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Opportunities for advancing ecosystem-based management in a rapidly changing, high latitude ecosystem

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Unprecedented and rapid changes are ongoing in northern high latitude, marine ecosystems, due to climate warming. Species distributions and abundances are changing, altering both ecosystem structure and dynamics. At the same time, human impacts are increasing. Less sea ice opens for the opportunity of more petroleum-related activities, shipping and tourism. Fisheries are moving into previously unfished habitats, targeting more species across more trophic levels. There is a need for ecosystem-based fisheries management (EBFM) and ecosystem-based management (EBM) to take the rapid, climate driven changes into account. Recently, there has been much development in qualitative, semi-quantitative, and quantitative scientific approaches to support EBFM and EBM. Here, we present some of these approaches, and discuss how they provide opportunities for advancing EBFM and EBM in one high-latitude system, namely the Barents Sea. We propose that advancing EBFM and EBM is more about adding tools to the toolbox than replacing tools, and to use the tools in coordinated efforts to tackle the increasing complexities in scientific support to management. Collaborative and participatory processes among stakeholders and scientists are pivotal for both scoping and prioritizing, and for efficient knowledge exchange. Finally, we argue that increasing uncertainty with increasing complexity is fundamental to decision making in EBFM and EBM and needs to be handled, rather than being a reason for inaction or irrelevance.

Keywords: climate change, ecosystem-based management, ecosystem risk assessment Barents Sea, fisheries, integrated ecosystem assessment.

Introduction

Unprecedented, large scale and rapid changes are taking place in northern high latitude, marine ecosystems. They have become warmer than previously observed, and sea ice has retracted rapidly (Cheung *et al.*, 2009; Wassmann *et al.*, 2011; Smedsrud *et al.*, 2013), affecting both ecosystem productivity and species abundances and distributions (Cheung *et al.*, 2009; Wassmann *et al.*, 2011; Dalpadado *et al.*, 2014; Fossheim *et al.*, 2015). In the Barents Sea, southern, boreal species have stretched their distributions into northern Arctic reaches (Kjesbu *et al.*, 2014; Fossheim *et al.*, 2015; Frainer *et al.*, 2017), where warmer waters and reduced ice coverage may provide more favourable and productive conditions (Dalpadado *et al.*, 2014; Kjesbu *et al.*, 2014). Such changes have been beneficial for the large and commercially important boreal fish stocks, such as Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus* Kjesbu *et al.*, 2014). The Barents Sea is currently housing the largest cod stock in the world (Kjesbu *et al.*, 2014). The Arctic species, however, are contracting and declining (Fossheim *et al.*, 2015; Frainer *et al.*, 2017). Such structural changes alter species interactions and the food web dynamics of the Barents Sea, and may increase system vulnerability to perturbations by, e.g. reducing system compartmentalization and enhancing the spread of system responses to perturbations (Kortsch *et al.*, 2015; Frainer *et al.*, 2017).

At the same time, a warmer climate and less sea ice makes the system more available for human use (Smith and Stephenson, 2013;

Rautio *et al.*, 2014). The Arctic sea route from the Atlantic to the Pacific ocean offers substantial savings in fuel and transport time leading to more shipping in the area (Smith and Stephenson, 2013). Less sea ice also means that the area is more available to tourism, petroleum extraction, and shipping oil and gas out of the region (Rautio *et al.*, 2014). While commercial fisheries in the Barents Sea may be more sustainable than just a decade ago due to more precautionary management, the fisheries are targeting more species across more trophic levels and operate in wider geographic areas (Christiansen *et al.*, 2014; Anon, 2017).

It is generally accepted that the increasing number and nature of human use of marine resources and space calls for ecosystem-based management (EBM, Levin *et al.*, 2009; Link and Browman, 2014). The main objective of EBM is to maintain socio-economic benefits while at the same time sustain healthy marine ecosystems. Central to EBM is the focus on cumulative impacts across human activities, identifying trade-offs among human uses, and interactions between human use and ecosystem processes (Browman *et al.*, 2004; Levin *et al.*, 2009). However, the increasing number and nature of human use increases the information needed for management (Burgess *et al.*, 2018), and data limitation is often regarded as one of the greatest obstacles to advance EBM (Patrick and Link, 2015). It is difficult to improve management if the current system state and interactions are poorly understood, and it is difficult to quantify interactions and trade-offs if the data needed to parameterize models of the system are unavailable. While the Barents Sea must be considered as a data rich system due to extensive monitoring programs (Eriksen *et al.*, 2018), advancing EBM in this region may still seem challenging due to the many data poor elements (e.g. species, habitats, processes), and that the system is both rapidly changing and moving outside the bounds previously observed. Thus, both scientists and managers, and persons dependent on these systems, may rely less on past scientific knowledge, and more on recent observations.

