Attuning to a changing ocean

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The ocean is a lifeline for human existence, but current practices risk severely undermining ocean sustainability. Present and future social–ecological challenges necessitate the maintenance and development of knowledge and action by stimulating collaboration among scientists and between science, policy, and practice. Here we explore not only how such collaborations have developed in the Nordic countries and adjacent seas but also how knowledge from these regions contributes to an understanding of how to obtain a sustainable ocean. Our collective experience may be summarized in three points: 1) In the absence of long-term observations, decision-making is subject to high risk arising from natural variability; 2) in the absence of established scientific organizations, advice to stakeholders often relies on a few advisors, making them prone to biased perceptions; and 3) in the absence of trust between policy makers and the science community, attuning to a changing ocean will be subject to arbitrary decision-making with unforeseen and negative ramifications. Underpinning these observations, we show that collaboration across scientific disciplines and stakeholders and between nations is a necessary condition for appropriate actions.

marine | climate change | biological

Human impacts on the ocean have historically been largely limited to waters immediately adjacent to populated coastlines. Today (1), we are increasingly affecting all marine systems (2, 3) by carbon dioxide (CO_2) emissions, pollution, or physical infrastructures, and overexploitation of biomass at different trophic levels (4, 5). The ocean has limited capacity to adapt to these stressors (6–8) with severe, and possibly irreversible, implications for humans likely on both short- and long-term time scales. Attuning to these changes and achieving the United Nation's Sustainable Development Goals (https://www.un.org) requires data and knowledge about the many facets of anthropogenic impacts on the ocean. We argue that lessons learned from the Nordic countries will be relevant for stimulating action associated with supporting ocean sustainability.

Acquiring data and developing knowledge is a long-term and costly investment. It requires funding, genuine curiosity, and development of expertise (9). The International Council for the Exploration of the

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Sea (ICES)—founded in 1902 and recognized as an intergovernmental organization since 1964—has played an instrumental role in this respect. Since its inception, hundreds of millions of measurements have been collected, stored, and analyzed by ICES and associated scientists, with a primary aim to understand the population dynamics of commercial fish species as well as other topics. HELCOM (Baltic Marine Environment Protection Commission - Helsinki Commission; established 1974), in turn, has focused on science and advice for the Baltic Sea, whereas OSPAR (Oslo-Paris Commission; established 1972), the North-East Atlantic Fisheries (NEAFC Convention, enforced in 1982 and replaced the 1959 Convention), and the Norwegian-Russian Fisheries Commission (established 1976) provide similar functions for the North and Barents Seas, respectively. As a starting point, however, the systematization of marine data, across economic zones and national territories, has enabled international, cross-disciplinary, and cross-sectorial collaborations to form, develop, and mature. We argue that this joint work has put the Nordic region in a unique position to contribute to knowledge relevant not only for its countries and their neighboring seas but also for the wider international community. By doing so, we provide a platform for adjusting—or attuning—research and management strategies to the entirely new situation we are facing currently with climate and environmental change.

Scientific Collaboration: A Catalyst for Knowledge and Action

The translation of scientific understanding to sustainable exploitation and conservation policies, for example, within ICES, HELCOM, NEAFC, and OSPAR, is paramount for sustainability and requires collaboration. These international institutions are supported by national universities and research institutes and have been integral to the success of current data collection programs that provide us with substantial spatial and temporal observations (Fig. 1 and *SI Appendix*, Fig. S1). They facilitate scientific synthesis and are also key institutions for policy makers to interact and make decisions about management action. In this study, we describe how science in this region (9) has contributed to an understanding of major ocean processes (Fig. 1 *A* and *B* and Table 1). We ask: What do we know, what remains to be understood about the ocean, and what lessons have we learnt?

The Ocean as a Driver and Recipient of Change

The seas neighboring the Nordic countries represent a key area for the circulation of the global ocean and host highly productive fisheries. The coastal seas connect directly to the Arctic Ocean, which, in turn, is one of the most receptive areas to global warming (10), and have potential to impact global circulation patterns. Any sustained perturbation of this intricate system is likely to have ramifications for ecosystems, coastal communities, and societies, as well as economies at all scales.

The Ocean Engine. Without redistribution of heat by winds in the atmosphere and currents in the ocean, only a small portion of Earth's surface would be habitable. In the Atlantic Ocean, the poleward transport of heat is largely accomplished by the Atlantic Meridional Overturning Circulation (AMOC), which varies in strength on seasonal to multidecadal time scales, with subsequent

