Quo Vadimus:

Inclusion of ecological, economic, social and institutional considerations when setting targets and limits for multispecies fisheries

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Abstract

Targets and limits for long-term management are used in fisheries advice to operationalize the way management reflects societal priorities on ecological, economic, social and institutional aspects. This study reflects on the available published literature as well as new research presented at the international ICES/Myfish symposium on targets and limits for long term fisheries management. We examine the inclusion of ecological, economic, social and institutional objectives in fisheries management, with the aim of progressing towards including all four objectives when setting management targets or limits, or both, for multispecies fisheries. The topics covered include ecological, economic, social and governance objectives in fisheries management, consistent approaches to management, uncertainty and variability, and fisheries governance. We end by identifying ten ways to more effectively include multiple objectives in setting targets and limits in ecosystem based fisheries management.

Key words: Ecosystem based fisheries management; multiple objectives; reference points, sustainability, variability

Introduction

Targets and limits are at the core of the scientific advice supporting decision-making of fisheries managers (Mace, 1994). The purpose of targets and limits is to operationalize how fisheries management decisions reflect societal priorities, which range from fish stock and ecological conservation objectives to economic and social goals. Targets define the goals that management aims to achieve, whereas limits define the boundaries of unacceptable or unsustainable conditions. Accompanying a given limit is an associated (low) level of accepted risks of exceeding the limit, whereas targets should be achieved on average, with equal or near-equal probabilities of being on either side of the agreed metric.

Guidelines for the selection of targets and limits for long-term fisheries management have varied from the target of obtaining the maximum sustained yield (MSY), as formalised in the 1950s (Schaefer, 1954; 1957), to limits being set to avoid stock collapse in the 1980s and 1990s (Garcia, 1995) and back to maximising sustainable yield as the largest yield that can be taken as a long-term average (Mace, 2001; Smith and Punt, 2001). Recent research has centred on defining *targets* to obtain the largest long-term average yield, and *limits* to ensure sustainability in an ecosystem context (i.e., the Ecosystem Approach to Fisheries, FAO, 2003; Zabel *et al*., 2003) and identifying 'satisficing' (rather than maximising) management strategies (e.g. Martinet *et al*., 2007; Miller and Shelton, 2010). The above initiatives focused largely on biological and ecological aspects, although socio-economic considerations have increasingly been included in more recent years (Martinet *et al*., 2007). However, recent legislation in many nations calls for policies that simultaneously apply ecological, economic, social and governance objectives (Garcia, 2003). Unfortunately, the majority of targets and limits continue to be defined on a single stock basis using stock-specific information only and hence excluding wider ecological, economic, social and governance objectives.

The original static and deterministic MSY target evolved when variability in stock productivity was seen to be a predominant feature of fully exploited stocks, leading to economic and social problems in fishing communities (Degnbol, supplementary material). To counter this, maintaining stable catches from existing fisheries was a priority. In this interpretation, MSY was incorporated into the United Nations Convention on the Law of the Sea in 1982 and progressively into national, regional and international fisheries policies and legislation. MSY was based on the productivity of individual species, ignoring interactions with/in the fishing process, and aiming to maximise the weight or value of landings under assumptions of constant vital rates (Mace, supplementary material). Over time, it became clear that the assumptions of constancy and independence in vital processes are rarely fulfilled and that a dynamic approach is necessary if interactions among species and with their environment are to be considered (Fogarty, 2014). Trade-offs among different targets may be addressed, for example, by maximising total yield, (e.g. landings in tonnes or value; Smith *et al*., 2011; Jacobsen *et al*., 2014), but this does not ensure the sustainability of individual stocks (Gislason, 1999; Voss *et al*., 2014). Further, obtaining the maximum yield does not provide the maximum value of fisheries in a single species sense, and even less so in a multispecies sense (Christensen, 2010; Hilborn *et al*., 2015). The need to trade off these various considerations triggered arguments for including economic and social considerations explicitly in management objectives (Charles, 2001; Hilborn *et al*. 2007, 2015; Fogarty, 2014; Prellezo and Curtin, 2015), thus aiming to encompass all four pillars of sustainability: ecological, economic, social and institutional/governance (Garcia, 2003).

