Ecosystem management approaches based on a review of the activity-pressures-effects chain towards achieving Good Environmental Status in the Marine Strategy Framework Directive

Deliverable 2.1

Co-funded by the European Union

UK Research and Innovation

Grant Agreement no. 101059877

Document Summary

Topic	HORIZON-CL6-2021-BIODIV-01-04
Grant Agreement Number	101059877
Start date of the project	01.09.2022
Project Coordinator	Angel Borja
Work Package	WP2
WP Co-Leader(s)	HCMR & IECS
Deliverable Title	Ecosystem management approaches based on a review of the activity-pressures-effects chain towards achieving Good Environmental Status in the Marine Strategy Framework Directive
Deliverable Number	2.1.
Deliverable Beneficiary	HCMR
Authors	Papadopoulou Nadia, Smith Christopher J, Franco Anita, Elliott Michael, Borja Angel, Andersen Jesper, Amorim Eva, Atkins Jonathan, Barnard Steve, Berg Torsten, Birchenough Silvana, Burdon Daryl, Claudet Joachim, Cormier Roland, Galparsoro Ibon, Judd Adrian, Katsanevakis Stelios, Korpinen Samuli, Lazar Luminita, Liquete Camino, Loiseau Charles, Lynam Chris, Menchaca Iratxe, O'Toole Christina, Pedreschi Debbi, Piet Gerjan, Reid David, Salinas-Akhmadeeva Irene A., Stelzenmüller Vanessa, Tamis Jacqueline, Uusitalo Laura, Uyarra Maria C.
Dissemination level	PU
Submission date	31 MAY 2023

How to cite | Papadopoulou N., Smith C. J, Franco A., Elliott M., Borja A., Andersen J., Amorim E., Atkins J., Barnard S., Berg T., Birchenough S., Burdon D., Claudet J., Cormier R., Galparsoro I., Judd A., Katsanevakis S., Korpinen S., Lazar L., Liquete C., Loiseau C., Lynam C., Menchaca I., O'Toole C., Pedreschi D., Piet G., Reid D., Salinas-Akhmadeeva I. A., Stelzenmüller V., Tamis J., Uusitalo L., Uyarra M. C., 2023. GES4SEAS Deliverable 2.1. Ecosystem management approaches based on a review of the activity-pressures-effects chain towards achieving Good Environmental Status in the Marine Strategy Framework Directive. 161 pp.

Acknowledgements: Camino Liquete, EC Knowledge Centre for Biodiversity, for valuable insights during our workshops, and Marta Coll, CSIC, for critically reading and reviewing this deliverable.

GES4SEAS (Achieving Good Environmental Status for maintaining ecosystem services, by assessing integrated impacts of cumulative pressures) project is funded by the European Union under the Horizon Europe program (grant agreement no. 101059877). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or UK Research and Innovation. Neither the European Union nor the granting authority can be held responsible for them.

Table of contents

List of figures

List of tables

1. GES4SEAS Project Summary

Human activities at sea (e.g., maritime transport, extraction of living and non-living resources, etc.) and coastal areas (e.g., agriculture, leisure and recreation, etc.) have expanded considerably, leading to an increased level of pressures and subsequent degradation of ocean health and, ultimately, human health. Single and cumulative impacts of these activities are likely to increase, driven by human demands and enhanced by climate change.

Human activities evolve following socio-economic drivers leading to pressures, which often are studied in isolation from each other even though their impacts on marine ecosystems can interact, making the effects cumulative (e.g., synergistic, antagonistic or a combination). Knowledge on these interactions and their cumulative effects in the marine environment has increased in recent years, but huge challenges still remain to be solved. Thus, there is little predictability with which to inform decision-making processes, especially on ecological tipping points, which, if exceeded, could lead to a point of no-return for the system. In this context, an ecosystem-based management (EBM) approach to the management of human activities at sea and on land should ensure that the combined pressure of such activities is kept within levels compatible with the requirements of Good Environmental Status (GES) (within the Marine Strategy Framework Directive – MSFD), against a background of climate change. This means that the capacity of marine and coastal ecosystems to respond to human-induced changes is not compromised, enabling the sustainable use of marine goods and services by present and future generations.

Thus, the main objective of GES4SEAS is to inform and guide marine governance in minimizing human pressures and their impacts on marine biodiversity and ecosystem functioning, while maintaining the sustainable delivery of ecosystem services. This will be achieved through developing an innovative and flexible toolbox, tested, validated, demonstrated and upscaled, in the context of adaptive EBM approach. The toolbox will allow competent authorities 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 level. Ultimately, this will ensure they achieve GES, and support different policies at national, European and global levels (e.g., Birds and Habitats Directives (BHD), Biodiversity Strategy 2030, United Nations Sustainable Development Goals (SDG)).

Stakeholders and the key competent authorities (including national, regional and European levels) are integrated in a Practitioner Advisory Board (PAB) to co-create and validate the toolbox and the

EBM approach. This will result in a real problem-solving approach with iterative and incremental development steps.

GES4SEAS will also rely on existing multi-actor networks to involve and engage with stakeholders. This multi-actor approach will ensure that the research and deliverables are relevant to marine managers all around the world. Lastly, it is important to highlight that the toolbox will be tested and demonstrated at 11 Learning Sites (LSs) covering all European regional seas (and also overseas), and environments. Thus, it is expected that GES4SEAS will achieve Technological and Societal Readiness Levels 6. This will be achieved by the participation of 20 partners, covering the four European regional seas and Canada.

It is expected that GES4SEAS will:

- Operationalize integrative and holistic solutions for EBM, based upon a software toolbox for analysing, assessing and mapping cumulative pressures, GES and ecosystem services.
- Provide evidence (and training) to key stakeholders of the benefits of using the toolbox that will be developed in GES4SEAS for assessing the environmental status of marine waters and the ecosystem services considering the effects of multiple pressures so opt for using it.
- Ensure the EBM approach and guidelines for the management of Invasive Alien Species (IAS), harmful algal blooms (HABs) and jellyfish, the approach for monitoring top predators are used by end-users.
- Investigate, using models, the best ways to obtain thresholds of GES/non-GES status and tipping points (system breaking points).
- Reach and engage a wider society, and specifically young people and educators, on key messages steaming from this project, so GES4SEAS contributes to societal ocean literacy and responsible behaviours.

2. Deliverable summary and objectives

Deliverable "D2.1: Ecosystem management approaches based on a review of the activity-pressures-effects chain towards achieving Good Environmental Status in the Marine Strategy Framework Directive" reports on the two following tasks.

Task 2.1. Setting up the state-of-the-art of cumulative pressure impacts and ecosystem management approaches towards achieving GES within the MSFD:

Subtask 2.1.1. Based on existing practice, identifying a common list and typologies of activities, pressures, and ecosystem functions and services, to best suit the MSFD. To ensure a harmonized approach and understanding throughout the project, a glossary of terms and definitions to create a common understanding will be prepared by M2.

Several key terms related to this deliverable are also included in the main text of this Deliverable. This terminology report (Smith et al., 2022) is included in Appendix 1 and is already available at:

https://www.ges4seas.eu/msfd-terminology-definitions/

https://www.ges4seas.eu/wp-content/uploads/2022/11/GES4SEAS__Report-Definitions-and-Lists-17112022final.pdf

Subtask 2.1.2. Identifying existing Ecosystem-Based Management (EBM) approaches (including input/output measures such as pressure and impact mitigation, reduction and restoration). This entails collating and reviewing via a SWOT analysis, the published/grey literature conceptual and management approaches, with emphasis on those from recent EU projects, and will help to select a common approach that links activity/pressures (including climate change), environmental impacts/effects (highlights on organism levels, functions, biotic effects, sex segregation, ecosystem services), delivering of ecosystem services linked to societal goods and benefits including human health and welfare. This identifies those aspects most suitable for uptake by WP3 ("Understanding the mechanisms that determine the cumulative impacts of human activities and climate change" for model proposals), WP4 ("Linking pressures and status assessment with the capacity to supply ecosystem services into a unifying holistic framework and nested toolbox development" for the toolbox development) and the LSs (WP5: learning sites- testing and synthesis). This approach will accommodate the requirements from MSFD, BHD, RSCs and the Biodiversity Strategy, under a common understanding on what GES should consider, including harmonizing the different concepts under those legal instruments.

Deliverable Summary

The GES4SEAS Deliverable D.2.1. **"Ecosystem management approaches based on a review of the activity-pressures-effects chain towards achieving Good Environmental Status in the Marine Strategy Framework Directive"** sets the background to the project and reports on 2 separate subtasks.

Setting up the state-of-the-art of cumulative pressure impacts and ecosystem management approaches towards achieving GES within the MSFD.

To ensure a harmonized approach and understanding throughout the project, as well as a coherent application in line with policy requirements, a list of terms, definitions and typologies of activities, pressures, and ecosystem functions and services was created. This includes 54 terms, with definitions. Preference was given to definitions arising from official and Marine Strategy Framework Directive (MSFD) guidance documents, but with supplemental information for clarification and examples of application, all fully referenced. The work also collated official MSFD lists for descriptors, descriptor criteria, activities, pressures, species groups and habitats, for a one-stop project guide. The terminology report was created to best suit the MSFD and be used by the project and where possible by 'sister' projects through exchange and wide dissemination via GES4SEAS project channels. It is included in full in the Deliverable Appendix 1 (also available at: https://www.ges4seas.eu/msfd-terminology-definitions/). The terminology report will be updated throughout the project with new terms (and further supplemental information) as new project needs arise.

Identifying existing Ecosystem-Based Management (EBM) approaches

The deliverable reviews and discusses conceptual and management approaches in support of Ecosystem Based Management (EBM) aiming to link selected EBM approaches to the core work of the GES4SEAS project. This entailed reviewing the origin of the term and application of the concept of EBM within major EU policies and strategies, Regional Sea Convention (RSC) strategies or action plans, and other international bodies such as the European Environmental Agency and global bodies. Examples of EBM applications are also given, focusing on specific sectors (e.g. fisheries or offshore wind farms), policies (e.g. Marine Spatial Planning) and specific problems (e.g., harmful algal blooms, non-indigenous species) as well as from EU related projects.

The review followed a structured step-wise approach. As a first step, the definitions of the EBM concept were deconstructed to include essential relevant EBM principles (as originally given by the Convention of Biological Diversity) and these were then matched to key EBM elements delivering the principles. For example, the principle of 'Ecological Integrity and Biodiversity' needs to consider various key EBM elements that singly and collectively contribute to determining the Ecological Integrity and Biodiversity of the system in question; this includes the status of ecosystem components via Good Environmental Status (GES) assessments, the presence of threatened species or major risks, specific functions and impacts, presence of biotic, cumulative and in-combination effects. A total of 26 EBM principles were reviewed and numerous related EBM elements. Key EBM elements relevant to the GES4SEAS core objectives were chosen and matched to different methodological approaches and tool groups that can deliver, singly or in combination with others, the chosen EBM element.