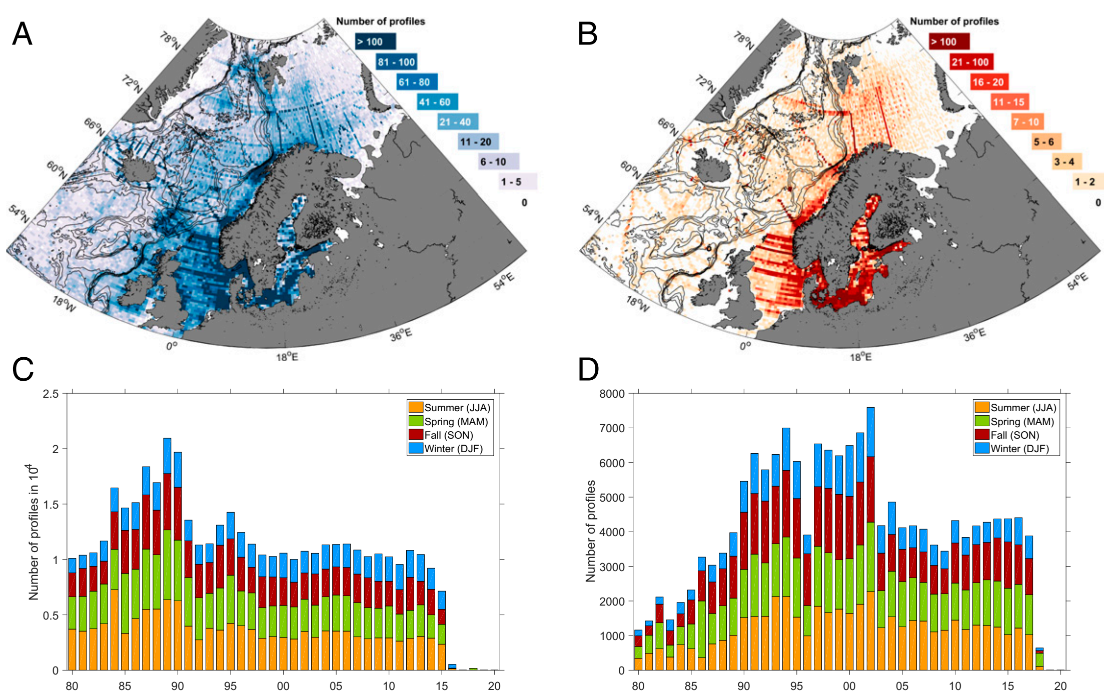

Fig. 1. Data distribution of (*A* and *C*) temperature/salinity and (*B* and *D*) nutrients/oxygen. (*A* and *B*) Total number of vertical profiles per 0.5° longitude × 0.25° latitude bin since 1980. (*C* and *D*) Number of vertical profiles per year, color coded by season. Note the different scales. The data were obtained from Unified Database for Arctic and Subarctic Hydrography, ICES, World Ocean Database, the international Argo program, Global Ocean Data Analysis Project version 2, Institute of Marine Research (Norway), Marine and Freshwater Research Institute of Iceland, and the Norwegian Iceland Seas Experiment database. Duplicates between the archives have been discarded. Note the asymmetry in spatial data, with high coverage in the eastern part of the basin where current change is least and vice versa. There is a considerable seasonal bias in data available from the seas neighboring the Nordic countries, with highest density for spring and summer, a feature prone to impact our understanding of past as well as future changes. JJA, June, July, August; MAM, March, April, May; SON, September, October, November; DJF, December, January, February.

Table 1. An overview of the drivers and associated changes addressed in this Perspective

	Examples of	Current insights	Scientific challenges	Lessons learned	Key issues for science policy dialogue
Environmental change	The ocean circulation	AMOC will weaken, but the Gulf Stream will not stop (11)	Increase mechanistic understanding of how climate-induced fresh water runoff will impact ocean circulation in the northern Atlantic	The importance of continued spatiotemporal time series observations, preferably involving clusters of countries	Global change will impact ocean circulation, generating feedback effects and influencing ecosystem services
	The arctic sea ice cover	Summer sea ice will continue to recede in the foreseeable future (21, 24)	Pinpoint and understand the effects and dynamics resulting from a receding sea ice	Summer ice loss is irreversible on human time scale unless CO_2 emissions are substantially reduced	The rate of change calls for regular interaction between science and policy makers
	The ocean's capacity to absorb changes	Ocean will continue to buffer, but not stop the effect of climate change (30)	The large-scale buffering capacity is poorly known; need for large-scale studies and realistic models	The limited capacity of the ocean to absorb CO_2 stresses the entire ecosystem; open oceans and coastal seas have different evolution of pH under anthropogenic perturbations	The ocean will ease the effects of the Anthropocene, but will not solve the problems
Biological consequences	The ocean's productivity	Biomass productivity will increase (but not for ice-dependent assemblages) (43, 45)	Track and understand the spatiotemporal dynamics of ocean productivity	The effect on higher-trophic levels of changes in production period is not fully understood	Increased productivity does not automatically benefit humans, and can induce a geopolitical conflict
	The marine biodiversity	Biodiversity at all levels is threatened (52)	Determine how interaction among various drivers impact the marine system	Sustainable management regimes require multitrophic long-term monitoring	Loss of biodiversity impairs ecosystem services
	The biotic and abiotic ecosystem changes	Large potential impacts for individual species, but ecosystem-level consequences are poorly understood (59)	Complex and dynamic interactions typically makes ecosystem responses difficult to predict	Without large-scale long-term studies, ecosystem-level interactions and consequences cannot fully be assessed	Ocean acidification has the potential to compound many adverse climate effects for marine ecosystems
Societal consequences	The exploitation of ocean resources	Increased demand for seafood products linked to global change will impact fish stocks and food security (66)	Integrate social–ecological and collapse–recovery mechanisms of fisheries	Engage major ocean industries in science-based dialogues about the ocean	Adhere to scientific results for management of individual fish stocks and entire ecosystems
	Human health	Conclusive evidence that human health depends on a healthy ocean (70)	The lack of multidisciplinary efforts impede further understanding of the ocean–human health nexus	Coupling long-term monitoring/observational data with experimental studies is needed to design regulation of marine pollution	We need a healthy ocean to support healthy humans
	Human communities	Human well-being directly linked to local natural resources; high rates of change, increasing vulnerability of Arctic communities (84)	Understand how ecological, sociocultural, and economic climate affects Arctic communities, both indigenous and otherwise	The entire human community depends on a healthy and resilient ocean	Local communities need means to promote adaptive behavior and adaptive institutions

The table summarizes examples of the current insights from the seas neighboring Nordic countries (associated exemplifying references in brackets). Corresponding scientific challenges, lessons learned, and needs for dialogue between scientists and decision makers are also presented.

impacts on the large-scale climate and marine ecosystems. Model simulations without an AMOC indicate a widespread cooling throughout the Northern Hemisphere, in particular, northwestern Europe (11), emphasizing the importance of this circulation.

As an extension of the Gulf Stream, warm waters flow northward into the subpolar North Atlantic, gradually releasing heat to the atmosphere. Here, the cooled waters sink to great depth, and form the headwaters of the deep component of the AMOC. Despite recent progress, the exact pathways and mechanisms of this deep-water formation remain unclear (Table 1).

While climate models project a gradual weakening of the AMOC during the 21st century (12), a collapse of AMOC is considered very unlikely. However, a recent study implies that most current climate models are biased toward a more stable AMOC (13), and there is paleoevidence that shutdowns have occurred in the past (e.g., ref. 14), with direct consequences for the regional biota if the system should fall into a period of rapid glaciation (13).

Some indications of an AMOC weakening have been reported in the North Atlantic (15). However, long time series of inflows and outflows spanning the entire boundary of the Arctic basin, some of which exceeded 20 y, document the exchange flow across the Greenland–Scotland Ridge showing no such decline. Instead, the measurements showed that the exchange flow remained remarkably stable in the period from the mid-1990s to the mid-2010s (16). Those measurements were initiated in 1993 within the Nordic World Ocean Circulation Experiment project (a cooperation between the Nordic countries to measure the flows across the Greenland–Scotland Ridge). This was later expanded to cover all gaps between the Arctic and the Atlantic and Pacific Oceans (Table 1). There is, however, concern that deep-water formation in the seas neighboring the Nordic countries could be reduced due to increased meltwater runoff from Greenland, release of freshwater presently accumulating in the Arctic Ocean, or diminishing atmospheric forcing. Over time, substantial reductions in the rate of deep-water formation would tend to weaken the AMOC (17). Projections for the northern oceanic climate under moderate anthropogenic forcing scenarios indicate a slight weakening of the AMOC, but the expected cooling will be offset by global warming (18).

