frontiers | Frontiers in Ocean Sustainability

TYPE Policy and Practice Reviews
PUBLISHED 04 January 2024
DOI 10.3389/focsu.2023.1308125

OPEN ACCESS

EDITED BY
Gillian Glegg,
University of Plymouth, United Kingdom

REVIEWED BY
Carlos German Massone,
Pontifical Catholic University of Rio de Janeiro, Brazil
Cláudio Ernesto Taveira Parente,
Federal University of Rio de Janeiro, Brazil

*CORRESPONDENCE
Angel Borja
aborja@azti.es

RECEIVED 05 October 2023
ACCEPTED 05 December 2023
PUBLISHED 04 January 2024

CITATION
Borja A, Elliott M, Teixeira H, Stelzenmüller V, Katsanevakis S, Coll M, Galparsoro I, Fraschetti S, Papadopoulou N, Lynam C, Berg T, Andersen JH, Carstensen J, Leal MC and Uyarra MC (2024) Addressing the cumulative impacts of multiple human pressures in marine systems, for the sustainable use of the seas. *Front. Ocean Sustain.* 1:1308125.
doi: 10.3389/focsu.2023.1308125

Addressing the cumulative impacts of multiple human pressures in marine systems, for the sustainable use of the seas

Angel Borja[1]*, Michael Elliott[2,3], Heliana Teixeira[4], Vanessa Stelzenmüller[5], Stelios Katsanevakis[6], Marta Coll[7], Ibon Galparsoro[1], Simonetta Fraschetti[8,9], Nadia Papadopoulou[10], Christopher Lynam[11], Torsten Berg[12], Jesper H. Andersen[13,14], Jacob Carstensen[15], Miguel C. Leal[16] and María C. Uyarra[1]

[1]AZTI, Marine Research, Basque Research and Technology Alliance (BRTA), Herrera Kaia, Portualdea s/n, Pasaia, Spain, [2]School of Environmental Sciences, University of Hull, Hull, United Kingdom, [3]International Estuarine & Coastal Specialists (IECS) Ltd., Leven, United Kingdom, [4]Department of Biology & CESAM, University of Aveiro, Campus de Santiago, Aveiro, Portugal, [5]Thünen Institute of Sea Fisheries, Bremerhaven, Germany, [6]Department of Marine Sciences, University of the Aegean, Mytilene, Greece, [7]Institute of Marine Science (ICM-CSIC), Passeig Marítim de la Barceloneta, Barcelona, Spain, [8]Department of Biology, University of Naples Federico II, Naples, Italy, [9]National Biodiversity Future Center (NBFC), Palermo, Italy, [10]Hellenic Centre for Marine Research, IMBRIW, Heraklion, Greece, [11]Centre for Environment, Fisheries and Aquaculture Science, Lowestoft Laboratory, Lowestoft, United Kingdom, [12]MariLim Aquatic Research GmbH, Schönkirchen, Germany, [13]NIVA Denmark Water Research, Copenhagen, Denmark, [14]Aquatic Synthesis Research Centre (AquaSYNC), Copenhagen, Denmark, [15]Department of Ecoscience, Aarhus University, Roskilde, Denmark, [16]Science Crunchers, Scitation Lda, TecLabs - Campus da FCUL, Lisbon, Portugal

Human activities at sea have increased, causing subsequent degradation of ocean health and affecting ecosystem services and societal goods and benefits. Climate change further exacerbates the cumulative effects of these activities and their associated pressures. Hence, effective management of these multiple activities is imperative to ensure the sustainable use of the ocean. In response to these challenges, we have developed a comprehensive conceptual framework model within an ecosystem-based approach. This framework encompasses a versatile toolbox designed to assess cumulative pressures effects and the environmental status under the European Marine Strategy Framework Directive, in compliance with the Birds and Habitats Directives requirements and the need to secure the maintenance of ecosystem services and provision of societal benefits. Although we use European examples in the current discussion, we consider that there are similar challenges in many seas worldwide and so the recommendations here are widely applicable. Our aim is to facilitate the validation, harmonization, and demonstration of this toolbox across European regional seas and several countries, at different scales, from local to regional, including overseas territories. This approach aims to foster comparability in environmental status assessments. We anticipate that the proposed methodologies will serve as a foundational benchmark against which progress can be assessed in line with expectations and policy requirements. Additionally, this work prepares the groundwork for the forthcoming evaluation of the suitability, robustness, and applicability of these solutions and tools, thereby assisting managers in achieving Good Environmental Status (GES), both in European and wider global contexts, to address challenges which are common worldwide.

KEYWORDS

cumulative effects, risk management, ecological status, environmental status, assessment tools, ecosystem-based management, policy support

1 Introduction

Human activities at sea, such as the production and extraction of living and non-living resources, maritime transport, maritime infrastructure construction, and land-based activities affecting marine ecosystems, have significantly expanded in recent decades. These activities impose substantial pressures with a subsequent degradation of ocean health (Halpern et al., 2008, 2015; Reker et al., 2019; Korpinen et al., 2021; United Nations., 2021a,b), and, ultimately, affecting human wellbeing (Borja et al., 2020). Each activity has a designated area of operation (an activity footprint), in turn creating footprints of pressures (mechanisms of effect), and footprints of effects on the natural and social systems (Elliott et al., 2020a). These footprints then require to be addressed and managed, using management response-footprints (Cormier et al., 2017). As yet, the greatest challenge in marine management is in addressing the cumulative footprints of all activities and their associated pressures to mitigate the risk of adverse effects of their combined effects on ecosystem structure and functions (Stelzenmüller et al., 2018; Lonsdale et al., 2020).

Despite efforts to create a Sustainable Blue Economy and the European Green Deal to minimize human impacts on marine ecosystems and their services and societal goods and benefits (European Commission et al., 2022), maritime and upstream activities, driven by increasing human demands (Nash et al., 2020), are likely to increase. While regulations and planning tools exist, including maritime spatial planning (e.g., in Europe, the Maritime Spatial Planning Directive, MSPD; European Union, 2014), their cumulative impacts may translate to severe impacts on human welfare. The cumulative impacts of human activities and their pressures can be further enhanced by the effects of climate change (Gissi et al., 2021; IPCC, 2021), which is altering the ocean, with large-scale and severe effects on marine biodiversity worldwide (Duarte, 2014; Poloczanska et al., 2016; Pecl et al., 2017; Pörtner et al., 2021; Nikolaou and Katsanevakis, 2023).

Ensuring sustainable and regulated marine and coastal human activities is crucial to achieving established goals, such as the Biodiversity Strategy targets for 2030 (European Commission, 2020); Good Environmental Status (GES) under the Marine Strategy Framework Directive (MSFD; European Commission, 2008); the Good Ecological and Chemical Status under the Water Framework Directive (WFD; European Commission, 2000), for transitional and coastal waters; and the Favorable Conservation Status of vulnerable habitats and species [Birds and Habitats Directives, BHD (92/43/EEC)]. This aligns with the United Nations (UN) Decade of Ocean Science for Sustainable Development (2021–2030) (Claudet et al., 2020) and the UN Sustainable Development Goals (SDGs) (e.g., Molony et al., 2022). Additionally, the recently proposed EU Nature Restoration Law (European Commission, 2022) and the UN Decade of Ecosystems Restoration (Waltham et al., 2020) link sustainable use, planning of human activities, and the no deterioration clause with binding targets for ecosystem recovery by 2050. Achieving these goals will increase the likelihood of maintaining the provision of marine and coastal ecosystem services and societal goods and benefits under climate change, increasing the resistance and resilience of marine and societal systems (Runting et al., 2017; Gissi et al., 2021).

In this context, we present a conceptual model (Figure 1) developed as part of the Horizon Europe research project GES4SEAS[1]. The goal is to guide marine governance processes on minimizing the cumulative human pressures and their impacts on coastal and marine biodiversity and ecosystem functioning while maintaining the sustainable delivery of ecosystem services. Here, marine governance is defined as the sum of policies, politics, administration and legislation required to manage the marine system across all sectors (fisheries, shipping, seabed extraction, etc.), for tackling these complex issues (Elliott and Wither, 2023). We aim to achieve this objective by developing an innovative toolbox, tested, validated, and demonstrated in the context of adaptive ecosystem-based management (EBM) (Cormier et al., 2017). The co-creation of a toolbox with a focus on real problem-solving must start by understanding the uppermost assessment needs faced by stakeholders as well as their expectations regarding the main features or capacities of such an environmental assessment toolbox.

This toolbox will allow the competent marine authorities and regional seas conventions to assess and predict the effect of multiple stressors (including climate change) and pressures from human activities at the national, sub-regional, regional, and European levels, take informed management decisions, implementing measures that ultimately, will contribute to achieving GES. This framework is operating under the above environmental, socio-economic, and governance context, as shown in Figure 1.

Human activities are the result of socio-economic drivers and societal needs (Figure 1), leading to pressures that typically overlap in space and time, making the effects of their interactions cumulative (e.g., additive, synergistic, antagonistic, or a combination of these) (Elliott et al., 2020a; Lonsdale et al., 2020). Even though they are often studied in isolation, our knowledge of these interactions and their effects on the marine environment has increased in recent years (Crain et al., 2008; Ban et al., 2010; Coll et al., 2012; Korpinen and Andersen, 2016; Simeoni et al., 2023), but huge challenges remain to be solved. This includes our ability to consider the effects of all components of an activity, of all activities in an area and all areas constituting a marine management region on all receptors (ecological components).

Although physical and chemical processes can be predicted and based on deterministic relationships, marine physical, chemical and biological dynamics are often not linear. The consequence is that there is little predictability regarding stochastic ecological processes with which to inform decision-making processes, especially on ecological tipping points and thresholds of change (Dudney and Suding, 2020; Wedding et al., 2022), which, if exceeded, could inflict irreversible ecosystem damage (Lauerburg et al., 2020). In this context, an ecosystem-based and systems analysis approach to the management of human activities at sea and on land (Borja et al., 2016; Link and Browman, 2017; Elliott et al., 2020b) should ensure that the combined pressure of such activities is kept within levels that are compatible with the requirements of GES, against a background of climate change (Figure 1). This means that the

1 GES4SEAS: "Achieving good environmental status for maintaining ecosystem services, by assessing integrated impacts of cumulative pressures", (www.ges4seas.eu).

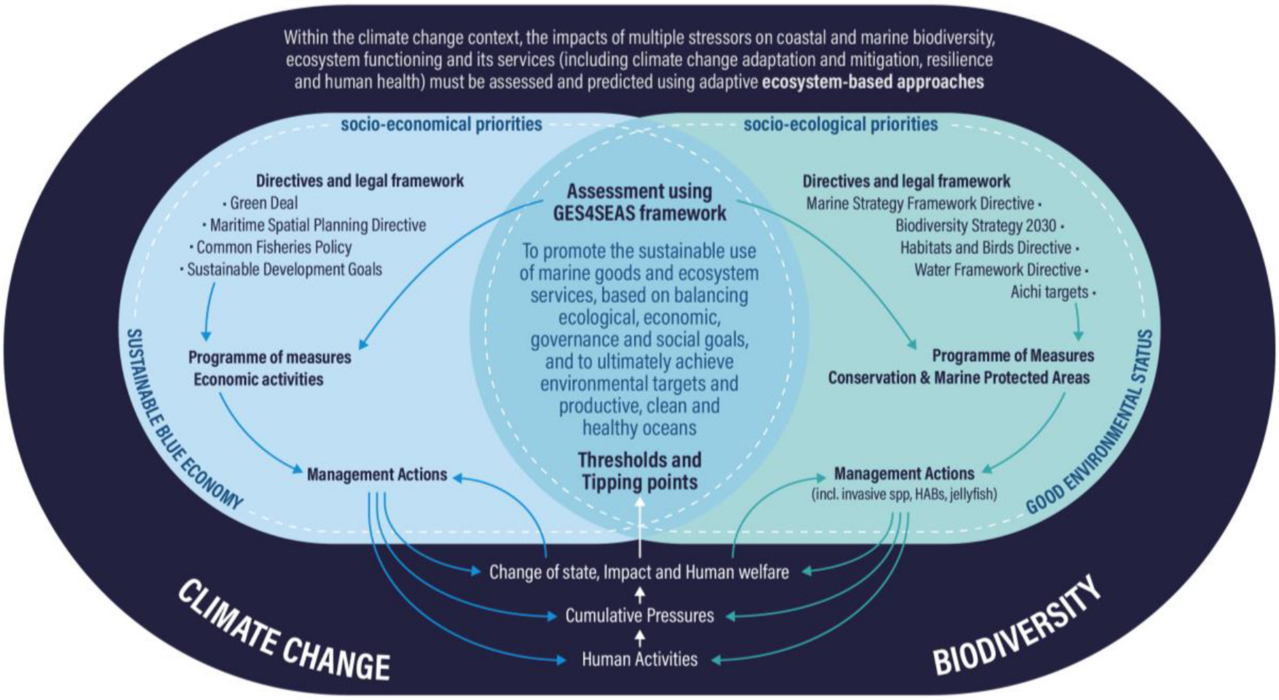

FIGURE 1
Socio-ecological, socio-economic and governance context of cumulative pressures effects management at sea, in which the project GES4SEAS is embedded.

capacity of marine and coastal ecosystems to respond to human-induced changes is not compromised, enabling the sustainable provision and use of marine goods and benefits by present and future generations. Furthermore, marine systems need to be kept resistant and resilient to rapid climate and environmental changes, as advocated by the Green Deal, IPBES, and IPCC (IPCC, 2021; Pörtner et al., 2021). However, more information is needed to reduce the gaps in spatial and temporal marine data (Maes et al., 2020) and in our understanding and knowledge of the impacts of cumulative pressures on ecosystem functioning.

