



Introduction to the Symposium: 'Targets and Limits for Long Term Fisheries Management' Quo Vadimus

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

Anna Rindorf^{1*}, Catherine M. Dichmont², James Thorson³, Anthony Charles⁴,
Lotte Worsøe Clausen¹, Poul Degnbol⁵, Dorleta Garcia⁶, Niels T. Hintzen⁷, Alexander Kempf⁸,
Phillip Levin⁹, Pamela Mace¹⁰, Christos Maravelias¹¹, Coilín Minto¹², John Mumford¹³,
Sean Pascoe², Raul Prelezo⁶, André E. Punt¹⁴, David G. Reid¹⁵, Christine Röckmann⁷,
Robert L. Stephenson¹⁶, Olivier Thebaud¹⁷, George Tserpes¹⁸, and Rüdiger Voss¹⁹

¹DTU Aqua National Institute of Aquatic Resources, Technical University of Denmark (DTU), JægersborgAlle 1, Charlottenlund Castle, Charlottenlund 2920, Denmark

²47 Pioneer Rd, Sheldon, Queensland 4157, Australia

³1 Fisheries Resource Assessment and Monitoring Division, Northwest Fisheries Science Center, National Marine Fisheries Service, NOAA, Seattle, WA, USA

⁴School of the Environment and School of Business, Saint Mary's University, Halifax, Nova Scotia B3H3C3, Canada

⁵Innovative Fisheries Management, Aalborg University, Aalborg DK 9000, Denmark

⁶Azti-Tecnalia. Txatxarramendi Ugarte 48395, Spain

⁷Institute for Marine Resources and Ecosystem Studies (IMARES), Wageningen University & Research Centre (WUR), AB IJmuiden 1970, The Netherlands

⁸Thünen Institute of Sea Fisheries, Hamburg 22761, Germany

⁹National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington, USA

¹⁰Ministry for Primary Industries, Wellington, New Zealand

¹¹Hellenic Centre for Marine Research (HCMR), Anavyssos, Attica 19013, Greece

¹²Marine and Freshwater Research Centre, Galway-Mayo Institute of Technology, Galway, Ireland

¹³Centre for Environmental Policy, Imperial College London, Silwood Park Campus, Ascot, Berkshire SL5 7PY, United Kingdom

¹⁴School of Aquatic and Fishery Science, University of Washington, Seattle, WA 98195-5020, USA

¹⁵Marine Institute, Rinville, Oranmore, Galway H91 R673, Ireland

¹⁶Canadian Fisheries Research Network, St. Andrews Biological Station, St. Andrews NB E5B 2L9, Canada

¹⁷Ifremer, UMR 6308, AMURE, Unité d'Economie Maritime, Plouzané Cedex BP 70, F-29280, France

¹⁸Hellenic Centre for Marine Research, Institute of Marine Biological Resources and Inland Waters, Heraklion, Crete 71003, Greece

¹⁹Department of Economics, University of Kiel, Kiel 24118, Germany

*Corresponding author: tel: + 45 35883378; e-mail: ar@aqu.dtu.dk

Rindorf, A., Dichmont, C. M., Thorson, J., Charles, A., Clausen, L. W., Degnbol, P., Garcia, D., Hintzen, N. T., Kempf, A., Levin, P., Mace, P., Maravelias, C., Minto, C., Mumford, J., Pascoe, S., Prelezo, R., Punt, A. E., Reid, D. G., Röckmann, C., Stephenson, R. L., Thebaud, O., Tserpes, G., and Voss, R. Inclusion of ecological, economic, social, and institutional considerations when setting targets and limits for multispecies fisheries. – ICES Journal of Marine Science, 74: 453–463.

Received 11 May 2016; revised 15 November 2016; accepted 17 November 2016; advance access publication 28 January 2017.

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.