The Arctic Lid. Models project that the Arctic will become warmer, especially during winter, and the change will occur faster there than anywhere else on Earth. This anticipated trend is already confirmed by observations (19), but the largest changes are still to come. The rapid decline in volume and extent of summer sea ice in the Arctic Ocean is a case in point. From 1979 to 2014, the sea ice extent measured in September, the month with minimum sea ice cover, has declined by, on average, 13.3% per decade, and the decline has occurred about 4 times faster during the second half of the time period (20). In addition, the thickness of the ice has shown a strong decline accompanied by significant loss of multiyear ice (21). The pronounced retreat of sea ice and increasing influence of warm Atlantic water has characterized climate shifts in the regions north of Svalbard and in the Barents Sea, leading to the borealization of the region (22).

The severity of projected future declines is strongly linked to the emissions scenario being considered. Under a high-emissions scenario, Arctic Ocean sea ice cover in September is projected to nearly disappear by the middle of this century (23, 24). However, when considering a modest increase in CO_2 levels, only one-third of the models indicate ice-free summer conditions by the end of this century (25). There is, therefore, a consensus that the sea ice coverage in the Northern Hemisphere will continue to decrease in the coming decades (Table 1), but the rate of decline is uncertain for both summer and winter (26). Sea ice in the Baltic Sea is seasonal, with historic periods of nearly full coverage in winter. However, recent trends and predicted future climate change present evidence of shrinking winter ice coverage (27).

The long time series of oceanographic data in the Barents Sea region, as well as in the waters between Svalbard and Greenland, are crucial baselines for observing changes of the Arctic Ocean that are outside natural variability (28). For instance, long-term measurements of ocean heat transport into the Barents Sea provide the basis for predictability of local sea ice cover 1 y to 2 y in advance (29)

The Ocean's Capacity to Mitigate CO_2. The ocean system has a critical global climate-regulating role, including carbon dioxide absorption from the atmosphere. The ocean has taken up roughly 30% of the CO_2 emitted by human activities and absorbed 93% of the energy associated with warming from 1971 to 2010 (30). However, the combined effects of increased CO_2 and heat uptake suggest that the ocean is undergoing a substantial transformation, with unforeseen consequences. Despite this vast buffering capacity for absorbing CO_2 and heat, a minor change in the rate of this uptake will have a profound impact on future climate (Table 1). Anticipated changes can include shifts in ocean circulation/ventilation/stratification, sedimentation of organic matter to the deep ocean, and/or changes of land–ocean fluxes (31). There is consensus that the ocean will continue to be an important sink for heat and CO_2, but the magnitude remains uncertain due to feedbacks on the exchange of CO_2 between atmosphere and ocean. Carbon data from the Greenland Sea covering the last 25 y represent an important record for understanding the oceanic CO_2 sink in this deep-water formation region (32).

In a warmer world, large parts of the surface ocean will become more stratified. Coastal seas are projected to be loaded with more nutrients by river runoff, leading to intensified seasonal primary production and thus the potential for a larger CO_2 sink (33). However, runoff also supplies the ocean with dissolved organic carbon (DOC) that partly decays to CO_2. Supersaturation of CO_2 in the surface waters on the Siberian shelves has been observed in summer, even when primary production has consumed all available nutrients. This example shows the importance of terrestrial DOC degradation to CO_2 fluxes as a source of CO_2 to the atmosphere (34). As sea level rise accelerates, coastal erosion will be a major issue along many coastlines, further enhancing the input of organic carbon and nutrients to the sea. The changes due to these processes, which act as both sources and sinks of atmospheric CO_2, will occur in addition to the increase in oceanic uptake of anthropogenic CO_2. The outflow of upper waters from the Arctic Ocean along the East Greenland Current gives information on these processes, and current data illustrate the variability in the signature of this outflow (35).

Changes in the supply of DOC from rivers entering the northern Baltic Sea have also been reported (36), as well as the impact this has on the marine ecosystem (37). Models of the Baltic Sea system, based on long historic time series, project a future increase in the seasonal amplitude of pH (38). This will occur in addition to the long-term reductions in pH, that is, ocean acidification, adding further stress on the marine environment. The aggregated effect may be particularly severe as pH levels move outside of the range experienced by marine organisms and ecosystems over the past millions of years (39).

Biological Consequences of the Changing Ocean

A Warm Ocean, Productive Arctic. The past decade has been the warmest on record for the Arctic seas (40) and has seen an associated increase in productivity and bottom-up, resource-driven, regulation (41). The onset of primary production (the phytoplankton spring bloom) is now 50 d earlier in the northeastern Barents Sea compared to the late 1990s (42). In the Barents Sea, we observe a large increase in the biomass of both demersal and pelagic fish, together with increased shrimp and zooplankton biomass (43). Since 2007, the biomass of the ecologically and economically important northeast Atlantic mackerel stock (*Scomber scombrus*) in the Norwegian Sea has increased, and its distribution has shifted (44). The expanded distribution of mackerel means that the stock is within the economic exclusive zone of many coastal states, namely Iceland, Greenland, and the Faroe Islands, Norway, and the European Union, causing a still-unresolved decade-old rift in quota sharing (44).

Model projections of primary production in the Arctic for the next century suggest an increase of more than 150% (45), but there is strong variation between models. Productivity at northern latitudes is controlled both by temperature, which is increasing, and by the light condition, which is not affected by global warming through light seasonality but through the sea ice condition. However, the limiting factor for productivity is nutrient availability (46), and nutrient supply and water mass mixing are thus key factors that can limit the ability of biological systems to exploit increased temperature. Receding ice cover is expected to be favorable to planktivorous fish that rely on vision for foraging, thereby increasing top-down regulation in the Arctic (47). However, although the productivity of high-latitude species will generally increase, the impact on sea ice-dependent species is likely to be negative. For instance, as sea ice retracts in the Arctic, Polar cod (*Boreogadus saida*) may become extirpated in most of its current distribution range (48, 49).

