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Introduction

'Adaptation science' is needed to inform the sustainable management of the world's oceans in the face of climate change

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The global response to the challenge of increasingly rapid and severe climate change is shifting from a focus on mitigation and remediation of impacts to a pragmatic adaptation framework. Innovative adaptive solutions that transform the way in which we manage the world's oceans and, particularly, the harvesting of marine resources in a sustainable manner, are urgently needed. In that context, *ICES Journal of Marine Science* solicited contributions to the themed article set (TS), "*Exploring adaptation capacity of the world's oceans and marine resources to climate change*". We summarize the contributions included in this TS that provide examples of emerging climate change impacts, assess system risks at subnational and international scales, prove and evaluate different adaptation options and approaches, and explore societal and stakeholder perceptions. We also provide some "*food for thought*" on possible future developments in a transdisciplinary "adaptation science" working at the interface between ecology, socio-economics, and policy-governance, and that will have to provide concrete solutions to the challenges represented by climate-change and anthropogenic activity. Success will depend on the extent to which new knowledge and approaches can be integrated into the decision-making process to support evidence-based climate policy and ecosystem-based management. This includes testing their effectiveness in real systems, but also consider how social acceptance of adaptive measures will/will not support their full implementation.

Keywords: adaptation to climate change, climate change risks, ecosystem-based management, governance, marine resources management transformation, resilient ecosystems, social resilience, vulnerable marine ecosystems.

Background and motivation for this themed article set

Climate-induced changes in marine ecosystems are advancing inexorably at a higher rate and with a wider range of ecological and societal impacts than foreseen. Society, policy makers and stakeholders are requesting innovative adaptive solutions that transform the way in which we manage the world's oceans and, particularly, the harvesting of marine resources. As a response to climate change, "adaptation" is defined as *the process allowing organisms, ecosystems and human societies to adjust to the effects of climate change and, in the case of human societies, to anticipate future risks* (IPCC, 2014). It has become indeed a mandatory process at all scales and in all the oceans, from coastal to open ocean ecosystems, or from artisanal to large-scale industrial fisheries. However, the inherent complexity of socio-ecological systems, and the multiple pathways of response to climate change, require a diversity of responses and actions from institutions and management (Pelling 2010; Few *et al*., 2017; Fedele *et al*. 2019).

A plethora of integrative and holistic approaches have been developed to bring change to socio-ecological systems with the aim of improving the performance of management systems, enhancing the resilience of fisheries, reducing their vulnerability to climate change, preserving livelihoods, and enabling managers to respond in a timely manner to both projected and unexpected changes in the dynamics of marine resources and ecosystems (Bahri *et al*., 2021). However, the potential for socio-ecological systems to adapt – naturally or assisted by human intervention – remains unclear and has become a major item on the global, national and regional agendas of cross-cutting research topics (e.g. Horizon Europe Mission on Adaptation to Climate change, European Commission, 2021; 4th National Climate Assessment for the US, NCA, 2018).

During the last decades, the increasing importance of climate change adaptation has been fueled by the change of paradigm from a strong focus on mitigation and remediation of climate change impacts to the current broadly accepted concept of adaptation (Barange and Cochrane, 2018), which has notably increased since the mid-2000s (Figure 1). The manner in which adaptation actions are portrayed is also shifting. Conventional coping strategies based on "incremental adaptation" (i.e. maintaining the essence and integrity of a system or process at a given scale) may not always be effective

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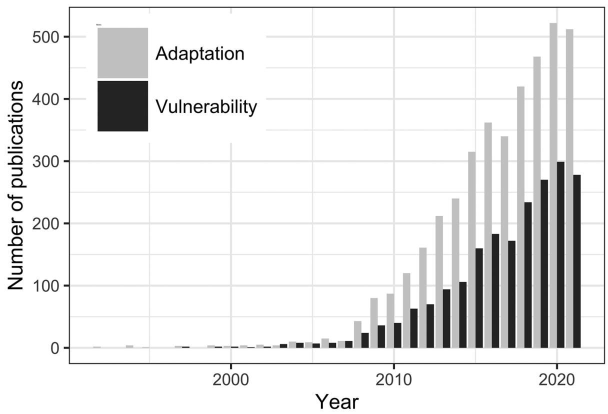