However, these challenges may indeed be surmountable in that (i) they need not prevent a more holistic management framework from improving upon status quo, and (ii) improvements may not always include more complex data or analytical approaches, or rely on “godzilla”-sized ecosystem models (although they are useful, Patrick and Link, 2015; Burgess *et al.*, 2018). Rather, EBM is about being more comprehensive in the factors being considered to manage a fishery or any other sector (Hobday *et al.*, 2011; DePiper *et al.*, 2017; Melbourne-Thomas *et al.*, 2017). While the objectives of EBM can be both complex and even conflicting (DePiper *et al.*, 2017), sustainable use of marine resources, secure species and habitats, and secure ecosystem structure, function and dynamics are overarching objectives that lies to the core of EBM (Pikitch *et al.*, 2004; Gullestad *et al.*, 2017, Figure 1). Recently, diverse approaches have been developed to provide science support to better achieve these management objectives. These approaches range from qualitative, semi-quantitative to fully quantitative, and from low to high socio-ecological complexity targeting species, communities, and systems (Figure 1). The development has typically depended on the salient information, data availability and the focal research questions. In this paper, we discuss how these approaches, used in a coordinated fashion, offer pragmatic opportunities to advance EBM in the Barents Sea (Figure 1). As fisheries and climate impacts have been the major drivers of change in this ecosystem (Johannesen *et al.*, 2012; ICES, 2016), we focus firstly on opportunities to advance ecosystem-based fisheries management (EBFM, Pikitch *et al.*, 2004), taking into account recent changes in both the ecosystem and in fisheries, before placing fisheries management within the context of other sectors in EBM.

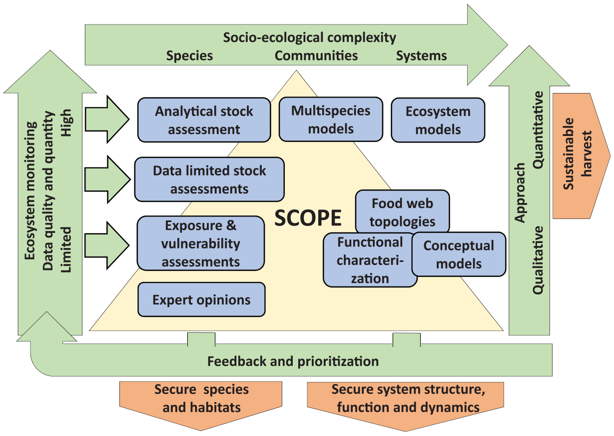

Figure 1. Approaches presented and discussed in relation to advancing EBFM and EBM in the Barents Sea. The approaches range from qualitative to semi-quantitative to quantitative (right vertical axis), based on limited to high data availability/quality (left vertical axis), and includes low to high socio-ecological complexity (top horizontal axis). The scoping triangle (yellow triangle) indicate the hierarchical relationship in the scope of the approaches; in general the qualitative approaches have a wider scope in terms of number of species or interactions assessed than the quantitative approaches. The approaches provide feedback to ecosystem monitoring in terms of prioritization (bottom axis), and support species to system management objectives (orange arrows). Please refer to text for descriptions of the approaches.

Advancing EBFM in the Barents Sea

EBFM is centred on harvesting marine resources without degrading the marine ecosystems, including their species (target and non-target, vulnerable and endangered species), life-stages and habitats (Pikitch *et al.*, 2004). Pikitch *et al.* (2004) argue that while single species target and limit reference points traditionally used in fisheries management are still appropriate, they will need to be modified in the context of the ecosystem. In the Barents Sea, mixed fisheries and bycatch is limited (Gullestad *et al.*, 2017). A major concern is how the climate-related changes in habitats and food webs impact the commercial species and their prey, as well species and system vulnerabilities to combined impacts of climate and fisheries. Such changes can be considered in both tactical management decisions on year-to-year changes in harvest levels and quotas, and in strategic management decisions on longer term harvesting levels, often by defining harvest control rules (HCRs).

