frontiers in Marine Science

ORIGINAL RESEARCH
published: 14 June 2016
doi: 10.3389/fmars.2016.00093

CrossMark

Stakeholder-Informed Ecosystem Modeling of Ocean Warming and Acidification Impacts in the Barents Sea Region

Stefan Koenigstein[1]*, *Matthias Ruth*[2] and *Stefan Gößling-Reisemann*[1]

[1] Sustainability Research Center (artec) and Department for Resilient Energy Systems, University of Bremen, Bremen, Germany, [2] School of Public Policy and Urban Affairs, Department of Civil and Environmental Engineering, Northeastern University, Boston, MA, USA

OPEN ACCESS

Edited by:
Beate M. W. Ratter,
University of Hamburg, Germany

Reviewed by:
Carolyn J. Lundquist,
National Institute of Water and Atmospheric Research, New Zealand
Edward Jeremy Hind,
Manchester Metropolitan University, UK

***Correspondence:**
Stefan Koenigstein
koenigstein@uni-bremen.de

Specialty section:
This article was submitted to Marine Conservation and Sustainability,
a section of the journal Frontiers in Marine Science

Received: 18 March 2016
Accepted: 27 May 2016
Published: 14 June 2016

Citation:
Koenigstein S, Ruth M and Gößling-Reisemann S (2016) Stakeholder-Informed Ecosystem Modeling of Ocean Warming and Acidification Impacts in the Barents Sea Region. Front. Mar. Sci. 3:93. doi: 10.3389/fmars.2016.00093

Climate change and ocean acidification are anticipated to alter marine ecosystems, with consequences for the provision of marine resources and ecosystem services to human societies. However, considerable uncertainties about future ecological changes and ensuing socio-economic impacts impede the identification of societal adaptation strategies. In a case study from the Barents Sea and Northern Norwegian Sea region, we integrated stakeholder perceptions of ecological changes and their significance for societies with the current state of scientific knowledge, to investigate the marine-human system under climate change and identify societal adaptation options. Stakeholders were engaged through personal interviews, two local workshops, and a web based survey, identifying the most relevant ecosystem services potentially impacted and developing an integrated system dynamics model which links climate change scenarios to the response of relevant species. Stakeholder perceptions of temperature-dependent multiannual fluctuations of fish stocks, interactions among fish, marine mammal, and seabird populations, and ecological processes such as primary production are represented in the model. The model was used for a discourse-based stakeholder evaluation of potential ecosystem changes under ocean warming and acidification scenarios, identifying shifts in ecosystem service provision and discussing associated societal adaptation options. The results pointed to differences in adaptive capacity among user groups. Small-scale fishers and tourism businesses are potentially more affected by changing spatial distribution and local declines in marine species than industrial fisheries. Changes in biodiversity, especially extinctions of polar species, and ecosystem functioning were a concern from an environmental conservation viewpoint. When considering potential additional impacts of ocean acidification, changes observed in the model projections were more uniformly valued as negative, and associated with an increased potential for conflicts among user groups. The stakeholder-informed ecosystem modeling approach has succeeded in driving a discussion and interchange among stakeholder groups and with scientists, integrating knowledge about climate change impacts in the social-ecological system and identifying important factors that shape societal responses. The approach can thus serve to improve governance of marine systems by incorporating knowledge about system dynamics and about societal uses and values.

Keywords: participatory modeling, marine ecosystem services, marine systems, climate change adaptation, ocean acidification, Barents Sea

INTRODUCTION

Under global climate change, the oceans are undergoing profound changes. Ocean warming, acidification (decreasing pH values), deoxygenation (insufficient oxygen levels), and other physical and chemical changes are anticipated to affect marine species, drive changes in marine ecosystem structure and dynamics, and impact the productivity of marine ecosystems and the provision of ecosystem services to human societies (Pörtner et al., 2014; Gattuso et al., 2015). Ocean warming is already observed to lead to poleward shifts in the spatial distribution of marine organisms, facilitating species invasions into regional ecosystems, and causing local or regional extinctions by exceeding the thermal tolerance limits of organisms (Poloczanska et al., 2013). Ocean acidification, the decrease in water pH via increasing solution of atmospheric CO_2, is anticipated to impact different organism groups in marine ecosystems (Kroeker et al., 2013). Increased mortality and structural damages observed in laboratory experiments with early life stages of fish under future ocean pH values cause concern about the future of fish stocks (Munday et al., 2010; Denman et al., 2011).

Nevertheless, considerable uncertainty compounds the analysis of ecosystem-level effects of multiple climate change drivers, and their interactions with anthropogenic impacts and human uses (Gattuso et al., 2015; Riebesell and Gattuso, 2015). Ecological models are increasingly playing an important role in an integrated assessment of these effects in marine social-ecological systems (Perry et al., 2010; Osterblom et al., 2013). A wide range of human uses and activities will be affected by climate change impacts on marine systems (Allison and Bassett, 2015). Economic and nutritional dependence on marine resources, and vulnerability toward change differs strongly among countries (Allison et al., 2009). While societies have a range of options to adapt to changes in marine living resources, e.g., increase of exploitation efforts or economic diversification, these depend on economic, social and cultural conditions (Perry et al., 2011; Haynie and Pfeiffer, 2012). The ecosystem services concept (Millenium Ecosystem Assessment, 2005) can serve as a framework for assessing changes in societal benefits provided by marine ecosystems, like food provision from fisheries and aquaculture, carbon uptake and climate regulation, bioremediation, and nutrient cycling, or recreation and cultural services (Beaumont et al., 2007). To improve the scientific basis for quantifying changes in the provision of these services and important trade-offs among services, assessment methodologies must be equipped to capture the multidimensional nature of the value of ecosystems, to enable better informed individual and institutional decisions and improve governance mechanisms (Daily et al., 2009; Kittinger et al., 2014). Since ecosystem services are ultimately defined by society and governance decisions should be more effective when supported by affected societal groups, there is strong rationale for stakeholder participation as an integral part of ecosystem assessment processes.

We present a regional case study on climate change impacts on ecosystem service provision in the Barents Sea and Northern Norwegian Sea area. In Norway, the oceans play an important economic and cultural role. The fisheries sector with a production of 2.3 million tons of fish and 12.800 employees in 2011 makes the country the world's second-largest seafood exporter after China (FAO, 2013), divided between industrial off-shore fishing, aquaculture mostly of Atlantic salmon, and small-scale coastal fisheries. Main capture fish species are Atlantic cod (*Gadus morhua*), Atlantic herring (*Clupea harengus*), capelin (*Mallotus villosus*), Atlantic mackerel (*Scomber scombrus*), saithe (*Pollachius virens*), and other whitefish. Norway's national fisheries management is generally seen as well-regulated, science-driven, internationally cooperative and sustainable (FAO, 2013, 2014). Fishers participate in management via national and regional fisheries associations and provide catch information (Johnsen, 2013; Jentoft and Mikalsen, 2014). In recent years, good management and favorable environmental conditions under ocean warming have facilitated large fish stock sizes such as of Barents Sea cod (Eide et al., 2013; Kjesbu et al., 2014). Nevertheless, future climate change represents a considerable challenge for Norwegian fisheries management (Harsem and Hoel, 2012), and recent integrated, ecosystem-based coastal zone management plans recognize important knowledge gaps with regard to the impacts of climate change and ocean acidification (Hoel and Olsen, 2012).

The Barents Sea is projected to experience rapid ocean warming in the next decades, which together with a reduced extent of Arctic sea ice is already leading to pronounced changes in ecological community composition, spatial distribution and biomass of fish stocks, and thus, fisheries provision (Hollowed and Sundby, 2014; Fossheim et al., 2015; Kortsch et al., 2015). At the same time, Arctic and subarctic areas will be affected by the strongest pH changes expected worldwide until the end of the century, with Arctic waters becoming corrosive to some shell-producing organisms. Thus, changes in food web structure and also direct impacts on fish stocks are expected, but still subject to high scientific uncertainty (AMAP, 2013). The comparatively simple food web in the Barents Sea is expected to be more vulnerable to impacts on certain keystone or bottleneck species than ecosystems with higher species diversity (Wassmann et al., 2006; Duarte et al., 2012).

