMOs (e.g., ICCAT's multiple "Dialogue between Managers and Scientists" meetings; the Gulf of Maine Research Institute's Marine Resource Education Program in the USA; and multiple initiatives through the International Council for the Exploration of the Seas in Europe, including the Judgement and Knowledge in Fisheries Involving StakeHolders (JAKFISH) project; Pastoors 2016). Additionally, stakeholder groups that are willing to provide educational outreach to their members regarding the basics of the MSE process are helpful, because the more informed an MSE participant (or stakeholder influenced by the results of an MSE) is, the more willing they will be to accept

Table 6. Key challenges and potential solutions associated with stakeholder participation in MSE.

Key challenge	Illustrative solution
Unfamiliarity with analytical approaches	Provide opportunities for process-based education Implement educational workshops prior to MSE development Conduct interactive workshops
Resistance to participate	Communicate the linkage between participation and action Inclusion of and promotion by regional fisheries management organizations Salesmanship
Establishing and maintaining trust	Establish a commitment to the process (terms of reference) Foster effective listening skills Enquire about and promote understanding of different point of views
Ensuring access and opportunity for all stakeholders	Disseminate information broadly (e.g., resource user groups, scientific experts, and fishery managers) Provide methods to participate remotely
Defining a workable, yet representative, group size	Form advisory bodies to represent key constituent groups Utilize existing hierarchy communicative structures (e.g., councils and fishing representatives)
Opportunity for all opinions to be heard	Ensure key social, economic, political, cultural, and biological perspectives are represented Hire an experienced meeting facilitator
Soliciting clear objectives from participants	Refine objectives based on means goals to those based on end (results) goals Outreach to main constituent groups
Ensuring the MSE process results in workable solutions	Promote understanding of explicit decision point trade-offs Consider legality and legal protections Promote strategic decisions that are mutually beneficial
Maintaining continuity of participants throughout the MSE process	Outreach and engagement Provide stipend to participants to cover attendance costs Interactive and positive meeting facilitator

Note: These issues were identified through analysis of the example MSE processes for Atlantic tunas, Atlantic herring, and eastern oyster and were supplemented by similar suggestions from the participatory modeling and MSE literature (e.g., Kolody et al. 2008; Reed 2008; Punt et al. 2016; Voinov et al. 2016; Thompson et al. 2017*a*, 2017*b*; Jordan et al. 2018).