Critical changes in ecosystem components leading to degraded ecosystem health are, for example, the shifts from high diversity habitats to unnaturally low diversity ones, the accumulation and increasing spread of invasive species or the increased frequency of harmful algal blooms (HABs) and jellyfish outbreaks, hence challenging the management of human activities (Fortuna et al., 2023; Katsanevakis et al., 2023; Sagarminaga et al., 2023a,b). Therefore, achieving "clean, healthy and productive oceans," *sensu* MSFD, is a delicate balance between the socio-economic needs and the socio-ecological goals (Figure 1), framed by existing agreed thresholds and observed/anticipated tipping points.

Our perspective of the combined effects of traditional and new sustainable Blue Economy activities is summarized in Figure 2. In principle, without human activities offshore, in coasts, or land, seas could be considered in GES. The sea can be regarded as having a finite assimilative capacity to accommodate human activities, their pressures and effects without adverse effects being manifest. With each additional activity permitted in a sea area, a portion of that assimilative capacity is then used up and so current activities can compromise achieving GES without adequate management measures (Elliott et al., 2018). The total sum of such management actions is defined in European terms as the Programme of Measures (PoM), *sensu* MSFD and WFD and those PoM will include mitigation and/or compensation methods to reduce the adverse effects of the activities and therefore recover some of the lost Assimilative Capacity; hence it is valuable to consider the carrying capacity of an sea area to support human activities without damage to ecosystem health (Elliott and Wither, 2023). Eventually, if mitigation cannot remove all adverse consequences, the number of activities and their pressures and effects would exceed GES and hence breach the national obligation to maintain a sea area in GES. Each of the Blue Economy activities can degrade environmental status, even if carried out in the most sustainable manner. Therefore, in consequence, without management or with poor management, the assimilative capacity of the system can be exceeded, despite existing solutions (Claudet, 2021).

There is an urgency in making the Blue Sustainable Economy compatible with the objectives of existing environmental policies for which tools are needed (European Commission, 2021). We aim at contributing to balanced, sustainable development, linking climate change and the cumulative effects of multiple activities on environmental status, ecosystem processes, functions, and services. A major challenge in marine management is to describe and quantify the impacts on specific ecosystem components, accounting for space and time lags, especially when the impacts do not all co-occur in space and/or time (Mazaris et al., 2019; Galparsoro et al., 2022). Therefore, here we propose methodologies and approaches to develop a framework for adaptive EBM, which

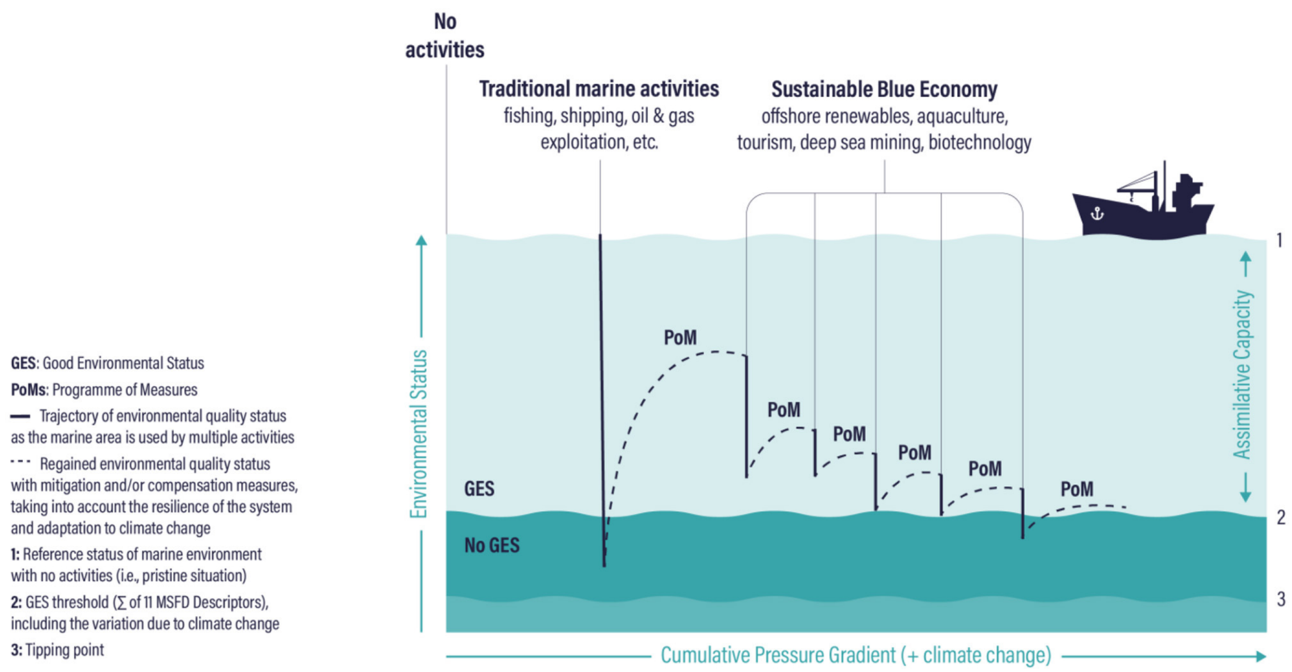

FIGURE 2
Illustration of the relationship between cumulative pressures, environmental status and the achievement of Good Environmental Status (GES). The magnitude of impact/recovery as well as the order by which activities are included in the figure are illustrative only [adapted from Elliott et al. (2018)].

by necessity includes a toolbox to assess cumulative pressures effects, the status under the MSFD and the BHD requirements (which use implementation cycles, favoring such an adaptive approach), and the maintenance of ecosystem services, in line with the goals of the EU Biodiversity Strategy 2030, the Green Deal and Mission Starfish 2030, for restoring ocean and seas (European Commission et al., 2020). This toolbox would be validated, harmonized, and demonstrated across EU regional seas and countries, at different scales, from local to regional, including overseas territories, allowing comparability in the GES assessments and use by the Member States and Regional Sea Conventions. We anticipate that this effort would serve as a baseline against which to check the progress against expectations and policy needs as well as fitness, robustness, and applicability of solutions and tools of this framework, to address challenges which are common worldwide.

2 Stakeholder involvement in a co-creation process

To achieve the abovementioned objective and meet the relevant policy objectives of the Biodiversity Strategy, Regional Seas Conventions, the MSFD, WFD and BHD, we consider that stakeholder involvement is crucial, guaranteeing a fit-for-purpose, pragmatic and validated outcome (Figure 3). Setting the scene with stakeholders has a pivotal role, identifying the policy and societal needs and validating the solutions proposed, engaging key stakeholders in the co-development of the framework and its accompanying toolbox. Therefore, as part of the stakeholder involvement process, a Practitioner Advisory Board (PAB) is required, including key actors to guide the co-creation approach.

Meeting the expectations of stakeholders on the main features or capacities expected from an environmental assessment toolbox is key to its acceptance. A preliminary survey engaging 22 stakeholders occupying key roles in marine governance and assessment (from the GES4SEAS project Stakeholder Initial Survey, 2022) retrieved 78 suggestions, many of which reflect a common desire for policy and regulatory compliance, flexibility of the toolbox, a clear link to pressures and to management, consideration of confidence of the assessments, compatibility and interoperability and clear guidance on its use (Supplementary Table S1), and compiled in Figure 4. A strong PAB together with other relevant stakeholders is also crucial to identify the main challenges currently faced by those carrying out or using the information from environmental assessments and drive science knowledge toward solutions and well-suited developments (Figure 4). Hence, the main outcome outlined above can be achieved and ensure compliance with policy and regulatory obligations, focusing on real problem-solving and following an iterative and incremental development approach (Larman and Basili, 2003), including communication and dissemination. This approach would also be used for software creation, which involves deconstructing the required comprehensive management system into smaller, manageable items. The iteration process should comprise several stages: Planning, Designing, Implementing, Testing, and Evaluating. As such, the proposed framework will need to progress through feedback loops and reiteration stages that refine the toolbox until it meets the objectives, under the guidance of the PAB.

This iterative process can partly be achieved through consultation during which different social research tools are used (e.g., focus groups, interviews) which include information-enhancing loops between the stakeholders and scientists (learning and showcasing bi-directionally). The concept of "learning" is central in this framework, which therefore should include a series of Learning Sites (i.e., case-study test areas), connecting stakeholders and scientists in the co-development and co-learning process, and bridging end-user needs with the scientific activities.

It is critical for the success of this collaborative process to involve those stakeholders that have an influence on both the specific goals and end-products to be achieved. The implementation of the Green Deal and the new EU Biodiversity Strategy requires that Member States collaborate, supported by Regional Seas Conventions, to enable meeting the targets required by these major environmental policies [also including MSFD, BHD, WFD, Common Fisheries Policy (CFP)]. Often, such policies are misaligned spatially and temporally to a certain degree regarding monitoring, reporting and targets (e.g., Franco et al., 2021). This is despite them often converging and overlapping partially in their objectives.

These outcomes would be communicated and promoted by being adapted for dissemination to external and wider audiences, and future exploitation. This co-creation approach provides legitimacy to the outputs developed, i.e., their validity within the targeted policies context; commitment to its future use, as key stakeholders are more likely to feel a co-ownership of the solutions generated, and increased efficiency of its implementation. The ultimate outcome would be knowledge transfer, real use and uptake by the practitioners of a co-developed toolbox, necessary for implementing the EBM approach.

3 A conceptual framework to solve problems

The conceptual framework and theory, underpinning the whole process to be operationalized in the different phases, should be defined (Figure 5). It should indicate the boundaries for the models to be used, the scenarios related to human activities and climate change predictions, and the toolbox required to be used in the Learning Sites, in a logical sequence to fit or contribute to EBM approaches (Figure 5). It will identify all relevant human activities both at sea and on land and how their pressures impact the ecosystem and its components and guide EBM toward achieving GES. Based on existing work (e.g., Culhane et al., 2019), we are determining how the ecosystem service capacity depends on marine ecosystems and GES (Elliott, 2023; Van de Pol et al., 2023). As the focus is on the sustainable use of coastal and marine ecosystems to perform services from which society obtains goods and benefits and be resistant and resilient to the effects of unmanaged exogenous pressures (e.g., climate change) (Borja et al., 2010), we are focusing on those ecosystem services that are sensitive to ecosystem change and health status, including the way they lead to societal goods and benefits, including human health and welfare (e.g., Charles et al., 2016; Elliott, 2023).

Within this framework, exogenic unmanaged pressures are defined as "causes of change which have their origin outside of a management system and cannot be controlled by local measures whereas the consequences which occur in the management site are subject to management measures" while endogenic managed pressures are defined as "anthropogenic pressures which originate within management system, i.e., the causes of change can be controlled and their consequences addressed" (Smith et al., 2022; Elliott and Wither, 2023). All this work provides the theoretical and practical basis, and it guides the process of data analyses and model building that constitutes the knowledge-base required to address the policy and stakeholder requirements. This includes data and methods for determining the spatial and temporal activity-, pressure-, effect-, and management response- footprints (Elliott et al., 2020a) and will separate these according to endogenic and exogenic pressures using the causes-consequences-responses pathways (e.g., Elliott et al., 2017; Cormier et al., 2019). To do this, a solid commitment to building on the work of previous projects, and the conceptual approaches they have developed (e.g., Knights et al., 2015; Patrício et al., 2016; Smith et al., 2016; Borgwardt et al., 2019; Pedreschi et al., 2019), is necessary.