To fully address cumulative pressure impacts and ecosystem management approaches towards achieving GES within the MSFD, 18 EBM elements were selected. These were aimed to inform on activity-pressures-effects chains, links and footprints, considering various levels of impacts (to single species, the ecosystem and potential delivery of ecosystem services) and addressing uncertainty and management response measures. These are discussed in relation to conceptual management cycle frameworks around adaptive EBM strategy, including the PACE (plan, action, check, evaluate) and DPSIR-related (drivers, activities, pressures, state, impacts, response) frameworks such as DAPSES-MMM and DAPSI(W)R(M) typically used by the European Commission, Regional Seas Conventions (RSCs) and EU research projects).

A total of 19 methodological approaches and tool groups supporting these EBM elements were also selected with 15 of them ranking higher, using an expert-judgement workshop, in their ability to deliver fully the chosen EBM element. Key EBM elements are identifying (i) the change in status of various ecosystem components due to single human activities or pressures and (ii) the cumulative effects of all the activities operating in the marine space negatively e.g., causing adverse effects and loss but also positively e.g., through protection, conservation and restoration actions. Both elements look at the health of the natural system. There are two key tool group categories that fit this purpose, and these include NEAT (for GES assessments through structured ecosystem component changes assessments) and Halpern et al., 2008 EcoImpactMapper (for spatial extents and cumulative effects assessments). However, despite the high specificity and specialization of some tool groups, given the complexity of the marine environment and the need for its management to cope with a multi-component, multi-functioning, multi-sectoral, multi-user, multi-agency and multi-legal jurisdiction environment, several or many tools would be required to be used together to support EBM. This approach fulfils the requirements from the MSFD, BHD, RSCs and the EU Biodiversity Strategy, under a common harmonised understanding on what GES should consider as the ultimate overarching high level environmental policy objective of the EU. The 15 tool groups of this analysis will be taken forward for work by GES4SEAS in Task 2.3. for further analysis (i.e., defining practical options for EBM) and uptake by WP3 ("Understanding the mechanisms that determine the cumulative impacts of human activities and climate change" for uptake and capacity building), WP4 ("Linking pressures and status assessment with the capacity to supply ecosystem services into a unifying holistic framework and nested toolbox development" for incorporation in the GES4SEAS toolbox) and WP5 (Learning Sites for testing and synthesis).

3. Introduction and scope

Managing human activities impacting marine systems focusses on one central theme – the need to have the appropriate physical, chemical and biological conditions, in order to protect and maintain ecological structure and functioning while at the same time ensuring that the natural system satisfies ecosystem services, from which society gains goods and benefits after inputting human capital and complementary assets (Elliott, 2013). For example, the marine system physical, chemical and biological conditions can ensure that fish stocks are maintained but then complementary assets of time, money, energy, skills and knowledge are required to ensure that society benefits from those fish. Hence, marine management and governance must be aimed at ensuring sustainable marine systems in which the above central theme is satisfied (Borja et al., 2010).

Sustainable development, management and governance relies on an adequate understanding of the complex interplay of science, technology, and management skills. This section includes some of the fundamental management philosophies which underpin the holistic approach required to achieve sustainable development and management of coastal and marine activities. The main underlying philosophy for these is summarised as managing the ecosystem in which humans are regarded as an integral part. This is summarised as the Ecosystem Approach (EA or EcAp), the Ecosystem-Based Approach and/or Ecosystem-Based Management (EBM) or variants of the term (Kirkfeldt, 2019); however, it can be argued that the term 'based' is redundant and any ecosystem approach must be based in the ecosystem, with its natural and human features. Despite this, the semantics of these terms have been interrogated and even subtle but meaningful differences between the terms have been analysed (e.g., Kirkfeldt, 2019). Despite this, in this report, the term EBM is taken to include all variants of the concept.

The Ecosystem Approach was first developed by the UN Convention for Biological Diversity (CBD, 2000, 2004) as a set of 12 principles (CBD 1992) (Table 1) and defined as 'a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way'. As such, its application will help to reach a balance of these three objectives of the Convention. It is based on applying appropriate scientific methodologies focused on levels of biological organization which encompass the essential processes, functions and interactions among organisms and their environment. Furthermore, it recognizes that humans, with their cultural diversity, are an integral component of ecosystems.

Table 1. The original 12 principles of the Ecosystem Approach following Convention for Biological Diversity.

1. The objectives of management of land, water and living resources are a matter of societal choices. 2. Management should be decentralized to the lowest appropriate level. 3. Ecosystem managers should consider the effects (actual or potential) of their activities on adjacent and other ecosystems. 4. Recognizing potential gains from management, there is usually a need to understand and manage the ecosystem in an economic context. Any such ecosystem-management programme should: a) Reduce those market distortions that adversely affect biological diversity; b) Align incentives to promote biodiversity conservation and sustainable use; c) Internalize costs and benefits in the given ecosystem to the extent feasible. 5. Conservation of ecosystem structure and functioning, in order to maintain ecosystem services, should be a priority target of the ecosystem approach. 6. Ecosystems must be managed within the limits of their functioning. 7. The ecosystem approach should be undertaken at the appropriate spatial and temporal scales. 8. Recognizing the varying temporal scales and lag-effects that characterize ecosystem processes, objectives for ecosystem management should be set for the long term. 9. Management must recognize the change is inevitable. 10. The ecosystem approach should seek the appropriate balance between, and integration of, conservation and use of biological diversity. 11.The ecosystem approach should consider all forms of relevant information, including scientific and indigenous and local knowledge, innovations and practices. 12.The ecosystem approach should involve all relevant sectors of society and scientific disciplines.

This report constitutes Deliverable 2.1 of the GES4SEAS project with the fourth outcome indicated in the Horizon Europe proposal call [HORIZON-CL6-DEC-2021-00-00: Assess and predict integrated impacts of cumulated direct and indirect stressors on coastal and marine biodiversity, ecosystems and their services] (OUT4). This aims to identify and interrogate the current EBM approaches and policy measures for activities to reduce pressures to ensure that Good Environmental Status (GES) can be achieved thereby enabling the sustainability of coastal and marine ecosystems to deliver services and societal goods and benefits while at the same time being resilient to rapid climate and environmental changes. As such the report provides the background to successive tasks and work packages in the project. In particular, the report firstly presents the current understanding of EBM and the wider principles on which it is based. Secondly, the tools available and as used to test each principle are listed and then described. Thirdly, the report presents conclusions regarding the use of those tools and briefly indicates the way in which they can be combined into a toolbox in order to achieve EBM. These aspects include the way in which EBM is mentioned in international agreements and treaties, regional seas conventions, assessment strategies, EU Directives and national and regional instruments. The report considers 26 EBM principles and 18 EBM elements (given in Table 1 and 3) and then it considers the tool groups covering the description, application and requirements of these elements and tool groups. Finally, an expert judgement approach was used to rank these elements and the tool groups in order to create a comprehensive toolbox for the implementation of EBM both in the GES4SEAS project and further afield.

4. What is Ecosystem-Based Management

4.1 The EBM concept

The term EBM has multiple (not always very clear and unambiguous) definitions (Kirkfeldt, 2019; Delacámara et al., 2020), but in the GES4SEAS terminology report (https://www.ges4seas.eu/wp-content/uploads/2022/11/GES4SEAS__Report-Definitions-and-Lists-17112022final.pdf, published online earlier but part of Deliverable 2.1.) Term 53 defines EBM as follows:

"Ecosystem-based approach (to management), an 'ecosystem-based approach' or 'ecosystem-based management' is an integrated approach to management of human activities that considers the entire ecosystem including humans. The goal is to maintain ecosystems in a healthy, clean, productive and resilient condition, so that they can provide humans with the services and goods upon which we depend. It is a spatial approach that builds around a) acknowledging connections, b) cumulative impacts and c) multiple objectives" (see Figures 1 and 2 visualising these concepts). In this way, it differs from traditional approaches that address single concerns e.g., species, sectors, or activities (CSWD, 2020).

An ecosystem approach to management recognizes the full array of interactions within a marine ecosystem, including humans, rather than considering single issues, species, or ecosystem services in isolation. The goal of ecosystem-based marine management is to maintain marine ecosystems in a healthy, productive, and resilient condition so that they can sustain human uses of the ocean and provide the goods and services humans want and need (McLeod et al., 2005).

It encompasses the comprehensive integrated management of human activities based upon the best available scientific knowledge about the ecosystem and its dynamics, helping to ensure activities are captured and managed accordingly with the relevant legislation (ICES, 2020), aiming to identify and act on influences which are critical to the health of marine ecosystems, thereby achieving sustainable use of goods and services and maintenance of ecosystem integrity (ICES, 2003).

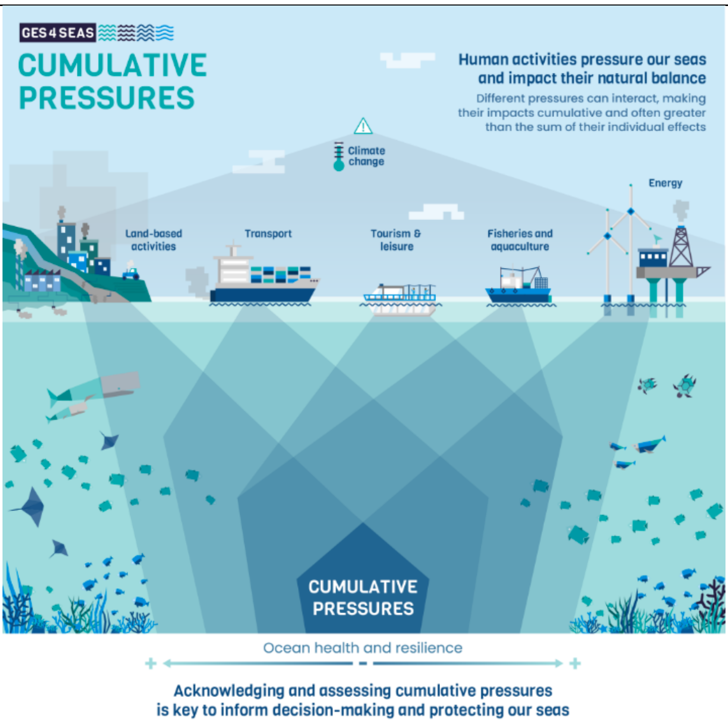


Figure 1. Visualising cumulative pressures at sea (GES4SEAS infographic by Science Crunchers)