Here, we examine the latest progress on the scientific basis for including ecological, economic, social and institutional objectives in management advice, aiming to identify ways to advance sustainable development to meet the needs of the present and (near) future without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development 1987). The analysis arose out of the international ICES/Myfish Symposium on Targets and Limits for Long Term Fisheries Management (www.myfishproject.eu). Input to this paper was provided through presentations at the symposium and referenced by the name of the presenter. The presentations are summarised in the supplementary material. Further input was derived from group discussions, using randomly chosen groups and following a semi-structured plan, and written 'free text' comments provided by participants following each session. This article uses these inputs to highlight issues relevant to holistically addressing ecosystem-based fisheries management by improving: (1) ecological, economic, social and governance sustainability in fisheries management, (2) internally consistent targets and limits for management, (3) mechanisms for addressing uncertainty and variability and (4) effective governance.

Ecological, economic, social and governance sustainability in fisheries management

Ecological sustainability encompasses sustainability of both exploited and non-exploited species, as well as sustainability of ecosystems overall. A key focus in sustainability of commercially exploited species is the management of trade-offs related to multispecies and mixed fisheries, where fished stocks are intricately linked to one another and to other ecosystem components through either a multispecies food web or technical interactions in the fishing process. Ecological and yield trade-offs occur across a range of levels of fishing effort (Cubillos *et al*.; Duplisea; Hidalgo *et al*.; Smout e*t al*.; Vinther, supplementary material; Gachias *et al*., this issue), introducing the need for policy decisions. In a multispecies context, there is no single combination of fishing mortalities for different stocks that provides MSY for all species simultaneously (Dolder *et al*.; Reeves and Thorpe; Vinther *et al*., supplementary material; Gachias *et al*., this issue). Accounting for stock productivity and ecosystem trade-offs is key to providing reliable advice and to avoiding unrealistic expectations (such as yields or biomass levels that cannot be reached), as dynamic interactions between stocks are fundamental properties of ecosystems. Further, it is essential to be able to provide fisheries advice that does not compromise the sustainability of non-exploited ecosystem components. This means that management is more likely to meet policy objectives if it incorporates these interactions than would be the case if advice was just given from a single species perspective.

Economic objectives such as maximum economic yield (MEY) lead to additional complexity; their consideration requires additional analytical and advisory effort to quantify trade-offs between ecological and economic considerations, such as the exploitation of sensitive species and the resulting net revenue from fishing (Garcia *et al*., this issue; Smout *et al*., supplementary material), or the speed at which overexploited stocks are allowed to rebuild (Hamon *et al*.; Henriquez *et al*., supplementary material). Often, the trade-offs between, for example, employment and net revenue can also be investigated (Voss *et al*., 2014; Hoff and Frost; Mahevas *et al*.; Tserpes *et al*., supplementary material; Kempf *et al*. supplementary material, 2016). The Australian experience with implementing such reference points (e.g., Dichmont *et al*., 2010) shows that substantial additional complexities, relating for example to the specification of acceptable transition paths, treatment of prices and costs, and the identification of proxies in data-poor contexts, must be addressed (Pascoe *et al*., 2014; Hamon *et al*.; Henriquez *et al*. supplementary material; Pascoe *et al*., this issue).

In contrast, social objectives in management seem quite far from being integrated into the current fisheries management approach on a routine and tactical basis, despite a wealth of research on the topic (e.g. Charles, 1988; Aanesen *et al*., 2015; Hoefnagel *et al*., 2015; Northridge, supplementary material). The integration is challenged by the lack of approaches to couple knowledge gained from qualitative and quantitative methods (Haapasaari *et al*., 2012; Röckmann *et al*., 2015), and the lack of well-defined and broadly agreed social objectives and associated indicators (Pascoe *et al*., 2014, 2015; Brooks *et al*., 2015; Pascoe *et al*., this issue). Social goals, while often included in legislation and policy, tend to be defined in broad, non-quantified terms, and require further articulation to be made operational. Variation in the views of different stakeholders of the importance, magnitude and direction of alternative social goals raises the question of who should define goals and what process should be used to set objectives (Mumford *et al*, supplementary material; Pascoe *et al*., this issue; Rindorf *et al*., 2016a), particularly in the case where not all stakeholders are local (Drakou and Pendleton, supplementary material). Providing operational goals and including these in mainstream management requires a substantial dedicated effort.