The background and approaches to fill knowledge gaps in our assessment of effects of multiple pressures on the ecosystem and its functioning, i.e., using meta-analyses quantifying the direction and magnitude of links between activities-pressures-ecosystem components-processes-functions-ecosystem services-societal goods and benefits and how these can inform EBM are central to the proposed approach. In addition, having monitoring data, based on the background related to possible lines of physical-chemical, ecotoxicological and ecological evidence, it could be possible to detect acute and chronic changes related to anthropogenic activities. Having thus increased our understanding on the response of organisms, ecosystems, processes, functions and services to anthropogenic pressures and environmental changes, the results from the information analysis would (i) support analyses toward methods to identify reference levels and potential tipping points, (ii) set thresholds where possible (Lauerburg et al., 2020), and (iii) evaluate the consequences of management options aimed at protecting marine habitats and species, building on previous studies (Halpern et al., 2008; Cormier et al., 2013, 2017, 2019; Andersen et al., 2015; Elliott et al., 2017, 2020a,b; Korpinen et al., 2019; Lonsdale et al., 2020). However, differentiating between service capacity and its human use is needed. That service capacity can be linked to GES, but its use may not, as not all services are linked to GES (Elliott, 2023).

In addition to the cause-consequence-response framework DAPSI(W)R(M) [Drivers, Activities, Pressures, State changes (on the natural system including ecosystem services), Impacts (on human Welfare, including the effects on societal goods and benefits), Responses (using management Measures)] (Elliott et al., 2017), as a unifying approach, we are incorporating the Commission Staff Working Document recommendation to use

 10.3389/focsu.2023.1308125

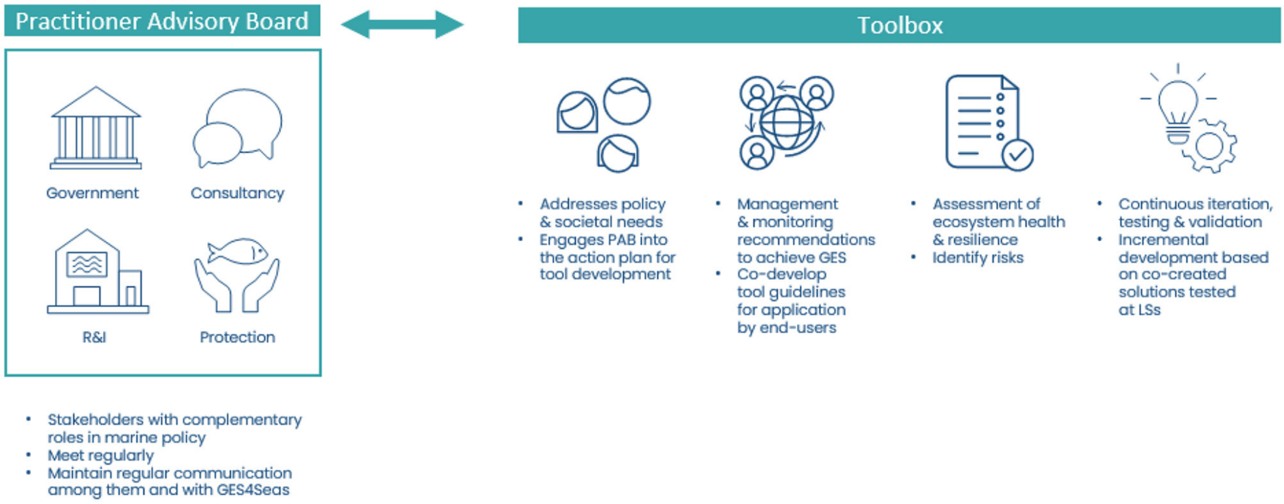

FIGURE 3
Stakeholder engagement to co-create suitable tools for marine management. GES, Good Environmental Status; LSs, Learning Sites; PAB, Practitioner Advisory Board.

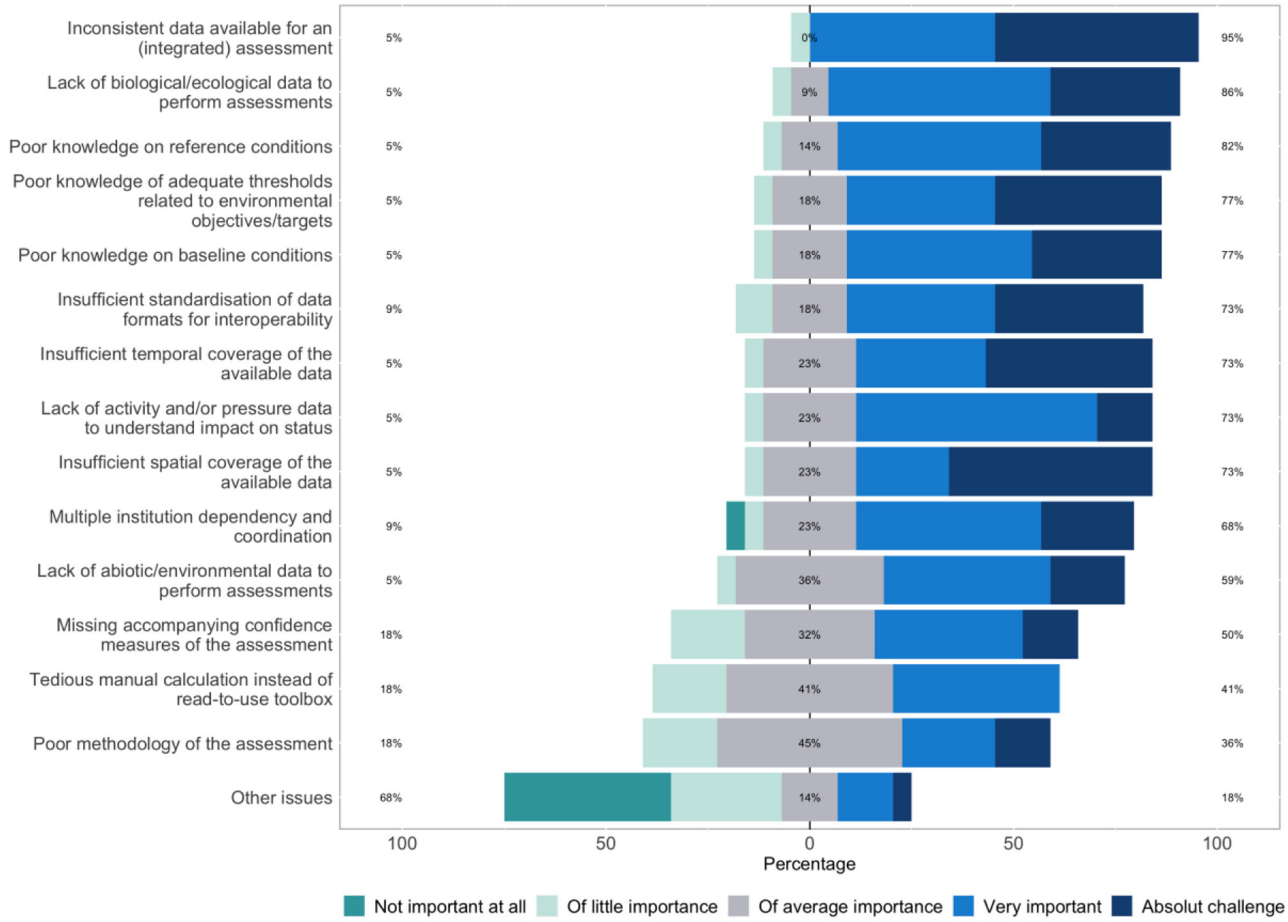

FIGURE 4
Main challenges faced with environmental assessments. Perspective from 22 stakeholders occupying key roles in marine governance and assessment in national ministries and competent authorities, NGO's, Regional Sea Conventions, European Commission and agencies (from the GES4SEAS project Stakeholder Initial Survey, 2022).

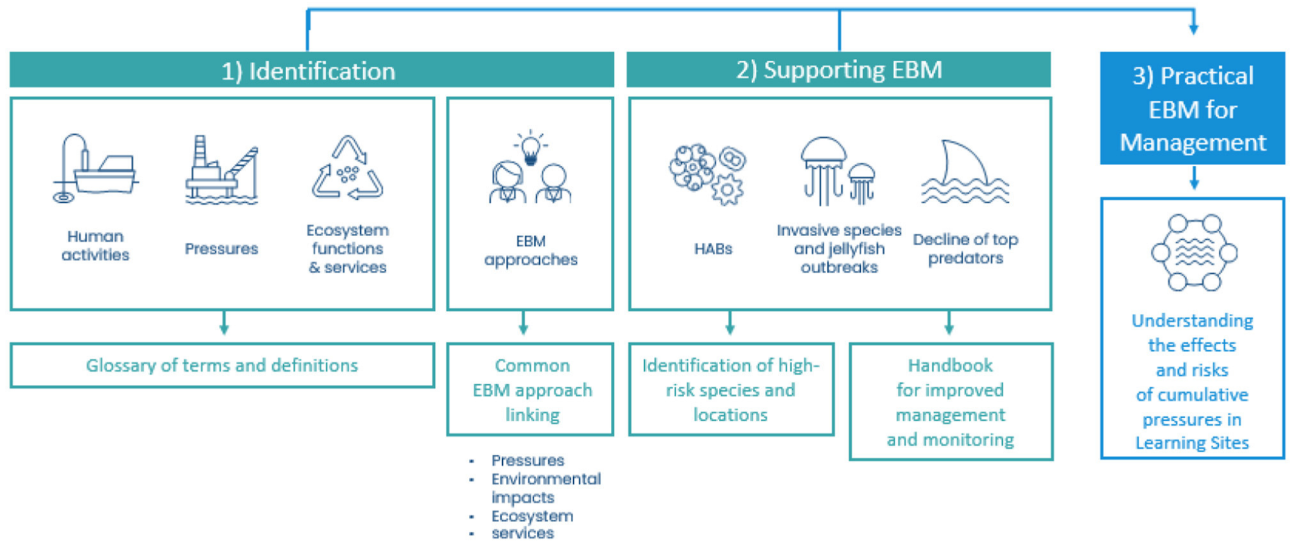

FIGURE 5
Developing a conceptual framework and knowledge base for Ecosystem-Based Management (EBM). HABs, Harmful Algal Blooms.

the DAPSES-MMM approach[2], which is similar but which adds confusion through the explicit separation into natural ecosystem services and societal ecosystem services (cf. Elliott, 2023), as well as goods and benefits, including human health and welfare. However, the latter approach extends the acronym to mention monitoring, measures and management, linked to MSFD (e.g., articles 11 and 13) and inherently included in R(M), in DAPSI(W)R(M). These frameworks give the ability to develop a unified approach that connects activities with pressures to state change on the natural system and impact on the human system, and the capacity to supply ecosystem services which then, after inputting human complementary assets and capital, provides goods and benefits for human health and wellbeing, combining the model components together into a coherent system.

In turn, this would be made operational at the Learning Sites, in close collaboration with the PAB, in showing how to develop solutions (responses and management measures) (Stelzenmüller et al., 2020). A risk-based approach based on Exposure × Effect or Hazard × Vulnerability links (see Galparsoro et al., 2021), such as the widely used and ISO standard Bow-tie method and software, should be also included (Cormier et al., 2019). It would also use a modified method to give stakeholder-led assessment and opportunities in marine environmental management (Elliott et al., 2020c). Importantly, this involves defining the role of all actors well in advance by showing what to expect from whom. For example, bringing into the spotlight marine invasive species, HABs, jellyfish outbreaks, and the decline of top predators that affect the biodiversity of all European marine regions (Katsanevakis et al., 2014, 2016; Sanseverino et al., 2016; Prieto, 2018; Tsiamis et al., 2018; Karlson et al., 2021; Zingone et al., 2021) we have reviewed in depth the Drivers, Pressures, State change, and affected ecosystem services (Fortuna et al., 2023; Katsanevakis et al., 2023; Sagarminaga et al., 2023a,b). Best practices and existing knowledge in monitoring, assessment, predicting, and managing these issues, and compiling a set of guidelines and tools for improved management, also accounting for the potential of new technologies and novel methods, such as eDNA, metabarcoding, remote sensing, and biologgers, have been also completed (Fortuna et al., 2023; Katsanevakis et al., 2023; Sagarminaga et al., 2023a,b).