Keywords: 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 formalized in the 1950s (Schaefer, 1954, 1957), to limits being set to avoid stock collapse in the 1980s and 1990s (Garcia, 1995) and back to maximizing 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 maximizing) 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 maximize 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 maximizing 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, 2007; Fogarty, 2014; Hilborn et al., 2015; Prelezo 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 summarized 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 *et al.*; Vinther, [Supplementary material](#); Gachias *et al.*, 2017), 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.*, 2017). 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.*, 2017; 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; Merino *et al.*, 2015; Quetglas *et al.*, 2016; Hoff and Frost; Mahevas *et al.*, Tserpes *et al.*, [Supplementary material](#); Kempf *et al.*, 2016, [Supplementary material](#)). 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.*, 2017).

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.*, 2014; 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.*, 2017). 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.*, 2017; Rindorf *et al.*, 2016), 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.*, 2016).

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.*, 2017, this issue; Rindorf *et al.*, 2017, 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.*, 2017, 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.*, 2017, 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.*, 2017; Ulrich *et al.*, 2017, 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.*, 2017, 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.*, 2017; Rindorf *et al.*, 2016). 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.*, 2014), 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.*, 2017; 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, 2017; Pascoe *et al.*, 2017; 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,

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 North Sea small pelagics and North Sea cod under different zooplankton productivity regimes	Stewart and Martell (2015) Beaugrand <i>et al.</i> (2003); Clausen <i>et al.</i> , Supplementary material, this article
Spatial distribution	Atlantic mackerel shifting into Icelandic waters Big skate in the California Current North Sea stocks at the extremes of their distribution	Nøttestad <i>et al.</i> (2016) Thorson <i>et al.</i> , Supplementary material, this article Perry <i>et al.</i> (2005) and Rindorf and Lewy (2006)
Natural mortality	Gulf of St. Lawrence cod North Sea gadoids and small pelagics Ten species on Georges Bank	Swain and Benoit (2015) Vinther <i>et al.</i> , Supplementary material, this article Gaichas <i>et al.</i> , Supplementary material, this article
Growth and weight at age	Walleye pollock in the eastern Bering Sea Small pelagics under different productivity regimes	Ianelli <i>et al.</i> (2015) Clausen <i>et al.</i> Supplementary material, this article and Harma <i>et al.</i> (2012)
Fishery selectivity at age	Gulf of St. Lawrence cod North Sea cod Walleye pollock in the eastern Bering Sea	Swain <i>et al.</i> (2012) Nielsen and Berg (2014) Ianelli <i>et al.</i> (2015)
Catch composition for multispecies fisheries	US West Coast bottom trawl fishery	Hilborn <i>et al.</i> (2012)
Fishing efficiency	Changing technology for fishing in the Australian northern prawn fishery Southern North Sea demersal fish	Bishop <i>et al.</i> (2008) and Pascoe <i>et al.</i> (2012) Stäbler <i>et al.</i> , Supplementary material, this article
Changes in cost structure	Effect of changing technology in trawl and seine fishing in general, using examples from the North Sea and Australia Uncertainty regarding the definition of fixed versus variable costs Sensitivity of variable costs to different cost–stock elasticities	Eigaard <i>et al.</i> (2014) Dichmont <i>et al.</i> (2010) Röckmann <i>et al.</i> (2009)
Changes in prices/market demand	Uncertainty in first-sale prices of fish landed Simulated effects of market structure on fish stocks	Doyen <i>et al.</i> (2012) Quaas <i>et al.</i> , Supplementary material, this article

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 Rijnsdorp, 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, 2016; 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 difficulty 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-utilization, 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, 2017). 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.*, 2017, 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; Bailey *et al.*, 2017).

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*; McGarvey *et al.*, 2017; Bailey *et al.*, 2017). 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 an appropriate role for participants that recognizes 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, 2017). 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 identifying participants for the process (Bailey; Rindorf and Fisher; Stephenson, *Supplementary material*; Bailey *et al.*, 2017).