We constructed an ecological model of the expected impacts of ocean warming and acidification on marine ecosystem services in the Barents sea region, based on input from potentially affected stakeholder groups (Costanza and Ruth, 1998; Voinov and Bousquet, 2010). We incorporated stakeholder input regarding which ecosystem elements and processes to include in the model, and used stakeholder perceptions to assess which human uses and societal groups may be impacted by environmental changes in the region. Thus, stakeholders served as representatives of society, to integrate local knowledge and concerns, identify relevant ecosystem elements and services, evaluate projected changes under scientific uncertainties, and identify societal adaptation options (Walker et al., 2002). This integrated social-ecological systems approach is applied with the aim of increasing resilience of marine-human systems and improving adaptive capacity (Hughes et al., 2005), to discover governance options for a more sustainable use of marine resources under climate change.

MATERIALS AND METHODS

Stakeholder Consultation

For an initial compilation of potential ecosystem changes under climate change in the focus area, the scientific literature was screened for an overview of the problem (reviews on regional ecosystems and on climate change and ocean acidification impacts, reports of expert groups, news, and outreach products produced by regional scientific institutes). To compare these findings to relevant topics of concern for the users, internet-based news portals aimed at regional stakeholders, archives of newspapers of general interest and for user groups (e.g., fisheries magazines) were screened for recent prominent topics. Ten interviews with regional scientific experts with a background in marine ecology, governance of marine resources and areas, oceanography, ecosystem modeling, fisheries science, and other disciplines, further helped to identify potentially affected ecosystem services and stakeholders. Interviews with 25 stakeholders of potentially affected groups from Norway and Russia were conducted in different locations in Norway (Oslo, Bergen, Tromsø, Bodø, Lofoten Islands, Finnmark, Svalbard) or via email between March and September 2013. Stakeholders included representatives from fishing associations and aquaculture companies, individual small-scale fishers, tourism operators (hotels/camps, sport fishing, whale watching), non-governmental organizations (including environmental conservation and indigenous Sami groups), and governmental agencies (Fisheries and Environmental Directorates). The personal interviews aimed at identifying (1) the general socio-economic situation of participants, (2) perceptions and concerns about regional ecosystem impacts of climate change, (3) the communication between science, politics and stakeholders about expected impacts, (4) societal impacts and adaptation options to climate change, and (5) management options and political adaptation strategies (Supplemental File S1: Interview questionnaire). Participants were also asked for their personal opinion on further potentially affected societal groups, to open up the investigation to ecosystem services and user groups not initially identified.

The most frequently mentioned ocean uses, climate-related concerns, and ecosystem interactions from stakeholder interviews which could be linked to elements of the marine ecosystem, were compiled to form the basis of the model (**Table 1**). A model-building workshop with stakeholders was held in Bergen, Southern Norway in October 2013, where stakeholders were introduced to the topics of the research project and the current state of scientific knowledge about climate change impacts on marine ecosystems. A draft of the model structure based on the identification of relevant ecosystem services and elements from the interviews was presented. Stakeholder comments on the model structure and requests for further elements and services to be included were collected to inform further model development (Koenigstein and Goessling-Reisemann, 2014).

Integrative System Dynamics Model

A system dynamics model (Costanza and Ruth, 1998) was developed in the modeling software STELLA 9.1, and later converted to STELLA Professional 1.0 (www.iseesystems.com). Its structure was based on the most relevant ecological elements and processes that can be linked and quantified using empirical biological results. Graphical icons for species and ecosystem services were designed and integrated into the model interface to make the model structure more easily accessible to stakeholders. The model was based on a multi-species population structure, with biological processes governing population dynamics of the integrated species, and interactions among species represented by predation and consumption (**Figure 1**).

The model structure incorporates the marine species of high importance to the various stakeholder groups, and the most commonly mentioned biological processes. Some ecologically similar species were aggregated to groups ("other baleen whales," seals, "other seabirds") to limit model complexity, and/or combined in modules (tooth whales, baleen whales, seabirds) in the model interface. Aggregate representations of lower trophic levels (one phytoplankton and three zooplankton groups) were used to base the biomass flow through the food web on a primary production process, integrating stakeholder concerns about primary production and the ecosystem services of carbon uptake and export (**Figure 1A**). Due to the importance of fish stock recruitment in stakeholder concerns, fish populations were divided into two to four life stages and embedded in a self-enhancing feedback of reproduction and recruitment processes.

Ocean warming and acidification were incorporated as changes in fish and zooplankton consumption and growth, based on physiological thermal growth windows (Pörtner and Farrell, 2008) and assuming an increasing loss of metabolic energy under acidification reaching up to 10% of the total energy uptake (**Figure 1C**). Driver scenarios for temperature and pH were incorporated based on IPCC (Intergovernmental Panel on Climate Change) ensemble earth system model projections for the Barents Sea under the RCP (Representative Concentration Pathway) 8.5 ("business-as-usual") emission scenario (AMAP, 2013; Bopp et al., 2013; Collins et al., 2013). Temperature was additionally adjusted to undergo seasonal fluctuation and an inter-annual oscillation with a period of 8 years (**Figure 1B**),

TABLE 1 | Stakeholder concerns and observations with regard to climate change impacts on marine ecosystems, from personal interviews with stakeholders from the fisheries sector (F), tour providers and other tourism businesses (T), and environmental and other non-governmental organizations (E), ranked by sum over sectors (seven participants for each sector, one additional aquaculture representative for the fisheries sector).

Species of interest and/or concern				
	F	***T***	***E***	***Σ***
Atlantic cod	7	5	5	17
Mackerel	6	5	5	16
Kelp/Seaweeds	2	1	4	7
Herring	6		1	7
King crab	2		3	5
Capelin	3		1	4
Atlantic Halibut	1	2	1	4
Haddock	2		2	4
Shellfish (mussels, scallops, etc.)	2	1	1	4
Zooplankton	2		1	3
Sea urchins		1	2	3
Blue whiting	3			3
Lobster	0	1	1	2
Shrimps	2			2
Atlantic salmon			2	2
Seabass	1		1	2
Saithe	1		1	2
(Cold water) corals	1		1	2
Dolphins and pilot whales		2		2
Minke whales	1	1		2
Orcas		2		2
Redfish	1	1		2
Seabirds		1	1	2
Seals		1	1	2
Sperm whales		1	1	2
Total: marine mammals	1	7	2	10
Total: fish	30	14	20	64
Total: benthic organisms	12	4	12	28

General ecosystem observations				
	F	***T***	***E***	***Σ***
Feeding interactions/competition	8	3	3	14
Fish larvae/spawning/stock recruitment	5	5	2	12
Natural fluctuations in abundance	5	2	2	9
Primary production	4	1		5
Phenology/migration patterns	2	1	2	5
Local fish declines in fjords			3	3
Regime shifts			2	2
Fish size	1	1		2
Fish more distant to coast		1		1
Observations and concerns linked to climate change				
Fish stock abundance or productivity changes	6	4	4	14
Distribution range shifts	7	2	4	13
Ocean warming	6	2	3	11
Immigrating species	4	3	3	10
Ice melting/ice coverage	4	1	3	8
Sea level rise/wave height		4	3	7
Ocean acidification	3		2	5
Oceanic currents	2		1	3
Threatened Arctic species		1	2	3
International disputes	3			3
Habitat reduction		1	1	2
Snow melt		2		2
Increased precipitation and nutrient influx			2	2
Harmful algae blooms			2	2
Extreme weather events	1		1	2
Milder winters	1			1
Fish migrations to deeper waters	1			1
Anoxia in fjord depths			1	1