High level governance objectives are specified in many policy documents. An example is the base regulation of the EU Common Fisheries Policy (EC 2013), which states in legal text that certain 'principles (of good governance) include decision-making based on best available scientific advice, broad stakeholder involvement and a long-term perspective'. Such requirements for evidence-based decision making, inclusiveness and ultimately legitimacy are commonplace and have been increasingly incorporated in the study of natural resource management systems in coastal and marine domains (Dutra *et al*., 2015). The issue is therefore not whether such objectives have been stated, but whether they are implemented in substance. This divide is highlighted by the large emphasis made by stakeholders on process (Rindorf *et al*., 2016a).

Defining internally consistent targets and limits for management

When objectives have been agreed for all four pillars, two major challenges are (1) reaching agreement on what should be considered targets and limits within ecosystem-based management, followed by (2) providing advice that is internally consistent with all stated objectives whenever possible and clearly demonstrates conflicts when it is not. Often, internal consistency between reference points is low or non-existent, and advice focuses on trade-offs among objectives. However, MSY reference points are frequently derived from relationships showing little change in yield over a range of fishing mortalities, reducing the change in long-term yield by deviating slightly from the agreed reference points (Gaichas *et al*., this issue; Rindorf *et al.*, b, this issue; Vinther *et al*., supplementary material). In practice, the trade-offs are therefore often less stringent than they would appear and there are broader choice sets enabling multiple objectives to be satisfied than expected at first glance.

A realizable pathway to include at least multispecies trade-offs in management targets could be 'Pretty Good Yield' (PGY) and the multispecies version 'Pretty Good Multispecies Yield' (PGMY) (Hilborn, 2010; Rindorf *et al*., b, this issue). PGY is defined as achieving at least a specified high percentage of the MSY while allowing scope for achieving additional objectives. This definition leads to ranges of MSY-related fishing mortalities that bracket F_{MSY} rather than point estimates, and thus adds flexibility in achieving multiple targets (Rindorf *et al*., b, this issue). MSY-based PGMY ranges may provide a way to account for mixed fisheries, ecosystem issues and possibly economic considerations to allow policy makers to address 'choke' species issues, while providing scientific limits to policy choices. This can also provide a formal way to integrate annual fluctuations of all stocks and fleets in mixed fisheries (Garcia *et al*., this issue; Ulrich *et al*., this issue), and may represent a way forward for European fisheries management to bridge across ecosystem objectives and technical interactions. On the other hand, there are situations where simultaneous good yields of different stocks cannot be achieved or where ecological, economic and social objectives conflict (Rindorf *et al*. b, this issue). Further, social objectives may not be directly related to fishing pressure and therefore a 'Pretty Good Social Yield' may not be ensured by defining specific combinations of fishing mortalities.

Achieving governance objectives can be challenging. One example of the complexity involved is the problem arising when defining trade-offs among conflicting objectives. Regional differences in preferred objectives are substantial, and no poll or focus group can be considered as having the 'correct' or 'universal' set of opinions and values (Levin *et al*., 2015; Pascoe *et al*., this issue; Rindorf *et al*., 2016a). Hence, the decision on which stakeholders (here including scientists, representatives of the fishing industry and non-governmental organizations, and managers) should be invited to define objectives is critical to the outcome (Aanesen *et al*., 2015), and as a consequence is specified in policies in many jurisdictions. Examples include the composition of Regional Fishery Management Councils in the USA (US, 2007) and Australian Management Advisory Committees (Smith *et al*., 1999). An adequate participatory involvement in the process of designing the rules and processes of management is key to good governance (Link, 2010; Dutra *et al*. 2015; Long *et al*., 2015; Sampedro *et al*., this issue; Mumford *et al*.; Stephenson, supplementary material).