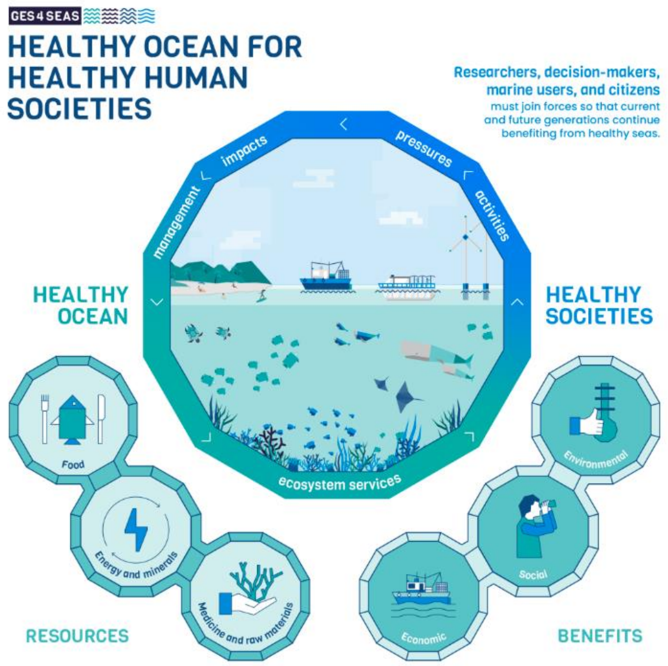


Figure 2. Visualising connections and dependencies and the healthy oceans for healthy societies concept (GES4SEAS infographic by Science Crunchers)

4.2 EBM Principles, Contents and Process

EBM is supported by several fundamental or key principles that are in line with the concept requirements and pave the way for its operationalization and implementation. Long et al. (2015) review the origin of the concept of principles and its evolution over time. They include the EBM principles in their definition of EBM: *"Ecosystem-based management is an interdisciplinary approach that balances ecological, social and governance principles at appropriate temporal and spatial scales in a distinct geographical area to achieve sustainable resource use"* (Long et al., 2015). In their literature review of EBM principles (up to 2010) they select the 15 more important/commonly cited principles from a list of 26 principles. They note three emerging Key Principles such as 'Consider Cumulative Impacts', 'Apply the Precautionary Approach' and 'Explicitly Acknowledge Trade Offs' that could help shape and successfully apply EBM.

Various EU projects and expert working groups around the world have since used this list and consequently chosen the EBM principles most fit for their aims/mandate.

A trilateral working group on the ecosystem approach to ocean health and stressors was established in 2016 by the United States, the EU and Canada, under the Atlantic Ocean Research Alliance (AORA) to investigate implementation of EBM in the North Atlantic. Dickey-Collas et al. (2022), as part of the AORA, review and contrast 20 Principles considered for implementation across Canada, the EU, the United States and Areas Beyond National Jurisdictions (ABNJ). The 20 principles considered by AORA are from Ruud et al. (2018) and are based on the Convention on Biological Diversity 12 principles of the Ecosystem Approach (CBD, 2000: principles and rationale; CBD, 2004: with annotated rationale and implementation guidelines) and the 17 FAO Ecosystem Approach to Fisheries Principles (Garcia et al., 2003). The AORA list includes principles such as 'the ecosystem approach should seek the appropriate trade-off (balance) between, and integration of, conservation and use of marine resources (e.g., biological diversity)', 'the ecosystem approach should consider all forms of relevant information, including scientific and indigenous and local knowledge, innovations and practices' and 'the ecosystem approach should involve all relevant sectors of society and scientific disciplines' (Dickey-Collas et al., 2022).

To clarify and codify the priorities for EMB in Aotearoa New Zealand (an island nation with the 4th largest Exclusive Economic Zone in the world), a set of narratives and EBM principles were developed (partly based on CBD/existing principles) around seven themes. One of these is explicitly addressing indigenous people and co-governance and two others acknowledge that 'humans along with their multiples uses and values for the marine environment are part of the ecosystem' and EBM should be 'tailored, place and time specific, recognising all ecological complexities and connectedness, and addressing cumulative and multiple stressors' (Hewitt et al., 2018; Le Heron et al., 2020). Guilhon et al. (2021), working on ABNJ and deep-sea mining (DSM) activities in the "Area", grouped EBM principles into 8 categories: core, ecological, impacts, knowledge, management, participation, socio-economic and spatial-temporal scales.

The EU AQUACROSS project has reviewed the Long et al. (2015) 15 principles and added 'Consider cumulative impacts' as essential to their work and when addressing human activities and their pressures in the aquatic environment (Piet et al., 2017). They categorise and link the principles to system-oriented criteria to assess the knowledge base of the socio-ecological systems (SES) and ecosystem aspects (e.g., ecological integrity and biodiversity) and process-oriented criteria to assess the SES governance in terms of its capacity to implement EBM and policy dimensions (e.g., ensure decisions reflect societal choices).

4.3 Ecosystem-Based Management and EU, Directives and Strategies

To date, there is a real commitment to document and understand marine ecosystems, their interactions and pressures. Therefore, there is a real drive to comply and apply EBM, as it is seen as an iterative and ongoing process. Regional Sea Conventions, the EU (both in policy and in research support with numerous projects) along with various organisations such as ICES have considered the EBM into their planning of science and evidence and including the principles of EBM into their data, science and advisory programmes. EBM is an approach developed to work on wicked environmental problems i.e., on problems they are persistent, they have no clear end, and involve moral choices and as such recognizes the need to incorporate systems thinking into natural resource management (O'Higgins et al. 2020) while incorporating wider issues (e.g., climate change). It is important to acknowledge that due to the complexities involved in marine and aquatic social-ecological systems, there is neither a design of a one-size-fits-all EBM approach nor just one EBM implementation path (Delacámara et al., 2020). It is essential therefore that review processes are regularly undertaken to ensure the current toolbox of EBM is regularly updated, reviewed and includes new tools and tool combinations to improve and support the process.

4.3.1. EBM in MSFD and major EU Strategies

There is no definition of EBM embedded in EU law (O' Hagan, 2020). The MSFD text (EU, 2008) does not provide a definition (but see CSWD, 2020 and section 4) of an ecosystem-based approach to management but requires its application. In the MSFD preamble point (8) states *"by applying an ecosystem-based approach to the management of human activities while enabling a sustainable use of marine goods and services, priority should be given to achieving or maintaining good environmental status in the Community's marine environment, to continuing its protection and preservation, and to preventing subsequent deterioration".* Article 1.3 *states "Marine strategies shall apply an ecosystem-based approach to the management of human activities, ensuring that the collective pressure of such activities is kept within levels compatible with the achievement of good environmental status and that the capacity of marine ecosystems to respond to human-induced changes is not compromised, while enabling the sustainable use of marine goods and services by present and future generations".* The 11 descriptors of the MSFD form the different sectors of the ecosystem-based approach as seen by the EU, as they include the most important ecosystem features of concern as well as human pressures on the ecosystems and their resulting alterations (Berg et al., 2015).

While the MSFD is the first piece of EU legislation to adopt an EBM aiming at the protection of the full range of marine biodiversity, the European Commission considers the Natura 2000-regime as one of the legal components of the implementation of this approach for the marine environment. Implementing Natura 2000 is therefore seen as part of a progressive step wise implementation of the ecosystem approach considering the concepts of favourable conservation status and the good ecological status as required by the Habitats and Birds Directives and the Water Framework Directive (Bastmeijer, 2018). Both Natura 2000 and WFD objectives are in line with some of the EA principles (e.g., ecosystems must be managed within the limits of their functioning, assess cumulative impacts and natural boundaries of ecosystems, conserve ecosystem structure and functioning to maintain ecosystem services) and therefore the EA is considered a good framework to aid their implementation (Vlachopoulou et al., 2014; Bastmeijer, 2018).

In the preamble (point 3) of the Maritime Spatial Planning Directive (MSPD) it is acknowledged that *"The application of an ecosystem-based approach will contribute to promoting the sustainable development and growth of the maritime and coastal economies and the sustainable use of marine and coastal resources".* The preamble (point 14) explicitly refers to MSFD and an ecosystem based approach stating that *"in order to promote the sustainable growth of maritime economies, the sustainable development of marine areas and the sustainable use of marine resources, maritime* *spatial planning should apply an ecosystem-based approach as referred to in Article 1(3) of Directive 2008/56/EC9 with the aim of ensuring that the collective pressure of all activities is kept within levels compatible with the achievement of good environmental status and that the capacity of marine ecosystems to respond to human-induced changes is not compromised, while contributing to the sustainable use of marine goods and services by present and future generations".* Additionally, preamble (point 22) reiterates links with MSFD which *"… require Member States to take the necessary measures to achieve or maintain good environmental status in the marine environment by 2020 and which identify maritime spatial planning as a tool to support the ecosystem-based approach to the management of human activities in order to achieve good environmental status".*

Article 2 of the Common Fisheries Policy (CFP) (EU, 2013) states that *"the CFP shall implement the ecosystem-based approach to fisheries management so as to ensure that negative impacts of fishing activities on the marine ecosystem are minimised, and shall endeavour to ensure that aquaculture and fisheries activities avoid the degradation of the marine environment"* while article 3 clarifies that *"ecosystem-based approach to fisheries management means an integrated approach to managing fisheries within ecologically meaningful boundaries which seeks to manage the use of natural resources, taking account of fishing and other human activities, while preserving both the biological wealth and the biological processes necessary to safeguard the composition, structure and functioning of the habitats of the ecosystem affected, by taking into account the knowledge and uncertainties regarding biotic, abiotic and human components of ecosystems".* Article 9 calls for multiannual plans *"to include specific alternative conservation measures, based on the ecosystem approach, for some of the stocks that it covers".*