Number of instances mentioned across interviews for species of interest or concern (only species mentioned more than once), general ecosystem observations, and observations or concerns explicitly linked to climate change impacts (detailed interview questions given in Supplemental File S1).

mimicking the natural fluctuations linked to the North Atlantic Oscillation (Ottersen et al., 2001) as mentioned in the stakeholder interviews. Marine mammal and seabird populations were modeled without direct effects of warming or acidification, as empirically observed changes are mostly indirectly caused through food web changes (Sandvik et al., 2005; Simmonds and Isaac, 2007). Fishing was incorporated as an additional biomass extraction process for fish and minke whales (*Balaenoptera acutorostrata*), defined as fixed relationships between stock sizes and landings in the following year, based on past quota agreements. Details of model parameterization, calibration and validation will be described in a separate publication, as we focus on the incorporation of stakeholder perceptions into the model and their assessment of the results here. The graphical interface of the model included dynamic displays of the states of the relevant biomass compartments and other indicators in the model over time, grouped in combined graphs aimed at each of the three stakeholder groups in the model valuation workshop (**Figure 1D**).

Model Evaluation and Identification of Adaptation Options

A web-based online survey was prepared to evaluate the relative importance of socio-economic framing factors identified in the interviews, created in a Norwegian and an English version using the platform Limesurvey by the provider Limeservice (www.limeservice.com). This served to prepare input for the discussions in the second workshop and helped the creation of framing scenarios at a later time. Factors already included in the model (e.g., ocean temperature or marine organism abundances) were not surveyed.

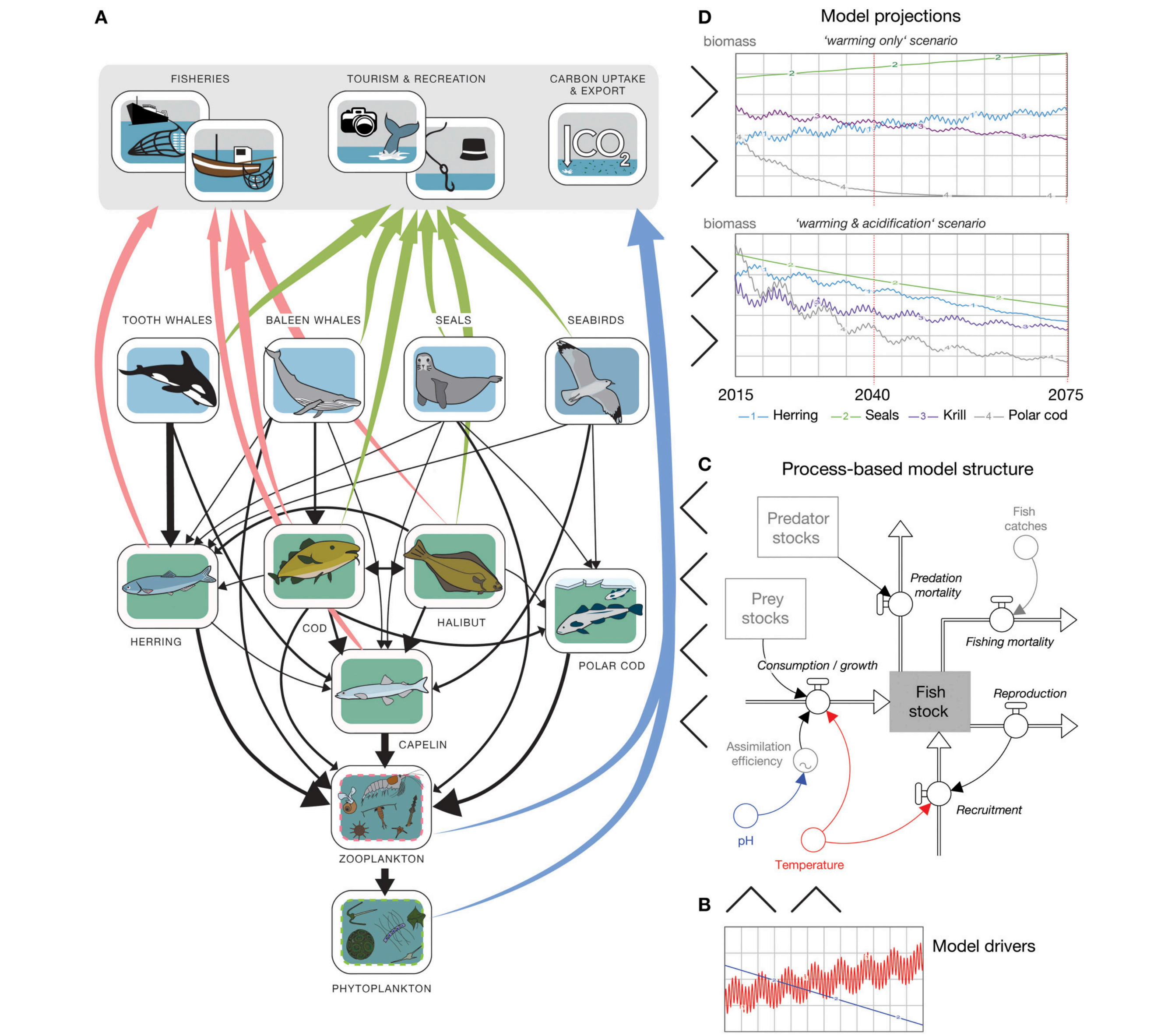

FIGURE 1 | Structure, drivers, and exemplified projections of the developed system dynamics model. (A) Top-level interface of the model, with modules of the most relevant species interacting in the marine food web, and links to provided ecosystem services (gray shaded top row). Thin black arrows mark predation on other species in the food web, wide colored arrows mark connections to the ecosystem services fisheries (pink), tourism (green), and carbon uptake and export by primary production and plankton mortality (blue). Icon design for organism and ecosystem services by Leonard Rokita, Bremen. **(B)** Temperature and pH over model time frame as drivers of the model, affecting biological processes. **(C)** detailed structure of the species included in the model in system dynamics notation, based on biomass flows (thick arrows) which determine the state of each fish stock and the dynamic links to other stocks in the model (boxes), and are influenced by the environmental drivers temperature and pH, and by fish catches (circles, thin arrows). **(D)** examples for resulting model projections under "warming only" and "warming and acidification" scenarios (different biomass scales), which qualitatively reproduce natural fluctuations and were evaluated by stakeholders at two time points, the model years 2040 and 2075 (red dotted lines).

A second stakeholder workshop for model valuation was held in Tromsø, Northern Norway in June 2015 with representative stakeholders from fisheries, tourism and environmental conservation. Structure and functioning of the parameterized model was explained, model assumptions and scientific uncertainties discussed, and model runs performed under two scenarios, driven by ocean warming alone, and warming and acidification combined, respectively. At two time points in the simulation—the year 2040 and at the end of the simulation in the year 2075—model runs were stopped and stakeholders asked to discuss the developments in stock levels and ecosystem indicators in groups by sector. Stakeholders agreed on a rating in terms of the significance for their business and interests on a scale of +5 to −5, where: +5 refers to a high preference, i.e., the best imaginable event for participants' business or interests; 0 is neutral, and −5 is catastrophic for economic survival or the stakeholders' main interests.

Then, stakeholders were asked to decide whether they needed to change their business, take organizational decisions or other steps to adapt to the projected ecosystem changes. Groups discussed and proposed possible adaptation options for their sector. Finally, general societal adaptation options were discussed among all stakeholders, and common policy recommendations developed among the participants of the different sectors. During this process, stakeholders had access to all model variables and indicators (dynamics of species abundance and processes, biodiversity and ecosystem indicators, etc.), which together reflect the complexity of the underlying ecosystem.