Scientific presentations often use Decision Support Tools, such as traffic lights or other graphical distillations of complex multiple objectives (Punt, 2015; Pascoe *et al*., this issue; Kempf *et al*., 2016; supplementary material). Such decision support tools can be quantitative, qualitative or mixed, showing scenario comparisons to allow an informed decision when there is no single or clear optimal path. Successful decision support tools are generally developed on an appropriate platform for collaboration among all stakeholders and should be embedded in the governance structures (Rehr *et al*., 2014; Levin *et al.*, 2015). The user of the tools should be able to tease out operational trade-offs as well as critical model assumptions, uncertainties and robustness of results. The complexity in presenting trade-offs on chosen objectives depends on which indicators are used to demonstrate these. Together with greater development and use of decision support tools, selecting a limited number of crucial indicators may aid in enhancing the clarity of advice and reducing the risk of disjunction between scientific representations and management reality. Decision-makers and other stakeholders often have very little time to consider key implications of their decisions, and are being called on to make decisions in fields in which they have limited experience. Lengthy narratives or series of tables are unlikely to be closely scrutinized and are hence of limited value. Further, it is important to overcome the tendency of scientists to communicate in a highly technical language, focussed on detail rather than the larger picture. Making results understandable for a non-technical audience, and ensuring that the message transmitted is interpreted in accordance with expectations, requires a dedicated effort (Levontin *et al*., supplementary material). For example, communication of the consequences of different management measures and understanding of inherent trade-offs is essential for decision making (Hintzen *et al*., supplementary material). Natural, economic and social scientists are influential in decision making and need to take responsibility that their message can be perceived as intended. Overall, there is a need for all participants to use common language, as well as to ensure that open and transparent communication covers the entire advice and decision making process, including a double check of agreements and iterative loops for feedback. Equally, other stakeholders will need to make their objectives clear, rather than objecting to science advice after the facts are presented.

Addressing uncertainty and variability

Ecological, economic, and social circumstances change over time and these changes affect scientific advice and management outcomes. While ecological and fisheries processes are frequently assumed to be constant, in reality, they may exhibit temporal variation and hence affect the quantitative levels of management metrics such as MSY (Table 1). Evaluating the likely impact of changes in fisheries management regulations has a long history in fisheries science (Hilborn and Walters, 1992; Charles, 1995), although there is a need for greater focus on the potential impact of varying economic or social conditions for fishers and other stakeholders. Recent research efforts have sought to include this in the evaluation of trade-offs associated with alternative management strategies (Doyen *et al*., 2012; Hamon *et al*., 2013; Gourguet *et al*., 2014), in some cases using elasticity analysis (e.g., Röckmann et al., 2009; Thorson et al., in press) and Monte Carlo simulation (Haltuch and Punt, 2011). The ICES/Myfish symposium identified three main considerations around variability that require further attention: the need to communicate 'uncertainty' and 'variability', the importance of considering spatial dynamics and changes in spatial distribution, and the process by which variability is included in policy decisions.

First, it must be recognized that 'uncertainty' and 'variability' arise in all components of the fishery system from ecological to economic, social and governance dimensions. 'Uncertainty' refers to the degree to which our knowledge and understanding of the system is incomplete and hence the status of, for example, the stock or its dynamics being not exactly known (Patterson; Reeves and Thorpe, supplementary material). 'Variability' refers to changes in dynamic processes, such as recruitment success and growth or fish prices between years, thereby implying incomplete knowledge of conditions in the coming years. With increased knowledge, uncertainty can be reduced, but usually we are not able to predict the outcomes of variability. It is essential that these two concepts be clearly distinguished when communicating management advice. In particular, while research is needed on variability, this should not be perceived as reflecting high uncertainty and/or lack of understanding of the system on behalf of the scientists (Charles, 1998). Such a perception may undermine the credibility of scientific advice. In fact, identifying key sources of variability can in some cases allow for increased scientific credibility. For example, accurately accounting for time-varying growth, selectivity, and recruitment has allowed probabilistic population forecasts of Pacific hake to estimate future population size (Hicks *et al.*, 2014). It is important for stakeholders and policy makers to understand that there are different implications of uncertainty and variability in terms of decisions about immediate measures and potential future improvements through the collection of evidence and conducting new research. Conventionally, when scientists have incorporated uncertainty in assessment outputs, information on possible management responses has not been provided. Efforts to rectify this gap have driven recent developments in the evaluation of the bio-economic impacts of alternative management strategies, using stochastic simulation modelling (Doyen *et al*., 2012; Gourguet *et al*., 2014).