Tactical management decisions

Although fish stock production can be strongly impacted by ecosystem interactions and ocean climate (Vert-pre *et al.*, 2013; Kjesbu *et al.*, 2014), most fish stocks are assessed using single species assessment models with no explicit implementation of such processes or trade-offs with other stocks (Skern-Mauritzen *et al.*, 2016). For commercially important stocks, vital rates such as recruitment, growth, and natural mortality are monitored and included in analytical assessments. Such vital rates thus integrate changes in stock productivity associated with changes in the physical or biological system. Nevertheless, single species models and projections can be biased by failing to account for ecosystem-level interactions or impact by a warming environment (Vert-pre *et al.*, 2013; Kjesbu *et al.*, 2014). Such biases may lead to management decisions less, or more, precautionary than initially aimed for (Vert-pre *et al.*, 2013; Kjesbu *et al.*, 2014).

A recent scoping process with Norwegian managers and scientists addressed how to improve fisheries management in light of EBFM and recent ecosystem changes (Huse *et al.*, 2018). It was concluded that three criteria should be fulfilled before single species models used for tactical decisions on harvest levels were to be replaced with extended single species models, explicitly including impacting processes, or with multispecies models (Huse *et al.*, 2018). First, there needs to be a strong impact, from either changing environment or changing species interactions, so that increasing uncertainties with increasing number of parameters with associated errors are counteracted by decreasing process errors. Second, the interaction needs to be monitored, quantifiable and predictable, as fisheries quotas are given for the year ahead based on short-term predictions of stock development. Third, in case of interactions between commercially important stocks, there must be an agreement between stakeholders on objectives, and how to trade off quotas to optimize, e.g. yield in biomass or economic terms, influencing the sharing of catches and economic values among nations, fleets, and their communities. Due to these constraints, it was anticipated that single-species assessments will form the core of the tactical, year to year management advice on quotas in the foreseeable future (Huse *et al.*, 2018), and that extended single species models and multispecies models will be limited to a few, economically and ecologically dominant species. In the Barents Sea, such approaches are already implemented for cod, haddock, and capelin (Skern-Mauritzen *et al.*, 2016; ICES, 2017a), but was regarded as relevant also for herring, shrimp, and redfish, as these species are important prey for the large cod stock (Huse *et al.*, 2018). Such approaches require extensive monitoring to track changes in both stock specific population parameters, distributions and trophic interactions (e.g. diet, distribution overlap) to reduce parameter uncertainties to acceptable levels.

A consequence of EBFM is an increased focus on sustainable management of commercially less important, typically data limited, stocks (Hobday *et al.*, 2011; Carruthers *et al.*, 2014), also in the Barents Sea (Gullestad *et al.*, 2017). This broadening of focus has prompted the development of a suite of methods for estimating overfishing thresholds and setting catch limits for stocks typically lacking adequate catch and survey data used to estimate abundance and catch limits using conventional stock assessment methods (Costello *et al.*, 2012; Carruthers *et al.*, 2014; Gullestad *et al.*, 2017). Depending on data limitations, these approaches may rely heavily on borrowing parameters from the scientific literature on similar stocks in the same or in other systems, assembly rules from meta-analyses and comparative studies demonstrating how, e.g. natural mortality and growth covary, so knowing one gives you the other (Carruthers *et al.*, 2014). While such practices introduce uncertainties and biases in stock assessments, these can be improved by statistically modelled life-history parameters (Thorson *et al.*, 2012; Carruthers *et al.*, 2014; Thorson *et al.*, 2017), or using super-ensemble modelling techniques (Rosenberg *et al.*, 2017).

Nevertheless, applying these data-limited approaches for stocks in the Barents Sea are challenged by the fact that climate warming may significantly alter species' traits affecting stock productivity (fecundity, recruitment, growth, and natural mortality), either directly as a response to increasing temperatures and associated changes in water chemistry, or indirectly through changing ecosystem interactions (Pörtner *et al.*, 2001; Roessig *et al.*, 2004; Kjesbu *et al.*, 2014; Koenigstein *et al.*, 2017). Collecting empirical data to estimate these parameters over time is costly and time consuming, and will not realistically cover all harvested species. The cost of monitoring the commercial species must be somewhat scaled to the benefits of harvesting. In Norwegian waters the data limited species number around sixty species, accounting for around 10% of the first-hand value from fisheries (Gullestad *et al.*, 2017). However, information on species traits are increasingly used in qualitative assessments of species vulnerability and responses to drivers of change, such as climate or fisheries (Hobday *et al.*, 2011; Hare *et al.*, 2016, Figure 1). For instance, Hare *et al.* (2016) performed a climate vulnerability assessment of harvested marine species in the US, by combining metrics of climate exposure (e.g. magnitude of expected climate change in area) with traits related to species sensitivity attributes indicative of an ability or inability of a species to respond to environmental change (e.g. prey specificity, habitat specificity, sensitivity to temperature, mobility). Such vulnerability assessments, typically wide in scope (i.e. in number of species, Figure 1), fill the need for broad, transparent, and relatively quick evaluations species vulnerabilities. They can guide monitoring and research effort to focus on the most vulnerable species (Hare *et al.*, 2016). They can also guide the borrowing of trait parameters across geographic or temporal scales for assessing stock status; a species experiencing high climate exposure and/or have high sensitivity to climate change calls for greater care in testing sensitivity to uncertainty and bias in input parameters.