Figure 1. The number of publications per year returned by a search of the Web of Science Core Collection for the terms "adaptation and marine and climate change" (Adaptation in the plot) and "vulnerability and marine and climate change" (Vulnerability in the plot) over the period 1992–2021, conducted on 29 November 2021 (data available in table S1 of the Supplementary Material). See also Galappaththi *et al.*, (2021) for a meta-analytical review of publications on climate change adaptation to fisheries.

at helping people or ecosystems to reduce their vulnerabilities to climatic change (Pelling 2010; Fedele *et al.* 2019). The need for "transformative adaptation" (i.e. changing the fundamental attributes of a socio-ecological system in anticipation of climate change and its impacts) has been the subject of many recent discussions on climate change adaptation (Few *et al.*, 2017; Fedele *et al.* 2019). Transformative adaptation implies going beyond adjustments to existing practice toward measures that fundamentally reduce exposure to anticipated or observed impacts through a major change in the type, intensity or distribution of a practice (Kates *et al.*, 2012). It has become clear that the efficiency of adaptation tools, and our capacity to develop concrete solutions, will depend on the success of achieving persistent and transformative changes in socio-ecological systems at different levels (Magnan *et al.*, 2020; Wood 2022). The development of concrete solutions will likely be supported by co-creation (i.e. collaborative development of new values, actions, or measures), which combine analytical and participatory processes with both scientists and stakeholders involved to provide knowledge, methods and tools that can be applied to policy-making (e.g. the foundations of co-designed transformative science, UN Ocean decade 2021).

To contribute to the consolidation of climate-adaptation research, and improve our understanding of whether and how transformative adaptation of marine ecosystem management and governance is possible, *ICES Journal of Marine Science* solicited contributions to the themed article set (TS), "*Exploring adaptation capacity of the world's oceans and marine resources to climate change*". The intention was to motivate the submission of articles reporting recent advances on: species' adaptations across life history strategies, functions and physiological sensitivities, as well as their ecological implications; the identification of possible tipping points in the adaptive capacity of ecosystems and users; emerging approaches that bridge social and ecological information: tools, methods and new technologies; qualitative and quantitative vulnerability and risk assessment tools across multiscale natural and anthropogenic drivers; scenarios development and projections of future trajectories of socio-ecological systems; vulnerability and adaptation to climate change at transboundary and transoceanic scales; implementation and assessment of adaptation and transformation action plans; and the perception assessment of end-user to adaptation options. The contributions to this TS provide new information on many of these topics including some "*food for thought*" on the future developments of "adaptation science", which we see as applied research that embraces a diversity of disciplines, from ocean sciences to management and governance studies, to effectively face the impacts of climate change. The generation of scientific knowledge on marine ecosystems and climate change impacts is not in and of itself sufficient to make the needed impact. Therefore, adaptation science emerges as an emblematic example of the transdisciplinary science needed to construct knowledge at the "science-policy" interface in the coming decades.

About the articles in this themed set

Risk assessment and understanding new impacts

Impacts of ocean warming such as sea level rise, shifts in species distribution, timing of biological events and changes in the productivity of ecosystems and the commercially important resources that they support are now well-documented (e.g. Hoegh-Guldberg and Bruno, 2010; Pinsky *et al.*, 2020). Heatwaves and extreme weather events and their impacts are more frequent and numerous (e.g. Hobday *et al.*, 2018; Oliver *et al.*, 2018; Maxwell *et al.*, 2019; Cheung *et al.*, 2021), while projections of their frequency and occurrence remain challenging, at least at regional scales (but see, Adloff *et al.*, 2015; Damaraki *et al.*, 2019). Other impacts of global warming that are more challenging to assess are, for instance, expected changes in mesoscale and regional circulation patterns. These will have strong impacts on the dispersal and connectivity pathways among different subpopulations and, eventually, on the long-term modification of species population structure, and on the redistribution of stock productivity among neighboring countries (i.e. transboundary stocks) (Palacios-Abrantes *et al.* 2022). In this TS, van de Wolfshaar *et al.* (2021) show that the combination of expected warming and wind patterns in the North Sea will impact growth and survival of early life stages of common sole (*Solea solea*) in different nursery areas resulting in changes in biomass in waters under the national jurisdiction of the different countries harvesting this species. The study demonstrates the need to understand and predict possible consequences of future climate conditions, at the regional level, on population dynamics to be able to design efficient adaptation measures at the management level. This is consistent with recent studies calling for a broader vision of different type of impacts, as well as a greater concern for cross-scale and multi-life stage mechanistic understanding of climate change-driven impacts (Twiname *et al.*, 2020).

