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Multidisciplinary perspectives on living marine resources in the Arctic

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Abstract

Many areas in the Arctic are vulnerable to the impacts of climate change. We observe large-scale effects on physical, biological, economic and social parameters, including ice cover, species distributions, economic activity and regional governance frameworks. Arctic living marine resources are affected in various ways. A holistic understanding of these effects requires a multidisciplinary enterprise. We synthesize relevant research, from oceanography and ecology, via economics, to political science and international law. We find that multidisciplinary research can enhance our understanding and promote new questions and issues relating to impacts and outcomes of climate change in the Arctic. Such issues include recent insights on changing spawning migrations of the North-east Arctic cod stock that necessitates revisions of socioeconomic estimates of ecosystem wealth in the Barents Sea, better integrated prediction systems that require increased cooperation between experts on climate prediction and ecosystem modelling, and institutional complexities of Arctic governance that require enhanced coordination.

Keywords

Atlantic cod; climate change; fisheries management; international cooperation; research challenges; scientific collaboration

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Abbreviations

EEZ: exclusive economic zone
ICES: International Council for the Exploration of the Sea
UNCLOS: United Nations Convention on the Law of the Sea
UNFSA: United Nations Fish Stocks Agreement

Introduction

Anthropogenic climate change drives alterations to ocean physics, ecosystems and economies (IPCC 2014, 2019), manifested in the Arctic by, for example, reduced ice cover, ocean warming (Pavlov et al. 2013; Ivanov et al. 2016; Hordoir et al. 2022) and the borealization (Pinsky et al. 2013; Fossheim et al. 2015; Polyakov et al. 2020) of marine ecosystems. As predicted by the *Arctic climate impact assessment* (ACIA 2005), these developments bring a potential for increased economic activity in tourism, fisheries, marine transportation, mineral exploration and exploitation, and petroleum-related activities (Hoel 2009; Bekkers et al. 2018). These potentials are already being realized in the sub-Arctic, including with respect to port development, exploration for oil and gas and cruise tourism (Kaiser et al. 2016; Hoel 2018; Kaiser, Kourantidou, Vestergaard et al. 2018; Pahl & Kaiser 2018; Stocker 2019). Development, however, raises questions regarding the capacity of governance systems to address changes in human activities and to ensure sustainable development. The scale and complexity of the climate-driven changes are unprecedented and represent a major challenge to the scientific community's ability to grasp and understand the totality of their impacts (Díaz et al. 2019). More knowledge of the Arctic environment and human activity is required to increase our understanding of management needs in different parts in the Arctic (Snoeijs-Leijonmalm et al. 2020).

The purpose of this study is to present the status of knowledge of climate change and impacts on living marine resources in the Arctic, and we present the main findings from recent research by a multidisciplinary research group with expertise on the natural environment, governance, and fisheries economics and management. First, we consider the different academic perspectives represented in our group, which emerged from the research project Arctic Marine Resources under Climate Change: Environmental, Socio-Economic Perspectives and Governance (ARC-Change). We then bring these perspectives together in analysing the management of North-east Arctic cod (*Gadus morhua*), a stock of major importance in Arctic fisheries. In a multidisciplinary context, we have studied Arctic marine resources and their

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management under climate change. Here, we present a synthesis of our research whilst also placing it in the context of the wider literature. In the next section, we discuss some issues of multi- and interdisciplinary research and our approach to summarize research findings and emerging challenges. The subsequent sections discuss recent research from the different disciplinary areas. We then focus on North-east Arctic cod and findings and challenges that emerge from our multidisciplinary scope. To conclude our research synthesis, we discuss some emerging perspectives of increasing importance for research on Arctic marine resources under climate change. These include improved predictive powers for environmental and resource conditions; new and improved observation technologies and more and readily accessible data; the impact of technological change on fisheries, aquaculture and other industries; and the importance of promoting multidisciplinary perspectives on Arctic marine resources, their management and utilization.

A range of factors leave many Arctic marine ecosystems poorly understood, including limited accessibility and low commercial and other activities. Rapid ongoing climate change as well as increased sensitivity to, and impacts of, resulting environmental changes challenge current knowledge and understanding of the Arctic system. Uncertainty of climatic effects is, therefore, potentially larger than at lower latitudes (Vestergaard 2018). At the same time, some Arctic ecosystems are amongst the best researched worldwide, for example, the Barents Sea (Eriksen et al. 2018). No single scientific discipline can provide a comprehensive understanding of the impacts that Arctic climate change has and is likely to bring in the future. Furthermore, isolation of the relative impact of different drivers is difficult or, in some cases, impossible (ACIA 2005) and requires consideration of multiple perspectives.

A disclaimer: the scientific literature on climate change in the Arctic is vast and rapidly developing. A complete or fully representative overview is beyond our scope and ambition. The selected citations are, therefore, contingent on our research. We do not discuss issues of marine pollution or evolutionary responses (Heino et al. 2015), both topics of importance for sustainable use of Artic marine resources. Neither do we consider issues related to indigenous populations or the increased potential for Arctic shipping or tourism. Authoritative and fairly comprehensive reviews of climate change in the Arctic and beyond are published by the Intergovernmental Panel on Climate Change and the Arctic Monitoring and Assessment Program.

Methodology

Climate change gives rise to complex problems for research and governance that require scientific pluralism (Hazard et al. 2020). Researchers trained in different disciplines may use and comprehend terminologies differently and have different academic work modes and requirements. These differences are generally not widely articulated, and our collaboration shows they are not insurmountable (although work modes differ, say, between field and office work). Nevertheless, multidisciplinary teams such as ours, dealing with complex climate change problems, encounter uncertainty and ambiguity that arise from disciplinary diversity. Research may aim to reveal universal laws of a phenomenon or foster agency that supports stakeholders' ability to take appropriate action (Hazard et al. 2020), and the tension between these objectives is latent in our work.

Our work has brought together insights from oceanography, marine biology, economics, political science and international law. We have pursued an eclectic selection of topics, ranging from the impact of sea ice on maritime activity and climate change effects on spawning conditions for North-east Arctic cod, to fisheries productivity and Barents Sea ecosystem wealth, to international fisheries agreements and the ocean governance regime in the Arctic. This research brought together scholars from different disciplines but with a common interest in and—as the research has progressed—a common understanding of challenges and opportunities regarding climate change and fisheries in the Arctic. Some of our work concerns ecosystem-based fisheries management, and in that regard, Macher et al. (2021) observe difficulties related to scientific collaboration. Some pertinent difficulties are the mismatch between the pace of research and short-term political agendas, inconsistencies between science and management needs, and facilitation of knowledge integration between scientific fields.