Effective governance structures

Governance structures, that favour 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, although 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, decision 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 (Eliassen *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 summarize 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) *recognize that choices regarding trade-offs reflect a political process*. Greater development and use of decision support tools, which fully embrace the complexity of fisheries

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	Recognize 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 emphasize 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

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 emphasize 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 operationalize 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. Although this is listed last in Table 2, it is perhaps the most important aspect in moving forward towards an incorporation of all societal aspects in an efficient ecosystem based fisheries management.

Supplementary data

Supplementary material is available at the ICESJMS online version of the manuscript.

Acknowledgements

The authors would like to thank all participants of the Joint ICES/Myfish symposium on targets and limits in long-term fisheries management for their enthusiastic participation in discussion and reflections.

Funding

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007–2013) under Grant agreement MYFISH number 289257 (A. R., L. W. C., D. G., N. H., A. K., C. Ma., J. M., R. P.,

D. R., C. R., G. T., and R. V.). A. C. and R. L. S. acknowledge funding from the Natural Sciences and Engineering Research Council of Canada, and A. C. acknowledges the Social Sciences and Humanities Research Council of Canada.

References

- Aanesen, M., Armstrong, C. W., Bloomfield, H. J., and Röckmann, C. 2014. What does stakeholder involvement mean for fisheries management? *Ecology and Society*, 19: 35.
- Bailey, J. L., Liu, Y., and Davidsen, J. G. 2017. Bridging the gap between fisheries science and society: exploring fisheries science as a social activity. *ICES Journal of Marine Science*, 74: 598–611.
- Baugrand, G., Brander, K. M., Lindley, J. A., Souissi, S., and Reid, P. C. 2003. Plankton effect on cod recruitment in the North Sea. *Nature*, 426: 661–664.
- Berkes, F., Hughes, T. P., Steneck, R. S., Wilson, J. A., Bellwood, D. R., Crona, B., Folke, C. *et al.* 2006. Globalization, roving bandits, and marine resources. *Science*, 311: 1557–1558.
- Bishop, J., Venables, W. N., Dichmont, C. M., and Sterling, D. J. 2008. Standardizing catch rates: is logbook information by itself enough? *ICES Journal of Marine Science*, 65: 255–266.
- Brooks, K., Schirmer, J., Pascoe, S., Triantafillos, L., Jebreen, E., Cannard, T., and Dichmont, C. M. 2015. Selecting and assessing social objectives for Australian fisheries management. *Marine Policy*, 53: 111–122.
- Cadigan, N. G., and Wang, S. 2016. Local sensitivity of per-recruit fishing mortality reference points. *Journal of Biological Dynamics*, 10: 525–545.
- Charles, A. 1988. Fishery socioeconomics: a survey. *Land Economics*, 64: 276–295.
- Charles, A. 1995. Fishery science: the study of fishery systems. *Aquatic Living Resources*, 8: 233–239.
- Charles, A. 1998. Living with uncertainty in fisheries: analytical methods, management priorities and the Canadian groundfishery experience. *Fisheries Research*, 37: 37–50.
- Charles, A. 2001. *Sustainable Fishery Systems*. Wiley-Blackwell, Oxford, UK, 384p.
- Christensen, V. 2010. MEY=MSY. *Fish and Fisheries*, 11: 105–110.
- Dichmont, C. M., Pascoe, S., Jebreen, E., Pears, R., Brooks, K., and Perez, P. 2013. Choosing a fishery's governance structure using data poor methods. *Marine Policy*, 37: 123–131. DOI 10.1016/j.marpol.2012.02.018.
- Doyen, L., Thébaud, O., Béné, C., Martinet, V., Gourguet, S., Bertignac, M., Fifas, S., and Blanchard, F. 2012. A stochastic viability approach to ecosystem-based fisheries management. *Ecological Economics*, 75: 32–42.
- Dutra, L. X., Thébaud, O., Boschetti, F., Smith, A. D., and Dichmont, C. M. 2015. Key issues and drivers affecting coastal and marine resource decisions: Participatory management strategy evaluation to support adaptive management. *Ocean & Coastal Management*, 116: 382–395.
- Eigaard, O. R., Marchal, P., Gislason, H., and Rijnsdorp, A. D. 2014. Technological development and fisheries management. *Reviews in Fisheries Science and Aquaculture*, 22: 156–174.
- Eliassen, S. Q., Hegland, T. J., and Raakjær, J. 2015. Decentralising: the implementation of regionalization and co-management under the post-2013 Common Fisheries Policy. *Marine Policy*, 62: 224–232.
- EU. 2013. Council and Parliament. Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. In: *Official Journal of the European Communities*, L 354 (28.12.2013), pp. 22–61. http://faolex.fao.org/cgi-bin/faolex.exe?rec_id=130290&data