RESULTS

Stakeholder Perceptions and Concerns

Marine species most often mentioned by stakeholders with regard to ecosystem changes in the interview series were the fish species Atlantic cod, mackerel and herring, as well as kelp and seaweeds, king crabs, and followed by other fish species (**Table 1**). Stakeholders exhibited a high level of ecological knowledge in their observations and concerns about marine organisms. The most prominent environmental changes linked to climate change were distribution range shifts of fish and other marine species, changes in fish abundance or productivity of fish stocks, an increased occurrence of newly immigrated species such as mackerel, and the factor which was attributed as the main cause of these changes, ocean warming. When describing their observations and/or concerns, stakeholders frequently mentioned ecological processes, mainly feeding interactions, e.g., among herring, cod and capelin, fish stock spawning and recruitment, and inter-annual environment-related fluctuations and variability of fish stocks. Ocean acidification as a relatively newly discovered additional factor was known to fewer stakeholders, but was incorporated as a model driver as it was a central topic of the project, and because it could be linked to warming effects via physiological mechanisms. Upon presentation of scientific results from laboratory experiments on ocean warming and acidification at the workshops, acidification was perceived as an additional concern, but uncertainty with regard to effects in the ecosystem was recognized.

A compilation of stakeholder statements and backgrounds on the topics in the interviews and the first workshop was published in an open-access report (Koenigstein and Goessling-Reisemann, 2014). Based on these interview results and discussions at the model-building workshop, the ecosystem elements and services of highest relevance to stakeholders, and which were suitable for integration in a foodweb-based model consistent with ecological knowledge, were selected to represent ecosystem service provision in the model. These were the commercially harvested fish stocks Atlantic cod, herring, capelin and halibut, as well as minke whales for food provision via fisheries. Mackerel, which was regularly mentioned in interviews as a newly immigrated fish species in Northern Norway, was not integrated because data on feeding interactions is not yet available. For tourism and recreation services, baleen whales (Humpback whales, *Megaptera novaeangliae*, and fin whales, *Balaenoptera physalus*), sperm whales (*Physeter macrocephalus)*, killer whales (*Orcinus orca*), Atlantic puffin (*Fratercula arctica),* and other seabirds, as well as Greenland halibut (*Reinhardtius hippoglossoides*) and Atlantic cod stocks relevant for sports fishing were integrated. To represent a potentially threatened Arctic species dependent on sea ice, and because experimental data on warming and acidification impacts was available, Polar cod (*Boreogadus saida)* was also included. Lower trophic levels (phyto- and zooplankton) integrated primary production and food availability for fish. These elements thus represent the ecosystem services of food provision to industrial and small-scale fisheries, tourism and recreation as income-generating and cultural services (sports fishing, tours for whale, sea lion, and seabird watching, and other nature-related activities), and regulating and supporting services by carbon uptake via primary production and carbon export via sequestration. Species diversity (Shannon index) was incorporated as an indicator of ecosystem state on demand of stakeholders from the environmental sector in the model valuation workshop.

In the interviews, the most prominent socio-economic concern unrelated to climate change was pollution by oil drilling, mining sewage, dumping, or other sources, followed by fish market prices and labor availability. In the web-based survey conducted to gain additional insights on socio-economic factors and to prepare the valuation workshop, participants (12 completely answered surveys) rated sustainability-oriented management of resources, oceanographic changes, fish price, global economic growth and fishing quota as the most important external factors for their business or interest, with differences in importance among sectors (**Figure 2**).

Stakeholder Valuation of Model Projections

Stakeholder valuations of model projections in the second workshop differed markedly among stakeholder groups (Supplemental File S2: stakeholder valuations). Stakeholders noted that their valuations of the model projections depend on the trend displayed up to the stop in simulation time, i.e., the same stock level was rated more negatively when stock levels had been descending to this level as opposed to when they had ascended. The full development was only revealed after the simulation restarted to complete the run, reflecting uncertainty about the future in decision making in real life.

Projected changes in the warming-only scenario included increases in most fish stocks, orcas and "other seabirds," and decreases in sperm whales, seals, krill, and carbon export associated with zooplankton mortality. This scenario was rated as positive for fisheries, but as negative by tourism stakeholders due to decreased sperm whale levels, and caused concern for environmental conservation due to declines in species diversity and the collapse of Polar cod (**Table 2**). In the "warming and acidification" scenario, most species showed declines due to the energetic loss under ocean acidification incorporated in the model. Stakeholders from the fisheries sector viewed the projections for 2040 as "economically painful," given locally strong socio-economic impacts for fishers, and possible conflicts

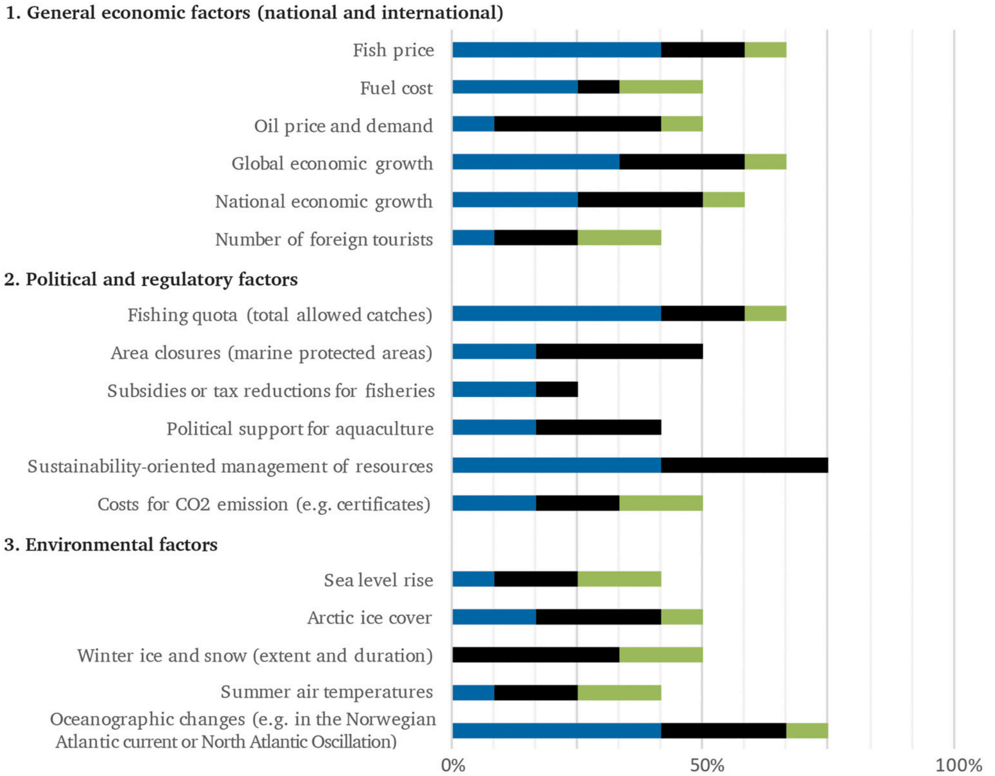

FIGURE 2 | Importance of selected economic, political and regulatory, and environmental framing factors for the business or interest of regional stakeholders (percentage of stakeholders denoting factors as "important") from a web-based survey, $N = 12$. Colors indicate self-designated sectors of participants: fisheries (blue, five participating stakeholders), environmental conservation (black, four persons) and tourism (green, three persons).

between large vessels and small-scale fishers. Further decreased stocks and the collapse of the Atlantic cod stock toward the end of the simulation in the year 2075 were perceived as leading to strong socio-economic impacts and a challenge for fisheries policies. At the model valuation workshop, present stakeholders from the fisheries sector noted that haddock, saithe, and the increasingly immigrating mackerel were also important species for regional fisheries (or expected to become important in the future), and should be added to the model.