The identification and qualitative assessment of climate change risks is commonly done through climate vulnerability assessment (CVA, more recently termed climate risk assessment, CRA) as a formal approach for identifying and prioritizing the vulnerabilities of a system, but also possible opportunities (e.g. new target species –non-indigenous species–, or increased local productivity of high value commercial species, e.g. Öztürk, 2021). In this TS, Aragão *et al.* (2022) develop a regional CVA comparing Atlantic and Mediterranean demersal fisheries in Spain. They emphasize that the spatial scale considered in the development of CVAs must recognize the spatial heterogeneity and gradients in the socio-ecological system using indicators that are meaningful at the scale being considered. Their results also demonstrated that Mediterranean regions are at greater risk of exposure to climate change than Atlantic regions, and that the adaption capacity (mainly social and economic) is much higher in the Atlantic. These results suggest that spatial heterogeneity in the vulnerability to climate change must be considered when combining international, national and regional adaptation measures into fisheries management. This is consistent with recent research noting that differences in the scale, response and severity of climate effects result in disproportionate impacts on different regions and groups of people (Österblom *et al.,* 2020; Tittensor *et al*., 2021), even within smaller regions (Ramirez *et al*, 2018, 2021). Therefore, differences in the adaptation capacity at the local governance level will affect the ability of socio-economic systems to deal with emerging and on-going changes (Kleisner *et al*., 2022 in this TS, see below).

Adaptation options: from socio-ecological resilience to planning climate-related adaptation actions

Climate adaptation covers a diversity of options, from institutional and management actions to measures preserving livelihoods or those enhancing social and ecological resilience. Such measures should: explicitly address climate-related risk(s), have sufficient basis to assess effectiveness or robustness, be a win-win or lose-win option, be flexible and responsive, and be socially acceptable (e.g. Grafton 2010, Bahri *et al*., 2021). However, to be effective, adaptation measures need to be commensurate with the context and capacities of the countries in each sub-region, which often generates trade-offs or potential conflicts between well-intended measures or across neighboring countries or regions. Numerous toolboxes, guidelines and local and regional examples and reviews describing diverse adaptation options are already available (e.g. Poulain *et al*., 2018, Bahri *et al*., 2021, Galappaththi *et al*., 2021). In this TS, Woods *et al.,* (2022) present a thorough and comprehensive review of adaptation options aimed at supporting social or ecological resilience and/or aiding adaptation to changes induced by environmental or social stressors in North America, Europe and the South Pacific. Contrary to their expectations, most examples focus on management adaptation aiming at enhancing ecological resilience in response to environmental or social stressors outside of the context of climate change and are, thus, poorly tailored to face its impacts. Their results highlight a lack of planning on how adaptation options, particularly those addressed to the local stakeholders, are developed and implemented.

Ecosystem-based management (EBM) recognizes structural trade-offs, searches for optimal management strategies and calls for monitoring of status indicators and updates of management measures when needed. EBM relies on the Integrated Ecosystem Assessment (IEA) framework that synthetizes and analyses information to support decisions in relation to specific ecosystem management objectives (Levin *et al.,* 2009). In this context, Woods (2022) presents a '*Food for Thought*' essay illustrating the work needed to align IEA to planned climate change adaptation by comparing NOAA's IEA approach to that of the United Nations Development Programme-Global Environment Facility Adaptation Policy Framework (Burton *et al*., 2004). The essay proposes three steps to achieve climate change adaptation: *i)* recognize the need and fund the adaptation planning, *ii)* evaluate which social and ecological information is lacking to implement better adaptation planning and identify the actors to be involved in the whole process, and *iii)* institutionalize and operationalize the process for creating adaptation options based on co-management principles, incorporating stakeholder engagement for the purpose of developing options that promote social and ecological resilience.