4 Understanding the mechanisms of cumulative effects

The proposed approach is also underpinned by our development of the knowledge base to quantify, assess and forecast the consequences of anthropogenic perturbations on ecosystem sustainability, productivity, and resilience, from the conceptual and theoretical framework raised previously, under scenarios of climate change by 2050 (including particular aspects, such as sex segregation of species, depending on environmental factors, and extreme events). The objective is to understand the mechanisms that determine cumulative effects (Figure 6).

This includes refining methods and using existing models to set thresholds and establish tipping points. Here, tipping points are defined as "zones of rapid change in a non-linear relationship between the state of an ecosystem or ecosystem component and intensity of a driver, human activity or pressure. This leads to abrupt transitions beyond a critical level, in which the system is unable to return to the precedent stable stage" [term adapted after Selkoe et al., 2015 and Stelzenmüller et al., 2018 in Smith et al. (2022)]. Thresholds are defined as "a value or range of values that allows for an assessment

2 DAPSES-MMM: Drivers, Activities, Pressures, State of Change, Ecosystem Services, Management, Measures, Monitoring, (https://data.consilium.europa.eu/doc/document/ST-9161-2020-ADD-5/en/pdf).

10.3389/focsu.2023.1308125

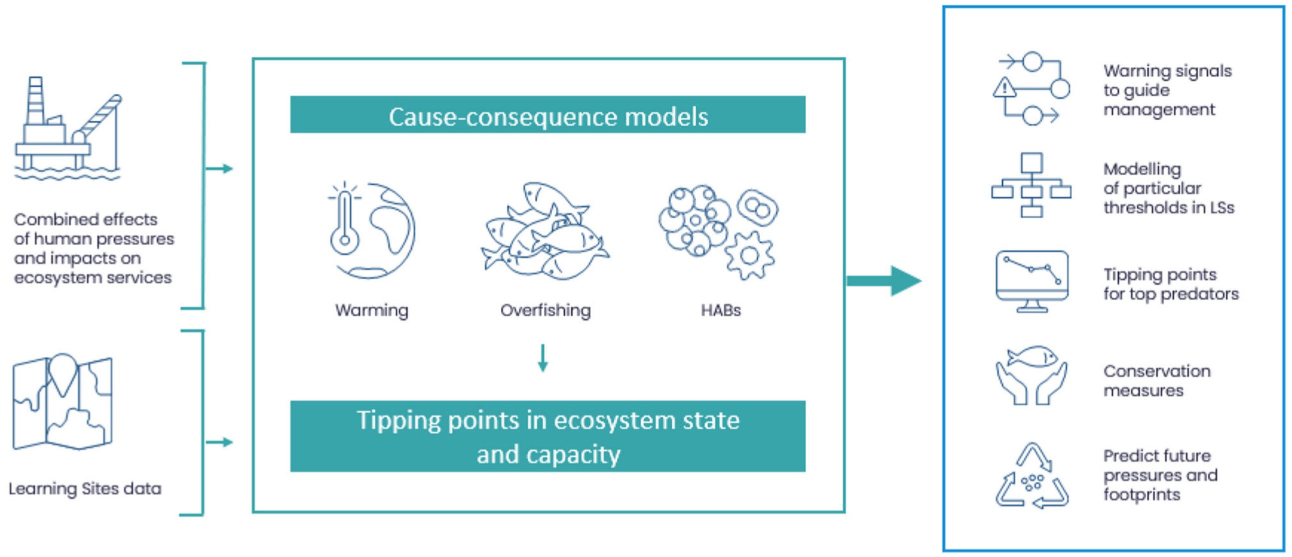

FIGURE 6
Understanding the mechanisms that determine the cumulative effects of human activities and climate change. HABs, Harmful Algal Blooms.

of the quality level achieved for a particular criterion, thereby contributing to the assessment of the extent to which GES is being achieved" [after the European Commission, 2017, in Smith et al. (2022)].

Mechanistic models would need to be parametrized from data analyses together with existing knowledge [analysis on impact-chains covering each of the two main risk aspects (i.e., exposure and potential effect)], stakeholder input and specific analyses at the Learning Sites, and their outcomes (codes and interfaces) should be then implemented. The integration of two approaches would be needed: combined effects (pressures) and environmental status and dynamics, making this integration operational. This would enable the assessments relevant to the implementation of the MSFD, BHD and Biodiversity Strategy, to be included in the toolbox. In generating the approach proposed here, by necessity, we are building upon the work from previous projects and other initiatives, in linking human activities and pressures and impacts/state/ecosystem services, using a variety of models (Coll et al., 2012, 2016, 2019, 2020; Uusitalo et al., 2016b; Lynam et al., 2017; Stelzenmüller et al., 2018, 2020; Cormier et al., 2019). This work sets the scene and defines the ways to undertake the work in the Learning Sites and the further development of the software toolbox as well as the inclusion of the links between GES and the capacity to deliver ecosystem services (Broszeit et al., 2017; Leenhardt et al., 2017), using the Common International Classification of Ecosystem Services (CICES; Haines-Young Potschin, 2018). Models are being used to investigate the most appropriate ways to obtain thresholds and tipping points, building on previous evidence (Scheffer and Carpenter, 2003; deYoung et al., 2008; Scheffer et al., 2009; Lynam et al., 2016; Dudney and Suding, 2020; Hillebrand et al., 2020; Lauerburg et al., 2020; Rogers et al., 2020; Thrush et al., 2021) and tools (e.g., Fulton et al., 2015) under the climate change context.

5 Developing a software tool for assessing the status of the ocean

The approach proposed here relies on integrative and holistic solutions which are being operationalized to identify a scientific framework and software toolbox for mapping, analyzing and assessing (i) cumulative pressures [Cumulative Impact Assessment/Combined Effects Assessment (CIA/CEA)], (ii) GES, and (iii) ecosystem services in a systematic and holistic way (Figure 7). To date, these three assessments have often been carried out separately, in some projects and by Regional Seas Conventions. Nonetheless, there is a high degree of interaction and dependencies within these three assessments (Birk et al., 2020; Culhane et al., 2020). These assessments have the potential to be aligned, starting by combining and improving existing tools and frameworks [e.g., Nested Environmental status Assessment Tool –NEAT (Borja et al., 2016), the CIA and EcoImpactMapper methods (Halpern et al., 2008; Stock, 2016), and the "Marine Ecosystem Capacity for Service supply Assessment" method (MECSA) (Culhane et al., 2020)]. Hence, this would produce an innovative and flexible toolbox, which can deliver science-based assessments with both numerical and spatial output; in consequence, the toolbox will also enable guiding the management process [in terms of DAPSI(W)R(M), see Elliott et al., 2017], to inform decision making (e.g., as required under the MSFD, BHD, Biodiversity Strategy) (Loiseau et al., 2021). An added value of such integration is the improved incorporation of the spatial extent of both human activities and ecosystem components and the possibility to cross-refer and validate the assessment results to the various data sources used. The toolbox should be iteratively adjusted, tested and validated at the Learning Sites, in collaboration with feedback from the PAB.

This integrative toolbox will be required/invaluable for use by managers and decision-makers for assessing the effects of pressures on both the ecosystem status (e.g., MSFD GES, or

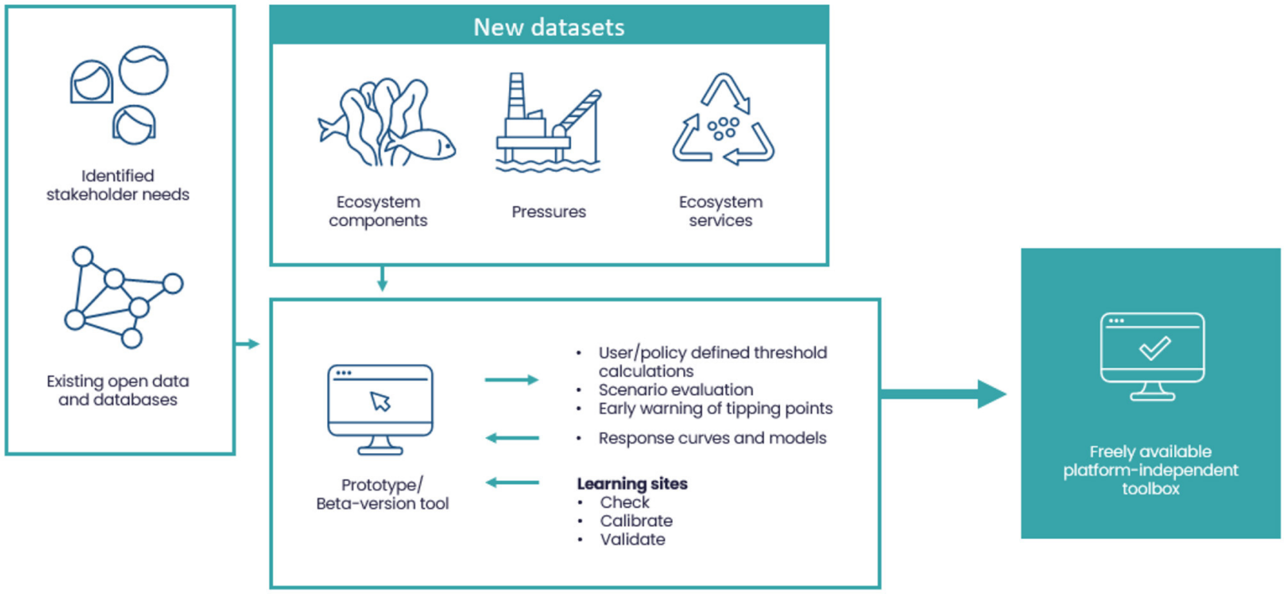

FIGURE 7
Linking pressure and status assessment with the capacity to supply ecosystem services into a unifying holistic framework and nested toolbox.

BHD favorable conservation status) and on the capacity to supply ecosystem services within contrasting scenarios of human activities and climate change. The objective is to advance from the current situation with multiple disparate assessment frameworks and tools (see Smit et al., 2021, for an overview) to a comprehensive integrative and hierarchical framework with multiple inputs and outputs, linkages and/or crosswalks between them, and an accompanying confidence assessment. It is further emphasized that the ability to understand and manage such a complex socio-ecological system therefore requires a systems analysis approach which has a solid underpinning theoretical framework, but which is then able to be implemented by stakeholders (Elliott et al., 2020b). As such, a simplicity of implementation, flexibility, and transparency are key to this process, as it enhances acceptance by key stakeholders, especially as a decision support tool (Nygård et al., 2020; Schumacher et al., 2020).

To meet the overall objectives, an iterative and incremental development approach is required to be applied, following the steps: (i) development of a prototype based on existing tools and software, after inputs from PAB stakeholder needs; (ii) co-development of an assessment framework and a tool that overcome weaknesses of existing approaches, and (iii) based on rigorous testing of the toolbox, in Learning Sites, with further improvement (iterations with PAB) and dissemination to stakeholders (Figure 3). Key challenges to overcome in the three steps are:

- Step 1: Combining existing tools into a unifying toolbox. This would be achieved by initially combining three existing tools: (i) NEAT (Borja et al., 2016, 2021; Uusitalo et al., 2016a; Pavlidou et al., 2018), (ii) EcoImpactMapper, an open-source tool for mapping of cumulative effects (Stock, 2016), and (iii) the MECSA methodology (Culhane et al., 2020).
- Step 2: Improving existing and widely used frameworks/tools. The prototype toolbox developed in step 1 would be further developed, focusing on a range of well-known weaknesses (e.g., Quemmerais-Amice et al., 2020) that will be overcome, e.g.,: (i) supplement the linear and unidirectional relation between pressures and ecosystem responses with response curves and thresholds models; (ii) enhance the current flat/sectoral structure to a hierarchical one using e.g., conceptual ecosystem models connecting ecosystem components with pressures and the resulting state changes and the ecosystem services and resultant societal goods and benefits that they provide (e.g., Griffiths et al., 2017); (iii) supplement the use of expert judgement (currently extensively applied) for the setting of weighting factors with data-driven/evidence-driven approaches; (iv) allowing flexibility in the selection of aggregation/integration methods, depending on the regional needs; (v) include uncertainty assessment as an output from the tool (e.g., Uusitalo et al., 2016a; Quemmerais-Amice et al., 2020; Carstensen et al., 2023), and (vi) define data structures and interfaces that enable direct linkage between existing data and databases and the tool, and thus minimize the need for manual data input, a hurdle to key stakeholders characterizing many standalone assessment tools.
- Step 3: Based on the testing of the toolbox in Learning Sites with more data, and the risk-based approach, the modules could be fine-tuned, tested in Learning Sites with limited data and upscaled to regional seas, documented and published as a final version of the toolbox, also engagement with PAB to anchor the developed tool within the stakeholder community.