Adaptation Options

Continued adjustment of fishing quota and intensified regulation of stock management were proposed as an adaptation option to climate change effects for fisheries in the interviews and the valuation workshop. Stricter quotas in times of declining stocks, potentially aided by a diversification of quotas and the regulation of by-catches may support a recovery of stocks. Larger vessels can also respond by moving further out to open waters, following moving fish stocks. In the valuation workshop, switching fisheries to other species (e.g., crab, mackerel, mollusks) was viewed as an additional option for reducing economic losses. Also, in the opinion of the stakeholders, increased fines for illegal fishing and catch limitations for tourist fishing may become necessary. Increased research on and investment in aquaculture as an alternative for food provision was discussed as a further adaptation option with explicit mention of sustainable and multi-species aquaculture, including species such as seaweeds and sea urchins, depending on market demand and cultural acceptance, and research into zoo- and phyto-plankton as a food source.

The tourism sector would also suffer from local collapses of small-scale fisheries, and generally decreased fish stock levels. One of the suggested adaptation options was to change marketing, focusing less on marine animals and more on cultural heritage and landscapes, and possibly on winter business to make use of the modest declines projected for orcas, and strengthen networking with small-scale fishers. The potential impacts of aquaculture on tourism and the possible use of aquaculture facilities as a tourist option could be explored. Stakeholders from environmental conservation called for an extension of marine protected areas, e.g., for nursery grounds of polar cod and whales, to mitigate ecological impacts of warming and acidification, and a stricter regulation of additional anthropogenic stressors, e.g., pollution by the deposition of mining wastes in fjords.

Commonly agreed policy recommendations of the participants of the second workshop for the projected warming and acidification scenarios were to explore the potential of increased seaweed farming and other alternative aquaculture food. For this, creating training and education, and conserving local economies by appropriate government strategies and incentives would be necessary. Abandoning the consumption

TABLE 2 | Stakeholder concerns about socio-economic impacts on their business or interest, and societal and personal adaptation options to climate change impacts, from personal interviews with stakeholder from the fisheries sector (F), tour providers and other tourism businesses (T), and environmental and other non-governmental organizations (E), ranked by sum over sectors (Σ), seven participants for each sector (one additional aquaculture representative for F).

	F	*T*	*E*	Σ
SOCIO-ECONOMIC CONCERNS AND OTHER IMPACTS ON BUSINESS				
Oil drilling pollution	5	1	1	7
Garbage dumping and other/unspecified pollution	3	2	1	6
Fish market prices	5			5
Mining discharges pollution	1		3	4
Labor market	3		1	4
Ecological impacts of aquaculture	1		2	3
Increasing aquaculture activity	1	1		2
Bad weather		2		2
Unfair distribution of fishing rights			2	2
Heavy metals/seafood health effects	1		1	2
General economic situation		1		1
Seismic exploration		1		1
CO_2 storage	1			1
ADAPTATION OPTIONS TO CLIMATE CHANGE IMPACTS				
Quota adjustments	6	4	1	11
Increase vessel search area	4	2		6
Protected areas/local management	1	1	2	4
New technologies	2		1	3
Reduce or compensate CO_2 emissions	2		1	3
Change target species	2			2
Move business to other location		1		1
Change profession		1		1

Number of instances mentioned across interviews (detailed interview questions given in Supplemental File S1).

of seagull eggs, seals and whales may be advisable, and would necessitate some cultural changes. Under the projected strong stock declines, renegotiations of fishing rights and quotas may become necessary. This would call for the respective political will and actions for conflict resolution among fisheries in Norway.

DISCUSSION

Integration of Stakeholder Perceptions about Climate Change and Ocean Acidification Impacts

All interviewed stakeholders reported plausible climate change effects on marine species, thus their personal accounts substantiated recent scientific results (Fossheim et al., 2015). However, many participants also pointed to the great variability in marine ecosystems in the region, especially fish stocks, which makes it difficult to distinguish environmental fluctuations from long-term change, and thus increases uncertainty about climate-related trends (Johannesen et al., 2012). Because of the high importance of ecological processes and species interactions for stakeholders in the initial interview series, the ecosystem model was based on the foodweb interactions among pelagic and demersal species in the Barents Sea (Bogstad et al., 2015), explicitly integrating the biological processes of interest (Koenigstein et al., 2016). This enabled the incorporation of a large fraction of the species of interest to the stakeholders into the model, and also allowed us to incorporate fishing quotas as the most important adaptation option and anthropogenic driver initially identified in the interviews. However, this choice of model structure came at the expense of being unable to consider spatially explicit distribution shifts and benthic species such as macroalgae, shellfish, or echinoderms. These are often restricted to coastal and fjord habitats and undergo highly localized conditions, e.g., with regard to freshwater influx or hypoxia. In comparison to mental models or other probabilistic models often used in participatory modeling, the deterministic ecosystem model developed here resolves to some degree the emergent behavior of the ecosystem under different conditions, and enables the integration of scientific knowledge, assessing dynamic trade-offs in effects among species and among biological processes under future climate change conditions (see subsection "Towards ecological realism...").

The main non-climate related concern was pollution, caused by oil and gas exploration, residues from mineral mining along the coasts, or shipping. For whale watching companies, noise pollution from shipping and seismic exploration was a prevalent concern. Due to high scientific uncertainty and highly localized ecological impacts, these concerns could not be incorporated into the model. Also, as aquaculture is not directly linked to marine foodwebs, and was not often mentioned as a factor or concern by the stakeholders in the interview phase, the aquaculture sector was not further considered at this point. Melting of the Arctic sea ice and sea level rise, although of high relevance in the interviews, were also not incorporated due to unclear links to the marine organisms in the model. The scenario-based incorporation of pollution, sea ice and aquaculture is planned for a future extension of the model.

Although impacts of marine ecosystem changes on tourism are far less prominently covered in the scientific literature and the media, the relevance of shifts in marine food ecosystems was immediately obvious to most interviewed stakeholders from the tourism sector. Worldwide, biodiversity loss and reduced aesthetic value of landscapes are expected to impact tourism under climate change, among a range of other factors (Simpson et al., 2008). Tourism in our study region is to a high degree dependent on certain locally abundant species (sperm whales, cod, halibut, seals), thus pointing to highly localized climate change impacts on tourism and recreation, and to the necessity for a detailed assessment of local conditions. Biodiversity and cold-water coral reefs were also mentioned as threatened by climate change, and valuation studies point to a very high willingness-to-pay of the Norwegian public to conserve cold-water coral reefs (Aanesen et al., 2015). Stakeholders of all sectors had agreed in the model-building workshop on conserving the protected status of coral reef areas (e.g., prohibition of trawl fisheries) and not including reefs in the model, putatively reflecting the cultural and existence value of this reefs, but also low economic importance of these areas for fisheries.

Adaptation Options for Stakeholders to Projected Ecosystem Changes

Stakeholder valuations and discussions at the valuation workshop showed that small-scale fisheries and tourism businesses have less, or more constrained adaptation options for the ecological changes projected by the model (cf. **Table 3**). For instance, small-scale fishers often cannot follow moving fish stocks far away from the coast, or have the funds to invest in different gear. The commercially relevant whale-watching and other tour activities in the area are heavily dependent on the sighting probability of certain species (e.g., sperm whales). Adaptation options for sightings decreasing below a critical level would entail drastic changes in the character of tourism activities, with probable reductions in customer numbers and income.

