frontiers | Frontiers in Marine Science

TYPE Editorial
PUBLISHED 28 August 2025
DOI 10.3389/fmars.2025.1684348

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OPEN ACCESS

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RECEIVED 12 August 2025
ACCEPTED 18 August 2025
PUBLISHED 28 August 2025

CITATION
Robinson C, Hobday AJ, Murphy EJ, Nayak PK and Newton A (2025) Editorial: Integrated marine biosphere research: ocean sustainability, under global change, for the benefit of society. *Front. Mar. Sci.* 12:1684348. doi: 10.3389/fmars.2025.1684348

Editorial: Integrated marine biosphere research: ocean sustainability, under global change, for the benefit of society

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KEYWORDS

IMBeR, marine biosphere, interdisciplinary, sustainability, global change, action plan

Editorial on the Research Topic
Integrated marine biosphere research: ocean sustainability, under global change, for the benefit of society

The Integrated Marine Biosphere Research (IMBeR) initiative is an interdisciplinary global environmental change research network with the mission to promote integrated marine research and enable capabilities for developing and implementing ocean sustainability options within and across the natural and social sciences, and to communicate relevant information and knowledge needed by society to secure sustainable, productive and healthy oceans. IMBeR began in 2005, and currently includes four regional programmes (Climate Impacts on Oceanic Top Predators (CLIOTOP), Ecosystem Studies of Sub-arctic and Arctic Seas (ESSAS), Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED), and Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER)), five working groups (Human Dimensions (HDWG), Continental Margins (CMWG), SOLAS-IMBeR Ocean Acidification (SIOA), and Integrated Ocean Carbon Research (IOC-R)), and three study groups (Eutrophication, Indo-Pacific Region and Ocean colour), encompassing a community of more than 6000 individual researchers from more than 110 countries.

The 31 articles included in this Research Topic developed from contributions to IMBeR's second open science conference Future Oceans 2, or from studies either supported or influenced by IMBeR activities. The global and collaborative nature of this effort is demonstrated in the Research Topic – the first authors of these articles represent 14 countries, 23 of the articles have co-authors from institutions in more than one country (a range of 1 – 10 countries per article, mean 3.4 countries) and all but one article are multi-authored (1 – 27 co-authors per paper, average 8.4). A companion Research Topic: *'Solving complex ocean challenges through interdisciplinary research: Advances from early career marine scientists'* was initiated at the same conference and led by members of the IMBeR network for early career researchers, the Interdisciplinary Marine Early Career Network

(IMECaN) (Brodie et al., 2022). This also highlighted strong global collaboration with 41 first authors representing 16 countries.

To achieve the IMBeR mission, the 2016 – 2025 IMBeR science plan (Hofmann and the IMBeR Scientific Steering Committee, 2016) identified three Grand Challenges (GC): I) to understand and quantify the state and variability of marine ecosystems; II) to improve scenarios, predictions and projections of future ocean-human systems at multiple scales; and III) to improve understanding and interaction between IMBeR science, policy and society to achieve improved governance, adaptation to and mitigation of global change, and transitions towards sustainability including human well-being. Each of the papers in the Research Topic contributes to one or more of these Grand Challenges, as described below.

GC I: To understand and quantify the state and variability of marine ecosystems

This GC is directed at using a whole-ecosystem approach to understand, detect, and quantify the effects of natural and anthropogenic change on marine ecosystems. The two priority research areas address linkages between food webs and biogeochemical cycles, with a focus on the processes that affect ecosystem structure and functioning and responses to change, and the range of time and space scales over which these processes and responses operate.

Articles in this Research Topic that contribute to GC I include those which investigate the relationships between key modes of climate variability, such as the El Niño Southern Oscillation (ENSO) and marine heatwaves (Su et al.) or the catch of functional groups such as fish, crabs, and eels (Alms and Wolff). The marked increase in the amount of both *in situ* and remotely sensed observations used to assess natural and human-induced changes in the marine environment requires the development of tools to handle large amounts of data and to generate products for both scientists and policymakers. Schmidt et al. describe the strategy of Ocean Data Information and Services (ODATIS) to become the gateway for all French marine data according to Findable, Accessible, Interoperable, and Reusable (FAIR) principles for data producers and users.