While no formal vulnerability assessment has yet been performed for the Barents Sea species, recent findings support that species responses to climate impact is indeed related to the sensitivity attributes selected by Hare *et al.* (2016). The boreal species in the Barents Sea currently expanding in distributions and increasing in abundance, including cod and haddock, are typically large-bodied generalists with high mobility, which gives them flexibility in utilizing a changing environment (Wiedmann *et al.*, 2014a, b; Frainer *et al.*, 2017). The Arctic species, however, currently contracting and declining, are typically small bodied, sedentary and bottom-dwelling specialists, with limited flexibility and therefore high vulnerability to change. In addition, they are likely exposed to both competition and predation by the larger, immigrating generalists (Wiedmann *et al.*, 2014a, b; Fossheim *et al.*, 2015; Frainer *et al.*, 2017).

Typically, such vulnerability assessments have focused on exposure and vulnerability to either fisheries (Hobday *et al.*, 2011) or climate (Hare *et al.*, 2016). However, for the Barents Sea they could easily be extended to assess vulnerability to combined impacts of climate and fisheries, of both target and non-target species and habitats, to further support prioritization of science and monitoring required for supporting fisheries management decisions in a changing climate (Figure 1).

Harvesting strategies and harvest control rules

Recent changes in northern high latitude systems has indeed strengthened the focus on seeing fish stocks and fisheries in an ecosystem context also on a more strategic level (Skaret *et al.*, 2015;

Duffy-Anderson *et al.*, 2017). In the Barents Sea, the large and expanding cod stock may have adverse and unwanted effects on other species in the system. Cod is the dominant predator in this system, in terms of biomass consumed (Bogstad *et al.*, 2000). Increased cod predation has been linked to a recent capelin stock collapse, and the decline in Arctic fish species (Fossheim *et al.*, 2015; ICES, 2016; Frainer *et al.*, 2017). Also, cod may negatively impact marine mammals through competition (Bogstad *et al.*, 2015). Due to these negative impacts, it was agreed in the Joint Russian Norwegian Fisheries Commission in 2016 to implement a two-step HCR, with higher fishing rates at high cod abundances than at intermediate abundances (ICES, 2017b). Similarly, such wider ecosystem considerations are central in the proposed Norwegian management plan for *Calanus finmarchicus*, in response to a recently developing harvest of that species (Anon, 2017). The Norwecom end-to-end model (Utne *et al.*, 2012) was used to estimate *C. finmarchicus* biomass, production and how much of the production was channeled up the food web (Anon, 2017). Based on these quantifications, the proposed catch limit was set to 10% of the standing biomass. However, the proposed quotas were set *ad hoc* to 10% of the catch limit, thus 1% of the standing biomass, attempting a precautionary approach by recognizing both the key role of *C. finmarchichus* in the food webs and buffering against uncertainties in model estimates.

Common to the above examples, are management decisions at strategic levels taking multispecies and ecosystem considerations into account, informed by both empirical studies and multispecies and ecosystem models (Figure 1). The high precision required for quantifying species interactions to trade off quotas between interacting species for year-to-year tactical decisions is somewhat relaxed, and the implemented harvesting strategy buffer against the uncertainties in the model systems applied (Anon, 2017). These examples provide pragmatic evolutions of single species approaches in an EBFM, where single species assessment models for tactical decisions are increasingly rooted in harvesting strategies placed in multispecies and ecosystem contexts. In the Norwegian scoping process, it was agreed that testing harvesting strategies and HCRs in multispecies and ecosystem models was particularly important when initiating or escalating harvesting on species with (potentially) key functions in the ecosystem, such as zooplankton and mesopelagic organisms, and to assess the overall system vulnerabilities and risks associated with cumulative impacts of fisheries removal, recognizing that managing interacting fish stocks individually to maximum sustainable yield (MSY) may result in ecosystem overfishing (Bundy *et al.*, 2012; Link, 2017; Huse *et al.*, 2018). It is critically important that these harvesting strategies are also tested across climate change scenarios, considering the large scaled changes in system structure that has occurred already.