- base=faolex&search_type=link&table=result&lang=eng&format_name=@ERALL
- FAO. 1995. Code of Conduct for Responsible Fisheries. Food and Agriculture Organization of the United Nations, Rome, Italy. 49 pp.
- FAO. 2003. The ecosystem approach to fisheries. FAO Technical Guidelines for Responsible Fisheries, 4(Suppl. 2): 1–112.
- Fogarty, M. J. 2014. The art of ecosystem-based fishery management. *Canadian Journal of Fisheries and Aquatic Science*, 71: 479–490. dx.doi.org/10.1139/cjfas-2013-0203
- García, D., Prellezo, R., Sampedro, P., Castro, J., Cerviño, S., Da-Rocha, J., Cutrin, J., and Gutierrez, M. 2017. Bio-economic multistock reference points as a tool to overcome the drawbacks of landing obligation. *ICES Journal of Marine Science*, 74: 511–524.
- Gaichas, S., Fogarty, M. J., Fay, G., Gamle, R., Lucey, S., and Smith, L. 2017. Combining stock, multispecies, and ecosystem level fishery objectives within an operational management procedure: simulations to start the conversation? *ICES Journal of Marine Science*, 74: 552–565.
- García, S. M. 1995. The precautionary approach to fisheries and its implications for fishery research, technology and management: an updated review. FAO Technical Paper, 350.
- García, S. M. 2003. The ecosystem approach to fisheries: issues, terminology, principles, institutional foundations, implementation and outlook. FAO Technical Paper, 443.
- Gezelius, S. S., Hegland, T. J., Palevski, H., and Raakjær, J. 2008. The politics of implementation in resource conservation: comparing the EU/Denmark and Norway. *In Making Fisheries Management Work. Reviews: Methods and Technologies in Fish Biology and Fisheries*, 8, pp. 207–229. Ed. by S. S. Gezelius and J. Raakjær. Springer, London.
- Gislason, H. 1999. Single and multispecies reference points for Baltic fish stocks. *ICES Journal of Marine Science*, 56: 571–583.
- Gourguet, S., Thébaud, O., Dichmont, C., Jennings, S., Little, L. R., Pascoe, S., Deng, R., and Doyen, L. 2014. Risk versus economic performance in a mixed fishery. *Ecological Economics*, 99: 110–120.
- Gray, S., Chan, A., Clark, D., and Jordan, R. 2012. Modeling the integration of stakeholder knowledge in social–ecological decision-making: Benefits and limitations to knowledge diversity. *Ecological Modelling*, 229: 88–96.
- Haapasaaari, P., Kulmala, S., and Kuikka, S. 2012. Growing into interdisciplinarity: how to converge biology, economics, and social science in fisheries research? *Ecology and Society*, 17: 6.
- Haltuch, M. A., and Punt, A. E. 2011. The promises and pitfalls of including decadal-scale climate forcing of recruitment in groundfish stock assessment. *Canadian Journal of Fisheries and Aquatic Sciences*, 68: 912–926.
- Hamon, K., Frusher, S., Little, L. R., Thébaud, O., and Punt, A. 2013. Adaptive behaviour of fishers to external perturbations: simulation of the Tasmanian rock lobster fishery. *Reviews in Fish Biology and Fisheries*, 24: 1–16.
- Harma, C., Brophy, D., Minto, C., and Clarke, M. 2012. The rise and fall of autumn-spawning herring (*Clupea harengus* L.) in the Celtic Sea between 1959 and 2009: temporal trends in spawning component diversity. *Fisheries Research*, 121: 31–42.
- Hicks, A. C., Taylor, N., Grandin, C., Taylor, I. G., and Cox, S. 2014. Status of the Pacific Hake (whiting) Stock in U.S. and Canadian Waters in 2013. International Joint Technical Committee for Pacific Hake, Seattle, Washington, USA (2014).
- Hilborn, R. 2007. Managing fisheries is managing people: what has been learned? *Fish and Fisheries*, 8: 285–296.
- Hilborn, R. 2010. Pretty good yield and exploited fishes. *Marine Policy*, 34: 193–196.