10.3389/focsu.2023.1308125

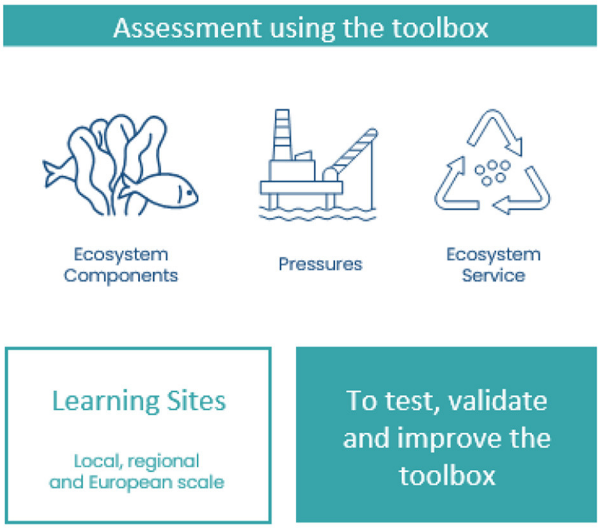

FIGURE 8
Learning sites to test and validate the toolbox and synthesize recommendations for stakeholders.

6 Learning together, by testing together

Working with the Learning Sites and the PAB, the proposed strategy would contrast different approaches and extract clear, concise, operational, and harmonized conclusions (Figure 8). A central aim for all Learning Sites would be to provide the developing, testing and demonstration ground for the assessment toolbox and validate its value with respect to the EBM and specifically, the risk of adverse effects on GES, selected ecosystem services, functions and processes, human health and wellbeing, in the face of cumulative human pressures and climate change scenarios.

The Learning Sites should facilitate mutual learning and collaboration, providing additional skills (e.g., modeling, use of integrative tools, etc.), or knowledge and skills-exchange transverse to the sites (i.e., use of satellite data to set HABs extent, molecular methods to detect invasive species, etc.). This ensures that knowledge is transferred from one site to another, experiences from stakeholders are shared from a regional sea to another, and finally, the outputs can be shared, harmonized and understood in different geographical areas and at various spatial scales, readily applicable to stakeholders. To increase this knowledge transfer, cooperation should be established with main actors in marine assessment, by providing and harnessing data and applying an integrated conceptual framework, both at national and international level. Furthermore, this gives the much-needed potential to take experience from skills and data-rich areas to areas with a lesser experience of these aspects.

With this aim, Learning Sites should cover a broad variety of human activities and pressures affecting the marine environment, as well as the different environmental (MSFD Descriptors) and ecosystem services and societal goods and benefits (CICES: Haines-Young Potschin, 2018; Elliott, 2023) affected. In order to test and validate fully the approach, Learning Sites should vary greatly in terms of geographical scope and spatial scales (i.e., local, subregional, regional, continental, overseas), political context (i.e., EU and non-EU countries), state of knowledge regarding cumulative impacts, ecosystem services and their interplay with climate change, as well as data and knowledge availability. The sharing and use of data from portals such as EMODnet[3], WISE Marine[4], and Copernicus[5] should be promoted. The stocktake of current knowledge also comprises data from other resources such as national data reported to the EU under different directives, to the Regional Seas Conventions, or published literature. The Learning Sites would enable the ability to:

- Explore the specificities of Learning Sites stemming from different geographical locations, especially with regards to the impacts of cumulative pressures (including climate change) in the functioning of ecosystems (and the capacity for providing ecosystem services, and benefits for human health), so they can be better managed. To this end, Learning Sites with different sets of activities, pressures, impacts, ecosystem services and societal goods and benefits should be covered in detail.
- Determine how the toolbox developed can work at a large pan-European scale, exploring comparability and harmonization across regional seas, integrating cumulative pressures, impacts (status) and ecosystem services delivery.
- Gain understanding on the functioning of transverse topics, such as invasive species, HABs and jellyfish blooms, as well as aspects related to top predator monitoring (Ferrer et al., 2015; Ferrer and Pastor, 2017; Ferrer and González, 2021); in addition, it would encompass developing and testing methods based on biologging, remote sensing, and genomics (eDNA), for different ecosystem components.
- Learn how to best manage transboundary issues, especially with non-EU countries, including barriers to coherence and equivalence of outcomes, which may often hinder the process and/or successful policy implementation and effectiveness (e.g., Elliott et al., 2023).
- Internationalize outputs and receive inputs by going beyond the EU frontier reaching other non-EU Seas. This is of particular interest as while sharing the SDGs framework, the marine management approaches elsewhere may or may not differ from those in the EU.
- Identifying requirements and potential limitations for the application of the toolbox and, in an iterative process, adapt them to the stakeholder needs, thereby testing, validating, and demonstrating the toolbox in areas with different amounts of data, and upscaled to regional seas and all European seas.
- Implementing cumulative impact models (Katsanevakis et al., 2016) associated with hazardous events.
- Synthesizing the lessons learnt across Learning Sites with regard to (a) cumulative impacts, from different pressures on marine biodiversity and ecosystems components and

3 https://emodnet.ec.europa.eu/en
4 https://water.europa.eu/marine
5 https://www.copernicus.eu/en

functions, as required by the MSFD, (b) estimating extinction risks of species, communities and structures that are essential to ecosystem functioning and the conservation of marine biodiversity, (c) advanced understanding of approaching tipping points, (d) assess the risks to ecosystem services, and to societal goods and benefits including human health and wellbeing, and (e) mitigation strategies to achieve GES targets, in relation to the MSFD PoM. All these lessons will set the basis for an EBM approach, which would be completed in close collaboration with PAB.

Given the above requirements, actions and activities, there is the need to make solutions available and ready to use. The lessons learnt at the Learning Sites, and the outputs generated, will need to be transferred to the stakeholders, but also further afield as the proposed approach will enhance societal and public engagement and understanding of ecosystem functioning and human health through ocean literacy, ensuring adequate dissemination and exploitation. The dissemination would be based on an innovative set of tasks, which use ocean literacy (based on IOC-UNESCO guidelines). Importantly, this will contribute to behavioral change in society, as well as educating and training (i.e., school and adult education, summer schools, citizen science platforms) a new generation of researchers in tools developed, using the lessons learnt. This additionally has the benefit of ensuring cooperation with international organizations and initiatives, by providing and harnessing data and applying an integrated conceptual framework, in close cooperation with PAB.

7 Enhancing the impact of the outcomes

With its results, outcomes and impacts, the proposed approach described here will contribute to accelerate the ecological transition required by the European Green Deal, specifically within the Destination "Biodiversity and ecosystem services," as proposed in Table 1.

The outcomes and results would then need to be disseminated, exploited and communicated following a plan that can be carefully designed based on the Lasswell's Communication Model. This model focuses on "Who says What to Whom in Which channel and with What effect," as a means to maximize the impact of any action (Figure 9).

Usually, maximizing the impact outputs requires (i) reaching key stakeholders so that they can better manage pressure impacts and (ii) bridging the existing gap between science and other sectors (i.e., competent implementing authorities/policy-makers, scientists, society at large, and younger generations) by increasing ocean literacy. This objective can be achieved through dedicated workshops, selecting the key messages on which we want to focus, e.g., what and why is ocean functioning so complex? What do cumulative pressures mean in the ocean context? How can we integrate information to conclude whether the oceans are healthy or not?

In such workshops, the main target groups should be identified e.g., (i) key stakeholders (national and statutory authorities implementing and reporting the MSFD, BHD, CFP, Biodiversity Strategy and Regional Seas Conventions, EEA, DG-ENV and DG-MARE), (ii) scientists working on cumulative pressures and impacts (e.g., in working groups in ICES and elsewhere), including experts providing services, from private consultancies, and early career researchers, (iii) society at large, and (iv) young people and educators.

8 Challenges to complete the proposed framework

Here, we have proposed a framework for an adaptive EBM of multiple human activities and pressures at sea. As identified here and in the accompanying references, this builds on a large body of knowledge, experience and expertise. However, we are conscious that each of the steps explored in each section, presents multiple challenges that can prevent completing the objectives. For each step, some of the most important challenges have been identified and listed below.

- ***Stakeholder involvement in a co-creation process***: stakeholder fatigue, which can result in a lack of engagement, is one of the most common challenges in science-policy projects, needing specific actions to overcome this problem (Durham et al., 2014). Another could come from not involving the most influential stakeholders, in terms of legitimacy of the solutions proposed, due to the complex relations in the science-policy interface (Støttrup et al., 2019).
- ***A conceptual framework to solve problems***: difficulty to determine quantitatively the assimilative capacity of the systems (Elliott et al., 2018), and, as such, not being able to determine when it has been exceeded.
- ***Understanding the mechanisms of cumulative effects***: inability to assess the individual characteristics or link in the chain of activity-pressure-impact-welfare, especially when integrating across multiple activities and pressures and climate change (Gissi et al., 2021). Also, the knowledge on reference conditions, thresholds, and tipping points, is still poor (Dudney and Suding, 2020; Hillebrand et al., 2020).
- ***Developing a software tool for assessing the status of the ocean***: from previous assessment tools development, we are aware of some challenges (Borja et al., 2019), which can include: (i) combination of different tools into a unique software, (ii) solving the types of relationships between pressures and ecosystem components (linear, non-linear, unidirectional, etc.), (iii) defining the adequate hierarchical structure to integrate species, indicators, ecosystem components or areas, (iv) how to set weighting factors in an objective way, (v) how flexible should be the tool, to meet the stakeholder expectations, or (vi) technicalities linked to the use of existing massive datasets and outputs from the software, among others. However, recent advances in Artificial Intelligence to interrogate large data sets may indicate solutions.
- ***Learning together, by testing together***: one of the most common challenges could be the lack of actual qualitative or quantitative suitable data (either from pressures, ecosystem components or services) (Borja et al., 2019). But also,

TABLE 1 **Description of the expected results toward the outcomes and impacts required by the European Commission, including the indicators to measure the success and final impact.**

Required outcome (OUT)	Expected results	Expected outcomes	Expected impact	Indicator
OUT1- Policy implementing authorities at national and regional level can assess and predict impacts (including tipping points) of multiple stressors on coastal and marine biodiversity, ecosystems functioning and relevant services (including CC).	Capacity-building on the use of a validated, tested and demonstrated toolbox, including holistic assessment of pressures, impacts on biodiversity and ecosystem services delivery, taking into account CC.	Key stakeholders master the use of the toolbox that facilitates the reporting for MSFD, Regional Seas Conventions, BHD and Biodiversity Strategy.	Policy implementing authorities are able to more efficiently report in a comparable and flexible way across MSs and Regional Seas Conventions, and they anticipate and respond to tipping points.	Number of MSs and Regional Seas Conventions experts trained and capable to use the toolbox by 2026.
OUT2- Better management and impact assessment of invasive species, harmful algal and jellyfish blooms.	Proposal for better management of these impacts, based on the results from Learning Sites, which include transverse testing across Regional Seas Conventions.	Adoption of approaches by implementing authorities.	Most accurate assessment of invasive spp., HABs and jellyfish, having harmonized monitoring and assessment methods.	DG-ENV incorporates the suggestions in the guidelines for MSs and Regional Seas Conventions and they adopt them.
OUT3- Implementation of the MSFD by determining pressure levels that clearly equate to acceptable levels of environmental impact on the GES.	A proposal for a systemic approach for the integrated impact assessment of cumulative pressures, based on the validated, tested and demonstrated toolbox.	Use of the approach and toolbox by key stakeholders to assess and predict impacts from multiple pressures and reporting.	Policy implementing authorities are able to determine pressure levels that prevent GES and favorable status from being achieved.	Number of MSs, Regional Seas Conventions, EEA, scientists, and consultancies using the systemic approach by 2026.
OUT4- EBM approaches and policy measures for activities to reduce pressures to ensure GES and will enable the sustainability of coastal and marine ecosystems to deliver services and be resilient to rapid climate and environmental changes.	Proposal, after testing in Learning Sites, of an EBM approach and policy measures for activities to reduce pressure impacts, including effects from CC, to ensure GES.	Use by key stakeholders of the EBM approach and policy measures, including its use for CFP.	Contribution to attaining GES, by MSs, Regional Seas Conventions and EEA adopting the EBM approach and policy measures proposed	Number of MSs and Regional Seas Conventions adopting EBM proposal by 2026, and DG-MARE.

D, Deliverable; CC, climate change; MSFD, Marine Strategy Framework Directive; EEA, European Environment Agency; MSs, Member States; BHD, Birds and Habitats Directives; HABs, Harmful Algal Blooms; EBM, Ecosystem-Based Management; CFP, Common Fisheries Policy; GES, Good Environmental Status; DG-ENV, Directorate General of the Environment; DG-MARE, Directorate General of Maritime Affairs; MS, Member State.