Identification of spatial dynamics and shifts in species distribution requires the development of adequate sampling methods and indicators. Distributional shifts have previously been highlighted as a key impact of climate change (Schmidt *et al*. 2009; Pinsky *et al.* 2013), and methods to distinguish inter-annual variability, density dependence and climate impacts remain a topic of ongoing research (Rindorf and Lewy 2012; Thorson *et al*., in press; Thorson *et al*., supplementary material). Parallel to this, shifts in the spatio-temporal distribution of fishing fleets can be equally important, and are increasingly being incorporated in impact assessments of alternative management interventions (Berkes *et al*., 2006; Poos and Rijnsdrop, 2007; Vermard *et al*., 2008).

Scientists often discuss the consequences of changes in ecological, economic, and social processes for fisheries management. For example, break-point analyses have been used to justify shifts in reference points used for fisheries management (Wayte, 2013; Punt *et al*., 2014) and fisheries scientists can estimate shifts in stock-recruitment relationships, where these changes signal a change in MSY (Minto *et al*., 2013; Vert-pre *et al.* 2013, Cadigan and Wang; Cadigan *et al*.; Clausen *et al*.; Cubillos and Curin-Osorio; Licandeo et al.; Minto, supplementary material) or MEY (Quaas *et al*.; Stäbler et al., supplementary material). However, research is ongoing regarding the trade-offs of responding or not responding to changing productivity, given the difficultly of definitively identifying these. For example, a regime-based harvest control rule will sometimes identify a regime-shift when none exists, and therefore lead to over- or under-utilisation, while a time-invariant harvest control rule will sometimes attempt to rebuild a fish stock to a level that is not possible given present environmental conditions (Haltuch and Punt, 2011; Szuwalski and Punt, 2013). Such cases affect the acceptance among managers of changing fisheries targets and limits over time.

Including variability in policy decisions is particularly challenging, and there is a strong need for awareness, assessment and dissemination of information about variability in economic, social and institutional aspects of a fishery (Punt, this issue). Policy frameworks are in effect often based on deterministic equilibrium models and hence an implicit notion that reference points are constants (UN Fish Stocks Agreement 1995; EC 2013). This is partly a result of the often lengthy policy process preceding the agreement on reference points, a fact that is often not appreciated by scientists, who tend to be more focused on the sensitivity of the reference points to underlying assumptions. Scientists may perceive changes in reference points to be a fundamental aspect of the system, which should be incorporated into management decisions as they occur (Gaichas *et al*., this issue). However, managers and other stakeholders, may view this as reflecting the inability of scientists to estimate the relevant constants to inform long lasting advice - and as such reflecting poor knowledge or previous errors rather than environmental change. To bridge this divide, scientists and other stakeholders should collaborate to identify and communicate the ecological and fisheries processes that may vary over time, as well as a realistic estimate of the time required to accommodate such changes in the management system (Bailey; Rindorf and Fisher, supplementary material).

The likely magnitude of variation over time in values such as productivity can be estimated (Thorson *et al*., 2014; Thorson and Minte-Vera, in press), along with the associated relative sensitivity to variation of stock assessment models or fisheries management performance (Lorenzen, 2016). This public process may make the response to temporal variation both more transparent and more acceptable to managers, although there is no guarantee of this (Gray *et al*., 2012). A transparent process would also help in the coordination of data collection, survey design, and statistical analysis necessary when investigating time-variation in ecological, economic, or social processes. For example, if a transparent process identified natural mortality as the most important time-varying process, data collection could then prioritize the estimation of predator diets. Implementation of

Management Strategy Evaluation (MSE) approaches has shown the benefits of stakeholder involvement in all stages of the fisheries management process (Smith *et al*., 1999, Dutra et al, 2015), and recent research effort in this domain emphasizes the importance of methods that may assist the process of stakeholder engagement in the face of uncertainty (Thébaud *et al*., 2014).

Effective governance

The approaches to achieving effective governance considered at the ICES/Myfish symposium focused on two major themes: operationalizing collaborative management and effective governance structures.