To highlight some of these perspectives, we focus on the North-east Arctic cod and present a systematic tabular overview of related research and research challenges. The Barents Sea and the North-east Arctic cod—which sustains the largest cod fishery in the world—are pivotal subjects in our research and serve as relevant examples of how research agendas from different academic disciplines are connected to each other and benefit from multidisciplinary perspectives. We find it useful to organize both our table on North-east Arctic cod-related research and our exposition according to major research areas. Scholars, as well as research and educational institutions, remain oriented along traditional subject fields, and research questions and challenges are rooted in this structure. These questions and challenges take on a deeper significance as they are influenced by demands and insights from other research areas and from the applied context. Furthermore, there are topics and challenges that can only be understood as interdisciplinary exercises

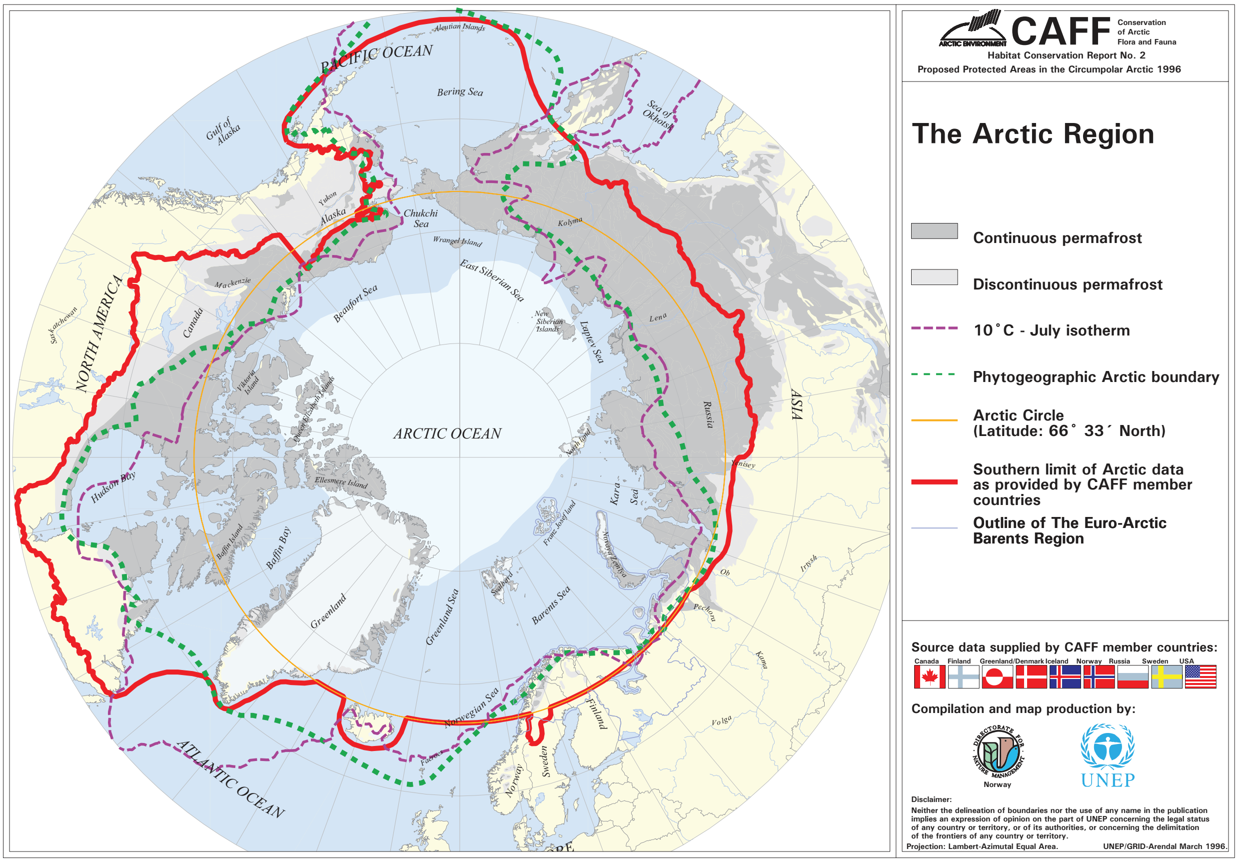

Fig. 1. The Arctic. (Figure downloaded at https://abds.is on 12 September 2022, used with permission of Conservation of Arctic Flora and Fauna.)

and that must be handled as different perspectives converge on these topics and challenges. Our tabular overview is extended with examples of such ongoing research and with related challenges.

The natural environment

In the context of our study, "the Arctic" is used in a wide sense, encompassing also sub-Arctic areas (Fig. 1), in line with the definition used by the Arctic Monitoring and Assessment Programme, a working group under the Arctic Council. Including the sub-Arctic seas provides a more comprehensive understanding of human activity in the Arctic, as well as of the connectivity between the sub-Arctic seas and the Arctic Ocean proper.

Physics

Conditions vary considerably from region to region in the Arctic. In the European Arctic, ocean temperatures are relatively high because of the influence of the Atlantic Water inflow (Ivanov et al. 2016; Renner et al. 2018; Polyakov et al. 2020). The varying strength and extent of the cold and fresh sub-polar gyre in the North Atlantic have strong impacts on the marine ecosystem on inter-annual to decadal time scales (Hátún et al. 2005; Hátún et al. 2009). The corresponding sea-surface temperature anomalies, propagating from the North Atlantic along the Norwegian coast and further into the Barents Sea, influence the abundance of important resources such as the North-east Arctic cod stock (Årthun et al. 2018) on multi-year time scales.

Increased levels of CO_2 and resulting climate change affect the natural environment in the Arctic in many ways, including increased ocean temperature, reductions in sea-ice cover and thickness, ocean acidification and changing salinity (AMAP 2018). Sea-level rise, a key consequence of climate change in other parts of the world, is of less consequence for Arctic marine resources but may affect societies, particularly indigenous communities. Changes in the physical environment are particularly pronounced in the inflow regions of Atlantic Water, that is, the Barents Sea, Fram Strait and areas north of Svalbard (Onarheim et al. 2014; Sandø et al. 2014; Renner et al. 2018) but are present all over the Arctic. Ocean temperatures measured along the Norwegian coast have been rising for more than three decades, and surface air and sea-surface temperatures in the Arctic Ocean increase at twice the global rate (Hansen et al. 2006; Skagseth et al. 2015; Overland et al. 2017). The environment that was once dominated by multi-year sea ice is now dominated by first-year sea ice (AMAP 2017 and references therein). Predictions are that the central Arctic Ocean will be ice-free in summers well before the end of this century (IPCC 2019), likely at least once by 2050 (IPCC 2021). Furthermore, surface measurements from Iceland and the Norwegian Sea suggest that ocean water in the Arctic is becoming more acidic (AMAP 2018).

Two recent studies of heat transfer from the Atlantic, impacts on sea ice and the role of wind found complex relationships between water layers, ocean currents and wind forcing that are determining ice concentrations (Renner et al. 2018; Lundesgaard et al. 2021). In particular, an existing ice cover isolates the cold and fresh surface layer from the warm Atlantic Water and reduces the heat exchange between ocean and atmosphere. The results further suggest accelerating feedbacks between reduced ice cover and lack of ice formation in the winter. The latter point is in line with findings from the Laptev Sea and adds to accumulating evidence that the Arctic Ocean becomes more similar to the Atlantic in terms of temperature and other parameters (Polyakov et al. 2017; Ingvaldsen et al. 2021).

Changes to the physical environment in turn affect biology at all ecosystem levels. For example, increased ocean temperatures and improved light conditions from less and thinner sea ice change the basis for primary production (Mundy et al. 2009; AMAP 2017), and various studies find increased plankton blooms and primary production (Dalpadado et al. 2014; Overland et al. 2017; Sandø et al. 2021). Dalpadado et al. (2014) suggest that the increased primary production in the Barents Sea is an ecosystem response to climate change and find significant linkages to fish biomass, indicating bottom-up trophic interactions. Also, temperature is a key limiting factor for the spatial distribution of fish stocks (Hollowed et al. 2013). Several Arctic marine mammals depend on sea ice for survival and reproduction. Ocean acidification can negatively impact calcifying species such as crustaceans, while seagrasses and certain phytoplankton species may benefit. However, how acidification will impact food webs, and ecosystems is yet largely unknown (AMAP 2018).