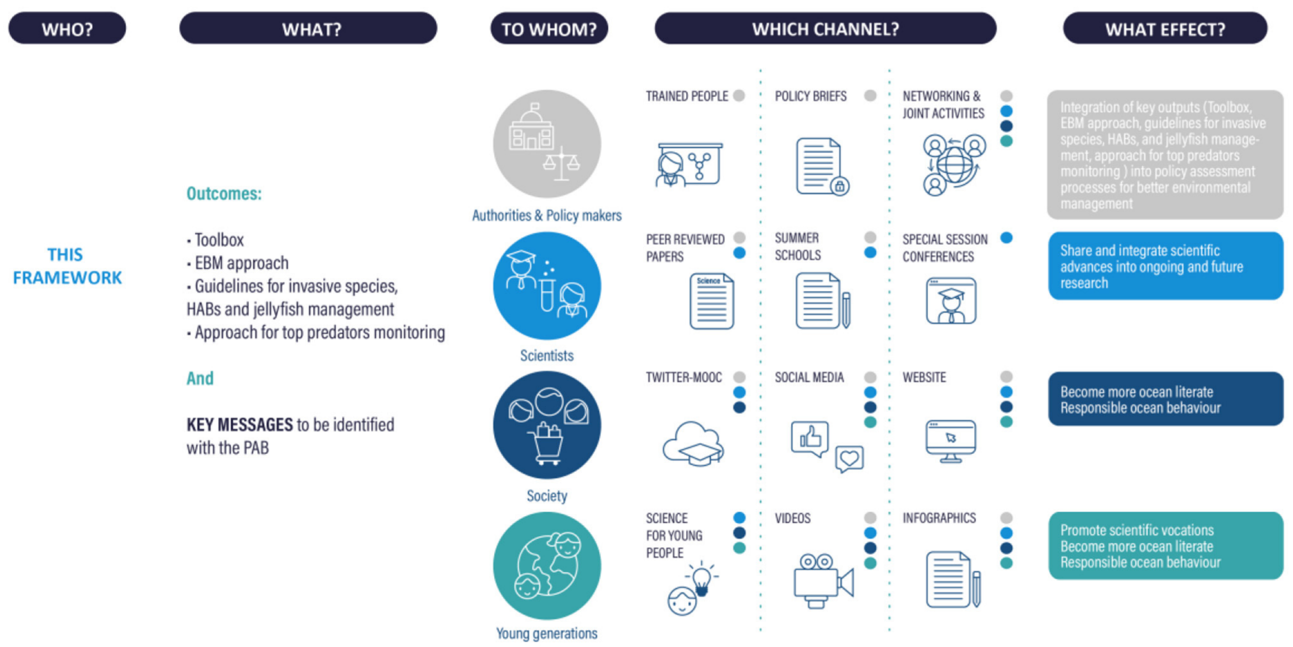

FIGURE 9
An example of applying the Lasswell's communication model to disseminate, exploit and communicate activities within the proposed framework. Only main channels are included. EBM, Ecosystem-based management; PAB, Practitioner Advisory Board; HABs, Harmful Algal Blooms.

there are difficulties for harmonizing data for an effective intercomparison in support of decision-making, the difficulties in cooperation among partners and stakeholders (e.g., cultural drawbacks, transboundary issues, etc.), or a difficulty to validate the toolbox (not only from a scientific point of view, but also by the influential stakeholders, deciding on methodologies to be used officially by Member States or Regional Seas Conventions).
- ***Enhancing the impact of the outcomes***: they can be various, but we consider the most important the challenge to reach key stakeholders, and an inadequate identification of key messages, which can hamper the dissemination and future exploitation of the tools.

Some of these challenges can be overcome with collaboration among partners, stakeholders, different national and international projects working in the same topics, and with Regional Seas Conventions. New techniques aimed at extracting, combining and interrogating data and information, even using textural analysis and Artificial Intelligence, may help to overcome some of these challenges. Similarly, it is noted that the many marine projects currently underway as part of the European Horizon Europe programme will create data, skills and tools that may help to overcome these challenges.

9 Final considerations

Despite the challenges identified, with this proposed approach we aim to advance considerably the knowledge of cumulative effects of multiple pressures on marine ecosystems and their services, to provide a toolbox to stakeholders which can allow them to assess pressures, impacts and provision of goods and benefits. More importantly this will allow them to support the sustainable use of the seas and to take EBM decisions to reverse the situation if their assessment areas are failing to achieve GES. This policy and practice review paper serves to set the scene of knowledge on these topics and, throughout the methodology proposed and already in the process of being developed, envisage the potential achievements and the impacts they can have on marine management in Europe and worldwide. Once the outputs currently being developed have been finalized, this policy paper can serve to measure the success of the research and implementation carried out and the progress of the topic in implementation of the proposed framework.

Author contributions

AB: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Writing—original draft, Writing—review & editing. ME: Conceptualization, Investigation, Methodology, Writing—original draft, Writing—review & editing. HT: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing. VS: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing. SK: Conceptualization, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing. MC: Conceptualization, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing. IG: Conceptualization, Investigation, Methodology, Validation, Writing—original draft. SF: Conceptualization, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing. NP: Conceptualization, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing. CL: Conceptualization, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing. TB: Conceptualization, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing. JA: Conceptualization, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing. JC: Conceptualization, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing. ML: Conceptualization, Methodology, Validation, Visualization, Writing—original draft, Writing—review & editing. MU: Conceptualization, Funding acquisition, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This manuscript is a result of GES4SEAS (Achieving Good Environmental Status for maintaining ecosystem services, by assessing integrated impacts of cumulative pressures) project, funded by the European Union under the Horizon Europe program (grant agreement No. 101059877) (www.ges4seas.eu). ME and CL were supported by UKRI, under grant agreements 10050522 and 10040266, respectively.

Acknowledgments

This manuscript is based on the discussions taken during the 18th edition of AZTI's summer school (1st GES4SEAS), held in the Aquarium of San Sebastián (Spain), on 8th and 9th September 2022. Science Crunchers have designed all figures included in the manuscript. The editor and two reviewers have provided positive and constructive comments, which have contributed to improve the last version of the manuscript. This is contribution nr 1199 from AZTI's Marine Research, Basque Research and Technology Alliance (BRTA).

Conflict of interest

ME is employed by IECS Ltd. and ML by Science Crunchers. TB was employed by MariLim Aquatic Research GmbH.

The remaining 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.

The authors AB, HT, SK, IG, and JA declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/focsu.2023.1308125/full#supplementary-material

References

Andersen, J. H., Halpern, B. S., Korpinen, S., Murray, C., and Reker, J. (2015). Baltic Sea biodiversity status vs. cumulative human pressures. *Estuar. Coastal Shelf Sci.* 161, 88–92. doi: 10.1016/j.ecss.2015.05.002

Ban, N. C., Alidina, H. M., and Ardron, J. A. (2010). Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. *Mar. Policy* 34, 876–886. doi: 10.1016/j.marpol.2010.01.010

Birk, S., Chapman, D., Carvalho, L., Spears, B. M., Andersen, H. E., Argillier, C., et al. (2020). Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems. *Nat. Ecol. Evolut.* 4, 1060–1068. doi: 10.1038/s41559-020-1216-4

Borgwardt, F., Robinson, L., Trauner, D., Teixeira, H., Nogueira, A. J. A., Lilleb,ø, A. I., et al. (2019). Exploring variability in environmental impact risk from human activities across aquatic ecosystems. *Sci. Tot. Environ.* 652, 1396–1408. doi: 10.1016/j.scitotenv.2018.10.339

Borja, A., Elliott, M., Andersen, J. H., Berg, T., Carstensen, J., Halpern, B. S., et al. (2016). Overview of integrative assessment of marine systems: the Ecosystem Approach in practice. *Front. Mar. Sci.* 3, 20. doi: 10.3389/fmars.2016.00020

Borja, Á., Elliott, M., Carstensen, J., Heiskanen, A-., S., and van de Bund, W. (2010). Marine management–towards an integrated implementation of the European Marine Strategy Framework and the Water Framework Directives. *Mar. Pollut. Bull.* 60, 2175–2186. doi: 10.1016/j.marpolbul.2010.09.026

Borja, A., Garmendia, J. M., Menchaca, I., Uriarte, A., and Sagarmínaga, Y. (2019). Yes, We Can! Large-scale integrative assessment of European regional seas, using open access databases. *Front. Mar. Sci.* 6, 19. doi: 10.3389/fmars.2019.00019

Borja, A., Menchaca, I., Garmendia, J. M., Franco, J., Larreta, J., Sagarminaga, Y., et al. (2021). Big insights from a small country: the added value of integrated assessment in the marine environmental status evaluation of malta. *Front. Mar. Sci.* 8, 638232. doi: 10.3389/fmars.2021.638232

Borja, A., White, M. P., Berdalet, E., Bock, N., Eatock, C., Kristensen, P., et al. (2020). Moving toward an agenda on ocean health and human health in Europe. *Front. Mar. Sci.* 7, 37. doi: 10.3389/fmars.2020.00037

Broszeit, S., Beaumont, N. J., Uyarra, M. C., Heiskanen, A-., S., Frost, M., et al. (2017). What can indicators of good environmental status tell us about ecosystem services? Reducing efforts and increasing cost-effectiveness by reapplying biodiversity indicator data. *Ecol. Indic.* 81, 409–442. doi: 10.1016/j.ecolind.2017.05.057

Carstensen, J., Murray, C., and Lindegarth, M. (2023). Mixing apples and oranges: assessing ecological status and its confidence from multiple and diverse indicators. *J. Environ. Manag.* 344, 118625. doi: 10.1016/j.jenvman.2023.118625

Charles, M., Mongruel, R., Beaumont, N., Hooper, T., Levrel, H., Thiébaut, E., et al. (2016). "Towards effective ecosystem services assessment in marine and coastal management," in *Routledge Handbook of Ecosystem Services,* eds. M. Potschin, R. Haines-Young, R. Fish, R.K. Turner (London: Routledge). doi: 10.4324/9781315775302-31

Claudet, J. (2021). The seven domains of action for a sustainable ocean. *Cell* 184, 1426–1429. doi: 10.1016/j.cell.2021.01.055

Claudet, J., Bopp, L., Cheung, W. W. L., Devillers, R., Escobar-Briones, E., Haugan, P., et al. (2020). A roadmap for using the UN decade of ocean science for sustainable development in support of science, policy, and action. *One Earth* 2, 34–42. doi: 10.1016/j.oneear.2019.10.012

Coll, M., Pennino, M. G., Steenbeek, J., Sole, J., and Bellido, J. M. (2019). Predicting marine species distributions: complementarity of food-web and Bayesian hierarchical modelling approaches. *Ecol. Model.* 405, 86–101. doi: 10.1016/j.ecolmodel.2019.05.005

Coll, M., Piroddi, C., Albouy, C., Ben Rais Lasram, F., Cheung, W. W. L., Christensen, V., et al. (2012). The Mediterranean Sea under siege: spatial overlap between marine biodiversity, cumulative threats and marine reserves. *Global Ecol. Biogeogr.* 21, 465–480. doi: 10.1111/j.1466-8238.2011.00697.x

Coll, M., Shannon, L. J., Kleisner, K. M., Juan-Jord,á, M. J., Bundy, A., Akoglu, A. G., et al. (2016). Ecological indicators to capture the effects of fishing on biodiversity and conservation status of marine ecosystems. *Ecol. Indic.* 60, 947–962. doi: 10.1016/j.ecolind.2015.08.048

Coll, M., Steenbeek, J., Pennino, M. G., Buszowski, J., Kaschner, K., Lotze, H. K., et al. (2020). Advancing global ecological modeling capabilities to simulate future trajectories of change in marine ecosystems. *Front. Mar. Sci.* 7, 567877. doi: 10.3389/fmars.2020.567877

Cormier, R., Elliott, M., and Rice, J. (2019). Putting on a bow-tie to sort out who does what and why in the complex arena of marine policy and management. *Sci. Total Environ.* 648, 293–305. doi: 10.1016/j.scitotenv.2018.08.168

Cormier, R., Kannen, A., Elliott, M., Hall, P., and Davies, I. M. (2013). Marine and coastal ecosystem-based risk management handbook. *ICES Cooper. Res. Rep.* 317, 60.