- Hilborn, R., and Walters, C. J. 1992. *Quantitative Fisheries Stock Assessment — Choice, Dynamics and Uncertainty*, 1st edn. Springer, Norwell, MA.
- Hilborn, R., Fulton, E. A., Green, B. S., Hartmann, K., Tracey, S. R., and Watson, R. A. 2015. When is a fishery sustainable? *Canadian Journal of Fisheries and Aquatic Sciences*, 72: 1433–1441.
- Hilborn, R., Stewart, I. J., Branch, T. A., and Jensen, O. P. 2012. Defining trade-offs among conservation, profitability, and food security in the California Current Bottom-Trawl Fishery. *Conservation Biology*, 26: 257–268.
- Hoefnagel, E., de Vos, B., and Buisman, E. 2015. Quota swapping, relative stability, and transparency. *Marine Policy*, 57: 111–119.
- Ianelli, J. N., Honkalehto, T., Barbeaux, S., and Kotwicki, S. 2015. Assessment of the walleye pollock stock in the Eastern Bering Sea. NPFMC Bering Sea and Aleutian Islands SAFE. Alaska Fisheries Science Center, Seattle.
- Jacobsen, N. S., Gislason, H., and Andersen, K. H. 2014. The consequences of balanced harvesting of fish communities. *Proceedings of the Royal Society. B. Biological Science*, 281: 20132701. doi:10.1098/rspb.2013.2701.
- Jacobsen, R. B., Wilson, D. C. K., and Ramirez-Monsalve, P. 2011. Empowerment and regulation – dilemmas in participatory fisheries science. *Fish and Fisheries*, 69: 1–12.
- Kempf, A., Mumford, J., Levontin, P., Leach, A., Hoff, A., Hamon, K. G., Bartelings, H. *et al.* 2016. The MSY concept in a multi-objective fisheries environment – lessons learned from the North Sea. *Marine Policy*, 69: 146–158.
- Levin, P. S., Williams, G. D., Rehr, A., Norman, K. C., and Harvey, C. J. 2015. Developing conservation targets in social-ecological systems. *Ecology and Society*, 20: 6.
- Link, J. 2010. *Ecosystem-based Fisheries Management: Confronting Tradeoffs*. Cambridge University Press, Cambridge, UK.
- Long, R. D., Charles, A., and Stephenson, R. L. 2015. Key principles of marine ecosystem-based management. *Marine Policy*, 57: 53–60.
- Lorenzen, K. 2016. Toward a new paradigm for growth modeling in fisheries stock assessments: embracing plasticity and its consequences. *Fisheries Research*, 180: 4–22.
- Mace, P. M. 1994. Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. *Canadian Journal of Fisheries and Aquatic Sciences*, 51: 110–122.
- Mace, P. M. 2001. A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. *Fish and Fisheries*, 2: 2–32.
- Mackinson, S., and Wilson, D. C. K. 2014. Building bridges among scientists and fishermen with participatory action research. *In Social Issues in Sustainable Fisheries Management*. Springer, New York. pp. 121–139.
- McGarvey, R., Linnane, A., Matthews, J. M., and Jones, A. 2017. Decision rules for quota setting to support spatial management in a lobster (*Jasus edwardsii*) fishery. *ICES Journal of Marine Science*, 74: 588–597.
- Martinet, V., Thébaud, O., and Doyen, L. 2007. Defining viable recovery paths toward sustainable fisheries. *Ecological Economics*, 64: 411–422.
- Merino, G., Quetglas, A., Maynou, F., Garau, A., Arrizabalaga, H., Murua, H., Santiago, J. *et al.* 2015. Improving the performance of a Mediterranean demersal fishery towards economic objectives beyond MSY. *Fisheries Research*, 161: 131–144.
- Miller, D. C., and Shelton, P. A. 2010. “Satisficing” and trade-offs: evaluating rebuilding strategies for Greenland halibut off the east coast of Canada. *ICES Journal of Marine Science*, 67: 1896–1902.
- Minto, C., Mills Flemming, J., Britten, G. L., and Worm, B. 2013. Productivity dynamics of Atlantic cod. *Canadian Journal of Fisheries and Aquatic Sciences*, 71: 203–216.
- Nielsen, A., and Berg, C. W. 2014. Estimation of time-varying selectivity in stock assessments using state-space models. *Fisheries Research*, 158: 96–101.