Biology

Melting sea ice and northward shifts of warm water inflows will create new regions potentially suitable for plankton, fish and marine mammals (Hollowed et al. 2013; Fossheim et al. 2015). Likely biological adaptations include changes in habitat and distribution and changes to migration patterns. The already observed widening of the marginal ice zone (Strong & Rigor 2013), with lower ice concentrations at higher latitudes, may open up new regions for commercial fishing in the future. However, whilst water temperature is considered to be a significant environmental factor to limit the spatial distribution of fish stocks (Ingvaldsen & Gjøsæter 2013; Haug et al. 2017), several additional factors, such as zooplankton abundance, bottom topography, spawning conditions and distribution of other stocks, are important as well. How plankton abundance and species composition will evolve in response to change in oceanographic conditions raise complex questions (Planque et al. 2011), but a northward shift across trophic levels seems clear (Cheung et al. 2010; Fossheim et al. 2015; see also Karp et al. 2019; Link et al. 2020 and references in these).

Observations over the last decades show that both North-east Arctic cod and capelin (*Mallotus villosus*) have expanded their distribution limits north- and eastwards in the Barents Sea (Michalsen et al. 2013; Kjesbu et al. 2014; Ingvaldsen et al. 2015). This habitat expansion is strongly correlated with oceanographic changes (Eriksen et al. 2018; Fall et al. 2018). Recent evidence also suggests that cod migrates westward across Fram Strait, but the observations encompass only few individual fish (Gjøsæter et al. 2020) and are not connected to environmental changes. Cod spawning areas may be affected as well (Sundby & Nakken 2008; Sandø et al. 2020). Eriksen et al. (2017) found significant increases of pelagic biomass in the Barents Sea, correlated with increasing temperatures and primary production.

Atlantic mackerel (*Scomber scombrus*) in the North Atlantic is another species that recently has expanded its distribution. In recent years, it has been observed as far north as Svalbard and off eastern Greenland in the west (Stiansen et al. 2018), whilst fisheries are located at lower latitudes. Warmer waters are partly the reason for the mackerel expansion (Bruge et al. 2016). Increased abundance of mackerel in the Norwegian Sea affects access to food for other fish stocks, and thereby their abundance and fisheries (Huse et al. 2012). The presence of mackerel in new areas, and its effect on other stocks, deepens conflict of interest between different segments of fishing fleets as well as between traditional and new coastal states (Bjørndal & Ekerhovd 2014; Ekerhovd & Steinshamn 2016; Stiansen et al. 2018).

Red king (*Paralithodes camtschaticus*) and snow crabs (*Chionoecetes opilio*) are relatively new species in the Barents Sea. Both are of substantial commercial importance (Sundet & Hoel 2016; Kaiser, Kourantidou & Fernandez 2018). Red king crabs were introduced by humans, whilst snow crabs seem to have expanded their range naturally along the coast of Siberia and westward to the Barents Sea. This habitat expansion may have been rendered possible by environmental change. According to Roberts (2012: 193), invasive species are "one of the five horsemen of the apocalyptic loss of biodiversity that is sweeping the planet" but are often a neglected issue, perhaps particularly at sea. Distribution shifts or expansion, for any species, may impact stock size estimates, reference points and, ultimately, management advice (Szuwalski & Hollowed 2016). Unobserved or uncertain changes may escalate through a chain of impacts. Invasive species increase ecological uncertainty but can also have commercial value and bring conflicting interests over areas or jurisdictions.

Anticipating changes in environment or ecology requires forecasts that in most management contexts are unavailable. Uncertainty in the scientific basis for management advice induced by environmental change may erode the confidence that stakeholders may have in managers, which may limit the use of more accurate advice that, however, has a higher uncertainty (Karp et al. 2019).

Compared to changes in foraging areas, the location of spawning areas and the migration patterns between spawning, feeding and wintering areas may be more resistant to change, as Hop & Gjøsæter (2013) conclude for polar cod (*Boreogadus saida*) and capelin in the Barents Sea. However, if a persistent, significant rise in temperatures forces a species to abandon its spawning area and migration pattern, its continued existence would depend on whether it could establish new spawning, nursery, feeding and wintering areas in cooler waters. Such changes would depend on a range of factors, such as topographic and hydrographic features, presence of prey, water mass dynamics such as water column stratification and ocean currents, and, for bottom-spawning species such as capelin, a suitable bottom substrate (Hollowed et al. 2013). Whether a change implies an expansion of the species distribution area or displacement into a new area will depend on the temperature tolerance of a given species. The total effect on commercial fish stock abundance from climate changes may be positive for some fish stocks and negative for others. Hollowed et al. (2013) identify six species that may expand their habitat into the High Arctic under certain conditions, and Kjesbu et al. (2022) concluded that most of the assessed fishery resources in the North-east Atlantic will respond positively to climate change, contrary to prevailing fisheries forecasts elsewhere.

A fish stock of particular interest that has shown temperature sensitivity in distribution and recruitment is the North-east Arctic cod (Hare et al. 2010). It is the largest cod stock in the world today and potentially the most valuable whitefish fishery in the world (Diekert & Schweder 2017). The stock has been large for the last 10 years, and, as mentioned, its distribution on the feeding grounds in the Barents Sea has expanded with warming and sea-ice retreat. In a recent study, Sandø et al. (2020) question whether spawning sites in Lofoten, in northern Norway, and nearby areas will become less ideal in terms of physical properties as warming continues, and they discuss what areas will have ideal spawning conditions in the future; see also early discussions by Drinkwater (2005) and Sundby & Nakken (2008). To answer these questions, Sandø et al. (2020) use a downscaled climate model under the moderate RCP4.5 scenario, in which emissions of climate gases are described to peak around 2040, decline and thereafter stabilize at an increased radiative forcing of 4.5 W/m^2 in 2100 relative to preindustrial time. They compare hydrographic projections (water temperature, salinity) to observed spawning site levels. They find that in 50 years from now, the hydrographic conditions at southern locations may no longer be suitable for spawning. New ideal water masses are rather found further north and east.

Whether ocean warming is detrimental to the general health of the North-east Arctic cod population is a different question. Records of a rich cod fishery off Svalbard during the warm 1930s (see Roberts 2012: 87), for example, and the identification of potential habitats at the north-east Greenland Shelf (Strand et al. 2017), suggest that cod may redistribute and thrive. Improved conditions for primary production may be beneficial but depends on a string of food-web interactions. Kjesbu et al. (2014) find that higher temperatures have increased the feeding area for cod in the Barents Sea, which, together with reduced fishing pressure, have resulted in a larger population size. The overall, long-term effect of ocean warming, however, is largely an open question, for cod but also for other populations (Haug et al. 2017).

The stock-recruitment relationship is fundamental to modern fisheries management but is fraught with problems of predictability. Recruitment dynamics depend on a host of factors that vary between stocks and over time. Zimmermann et al. (2019) question whether there are common trends in the recruitment dynamics of North-east Atlantic fish stocks and suggest that a broader scope of investigations, in terms of environmental factors, trophic interactions, and time-lag effects, may improve understanding and predictability. Whilst the overall results are mixed, their identification of shared, synchronous trends in recruitment and stocks may benefit integrated assessment and management of many fish stocks. Munch et al. (2018) established similar findings with regard to time lags in a global meta-analysis, whilst Årthun et al. (2018) achieved highly skillful climate-based, long-term predictions of the Barents Sea cod stock. These studies are just some recent contributions to efforts to incorporate broader environmental and ecological observations, with new ways of dealing with large datasets, in ecosystem-based fisheries management.