Of course, such approaches are challenged by increasing uncertainties with increasing model complexity and increasing projection time (Hawkins and Sutton, 2009; Lehuta *et al.*, 2016). Therefore, uncertainties in model projections should be thoroughly explored, relative to scenario uncertainty (reflecting the unknown future socio-economic landscape), model uncertainty (reflecting inaccuracies in the models), and internal variability (variability within the system with no systematic forcing, Hawkins and Sutton, 2009). Furthermore, additional levels of vetting, and further development of approaches for skill assessments of the more complex models are required, in particular for comprehensive models with long run times preventing sensitivity testing across larger proportions of input parameters (Kaplan and Marshall, 2016; Lehuta *et al.*, 2016; Olsen *et al.*, 2016a). Multimodel approaches can provide strength to model predictions, if results across models of different complexities or different process formulations are pointing in the same direction. For the Barents Sea system both multispecies and whole ecosystem models are available (Blanchard *et al.*, 2002; Utne *et al.*, 2012; Howell and Filin, 2014; Hansen *et al.*, 2016), as are downscaled decadal climate predictions and climate projections (Sandø *et al.*, 2014; Årthun *et al.*, 2017), providing opportunities for coordinated efforts to test harvesting strategies across multiple species, taking indirect food web-mediated responses and different climate regimes into account. As these are data and computer intensive, and time consuming, approaches, the initial scoping among scientists and managers is crucial for prioritization among strategies to be tested, and to coordinate efforts across models on management relevant scenarios (Figure 1).

Finally, large uncertainties do not imply lack of relevance for management. While fisheries assessments and management traditionally rely on evaluations of the risk of population collapse under various fisheries harvest rates, other assessments, such as the IPCC (Intergovernmental Panel on Climate Change) assessments, rely on more broad definitions of risks as "the potential for consequences where something of value is at stake and where the outcome is uncertain" (IPCC, 2014). This definition intentionally spans quantitative and more holistic understandings of risk, applying to situations also where probabilities or consequences cannot be fully quantified. Advancing EBFM with harvesting strategies taking ecosystem interactions and climate impact into account, emphasizing the importance of complex interactions through space and time, implies both a broadened view on the risks to be assessed by fisheries management, and that uncertainties are fundamental to the decision making, rather than a reason for inaction or irrelevance (Pikitch *et al.*, 2004; Mach and Field, 2017). Also, increasing uncertainties put further challenges on the knowledge exchange between scientists, managers and other stakeholders, which should be met through collaborative and participatory processes (Reed *et al.*, 2014; Cvitanovic *et al.*, 2015).

Advancing EBM of the Barents Sea

Managers recognize an urgent need for a holistic EBM taking the rapid climate driven changes in the Barents Sea into account (von Quillfeldt, 2010). Fisheries, tourism, petroleum, and shipping increasingly compete for space (White *et al.*, 2012). All the human activities impact the Barents Sea ecosystem to some degree (Olsen *et al.*, 2007; von Quillfeldt, 2010), and can most efficiently be managed and necessary conservation measures taken when there is an understanding of the full range of management options, taking cumulative impacts and potential trade-offs into account (Levin *et al.*, 2009). It is also important to avoid false trade-offs and conflicts, and to identify win–win opportunities (Olsen *et al.*, 2007; White *et al.*, 2012; Lester *et al.*, 2013; Rassweiler *et al.*, 2012).

The Barents Sea management plan

The need for integrated management across sectors was early recognized in the Barents Sea, following both an international push for implementing EBM and a conflict of interest between petroleum and fishing industries (Olsen *et al.*, 2016b). As a result, the Norwegian Barents Sea management plan (BSMP) was

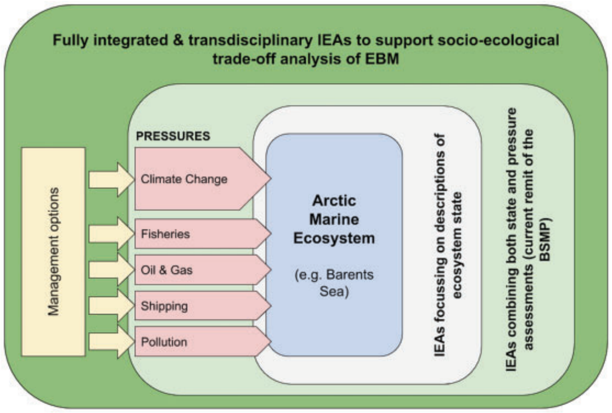

Figure 2. A conceptual figure of the Barents Sea, the main pressures, management actions and how integrated ecosystem assessments (IEA) can support integrated ecosystem-based management (EBM) and the Barents Sea management plan (BSMP) at different levels of complexities.