- Nøttestad, L., Utne, K. R., Óskarsson, G. J., Jonsson, S., Jacobsen, J. A., Tangen, Ø., Anthonypillai, V. *et al.* 2016. Quantifying changes in abundance, biomass and spatial distribution of Northeast Atlantic (NEA) mackerel (*Scomber scombrus*) in the Nordic Seas from 2007 to 2014. *ICES Journal of Marine Science*, 73: 359–373.
- Pascoe, S., Coglan, L., Punt, A. E., and Dichmont, C. M. 2012. Impacts of vessel capacity reduction programmes on efficiency in fisheries: the case of Australia's Multispecies Northern Prawn Fishery. *Journal of Agricultural Economics*, 63: 425–443.
- Pascoe, S., Hutton, T., Thebaud, O., Deng, R., Klaer, N., and Vieira, S. 2015. Setting economic target reference points for multiple species in mixed fisheries, FRDC Final Report. CSIRO, Brisbane.
- Pascoe, S. D., Plagányi, É. E., and Dichmont, C. M. 2017. Modelling multiple management objectives in fisheries: Australian experiences. *ICES Journal of Marine Science*, 74: 464–474.
- Pascoe, S., Thebaud, O., and Vieira, S. 2014. Estimating proxy economic target reference points in data-poor single-species fisheries. *Marine and Coastal Fisheries*, 6: 247–259.
- Perry, A. L., Low, P. J., Ellis, J. R., and Reynolds, J. D. 2005. Climate change and distribution shifts in marine fishes. *Science*, 308: 1912–1915.
- Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L., and Levin, S. A. 2013. Marine taxa track local climate velocities. *Science*, 341: 1239–1242.
- Poos, J. J., and Rijnsdorp, A. D. 2007. An “experiment” on effort allocation of fishing vessels: the role of interference competition and area specialization. *Canadian Journal of Fisheries and Aquatic Sciences*, 64: 304–313.
- Prellezo, R., and Curtin, R. 2015. Confronting the implementation of marine ecosystem-based management within the Common Fisheries Policy reform. *Ocean and Coastal Management*, 117: 43–51.
- Punt, A. E. 2017. Strategic management decision-making in a complex world: quantifying, understanding, and using trade-offs. *ICES Journal of Marine Science*, 74: 499–510.
- Punt, A. E., Szuwalski, C. S., and Stockhausen, W. 2014. An evaluation of stock–recruitment proxies and environmental change points for implementing the US Sustainable Fisheries Act. *Fisheries Research*, 157: 28–40.
- Quetglas, A., Merino, G., Ordines, F., Guijarro, B., Garau, A., Grau, A. M., Oliver, P., and Massutí, E. 2016. Assessment and management of western Mediterranean small-scale fisheries. *Ocean and Coastal Management*, 133: 95–104.
- Ramírez-Monsalve, P., Raakjær, J., Nielsen, K. N., Santiago, J. L., Ballesteros, M., Laksá, U., and Degnbol, P. 2016. Ecosystem Approach to Fisheries Management (EAFM) in the EU – current science–policy–society interfaces and emerging requirements. *Marine Policy*, 66: 83–92.
- Rehr, A. P., Williams, G. D., and Levin, P. S. 2014. A test of the use of computer generated visualizations in support of ecosystem-based management. *Marine Policy*, 46: 14–18.
- Rindorf, A., and Lewy, P. 2006. Warm, windy winters drive cod north and homing of spawners keeps them there. *Journal of Applied Ecology*, 43: 445–453.
- Rindorf, A., and Lewy, P. 2012. Estimating the relationship between abundance and distribution. *Canadian Journal of Fisheries and Aquatic Sciences*, 69: 382–397.
- Rindorf, A., Mumford, J., Baranowski, P., Clausen, L. W., Garcia, L., Hintzen, N., Holt, J. *et al.* 2016. Expanding the MSY concept to reflect multidimensional fisheries management objectives. Submitted for publication.
- Rindorf, A., Dichmont, C. M., Levin, P. S., Mace, P., Pascoe, S., Prellezo, R., Punt, A. E. *et al.* 2017. Food for thought: pretty good multispecies yield. *ICES Journal of Marine Science*, 74: 475–486.
- Röckmann, C., Tol, R. S. J., Schneider, U. A., and John, M. A. S. 2009. Rebuilding the Eastern Baltic cod stock under environmental change (part II): taking into account the costs of a marine protected area. *Natural Resource Modeling*, 22: 1–25.