Operationalizing collaborative management

Collaborative approaches to management include those that inform decision makers as well as those where the collaborative mechanism is the formal decision making structure. They have multiple advantages, including increased transparency of scientific advice, greater inclusion of economic and social concerns, inclusion of local knowledge, as well as the potential for increased value of fisheries (Bailey; Linnane *et al*.; Rindorf and Fisher, supplementary material). Further, the gradual incorporation of collaborative methods has often substantially increased the trust among stakeholder groups, improving communication and mutual understanding (Mackinson and Wilson, 2014; Charles; Stephenson, supplementary material). It has often proven challenging to find aa appropriate role for participants that recognises the need for them to assist in an informed decision making process without introducing their own bias towards specific objectives – but this has nevertheless been attempted in some cases (Schwach *et al*., 2007; Wilson, 2009).

The process by which participants in collaborative management decision-making are included is key to the outcome. In many cases, stakeholder composition is determined by policy makers, and it sometimes seems that the invitation list for collaborations has focused on industry representatives, whereas other groups, such as NGOs, have less often been invited. Further, even among those invited, some may be unable to participate, for example, due to lack of resources, such as funding or time (Jacobsen *et al*., 2011). The result of this is likely to be that scientists and well-funded industry representatives are more aware of recent developments and scientific issues than other stakeholder groups, potentially introducing a bias towards views of only some stakeholder groups.

Finally, it is important to maintain the level of trust in the process. Even in cases where trust is initially high among parties, cases where the final decision is undesirable may decrease the general trust and satisfaction in the process if participants fail to accept that a trustworthy process may yield an outcome which is unsatisfactory to individual stakeholders (Rindorf and Fisher, supplementary material). A special instance of this is where there is an expectation on behalf of a stakeholder that science will support specific decisions, such as the expectation by local industry that local scientists will support local socioeconomic considerations (Rindorf and Fisher, supplementary material) or the expectations by eNGO representatives that scientists will support ecosystem sustainability concerns (Knigge et al.; Veitch et al., supplementary material). Occasionally, managers attempt to achieve rapid answers by bypassing the collaborative process and simply asking scientists for their opinion on the most appropriate strategy (Punt, this issue). It is imperative that the role of scientists is made clear from the outset of the collaboration to maintain a clear division between policy decisions and scientific assessments, specifying that the decision on specific trade-offs is a policy decision. Hence, obtaining a functioning collaborative environment is an ongoing effort, which goes beyond identifyting participants for the process (Bailey; Rindorf and Fisher; Stephenson, supplementary material).

Effective governance structures

Governance structures, that favor stakeholder inclusiveness and incorporate all four pillars of sustainability, have a strong bearing on the successful implementation of targets and limits. Based on the presentations and discussions at the ICES/Myfish symposium, we identified three areas of concern: the dominance of single species considerations in current fisheries management systems, decision frameworks with stated objectives of good governance, which are not delivering effectively, and the prevalence of natural sciences in the current advisory process.

First, current fisheries management remains dominated by consideration of single stock biological advice, though it has the potential to evolve to include broader ecological, economic, social and governance considerations. However, full integration of the four pillars of sustainability is a substantial challenge for policy makers, scientists and other stakeholders. For example, existing governance structures in Europe do not provide much support for the inclusion of broader societal objectives, nor do they clearly allow for an inclusive process (Prellezo and Curtin, 2015). While there are structures and processes in many jurisdictions to debate the ecological, and to some extent the economic, aspects of fisheries management among ecosystem and economic scientists, there are generally no such structures and processes for discussing social aspects. It should be possible to expand the current structures to provide ecological and economic integrated input to management, with dedicated advice on social aspects, which is subsequently coordinated through existing advisory structures.

Second, decison frameworks with a stated objective of good governance may have been established in law, without subsequently delivering fully in substance (Geers *et al*.; Knigge *et al*.; Veitch *et al*., supplementary material). Reasons for this may include previous decisions made, lack of consideration of power and incentive structures, and fisheries policy institutions that are subordinated to general frameworks for legislation and implementation (Gezelius *et al*., 2008) or where underlying definitions, principles, practice - and especially (legal) accountabilities – are different across decision frameworks. An example is the Common Fisheries Policy of the European Union, which states as one of its objectives that the policy ‘shall implement the ecosystem based approach to fisheries management’, while the Lisbon Treaty splits competencies for the marine environment and for fisheries policy into two different levels of governance (Member State and Community, respectively). This in practice becomes a hindrance for the implementation of an ecosystem approach. Fisheries management plans within the EU are limited by path dependency by being subject to the concept of 'relative stability', which dictates a stock-by-stock perspective, making inclusion of biological interactions among species virtually impossible (Ramírez-Monsalve *et al*., 2016). While these issues have prevented requests for integrated advice being issued from a single managing body, they do provide the necessary policy focus for scientific advice to accommodate ecological, economic and social aspects, and for that advice to be provided. While this would not eliminate the need for a clarification on the decision-making responsibilities, it would remove the lack of clear scientific advice as an explanation for not acting in accordance with the stated policies.