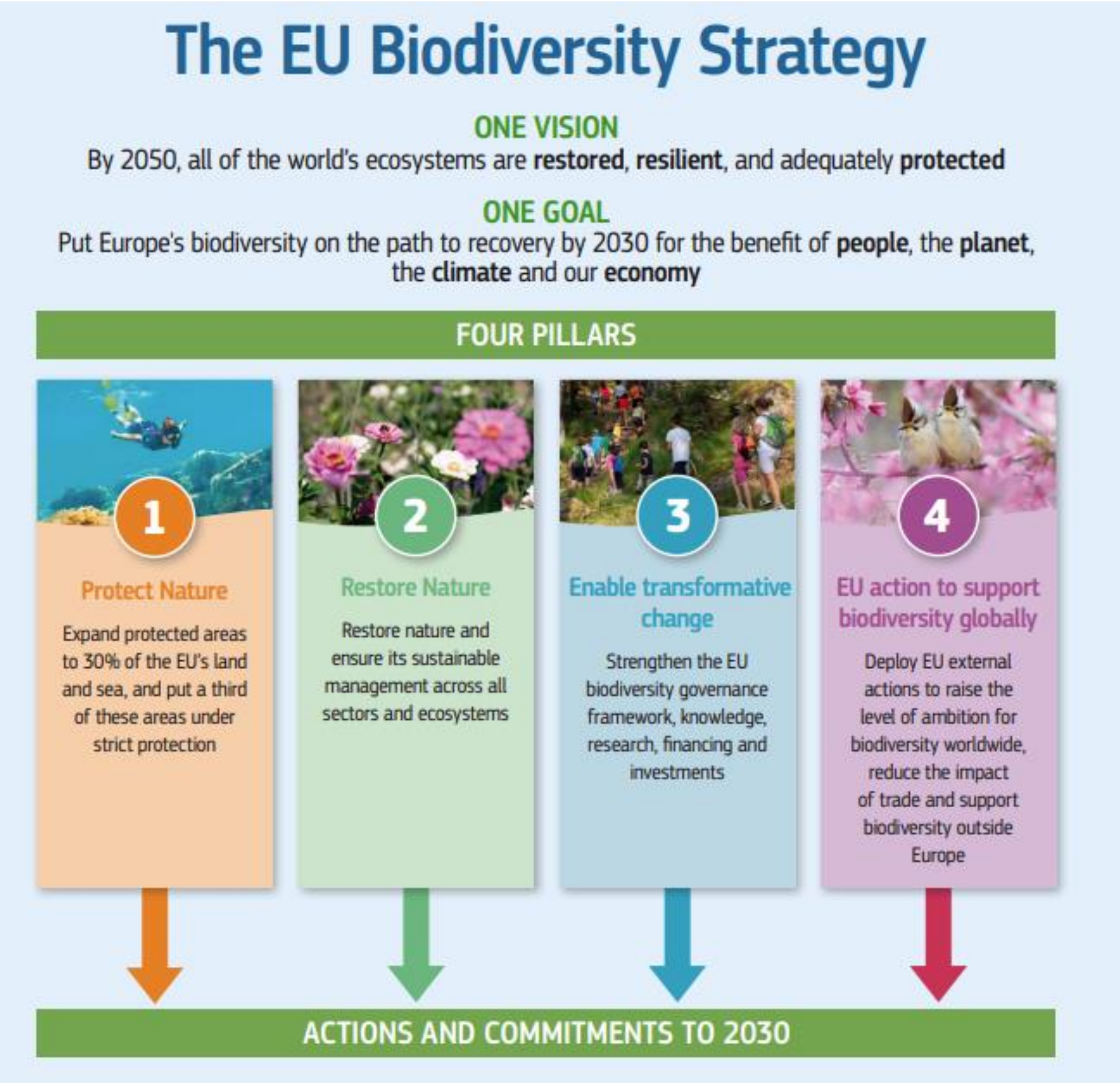


Figure 3. EU Biodiversity Strategy 2030, a strategy to protect and restore ecosystems and better apply the ecosystem-based approach to management (Source: EU, 2021).

The EU Biodiversity Strategy 2030 (EC, 2020, Figure 3 headline motto) does not define the EBM but reiterates the benefits from its application. It states, *"the application of an ecosystem-based management approach under EU legislation (CFP, MSFD and MSPD) will reduce the adverse impacts of fishing, extraction and other human activities, especially on sensitive species and seabed habitats".* It also introduces the forthcoming EU Nature Restoration Law (EC, 2022) and the Action Plan to conserve fisheries resources and protect marine ecosystems (EC, 2023a). With this action plan the European Commission aims to achieve a more consistent implementation of the EU's environmental policy and the common fisheries policy with its three – environmental, economic and social -

sustainability pillars. It provides a forward-looking strategy on how to better apply the ecosystem-based approach to fisheries management (EC, 2023a). The EC will focus efforts in 2023 and 2024 on developing scientific advice in support of the EBM to EU fisheries management, through steering the dialogue with the scientific community and stakeholders and aiming to develop a Fisheries and Oceans Pact towards sustainable, science-based, innovative and inclusive fisheries management (EC, 2023b).

4.3.2. Application of the EBM in CBD

EBM is not explicitly stated in The Convention on Biological Diversity (CBD). However, as the Convention acknowledges that an ecosystem is *“a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit"* (Article 2 of the Convention), the 5th meeting of the COP in 2000 set the ecosystem-based approach as the primary framework for action under the Biodiversity Convention. The approach was defined as *“a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way”* (CBD, 2000, COP 5, Decision V/6). The application of the ecosystem approach is expected to help to reach a balance of the three objectives of the CBD: conservation; sustainable use; and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources.

The recent (12/2022) 15th Conference of Parties to the UN Convention on Biological Diversity adopted the “Kunming-Montreal Global Biodiversity Framework” (GBF), which includes four goals and 23 targets for achievement by 2030. Three of these targets re-iterate the need to ‘apply the ecosystem approach’ and ensure the use, harvesting and trade of wild species is sustainable (Target 5), ‘to minimize the impact of climate change and ocean acidification on biodiversity through nature-based solution and/or ecosystem-based approaches’ (Target 8) and to ‘restore, maintain and enhance nature’s contributions to people, including ecosystem functions and services, …, through nature-based solutions and ecosystem-based approaches for the benefit of all people and nature’ (Target 11) (CBD, 2022).

4.3.3. Application of the EBM in the HELCOM assessment strategy and practice in the Baltic Sea

The Baltic Sea Marine Environment Protection Commission (HELCOM) has built its monitoring and assessment strategy on the concept of an ecosystem approach. The strategy covers all the components of a marine ecosystem and the pressures impacting it, whereas the climate change agenda is only recently being included. The monitoring part aims to ensure that the key parameters of the ecosystem are monitored in the region (incl. land-based loads) and it continuously develops new methods (e.g., earth observation, drop videos) to ensure that modern data sources are utilized for the assessment part of the strategy. HELCOM's integrated assessments of the Baltic Sea are based on a few key features: (i) commonly agreed assessment areas, which in a nested way are defined for each assessment indicator, (ii) quantitative core indicators which have been developed following commonly agreed criteria, (iii) indicator threshold values, sometimes subregion-specific, which define good environmental status, and (iv) multi-metric indicator-based assessment tools which utilize the assessment areas, indicators, and thresholds.

The HELCOM assessment strategy is not only about the state of the environment but gives also due focus to human activities, pressures and their impacts on the ecosystem and society. The HELCOM pressure assessments started with pollution load compilations already in 1980s, followed by shipping, port activities, dumping and dredging, and finally including also fisheries, hunting and other human activities. In 2010, the HELCOM holistic assessment introduced the cumulative impact assessment of anthropogenic pressures, following the global assessment method by Halpern et al. (2008) and Korpinen et al. (2012). The 5 km x 5 km grid was relatively crude for a map of potential cumulative impacts, but it advised the HELCOM decision-makers to focus on areas, as well as on the underlying main pressures impacting those areas. Since 2010 and HELCOM's Moscow Ministerial meeting, the sequential ministerial meetings in 2013, 2018 and 2021 have been supported by the HELCOM multi-metric indicator-based assessment tools (HEAT, BEAT and CHASE) and the cumulative impact assessment (CIA). The latest HELCOM (HOLAS III) provides a comprehensive overview of the ecosystem health of the Baltic Sea, covering the assessment period of 2016–2021 (https://helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2023/). It includes four thematic assessments covering the topics of economic and social analyses; spatial distribution of pressures and impacts (HELCOM, 2023); hazardous substances, marine litter, underwater noise and non-indigenous species; and a part on biodiversity. The complete biodiversity assessment, the thematic assessment on eutrophication, and the summary report on State of the Baltic Sea 2023, will be published later in 2023, together with a dedicated State of the Baltic Sea – website. The assessments will also serve to keep track of the implementation and the effectiveness of the HELCOM Baltic Sea Action Plan (BSAP) (https://helcom.fi/baltic-sea-action-plan/). Supported by the ACTION tool (Ahtiainen et al., 2021), which follows the DPSIR concept, the ministerial meeting in 2021 agreed on the entirely revised Baltic Sea Action Plan (HELCOM, 2021a).

4.3.4. Application of EBM in Barcelona Convention/UNEP/MAP

The Barcelona Convention adopted the ecosystem approach (EcAp) in 2008 as the guiding principle to all policy implementation for a healthy Mediterranean with marine and biological ecosystems that are productive and biologically diverse for the benefit of present and future generations. The EcAp MED III 2020-2023 project *"Support to Efficient Implementation of the Ecosystem Approach (EcAp)-based Integrated Monitoring and Assessment of the Mediterranean Sea and Coasts and to delivery of data-based 2023 Quality Status Report in synergy with the EU MSFD"* (EcAp MED III) is an EU project, following on from EcAp MED I (2012-2015) and EcAp MED (2015-2019). Its overall aim is to further assist the Southern Mediterranean Contracting Parties to implement the Integrated Monitoring and Assessment Programme (IMAP), adopted in 2016, as part of the implementation of the Ecosystem Approach Roadmap. EcAp MED III also contributes to Sustainable Development Goal 14, the achievement of Aichi Biodiversity Target 11, and to the implementation of the MSFD and of the 2014 Union for the Mediterranean (UfM) Ministerial Declaration on Environment and Climate Change.

The COP15 UNEP/DEPI/Decision IG 17/6: *'Implementation of the ecosystem approach (EcAp) to the management of human activities that may affect the Mediterranean marine and coastal environment'* (UNEP(DEPI)/MED IG.17/10 Annex V, COP15/2008) defines the roadmap with the following 7 steps: (i) Definition of an ecological Vision for the Mediterranean, (ii) Setting of common Mediterranean strategic goals, (iii) Identification of important ecosystem properties and assessment of ecological status and pressures while also considering the appropriate spatial and temporal scale of application of the approach, (iv) Development of a set of ecological objectives corresponding to the Vision and strategic goals, (v) Derivation of operational objectives with indicators and target levels, (vi) Revision of existing monitoring programmes for ongoing assessment and regular updating of targets, and (vii) Development and review of relevant action plans and programmes.

4.3.5. Application of EBM in the Black Sea Commission

In April 1992, the Convention on the Protection of the Black Sea Against Pollution, also known as the Bucharest Convention, was signed, and subsequently ratified by all six Black Sea riparian countries, including Bulgaria, Georgia, Romania, Russia, Türkiye, and Ukraine. The Convention comprises the primary agreement and three specific protocols that address land-based pollution control, waste dumping, and joint action in the event of accidents such as oil spills. The Black Sea Commission also called the Commission on the Protection of the Black Sea Against Pollution, is responsible for enforcing the Convention's provisions and implementing the Black Sea Strategic Action Plan.

Although the Bucharest Convention and its Protocols do not explicitly mention EBM and EcAp, the main challenges to implementing are linked to combating pollution from land-based sources and maritime transport, achieving sustainable management of marine living resources, and pursuing sustainable human development.

Thus, the Convention on the Protection of the Black Sea, the Black Sea Strategic Action Plan 1996 and the Strategic Action Plan for the Environmental Protection and Rehabilitation of the Black Sea 2009 require a holistic approach to the Black Sea ecosystem. This holistic approach was used by the Black Sea network of institutions for the development of the Black Sea Integrated Monitoring and Assessment Programme (BSIMAP). The main activities for the implementation of the BSIMAP are designed to:

- Reaching consensus on common principles for regional monitoring and assessment programmes,
- Establishment of an initial affordable program to harmonize assessment methodologies, analytical techniques, reporting formats, etc.,
- Harmonization of assessment methodologies on a regional level,
- Elaboration of environmental quality criteria/objectives,
- Development and establishment of mechanisms of integration of scientific results into the assessment process,
- Elaboration of mechanisms and procedures for quality assurance quality control,
- Elaboration and maintenance of the Black Sea Information System for supporting the decision-making process of the Black Sea Commission.