implemented in 2006, with the overall strategic objective to promote economic development within sustainable limits for the Norwegian sector (Figure 2, Olsen *et al.*, 2007, 2016b). The plan also aims to increase management responsiveness to ecosystem change, and facilitate coexistence between different users. A broad scoping phase from 2002 to 2006 involved a number of government directorates and institutions, as well as main stakeholders (main industries and environmental and economic NGOs), and included ecosystem status reports, assessments of socioeconomic aspects, identification of particularly valuable areas for ecosystem function, and impact assessments of both climate and the main operating sectors (petroleum, fisheries, and shipping, Figure 2). Among the final management outputs were a zoning plan for petroleum activities, and IMO sanctioned mandatory shipping lanes separating north and southbound ship traffic (Olsen *et al.*, 2007). The BSMP is followed up through annual assessments of indicators, triannual assessments of ecosystem state, and more comprehensive revisions every twelfth year. Updates and revisions are based on broader assessment of the ecosystem and human activities and impact. Furthermore, a Russian management plan for the Russian sector of the Barents sea is in development, in collaboration with Norwegians through the joint Norwegian-Russian Commission on Protection on the Environment.

Integrated assessment of the Barents Sea

To scientifically support the advancement of EBM in the Barents Sea, a joint Norwegian-Russian Working Group on Integrated Ecosystem Assessment for the Barents Sea (WGIBAR) was established in 2013 under ICES (International Council for the Exploration of the Seas; ICES, 2016). In essence, IEAs provide a scientific, transparent framework for combining data series across ecosystem components; summarizing the status and development of the ecosystem; revealing the impacting processes; screening and prioritizing potential risks; and finally evaluating alternative management strategies against a backdrop of environmental conditions (Levin *et al.*, 2009, Figure 1). ICES regards IEAs as a core framework to meet the challenge of integrated science and advice to support EBM of marine systems (ICES, 2013). ICES IEA Working Groups have been established for eight ecoregions, including the Arctic Ocean, Norwegian Sea, and the Barents Sea. Initially, the ICES IEA groups typically focused on compiling and implementing data across ecosystem components in quantitative analyses of changes in ecosystem state, and to identify the important drivers of change (Dickey-Collas, 2014, see Figure 2). In recent years, however, their focal areas have expanded to include more steps of the IEA cycle (DePiper *et al.*, 2017; ICES, 2017c, Figure 2).

Synergies between BSMP and IEA approaches

In the Barents Sea, there is a strong potential for synergies among both scientific and advisory processes to advance the EBM. The comprehensive BSMP scoping process, with high stakeholder involvement and defined management objectives for all main sectors (e.g. keeping fish stocks above sustainable levels, protecting vulnerable and threatened species and habitats, minimizing environmental risk of spills and pollution, von Quillfeldt, 2010), provide both a valuable starting point for the IEA as well as solid platform for cross sector collaboration among stakeholders and scientists. However, although recognizing an urgent need for taking the rapid climate driven changes into account (von Quillfeldt, 2010), the BSMP is criticized for not specifically addressing climate change impacts in objectives or in the selected indicators, and for lacking operational indicators to assess cumulative impacts and evaluate trade-offs among management objectives (van der Meeren *et al.*, 2015). Furthermore, much of the complexities regarding such trade-offs remains hidden in the BSMP process through a striving for consensus among sectors and stakeholders (see Figure 2, Knol, 2010; Olsen *et al.*, 2016b).

In contrast to the policy driven BSMP, the ICES IEA work is more dynamic and science driven, focusing on developing transdisciplinary scientific approaches to tackle each step of the IEA cycle, including the full breadth of trade-offs among objectives and sectors (DePiper *et al.*, 2017). Importantly, while the BSMP is Norwegian with a focus on the Norwegian sector only, the IEA work is international and based on a strong collaboration with Russia as a natural extension of joint work on fisheries research and management. Also, the IEA focus on the entire BS ecoregion. Within IEAs, ecosystem risk assessments (ERA) form a critical link between identifying pressures and impacts, and evaluating potential management strategies in terms of ecological risk and consequences for ecosystem services to human society (Levin *et al.*, 2009). Also ERAs build on the broader concept of risk, applying to both situations where risk can be represented as the probability of hazards occurring multiplied by the consequences that would result, but also where probabilities or consequences cannot be fully quantified.