- Röckmann, C., van Leeuwen, J., Goldsborough, D., Kraan, M., and Piet, G. 2015. The interaction triangle as a tool for understanding stakeholder interactions in marine ecosystem based management. *Marine Policy*, 52: 155–162.
- Sampedro, P., Prellezo, R., García, D., Da-Rocha, J. M., Cerviño, S., Torralba, J., Touza, J. *et al.* 2017. To shape or to be shaped: engaging stakeholders in fishery management advice. *ICES Journal of Marine Science*, 74: 487–498.
- Schwach, V., Bailly, D., Christensen, A. S., Delaney, A. E., Degnbol, P., Van Densen, W. L., Holm, P. *et al.* 2007. Policy and knowledge in fisheries management: a policy brief. *ICES Journal of Marine Science*, 64: 798–803.
- Smith, A. D., Brown, C. J., Bulman, C. M., Fulton, E. A., Johnson, P., Kaplan, I. C., Lozano-Montes, H. *et al.* 2011. Impacts of fishing low-trophic level species on marine ecosystems. *Science*, 333: 1147–1150.
- Smith, A. D. M., Sainsbury, K. J., and Stevens, R. A. 1999. Implementing effective fisheries-management systems –management strategy evaluation and the Australian partnership approach. *ICES Journal of Marine Science*, 56: 967–979.
- Smith, T., and Punt, A. E. 2001. The gospel of maximum sustainable yield in fisheries management: birth, crucifixion and reincarnation. *In Conservation of Exploited Species*. Ed. by J. D. Reynolds, G. M. Mace, K. H. Redford, and J. G. Robinson. Cambridge University Press, Cambridge, UK. 41–66pp.
- Stewart, I. J., and Martell, S. 2015. Assessment of the Pacific halibut stock at the end of 2014. *International Pacific Halibut Commission Report of Assessment and Research Activities 2014*, pp. 169–196. *International Pacific Halibut Commission*, Seattle, WA.
- Swain, D. P., and Benoît, H. P. 2015. Extreme increases in natural mortality prevent recovery of collapsed fish populations in a Northwest Atlantic ecosystem. *Marine Ecology Progress Series*, 519: 165–182.
- Swain, D. P., Savoie, L., and Aubry, É. 2012. Recovery Potential Assessment for the Laurentian South designatable unit of Atlantic Cod (*Gadus morhua*): the southern Gulf of St. Lawrence cod stock (NAFO Div. 4T-4Vn (Nov–Apr)). *DFO Can. Sci. Advis. Sec. Res. Doc.* 2012/052. iii + 51 p.
- Szuwalski, C. S., and Punt, A. E. 2013. Fisheries management for regime-based ecosystems: a management strategy evaluation for the snow crab fishery in the eastern Bering Sea. *ICES Journal of Marine Science*, 70: 955–967.
- Thebaud, O., Ellis, N., Little, L. R., Doyen, L., and Marriott, R. J. 2014. Viability trade-offs in the evaluation of strategies to manage recreational fishing in a marine park. *Ecological Indicators*, 46: 59–69.
- Thorson, J. T., Jensen, O. P., and Zipkin, E. F. 2014. How variable is recruitment for exploited marine fishes? A hierarchical model for testing life history theory. *Canadian Journal of Fisheries and Aquatic Sciences*, 71: 973–983.
- Thorson, J. T., and Minte-Vera, C. (In press) Relative magnitude of cohort, age, and year effects on size at age of exploited marine fishes. *Fisheries Research*.
- Thorson, J. T., Pinsky, M. L., and Ward, E. J. 2016. Model-based inference for estimating distribution changes in marine species. *Methods in Ecology and Evolution*
- Ulrich, C., Vermard, Y., Dolder, P. J., Brunel, T., Jardim, E., Holmes, S. J., Kempf, A. *et al.* 2017. Achieving maximum sustainable yield in mixed fisheries: a management approach for the North Sea demersal fisheries. *ICES Journal of Marine Science*, 74: 566–575.
- US. 2007. Magnuson-Stevens Fishery Conservation Management Reauthorization Act of 2006. *Public Law*, 479.
- Vermard, Y., Marchel, P., Mahevas, S., and Thebaud, O. 2008. A dynamic model of the Bay of Biscay pelagic fleet simulating fishing trip choice: the response to the closure of the European anchovy