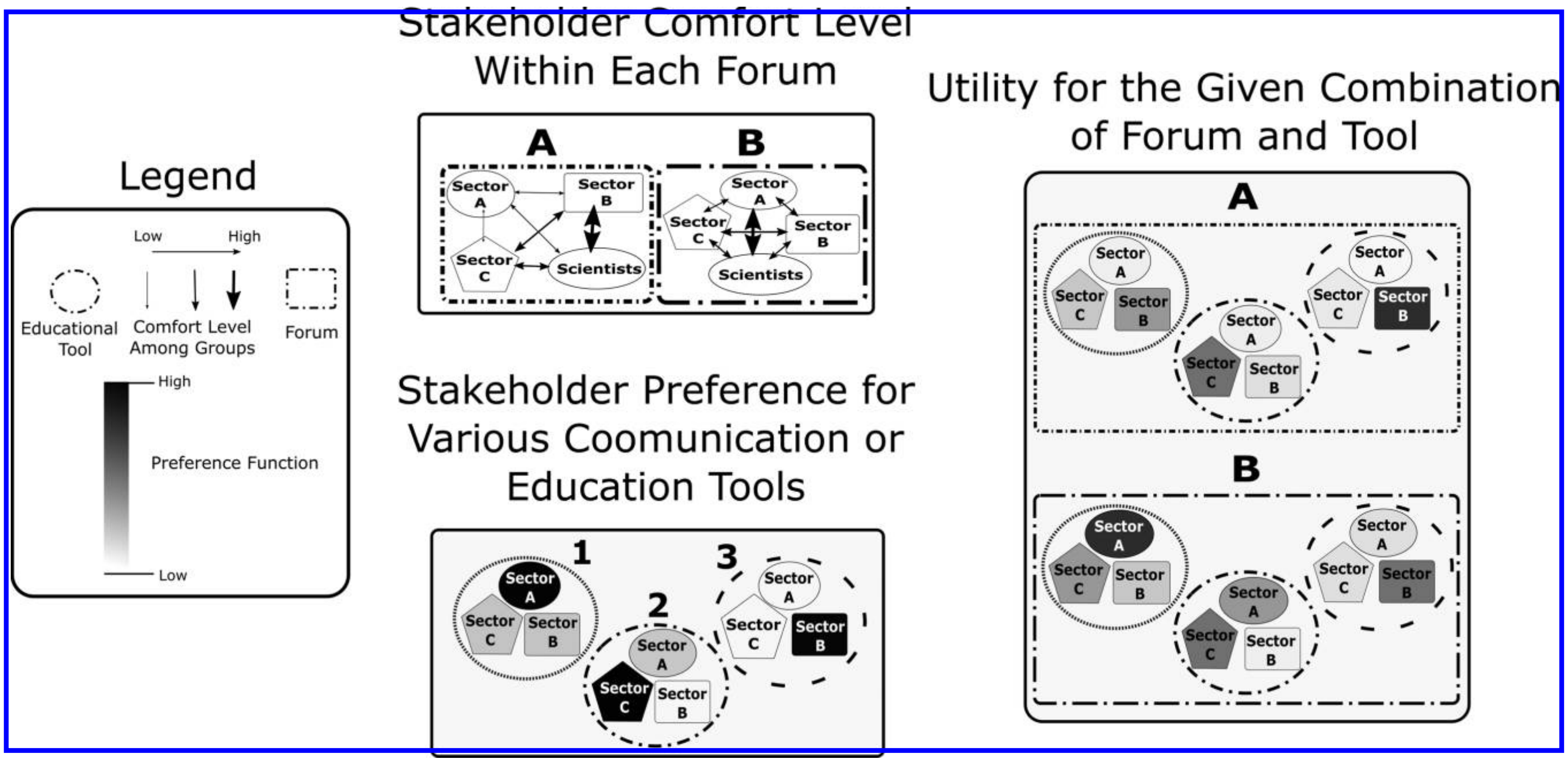
the outcome of the process (Karadzic et al. 2014). However, not all stakeholders have the ability to participate in education programs external to the MSE process, and many operational MSEs will need to devote large amounts of time educating and training participants during the process (e.g., as was done in the OysterFutures MSE process).

Open communication enables clear expectations

One of the primary challenges to successful implementation of MSE, and post-normal science in general, is that of developing open channels of communication among all participants (e.g., across disciplines, among scientists and managers, and from stakeholders to technical experts) at each step in the process (see Fig. 1) and fostering an atmosphere of trust (Table 6; de la Mare 1998; Garcia and Charles 2008; Kolody et al. 2008). The primary path to stakeholder ownership in, and acceptance of, the MSE is through clear, open, and flexible communication, where repetition and iteration will be necessary for all parties to understand the objectives, performance measures, trade-offs, and uncertainties involved in the MSE (Table 5). Setting clear expectations for all participants from the outset of the MSE process can promote ownership and acceptance and improve the likelihood of a successful outcome (Reed 2008). However, it is essential to temper the expectations of stakeholders by working with them to clearly define the scope and goals of the MSE and firmly indicating what the MSE process can and cannot accomplish (Chuenpagdee and Jentoft 2007; Kolody et al. 2008). As is the case with any modeling exercise, MSE suffers from a number of technical limitations, and it is not a panacea for all issues of marine resource management (Kolody et al. 2008; Rochet and Rice 2009; Kraak et al. 2010). Not all system uncertainties are foreseeable or understood, and management strategies cannot be expected to perform well outside the range of simulated scenarios that are tested (Butterworth 2007). By being transparent about the limitations of an MSE, the possibility of participants becoming disenfranchised with the process due to unattainable or ambiguous goals can be avoided (Cox and Kronlund 2016).