Climate change mediates the strong geographic dependency of zooplankton production and fish recruitment, but deeper knowledge of the factors controlling the distribution of various key marine species is required (Table 1) (50). A better understanding is also needed as to how changes in these distributions ultimately will impact fisheries and fishing patterns, as climate continues to change (51). A large-scale ecosystem model covering the entire Arctic basin suggests that, overall, long-term changes may not be equal everywhere in the basin, due to varying currents, stratification, and productivity (46).

Anthropogenic Impacts Threaten Marine Biodiversity. Marine ecosystems are expected to change dramatically over the next few decades. Impacts are expected across all levels of ecosystem structure and functioning, from individual- and population-level adaptation and species distributions to food webs and trophic interactions. Comprehensive analyses from northern European seas exist for the historic development of climate and ecosystem responses (52), the environmental forcing functions for biota (27), and overall descriptions of biodiversity changes (53). Shifts in species distributions are already appearing faster than projected by current models, and the resulting mixing of species of differing biogeographic origins may lead to new evolutionary pressures and adaptations (50). Changes in the environment will not only alter the distribution patterns of native species but also open routes for invasive ones (54), with potentially large impacts on native biota and ecosystem services (e.g., seafood production).

Fish are expected to show plastic and adaptive responses to the warming ocean, including reduced body sizes in response to increased metabolic rates (55). This is expected to alter predator–prey interactions and population growth through increases in natural mortality (56), thus reducing resilience to fishing and the ability to recover (Table 1). Intensive fishing coupled with fish life history changes toward smaller adult body size and reduced size at maturity can therefore lead to increased fluctuations in fish abundance (57) and in ecosystem dynamics, from primary production to fish population dynamics (58).

Ocean Acidification Has Global and Local Ecosystem Consequences. The current rate of ocean acidification is unprecedented within the last 65 million years (59). This increase in acidity threatens many organisms, such as corals, fish, and shellfish, but also phytoplankton, copepods, and pteropods, which are key prey species in marine ecosystems (35, 40, 60–62). There is overwhelming evidence from experimental and field studies that, as seawater pH declines, many species and ecosystems will be negatively affected, both directly and indirectly through ecological interactions (35, 40, 62). Large spatiotemporal variations in the magnitude of ocean acidification are expected, while the biological consequences are highly species and even population specific (60).

Important ocean acidification thresholds have already been exceeded in the seas neighboring the Nordic countries, with impacts already observed on some polar marine species (35). For example, shelled pteropods captured from polar waters that were locally more acidic have begun to show elevated levels of shell damage (61). Pteropods are consumed by commercially important species such as pink salmon (*Oncorhynchus gorbuscha*), and their loss may therefore have significant consequences for the marine food web (61). Ocean acidification also greatly increases the risk of collapse in the northeast Arctic cod (*Gadus morhua*) fishery in the Barents Sea (35).

Societal Consequences of the Changing Ocean

The collapse and recovery of fish populations result from interacting direct and indirect effects of social, ecological, and environmental components (63). While the vast majority of fish populations globally are still managed with a single-species approach, with limited consideration of interactions with other species or habitats, the seas neighboring the Nordic countries contain many exceptions (64). Understanding the complex interactions between species is critical in order to properly restore target populations to a "good" status and to appreciate the ecological and socioeconomic implications of changing population status (65).

Given the present trajectory of fish stocks globally (66), and expected increase in demand (67), it is critical to learn from both management successes [e.g., of cod in the northeast Atlantic (68), and North Sea stocks of herring *Clupea harengus* (69)], failures [Baltic Sea cod (70)], and other examples of management challenges in a changing ocean [northeast Atlantic mackerel (44)].

The Seas Neighboring the Nordic Countries Mirror Anthropogenic Pollution Trends. Although there are well-documented health benefits of eating seafood (see, e.g., ref. 71), there is also strong evidence of human health risks (72, 73). Anthropogenic pollution (both organic and inorganic contaminants) is increasing in the ocean system. This is true even in remote areas with few coastal inhabitants, as a result of long-range transport.

The bioaccumulation and biomagnification of contaminants pose a direct threat to wildlife, but they also represent a hazard to human health. For example, food safety maximum limits of polychlorinated biphenyls (PCBs) and dioxins allowed in Atlantic cod by the European Union are currently exceeded for cod liver from the Baltic and North Sea (74). Significantly higher levels of brominated flame retardants (BFRs) were also found in the liver of cod and saithe (*Pollachius virens*) caught in the North Sea and Skagerrak compared to fish caught in the Norwegian Sea and Barents Sea (75), and there is general advice against eating cod liver from coastal populations in Norway. Furthermore, studies of biomarkers in natural populations of cod and haddock (*Melanogrammus aeglefinus*) indicate significant background pollution in the North Sea, potentially linked to decades of oil production and other anthropogenic sources (76).

Data support a trend of higher levels of contaminants in fish from southern areas in the seas neighboring the Nordic countries compared to areas north of the Arctic Circle, as exemplified by BFRs for Norwegian Spring Spawning herring, Atlantic halibut (*Hippoglossus hippoglossus*), Greenland halibut (*Reinhardtius hippoglossoides*), capelin (*Mallotus villosus*), European hake (*Merluccius merluccius*), and tusk (*Brosme brosme*) (75). Although these geographical trends seem to be stable over time, hot spots of high levels of contaminants have been worryingly detected in remote marine areas such as near Sklinnabanken in the Norwegian Sea (between 65°N and 66°N). In this area, high levels of mercury, dioxins, and dioxin-like PCBs were found in Atlantic halibut, leading to a local ban on halibut fishing.

Human Communities. In Arctic communities, human well-being is often intimately linked to natural resources, which are expected to be substantially impacted by climate change (77). Arctic indigenous people include, for example, Inuit, Nenets, and Saami, who are dependent on natural resources for food, local economies, and cultural and social identity. They will face challenges regarding health, food security, and possibly also the survival of lifestyles and cultures (78). The northward movement of natural resource exploitation will challenge current dwelling sites and harvest practices, and changing weather patterns will further compound the risks (79).

Climate change may also positively impact marine ecosystem services such as fisheries and aquaculture, benefiting local and indigenous communities. For example, it is projected that high-latitude areas will increase their catch potential by, on average, 30 to 70% by 2055 (80). Regional studies show greater stock fluctuations over time, but also potentially positive effects for countries like Iceland, Greenland, and Norway (81, 82). However, science-based resource management has been shown to be of even greater importance than climate change for the economic sustainability of fisheries in the region (82).