On the other hand, integrated evaluation tools are generally missing from BSIMAP with one exception consisting of eutrophication assessment tools, TRIX (Vollenweider et al., 1998) and BEAST (Black Sea Eutrophication Assessment Tool; Slobodnik et al., 2017).

The current situation in the Black Sea region has accentuated the lack of cooperation and consensus, thus being far away from the target of a holistic and integrated approach to ecosystem management, considering the complex interactions between ecological, social, and economic factors.

4.3.6. EBM in OSPAR Convention

The OSPAR Convention considers a framework for the regulation of most human activities, which would likely influence marine ecosystems and the overall biodiversity in the North-East Atlantic. Both, the Helsinki and OSPAR Commissions have in their vision and mission the need to consider the concept of Ecosystem Approach (EA; https://www.ospar.org/convention/principles/ecosystem-approach). The EA definition used is *“the comprehensive integrated management of human activities based on the best available scientific knowledge about the ecosystem and its dynamics, in order to identify and take action on influences which are critical to the health of marine ecosystems, thereby achieving sustainable use of ecosystem goods and services and maintenance of ecosystem integrity”* (Helsinki and OSPAR Commissions, 2003). The EA is implemented in the North-East Atlantic by programmes and measures developed under OSPAR’s six thematic Strategies. The application of the ecosystem approach integrates conservation and management approaches, such as marine protected areas or measures targeted on single species and habitats, as well as other approaches carried out under existing national and international policy and legal frameworks. OSPAR work focuses on (i) promoting understanding and acceptance by all stakeholders of the EA to the management of human activities, (ii) monitoring the ecosystems of the marine environment, (iii) setting objectives for environmental quality, underpinned by monitoring, and (iv) assessing the impact of human activities upon biota and humans, both directly and indirectly through impacts on the non-living environment, together with the effects on the non-living environment itself.

4.3.7. Support of EBM in European Environment Agency (EEA)

EEA is addressing key EBM principles including Ecological integrity and Biodiversity, and Cumulative effects and support EU policies and strategies with evidence-based knowledge to help the European Union and EEA member countries achieve sustainability. EEA produces the EU State of Environment reports. The EEA adopted HELCOM's integrated assessment tools HEAT, BEAT, CHASE and BSPI/BSII (CIA/CEA) in the Marine Messages II report (Reker et al., 2019; see acronyms above). Moreover, the Marine Messages II ecosystem health assessment was made by a MESH tool which was specifically developed for the EEA assessment purposes and integrates different state indicators to reflect a holistic state of Europe's marine ecosystems. The bottlenecks for the pan-European assessments were especially the lack of data-driven indicators and the thresholds. The DEVOTES project had, however, developed those for many sea areas which allowed for a fresh assessment in 2019. In 2022, the European Topic Centre for Inland, Coastal and Marine Waters supported the EEA is taking stock of the Member States' MSFD reporting and transforming the assessment parameters and thresholds as marine indicators. This work will supplement the EEA's future use of the integrated assessment tools. Even if the monitoring data is not easily available to support pan-European indicators, pressure data is more easily accessible and that led to a pan-European cumulative effects assessment in 2019 (Korpinen et al., 2019, 2021). The EEA's Marine Messages III addressing key EBM elements (as with marine Messages II, EEA, 2019), is being prepared for 2026 and will again be based on updated version of the multi-metric indicator-based assessment tools.

4.3.8. EBM and the United Nations Convention on the Law of the Sea (UNCLOS)

The Law of the Sea Convention defines the rights and responsibilities of nations with respect to their use of the world's oceans, protection of the marine environment, as well as the management of marine resources. At present, the concept of Ecosystem Approach in the Convention is only implicitly mentioning, as the details referred to as a clear obligation to protect and preserve the marine environment (Article 192). Similarly, the use of measures to protect and preserve rare or fragile ecosystems as well as the habitat of depleted, threatened or endangered species and other forms of marine life (Article 194(5)). There is a clear desire to support EBM, but further implementation routes are needed to ensure these actions are covered and achieved. There is also a direct comment to the 1995 Fish Stocks Agreement, which is committed to protect marine biodiversity directly over the protection of target and non-target species and at an ecosystem level. The Agreement also includes a clear reference to cooperate in Regional Fisheries Management Organisations (RFMOs) or similar arrangements to recognise the transboundary nature of aquatic biodiversity and need for concerted coordinated action. Whilst the intention is to protect species and ecosystems, there is still a clear challenge to the current RFMOs approaches, as at such these initiatives do not cover all ocean areas. Additionally, some of the work still needs to be accounted by geographic area and specific fish species. In some cases, some areas and species remain ineffectively managed, with still areas to consider and improve management and protection.

4.3.9. Global progress in the application of the EBM and MEBM-PEG

The Marine Ecosystem-Based Management Progress Evaluation Group (MEBM-PEG) is an international group of EBM experts, established under the leadership of NOOA to investigate on global EBM implementation in the marine environment. In 2022, this group developed a survey with >150 responses and organized a workshop with 40 experts to discuss the survey results and to evaluate the progress towards EBM implementation. This resulted in a paper under review (Haugen et al., 2023), in which the experts identified the remaining impediments to further implementation of EBM: governance; stakeholder engagement; support; uncertainty about and understanding of EBM; technology and data; communication and marketing.

4.3.10. EBM applications focusing on single sector activities or specific policy requirements

An early example of this is the adoption of Ecosystem Approach to Fisheries (EAF) management (EAFM) (FAO, 2003). According to FAO, the main purpose of the EAF is to: *"Plan, develop and manage fisheries in a manner that addresses multiple needs and desires of societies, without jeopardizing the options of future generations to benefit from the full range of goods and services provided by aquatic ecosystems. It strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties of biotic, abiotic and human components of ecosystems their interactions and applying an integrated approach..."* (FAO, 2003). This definition highlights that while the EAF deals with all the ecological consequences of fishing, it also recognizes the social and economic implications of fishing and especially its management arrangements (FAO, 2021). According to FAO (2021) the EAF process has four main steps: (i) initiation and planning, (ii) identification of assets, issues and priorities, (iii) development of management system, and (iv) implementation, monitoring and performance review. Although the EAF concept has been introduced in the Common Fisheries Policy and its application has been discussed in the literature (Garcia et al., 2003, 2005; Morishita, 2008; Jennings and Rice, 2011), its operationalisation and implementation in European fisheries management have been limited so far (Wakefield, 2018; FAO, 2021). However, recent developments in this field are promising (e.g., Bentley et al, 2021, Howell et al., 2021; Haugen et al., 2023). ICES provides comprehensive fisheries assessments leading to formal ICES Advice (ICES, 2023) as well as mixed fisheries outputs and fisheries and ecosystem overviews supporting EBM in practice by considering the wider ecosystem and social system (ICES, 2021a, 2022a). These ICES products are continually developing to address changes in the ecosystem, legal framework, the drivers of fisheries as well as spatial management and regional priorities by ICES ecoregion (ICES, 2020a). SEAwise (2021-2025) is a very recent EU project focusing on the implementation of Ecosystem-Based Fisheries Management (EBFM) in Europe. Working in the Mediterranean, Western Waters, the North Sea and the Baltic Sea and with a network of partners and key fisheries stakeholders, SEAwise will deliver a fully operational tool that will allow fishers, managers, and policy makers to easily apply EBFM structures in their own fisheries (https://seawiseproject.org/). SEAwise aims to investigate the ecological and social impacts of fisheries, as well as the spatial management of these on the ecological system and the fisheries. Findings are expected to enable a holistic understanding of, and response to, the key challenges to EBFM in Europe. The EU Horizon 2020 EcoScope project (2021-2025) addresses ecosystem degradation and anthropogenic impacts that cause fisheries to be unsustainably exploited in several European Seas and promotes efficient, holistic, sustainable, ecocentric fisheries management (https://ecoscopium.eu/). The project aims to develop a robust decision-making toolbox, a series of online courses and a mobile application. These tools will be available through a single public portal, to support an efficient, ecosystem-based approach to the management of fisheries and achieve maximum and continuous participation of stakeholders.

More examples of the application of the EBM to a single sector are seen in the management of offshore wind farms (OWF) including on impact identification, risk-based approaches and reconciling OWF development with conservation objectives (Pezy et al., 2020; Copping et al., 2020; Galparsoro et al., 2022a; Maldonado et al., 2022). In terms of new human activities, Guilhon et al. (2021) review the adoption of EBM by deep-sea mining (DSM) concluding that the mere recognition of EBM principles in the regulatory framework does not guarantee its implementation and further clarification on the meaning of the Ecosystem Approach in the DSM context is needed. In another sectoral example, an ‘ecosystem approach to aquaculture’ (EAA) is defined as a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems (FAO, 2010). A recent review suggests that mainstreaming the EAA in planning processes has raised awareness and helped to steer the sector towards greater sustainability. The close links between the EAA, spatial planning and initiatives such as ‘blue growth’, constitute significant opportunities for the future of the approach (Brugère et al., 2019), although its ability to tackle increasingly complex governance issues may be limited.