Governance

Jurisdictional issues in the Arctic are largely settled, and most of the Arctic Ocean is under the jurisdiction of its five coastal states. Competing economic and political interests and security-related and legal disputes, however, are latent (Bertelsen 2018; Wegge 2020).

Over the last decades, global efforts to develop the governance framework for fisheries have resulted in a number of new instruments (Hoel & VanderZwaag 2014). The 1982 UNCLOS—known as the "Constitution of the Oceans"—provides the basic legal framework for all uses of the global oceans (Churchill & Lowe 1989). UNCLOS requires other international agreements to be in conformity with it. A critically important aspect of UNCLOS is the establishment of 200-nautical-mile EEZs, where coastal states have jurisdiction, or sovereign rights, over the natural resources. In the high seas area beyond the EEZs, UNCLOS provides that flag states are responsible for the activities of the vessels flying their flag. The 1995 UNFSA is an implementing agreement to UNCLOS. It provides additional global and more precise rules for fisheries management on the high seas.

The global framework provided by UNCLOS and UNFSA applies in the Arctic Ocean in the same way as elsewhere. The coastal states have sovereign rights over the natural resources within their EEZs, and therefore decide on their management. Generally, living marine resources are to be managed sustainably, aiming for maximum sustainable yield, based on the best available scientific evidence, and be utilized in an optimal manner (Hoel 2017b). Where resources are transboundary, the relevant states are to cooperate in their management (Hoel & VanderZwaag 2014; Hoel 2018). The coastal states in the Arctic have all established 200-mile zones, and most of the Arctic Ocean as well as the sub-Arctic seas, including continental shelves, are under the jurisdiction of coastal states. Almost all bilateral maritime boundaries in the Arctic are settled, formally or de facto. The only significant remaining boundary not yet negotiated is between Canada and the USA in the Beaufort Sea. As regards delimitation of outer limits of continental shelves, Norway is the only Arctic country with its outer limits recommended by the UN Commission on the Limits of the Continental Shelf, with pending claims from Canada, Russia and Denmark/Greenland.

In the high seas beyond the EEZs, UNCLOS requires states to establish regional fisheries management organizations or other arrangements for fisheries management. These provisions are expanded upon and strengthened in UNFSA. Changing transboundary distributions and migrations of fish between EEZs or EEZs and the high seas may bring governance challenges beyond assessment-related issues (Pinsky et al. 2018; Rayfuse 2018). Failure to agree on allocation of straddling fish stocks is a major reason why lasting agreements on management can be difficult to reach, as seen with pelagic species in the North-east Atlantic in recent years (Bjørndal & Ekerhovd 2014; Toumasatos & Steinshamn 2018). There are, however, rules in UNCLOS and UNFSA delineating the principles for allocation of resources in such situations (Henriksen & Hoel 2011). Rayfuse (2018) points out that stocks that migrate into high seas areas may have less conservation value for coastal states, and stocks shifting distribution across maritime zones may, therefore, in the absence of agreements on management, face increased fishing pressure.

After UNCLOS and UNFSA entered into force, the global fisheries management landscape has undergone vast changes, with widespread adoption of the precautionary approach, establishment of new regional fisheries management organizations and arrangements (Løbach et al. 2020) and strengthened enforcement of fisheries regulations. Under the auspices of the United Nations Food and Agriculture Organization, a number of global fisheries instruments have been negotiated, relating to deep-sea fisheries, the ecosystem approach to fisheries, flag state performance and port state measures to combat illegal fishing, among other things. The result is a comprehensive global framework where the main problem now is failure to implement the existing rules and regulations by fishing nations.

UNCLOS also has rules regarding the management of continental shelf resources, the marine environment and marine science. Coastal states have sovereign rights to continental shelf resources, including sedentary living marine resources, also beyond 200 nautical miles where the continental shelf extends further from the coastal baseline. With respect to environmental protection, UNCLOS provisions are rather vague and do not go much beyond a general obligation to protect the environment. A special provision regarding ice-covered areas allows coastal states to take pollution-related measures against vessels operating in ice-covered areas in their EEZ. These provisions are of increasing importance as both cruise tourism (Dawson et al. 2014) and commercial shipping (Eguíluz et al. 2016) develop in the Arctic. As regards marine scientific research, UNCLOS states that scientific activity should be promoted.

The basis for governance of activities in the high seas has been strengthened over the last decade through a number of new international agreements, including the 2009 Port State Measures Agreement against Illegal, Unreported, and Unregulated Fishing (in force 2016). Also, coastal state and regional cooperation in combatting illegal, unreported and unregulated fishing has been stepped up. The Northeast Atlantic Fisheries Commission has a management mandate in its regulatory areas in the high seas portions of the Norwegian Sea, the Barents Sea and the European wedge of the central Arctic Ocean. In the Norwegian Sea, arrangements for the management of three pelagic species—mackerel, herring (*Clupea harengus*) and blue whiting (*Micromesistius poutassou*)—exist but are unstable, and the configuration of states actually cooperating on management is changing over time. For all three species, a high seas part of the stock in question is set aside for the Northeast Atlantic Fisheries Commission to manage. It has proved difficult to operationalize and implement the allocation rules in UNCLOS and UNFSA (Henriksen & Hoel 2011) for these straddling stocks, as a significant part of the fisheries occurs in the high seas, and the temptation to free ride on the conservation efforts of others is high.

Brexit has added the UK as a new coastal state in the North Atlantic, with ramifications for the existing bilateral and regional fisheries agreements. Toumasatos & Steinshamn (2018) found that Brexit might incentivize deviant behaviour and destabilize agreements over the mackerel fishery in the Nordic seas. The same logic likely applies to the herring and blue whiting fisheries.

The 2018 agreement to prevent unregulated fishing in the central Arctic Ocean amongst the five coastal states and five distant water fishing countries (including the EU) is unique in that the parties commit to a de facto 16-year moratorium on commercial fishing, which, in the absence of other action, will be automatically extended by five-year intervals. Whilst prospects for future commercial fisheries in this large high-seas area are limited (Hollowed et al. 2013; Hoel 2018), the agreement represents a precautionary approach to the opening of new fisheries in the high seas in the Arctic. The agreement also establishes a joint programme for scientific research and monitoring.

Most of the major fisheries in the sub-Arctic occur on transboundary fish stocks that are shared between two or more countries or occur both in coastal state waters and in the high seas. A significant number of bilateral agreements and other cooperative arrangements exist for the management of these stocks (Hoel 2020). For example, the Norway–Russia Joint Fisheries Commission has managed fisheries in the Barents Sea since 1975. The cooperation includes enforcement of regulations and is supported by collaboration between marine research institutions in the two countries (Hoel 2018).

The Arctic coastal states are at the forefront of implementing the global oceans governance framework (Hoel 2017a), in particular with regard to fisheries management (Hoel 2018). Most of the actual governance takes place in the maritime areas of the Arctic coastal states. International agreements addressing a range of activities in the Arctic are in place: search and rescue (2011), oil spill prevention (2013), international scientific cooperation (2016), the International Maritime Organization's Polar Code (2017) and the above-mentioned agreement to prevent unregulated fisheries. A significant number of global agreements are also important in the Arctic. Smieszek et al. (2021) describe the governing system in the Arctic as an institutional complex rather than an integrated system and point out that coordination of the growing array of arrangements is a challenge. These challenges are exacerbated by the Russian invasion of Ukraine that has destroyed the political climate for international cooperation. Also, the concept of complex interdependence provides a perspective on the international relations in the Arctic (Byers 2017), where multiple arenas of interaction is a fundamental characteristic. Improved understanding of such interdependencies is important to address the new challenges to cooperation in Arctic Ocean governance.