Hence, although some fisheries are expected to expand poleward (51), local communities still need to have the adaptive capacity to pursue these new opportunities (83). Receding land ice and sea ice facilitates access to mining (deep sea and land-based), petroleum extraction, tourism, and transport, which may strengthen the economies of Arctic communities but will also heighten the risk of local pollution and environmental disasters (84). Furthermore, the wealth distribution effects of climate change may vary highly for different groups in affected societies (85). It therefore seems plausible that the Arctic will present a wide spectrum of winners and losers as a result of climate change (Table 1). Future scenarios for economic activities are typically hampered by uncertainties, as they tend to ignore how key ecosystems will respond [to, e.g., acidification, colonization of invasive species, changing management, and new governance regimes (86)].

The Ocean We Need for the Future We Want

Data and knowledge from the Nordic countries illustrate how baselines are shifting and how the ocean is changing (Table 1). ICES, HELCOM, NEAFC, OSPAR, and the Norwegian−Russian collaboration in the Barents Sea provide individual and holistic overviews of the temporal and spatial trends of the marine environment, including information on human impact and societal needs for adaptation (87). Our synthesis here spans across all of the seas neighboring the Nordic countries and combines physical, biological, and societal perspectives, across scientific disciplines, in a collaboration between scientists from five countries. We argue that this synthesis is the first of its kind. Our findings illustrate that there is substantial potential in interdisciplinary efforts to make better sense of the observed changes, and help prepare society for the necessary policy decisions and societal adaptations. The long-term and widespread information available from the region also highlights the critical importance of concerted international action aimed to mitigate and address negative impacts from climate change.

The ocean provides nutritious food to a growing human population and mitigates climate change through the uptake of both heat and CO_2. Most projections suggest that these two roles will increase in importance, yet there is limited empirical evidence that the international community is able to address and handle these challenges at a speed and scale that substantially reduce the risk of dramatic negative change while also creating novel opportunities for the future. We argue that increased scientific collaboration, across disciplines, and between science and multiple actors in society, can improve the understanding of what is happening, and what needs to be done—at national, regional, and global levels (88, 89).

Committed to the Ocean: Lessons Learned

The lessons that we have identified here are summarized in Table 1. Above all, the Nordic countries show the importance of collaboration across scientific disciplines and stakeholders and between nations as a necessary condition for taking appropriate action. The Nordic countries have been early in contributing to the understanding of the dynamic ocean, for example, as evident by the early 19th century study by Johan Hjort (90). Nordic economies were strained at the turn of the previous century, and the educational level was low compared to that of today. Fisheries were among the most important industries for all Nordic countries, in terms of export, food production/animal protein consumption, and employment. The appreciation that scientific insights about the ocean were of central importance to adequate understanding of population dynamics and sustainable management was emerging. Acknowledging this, the geographical and biological connectedness of the seas neighboring the Nordic countries, and the necessity of continued surveys and observations, were hard-won insights that the countries have remained committed to.

Our collective Nordic experience may be summarized in three points: 1) Without extensive long-term observations of the physical and biological processes, decision-making in Nordic countries would have been subject to a high risk of failed management because natural and human-imposed variability would not have been fully accounted for when developing management policies; 2) without well-established science organizations, advice to stakeholders would often have relied on a few advisors (be it people or organizations) which makes them prone to biased perceptions and hence inferior management policies; and 3) without a well-established trust between policy makers and the science community, attuning to a changing ocean will be subject to arbitrary decision-making which might have unforeseen and negative outcomes.

A key overall feature of the Nordic countries is the long tradition of close collaboration between scientists from all disciplines with policy makers in order to develop capacity to better understand and respond to novel and complex interactions in the marine system. For instance, decades of constructing a regional database and geochemical models for the Baltic Sea (91) resulted in the identification of costs, benefits, and timelines of nutrient reduction targets for the Baltic Sea. Today, HELCOM has adopted this tool, based on long-term data, an established and credible institution, and mutual trust, as their primary decision support system (92). Similarly, international collaborations between scientists and decision makers from the Soviet Union (and, today, Russia) and Norway have also been instrumental for a sustainable management of the Barents Sea (93).

Nordic scientists have also been instrumental in 1) developing and advancing scientific collaboration for the entire northeast Atlantic region (within ICES) (94, 95), 2) a science-based process of change among transnational seafood corporations (96) providing means to stimulate "corporate biosphere stewardship" among major ocean industries, and 3) coordinating the collection of evidence linking the antifouling agent tributyltin to extreme adverse effects on marine life and the effect of mitigation measures (97, 98). It is clear that the collection and sharing of data across national boundaries, and collaboration between scientific disciplines and with stakeholders (including collecting and using data from diverse stakeholders), are paramount for developing relationships based on trust and for science-based governance.

Working together for the common good is a long-term investment. A commitment to unbroken records of observations, educational opportunities, dissemination of knowledge and continuous knowledge exchange, collaborative learning, and communication between scientists, politicians, decision makers, corporate executives, indigenous communities, civil society organizations, and other stakeholders is critical. Humans are undoubtedly linked to the ocean. But the future of the ocean and all of its interacting physical components and ecosystems hinges both on our ability to ramp up the measures that can mitigate unwanted and unexpected effects due to an ever-stronger human influence on global climate and on our ability to collaborate in respectful, smart, and durable ways.

Our interdisciplinary assessment of current knowledge indicates that scientists need to better appreciate the interwoven, changing, and complex nature of the ocean and societies, in order to be able to provide a holistic understanding of the systems involved and potential pathways of change (99). We recognize the interdependency of processes and how their combination and interactions change the system across all levels, from physical and chemical dynamics to biological systems, human behavior, and management (100). This, however, is not how science is organized, and it has been a challenge—even in this small group—to develop an interest and understanding across disciplines. Most scientists are, indeed, not trained with adequate skills to understand and approach marine social–ecological systems in a holistic way, and from a broad spectrum of the natural and social sciences. The United Nation's Decade of Ocean Science for Sustainable Development starting in 2021 may further develop collaboration across disciplines and between nations. On the international scene, the high-level panel for a sustainable ocean economy (101, 102), led by the current Norwegian Prime Minister Erna Solberg, can be expected to profoundly contribute to this development, not least due to its international and interdisciplinary perspective.