Using data and information on anthropogenic nutrient loadings and their impacts, Malone and Newton compare seven coastal ecosystems to assess the synergies between anthropogenic nutrient loading, overfishing, coastal development and climate driven increases in sea surface temperature, acidification and rainfall. They conclude that sustained integrated research and monitoring is required to enable effectively enforced ecosystem-based management of both point and diffuse sources of nitrogen and phosphorus. Cui et al. showed that nutrients were linked to coliform bacterial (CB) abundance in surface seawater in Jiaozhou Bay, China, and the measured spatial heterogeneity suggested a link to human activities and sewage discharge. CB abundance decreased throughout the study period, with significant drops in abundance at times which aligned with implementation of environmental governance actions. The study concludes that long-term monitoring of CB is valuable not only for indicating seawater quality but also for informing environmental governance strategies and pollution control efforts.

The GC I focus on whole ecosystem understanding requires addressing little known or poorly studied aspects of marine food webs, including the role of zooplankton in ocean carbon storage. Halfter et al., in a review of the impact of zooplankton grazing and the production of fecal pellets on carbon export in the subantarctic, conclude that zooplankton play an important role in the magnitude of the biological carbon pump, but that method bias and under sampling of the mesopelagic zone impede understanding and quantification of the zooplankton carcass and migratory flux.

The Barents Sea is a high-latitude shelf ecosystem known for its significant fisheries, fluctuating harvesting pressure, and variable climatic conditions. Pedersen et al. utilized a food web model to analyze the carbon flow pathways and the impact of harvesting intensity and climate variability on the Barents Sea ecosystem. The study identified the krill pathway as crucial, supplying both medium and high trophic levels, and highlighted a complex interplay between fisheries and the variability of lower trophic level groups. This interaction differed between boreal and Arctic functional groups, underscoring its significance for ecosystem management.

The complexity of biogeochemical cycles and human interactions across scales of temporal and spatial variability are also key to GC I. Understanding the environmental parameters which drive these cycles and interactions at the local ecotype could ultimately be used to extend to the regional scale. Lundevall-Zara et al. used this approach to derive coastal methane emissions from measurements of methane flux and habitat characterization (algal biomass, sediment organic carbon, temperature and wind speed).

GC II: To improve scenarios, predictions and projections of future ocean-human systems at multiple scales

Central to GC II is recognition of the need to generate models and develop projections of the future state of connected ocean-human systems (also termed marine socio-ecological systems) across not only aspects of physical, biogeochemical, and ecological science, but also aspects of human systems and social sciences.

The Shared Socioeconomic Pathways (SSPs) framework was developed to encompass society-natural system interactions to provide scenarios of how the application of different socio-economic policy strategies in response to climate change (in aspects of mitigation and adaptation) affect the future state of the Earth system (O'Neill et al., 2017; Kriegler et al., 2012). IMBeR scientists and colleagues developed the SSPs approach to generate relevant scenarios for policy development for oceanic systems

(Maury et al., 2017). A key requirement is to develop approaches to generate assessments of the potential future outcomes of alternative policy strategies for different marine sectors (e.g. commercial fisheries, aquaculture, or local community fisheries) in regional and local oceanic systems.

Four articles in this Research Topic describe studies that include social-economic perspectives in the development of scenarios for assessing future impacts of climate change in regional and local ocean systems. Pinnegar et al. developed four SSPs and projections to explore different adaptation and mitigation strategies for European aquaculture and fisheries. The article highlights the importance of an open and collaborative process, involving diverse stakeholders with a high level of expert and specific system knowledge, to generate useful scenarios for regional application. The authors indicate that the approach can be adapted for application at different scales and call for the wider application of the SSPs scenario framework for exploring the potential impacts of climate change in ocean ecosystems. Hamon et al. and Kreiss et al. report how the scenarios created by Pinnegar et al. were applied to explore the potential impacts of change over the next two to three decades in aspects of European fisheries and aquaculture respectively. Hamon et al. describe how the quantitative information needed to apply bio-economic fisheries models in European wild-capture fisheries was generated. That process involved expert knowledge and information from diverse literature sources and workshops involving a wide range of stakeholders (including those directly involved in the fishing industry and policy makers) and identified a series of variables required for modelling the impacts of change. The authors then applied the scenarios in a specific case study of the North Sea Flatfish fishery using a spatially explicit bio-economic model. The derived projections indicated the importance of future fish and fuel prices in determining the future viability and sustainability of the fishery.

Kreiss et al. undertook a similar approach to derive appropriate scenarios based on the key factors for the aquaculture sector that could change in the future. The scenarios were applied to generate projections of the profitability of European aquaculture by the middle of the century and then used to explore the influence of different scenarios of climate change and societal and economic trends. The study indicated that, rather than the direct effect of climate-driven changes, future profitability of European aquaculture was more sensitive to the future costs and returns and more specific aspects of the local industry operation (e.g. marketing of products). The combination of studies (Kreiss et al.; Hamon et al.; Pinnegar et al.) suggest that the process of scenario development provides important tools for raising awareness of the potential impacts of future climate change, and that the application of a common scenario framework is important for assessing and comparing the potential bio-economic impacts of climate change across fisheries and aquacultural sectors.