A key to the ERAs is the inclusion of sequential steps on an increasingly quantitative scale of analyses, starting with an initial qualitative, rapid but comprehensive assessment based on expert judgements to a broad range of ecosystem components potentially at risk from a specific pressure (Level 1, Figure 1). Components identified potentially "at risk" in Level 1 are further considered in semi-quantitative (Level 2) assessments, including e.g. rank-based exposure-sensitivity analyses, such as the vulnerability assessments relative to fisheries (Hobday *et al.*, 2011) and climate (Hare *et al.*, 2016) already mentioned (Figure 1). Finally, components identified as medium to high risk in Level 2 are further evaluated using quantitative model-based approaches (Level 3 assessment). While the ERAs have typically focused on single pressures with no inclusion of indirect food web-mediated responses, Holsman *et al.* (2017) presented a conceptual roadmap for expanding the ERAs to include impacts of multiple pressures and food web-mediated responses. Moving up the quantitative and complexity scales (Figure 1) increases realism and the probability of identifying non-intuitive outcomes, but also increases uncertainties (Holsman *et al.*, 2017). No ERA is yet implemented as part of the BS IEA. However, bringing recently developed approaches into the Holsman *et al.* (2017) conceptual ERA framework, offer new opportunities bridging BSMP and IEA in assessing cumulative impacts on the Barents Sea ecosystem, and fill current gaps in the BSMP.

First, the BSMP scoping process, together with the longstanding cross sector collaboration among scientists and stakeholders, provide a solid platform for a cross sector expert opinion based Level 1 assessment, performed through participatory processes to (i) establish conceptual models linking diverse pressures to impacted ecosystem components and (ii) to flag potential high-risk cumulative impacts on species and interactions (Gray *et al.*, 2013; Robinson *et al.*, 2014; Holsman *et al.*, 2017). Second, semi-quantitative approaches relevant for Level 2 assessments, to assess not only vulnerability of ecosystem components to pressures, but also the vulnerability of food webs and ecosystem structure and function, are already established for the Barents Sea. These approaches include food web topologies and functional characterization of communities, based on species traits (Figure 1). Through extensive literature and data review, the Barents Sea food web was mapped from plankton to marine mammals, including 244 taxa and 1 589 trophic links (Planque *et al.*, 2014). Perturbing the food web components according to exposure to multiple pressures allows a qualitative assessment of impacts on structural system properties related to system vulnerability, such as connectivity, modularity and motifs, as well as on structurally important module connectors (Kortsch *et al.*, 2015). Also, trait matrices are constructed for marine mammals, seabirds, benthos, and zooplankton in ongoing research projects, in addition to fish (Wiedmann *et al.*, 2014a, b). Combining species distributions with species traits, community, and system vulnerability to pressures can be assessed using metrics of functional diversity, functional redundancy (i.e. overlap of traits among species) and changes in functional structures (Wiedmann *et al.*, 2014a, b). Also, conceptual models from scoping exercises can be translated into Qualitative Network Models (Melbourne-Thomas *et al.*, 2012). QNMs are mathematical models in which perturbations are assessed for their qualitative impact on the system (positive, neutral, or negative), and can identify compensatory ecosystem dynamics and non-intuitive outcomes of cumulative impacts and management actions (DePiper *et al.*, 2017). Hence, these approaches qualitatively and semi-quantitatively integrate single species sensitivities through to emerging properties of food webs affecting whole system vulnerability and systemic risk to pressures. Importantly, these approaches thus provide relatively simple opportunities for assessing vulnerabilities of food webs and system structure and function to determine the most risky cumulative impacts that should be assessed in quantitative assessments (e.g. Level 3, Fig. 1).