We posit that the scale of current challenges requires scientists to take on a greater responsibility and engage more actively in society, with policy makers and with business leaders from small, medium, and large firms (103). Lessons from the Nordic countries suggest that the role of independent basic science is more critical than ever before (104).

Data Availability

There are no data underlying this work.

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1 J. Zalasiewicz *et al.*, When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quat. Int.* **383**, 196–203 (2015).
2 H. Österblom, B. I. Crona, C. Folke, M. Nyström, M. Troell, Marine ecosystem science on an intertwined planet. *Ecosystems* **20**, 54–61 (2017).
3 W. Swartz, E. Sala, S. Tracey, R. Watson, D. Pauly, The spatial expansion and ecological footprint of fisheries (1950 to present). *PLoS One* **5**, e15143 (2010).
4 B. S. Halpern *et al.*, A global map of human impact on marine ecosystems. *Science* **319**, 948–952 (2008).
5 J.-P. Gattuso *et al.*, Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science* **349**, aac4722 (2015).
6 J. Rockstrom *et al.*, Planetary boundaries: Exploring the safe operating space for humanity. *Ecol. Soc.* **14**, 32 (2009).
7 B. S. Halpern *et al.*, Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nat. Commun.* **6**, 7615 (2015).
8 M. L. Pinsky, A. M. Eikeset, D. J. McCauley, J. L. Payne, J. M. Sunday, Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature* **569**, 108–111 (2019).
9 O. Paasche *et al.*, Connecting the Seas of Norden. *Nat. Clim. Chang.* **5**, 89–92 (2015).
10 T. B. H. Reusch *et al.*, The Baltic Sea as a time machine for the future coastal ocean. *Sci. Adv.* **4**, eaar8195 (2018).
11 L. C. Jackson *et al.*, Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Clim. Dyn.* **45**, 3299–3316 (2015).
12 Intergovernmental Panel on Climate Change, *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, H.-O. Pörtner *et al.*, Eds. (Intergovernmental Panel on Climate Change, 2019).
13 W. Liu, S.-P. Xie, Z. Liu, J. Zhu, Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Sci. Adv.* **3**, e1601666 (2017).
14 J. F. McManus, R. Francois, J. M. Gherardi, L. D. Keigwin, S. Brown-Leger, Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature* **428**, 834–837 (2004).