Ecosystem-based marine spatial planning (EBM-MSP) is a relatively recent practice (see Andersen et al. (2020) operationalising the EBM concept in Danish Action Plans) including through work in EU projects such as MESMA, MARCONS, ADRIPLAN, CAPACITY4MSP, ECOMAR (see European MSP platform, https://maritime-spatial-planning.ec.europa.eu/msp-practice/msp-projects) and the recent 'MarinePlan' which aims to support the ecosystem-based MSP in European Seas, the European Green Deal and the Biodiversity Strategy (https://www.marineplan.eu/). EBM-MSP is also an area of rich research, reviewing and analysing concepts, tools and critical issues for its implementation (Katsanevakis et al., 2011, 2020; Kirkfeldt, 2019; Stelzenmüller et al., 2013, 2018, 2020). For example, through the MSP Research Network (https://www.msprn.net/home), the EU MSP Platform (https://www.msp-platform.eu/) and the MEAM (Marine Ecosystems and Management; https://meam.openchannels.org/) a literature search was performed to locate English written peer review articles with the search words "ecosystem", "marine" and "planning" in the abstract, title or keywords, and published in the period of 2009–2019. In addition to the analysis of the selected plans and articles, a questionnaire was created to supplement the literature analysis. This focused on how MSP practitioners and researchers employ and combine the three most popular concepts that support EBM-MSP - EBM, the ecosystem-based approach (EBA) and EA - and how they define these concepts. Kirkfeldt (2019) then reports on the similarities and differences between EBM, EBA and EA, the key principles each concept includes (beyond the 7 common ones) and how different perceptions between MSP practitioners and stakeholders could lead to less ambitious or inadequate outcomes. In 2019, the Study on Integrating an Ecosystem-based Approach (EBA) into Maritime Spatial Planning was contracted by the European Commission. It resulted in a practical, stepwise approach for incorporating an EBA in maritime spatial plans (MSPs), including supporting documents (EC et al., 2021a-e). The literature study (EC et al., 2021c) indicated that while EBA is referenced in many reports and articles, it is often presented as a concept or broad implementation philosophy to 'give space to ecology' within the MSP process and decisions. Little practical evidence was found on the development and on-site application of approaches centering EBA principles in the MSP literature reviewed. Main findings of the literature review include (EC et al., 2021c): "*Practical applications related to understanding the ecological functioning of marine ecosystems are found in the Baltic Sea basin, where EBA has become an integral part of MSP and transboundary cooperation is encouraged through projects and HELCOM coordination; Few approaches and methods have been applied to capture the social and economic dimensions of marine ecosystems; Adaptive management* *is seldom addressed in the MSP literature, despite the considerable uncertainty and unexpected impacts of global (including climate) changes; Stakeholder mobilisation is frequently referenced in the literature. It covers however a broad range of mobilisation modes, with the large majority being consultation of key stakeholders from within set administrative boundaries that are unlikely to correspond to ecosystem boundaries. Transboundary stakeholder mobilisation is particularly limited and is rarely considered, even for marine ecosystems whose pressures and services delivered relate to activities beyond national boundaries*." The guidance (EC et al., 2021a) presents a set of key actions to integrate EBA in the main steps of the MSP process, including potential tools that can be applied as part of operationalizing EBA in MSP. The guidance uses a simple five-stage cycle (Figure 4; EC et al., 2021a): (i) Defining: setting the frame for the MSP, organising the MSP process and identifying its priority objectives and principles (societal goals); (ii) Developing: building the knowledge base including stocktaking and analysing data and other information; (iii) Assessing: Assessing and weighing planning alternatives; (iv) Implementing: Implementing the plan, and (v) Follow-up: Evaluating results and performance.

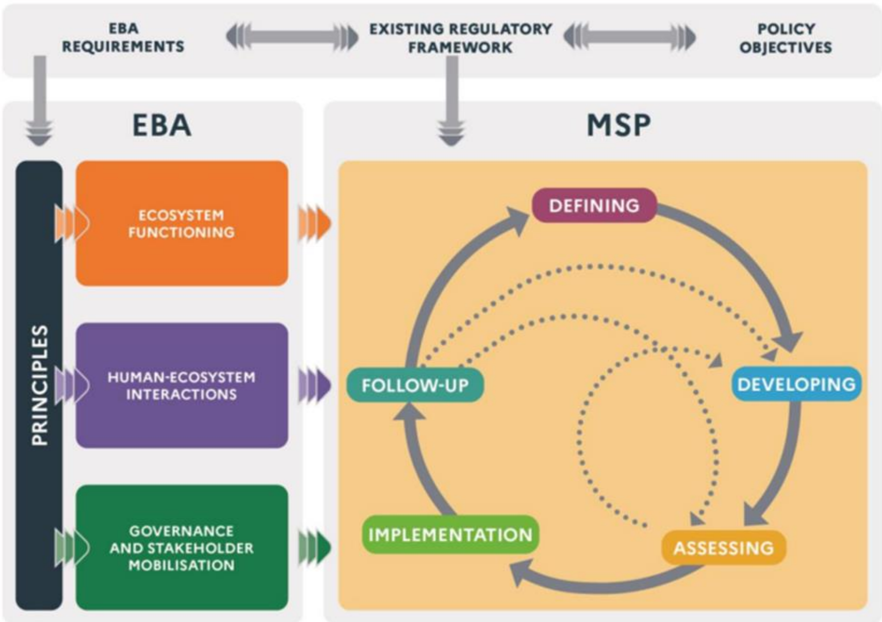


Figure 4. Ecosystem-Based Approach (EBA) themes can be applied in each step of the Maritime Spatial Planning (MSP) cycle (EC et al., 2021a).

4.3.11. EBM applications and Integrated Ecosystem Assessments

Other EBM applications include approaches linked to Integrated Ecosystem Assessments (IEA). First developed by the US National Oceanic and Atmospheric Administration's (NOAA), integrated ecosystem assessments (IEA) are an approach to operationalising EBM (Levin *et al.*, 2009, 2014;

Samhouri *et al.*, 2014). EBM is a US national priority within the National Oceans Policy, and the IEAs are seen as best practice to affect EBM (Dickey–Collas 2014). IEAs seek to integrate all components of an ecosystem, including humans, into the assessment to inform the decision-making process so that managers can balance trade-offs and determine what is more likely to achieve their desired goals. The approach is a NOAA-wide initiative, that provides a consistent national approach but is flexible to accommodate regional needs. It is overseen by the IEA program, which directs the execution of Integrated Ecosystem Assessments within five regions in the United States ocean and coastal ecosystems (https://www.integratedecosystemassessment.noaa.gov/). IEA has also been adopted by ICES, with the establishment of an ICES IEA Steering Group tasked to define the data needs and develop and apply IEA methods across the ICES ecoregions to advance ecosystem-informed science and advice to support ecosystem-based management (ICES, 2012). The ICES IEA groups work together to identify common tools and analytical approaches, which include risk assessment, ecosystem modelling, integrated trend analyses, and the use of reference points and indicators (https://www.ices.dk/community/groups/Pages/IEASG.aspx).

5. Deriving Key EBM Elements and Tools

5.1. Selection of key EBM elements and tool groups

For this task, we reviewed the 26 EBM principles from Long et al. (2015) and the recent literature (Ruud et al., 2018; Hewitt et al., 2018, 2020; Clark et al., 2022; Dickey-Collas et al., 2022) and reworded them to add clarity and to aid their operationalization (Table 2).

We matched the EBM principles (Table 2) to the GES4SEAS projects' core objectives (e.g., MSFD assessments, cumulative effects assessments, ecosystem services addressing uncertainty and acknowledging the importance of stakeholder engagement) for example the principles 'Determine Ecological Integrity and Biodiversity' (e.g., GES for MSFD) and 'Consider cumulative impacts' are at the core of the project work (based on keywords from the Description of Work, see also word cloud, Figure 5). Out of the 26 a number can be seen as processes, implicit in all the stages of the project (e.g., n.4 and n. 25 with the project participants, experts, PAB members and involved stakeholders using all forms of knowledge). Others were only of peripheral importance to GES4SEAS (e.g., n. 26 use of incentives, or 17 consider economic context) (Table 2). Table 3 shows the core EBM principles for GES4SEAS.

Figure 5. GES4SEAS word cloud (based on keywords).

We also matched the EBM principles to 4 management cycle phases based on the PACE: Plan-Act-Evaluate-Check framework (BSPC, 2006) (Figure 6, Table 2). PACE is a conceptual model of an adaptive EBM strategy, where planning, implementation, monitoring, assessment, and evaluation are linked. PACE is similar and compatible to the ISO9001:2015 process management PDCA model (Plan, Do, Check, Act). In the Planning phase of PACE, the overall vision and goals (e.g., GES, targets per descriptor or theme specific goals such as tackling eutrophication) are set and all the main threats to the system are identified. In the Evaluation and Check phases status assessments are preformed and distance to goals is evaluated (is GES reached? why GES is not achieved? is monitoring fit-for-purpose? are additional measures needed?). The core work of GES4SEAS is related to this Evaluation/Assessment phase.

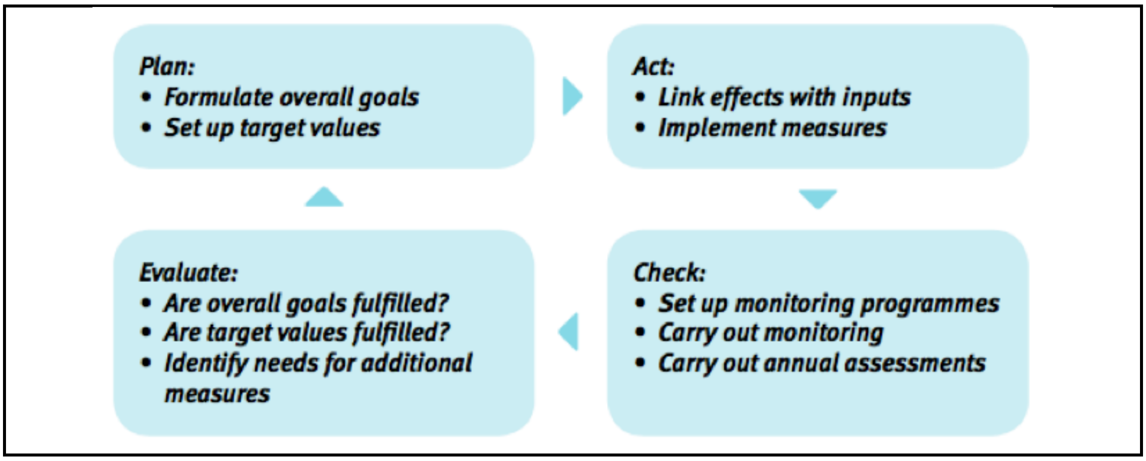


Figure 6. PACE (Plan, Act, Check, Evaluate) framework from (BSPC, 2006)

We then developed a framework linking the selected EBM principles (based on GES4SEAS core objectives and relevant PACE phases) to the methodologies and tool groups needed to address key EBM elements of the principles (Figure 7). Following this exercise, the group collated the list of EBM elements (Table 3) and all major relevant methodologies/ tool groups to assess the chosen EBM elements. The final selections going forward (based on the core objectives of GES4SEAS) are given in Tables 4 and 5 (below).

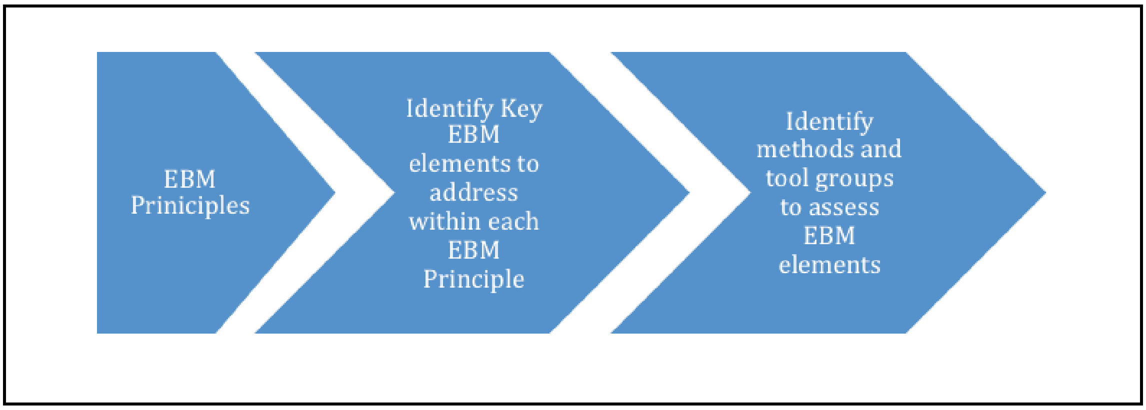


Figure 7. Schematic, pathway from Ecosystem-Based Management (EBM) principles to tools.