Fisheries economics and management

An important topic in our work is fishing, a major commercial activity in the sub-Arctic. Fishing is, as discussed above, heavily influenced by changes in the natural environment and in governance. There are no commercial fisheries in the central Arctic Ocean today, however, and an international agreement ensures there will be no commercial fisheries in the high seas of the central Arctic Ocean in the foreseeable future—if commercially viable fish populations were to be found there (Hoel 2018). But, the sub-Arctic seas host some of the world's most important fisheries (Vilhjalmsson et al. 2005; Eriksen et al. 2018). Many species that are impacted by climate change are also important target species in commercial fisheries. For example, cod, haddock (*Melanogrammus aeglefinus*) and saithe (*Pollachius virens*) in the Barents Sea are dominant in the Norwegian white fish fleet (Birkenbach et al. 2020). Fisheries for capelin, Greenland halibut (*Reinhardtius hippoglossoides*) and shrimps (*Pandalus borealis*) and crabs are also pursued in the Barents Sea. Mackerel, herring and blue whiting sustain major fisheries in the Norwegian Sea. In the Bering Sea, pollock (*Gadus chalcogrammus*) and snow crab are the main target species. As much as 15% of global marine fish catch is caught by Arctic countries in some years (Hoel 2018), much in sub-Arctic waters. Total annual fisheries catch in the Barents Sea, for example, exceeded 1 million tonnes on average over the years 2000–2014 (Eriksen et al. 2018).

The additional stress that climate change puts on governance structures in the Arctic and elsewhere (Hollowed et al. 2019) is demonstrated by harvest control rules in fisheries management (Kvamsdal et al. 2016). Harvest control rules are tactical management tools translating scientific knowledge into management advice (Punt 2010; Eikeset et al. 2013), implemented in a complex fisheries science–policy setting (Hauge et al. 2007; Dankel et al. 2012). Climate change upsets the biological and ecological understanding of fisheries and adds complexity and the need for more information in scientific advisory processes that harvest control rules rely upon. Furthermore, climate change forces new perspectives and uncertainty into socio-economic objectives that harvest control rules reflect. Changes in distribution or productivity in fish stocks require responsive harvest control rules (Karp et al. 2019; Link et al. 2020). Notwithstanding, few fisheries seemingly have harvest control rules that rely explicitly on environmental conditions (Skern-Mauritzen et al. 2015; Kvamsdal et al. 2016). A rationale for this apparent inconsistency is that most fisheries can be considered as systems with "slow–fast dynamics" (Scheffer 2009). Relative to the dynamics of climate change, the dynamics of a fishery are fast, and the ongoing and iterative fishery management process—including the application of the harvest control rule—can, in principle, adapt to the slow dynamics of climate change. But, the Arctic may be different (Vestergaard 2018), where observed environmental changes related to climate change occur faster than elsewhere and in certain cases also faster than expected (Overland et al. 2017). Arctic fisheries management and ocean governance in general may, therefore, require specific consideration of environmental conditions.

Different types of fishing vessels have different capacity to adapt to changes in distributions of fish stocks. Large, ocean-going vessels will often be able to adapt to stock expansions or migrations, depending on jurisdictional circumstances. Smaller coastal vessels, on the other hand, are less able to adapt to such changes as they fish in their home waters. Coastal vessels may switch to other species in their vicinity or start exploiting introduced species or new species that are expanding their ranges. However, change in fishers' behaviour is driven by other forces than the environment alone, such as regulations of fishing gear, quotas and their allocation, and restrictions on where and when to fish. Further human activities are important drivers of change, through social, economic and political processes (Kvamsdal et al. 2016). It is difficult to isolate the relative impact of the different drivers and attribute change in fisheries to climate (ACIA 2005). Fish stocks generally fluctuate from year to year, and the management and utilization of fisheries are adjusted in response. Small-scale fishers, as well as recreational fishing and marine tourism, are potentially more affected by changing spatial distributions and local declines or increases in marine species distributions than are large-scale industrial fisheries (Koenigstein et al. 2016). Generally, climate change increases the risk of fisheries conflict (Mendenhall et al. 2020).

Economic studies addressing problems relating to shifting international stock distributions started to emerge relatively recently. EEZ-related studies include analysis focusing on biological and economic implications (Hannesson 2007), the adaptive capacity of commercial fishers (Tiller & Richards 2018), the stability and resilience of existing sharing agreements (Ekerhovd 2010, 2013; Ellefsen 2013; Diekert & Nieminen 2017) and the nature of migration patterns (Hannesson 2013). Further studies include the strategic interactions under reactive and proactive management regimes (Liu & Heino 2013) and various sharing rules (Liu et al. 2014; Dankel et al. 2015; Toumasatos et al. 2022). Smith (2012) reviews more generic fisheries economics research that focuses on spatial dimensions. Miller et al. (2013) point out that, in theory, to address the resilience of cooperative management to a changing environment, one needs to replace fixed-share allocations with formulae allowing shares to adjust to shifting migratory patterns. Notwithstanding, practice shows that fixed allocation keys have been critical to the Norway–Russia cooperation in the Barents Sea.

Non-cooperative management of resources may lead to overexploitation. On the basis of game theoretic analysis, some basic principles of cooperative management have been derived (Bailey et al. 2010; Hannesson 2011). Given the ability of parties to communicate, at least three conditions must hold for a cooperative agreement to be preferred to competitive exploitation. First, the solution must be Pareto optimal. That is, all resources are allocated, and if one party (fleet) is to gain something more, it can only be at the expense of others. Second, the payoff from cooperation must be at least as great as from non-cooperation. All must gain from cooperation, in other words. Third, incentives to cooperate must be maintained over time, that is, the solution should be time consistent and resilient (Bjørndal & Ekerhovd 2014).

A complicating issue in fisheries negotiations emerges when the same fleets pursue several fisheries in the same area. This is the case in the Norwegian Sea, where fleets from Norway, EU, Iceland, Greenland, the UK and Russia pursue mackerel, herring and blue whiting, the three stocks that make up the Norwegian Sea pelagic complex (Skjoldal et al. 2004). From a theoretical perspective, considering several fisheries in the same agreement may be beneficial as comparative advantages in both availability and the production process (including differences in input costs, for example) can be exploited. The economic theory of trade is clear that fleets with comparative advantages in a given fishery should specialize as much as possible in that fishery. Furthermore, under a cooperative agreement, one can, to a certain degree, manipulate the Norwegian Sea pelagic complex promoting the most valuable fishery, reflecting the potential for natural growth, harvesting costs and market prices.

In a simplified model of the Norwegian Sea pelagic complex, where mackerel, herring and blue whiting all share a common zooplankton food source (Ekerhovd & Kvamsdal 2017), a recent study compared outcomes under both cooperative and competitive (non-cooperative) fishing (Ekerhovd et al. 2020). In the first-best scenario, where all parties cooperate with regard to management and allocation of quotas between fleets, all comparative advantages are exploited, the most valuable fishery (mackerel) is promoted, and fisheries outcomes are orders of magnitudes higher than under the fully non-cooperative scenario. However, to achieve such a first-best scenario would require substantial side-payments between fishing nations, essentially to keep fleets at bay, and substantial manipulation of the stock composition of the pelagic complex. The first-best scenario irrefutably produces winners and losers, a situation that may be politically untenable and that is unstable without side-payments. But, the analysis also derives hypothetical quota transfers (acting as side-payments) that would ensure a stable second-best scenario where all parties are better off than in the non-cooperative scenario. The second-best total fisheries profits are close to the first-best. More generally, the current reality of fisheries management in the Arctic and sub-Arctic includes fish stocks that enter into the EEZs of two or more coastal states, and high seas fisheries, where both coastal states and distant water fishing nations pursue straddling fish stocks under the auspices of regional fisheries management organizations or similar arrangements (Ekerhovd & Steinshamn 2016).