15 S. Rahmstorf *et al.*, Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nat. Clim. Chang.* **5**, 475–480 (2015).
16 S. Østerhus *et al.*, Arctic Mediterranean exchanges: A consistent volume budget and trends in transports from two decades of observations. *Ocean Sci.* **15**, 379–399 (2019).
17 P. Gierz, G. Lohmann, W. Wei, Response of Atlantic overturning to future warming in a coupled atmosphere-ocean-ice sheet model. *Geophys. Res. Lett.* **42**, 6811–6818 (2015).
18 T. Eldevik *et al.*, A brief history of climate—The northern seas from the Last Glacial Maximum to global warming. *Quat. Sci. Rev.* **106**, 225–246 (2014).
19 M. C. Serreze, R. G. Barry, Processes and impacts of Arctic amplification: A research synthesis. *Global Planet. Change* **77**, 85–96 (2011).
20 A. Dai, D. Luo, M. Song, J. Liu, Arctic amplification is caused by sea-ice loss under increasing CO_2. *Nat. Commun.* **10**, 121 (2019).
21 J. C. Comiso, Large decadal decline of the Arctic multiyear ice cover. *J. Clim.* **25**, 1176–1193 (2012).
22 M. Fossheim *et al.*, Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nat. Clim. Chang.* **5**, 673–677 (2015).
23 M. Wang, J. E. Overland, A sea ice free summer Arctic within 30 years? *Geophys. Res. Lett.* **36**, L07502 (2009).
24 SIMIP Community, Arctic sea ice in CMIP6. *Geophys. Res. Lett.* **47**, e2019GL086749 (2020).
25 J. C. Stroeve *et al.*, Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophys. Res. Lett.* **39**, L16502 (2012).
26 I. H. Onarheim, M. Årthun, Toward an ice-free Barents Sea. *Geophys. Res. Lett.* **44**, 8387–8395 (2017).
27 BACC II Author Team, *Second Assessment of Climate Change for the Baltic Sea Basin, Regional Climate Studies* (Springer International, Cham, Switzerland, 2015).
28 W. Walczowski, J. Piechura, Pathways of the Greenland Sea warming. *Geophys. Res. Lett.* **34**, L10608 (2007).
29 I. H. Onarheim, T. Eldevik, M. Årthun, R. B. Ingvaldsen, L. H. Smedsrud, Skillful prediction of Barents Sea ice cover. *Geophys. Res. Lett.* **42**, 5364–5371 (2015).
30 Intergovernmental Panel on Climate Change, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge University Press, Cambridge, United Kingdom, 2013).
31 L. Guo, C.-L. Ping, R. W. Macdonald, Mobilization pathways of organic carbon from permafrost to arctic rivers in a changing climate. *Geophys. Res. Lett.* **34**, L13603 (2007).
32 A. Olsen, A. M. Omar, E. Jeansson, L. G. Anderson, R. G. J. Bellerby, Nordic seas transit time distributions and anthropogenic CO_2. *J. Geophys. Res.* **115**, C05005 (2010).
33 J. T. Mathis, J. N. Cross, N. R. Bates, Coupling primary production and terrestrial runoff to ocean acidification and carbonate mineral suppression in the eastern Bering Sea. *J. Geophys. Res.* **116**, C02030 (2011).
34 L. G. Anderson, S. Jutterström, S. Hjalmarsson, I. Wåhlström, I. P. Semiletov, Out-gassing of CO_2 from Siberian Shelf seas by terrestrial organic matter decomposition. *Geophys. Res. Lett.* **36**, L20601 (2009).
35 Arctic Monitoring and Assessment Programme, *AMAP Assessment 2018: Arctic Ocean Acidification* (Arctic Monitoring and Assessment Programme, Tromsø, Norway, 2018).
36 J. Wikner, A. Andersson, Increased freshwater discharge shifts the trophic balance in the coastal zone of the northern Baltic Sea. *Glob. Change Biol.* **18**, 2509–2519 (2012).
37 E. T. Harvey, S. Kratzer, A. Andersson, Relationships between colored dissolved organic matter and dissolved organic carbon in different coastal gradients of the Baltic Sea. *Ambio* **44** (suppl. 3), 392–401 (2015).
38 A. Omstedt *et al.*, Future changes in the Baltic Sea acid–base (pH) and oxygen balances. *Tellus B Chem. Phys. Meteorol.* **64**, 19586 (2012).
39 C. Pelejero, E. Calvo, O. Hoegh-Guldberg, Paleo-perspectives on ocean acidification. *Trends Ecol. Evol.* **25**, 332–344 (2010).
40 IPCC, *Climate Change 2014: Impacts, Adaptation, and Vulnerability–Part B: Regional Aspects–Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, V. R. Barros *et al.*, Eds. (Cambridge University Press, Cambridge, United Kingdom, 2014).
41 K. T. Frank, B. Petrie, N. L. Shackell, The ups and downs of trophic control in continental shelf ecosystems. *Trends Ecol. Evol.* **22**, 236–242 (2007).
42 M. Kahru, V. Brotas, M. Manzano-Sarabia, B. G. Mitchell, Are phytoplankton blooms occurring earlier in the Arctic? *Glob. Change Biol.* **17**, 1733–1739 (2011).
43 E. Johannesen *et al.*, Changes in Barents Sea ecosystem state, 1970–2009: Climate fluctuations, human impact, and trophic interactions. *ICES J. Mar. Sci.* **69**, 880–889 (2012).
44 J. Spijkers, W. J. Boonstra, Environmental change and social conflict: The Northeast Atlantic mackerel dispute. *Reg. Environ. Change* **17**, 1835–1851 (2017).
45 A. Yool, E. E. Popova, A. C. Coward, Future change in ocean productivity: Is the Arctic the new Atlantic? *J. Geophys. Res. Oceans* **120**, 7771–7790 (2015).
46 D. Slagstad, P. F. J. Wassmann, I. Ellingsen, Physical constrains and productivity in the future Arctic Ocean. *Front. Mar. Sci.* **2**, 85 (2015).
47 T. J. Langbehn, Ø. Varpe, Sea-ice loss boosts visual search: Fish foraging and changing pelagic interactions in polar oceans. *Glob. Change Biol.* **23**, 5318–5330 (2017).
48 H. Hop, H. Gjøsæter, Polar cod (*Boreogadus saida*) and capelin (*Mallotus villosus*) as key species in marine food webs of the Arctic and the Barents Sea. *Mar. Biol. Res.* **9**, 878–894 (2013).
49 F. J. Mueter, J. Weems, E. V. Farley, M. F. Sigler, Arctic Ecosystem Integrated Survey, (Arctic Eis): Marine ecosystem dynamics in the rapidly changing Pacific Arctic Gateway. *Deep Sea Res. Part II Top. Stud. Oceanogr.* **135**, 1–6 (2017).
50 J. S. Christiansen *et al.*, Novel biodiversity baselines outpace models of fish distribution in Arctic waters. *Naturwissenschaften* **103**, 8 (2016).
51 M. L. Pinsky, B. Worm, M. J. Fogarty, J. L. Sarmiento, S. A. Levin, Marine taxa track local climate velocities. *Science* **341**, 1239–1242 (2013).
52 K. Kabel *et al.*, Impact of climate change on the Baltic Sea ecosystem over the past 1,000 years. *Nat. Clim. Chang.* **2**, 871–874 (2012).
53 Conservation of Arctic Flora and Fauna, *Arctic Biodiversity Assessment. Status And Trends in Arctic Biodiversity* (Arctic Council, Akureyri, Iceland, 2013).
54 A. J. Andrews *et al.*, Boreal marine fauna from the Barents Sea disperse to Arctic Northeast Greenland. *Sci. Rep.* **9**, 5799 (2019).
55 W. W. L. Cheung *et al.*, Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. *Nat. Clim. Chang.* **3**, 254–258 (2013).
56 A. Audzijonyte, A. Kuparinen, R. Gorton, E. A. Fulton, Ecological consequences of body size decline in harvested fish species: Positive feedback loops in trophic interactions amplify human impact. *Biol. Lett.* **9**, 20121103 (2013).
57 C. N. K. Anderson *et al.*, Why fishing magnifies fluctuations in fish abundance. *Nature* **452**, 835–839 (2008).
58 A. Kuparinen, A. Boit, F. S. Valdovinos, H. Lassaux, N. D. Martinez, Fishing-induced life-history changes degrade and destabilize harvested ecosystems. *Sci. Rep.* **6**, 22245 (2016).
59 R. E. Zeebe, A. Ridgwell, J. C. Zachos, Anthropogenic carbon release rate unprecedented during the past 66 million years. *Nat. Geosci.* **9**, 325–329 (2016).
60 A. C. Wittmann, H.-O. Pörtner, Sensitivities of extant animal taxa to ocean acidification. *Nat. Clim. Chang.* **3**, 995–1001 (2013).
61 N. Bednaršek *et al.*, *Limacina helicina* shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. *Proc. Biol. Sci.* **281**, 20140123 (2014).
62 IPCC, *Climate Change 2014: Impacts, Adaptation, and Vulnerability–Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field *et al.*, Eds. (Cambridge University Press, New York, NY, 2014).
63 S. J. Lade *et al.*, An empirical model of the Baltic Sea reveals the importance of social dynamics for ecological regime shifts. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 11120–11125 (2015).
64 M. Skern-Mauritzen *et al.*, Ecosystem processes are rarely included in tactical fisheries management. *Fish Fish.* **17**, 165–175 (2016).
65 T. Blenckner *et al.*, Climate and fishing steer ecosystem regeneration to uncertain economic futures. *Proc. Biol. Sci.* **282**, 20142809 (2015).
66 C. Costello *et al.*, Global fishery prospects under contrasting management regimes. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 5125–5129 (2016).
67 U. R. Sumaila *et al.*, Benefits of rebuilding global marine fisheries outweigh costs. *PLoS One* **7**, e40542 (2012).
68 O. S. Kjesbu *et al.*, Synergies between climate and management for Atlantic cod fisheries at high latitudes. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 3478–3483 (2014).