An aim of MSE should be to ensure stakeholders feel that their voices are being heard, that their ideas are being considered, and that their needs are being addressed (Soma 2003). It can be useful to encourage each stakeholder to write down their objectives of both the MSE process and potential management options (Jones et al. 2016). Clearly defining the terms of reference and group objectives for the project at the outset is imperative and is often a time-consuming process given the diverse interests of the participants (Reed 2008). Stated policy objectives should be expressed in terms of end (results) goals that describe desired outcomes, rather than as means goals that are intermediary steps leading towards the end goals. By referring back to stakeholders' initial thoughts, it will allow facilitators to be able to demonstrate how objectives are being met and how they have changed throughout the process (Jones et al. 2016; Sampedro et al. 2017). Mutual understanding of purpose and expectations allows for trust in the process (Table 6). Continued repetition of the scope of the project, desired outcomes, and stakeholder needs and wants will help ensure consistency in the decision-making process and maintain focus of the participants. For example, the consensus solutions approach utilized in the OysterFutures project fostered transparency and trust by maintaining a completely open voting process, wherein participants could continually reevaluate their own desired outcomes based on mutual learning of others' interests and concerns. Although no management approach will satisfy all stakeholder objectives or resolve conflicts among all user groups, engaging in open dialogue, clear communication, and group decision-making can often produce management procedures that "satisfice" the needs of all MSE participants (Miller and Shelton 2010) and reduce user group conflicts (Davis 2008; Msomphora 2016; Curseu and Schruijer 2017).

Fig. 2. Conceptual diagram illustrating how the combination of forum and educational or communication tool impacts the ability of each stakeholder sector to assimilate MSE concepts. Depending on the forum (large squares, labeled A and B), comfort level (arrows; thickness defines strength) among scientists and stakeholders varies due to differing types of interactions (top middle panel). Additionally, each stakeholder sector (small filled shapes, labeled A–C) will have a variable preference (shade of shape) for the diverse educational tools, communication methods, and visualization techniques (large circles, numbered 1–3) utilized by the scientists and facilitators (bottom middle panel). The combination of forum and tool utilized determines how well a stakeholder sector assimilates concepts (i.e., the shade of a stakeholder sector's shape within a forum; right panel). Within a given MSE process, an array of meeting locations along with variable communication and education tools are needed to ensure all stakeholder groups are fully engaged.



Avoid information overload

Once the MSE participants have collectively developed the terms of reference and scope of the MSE, it is useful to have the scientists, managers, and other technical experts narrow the modeling decisions to plausible and realistically implementable biological, assessment, and uncertainty scenarios to avoid overwhelming participants with too many options (Smith et al. 1999; Oates and Dodds 2017). Technical decisions are often better suited for a subgroup (e.g., a technical workgroup) that includes experts in a given field (as was done in all three of the MSE examples), because requiring participants to make decisions on every aspect of the MSE can delay the entire process unnecessarily and cause stakeholders to withdraw in response to these technical discussions (Punt et al. 2016). Decision-making by stakeholders may only be desirable at major decision points where the results are likely to broadly impact them (e.g., decisions on performance metrics and management alternatives). Distributing the main decisions across meetings can help maintain participant focus and can prevent information overload (i.e., avoiding the deficit model of scientist–stakeholder interaction; Rockmann et al. 2012; Pastoors 2016). However, the extent of stakeholder involvement in the decision-making process will likely depend on how much trust has been developed between the stakeholders and the team making the technical decisions.

The technical decisions and associated justification should be presented to the entire MSE group with a chance for questions and discussion as needed. Scientists should be ready to explain technical details to interested stakeholders, especially informally and individually, but including an overwhelming amount of technical detail upfront can be counterproductive (Smith et al. 1999; Odell and Smith 2016). Analysts in both the herring and oyster MSE processes noted the challenge of communicating results quickly, succinctly, and in terms that stakeholders could easily comprehend; similar challenges are now facing the MSE process for Atlantic tunas. Using simple to understand terminology rather than technical jargon can greatly improve stakeholder understanding of the technical aspects of the MSE (Table 5; Punt et al. 2001; Oates and Dodds 2017; Jordan et al. 2018). It is also beneficial to develop easily understood summary graphics (including multimedia and interactive) to aid decision support that emphasize the key concepts, management options, implications of potentially conflicting stakeholder objectives, and resulting trade-offs identified as important by the stakeholders (Table 5; Butterworth and Punt 1999; Punt et al. 2016; Levontin et al. 2017). Communication techniques should be adaptive with the MSE analysts learning from the stakeholder group about the types of presentations that they find useful (Fig. 2; Smith et al. 1999; Reed 2008; Sampedro et al. 2017). Scientists must also be careful to remain neutral when communicating results and trade-offs, providing enough information to contextualize results and educate stakeholders on potential implications (Wolters et al. 2016), but avoiding an advocacy role for any given management procedure (Dankel 2016; Punt et al. 2016).