Garteizgogeascoa et al. explored the development of future scenarios for the marine social-ecological systems associated with the Humboldt Current Upwelling System of Peru. The study generated narrative potential future trajectories for the next two decades through a co-development process by engaging with the interests, concerns and knowledge of stakeholders. The results emphasized the importance of acknowledging uncertainties in future scenarios, and of drawing on a wide range of different stakeholder perspectives in the co-development of scenarios. The study also highlighted the need to downscale and provide realistic contexts for scenario development for regional and local settings. The authors suggest that the multi-stage collaborative co-development approach reported in their study can provide a basis for incorporating crucial knowledge on aspects of social dynamics for assessing impacts of potential future change and policy development.

GC III: To improve understanding and interaction between IMBeR science, policy and society to achieve improved governance

The third GC focuses on marine governance, including the acquisition, mobilization and provision of evidence-based science advice for marine managers, policy makers and other research end-users. This topic is increasingly important as a growing number of sectors use the ocean for economic returns, and as such come into conflict with existing cultural and livelihood uses and the desire for recovery of previously overexploited systems. IMBeR has long advocated for the importance of collaborative, integrated and interdisciplinary research (Hofmann et al., 2015), a stance which becomes especially relevant to the solutions oriented United Nations Decade of Ocean Science for Sustainable Development (2021 - 2030) (UNESCO-IOC, 2021) and the Sustainable Development Goals (2015 – 2030, especially goal 14 on Life Below Water that promotes the conservation and sustainable use of the oceans, seas and marine resources for sustainable development). Collaboration with social scientists and inclusion of societal perspectives and human dimensions in analyses of ocean systems is central to IMBeR science, recognizing the importance of social-ecological and socio-economic processes in determining the future state of the ocean and for the development of ocean policy. For example, Melbourne-Thomas et al. (2022) argued for including human dimensions in decade scale prediction systems, despite considerable difficulties. To overcome this challenge, they highlighted the important role of co-production to build trust and ensure uptake with end users. van Putten et al., in a review of a decade of efforts moving towards interdisciplinarity within IMBeR, documented successes including significant increase in attendance of social scientists at IMBeR events, creation of specific human dimensions working groups and research focused on the socio-economic systems dependent on oceanic top predators (Evans et al., 2020). However, they also recognized that the original, largely natural science goals of the regional programmes, and the lack of institutional support and encouragement to initiate connections with social science, hindered interdisciplinarity. They propose that future research programmes should have a truly interdisciplinary strategic plan and integrate specific funding, interdisciplinary events, within-programme-reflections and social science champions.

Popova et al. also recognize a 'whole system' approach to the marine environment and introduce the concept of 'socio-oceanography' to describe this. These authors also identify significant barriers to the development of interdisciplinarity, ranging from funding and publication models favouring disciplinary projects and articles to institutional cultures focused on developing individuals rather than interdisciplinary teams. They call for marine natural scientists and their funders, governing bodies and communicators to embrace the interdisciplinary nature of marine science. One step further, transdisciplinarity (involving non-academic participants such as policy makers, managers, research communicators, stakeholders and indigenous knowledge holders) aims to ensure research is relevant and can be applied as a service to society. Traditional ecological knowledge held by Indigenous peoples, has the potential to significantly enrich scientific comprehension of the marine environment. Working with the Anindilyakwa people of the Groote Eylandt Archipelago, Australia, Davies et al. developed benthic habitat maps suitable for conservation and management planning while also supporting the prioritization of indigenous values in the decision-making process. The loss of indigenous fishery-related knowledge is seen as a major threat to the sustainable management of marine and freshwater fisheries in Fiji and the Pacific Islands (Kitolelei et al.). In a systematic review, these authors document the drivers of such loss and propose solutions to protect and enrich this vital contribution to the conservation of ecological keystone and culturally important species.

Marine protected areas (MPAs) are an important mechanism for coastal conservation and management, but concerns about their abilities to meet the combined conservation-development goals remain. Pelletier describes how a programme of transdisciplinary research was used to successfully measure the effectiveness of MPA management. The assessment recognizes four lessons learned that fostered science-based management, including early and inclusive co-design, and also highlighted the length of time (up to 15 years) needed to establish a successful transdisciplinary consortium.