69 M. Dickey-Collas *et al.*, Lessons learned from stock collapse and recovery of North Sea herring: A review. *ICES J. Mar. Sci.* **67**, 1875–1886 (2010).
70 M. Lindegren, C. Möllmann, A. Nielsen, N. C. Stenseth, Preventing the collapse of the Baltic cod stock through an ecosystem-based management approach. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 14722–14727 (2009).
71 C. D. Golden *et al.*, Nutrition: Fall in fish catch threatens human health. *Nature* **534**, 317–320 (2016).
72 M. R. Karagas *et al.*, Evidence on the human health effects of low-level methylmercury exposure. *Environ. Health Perspect.* **120**, 799–806 (2012).
73 A. C. Bosch, B. O'Neill, G. O. Sigge, S. E. Kerwath, L. C. Hoffman, Heavy metals in marine fish meat and consumer health: A review. *J. Sci. Food Agric.* **96**, 32–48 (2016).
74 H. Karl *et al.*, Large scale distribution of dioxins, PCBs, heavy metals, PAH-metabolites and radionuclides in cod (*Gadus morhua*) from the North Atlantic and its adjacent seas. *Chemosphere* **149**, 294–303 (2016).
75 O. J. Nøstbakken *et al.*, Factors influencing risk assessments of brominated flame-retardants; evidence based on seafood from the North East Atlantic Ocean. *Environ. Int.* **119**, 544–557 (2018).
76 L. Balk *et al.*, Biomarkers in natural fish populations indicate adverse biological effects of offshore oil production. *PLoS One* **6**, e19735 (2011).
77 J. N. Larsen, G. Fondahl, Eds., *Arctic Human Development Report: Regional Processes and Global Linkages* (Nordisk Ministerråd, Copenhagen, Denmark, 2015).
78 B. Evengård, J. Nymand Larsen, Ø. Paasche, Eds., *The New Arctic* (Springer International, Cham, Switzerland, 2015).
79 Arctic Climate Impact Assessment, *Impacts of a Warming Arctic: Arctic Climate Impact Assessment* (Cambridge University Press, Cambridge, United Kingdom, 2004).
80 W. W. L. Cheung *et al.*, Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Glob. Change Biol.* **16**, 24–35 (2010).
81 R. Árnason, Climate change and fisheries: Assessing the economic impact in Iceland and Greenland. *Nat. Resour. Model.* **20**, 163–197 (2007).
82 A. Eide, An integrated study of economic effects of and vulnerabilities to global warming on the Barents Sea cod fisheries. *Clim. Change* **87**, 251–262 (2008).
83 K. O'Brien, S. Eriksen, L. Sygna, L. O. Naess, Questioning complacency: Climate change impacts, vulnerability, and adaptation in Norway. *Ambio* **35**, 50–56 (2006).
84 E. J. Stewart, S. E. L. Howell, D. Draper, J. Yackel, A. Tivy, Sea ice in Canada's Arctic: Implications for cruise tourism. *Arctic* **60**, 370–380 (2007).
85 E. P. Fenichel *et al.*, Wealth reallocation and sustainability under climate change. *Nat. Clim. Chang.* **6**, 237–244 (2016).
86 B. R. MacKenzie, H. Gislason, C. Möllmann, F. W. Köster, Impact of 21st century climate change on the Baltic Sea fish community and fisheries. *Glob. Change Biol.* **13**, 1348–1367 (2007).
87 HELCOM, *State of the Baltic Sea–Second HELCOM holistic assessment 2011-2016: Baltic Sea Environment Proceedings 155*, L. Bergström *et al.*, Eds. (HELCOM, 2018).
88 A. L. Carew, F. Wickson, The TD Wheel: A heuristic to shape, support and evaluate transdisciplinary research. *Futures* **42**, 1146–1155 (2010).
89 D. J. Lang *et al.*, Transdisciplinary research in sustainability science: Practice, principles, and challenges. *Sustain. Sci.* **7**, 25–43 (2012).
90 J. Hjort, Fluctuations in the great fisheries of Northern Europe viewed in the light of biological research. *Rapp. Proces-verbaux Reunions Conseil Int. l'Exploration Mer* **20**, 1–228. (1914).
91 B. G. Gustafsson, M. R. Medina, "Validation data set compiled from Baltic Environmental Database–Version 2" (Tech. Rep. 2, Baltic Nest Institute, 2011), p. 25.
92 F. Wulff *et al.*, Reduction of Baltic Sea nutrient inputs and allocation of abatement costs within the Baltic Sea catchment. *Ambio* **43**, 11–25 (2014).
93 M. Hammer, A. H. Hoel, The development of scientific cooperation under the Norway–Russia Fisheries Regime in the Barents Sea. *Arct. Rev. Law Polit.* **3**, 244–274 (2012).
94 K. Stange, P. Olsson, H. Österblom, Managing organizational change in an international scientific network: A study of ICES reform processes. *Mar. Policy* **36**, 681–688 (2012).
95 R. L. Stephenson, K. L. Clark, The role of ICES herring investigations in shaping fisheries science and management. *ICES Mar. Sci. Symp.* **215**, 504–514 (2002).
96 H. Österblom, J.-B. Jouffray, C. Folke, J. Rockström, Emergence of a global science-business initiative for ocean stewardship. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 9038–9043 (2017).
97 P. Matthiessen, P. E. Gibbs, Critical appraisal of the evidence for tributyltin-mediated endocrine disruption in mollusks. *Environ. Toxicol. Chem.* **17**, 37–43 (1998).
98 M. Schøyen *et al.*, Levels and trends of tributyltin (TBT) and imposex in dogwhelk (*Nucella lapillus*) along the Norwegian coastline from 1991 to 2017. *Mar. Environ. Res.* **144**, 1–8 (2019).
99 A. E. Bates *et al.*, Biologists ignore ocean weather at their peril. *Nature* **560**, 299–301 (2018).
100 P. W. Boyd, S. T. Lennartz, D. M. Glover, S. C. Doney, Biological ramifications of climate-change-mediated oceanic multi-stressors. *Nat. Clim. Chang.* **5**, 71–79 (2015).
101 J.-G. Winther *et al.*, *Integrated Ocean Management* (World Resources Institute, Washington, DC, 2020).
102 J.-G. Winther *et al.*, Integrated ocean management for a sustainable ocean economy. *Nat. Ecol. Evol.*, 10.1038/s41559-020-1259-6.
103 European Commission, Rome Declaration on Responsible Research and Innovation in Europe. (2014). https://ec.europa.eu/digital-single-market/en/news/rome-declaration-responsible-research-and-innovation-europe. Accessed 23 July 2020.
104 A. Flexner, The usefulness of useless knowledge. *Harper's Magazine*, June/November 1939, pp. 544–552.