Foster an atmosphere of mutual learning and active participation

Involvement in an MSE differs from stakeholder participation in the normal fishery management process. Traditional stakeholder engagement is often limited to public comment periods during fisheries management meetings, where stakeholders are asked to provide input on scientific analyses and management options that were developed without their explicit input. This typical framework for developing fishery policy can result in stakeholders being in a reactive mode, because they are provided limited opportunity to inform or participate in the analyses that impact management decisions (Kell et al. 2006; Lynham et al. 2017). Conversely, MSE allows for proactive involvement of stakeholders in the management process. Fundamental to a successful MSE is developing a sense of mutual problem-solving and creating avenues for mutual learning among scientists and stakeholders (Berkes 2009; Jenkins et al. 2017), which produces active trust through discourse and transparency (Table 5; de Vos and van Tatenhove 2011; Rockmann et al. 2012). Scientists involved in the MSE process must commit to listening to and understanding stakeholder needs and perspectives, as well as answering all technical questions as clearly, honestly, and with as minimal jargon as possible (Rockmann et al. 2012). Two-way knowledge sharing during an MSE can help improve future scientific research and may lead to unique cooperative research opportunities, even if a particular discussion does not have any direct impacts on the current MSE (Cox and Kronlund 2008; Dixon 2016; Punt et al. 2016).

Additionally, participants must feel that they are involved in each stage and decision, thereby nurturing a sense of ownership of the resulting management (Fig. 1; Reed 2008; Pastoors 2016). It is critical to avoid passive engagement wherein stakeholders are interviewed rather than actively involved in problem-solving. This form of engagement often arises when the scope of and specific management issues to be resolved are prespecified instead of developed by the full MSE workgroup (Kaplan 2000; Kaplan and Kaplan 2003; Reed 2008). Active stakeholder participation from the beginning of an MSE ensures that analysts are addressing the right questions and managers are getting the most relevant information (Cox and Kronlund 2016; Sampedro et al. 2017). Therefore, a key point to emphasize is that stakeholders have the opportunity to proactively develop and clarify the management objectives and performance measures prior to, during, and after the analysis (Holland 2010). Stakeholders should be encouraged to think about what a good (or bad) management outcome would look like for their interests throughout the process and actively communicate to facilitators and analysts the types of regulations and performance metrics they would prefer. It is also useful to communicate to stakeholders that no management actions will be recommended until the conclusion of the MSE process. The acknowledgement that no group decision-making was final until the MSE process was concluded allowed the OysterFutures participants to consider a wider variety of potential management actions than they otherwise would have, because no one felt pressured to agree to any given decision prior to a full understanding of its impacts on final policy actions. Additionally, both the herring and oyster MSE applications were successful because of the dialogue that resulted among scientists and stakeholders, which led to a feeling of inclusion, garnering active and iterative problem-solving among all participants. Conversely, one of the major impediments to MSE applications for Atlantic tunas has been the difficulty in creating viable and active lines of communication among participants, which has raised questions of whether the MSE is a truly participatory exercise for all stakeholders.

Membership continuity

It is important to maintain continuity of participants throughout the process. This continuity minimizes backtracking, allows trust to be built among participants, and leads to deeper understanding of results and impacts of various assumptions, while also improving buy-in (Butterworth 2007). Maintaining membership can be more difficult as group size increases. Turnover among participants can lead to setbacks when meetings become devoted to reteaching the entire process to new members or rehashing previously made decisions (as was the case in the herring MSE), although some degree of revisiting background and conceptual ideas periodically will be necessary regardless of turnover. Laying out the expected time commitment early on, establishing protocols for allowing alternate representatives (or remote access), and prespecifying membership rules in the terms of reference can help ensure continuity (Smith et al. 1999). Reducing the number of meetings that stakeholders need to attend can reduce burnout and maintain retention.