- (*Engraulis encrasicolus*) fishery in 2005. Canadian Journal of Fisheries and Aquatic Sciences, 65: 2444–2453.
- Vert-pre, K. A., Amoroso, R. O., Jensen, O. P., and Hilborn, R. 2013. Frequency and intensity of productivity regime shifts in marine fish stocks. Proceedings of the National Academy of Sciences, 110: 1779–1784.
- Voss, R., Quaas, M. F., Schmidt, J. O., Tahvonen, O., Lindegren, M., and Möllmann, C. 2014. Assessing social–ecological trade-offs to advance ecosystem-based fisheries management. PLoS One, 9: e107811.
- Wayte, S. E. 2013. Management implications of including a climate-induced recruitment shift in the stock assessment for jackass morwong (*Nemadactylus macropterus*) in south-eastern Australia. Fisheries Research, 142: 47–55.
- Wilson, D. C. 2009. The paradoxes of transparency: science and the ecosystem approach to fisheries management in Europe. Amsterdam University Press, p. 304.
- World Commission on Environment and Development (WCED). 1987. Our Common Future. Oxford University Press.
- Zabel, R. W., Harvey, C. J., Katz, S. L., Good, T. P., and Levin, P. S. 2003. Ecologically sustainable yield. American Scientist, 91: 150–157.

Handling editor: Howard Browman