Third, the integration of social and governance considerations is complicated by the fact that the current advisory process in most jurisdictions is dominated by natural sciences. Evaluation of social and governance aspects of fisheries management requires integration of other disciplines or at the very least, parallel advice from other sources. Simply adding a collaborative dimension to an advisory process based on natural science only is not likely to address social considerations adequately (Payá, supplementary material), although these considerations are implicit in the political decisions on catch opportunities, for example in the EU (Voss *et al*., supplementary material). Instead, the decision-making system in which the process of science-management interactions occurs, from carrying out research to using research results in decision support, will need to be modified. A governance structure is needed to define clear objectives and operational frameworks that clarify stakeholder roles, responsibilities and mandates, such that collaboration between stakeholders and scientists from several disciplines can be productive and have an actual effect on management (Eliasen *et al*., 2015; Ramírez-Monsalve *et al.*, 2016; Charles, supplementary material).

Ways to evolve fisheries management

This paper has highlighted four priority areas to evolve and improve fisheries management: 1. addressing all four pillars of sustainability in fisheries management, 2. defining internally consistent targets and limits for management, 3. addressing uncertainty and variability, and 4. effective governance. For each of these main areas, we have suggested ways forward and summarise these below in a list of 10 possible ways to advance ecosystem based fisheries management (Table 2).

Addressing ecological, economic, social and governance dimensions of sustainability in fisheries management

A major challenge in fisheries management is that of reaching agreement on which targets should be considered within ecosystem-based management. While interpretations of MSY have evolved considerably since the concept was first conceived, there is no agreement on how the MSY concept is to evolve from its narrow single species interpretation to incorporate other aspects and reconcile interdependencies between the attainments of different objectives. The efforts to encompass ecological, economic and social objectives as well as governance processes in modelling of trade-offs has hitherto been limited mainly to ecological and to some extent the economic objectives, leaving out social objectives and governance processes. Addressing this shortcoming requires that we **(1) define agreed ecological, economic and social indicators with clear links to management measures**. Accompanying this, scientists should **(2) extend collaboration among ecological, economic and social scientists** even more so in cases where the governance structure differs among objectives, such as is seen in ecological- and fisheries-related objectives in the EU.

Defining internally consistent targets and limits for management

The current advice structures can be expanded with dedicated advice on social aspects, which is subsequently coordinated through existing advisory structures. This will lead to defining specified targets and limits for all indicators, and tolerance levels for their achievement, leading to a capability to **(3) provide advice that is internally consistent with all stated objectives whenever possible and clearly demonstrates conflicts where it is not.** A step in that direction can be to **(4) investigate the role of MSY-based PGMY ranges as a basis for the incorporation of mixed fisheries, ecological and economic considerations**. Suitable analytical advice must clearly communicate conflicts by being transparent with respect to the weights given in management decisions to ecological, economic and social considerations. Accompanying this more holistic approach is the need to **(5) recognise that choices regarding trade-offs reflect a political process**. Greater development and use of decision support tools, which fully embrace the complexity of fisheries social-ecological systems, as part of adaptive management approaches, may facilitate communication between science, and stakeholders involved in the decision-making process, leading to reduced risks of disjunctions between scientific advice and decisions.

Addressing uncertainty and variability

Fisheries management is undergoing a shift in philosophy, which is leading to more fully embracing uncertainty and complexity and to recognizing fisheries as social-ecological systems and more broadly as complex adaptive systems. This has two major implications. First, scientists and stakeholders need to approach the challenge to **(6) communicate 'uncertainty' and 'variability' and define the feasible range of management responses** to each of these. Related to this is the need to **(7) address spatio-temporal dynamics and changes in distributions of species and fishers, and more generally in the ecological, economic and social components of the fishery system, within scientific advice and institutions**.