Cormier, R., Kelble, C. R., Anderson, M. R., Allen, J. I., Grehan, A., Gregersen, Ó., et al. (2017). Moving from ecosystem-based policy objectives to operational implementation of ecosystem-based management measures. *ICES J. Mar. Sci.* 74, 406–413. doi: 10.1093/icesjms/fsw181

Crain, C. M., Kroeker, K., and Halpern, B. S. (2008). Interactive and cumulative effects of multiple human stressors in marine systems. *Ecol. Lett.* 11, 1304–1315. doi: 10.1111/j.1461-0248.2008.01253.x

Culhane, F., Frid, C., Royo Gelabert, E., and Robinson, L. (2019). *EU policy-based assessment of the capacity of marine ecosystems to supply ecosystem services.* ETC/ICM Technical Report 2/2019: European Topic Centre on Inland, Coastal and Marine Waters: 263 pp + Annexes.

Culhane, F. E., Frid, C. L. J., Gelabert, E. R., Piet, G., White, L., Robinson, L. A., et al. (2020). Assessing the capacity of European regional seas to supply ecosystem services using marine status assessments. *Ocean Coastal Manag.* 190, 105154. doi: 10.1016/j.ocecoaman.2020.105154

deYoung, B., Barange, M., Beaugrand, G., Harris, R., Perry, R. I., Scheffer, M., et al. (2008). Regime shifts in marine ecosystems: detection, prediction and management. *Trends Ecol. Evolut.* 23, 402–409. doi: 10.1016/j.tree.2008.03.008

Duarte, C. M. (2014). Global change and the future ocean: a grand challenge for marine sciences. *Front. Mar. Sci.* 1, 63. doi: 10.3389/fmars.2014.00063

Dudney, J., and Suding, K. N. (2020). The elusive search for tipping points. *Nat. Ecol. Evol.* 4, 1449–1450. doi: 10.1038/s41559-020-1273-8

Durham, E., Baker, H., Smith, M., Moore, E., and Morgan, V. (2014). *The BiodivERsA Stakeholder Engagement Hand-book*. Paris: BiodivERsA 108.

Elliott M, Franco A, Smyth K, Aytemix T, Bossier S, Catalán IA, et al. (2020c). *Deliverable 5, 1*. CERES Project.

Elliott, M. (2023). Marine Ecosystem Services and Integrated Management: "There's a crack, a crack in everything, that's how the light gets in"! *Mar. Pollut. Bull.* 193, 115177. doi: 10.1016/j.marpolbul.2023.115177

Elliott, M., Borja, A., and Cormier, R. (2020a). Activity-footprints, pressures-footprints and effects-footprints – Walking the pathway to determining and managing human impacts in the sea. *Mar. Pollut. Bull.* 155, 111201. doi: 10.1016/j.marpolbul.2020.111201

Elliott, M., Borja, Á., and Cormier, R. (2020b). Managing marine resources sustainably: a proposed integrated systems analysis approach. *Ocean Coastal Manag.* 197, 105315. doi: 10.1016/j.ocecoaman.2020.105315

Elliott, M., Borja, Á., and Cormier, R. (2023). Managing marine resources sustainably – ecological, societal and governance connectivity, coherence and equivalence in complex marine transboundary regions. *Ocean Coastal Manag.* 245, 106875. doi: 10.1016/j.ocecoaman.2023.106875

Elliott, M., Boyes, S. J., Barnard, S., and Borja, Á. (2018). Using best expert judgement to harmonise marine environmental status assessment and maritime spatial planning. *Mar. Pollut. Bull.* 133, 367–377. doi: 10.1016/j.marpolbul.2018.05.029

Elliott, M., Burdon, D., Atkins, J. P., Borja, A., Cormier, R., Jonge, V. N., et al. (2017). "And DPSIR begat DAPSI(W)R(M)!" - A unifying framework for marine environmental management. *Mar. Pollut. Bull.* 118, 27–40. doi: 10.1016/j.marpolbul.2017.03.049

Elliott, M., and Wither, A. (2023). *Environmental Consequences and Management of Coastal Industries: Terms and Concepts.* Amsterdam: Elsevier.

European Commission (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. *J. Eur. Union* L327, 1–72.

European Commission (2008). Directive 2008/56/EC of the European Parliament and of the Council establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). *J. Eur. Union* L164, 19–40.

European Commission (2017). Commission Decision (EU) 2017/848 of 17 May 2017 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU. *J. Eur. Commun.* L125, 43–74.

European Commission (2020). Communication from the Commission of the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, EU Biodiversity Strategy for 2030, Bringing nature back into our lives. *Brussels* 20, 27.

European Commission (2021). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on a new approach for a sustainable blue economy in the EU. Transforming the EU's Blue Economy for a Sustainable Future. *Brussels* 17, 21.

European Commission (2022). Proposal for a Regulation of the European Parliament and of the Council on Nature restoration. *Brussels* 22, 6.

European Commission, Directorate General for Maritime, Affairs, and Fisheries, Addamo, A., Calvo Santos, A., Guillén, J., Neehus, S., et al. (2022). *The EU blue economy report 2022.* Publications Office of the European Union. 232pp.

European Commission, Directorate General for Research Innovation, Lamy, P., Citores, A., Deidun, A., Evans, L., Galgani, F., et al. (2020). *Mission Starfish 2030 – Restore our ocean and waters.* Report of the Mission Board Healthy Oceans, Seas, Coastal and Inland Waters, 92.

European Union (2014). Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning. *J. Eur. Union* L257, 135–145.

Ferrer, L., and González, M. (2021). Relationship between dimorphism and drift in the Portuguese man-of-war. *Contin. Shelf Res.* 212, 104269. doi: 10.1016/j.csr.2020.104269

Ferrer, L., and Pastor, A. (2017). The portuguese man-of-war: gone with the wind. *Reg. Stud. Mar. Sci.* 14, 53–62. doi: 10.1016/j.rsma.2017.05.004

Ferrer, L., Zaldua-Mendizabal, N., Del Campo, A., Franco, J., Mader, J., Cotano, U., et al. (2015). Operational protocol for the sighting and tracking of Portuguese man-of-war in the southeastern Bay of Biscay: observations and modeling. *Contin. Shelf Res.* 95, 39–53. doi: 10.1016/j.csr.2014.12.011

Fortuna, C. M., Fortibuoni, T., Bueno-Pardo, J., Coll, M., and Franco, A., Giménez, J., et al. (2023). Top predator status and trends: ecological implications, monitoring and mitigation strategies to promote ecosystem-based management. *Front. Mar. Sci.* in press.

Franco, A., Okane, C., Elliott, M., Haines, R., and Sharkey, W. (2021). *Coordinated assessments of marine species and habitats under the Birds and Habitats Directives and the Marine Strategy Framework Directive: Process and Technical Review: Main Report (Final).* Luxembourg: Publications Office of the European Union 2021,

Fulton, E. A., Boschetti, F., Sporcic, M., Jones, T., Little, L. R., Dambacher, J. M., et al. (2015). A multi-model approach to engaging stakeholder and modellers in complex environmental problems. *Environ. Sci. Policy* 48, 44–56. doi: 10.1016/j.envsci.2014.12.006

Galparsoro, I., Korta, M., Subirana, I., Borja, Á., Menchaca, I., Solaun, O., et al. (2021). A new framework and tool for ecological risk assessment of wave energy converters projects. *Renew. Sustain. Energy Rev.* 151, 111539. doi: 10.1016/j.rser.2021.111539

Galparsoro, I., Menchaca, I., Garmendia, J. M., Borja, Á., Maldonado, A. D., Iglesias, G., et al. (2022). Reviewing the ecological impacts of offshore wind farms. *NPJ Ocean Sustain.* 1, 1. doi: 10.1038/s44183-022-00003-5

Gissi, E., Manea, E., Mazaris, A. D., Fraschetti, S., Almpanidou, V., Bevilacqua, S., et al. (2021). A review of the combined effects of climate change and other local human stressors on the marine environment. *Sci. Tot. Environ.* 755, 142564. doi: 10.1016/j.scitotenv.2020.142564

Griffiths, J. R., Kadin, M., Nascimento, F. J. A., Tamelander, T., Törnroos, A., Bonaglia, S., et al. (2017). The importance of benthic–pelagic coupling for marine ecosystem functioning in a changing world. *Global Change Biol.* 23, 2179–2196. doi: 10.1111/gcb.13642

Haines-Young and Potschin (2018). Common international classification of ecosystem services (CICES) V5, 1. *Eur. Environ. Agency* 33, 107. doi: 10.3897/oneeco.3.e27108

Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., Longo, C., et al. (2015). Spatial and temporal changes in cumulative human impacts on the world/'s ocean. *Nat. Commun.* 6, 8615. doi: 10.1038/ncomms8615

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., et al. (2008). A global map of human impact on marine ecosystems. *Science* 319, 948–952. doi: 10.1126/science.1149345

Hillebrand, H., Donohue, I., Harpole, W. S., Hodapp, D., Kucera, M., Lewandowska, A. M., et al. (2020). Thresholds for ecological responses to global change do not emerge from empirical data. *Nat. Ecol. Evol.* 4, 1502–1509. doi: 10.1038/s41559-020-1256-9

IPCC (2021). *Sixth Assessment Report.* Available online at: www.ipcc.ch/assessment-report/ar6/ (accessed August 13, 2023).

Karlson, B., Andersen, P., Arneborg, L., Cembella, A., Eikrem, W., John, U., et al. (2021). Harmful algal blooms and their effects in coastal seas of Northern Europe. *Harmful Algae* 102, 101989. doi: 10.1016/j.hal.2021.101989

Katsanevakis, S., Olenin, S., Puntila-Dodd, R., Rilov, G., Stæhr, P.A.U., Teixeira, H., et al. (2023). Marine invasive alien species in Europe: 9 years after the IAS regulation. *Front. Mar. Sci.* 10, 1271755. doi: 10.3389/fmars.2023.1271755

Katsanevakis, S., Tempera, F., and Teixeira, H. (2016). Mapping the impact of alien species on marine ecosystems: the Mediterranean Sea case study. *Diver. Distrib.* 22, 694–707. doi: 10.1111/ddi.12429

Katsanevakis, S., Wallentinus, I., Zenetos, A., Leppäkoski, E., Cinar, M. E., Oztürk, B., et al. (2014). Impacts of invasive alien marine species on ecosystem services and biodiversity: a pan-European review. *Aquatic Invas.* 9, 391–423. doi: 10.3391/ai.2014.9.4.01

Knights, A. M., Piet, G. J., Jongbloed, R. H., Tamis, J. E., White, L., Akoglu, E., et al. (2015). An exposure-effect approach for evaluating ecosystem-wide risks from human activities. *ICES J. Mar. Sci.* 72, 1105–1115. doi: 10.1093/icesjms/fsu245

Korpinen, S., and Andersen, J. (2016). A global review of cumulative pressure and impact assessments in marine environment. *Front. Mar. Sci.* 3, 153. doi: 10.3389/fmars.2016.00153

Korpinen, S., Klančnik, K., Peterlin, M., Nurmi, M., Laamanen, L., Zupančič, G., et al. (2019). *Multiple pressures and their combined effects in Europe's seas.* ETC/ICM Technical Report 4/2019: European Topic Centre on Inland, Coastal and Marine waters: 164pp.

Korpinen, S., Laamanen, L., Bergström, L., Nurmi, M., Andersen, J. H., Haapaniemi, J., et al. (2021). Combined effects of human pressures on Europe's marine ecosystems. *Ambio* 50, 1325–1336. doi: 10.1007/s13280-020-01482-x

Larman, C., and Basili, V. R. (2003). Iterative and incremental developments. a brief history. *Computer* 36, 47–56. doi: 10.1109/MC.2003.1204375

Lauerburg, R. A. M., Diekmann, R., Blanz, B., Gee, K., Held, H., Kannen, A., et al. (2020). Socio-ecological vulnerability to tipping points: A review of empirical approaches and their use for marine management. *Sci. Total Environ.* 705, 135838. doi: 10.1016/j.scitotenv.2019.135838

Leenhardt, P., Stelzenmüller, V., Pascal, N., Probst, W. N., Aubanel, A., Bambridge, T., et al. (2017). Exploring social-ecological dynamics of a coral reef resource system using participatory modeling and empirical data. *Mar. Policy* 78, 90–97. doi: 10.1016/j.marpol.2017.01.014

Link, J. S., and Browman, H. I. (2017). Operationalizing and implementing ecosystem-based management. *ICES J. Mar. Sci.* 74, 379–381. doi: 10.1093/icesjms/fsw247

Loiseau, C., Thiault, L., Devillers, R., and Claudet, J. (2021). Cumulative impact assessments highlight the benefits of integrating land-based management with marine spatial planning. *Science Total Environ.* 787, 147339. doi: 10.1016/j.scitotenv.2021.147339

Lonsdale, J-. A., Nicholson, R., Judd, A., Elliott, M., and Clarke, C. (2020). A novel approach for cumulative impacts assessment for marine spatial planning. *Environ. Sci. Policy* 106, 125–135. doi: 10.1016/j.envsci.2020.01.011

Lynam, C., Uusitalo, L., Patrício, J., Piroddi, C., Queiros, A., Teixeira, H., et al. (2016). Uses of innovative modelling tools within the implementation of the marine strategy framework directive. *Front. Mar. Sci.* 3, 182. doi: 10.3389/fmars.2016.00182

Lynam, C. P., Llope, M., Möllmann, C., Helaouët, P., Bayliss-Brown, G. A., Stenseth, N. C., et al. (2017). Interaction between top-down and bottom-up control in marine food webs. *Proc. Natl. Acad. Sci.* 114, 1952–1957. doi: 10.1073/pnas.1621037114

Maes, J., Teller, A., Erhard, M., Condé, S., Vallecillo, S., Barredo, J. I., et al. (2020). *Mapping and Assessment of Ecosystems and their Services: An EU ecosystem assessment.* Ispra: EUR 30161 EN, Publications Office of the European Union.