Many fisheries are seasonal undertakings, and sub-Arctic fisheries particularly so. Seasonality arises from biological adaptations to temperature and light changes, ocean currents and other environmental factors, and the fishes' matching to the behaviour of other species in the ecosystem. The seasonal ecological features are mirrored in fisher behaviour and decisions, prices, regulations and related scientific activity. Heuristic approximations of seasonality in management can have detrimental effects on fisheries outcomes (Kvamsdal, Maroto et al. 2020). Fisheries economics models should, therefore, reflect seasonal features. Whilst a certain range of special cases and empirical studies are developed (Smith 2012; Birkenbach et al. 2020), a generic, theoretical framework for decision making under seasonality is needed (Sandal et al. 2021).

The generic problem of time dependence in fisheries economics models is a long-standing topic, but a general numerical approach to periodic optimization problems, which include seasonal fisheries management models, was recently developed (Sandal et al. 2021). Kvamsdal, Maroto et al. (2020) apply the periodic approach to a simple theoretical example, in which costs are low in one quarter of the year. The example was inspired by the spawning migration of the North-east Arctic cod, which congregates along the Norwegian coast in winter. They found that a management plan that abstracted from the seasonal migration effect and adopted a heuristic simplification could fail in achieving a healthy long-run stock level. In particular, if the initial stock level was low and if fishers could observe and adapt to the temporal variation in harvesting costs, adaptations by fishers would undermine the rebuilding of the stock.

Following a recent interest in natural capital measures (e.g., Greaker et al. 2017; Yun et al. 2017), Kvamsdal, Sandal et al. (2020) developed measures of ecosystem wealth in the Barents Sea. The model, albeit simplified, takes account of ecosystem services via trophic interactions, stochastic population dynamics and capital stocks that are not directly utilized (Poudel & Sandal 2015). Whilst the current management regime is expected to maintain ecosystem wealth in the Barents Sea near today's levels, an alternative ecosystem-based management plan is predicted to increase this wealth by nearly 20% in the short run and by more than 25% in the long run. Further analysis suggests that prey species such as capelin and juvenile herring are undervalued when evaluated at market prices. What this latter point means is that official accounts, which typically rely on market prices, likely misrepresent the ecological and economic value of these species. And as long as official accounts are incomplete, related concerns over ecosystem-based management issues may have limited traction with decision-makers (Barbier 2011). In a larger context, efforts to account comprehensively for the value of natural capital align with both a fundamental critique of the current understanding of value creation in economic theory (Mazzucato 2018) and global concerns over the "deterioration of the fabric of life" (Díaz et al. 2019: 1). Bringing forward an integrated, quantitative understanding of feedbacks and factors in ecosystem service provisions is important (Fenichel et al. 2016). We need to understand

and document the contributions of all natural assets to human welfare to support integrated ocean management (Fenichel et al. 2020).

Regarding the Barents Sea, Norway has implemented an integrated management plan for the ecoregion since 2006 (Hoel 2009), and one may argue that the analysis by Kvamsdal, Sandal et al. (2020), which compared the current management regime with an alternative, compares outcomes from two different ecosystem-based management schemes. Whilst this distinction is not of importance for the results of that study, the distinction points to uncertainty and dissents regarding the term "ecosystem-based management," which can be comprehended in different ways (Hoel 2009; Dolan et al. 2016). Indeed, even when restricted to fisheries management, the term can refer to different degrees of integration (Link et al. 2020), for example, integrating different types of environmental or ecosystem knowledge, or integrating knowledge of fisheries on related stocks. An illustration of this polemic is, on the one hand, the aforementioned claim that environmental information is included in tactical fisheries management advice in few fisheries around the world (Skern-Mauritzen et al. 2015), whilst on the other hand, Marshall et al. (2019) report that many stock assessments in the US do include ecosystem information. Explaining the limited implementation of ecosystem-based management to fisheries, Link et al. (2020) identify the lack of clear operational guidance, which they then heroically provide, but the fuzziness of the term itself may be an equally important reason for confusion. Furthermore, the myriad of factors that need to be accounted for may prevent the normal mode of fisheries science to provide pertinent and timely management advice (Link et al. 2020), and rapid environmental change may lie outside the established scope of the science-to-management process (Karp et al. 2019). A related question is what information managers require, and how these demands affect research and monitoring priorities.

Integrated or ecosystem-based management may involve concerns or objectives that make established models for decision analysis intractable. For example, how to balance the trade-off between system resilience and commercial objectives of the predator–prey relationship of the high-valued cod and the vulnerable capelin in the Barents Sea can be studied using heuristic approaches (Ni et al. 2019). We need to enrich our arsenal of methodologies in the face of new and complex management problems.

Focus: north-east Arctic cod

Much of our research is focused on the North-east Arctic cod, and Table 1 presents a systematic overview of relevant research findings and challenges. The selected findings are based upon our exposition above and are, thus, already discussed. The list of research challenges is far from complete, but they are selected to illustrate how challenges depend on each other, within and across research areas. The research areas in the table are not mutually exclusive, but are overlapping and partially integrated. The location of topics, findings and challenges reflects our subjective views. In what follows, we discuss the research challenges in some more detail. Whilst topics and findings in Table 1 focus on the Barents Sea and the North-east Arctic cod, the listed research challenges have a broader application.

The first research area we consider is the natural environment (Table 1). A related challenge is continued environmental monitoring. Integrated ocean management requires extensive knowledge and data. Natural scientists have to continue monitoring the state of the ecosystem, documenting changes and impacts in the environment, and developing their understanding of the drivers of change in the ocean, including critical environmental thresholds for temperature, sea-ice extent, oxygen and pH levels. This work includes utilizing new data sources and more collaboration across sectors on data sharing for purposes of research and governance. Environmental monitoring in the Arctic, including the Barents Sea, is important with ongoing Arctic amplification of climate change impacts, species range shifts and changes in ecosystem services. On the basis of data from environmental monitoring systems, natural scientists can advance our knowledge and understanding of environmental drivers and ecosystem dynamics. Furthermore, to obtain better and more integrated prediction systems, experts on climate and marine ecosystem modelling need to cooperate more, as currently in the Nansen Legacy research programme. The importance of such cooperation is demonstrated in recent work, for example, in the study of future spawning conditions (Sandø et al. 2020) and the assessment of Barents Sea natural capital (Kvamsdal, Sandal et al. 2020). The importance of reliable ecosystem prediction will increase as we move towards ecosystem assessments and ecosystem-based management.

With regard to international cooperation, a current and future challenge is the continued implementation and coordination of the international legal framework at domestic and regional levels of governance, that is, translating international principles into regional and domestic management measures (Table 1). In this respect, research has a key role in providing the scientific underpinning of management measures. A related challenge is further strengthening of the science–policy nexus to enhance the uptake of scientific advice in policy. The example of harvest control rules as a means to turn scientific assessments

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Table 1 An overview of multidisciplinary perspectives on the North-east Arctic cod, organized into three research areas: the natural environment, international cooperation, and fisheries economics and management. This table also has an area for interdisciplinary synthesis that draws on several fields. Several topics are listed for each research area, and each topic is accompanied by a selection of research findings. The rightmost column summarizes the research challenges related to each area.