Fishing quota adjustments were seen as the primary adaptation option by fisheries and tourism stakeholders. However, small fishing boat owners, often located in more remote areas and with a partial income from sports fishing tours, perceived quota adjustment as less likely to be a sufficient measure for climate change impacts than stakeholders organized in fisheries associations. In a situation with reductions in several co-used fish stocks, as projected under the combined warming and acidification scenario, suggested adaptation options ceased to be sector-exclusive, and conflicts were expected to increase among industrial, small-scale, and sports fishing, when catch efforts would be increasingly concentrated on the remaining stable species (e.g., halibut). Conflict potential among and within sectors led to the recognition of the need for increased cooperation and networking among user groups. Increased investment in aquaculture was a heavily discussed adaptation option at the valuation workshop, which is very relevant worldwide in the context of securing food provision under overfishing of many fish stocks (FAO, 2014). Yet, there was a range of concerns from stakeholders with regard to the ecological impacts of aquaculture (pollution from nutrients and antibiotics, escaped individuals and parasites, spatial use conflicts). Also, the viability of this option depends on economic factors and the continued provision of small pelagic fish by capture fisheries for fish meal production. Stakeholders agreed on the need for increased research on ecological impacts and more sustainable methods of aquaculture production.

Environmental conservation stakeholders adopted a broader view on ecosystem functioning, asking for inclusion of a biodiversity indicator during the valuation workshop, and thus brought a precautionary aspect into the discussion. Declines in zooplankton and phytoplankton biomass levels were also negatively rated by stakeholders from the fisheries sector, reflecting concerns about indirect impacts on fish stocks. The discussion among different stakeholder groups was also shaped to some extent by implicit societal values, as e.g., the high cultural importance of the Atlantic cod fishery in Northern Norway and the significance of marine species for the coastal indigenous Sámi were mentioned. In the discussion of societal adaptation options, a focus on options which were undisputed among the workshop participants was observed, while options which would have more potential for conflicts (e.g., total catch bans or area closures for certain uses) were avoided topics. The group evaluation approach thus reproduced certain factors and constellations which govern societal decision-making, e.g., implicit valuing, social agreement, and power balances among stakeholders.

These results point to considerable differences in adaptation capacities to climate change impacts among stakeholders in the Northern Norwegian Sea and Barents Sea region, with less resilient small-scale fishers and tourism businesses. Potential food-web mediated impacts e.g., on whales and seabirds or lower trophic levels would thus lead to governance-relevant trade-offs among fish provisioning and other ecosystem services. As model development is ongoing and valuations are based on a preliminary, not finally validated version of the model, projections and societal adaptation options at this stage should be regarded as describing possible paths of system behavior. As framing and limiting conditions for stakeholder decisions have been identified during the valuation workshop, stakeholder decisions will be transferrable to validated projections as these become available.

Toward Ecological Realism in Assessments of Climate Change Impacts on Ecosystem Services

The participating stakeholders' main ecological concerns and the most relevant ecosystem services have been integrated into the developed ecosystem model, considering the scientific knowledge

TABLE 3 | Projected ecological impacts of climate change and ocean acidification for which a need for adaptation measures was recognized among 18 stakeholders during a model valuation workshop.

	Impact	Stakeholder rating (2040/2075)	Adaptation option	Condition/drawback
"WARMING ONLY" SCENARIO				
Fisheries	Increased fish stock levels (decreases in capelin 2075)	+4/+3	None (continue good fisheries management)	–
Tourism	Declines in sperm whales and seals, robust fish stocks, increases in orcas	–2.5/–3	Increase tour/search distance	Customer acceptance, increased fuel consumption
Conservation	High biomasses, but decreasing species diversity and polar species	–3/–4	Protect nursery areas (e.g. of polar cod and whales)	Political will
	Decreases in krill and carbon export	–3/–4	–	–
"WARMING AND ACIDIFICATION" SCENARIO				
Fisheries	Fish stock declines/cod stock collapse, zooplankton declines	–2.5/–4	Stricter catch regulations	Social quota redistributions
			Switch target species	Adaptation of catch gear and vessels
			Increased investment in aquaculture	Research on ecological impacts and market acceptance, conflict with fisheries
Tourism	Fish stock declines	–2/–3	Strengthen networks/cooperation with fishers	Resolution of conflicts with fishers
	Decreases in mammals and seabirds	–3/–5	Change tour focus	Customer acceptance for less ecological attraction
Conservation	Decreases in fish, mammals, zooplankton, and biodiversity	–4/–5	Area closures	Use conflicts
			Stricter regulation of other stressors	Economic impacts

Relevant aspects of impacts, with stakeholder rating on a scale from +5 to –5, adaptation options suggested by stakeholder groups, and conditions or potential drawbacks given for these adaptation options. Stakeholder rating +5 reflects an extremely beneficial effect on stakeholder group, –5 reflects a catastrophic effect.

on interactions among ecosystem elements and processes, and helping to build trust in the model. Importantly, this model structure also enables the assessment of indirect ecological climate change impacts (e.g., on marine mammals and seabirds relevant for tourism), thus exploring possible trade-offs among ecosystem services. The process-based structure of the developed model thus enables a more realistic representation of biodiversity (Queirós et al., 2015) and improves the potential for integrating empirical data into climate change projections (Koenigstein et al., 2016).

Models used in ecosystem service assessment are usually highly simplified in order to be easily understandable, and it is a challenge to communicate scientific uncertainty (Ruckelshaus et al., 2013). Our stakeholder-informed ecosystem model development represents an intermediate approach between participatory modeling of stakeholder perceptions without a direct empirical basis of ecosystem behavior, and the use of models e.g., in fisheries management, where a pre-developed model is often brought to the stakeholders and explained by scientists. The model developed and used here reproduces the inter-annual variability in ecosystem dynamics and interdependent fluctuations in fish populations observed by the stakeholders, which are governed by climatic fluctuations linked to the North Atlantic Oscillation (Ottersen et al., 2001; Dalpadado et al., 2012). The reflection of their perceptions in the model enabled the participants to "play" with it during the workshop, exploring effects that were in some cases not expected by the model developers, and finding their own explanations for model behavior. Importantly, it was understood and accepted that the model is not a scientifically proven prediction of the future, but has a range of internal uncertainties e.g., in parameter ranges and structural reliability, and depends on uncertain external parameters with regard to climatic and economic factors. The observed influence of the displayed trend in model projections on stakeholder valuations indicates that stakeholders implicitly extrapolate model trends (and fluctuations) into the future, incorporating the perceived uncertainty into their decision.

A focus on ecosystem services during model development helped to limit model complexity to ecosystem elements that can be linked to societal uses. The ecosystem service concept promises to improve the participation of stakeholders in the management and conservation of marine areas and resources (Kittinger et al., 2014; Leenhardt et al., 2015). However, ecosystem services have been criticized as being too simplistic and too much focused on monetization (Norgaard, 2010; Silvertown, 2015), and cultural services are often not considered in ecosystem service assessments (Chan et al., 2012). We addressed these issues through the use of a process-based ecosystem model, taking into account ecological complexity and variability, and dynamic trade-offs among ecosystem services. Cultural and ethical values were implicitly considered in the discourse-based valuation, which should improve the perceived legitimacy of the derived recommendations (Wilson and Howarth, 2002).

Altogether, our approach to combine stakeholder consultation and ecosystem modeling has been successful in conveying scientific backgrounds and associated uncertainties of climate change processes to stakeholders, motivating stakeholders to participate in the evaluation of impacts and the identification of societally acceptable adaptation options. In a next step, insights on environmental and socio-economic framing factors gained in this study will be integrated into consistent scenarios, and stakeholders will again be involved in finding adaptation options under these scenarios using an extended and validated version of the model. This forms a methodological basis for developing adaptation strategies under scientific uncertainties, that are informed both by knowledge about ecosystem dynamics and by societal uses and values. Characterization of societal responses in connection with the identified properties of the social-ecological system (e.g., species composition, ecological dynamics, human uses and user groups) can yield insights for research in situations with lower data availability and lower level of knowledge of stakeholders, where a comparably high model detail may not be possible.