Table 2. Ecosystem-Based Management (EBM) Principles (Long et al., 2015), relevance (R) to GES4SEAS core work (Yes=Y) and links to PACE (Plan, Act, Check, Evaluate) management phases. SMART: specific, measurable, achievable, relevant, and time-bound indicators.

No	R	PACE	EBM Principles	Reworded principles
1	Y	P	Consider Ecosystem Connections	Determine and ensure connectivity within and between areas
2	Y	P, A, C	Appropriate Spatial and Temporal Scales	Assess at temporal and spatial scales, appropriate to the ecosystem components of concern
3	Y	P, A, C, E	Adaptive Management	Use adaptive management in employing measures
4	Y	P, A, C, E	Use of Scientific Knowledge	Use best and fit-for-purpose scientific knowledge
5	Y	P, A, C, E	Integrated Management	Ensure integrated management is carried out
6	Y	P, A, C, E	Stakeholder Involvement	Ensure a fair and transparent stakeholder involvement at all stages
7		P, A, C,	Account for Dynamic Nature of Ecosystem	Ensure ecosystem functioning is assessed at relevant spatial and temporal scales accounting for change due to natural variability, natural and human made disturbances and climate change
8	Y	P, A, C,	Ecological Integrity and Biodiversity	Determine ecological integrity and biodiversity
9		P	Sustainability	Ensure the managed systems are sustainable in the long-term
10		P, E	Recognise Coupled Social-Ecological Systems	Include and integrate both ecological and social systems (humans are part of the marine system)
11		P, A	Decisions reflect Societal Choice	Ensure the outcomes respect societal choice
12	Y	P, A	Distinct Boundaries	Consider ecosystem and jurisdictional boundaries. Include spatial and temporal boundaries in the assessments.

13		P, A, C, E	Inter-disciplinarity	Ensure the assessments are multidisciplinary, including social and natural scientists
14		P, C	Appropriate Monitoring	Perform appropriate and fit-for-purpose monitoring
15	Y	P, A, C, E	Acknowledge Uncertainty	Measure and record uncertainty in the assessments
16		P	Acknowledge Ecosystem Resilience	Acknowledge ecosystem resilience in a narrative, in planning and when assessing the resilience of existing plans to current and emerging pressures.
17		P, A	Consider Economic Context	Determine the economic repercussions of action and non-action
18		P, A,	Apply the Precautionary Approach	Apply the precautionary approach in management
19	Y	P, C	Consider Cumulative Impacts	Assess the risk, identify and measure the cumulative impacts/effects (on both natural and social systems)
20		P, A	Organizational Change	Identify if organisational change is required in management and make recommendations
21		P, A,	Explicitly Acknowledge Trade Offs	Determine whether and what are the trade-offs in management measures
22		P	Consider Effects on Adjacent Ecosystems	Determine the effects and connectivity of an area on adjacent systems and vice versa
23		P, A	Commit to Principles of Equity	Ensure that actions and outcomes are just and equitable to nature and society
24		P	Develop Long Term Objectives	Record the long-term vision and ensure objectives are SMART and link to indicators
25	Y	P, A, C, E	Use of All Forms of Knowledge	Use best-available natural and social sciences, including indigenous knowledge
26		P, A	Use of Incentives	Use economic, societal and ecological incentives to achieve outcomes

Table 3. Core Ecosystem-Based Management (EBM) Principles for GES4SEAS, key elements within each principle and Methodological approaches/tool groups to assess each key EBM element. WP: Work Package; PAB: Practitioners Advisory Board; MSFD: Marine Strategy Framework Directive; GES: Good Environmental Status; BHD: Birds and Habitats Directives; NEAT: Nested Environmental status Assessment Tool; OHI: Ocean Health Index; BBN: Bayesian Belief Network; HAB: Harmful Algal Blooms, NIS: Non-Indigenous Species; HSM: Habitat Suitability Models; GIS: Geographical Information System.

No.	**Core EBM Principles**	**Key EBM elements within each core EBM principle**	**Methodological approaches/tool groups to assess key EBM elements**
6	Stakeholder Involvement	co-creation is the focus of WP1 (PAB and GES4SEAS participants)	iterative and incremental development approach; social science methods soliciting expert views or tools using judgement (e.g., on sensitivity to pressures in Halpern's 2008 global cumulative impacts analysis)

8	Ecological Integrity and Biodiversity	overall environmental status, MSFD GES assessments, ecosystem components, species and habitats and assessments e.g., BHD and OSPAR s specific effects and impacts including for example HABs/NIS/eutrophication, threatened species and habitats, biotic effects/ecosystem functions/sex segregation issues, cumulative and in combination effects	combination of simple/multimetric indicators, risk based approaches and spatial/temporal pressure-impact-mapping and models, integration tools like NEAT, OHI, conceptual models, BBN probabilistic approaches, bow tie risk based approaches exposure-effect-hazard-vulnerability, cumulative impact spatial mapping (Halpern et al. 2008, HOLAS, CUMI), impact risk ranking through linkage-chain-frameworks (ODEMM approach), specific effects and impacts with ecosystem models, food web models, HSM models, multispecies models (e.g., looking at tipping points).
12	Distinct Boundaries	implicit, spatial maps and reporting units, relevant for GES4SEAS LS and MSFD assessments (WP5)	GIS, spatial planning and systematic conservation planning models (MARXAN with zones, prioritize, zonation), VAPEM
15	Acknowledge Uncertainty	explicitly addressed in various models and tools used and developed by GES4SEAS	various (e.g., in NEAT the calculations are made using Monte Carlo iterations; uncertainty is also assessed by some of the modelling tools)
19	Consider Cumulative Impacts	assess cumulative and in combination effects, assess activities-pressures-impacts linkages and spatial and temporal footprints, assess risk and spatial overlap of activities/pressures with vulnerable habitats/ important areas	conceptual models, BBN probabilistic approaches, bow tie risk-based approaches exposure-effect-hazard-vulnerability, cumulative impact spatial mapping (Halpern et al. 2008, HOLAS, CUMI), impact risk ranking through linkage-chain-frameworks (ODEMM approach), GIS.
25	Use of All Forms of Knowledge	implicit in the project, scientists and stakeholders using all forms of knowledge	tools combining quantitative, monitoring, local knowledge data with expert judgement, social science methods

5.2. Narrative of the EBM elements

Following the procedure noted above, the group identified and chose the EBM elements shown in Table 4. These EBM elements were also linked to the PACE framework phases and are briefly presented below. The chosen tools fulfilling these EBM elements are shown in Table 5 and discussed in the next section.

*Table 4. List of chosen Ecosystem-Based Management (EBM) elements and links to PACE (Plan, Act, Check, Evaluate) management phases, * was added to the list to tick each tools' ability to address the issue (climate change, uncertainty, risk) and any additional policy needs. Within Planning-P we identified 3 groups P1: assessments, P2: Cumulative Effects Assessment (CEA) and spatial activities-pressures-effects footprints and P3: spatial and other measures related to management footprint. GES: Good Environmental Status; MSFD: Marine Strategy Framework Directive; NIS: Non-Indigenous Species; HAB: Harmful Algal Blooms; MSPD: Maritime Spatial Planning Directive; BHD: Birds and Habitats Directive.*

PACE	Chosen EBM elements
P1, P2, C	**Cumulative effects assessments -CEA**
C, E	**GES MSFD assessments**
C, E	**Whole ecosystem assessments**
P1,	**Ecosystem Services (delivery, impacts, valuation)**
C, E	**Special biotic effects/impacts**
P1,	**Specific Ecosystem functions (and impacts on functions)**
P2	**Pressures-Activities footprint**
P2	**Effects footprints (and/or Impacts footprints)**
P1,	**Links activities pressures impacts**
P1,	**Single MSFD Descriptors/single issues (e.g., eutrophication, NIS, HABs)**
C, E	**Single species, ecosystem Components State change**
C, E	**Threatened habitats and species**
*	**Climate change**
P3, A	**Pressure and impact reduction/mitigation**
P3, A	**Spatial and other measures**
*	**Uncertainty**
*	**Risks**
*	**Other Policy Requirements e.g., MSPD, BHD, Biodiversity Strategy**

Cumulative effects assessments: GES4SEAS term 42, Cumulative Effects Assessment (CEA) (often used interchangeably with Combined Effects Assessment, Cumulative Impact Assessment (CIA); In combination Effects Assessment; Cumulative Pressure and Impacts Assessment) is defined as the assessment of ecosystem changes that accumulate from multiple stressors, both natural and manmade (Dubé et al., 2013). CEAs are holistic evaluations of the combined effects of human activities and natural processes on the environment, constituting a specific form of environmental impact assessments (ICES (2019a). MSFD (EC, 2008) Article 8 requires Member States (MS) to perform assessments and an analysis of the predominant human activities, pressures and impacts including the main cumulative and synergetic effects on the environmental status of their waters.

The first global assessment was by Halpern et al. (2008), soon to be repeated by RSC and pan-European processes (e.g., HELCOM, 2010, 2023; EEA, 2019; Korpinen et al., 2019, 2021, presenting multiple pressures and their combined effects across the European seas; and Halpern et al., 2019, the latest global assessment). Since then, numerous studies follow covering large regions to small scale applications (e.g., by Micheli et al., 2013a and Coll et al., 2012, for the Mediterranean and the Black Sea; Andersen et al., 2015, 2020b, for the North Sea and the Baltic Sea; Holon et al., 2015, for French Mediterranean coasts; Fernandes et al., 2017, for Portugal; Menegon et al., 2018, for the Adriatic Sea; Hammar et al., 2020, for Sweden, Quemmerais-Amice et al., 2020, for France; Loiseau et al., 2021, for an island of French Polynesia). Studies also deviate by addressing different ecosystem components, instead of whole ecosystems to specific habitats and/or species (see Bevilacqua et al., 2018, for an example on Mediterranean coralligenous outcrops; Vaher et al., 2022, for an example on reef and sandbank habitats in the northeastern Baltic Sea; Carlucci et al., 2021, for an example on cetaceans; Maxwell et al., 2013, for example on marine predators; Coll et al., 2015, for marine vertebrates in the Mediterranean Sea).