Perhaps the critical impediment for any participatory process is convincing individuals to take part (Table 6). Many stakeholders suffer from consultation fatigue caused by involvement in previously ineffective participatory exercises (Reed 2008). Although the engagement and communication techniques suggested here can help assure stakeholders of the usefulness of a given MSE process, organizers must ensure that participants feel that their time is being adequately valued. MSE is a particularly time-consuming process, and stakeholders often benefit from incentives for participation. In certain fisheries, there are strong market-based incentives for implementing MSE (e.g., the Marine Stewardship Council requires the use of HCRs as part of their sustainable seafood certification criteria; Agnew et al. 2014). However, direct compensation for meeting attendance may be the best approach in most fisheries to reimburse stakeholders for travel, offset lost revenue (e.g., due to missed fishing opportunities), and demonstrate that organizers appreciate participants' time commitments. Providing compensation will better maintain continuity, increase participation of parties who would otherwise experience lost income, and reduce the influence of stakeholder groups with more resources (Dankel 2016; Lynham et al. 2017). Paying stakeholders to directly participate in MSEs can also diminish the influence of paid consultants (i.e., under the condition that a participant is not allowed to receive further compensation for attendance) and may improve negotiations and final decision-making (Lynham et al. 2017). Although paying stakeholders to participate in the MSE process may put further fiscal strains on fisheries agencies, it may be necessary to ensure active, high-quality participation. Providing additional incentives to stakeholders who had to choose between participating in a meeting or working facilitated the involvement of industry representatives in the OysterFutures project.

Transparent negotiations and government support

Managers and stakeholders should work together so that all participants develop a feeling of ownership and to ensure outcomes feature acceptable trade-offs (i.e., establish mutual accountability; Claytor 2000; Punt and Donovan 2007). Open session negotiations lead to transparent decisions, which encourage overall acceptance (e.g., the consensus solutions approach utilized in the OysterFutures project). By making the needs of each stakeholder broadly known, a better understanding of alternative viewpoints is made possible, which then forms the foundation for building trust and opens dialogue to negotiations. Agreement on how the MSE voting process should be handled (i.e., what is required to arrive at a final group decision) needs to be done early, preferably when drafting the terms of reference for the MSE, so that all stakeholders accept all final group decisions (Davis 2008).

In contrast, situations where authorities change decisions without stakeholder input (i.e., veto power) should be minimized to the extent practical at the outset; otherwise the transparent nature of the MSE process will be undermined (Smith et al. 1999; Reed 2008). Similarly, there needs to be assurance that the results of the MSE will be utilized by managers; otherwise stakeholders may be hesitant to participate due to lack of faith that the process will be a fruitful endeavor or that their input will be considered. The success of the herring and oyster MSE processes was, in part, because management representatives were directly involved, which convinced stakeholders that the outcomes would actually be utilized to improve management and led to broader participation (Table 2). The success or failure of an MSE depends on full governmental support for the project and a commitment to the resulting management regime for the long term (Table 6; Cochrane et al. 1998; Kolody et al. 2008; Smith et al. 2008). Sufficient legal and political protection for the process is also required to ensure that participants trust that the final product will be utilized, but such actions are outside of the purview of science and management (Smith et al. 1999; Holland 2010). If post hoc lawsuits by disgruntled parties or political lobbying are a threat to the process, then it will undermine credibility and prevent incentives for participants to pursue long-term planning (Cochrane et al. 1998). Generally, domestic fishery agencies have the ability to support and implement MSE initiatives as the sole management body for a given resource, but, as was illustrated in the Atlantic tuna MSE, political support for MSEs with international resources can be more difficult (Kolody et al. 2008; Nakatsuka 2017). Increasing the involvement of RFMO representatives in the MSE process together with stakeholders is necessary to ensure support for the final product.