A number of numerical models are implemented for the Barents Sea, including multispecies models (Howell and Filin, 2014) and spatially explicit and non-spatial end-to-end ecosystem models (Blanchard *et al.*, 2002; Utne *et al.*, 2012; Hansen *et al.*, 2016), all relevant tools for quantitative risk assessment (Level 3) by (i) running scenarios with impacts from climate predictions or projections and multiple pressures acting on multiple ecosystem components, to quantify direct and indirect food web-mediated effects on species, communities, and system and (ii) to test responses to management strategies (Fulton *et al.*, 2007, 2014; Carroll *et al.*, 2018; Fu *et al.*, 2018; Olsen *et al.*, 2018). Also, statistical modelling approaches, applicable to the univariate and multivariate spatially resolved time series typically used in the IEAs (ICES, 2017c) to understand, track and predict ecosystem responses across components (e.g. species, communities, trophic levels) to selected pressures are available (Planque and Arneberg, 2017 and references therein). As already discussed in relation to testing fisheries management strategies, such quantitative assessments are data and computer intensive, time consuming approaches, and hence cannot and should not be used to test impacts of "all" pressures on "all" components. Hence, a key to the Level 3 quantitative risk assessment is a focus on only the most risky impacts, as identified in Levels 1 and 2 assessments (Fig. 1).

Of course, the current knowledge, model and data availability may not suffice to quantify all potentially high risk impacts on the Barents Sea system, thus requiring iterations as new data and new knowledge becomes available. Also, the same issues regarding uncertainties as discussed above in relation to using complex models to test harvesting strategies applies here. Nevertheless, qualitative, semi-quantitative, and quantitative approaches are already available for the Barents Sea, and combined in a unifying ERA framework the use of these approaches is likely to significantly advance our abilities to tackle a main challenge under EBM; to assess direct and indirect, food web-mediated effects of multiple pressures, and provide guidance on management options (Figures 1 and 2, Rudd, 2014; Holsman *et al.*, 2017). It does entail a coordinated effort among managers and scientists across institutes, and across departments within institutes, in a joint focus on prioritized pressures and impacts. Such coordinated effort is indeed surmountable, but requires funding of larger projects (e.g. two to three times) than typically funded by the Norwegian Research Council (∼1 million Euro). However, fewer, but larger, coordinated efforts may be required to tackle the complexities in providing scientific support to advance EBM.

Concluding remarks

In this paper, we have pointed to recent development of pragmatic, scientific approaches that we believe can significantly advance EBFM and EBM in the Barents Sea. We propose coordinated efforts across these approaches to bring single species assessments and harvesting strategies into an ecosystem context to advance EBFM, as well as for assessing cumulative impacts across pressures and sectors, and associated management options, to advance EBM. While these approaches will not solve all challenges related to EBFM and EBM, they allow for a more efficient, consistent, and comprehensive consideration of relevant factors, such as, e.g. impacts of climate warming and increasing human activities, in the management of fisheries or any other sector. Hence, we anticipate that developing science for advice to EBFM and EBM in the Barents Sea is more about adding tools to the toolbox, rather than replacing tools.

These approaches, mostly already in place for the Barents Sea, range from relatively quick qualitative to more comprehensive quantitative assessments, targeting both single species, community and system level attributes in assessing impacts, vulnerabilities and risks, supporting species and system level management objectives (Figure 1). The reliance on qualitative and semi-quantitative approaches, typically developed to handle data poor situations, to advance EBFM and EBM in one of the worlds most monitored marine ecosystems may seem like a paradox, implying a failure of the Barents Sea monitoring program. However, providing monitoring and science for quantifying "all" processes and impacts is not a realistic goal of EBFM and EBM, as repeatedly argued by EBFM/EBM critics (Patrick and Link, 2015). For instance, to provide analytical stock assessments requires intensive monitoring specifically designed to the target stocks, e.g. to estimate age-specific abundance indices and catch at age. Such monitoring data cannot realistically cover the around 80 species harvested in Norwegian waters. The current monitoring program in the Barents Sea provide data for quantitative, analytical assessments for 8 fish stocks dominating ecologically and economically, but in addition provide information on distributions and relative abundances of zooplankton, benthos, fish, mammals, and seabirds, trophic interactions between selected key species, as well as data on pressures related to fisheries and ocean climate (Eriksen *et al*., 2018). Hence, the current monitoring program provides a solid platform for developing multispecies and ecosystem models, but also for the qualitative and semi-quantitative assessment approaches. Therefore, the comprehensive monitoring increases the value and reliability of these approaches as screening and prioritization tools for more quantitative species and system level assessments, and for identifying critical species and processes for more targeted monitoring.

Finally, central to the advancement of EBFM ad EBM is to scientifically handle and communicate increasing uncertainties associated with changing environment, limited data and increasing model complexities, but also to acknowledge that such uncertainties are fundamental to decision making in EBFM and EBM. Collaborative and participatory processes among managers and scientists are pivotal for both scoping and prioritizing, and for efficient knowledge exchange of complex scientific results and uncertainties underlying management advice.

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