CONCLUSIONS

Our integrative ecosystem model was designed to consolidate the dynamic simulation of climate change impacts with stakeholder perceptions and concerns. By reflecting the complexity of the biological processes underlying ecosystem dynamics, individual scientific results of ocean warming and acidification research can be integrated and communicated, interactions and uncertainties discussed with affected stakeholders, and trust gained in long-term projections under climate change. Stakeholder-informed ecosystem modeling and discourse-based evaluation are thus useful tools for ecosystem service assessments with multiple user groups, investigating trade-offs and balancing interests under multiple system drivers. Integrative models of intermediate complexity, like the one developed in this work, have the potential to improve understanding of regional social-ecological systems, and help to identify options for adaptive governance of marine systems under climate change and human use.

AUTHOR CONTRIBUTIONS

SG conceptualized the work program. SK conducted and evaluated the interviews, SG and SK conducted and evaluated the stakeholder workshops. SK, MR, and SG conceptualized, developed and validated the simulation model. SK drafted the manuscript, MR and SG contributed to the manuscript and reviewed the final version.

ETHICS STATEMENT

All human participants took part voluntarily and gave oral or written informed consent to participate. They also consented to the use of their statements for the study after anonymization. The purpose and background of the study and the planned use of the results were made transparent prior to interviews, surveys and workshops. The confidentiality of personal information and the right to omit uncomfortable questions or withdraw from the interview at any stage were provided.

FUNDING

This work was funded through the research program BIOACID (Biological Impacts of Ocean Acidification, phase II), by the German Federal Ministry of Education and Research (BMBF, FKZ 03F0655J).

ACKNOWLEDGMENTS

The authors thank Jannike Falk-Andersson (UiT), Nicola Beaumont (PML), Annette Breckwoldt (ZMT Bremen), and Christos Zografos (UAB) for advice on and support in preparing and conducting the stakeholder interviews, workshops and web survey. We thank Hauke Reuter (ZMT Bremen) for advice in model development, and Viola Logemann for help with interview transcription. We are indebted to numerous Norwegian colleagues at the Institute of Marine Research (IMR), the Arctic University in Tromsø (UiT) and the Fram Centre, for kindly providing support in workshop logistics, stakeholder contacts, and scientific expertise to make this work possible.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fmars.2016.00093

REFERENCES

Aanesen, M., Armstrong, C., Czajkowski, M., Falk-Petersen, J., Hanley, N., and Navrud, S. (2015). Willingness to pay for unfamiliar public goods: preserving cold-water coral in Norway. *Ecol. Econ.* 112, 53–67. doi: 10.1016/j.ecolecon.2015.02.007

Allison, E. H., and Bassett, H. R. (2015). Climate change in the oceans: human impacts and responses. *Science* 350, 778–782. doi: 10.1126/science.aac8721

Allison, E. H., Perry, A. L., Badjeck, M.-C., Neil Adger, W., Brown, K., Conway, D., et al. (2009). Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fish.* 10, 173–196. doi: 10.1111/j.1467-2979.2008.00310.x

AMAP (2013). *AMAP Assessment 2013: Arctic Ocean Acidification.* Oslo: Arctic Monitoring and Assessment Programme (AMAP).

Beaumont, N. J., Austen, M. C., Atkins, J. P., Burdon, D., Degraer, S., Dentinho, T. P., et al. (2007). Identification, definition and quantification of goods and services provided by marine biodiversity: implications for the ecosystem approach. *Mar. Pollut. Bull.* 54, 253–265. doi: 10.1016/j.marpolbul.2006.12.003

Bogstad, B., Gjøsæter, H., Haug, T., and Lindstrøm, U. (2015). A review of the battle for food in the Barents Sea: cod vs. marine mammals. *Front. Ecol. Evol.* 3:29. doi: 10.3389/fevo.2015.00029

Bopp, L., Resplandy, L., Orr, J. C., Doney, S. C., Dunne, J. P., Gehlen, M., et al. (2013). Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences Discuss.* 10, 3627–3676. doi: 10.5194/bgd-10-3627-2013

Chan, K. M. A., Guerry, A. D., Balvanera, P., Klain, S., Satterfield, T., Basurto, X., et al. (2012). Where are cultural and social in ecosystem services? A framework for constructive engagement. *Bioscience* 62, 744–756. doi: 10.1525/bio.2012.62.8.7

Collins, M., Knutti, R., Arblaster, J., Dufresne, J. L., Fichefet, T., Friedlingstein, P., et al. (2013). "Long-term climate change: projections, commitments and irreversibility," in *Climate Change 2013: The Physical Science Basis*, eds T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (Cambridge, UK; New York, NY: Cambridge University Press), 1–108.

Costanza, R., and Ruth, M. (1998). Using dynamic modeling to scope environmental problems and build consensus. *Environ. Manage.* 22, 183–195. doi: 10.1007/s002679900095

Daily, G. C., Polasky, S., Goldstein, J., Kareiva, P. M., Mooney, H. A., Pejchar, L., et al. (2009). Ecosystem services in decision making: time to deliver. *Front. Ecol. Environ.* 7, 21–28. doi: 10.1890/080025

Dalpadado, P., Ingvaldsen, R. B., Stige, L. C., Bogstad, B., Knutsen, T., Ottersen, G., et al. (2012). Climate effects on Barents Sea ecosystem dynamics. *ICES J. Mar. Sci.* 69, 1303–1316. doi: 10.1093/icesjms/fss063

Denman, K., Christian, J. R., Steiner, N., Pörtner, H.-O., and Nojiri, Y. (2011). Potential impacts of future ocean acidification on marine ecosystems and fisheries: current knowledge and recommendations for future research. *ICES J. Mar. Sci.* 68, 1019–1029. doi: 10.1093/icesjms/fsr074

Duarte, C. M., Agustí, S., Wassmann, P., Arrieta, J. M., Alcaraz, M., Coello, A., et al. (2012). Tipping elements in the Arctic marine ecosystem. *Ambio* 41, 44–55. doi: 10.1007/s13280-011-0224-7

Eide, A., Heen, K., Armstrong, C., Flaaten, O., and Vasiliev, A. (2013). Challenges and successes in the management of a shared fish stock – the case of the Russian–Norwegian barents sea cod fishery. *Acta Borealia* 30, 1–20. doi: 10.1080/08003831.2012.678723

FAO (2013). *Fishery and Aquaculture Country Profiles - Norway*. Available online at: http://www.fao.org/fishery/facp/NOR/en (Accessed September 30, 2013).

FAO (2014). *The State of World Fisheries and Aquaculture 2014*. Rome.

Fossheim, M., Primicerio, R., Johannesen, E., Ingvaldsen, R. B., Aschan, M. M., and Dolgov, A. V. (2015). Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nat. Clim. Chang.* 5, 673–677. doi: 10.1038/nclimate2647

Gattuso, J.-P., Magnan, A., Bille, R., Cheung, W. W. L., Howes, E. L., Joos, F., et al. (2015). Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science* 349:aac4722. doi: 10.1126/science.aac4722

Harsem, Ø., and Hoel, A. H. (2012). Climate change and adaptive capacity in fisheries management: the case of Norway. *Int. Environ. Agreements* 13, 49–63. doi: 10.1007/s10784-012-9199-5

Haynie, A. C., and Pfeiffer, L. (2012). Why economics matters for understanding the effects of climate change on fisheries. *ICES J. Mar. Sci.* 69, 1160–1167. doi: 10.1093/icesjms/fss021

Hoel, A. H., and Olsen, E. (2012). Integrated ocean management as a strategy to meet rapid climate change: the Norwegian case. *Ambio* 41, 85–95. doi: 10.1007/s13280-011-0229-2

Hollowed, A. B., and Sundby, S. (2014). Change is coming to the northern oceans. *Science* 344, 1084–1085. doi: 10.1126/science.1251166

Hughes, T. P., Bellwood, D. R., Folke, C., and Steneck, R. S. (2005). New paradigms for supporting the resilience of marine ecosystems. *Trends Ecol. Evol.* 20, 380–386. doi: 10.1016/j.tree.2005.03.022