Research area Topic	Findings	Research challenges
The natural environment		
Ocean temperature increase	0.2–4 degrees Celsius; Arctic amplification.[a]	Continued monitoring and documentation of the state and changes in the natural environment is fundamental to promote comprehensive ecosystem understanding as basis for integrated management.
Reduced sea ice	Ca. 60% Arctic ice loss; ca. 90 fewer days of ice cover.[a,b]	
Primary production	25% increase in double bloom occurrence.[a] Moderate increase in net primary production likely climatic response; significant linkages between primary production and fish biomass.[c,d]	
Recruitment	Ideal spawning conditions shifts north and east.[e,f] Dependence on environmental and ecological factors; time-lagged effects.[g,h,i]	Increased cooperation between experts on climate prediction and marine ecosystem modelling to obtain better and more integrated prediction systems.
Spatial distribution of fish stocks	Ice melting and warming will create new and increase habitat for cod and its prey.[j,k,l] Cod and capelin (key prey stock) have already expanded north- and eastwards.[m,n,o]	
Invasive species	Red king crab now of commercial importance and interferes with coastal cod fisheries, pose ecological uncertainty and create new management challenges.[p,q]	
International cooperation		
Transboundary resources	Norway–Russia well-established cooperation, supported by collaboration of national research institutions.[r] Shifting stock distributions may reduce conservation incentives.[q,s] Multispecies, multi-national fisheries viewed as discounted dynamic games.[t]	Implementation and coordination of global legal framework at domestic and regional levels of governance.
Implementation and enforcement	Fisheries governed by the Joint Norway–Russia fisheries commission; Norway and Russia cooperate on enforcement.[r,u] Cod management based on harvest control rule embedded in the ecosystem-based management plan.[r,v] Implementation of international agreements and their provisions on, e.g., the precautionary approach and the science needed to accomplish that is critical.[w]	Strengthening of the science-policy nexus. Investigate the complex interdependence between Arctic states. Improved understanding of potential landing zones for international negotiations.
Illegal, unreported and unregulated fishing	Port-state measures and a new Arctic governance regime have largely ended illegal fishing.[x]	
Brexit	Undermines stability of fisheries agreements that will require renegotiations.[y]	
Fisheries economics and management		
Environmental changes	Limited or no effect on profits, but dated evidence.[z] Outside current management scope.[aa]	Develop climate-ready fisheries management processes.
Technological development	Continued technological and technical progress, but dated evidence.[bb,cc] Analysis of investment incentives defining long-term fishing capacity.[dd]	Form integrated management objectives, reflecting impacts across sectors and stakeholders.
Socio-economic conditions	Environmental changes may reduce resource extraction costs; increasing global seafood demand.[ee] Small-scale fishers more vulnerable to shifting distributions.[ff]	A better understanding of value creation in fisheries, accounting for use and non-use values.
Harvest control rules	Currently aligns with economic and biological targets.[gg] No explicit recognition of environmental or ecological variables; vulnerable to complex science-policy interaction.[v]	
Multispecies and ecosystem-based management	Optimal multispecies management includes complex ecological dependencies.[hh] Bioeconomic multispecies modelling using ecosystem data and new methods.[ii,jj] Comparative evaluation of multi- and single-species modelling.[kk] Natural or socio-economic factors may impact fishing pressure across species and over seasons.[ll] Framework to operationalize the ecosystem-based approach to management.[mm]	
Seasonal or spatial variations	Seasonal or spatial effects impact optimal harvesting and fisher adaptations.[nn] Fisher adaptation to spawning aggregations.[ll]	

(*Continued*)

Table 1 (Continued) An overview of multidisciplinary perspectives on the North-east Arctic cod, organized into three research areas: the natural environment, international cooperation, and fisheries economics and management. This table also has an area for interdisciplinary synthesis that draws on several fields. Several topics are listed for each research area, and each topic is accompanied by a selection of research findings. The rightmost column summarizes the research challenges related to each area.

Research area Topic	Findings	Research challenges
Interdisciplinary synthesis		
Integrated ocean management	Integrated management poses problems that require new methods.[oo] Science-to-management system requires revisions to support sustainable fisheries management.[v,aa,mm]	Transgress wedge between advanced concepts of adaptive, integrated ocean governance and current practical and operational management.
Natural capital measurement and accounting	Understanding and document contributions of all natural assets to human welfare are important.[pp] Market prices misrepresent value of prey species and non-use assets; ecosystem-based management increases wealth and ensures sustainability.[qq,rr]	Tracking impacts of change in the environment through marine ecosystems, economic sectors depending on them and to social, political and legal systems.

[a]Overland et al. (2017). [b]Sandø et al. (2014). [c]Sandø et al. (2021). [d]Dalpadado et al. (2014). [e]Sundby & Nakken (2008). [f]Sandø et al. (2020). [g]Hare et al. (2010). [h]Årthun et al. (2018). [i]Zimmerman et al. (2019). [j]Hollowed et al. (2013). [k]Fossheim et al. (2015). [l]Kjesbu et al. (2022). [m]Michalsen et al. (2013). [n]Kjesbu et al. (2014). [o]Ingvaldsen et al. (2015). [p]Sundet & Hoel (2016). [q]Kaiser, Kourantidou & Fernandez (2018). [r]Hoel (2018). [s]Rayfuse (2018). [t]Ekerhovd et al. (2020). [u]Hoel (2020). [v]Kvamsdal et al. (2016). [w]Hoel (2017b). [x]Hoel (2017a). [y]Toumasatos & Steinshamn (2018). [z]Diekert & Schweder (2017). [aa]Karp et al. (2019). [bb]Hannesson et al. (2010). [cc]Kvamsdal (2016). [dd]Ekerhovd & Gordon (2020). [ee]Vestergaard (2018). [ff]Koenigstein et al. (2016). [gg]Eikeset et al. (2013). [hh]Poudel & Sandal (2015). [ii]Kvamsdal & Sandal (2015). [jj]Ekerhovd & Kvamsdal (2017). [kk]Ekerhovd & Steinshamn (2016). [ll]Birkenbach et al. (2020). [mm]Link et al. (2020). [nn]Kvamsdal, Maroto et al. (2020). [oo]Ni et al. (2019). [pp]Fenichel et al. (2020). [qq]Greaker et al. (2017). [rr]Kvamsdal, Sandal et al. (2020).

into management advice in fisheries illustrates this point. Adoption of harvest control rules has resolved some of the issues, for example by requiring explicit decision rules, thereby bringing transparency to complex fisheries science models used for management advice. An additional challenge is the formulation of the management objective that is subject to both scientific and political influence. Kvamsdal et al. (2016) discuss harvest control rules at some length; see also Punt (2010).

The third research area considered is fisheries economics and management (Table 1). Fisheries management in the Barents Sea, and in the Arctic more generally, is based on scientific advice and international cooperation with regard to implementation and enforcement of management measures regarding transboundary resources. A research challenge is to provide inputs to climate-adapted fisheries management that is fit-for-purpose. This challenge reflects the interdisciplinary nature of fisheries management in its reliance on continued monitoring and natural science research, a robust international cooperation framework for both science and governance, better and more detailed fisheries data, and adaptive and practical fisheries management tools (Kvamsdal & Sandal 2015). Another research challenge with regard to fisheries management is the alignment of broadly accepted ideas about integrated ocean management with fisheries management, which require consideration of impacts of fishing on marine ecosystems, such as implemented in the deep-sea regulations for fisheries in Norwegian waters that aims to prevent impacts on benthic flora and fauna (Jørgensen et al. 2020). The final research challenge listed in Table 1 is the need for a better understanding of value creation that accounts for use and non-use values, reflecting behavioural adaptations to climate and other changes. Relevant topics for value creation are, for example, bycatch issues and the impact of technological change and capital investments.