Conclusions

MSE has origins in the interdisciplinary field of operations or systems research (Charles 1995; de la Mare 1998), which has wide implementation in engineering, military, industrial, and business applications (e.g., the aforementioned auto safety system testing; Garcia and Charles 2008). The ultimate goal of MSE in implementation of the management-oriented paradigm is to determine appropriate management options given the information and science available while accounting for existing laws and stakeholder priorities. Otherwise, basing fishery policy simply on the best available science fails to recognize how that information is used within the management framework (de la Mare 1998; Cox and Kronlund 2016; Wolters et al. 2016). Failures in fishery management regimes are often attributed to two causes: (*i*) underestimating uncertainty by treating components (i.e., biological, economic, behavioral, and policy units) as modular, thereby ignoring the interactions among the units, the policy implemented to protect the resource, and the human response to both the regulatory framework and ecosystem dynamics (Charles 1995; de la Mare 1998; Garcia and Charles 2008); and (*ii*) failure to design systems of governance that adequately account for stakeholder participation in the development of policy and the science to support it (Cash et al. 2003; Kaplan 2000; Wilson 2009; Dankel 2016).

MSE and similar participatory modeling initiatives do not guarantee that the results will be adequately utilized and incorporated to develop true post-normal scientific advice. Developing successful ecological management paradigms requires that stakeholders feel involved in an active problem-solving initiative where "the purpose of the participatory activity is not to implement plans that someone else has already drawn up but to find innovative solutions to environmental problems while meeting the needs of the participants" (Kaplan 2000). Therefore, if participatory modeling and MSE processes are to be successful, it is imperative that scientists, managers, and other stakeholders not only work together to solve a given management problem, but also collectively frame the problem that needs to be addressed in the first place (Kaplan and Kaplan 2003; Reed 2008).

Fostering and developing these types of truly participatory modeling initiatives often requires institutional awareness of the breadth and scope of the expertise required (e.g., scientific modelers, economists, policy experts, anthropologists, sociologists, communication experts, outreach coordinators, and facilitators). Additionally, it necessitates admission by the scientific organizations often tasked with completing MSEs that they are not necessarily solely suitable to develop processes with the high levels of credibility, legitimacy, and saliency required (Cash et al. 2003; Wilson 2009). Thus, developing post-normal scientific advice requires interdisciplinary scientific and institutional collaboration aided by boundary organizations that can help facilitate exchanges among scientists and stakeholders (Guston 2001; Gustafsson and Lidskog 2018). Boundary organizations can organize the appropriate mix of expertise and skills for an MSE workgroup while ensuring stakeholder awareness and participation (Cash et al. 2003; Wilson 2009). In addition, development of MSE initiatives outside of purely scientific institutions helps ensure that a fully participatory project (i.e., actively engaging stakeholders in defining and solving the problem) is undertaken as opposed to a more passive stakeholder experience (i.e., asking participants for input on a prespecified problem; Kaplan 2000). Ultimately, stakeholder participation needs to be institutionalized in the long-term process of developing post-normal science to aid management decision-making if participatory modeling initiatives are to be effective (i.e., regulations accepted and adhered to; Reed 2008).

When it comes to managing a natural resource, tough decisions always need to be made regarding utilization, and MSE does not alleviate the need for making those decisions. However, it can formalize how those decisions are made and the trade-offs inherent in each (Punt 2015). By including the stakeholders directly in the development of the management problem to be addressed and finding potential solutions to that problem and the resulting negotiations to identify the management regime that satisfices all stakeholders, MSE creates a unique ability to develop integrated solutions instead of relying on tentative compromise (Dankel 2016). The increased capacity for inventive problem-solving created through participatory modeling and mutual learning can improve fisheries management regimes (Berkes 2009). Improved communication inherent in the implementation of co-management nurtures trust and transparency, which can support both sustainable fisheries and sustained fisheries management regimes. MSE is a powerful approach to developing fisheries policy, but it cannot be expected to solve all fisheries management issues. However, enhancement of participatory modeling and improved stakeholder communication through operational MSEs is expected to continue improving fisheries science and management by advancing post-normal science.

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