In most cases, quantifying the potential for adaption is an iterative process as the effectiveness of most of measures can only be assessed sometime after they have been implemented. This requires comprehensive and simple, reliable and cost-effective suites of socio-ecological indicators to evaluate the measures before and after their implementation. Nomura *et al*. (2022) apply network tools to assess the connectivity of small-scale fisheries in four regions of Baja California (Pacific coast of Mexico) to assess the degree of diversification of harvesting portfolios. Such diversification is an important adaptation option suggested for many fisheries as it can create multiple income sources in case one species becomes less abundant, less available or less valuable. The connectivity metrics gleaned from the study identified the areas where fisheries landings became increasingly asynchronous with each other, which may increase the potential for adaptive capacity due to the increase in diversification. A similar approach can be applied to assess the social connectivity that can inform the communication among different stakeholders and fishery actors. Social networks, particularly in fisheries, are integral elements to enhance adaptive capacity because social connectivity among the fishery components can enable knowledge and information sharing, facilitating the implementation of adaptive measures and improving their efficiency (Rubio *et al*. 2021). Different actors, occupying different network positions within the fishery, can value similar or different adaptive capacity strategies; social connectivity can contribute to the co-creation of common measures responding to their different demands and contexts.

Perception and acceptance of adaptation measures

Assessing societal and stakeholder perception and acceptance is an important element to link individual and sectorial behavior to governance and ultimately policy making. Rubio *et al*. (2022) surveyed skippers of Spanish purse seiners operating in the Atlantic, Indian, and Pacific Oceans that are harvesting tuna. Under a range of hypothetical scenarios to reduce fishing pressure and, thereby, decrease catch, a high percentage of skippers preferred adaptation and transformation measures (e.g. improving fishing gear technology, changing fishing areas or fishing frequency, among others) over strategies to facilitate exiting the fishery. The study also identifies adaptive characteristics of skippers contributing to this degree of acceptance, including flexibility, learning and socio-cognitive characteristics. Ryan *et al*. (2022) developed a perception study on the recreational fisheries, and considered fisher demographics (i.e. residence, gender or age group) and fishing behavior (avidity, bioregion fished and fishery types). Their results map the perception of recreational fishers to climate change related changes in species distribution and demonstrate that metropolitan and avid fishers show higher perception of climate change impacts and species responses. The recognition of climate change effects was also higher among metropolitan residents, female and younger responders. The authors highlight that engaging with recreational fishers to monitor fisheries over time is a robust approach to identify indicators that can help measure the impacts of climate change. They also recognize the added value of citizen science programs as a means to enhance data collection across the spatial and temporal time scales required to observe climate change impacts.

Policy pathways and governance in relation to climate adaptation

Given the heterogeneity of marine ecological and socioeconomic systems and the extensive national differences in resources, scientific-technical facilities and governance systems, the type of reforms and adaptation options to be implemented will need to be re-scaled and nuanced to regional and local levels-contexts. Kleisner *et al.* (2022) argue that the degree to which these capacities are available will determine, in part, the best policies to build resilience through transformative and adaptive measures that overcome systemic challenges to equity and sustainability when facing the diversity of climate change impacts. To assess the impacts of these differences in policy approaches, these authors apply a set of social–ecological resilience criteria to four case studies with contrasting adaptive capacities; from Myanmar, Belize, Peru, and Iceland. They assess several approaches available for achieving equitable, sustainable and resilient fisheries. This comparative study allows the identification of interactions (both synergies and trade-offs) between various social-ecological resilience criteria. The insights provided from this comparative approach can guide the identification of the most plausible adaptive and transformative policy approaches accounting for different capacities and contexts at regional and local scales.

Peterson Williams *et al.* (2022) present a study about the co-creation exercise between fishermen, conservationists and researchers to explore the 2020 closure of the directed Pacific cod (*Gadus macrocephalus*) fishery in the Gulf of Alaska. The closure was a consequence of the 2014–2016 marine heatwave in the northeast Pacific that triggered a decline in the cod population. The authors recommend that adaptive capacity tools and actions should be considered to better prepare for future warming and extreme events, such as the identification of habitat protection, development of environmental metrics and indicators that inform stock assessment and management, and development of species and stock specific climate risk analyses.