Several articles in this Research Topic address the role of the values and beliefs of local fishing communities in the resilience of small-scale fisheries to economic, policy and environmental challenges (Berenji et al.). Andrews et al. used narrative interviews with fishers to highlight values-oriented factors that shaped how fishers coped and adapted to change and uncertainty, emphasizing the need to incorporate fisher behavior into models, policies, and management approaches for improved governance outcomes. Personal values are also important in explaining support for sustainable management (Sánchez-Jiménez et al.). These authors assessed the effects on the pro-environmental behaviour of Costa Rican gillnet fishers of workshops which incorporated ecosystem modeling to present changes in the food web that result from fishing. The study indicates the importance of such education interventions to help participants perceive themselves as capable of implementing actions or changing their behaviour to strengthen co-management schemes.

Sultana et al. used a case study of the COVID - 19 pandemic and a 65-day seasonal fishery closure in coastal Bangladesh to investigate multilevel (individual, household and community) social-ecological systems resilience. They found that resilience relied on combining persistence (fishing remains the main source of income) with adaptation (diversifying income sources) and thus identified a range of policy implications of the study. Islam et al. investigated the fishers' perceptions of the socio-economic and ecological impacts of the same fishing ban, which was imposed to ensure the conservation of fish stocks. Almost half of the respondents thought that the closure would increase fishery catch when the ban was lifted, while almost all fishers perceived negative consequences related to the loss of income. The study highlighted the social inequity and environmental injustice involved in the fishery closure and made several recommendations to improve both conservation of resources and sustainability of the fisheries, based on involvement of fishers and their local ecological knowledge in an ecosystem-based management approach.

Integrated coastal and marine management (ICM) aims to restore biological productivity, biodiversity and habitat while also enhancing quality of life through economic development. Eger et al. assessed ICM governance arrangements in the Bay of Fundy, Canada with a view to improve national ICM operationalization and inform international efforts. These authors found site specific differences and so recommend more attention be given to strategies that incorporate local history, the unique capacity of actor groups and location-specific social-ecological systems objectives.

Integrated management is becoming a commonly articulated goal by regulators, managers and communities around the world, but progress is hampered by seemingly different but often conflicting approaches. For example, terms such as social-ecological systems approach, ecosystem-based management, integrated management, marine spatial planning and participatory co-management have parallel literature streams and seem to compete for attention. Stephenson et al. show that there are more similarities than differences in these integration concepts. Overall, the concepts reflect a strong focus on ecological and governance considerations, moderately strong for economic aspects, and are weakest for the social-cultural pillar of full spectrum sustainability. There is no hierarchy or best concept. Pragmatically, different concepts are used in different areas, and a combination of concepts and objectives will need to be woven together to achieve a cohesive quilt of sustainability and the development of more hybrid approaches.

Just as integrated terminology is diverse, so are the methods used to explore the outcomes in integrated ocean systems. Predictions, projections, scenarios, narratives, visions and intuitions can all be generated at a range of different spatial and temporal scales. While each can provide a different insight into a system future for a region, unified analysis remains elusive. Boschetti et al. propose a general framework to combine conceptual models, numerical projections and scenario narratives to generate a system view of the functioning of the Blue Economy sectors as applied to Australian oceans. This approach supports sector-based marine planning with a consistent and repeatable framing and can help researchers, managers and stakeholders reach a shared understanding of system interactions and the potential impact of future shocks to national and international drivers.

The expanding Blue Economy is seeing new sectors proposed, including deep-sea mining (DSM). This expansion should benefit communities through revenue generation, without compromising other values such as conservation and cultural connections. This latter risk is prominent in the Pacific, where traditional approaches to seabed resource management may be overlooked. In companion papers, Tilot et al. first consider how recognition of "Oceanian Sovereignty" should lead to policies, governance and management, and practices which acknowledge the value of environmental protection and social justice for marine spaces and resources. In the second paper, Tilot et al. expand on this concept as relevant to DSM from legal, environmental, anthropological, social, political, and economic science perspectives. They find that lessons from the Pacific have wide applicability in terms of reconciling competing perspectives.

When there is conflict between states and ocean users in contested regions, dispute resolution processes are sometimes enacted. Six case studies of maritime disputes around the world involving conflict, and in particular border disputes, are presented by Teff-Seker et al. In all cases, high ecological value, vulnerable ecosystems, and the need to conserve ecosystem services provided a shared interest for cooperation despite on-going diplomatic difficulties. As the Blue Economy expands, conflicts between sectors are likely to become more common and will undermine management and conservation objectives. Bellanger et al. also take a case study approach to examine how inter-sectoral conflicts can be addressed. They discuss the feasibility and key determinants of stakeholder collaboration and the use of compensation and incentive schemes. In this increasingly crowded ocean, future research must support policy development that considers the diversity of stakeholder interests and exposes the benefits of cross-sectoral coordination.