Finally, regarding interdisciplinary synthesis, we consider findings and research challenges that affect several subject fields (Table 1). A major interdisciplinary research challenge is to support the development and adoption of adaptive and integrated ocean management. Link et al. (2020) provide initial steps of this development, mapping out an operational framework to implement an ecosystem approach to fisheries management. Further steps may include new mechanisms to reconcile the concerns of various interests in conservation and use of the oceans. Integrated ocean management is a challenge that may benefit from convergence research, deep collaboration between multiple scientific disciplines (Roco 2016), building a common language and understanding, benefitting from knowledge of social–ecological systems, value creation and non-use values. An important, interdisciplinary research challenge is to track impacts of change in the geophysical environment through marine ecosystems, industries depending on them, to social, political and legal systems. Analyses of such pathways of change are fundamental to understand the impact of climate change on society and its governance (Crépin et al. 2017).

Concluding remarks

Climate change brings complex challenges that cannot be understood or resolved by any single academic discipline. Multidisciplinary research is demanding, however (Hazard et al. 2020). Here, we have drawn on different academic perspectives, bringing together insights from oceanography, marine biology, economics, political science and international law in an analysis of how climate change in the Arctic affects the management of specific fisheries. Our main focus has been on fish and fisheries. Fishing is an important commercial activity in the sub-Arctic, affected by environmental conditions, governance and economics and is consequently a relevant topic for multidisciplinary research.

The absence of commercially viable resources and international agreements limits fishing and other industrial activities in the High Arctic. Scientific activity is, therefore, likely to remain the main activity in the central Arctic Ocean in the foreseeable future. Polar regions are highlighted as areas that require enhanced understanding to contribute to the objectives of the UN Decade of Ocean Science for Sustainable Development (Pendleton et al. 2019). A key aspect of Arctic research is new and improved observation technologies such as data from the Automatic Identification Systems and autonomous ocean-going vessels. Available and accessible data may promote new and more comprehensive information for management and governance (Sala et al. 2018; Stocker et al. 2020).

A significant number of international agreements in addition to those discussed above are also important in the context of the governance of the central Arctic Ocean (PAME 2011). For science in particular, the International Arctic Science Committee, with more than 20 member countries, represents the international scientific community. The abovementioned Arctic Council science cooperation agreement as well as the Arctic Council working groups, the recent Arctic Science Ministerials in 2016, 2019 and 2021, ICES and the North Pacific Marine Science Organization all have important roles in these areas. ICES has an Arctic Fisheries Working Group that has existed for more than 50 years. A recent development is the cooperation amongst ICES, the North Pacific Marine Science Organization and the Arctic Council's working group for the Protection of the Arctic Marine Environment on an integrated ecosystem assessment for the central Arctic Ocean. Amongst the longer standing scientific cooperative efforts in the Arctic is the marine research in the Barents Sea by Russia and Norway, chronicled by Eriksen et al. (2018). In light of the Russian invasion of Ukraine and the deteriorating climate for international cooperation, these scientific mechanisms will inevitably be affected.

Industrial development in Arctic marine resource exploitation will depend on technology and price–cost relationships. The effect of technical change is pervasive in fisheries; some studies of Arctic and sub-Arctic fisheries are presented by Hannesson et al. (2010), Gordon & Hannesson (2015), Kvamsdal (2016) and Ekerhovd & Gordon (2020). Whilst essential to consider in fisheries management, technology is understudied in both theory and empirical work (Squires & Vestergaard 2013). Environmental change affects fisheries in ways not routinely addressed in established science-to-management processes (Karp et al. 2019). Such challenges point towards transformative change that require innovative governance, including regulations addressing adaptation to climate change and biodiversity concerns (Díaz et al. 2019).

Regardless of warming, Arctic and sub-Arctic environments will remain demanding to operate in. Higher temperatures and less sea ice may reduce resource exploitation costs (Vestergaard 2018), but costs are, nevertheless, likely to remain above costs in similar operations at lower latitudes. At the same time, increased pressure on global resources may increase demand and market prices for resources from the Arctic, including seafood from both capture fisheries and aquaculture. Aquaculture has increased significantly in the sub-Arctic over recent decades and will likely continue to grow in northern Norway, Russia, Iceland, the Faroes and Canada (Hoel 2017a). These industries are of global and local significance as they are large in these regions where populations are relatively small (Hoel 2018). To manage these and other industries under changing conditions may require proactive and dynamic adaptation, relying on updated and comprehensive data and perspectives from different academic disciplines.

The changing Arctic has generated interest not only from the Arctic coastal states but also from non-Arctic states (Hoel 2017a; Malinauskaite et al. 2019), which may increase the potential impact of economic activities on the environment and on communities (Meier et al. 2014; Bekkers et al. 2018). In a geopolitical perspective, the Arctic is at the centre of economic potential, political uncertainties and overlapping interests (Bertelsen 2018). Kaiser et al. (2016: 153) warn that promoting the Arctic as an open economic frontier may be misleading and detrimental to sustainable development. Industrial development potentials in the marine Arctic can suffer from various forms of market failure, and socially efficient outcomes require government interventions.

UNCLOS has proved to be a dynamic framework for global oceans governance, addressing new challenges as they arise. This happened in the 1990s with the negotiation of implementing agreements for fisheries and deep seabed minerals. The UN currently negotiates a new implementing agreement under UNCLOS for marine biodiversity in areas beyond national jurisdiction. A forthcoming agreement may interact with the 2018 agreement to prevent unregulated fisheries (Balton 2019). Also, through annual resolutions in the UN General Assembly, the world community regularly addresses the implementation of UNCLOS and its implementing agreements. Furthermore, UNCLOS recognizes the connected nature of the oceans and the need for comprehensive perspectives on ocean matters. The Arctic Ocean may be the tragedy of the commons that never happened—many important governance measures to prevent overexploitation have already been put in place.

In the Barents Sea, the cod stock is in fairly good condition, providing relatively high catches in recent years despite large fluctuations in its main prey, capelin. Overall, demersal stock levels in the ecoregion have declined over the last few years but are above the maximum sustainable yield biomass level that triggers need for management action (ICES 2021). A management plan and a stable sharing agreement between Russia and Norway have been in place for the cod fishery for a long time, but these may both be impacted by a deteriorating climate for international negotiations and the potential for rapid environmental changes triggered by climate change. Further issues facing future fisheries management in the area include incorporation of seasonalities across environmental, ecological and social dimensions, better integration of ecosystem-based management objectives and comprehensive assessments of sustainability and natural capital levels.

As climate change challenges both ecological structure and management institutions, the conceptual approach to natural resource management is changing as well (Ni et al. 2019). A gap seems to exist between advanced concepts of management (for example, ecosystem-based management and adaptive governance) and current operational management (Guerry et al. 2015; Skern-Mauritzen et al. 2015). The need to align scientific research, ideas and concepts with real-world management and operational tools is pressing (Arkema et al. 2006; Polasky et al. 2015; Link et al. 2020). We aim to demonstrate how bringing together insights from various perspectives can facilitate, improve or promote sustainable Arctic resource utilization and management under climate change.

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