Mazaris, A. D., Kallimanis, A., Gissi, E., Pipitone, C., Danovaro, R., Claudet, J., et al. (2019). Threats to marine biodiversity in European protected areas. *Sci. Total Environ.* 677, 418–426. doi: 10.1016/j.scitotenv.2019.04.333

Molony, B. W., Ford, A. T., Sequeira, A. M. M., Borja, A., Zivian, A. M., Robinson, C., et al. (2022). Editorial: Sustainable development goal 14 - life below water: towards a sustainable ocean. *Front. Mar. Sci.* 8, 829610. doi: 10.3389/fmars.2021.829610

Nash, K. L., Blythe, J. L., Cvitanovic, C., Fulton, E. A., Halpern, B. S., Milner-Gulland, E. J., et al. (2020). To achieve a sustainable blue future, progress assessments must include interdependencies between the sustainable development goals. *One Earth.* 2, 161–173. doi: 10.1016/j.oneear.2020.01.008

Nikolaou, A., and Katsanevakis, S. (2023). Marine extinctions and their drivers. *Reg. Environ. Change* 23, 88. doi: 10.1007/s10113-023-02081-8

Nygård, H., van Beest, F. M., Bergqvist, L., Carstensen, J., Gustafsson, B. G., Hasler, B., et al. (2020). Decision-support tools used in the Baltic sea area: performance and end-user preferences. *Environ. Manage.* 66, 1024–1038. doi: 10.1007/s00267-020-01356-8

Patrício, J., Elliott, M., Mazik, K., Papadopoulou, N., and Smith, C. (2016). DPSIR - two decades of trying to develop a unifying framework for marine environmental management? *Front. Mar. Sci.* 3, 177. doi: 10.3389/fmars.2016.00177

Pavlidou, A., Simboura, N., Pagou, K., Assimakopoulou, G., Gerakaris, V., Hatzianestis, I., et al. (2018). Using a holistic ecosystem-integrated approach to assess the environmental status of Saronikos Gulf, Eastern Mediterranean. *Ecol. Indic.* 96, 336–350. doi: 10.1016/j.ecolind.2018.09.007

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I, et al. (2017). Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science*, 355, eaai9214. doi: 10.1126/science.aai9214

Pedreschi, D., Bouch, P., Moriarty, M., Nixon, E., Knights, A. M., Reid, D. G., et al. (2019). Integrated ecosystem analysis in Irish waters; providing the context for ecosystem-based fisheries management. *Fisher. Res.* 209, 218–229. doi: 10.1016/j.fishres.2018.09.023

Poloczanska, E. S., Burrows, M. T., Brown, C. J., Garcia Molinos, J., Halpern, B. S., Hoegh-Guldberg, O., et al. (2016). Responses of marine organisms to climate change across oceans. *Front. Mar. Sci.* 3, 62. doi: 10.3389/fmars.2016.00062

Pörtner, H. O., Scholes, R. J., Agard, J., Archer, E., Arneth, A., Bai, X., et al. (2021). *Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change (Report).* Bonn: IPBES secretariat 256.

Prieto, L. (2018). "Diagnosis, prognosis, and management of jellyfish swarms," in *New Frontiers in Operational Oceanography,* eds. E. Chassignet, A. Pascual, J. Tintoré, and J. Verron (Mallorca: GODAE OceanView), 737–758. doi: 10.17125/gov2018.ch28

Quemmerais-Amice, F., Barrere, J., La Rivière, M., Contin, G., and Bailly, D. (2020). A methodology and tool for mapping the risk of cumulative effects on benthic habitats. *Front. Mar. Sci.* 7, 569205. doi: 10.3389/fmars.2020.569205

Reker, J., Murray, C., Royo Gelabert, E., Abhold, K., Korpinen, S., Peterlin, M., et al. (2019). *Marine Messages II. Navigating the course towards clean, healthy and productive seas through implementation of an ecosystem-based approach.* European Environment Agency, EEA Report. 17/2019 82.

Rogers, A. D., Aburto-Oropeza, O., Appeltans, W., Assis, J., Ballance, L. T., Cury, P., et al. (2020). *Critical Habitats and Biodiversity: Inventory, Thresholds and Governance.* Washington, DC: World Resources Institute. Available online at: www.oceanpanel.org/blue-papers/critical-habitats-and-biodiversity-inventory-thresholds-and-governance (accessed August 13, 2023).

Runting, R. K., Bryan, B. A., Dee, L. E., Maseyk, F. J. F., Mandle, L., Hamel, P., et al. (2017). Incorporating climate change into ecosystem service assessments and decisions: a review. *Global Change Biol.* 23, 28–41. doi: 10.1111/gcb.13457

Sagarminaga, Y., Garcés, E., Francé, J., Stern, R., Revilla, M., Magaletti, E., et al. (2023b). New tools and recommendations for a better management of harmful algal blooms under the European Marine Strategy Framework Directive. *Front. Ocean Sustain.* 1, 1298800. doi: 10.3389/focsu.2023.1298800

Sagarminaga, Y., Piraino, S., Lynam, C. P., Leoni, V., Nikolaou, A., Jaspers, C., et al. (2023a). Management of jellyfish outbreaks to achieve good environmental status. *Front. Mar. Sci.* (in press).

Sanseverino, I., Conduto António, D., Pozzoli, L., Dobricic, S., and Lettieri, T. (2016). *Algal bloom and its economic impact.* Luxembourg: EUR 27905, Publications Office of the European Union.

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., et al. (2009). Early-warning signals for critical transitions. *Nature* 461, 53–59. doi: 10.1038/nature08227

Scheffer, M., and Carpenter, S. R. (2003). Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends Ecol. Evol.* 18, 648–656. doi: 10.1016/j.tree.2003.09.002

Schumacher, J., Bergqvist, L., van Beest, F. M., Carstensen, J., Gustafsson, B., Hasler, B., et al. (2020). Bridging the science-policy gap – toward better integration of decision support tools in coastal and marine policy implementation. *Front. Mar. Sci.* 7, 587500. doi: 10.3389/fmars.2020.587500

Selkoe, K. A., Blenckner, T., Caldwell, M. R., Crowder, L. B., Erickson, A. L., Essington, T. E., et al. (2015). Principles for managing marine ecosystems prone to tipping points. *Ecosyst. Health Sustain.* 1, art17. doi: 10.1890/EHS14-0024.1

Simeoni, C., Furlan, E., Pham, H. V., Critto, A., de Juan, S., Trégarot, E., et al. (2023). Evaluating the combined effect of climate and anthropogenic stressors on marine coastal ecosystems: Insights from a systematic review of cumulative impact assessment approaches. *Sci. Total Environ.* 861, 160687. doi: 10.1016/j.scitotenv.2022.160687

Smit, K. P., Bernard, A. T. F., Lombard, A. T., and Sink, K. J. (2021). Assessing marine ecosystem condition: a review to support indicator choice and framework development. *Ecol. Indic.* 121, 107148. doi: 10.1016/j.ecolind.2020.107148

Smith, C., Papadopoulou, K-. N., Barnard, S., Mazik, K., Elliott, M., et al. (2016). Managing the marine environment, conceptual models and assessment considerations for the european marine strategy framework directive. *Front. Mar. Sci.* 3, 144. doi: 10.3389/fmars.2016.00144

Smith, C., Papadopoulou, N., Elliott, M., Franco, A., Barnard, A., Borja, Á., et al. (2022). *Marine Strategy Framework Directive Terminology Definitions and Lists.* GES4SEAS Project. p. 28.

Stelzenmüller, V., Coll, M., Cormier, R., Mazaris, A. D., Pascual, M., Loiseau, C., et al. (2020). Operationalizing risk-based cumulative effect assessments in the marine environment. *Sci. Total Environ.* 724, 138118. doi: 10.1016/j.scitotenv.2020.138118

Stelzenmüller, V., Coll, M., Mazaris, A. D., Giakoumi, S., Katsanevakis, S., Portman, M. E., et al. (2018). A risk-based approach to cumulative effect assessments for marine management. *Sci. Total Environ.* 612, 1132–1140. doi: 10.1016/j.scitotenv.2017.08.289

Stock, A. (2016). Open source software for mapping human impacts on marine ecosystems with an additive model. *J. Open Res. Softw.* 4, e21. doi: 10.5334/jors.88

Støttrup, J. G., Dinesen, G. E., Schumacher, J., Gillgren, C., Inácio, M., Schernewski, G., et al. (2019). The systems approach framework for collaborative, science-based management of complex systems. *J. Coastal Conserv.* 23, 881–889. doi: 10.1007/s11852-018-00677-5

Thrush, S. F., Hewitt, J. E., Gladstone-Gallagher, R. V., Savage, C., Lundquist, C., O'Meara, T., et al. (2021). Cumulative stressors reduce the self-regulating capacity of coastal ecosystems. *Ecol. Applic.* 31, e02223. doi: 10.1002/eap.2223

Tsiamis, K., Zenetos, A., Deriu, I., Gervasini, E., and Cardoso, A. C. (2018). The native distribution range of the European marine non-indigenous species. *Aquatic Invas.* 13, 187–198. doi: 10.3391/ai.2018.13.2.01

United Nations. (2021a). *The Second World Ocean Assessment. Volume I.* New York: United Nations publication.

United Nations. (2021b). The Second World Ocean Assessment. Volume II. New York: United Nations publication.

Uusitalo, L., Blanchet, H., Andersen, J., Beauchard, O., Berg, T., Bianchelli, S., et al. (2016a). Indicator-based assessment of marine biological diversity – lessons from 10 case studies across the European Seas. *Front. Mar. Sci.* 3, 159. doi: 10.3389/fmars.2016.00159

Uusitalo, L., Korpinen, S., Andersen, J. H., Niiranen, S., Valanko, S., Heiskanen, A. S., et al. (2016b). Exploring methods for predicting multiple pressures on ecosystem recovery: a case study on marine eutrophication and fisheries. *Contin.Shelf Res.* 121, 48–60. doi: 10.1016/j.csr.2015.11.002

Van de Pol, L., Van der Biest, K., Taelman, S. E., De Luca Peña, L., Everaert, G., Hernandez, S., et al. (2023). Impacts of human activities on the supply of marine ecosystem services: a conceptual model for offshore wind farms to aid quantitative assessments. *Heliyon* 9, e13589. doi: 10.1016/j.heliyon.2023.e13589

Waltham, N. J., Elliott, M., Lee, S. Y., Lovelock, C., Duarte, C. M., Buelow, C., et al. (2020). UN decade on ecosystem restoration 2021–2030—What chance for success in restoring coastal ecosystems? *Front. Mar. Sci.* 7, 71. doi: 10.3389/fmars.2020.00071

Wedding, L. M., Green, S. J., Reiter, S., Arrigo, K. R., Hazen, L., Ruckelshaus, M., et al. (2022). Linking multiple stressor science to policy opportunities through network modeling. *Mar. Policy* 146, 105307. doi: 10.1016/j.marpol.2022.105307

Zingone, A., Escalera, L., Aligizaki, K., Fernández-Tejedor, M., Ismael, A., Montresor, M., et al. (2021). Toxic marine microalgae and noxious blooms in the Mediterranean Sea: a contribution to the Global HAB Status Report. *Harmful Algae* 102, 101843. doi: 10.1016/j.hal.2020.101843