Capacity development

An important goal of IMBeR is the development of the next generation of interdisciplinary marine professionals, through mentoring, summer schools (Cvitanovic et al., 2024) and the creation of the Interdisciplinary Marine Early Career Network (IMECaN). The aim of IMECaN is to provide a networking platform for early career marine professionals to develop collaborations and provide training in areas not traditionally provided through formal education. A specific focus is on facilitating leadership opportunities particularly for early career researchers from developing nations and the Global South (Palacios-Abrantes et al., 2025). To ensure welcoming workplaces for early career marine scientists, it is important to understand the challenges they face (Osiecka et al.). These authors synthesized the results of an online survey of 492 people mostly aged between 22 and 35, female and from the USA or Europe who achieved their

FIGURE 1
Wordcloud of the themes, concepts, methods and geographies identified from the titles and keywords of the 31 articles in this Research Topic.

latest degree no longer than seven years ago. The responses highlighted strong economic barriers to access education and alarming levels of burn-out rates and mental health issues. Recommended actions to support early career marine professionals included mentoring, providing a safe working environment, adequate funding and fair pay to all field workers.

Future research priorities

One aim of this Research Topic was to review and assess scientific progress to help develop a future ocean research strategy. The timing of the Research Topic coincided with the global emergency of the COVID - 19 pandemic. Murphy et al. examined global scientific and policy responses to the pandemic to consider potential lessons for the ocean science community. These authors highlighted the importance of preparing and planning for future threats to the ocean and proposed the urgent need for the development of an '*Action Plan for the Ocean*'. To develop the *Action Plan*, the study defined a risk-based framework for application from local to global scales, involving multiple stakeholders and diverse perspectives. The authors called on the ocean science community to unite to develop an *Action Plan for the Ocean* and the activity continues to develop as an IMBeR research initiative with a goal of involving participants from more than 100 maritime nations.

Figure 1 helps us articulate the diversity of themes explored in contemporary socio-oceanography and marine sciences, highlighting key areas such as social-ecological systems, fisheries governance, climate impacts, traditional knowledge, marine policy, and ocean sustainability, among over 100 words, terms, concepts, methods, approaches, and geographies identified from the titles and key words of the 31 articles in this Research Topic through simple ocular enumeration. These themes offer a nuanced understanding of the broad range of future research areas, topics and priorities within the scope of integrated marine biosphere research aimed at making progress toward ocean sustainability.

Each of the IMBeR Grand Challenges has ongoing societal and governance relevance, and to ensure sustainable ocean use with a vibrant Blue Economy there is much work still to be done. The 31 articles in this Research Topic provide a rich scientific foundation for ongoing interdisciplinary research and policy/practice driven work. This is reflected in the diverse range of topics and formats (policy and practice review, case study, perspective etc.) used by the 260 authors. These 31 articles captured over 110 marine social-ecological topics, themes and concepts in socio-oceanography and marine sciences, and ecosystem types and geographical regions as the focal points for ongoing and future ocean-human systems research (Figure 1). This IMBeR Research Topic thus underscores the scientific capacity, motivation and vision within the research community to meet emerging challenges and make progress towards ocean sustainability for the benefit of society under pressing global change processes.

Author contributions

CR: Writing – original draft, Writing – review & editing. AH: Formal analysis, Writing – review & editing. EM: Writing – review & editing. PN: Visualization, Writing – review & editing, Formal analysis. AN: Writing – review & editing.

Funding

The author(s) declare financial support was received for the research and/or publication of this article. This IMBeR publication resulted from a meeting that was funded (in part) by a grant from the U.S. National Science Foundation to the Scientific Committee on Oceanic Research (SCOR) (Grants OCE - 1840868, 2140395 and 2513154). AN acknowledges the financial support of the Portuguese Foundation for Science and Technology (FCT) to CIMA (UID/0350/2020) and ARNET (LA/P/0069/2020).

Acknowledgments

We thank the staff of the IMBeR International Project Offices (Ocean Frontier Institute (OFI), Dalhousie University, Halifax, Canada and State Key Laboratory for Estuarine and Coastal Research (SKLEC), East China Normal University (ECNU), Shanghai, China) for their superb organization of the Future Oceans 2 conference. We thank all the authors for their contribution to this Research Topic, and all the reviewers who improved the individual contributions.

Conflict of interest

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.

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