Effective governance

A major implication in recognizing the complex systems nature of fisheries is the need to **(8) promote governance concepts and decision-making frameworks to emphasise adaptive collaborative management and reduce barriers** to the development of governance frameworks in which horizontal (between sectors) and vertical (international, regional, national, local) levels are well integrated**.** To operationalise collaborative management, a governance framework must be designed and implemented. This framework must **(9) define the composition and influence of stakeholders in decision-making processes clearly**. Though barriers do exist, the existing structures generally provide the necessary policy anchor for interdisciplinary scientific advice to accommodate ecological, economic and social aspects. Providing such advice would remove the lack of clear scientific advice as an explanation for not acting in accordance with stated policies.

Scientists, industry representatives, NGOs and managers need to know how to position themselves to act in collaboration. This requires that we **(10) build and maintain trust, interaction, common ground and common language**. Maintaining a functioning collaborative environment with responsibility in line with participation requires ongoing effort. Though this is listed last in Table 3, it is perhaps the most important aspect in moving forward towards an incorporation of all societal aspects in an efficient ecosystem based fisheries management.

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Table 1. Selected examples of temporal variability in processes often assumed to be constant when estimating MSY and MEY related reference points.

Process	Stock(s) and/or influential factor	Reference
Stock recruitment relationship	Pacific halibut under different oceanographic regimes	Stewart and Martell, 2015
	North Sea small pelagics and North Sea cod under different zooplankton productivity regimes	Beaugrand *et al*., 2003; Clausen *et al*. Table 1
Spatial distribution	Atlantic mackerel shifting into Icelandic waters	Nøttestad *et al*., 2016
	Big skate in the California Current	Thorson *et al*., Table 1
	North Sea stocks at the extremes of their distribution	Perry *et al*., 2005; Rindorf and Lewy, 2006
Natural mortality	Gulf of St. Lawrence cod	Swain and Benoît, 2015
	North Sea gadoids and small pelagics	Vinther *et al*., Table 1
	Ten species on Georges Bank	Gaichas *et al*., Table 1
Growth and weight at age	Walleye pollock in the eastern Bering Sea	Ianelli *et al.* 2015
	Small pelagics under different productivity regimes	Clausen *et al*. Table 1; Harma *et al*., 2012
	Gulf of St. Lawrence cod	Swain *et al*. 2012
Fishery selectivity at age	North Sea cod	Nielsen and Berg 2014
	Walleye pollock in the eastern Bering Sea	Ianelli *et al*. 2015

Catch composition for multispecies fisheries	US West Coast bottom trawl fishery	Hilborn *et al.* 2012
Fishing efficiency	Changing technology for fishing in the Australian northern prawn fishery	Bishop *et al*., 2008; Pascoe *et al*., 2012
	Southern North Sea demersal fish	Stäbler *et al*. Table 1
	Effect of changing technology in trawl and seine fishing in general, using examples from the North Sea and Australia	Eigaard *et al*., 2014
Changes in cost structure	Uncertainty regarding the definition of fixed versus variable costs	Dichmont *et al*., 2010
	Sensitivity of variable costs to different cost–stock elasticities	Röckmann *et al*., 2009
Changes in prices/market demand	Uncertainty in first-sale prices of fish landed	Doyen *et al*., 2012
	Simulated effects of market structure on fish stocks	Quaas *et al*., Table 1

Table 2. Suggested ways forward to include all four pillars of sustainability within operational ecosystem based fisheries management.

	Challenge
1	Define agreed ecological, economic and social indicators with clear links to management measures
2	Extend the collaboration between ecological, economic and social scientists
3	Provide advice that is internally consistent with all stated objectives whenever possible and clearly demonstrate conflicts where it is not
4	Investigate the role of MSY-based PGMY ranges as a basis for the incorporation of mixed fisheries, ecological and economic considerations
5	Recognise that choices regarding trade-offs reflect a political process
6	Communicate ‘uncertainty’ and ‘variability’ and define the feasible range of management responses to each
7	Address spatio-temporal dynamics and changes in distribution within scientific advice and institutions.
8	Promote governance concepts and decision-making frameworks to emphasise adaptive collaborative management and reduce barriers
9	Define the composition and influence of stakeholders in decision-making processes clearly
10	Build and maintain trust, interaction, common ground and common language in collaboration with stakeholders