The science we need to transform ocean sustainability management

Although the disciplinary silos and barriers between scientists, stakeholders, policy makers and managers have been reduced, contemporary and future challenges posed by climate change impacts require even closer interactions and synergies, as well as innovative ways to co-create in the 'science to governance' pathway, including increasing institutional linkages (Cvitanovic *et al.* 2021, Woods 2022). *"Adaptation science*'" is an example of where this cross-sectoral interaction is urgently needed and where the development of transdisciplinary science is necessary. While research on adaptive capacity has largely focused on either ecological (i.e. experiments, data-driven or modeled) or social systems, new research efforts aimed at supporting decision-making need to embrace insights on adaptation science beyond the boundaries of single disciplines. Adaptation science has emerged to generate the evidence-based knowledge required to guide action in socio-ecological systems and to promote an increase in their adaptive capacity and performance, consolidating the best knowledge around threats, risks, uncertainties and opportunities associated with climate change impacts. The articles published in this TS provide examples of improved understanding about the mechanisms of new impacts, assessing system risks at subnational and international scales, proving and assessing different adaptation options and approaches, as well as societal and stakeholder perceptions.

There are still important knowledge gaps to be addressed by research on climate change adaptation. For example, more work remains to be done on understanding the degree of phenotypic plasticity and/or adaptive genetic variation (and its rate) to respond to climate change, across species and regions, life history strategies, functions and physiological sensitivities, as well as the impacts of cumulative climate change effects and the ecological implications of the capacity (or lack thereof) to adapt. Improving our knowledge on how species and ecosystems are likely to respond to changing climate conditions, and the limits, would improve our ability to identify and possibly anticipate tipping points and their consequences. Also, while climate driven changes in the spatial distribution of species have been well documented (e.g. Baudron *et al.* 2020; Pinsky *et al.* 2020), other spatially variable properties are also of paramount importance for fisheries productivity, for instance: demographic expansions/truncations, divergent trends of independent or connected (sub)populations, shifts in critical spatially-dependent processes (nurseries, spawning), and changes in life stage dispersal and survival, among others. The effects of climate change on these spatial properties are still poorly understood.

Beyond the advances already in the literature, including the contributions to this TS, the limits, barriers and constraints to management and societal adaptation are numerous and will challenge the responses of fisheries systems and their ability to address the impacts of climate change (Galappaththi *et al.* 2021). Recent essays, reviews and technical reports have highlighted challenges in adaptation science (e.g. Bell *et al.*, 2020; Magnan *et al.*, 2020; Bahri *et al.*, 2021; Galappaththi *et al.*, 2021). Implementation of climate-adaptive fisheries management, and the evaluation of its success and effectiveness in real systems, is generally lacking. In addition, "readiness" (actual stage of the measure's technical and technological development), "lead time until full effectiveness" (time needed to reach full implementation and effectiveness) or "duration of the benefits" of the positive actions are also important elements that need further research (Magnan *et al.*, 2020) and will also depend on the regional or national context, as highlighted by Aragao *et al.* (2022) and Kristner *et al.* (2022). Societal acceptance of whatever measures are taken is also difficult to assess, but is required to support the full implementation of adaptive measures, particularly those that are transformative.

Adaptation options and their planning have become a nascent focus of research within fisheries, within or alongside standard fisheries management research (e.g. Barange and Cochrane 2018; Holsman *et al.*, 2019; Bell *et al.*, 2020; Ojea *et al.*, 2020, 2021; or Kleisner *et al.*, 2022, Woods *et al.*, 2022, Woods 2022). The advancement of climate change adaptation science will be pivotal to achieve effective transformation in the management of the world's oceans and their natural resources. Working at the difficult interface between ecology, socio-economics and policy-governance, adaptation science is expected to provide concrete solutions to contemporary challenges of marine socio-ecological systems.

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Supplementary Data

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

Data availability statement

The data displayed in Figure 1 are provided as Supplementary Material.

Author contribution

M.H. and H.I.B. conceived the Themed Set (TS). M.H. led the writing of the Introduction. All authors contributed to defining the scope of the TS, to editing the manuscripts submitted, commented on early drafts of this Introduction, and participated in revising and finalizing it.

Declarations of interest

The authors declare no conflicts of interest.

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Disclaimer

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