Jentoft, S., and Mikalsen, K. H. (2014). Do national resources have to be centrally managed? Vested interests and institutional reform in Norwegian fisheries governance. *Marit. Stud.* 13:5. doi: 10.1186/2212-9790-13-5

Johannesen, E., Ingvaldsen, R. B., Bogstad, B., Dalpadado, P., Eriksen, E., Gjosaeter, H., et al. (2012). Changes in Barents Sea ecosystem state, 1970-2009: climate fluctuations, human impact, and trophic interactions. *ICES J. Mar. Sci.* 69, 880–889. doi: 10.1093/icesjms/fss046

Johnsen, J. P. (2013). Is fisheries governance possible? *Fish Fish.* 15, 428–444. doi: 10.1111/faf.12024

Kittinger, J. N., Koehn, J. Z., Le Cornu, E., Ban, N. C., Gopnik, M., Armsby, M., et al. (2014). A practical approach for putting people in ecosystem-based ocean planning. *Front. Ecol. Environ.* 12, 448–456. doi: 10.1890/130267

Kjesbu, O. S., Bogstad, B., Devine, J. A., Gjøsæter, H., Howell, D., Ingvaldsen, R. B., et al. (2014). Synergies between climate and management for Atlantic cod fisheries at high latitudes. *Proc. Natl. Acad. Sci. U.S.A.* 111, 3478–3483. doi: 10.1073/pnas.1316342111

Koenigstein, S., and Goessling-Reisemann, S. (2014). *Ocean Acidification and Warming in the Norwegian and Barents Seas: Impacts on Marine Ecosystems and Human Uses*. University of Bremen, Artec Sustainability Research Center.

Koenigstein, S., Mark, F. C., Gößling-Reisemann, S., Reuter, H., and Pörtner, H.-O. (2016). Modeling climate change impacts on marine fish populations: process-based integration of ocean acidification, warming and other environmental drivers. *Fish Fish.* doi: 10.1111/faf.12155. [Epub ahead of print].

Kortsch, S., Primicerio, R., Fossheim, M., Dolgov, A. V., and Aschan, M. (2015). Climate change alters the structure of arctic marine food webs due to poleward shifts of boreal generalists. *Proc. Biol. Sci.* 282:20151546. doi: 10.1098/rspb.2015.1546

Kroeker, K. J., Kordas, R. L., and Crim, R. (2013). Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Glob. Change Biol.* 19, 1884–1896. doi: 10.1111/gcb.12179

Leenhardt, P., Teneva, L., Kininmonth, S., Darling, E., Cooley, S., and Claudet, J. (2015). Challenges, insights and perspectives associated with using social-ecological science for marine conservation. *Ocean Coast. Manage.* 115, 49–60. doi: 10.1016/j.ocecoaman.2015.04.018

Millenium Ecosystem Assessment (2005). *Ecosystems and Human well-being*. Washington, DC: World Resources Institute.

Munday, P. L., Dixson, D. L., McCormick, M. I., Meekan, M., Ferrari, M. C. O., and Chivers, D. P. (2010). Replenishment of fish populations is threatened by ocean acidification. *Proc. Natl. Acad. Sci. U.S.A.* 107, 12930–12934. doi: 10.1073/pnas.1004519107

Norgaard, R. B. (2010). Ecosystem services: from eye-opening metaphor to complexity blinder. *Ecol. Econ.* 69, 1219–1227. doi: 10.1016/j.ecolecon.2009.11.009

Osterblom, H., Merrie, A., Metian, M., Boonstra, W. J., Blenckner, T., Watson, J. R., et al. (2013). Modeling social–ecological scenarios in marine systems. *Bioscience* 63, 735–744. doi: 10.1093/bioscience/63.9.735

Ottersen, G., Planque, B., Belgrano, A., Post, E., Reid, P., and Stenseth, N. (2001). Ecological effects of the North Atlantic Oscillation. *Oecologia* 128, 1–14. doi: 10.1007/s004420100655

Perry, R. I., Barange, M., and Ommer, R. E. (2010). Global changes in marine systems: a social–ecological approach. *Prog. Oceanogr.* 87, 331–337. doi: 10.1016/j.pocean.2010.09.010

Perry, R. I., Ommer, R. E., Barange, M., Jentoft, S., Neis, B., and Sumaila, U. R. (2011). Marine social-ecological responses to environmental change and the impacts of globalization. *Fish Fish.* 12, 427–450. doi: 10.1111/j.1467-2979.2010.00402.x

Poloczanska, E. S., Brown, C. J., Sydeman, W. J., Kiessling, W., Schoeman, D. S., Moore, P. J., et al. (2013). Global imprint of climate change on marine life. *Nat. Clim. Chang.* 3, 919–925. doi: 10.1038/nclimate1958

Pörtner, H.-O., and Farrell, A. P. (2008). Physiology and climate change. *Science* 322, 690–692. doi: 10.1126/science.1163156

Pörtner, H.-O., Karl, D. M., Boyd, P. W., Cheung, W. W. L., Lluch-Cota, S. E., Nojiri, Y., et al. (2014). "Ocean systems," in *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*, eds C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White (Cambridge, UK; New York, NY: Cambridge University Press), 411–484.

Queirós, A. M., Bruggeman, J., Stephens, N., Artioli, Y., Butenschön, M., Blackford, J. C., et al. (2015). Placing biodiversity in ecosystem models without getting lost in translation. *J. Sea Res.* 98, 83–90. doi: 10.1016/j.seares.2014.10.004

Riebesell, U., and Gattuso, J.-P. (2015). Lessons learned from ocean acidification research. *Nat. Clim. Chang.* 5, 12–14. doi:10.1038/nclimate2456

Ruckelshaus, M., McKenzie, E., Tallis, H., Guerry, A., Daily, G., Kareiva, P., et al. (2013). Notes from the field: lessons learned from using ecosystem service approaches to inform real-world decisions. *Ecol. Econ.* 115, 11–21. doi: 10.1016/j.ecolecon.2013.07.009

Sandvik, H., Erikstad, K. E., Barrett, R. T., and Yoccoz, N. G. (2005). The effect of climate on adult survival in five species of North Atlantic seabirds. *J. Anim. Ecol.* 74, 817–831. doi: 10.1111/j.1365-2656.2005.00981.x

Silvertown, J. (2015). Have ecosystem services been oversold? *Trends Ecol. Evol.* 30, 641–648. doi: 10.1016/j.tree.2015.08.007

Simmonds, M. P., and Isaac, S. J. (2007). The impacts of climate change on marine mammals: early signs of significant problems. *Oryx*. 41, 19–26. doi: 10.1017/S0030605307001524

Simpson, M. C., Gössling, S., Scott, D., Hall, C. M., and Gladin, E. (2008). *Climate Change Adaptation and Mitigation in the Tourism Sector: Frameworks, Tools and Practices*. Paris: UNEP; University of Oxford; UNWTO; WMO.

Voinov, A., and Bousquet, F. (2010). Modelling with stakeholders. *Environ. Model. Softw.* 25, 1268–1281. doi: 10.1016/j.envsoft.2010.03.007

Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., et al. (2002). Resilience management in social-ecological systems: a working hypothesis for a participatory approach. *Conserv. Ecol.* 6:14. Available online at: http://www.consecol.org/vol6/iss1/art14/

Wassmann, P., Reigstad, M., Haug, T., Rudels, B., Carroll, M. L., Hop, H., et al. (2006). Food webs and carbon flux in the Barents Sea. *Prog. Oceanogr.* 71, 232–287. doi: 10.1016/j.pocean.2006.10.003

Wilson, M. A., and Howarth, R. B. (2002). Discourse-based valuation of ecosystem services: establishing fair outcomes through group deliberation. *Ecol. Econ.* 41, 431–443. doi: 10.1016/S0921-8009(02)00092-7

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.