Korpinen and Andersen (2016) reviewed 40 marine cumulative pressure and impact assessments (CPIA) around the world and found similar approaches: many of the assessments were based on habitats, mainly benthic but also pelagic, while some focused on species; methodologies including same assumptions (e.g. additive pressures, long lasting effects), a lack of benchmark for the pressures (i.e., a quantitative definition of a certain level of pressure, for which the impact, adverse effect occurs or sensitivity is estimated), a relationship between pressure and impact, based on expert judgment in a categorical way and with few empirical validations (but see Bevilacqua et al., 2018). Borja et al. (2016) also review five commonly used approaches and their commonalities and differences, in terms of use of the Ecosystem Approach; inclusion of multiple ecosystem components and pressures and impacts in the assessment; use of reference conditions; and determining uncertainty among others. Major assumptions and limitations of the CEAs, including uncertainty, have been identified (Halpern and Fujita, 2013), and methodologies have been proposed to assess the inherent uncertainty associated with CEAs, helping to identify data gaps, ensure transparency in decision-making and facilitate adaptative management (Gissi et al., 2017; Jones et al., 2018; Stock et al., 2016; Stock et al., 2018). Quemmerais-Amice et al. (2020) have proposed several modifications to the Halpern et al. (2008) method. These include a demonstrator tool able to map the Risks of Cumulative Effects (RCE) of different pressures on benthic habitats, the calculation of the Risk of Cumulative Effects' Confidence Index and other aspects such as spreading the pressure effect from point sources for each activity–pressure pair.

Recent assessments with a focus on ecosystem-based marine spatial planning applications are provided by Andersen et al. (2020a) and Fernandes et al. (2017). Additionally, Menegon et al. (2018) and Hammar et al. (2020) show how cumulative impact assessments (CIA) can support ecosystem-based MSP in practice through MSFD pressure-driven CEA, CEA-based marine ecosystem service threat analysis, maritime use conflict (MUC) analysis, elaboration of scenarios, while developing and applying methodological advancements (e.g., by using the Symphony-tool and the Tools4MSP GeoPlatform, and by addressing uncertainty and some pressures differently) to traditional assessments (e.g., Halpern et al., 2008).

Stelzenmüller et al. (2018, 2020) develop and operationalize a framework for risk-based cumulative effect assessments in the marine environment, thereby working with 11 national, subregional and regional case studies. They conclude with a key recommendation to differentiate CEA processes and their context in relation to marine spatial planning or governance and regulatory advice purposes.

Risk-based approaches have often been at the basis of CEAs for marine management (Tamis et al., 2016; Stelzenmüller et al., 2018). For estimating the risk of a rare or unpredictable event (i.e., calamities) such assessments follow a likelihood-consequence approach (Williams et al., 2011), whereas an exposure-effect approach is considered more suitable when assessing existing and (more or less) continuous or frequently occurring pressures (Smith et al., 2007; Knights et al., 2015). The estimation of exposure and effect can be based on (i) qualitative categories and expert-judgement scores (Knights et al., 2015; Borgwardt et al., 2019), (ii) a fully quantitative approach applying actual data (Piet et al., 2021) or (iii) a mix of qualitative and quantitative information (Piet et al., 2023a submitted). This latter approach can be readily applied using a categorical approach, e.g., in a new assessment or in case of a data-poor ecosystem but can be gradually improved over the longer term by incorporating quantitative information as it becomes available. Piet et al. (2023 b, submitted) builds on previous CEA/CIA approaches and their applications to inform management (Knights et al., 2015; Piet et al., 2015, 2017, 2019; Borgwardt et al., 2019; Culhane et al., 2019a). It uses the comprehensive categorical risk-based approaches but modified such that their outcome (Impact Risk from cumulative pressures) is conceptually identical to the outcome from the quantitative approaches.

In terms of indicator-based assessment methods, CumI ("Cumulative impact from physical pressures on benthic biotopes"), is a HELCOM core indicator (HELCOM, 2021b) to be used in HOLAS III assessments. CumI evaluates the cumulative potential/expected impact of several physical pressures on the benthic biotopes of the Baltic Sea, (partly) based on pressure-specific sensitivities. The method works with spatial data (e.g., VMS and fisheries SAR) and grids and is applicable to all pressure gradients and to MSFD D6 criteria D6C3 and D6C5. Thresholds for adverse effects are based on a categorial approach (6 disturbance categories from no to high). CumI is comparable with similar indicator development under OSPAR (i.e., BH3). Future developments include a more rigid approach to assess the uncertainty in CumI (WKBENTH3; ICES, 2022c). BH3 is operational at an OSPAR Region-scale, with spatial outputs generated for OSPAR assessments (see OSPAR, 2017b; Elliott et al., 2018) and applications for the MSFD by some Member States. BH3 also has relevance to components of D1- biodiversity (benthic habitats) and applies to D6C3 and informs D6C5 seafloor integrity. Thresholds considered for adverse effects are based on a categorial approach (9 disturbance categories). Outputs are developed with accompanying confidence maps to indicate uncertainty in component data layers used in assessments. Future developments include further exploration of threshold values and inclusion of more human activities (ICES, 2022c).

The OSPAR North-East Atlantic Environment Strategy 2030, Strategic Objective 7 acknowledges the need to "ensure that uses of the marine environment are sustainable, through the integrated management of current and emerging human activities, including addressing their cumulative impacts" (OSPAR, 2021). Taking this forward, in its QSR 2023 report (expected to be published online in July 2023 in the OSPAR website) new and further elaborated approaches to quantifying and assessing cumulative effects include:

a) Modified Bow Tie Analyses (mBTA) undertaken describing the connectivity of the DAPSIR components for each Thematic Assessment (for DAPSIR see section below on linking activities pressures and impacts).

b) Weighting of the Activity-Pressure-State (APS) connections in the mBTA following an adaptation of the ODEMM approach (Robinson et al., 2013; Knights et al., 2015) as an indicative assessment of those activities and pressures of greatest potential concern and meriting priority action.

c) Weighting of the State Impact (SI) connections as an indicative assessment of impacts on ecosystem services following a methodology developed by the OSPAR group on Economic and Social Analysis (Cornacchia, 2022).

d) Sankey diagrams generated for the biodiversity thematic assessments (pelagic habitats, benthic habitats, fish, marine birds, marine mammals) combining the outputs from (b) and (c) for APSI as an indicative assessment of cumulative effects.

e) Confidence in the cumulative effects assessment is also assessed (in line with guidance on communicating the degree of uncertainty in key findings of OSPAR assessments) using two criteria on (i) the level of evidence, and (ii) degree of agreement of the underlying assessments (OSPAR 2019).

GES MSFD assessments: GES4SEAS term 27, Assessment for the purposes of the MSFD, an assessment is both a process and a product. As a process, an assessment is a procedure by which information is collected and evaluated following agreed methods, rules and guidance. It is carried out from time to time to determine the level of available knowledge and to evaluate the environmental status. As a product, an assessment is a report that synthesizes and documents this information, presenting the findings of the assessment process, typically according to a defined methodology, and leading to a classification of environmental status in relation to the determination of GES (CSWD, 2020).

Term 20 defines Good Environmental Status (GES), *"The environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive within their intrinsic conditions, and the use of the marine environment is at a level that is sustainable, thus safeguarding the potential for uses and activities by current and future generations"* (EC, 2008). Previous European projects (e.g., DEVOTES), attempted to define the operational meaning of GES *''Good Environmental Status is achieved when physico-chemical (including contaminants, litter and noise) and hydrographical conditions are maintained at a level where the structuring components of the ecosystem are present and functioning, enabling the system to be resistant (ability to withstand stress) and resilient (ability to recover after a stressor) to harmful effects of human pressures/ activities/ impacts, where they maintain and provide the ecosystem services that deliver societal benefits in a sustainable way (i.e. that pressures associated with uses cumulatively do not hinder the ecosystem components in order to retain their natural diversity, productivity and dynamic ecological processes, and where recovery is rapid and sustained if a use ceases)''* (Borja et al., 2013). Numerous EU/DG ENV projects have worked/are working on various aspects of MSFD assessments (e.g., EcApRHA, NEA PANACEA, MEDCIS, MEDREGION, ABIOMMED).

Diverse studies have reviewed and investigated the official assessments undertaken by Member States (Magliozzi et al., 2021, 2023; Palialexis et al., 2014, 2019, 2021). These studies compare approaches and provide recommendations aiming to improve the consistency and representativeness of the MSFD assessments. Most publications on single country MSFD assessments focus on method applications or comparisons and a selected set of descriptors (e.g., Pavlidou et al. 2019; Borja et al., 2021).

Whole ecosystem assessments: whole ecosystem assessments like MSFD do exist but without the same strict structure and requirements of the MSFD e.g. in the Baltic Sea (HELCOM, 2010, 2023), in the Atlantic Ocean (OSPAR Commission, 2010, 2017, 2019; OSPAR QSR2023 in preparation https://www.ospar.org/work-areas/cross-cutting-issues/qsr2023), in the Mediterranean (UNEP-MAP, 2017), or in the Black Sea (Todorova et al., 2019).

Ecosystem services (delivery, impacts, valuation): this includes assessments of ecosystem services (ES) in terms of delivery and impacts as well as of value (see also tools narrative section: valuation methods and natural capital accounting methods). According to GES4SEAS Term 47, *"Ecosystem services are the final outputs or products from ecosystems that are directly consumed, used (actively or passively) or enjoyed by people"*. The Common International Classification of Ecosystem Services (CICES) is the 'EU reference' typology for all ecosystem services (CSWD, 2020). To this end Culhane et al. (2019a, b; 2020) developed an EU-level marine ecosystem-based assessment approach (i.e., a concept framework and method) that considers how ecosystem state affects its capacity for the supply of ecosystem services. The approach provides a way to translate marine ecosystem state into marine ecosystem capacity for service supply. Teixeira et al. (2019) identified the flow from biodiversity to ecosystem services supply for eight case studies across European aquatic ecosystems covering freshwater, transitional, coastal and marine waters realms. Recently, Piet et al. (in prep) conducted a cumulative impact assessment for the North Sea and combined the outcome with an assessment of the Ecosystem Service Supply Potential. Moving away from purely qualitative and score-based assessments, van de Pol et al. (2023) propose a 4-tiered method to aid quantitative assessments of ecosystem services supply linking the supply to the human activity and pressure of interest.

In line with the Biodiversity Strategy 2030 (EC, 2020) and the Climate Adaptation Strategy (EC, 2021), the EU is taking steps ensuring that the risks stemming from climate change and biodiversity loss do not jeopardise the availability of the goods and services that healthy marine ecosystems provide to fishers, coastal communities and humanity at large. By the end of 2023, the Commission will start developing a modelling tool to incorporate the concept of 'natural capital' in economic decisions. This will involve assessing and quantifying both the economic value of marine ecosystem services and the socio-economic costs and benefits derived from keeping the marine environment healthy (EC, 2023). Natural capital was first mentioned in the Biodiversity Strategy to 2020 under the headline motto "our life insurance, our natural capital" with further support for valuing and accounting of natural capital given in the EU Biodiversity Strategy for 2030 (EC, 2020). Although the application of the concept and the progress so far varies significantly between countries and types of ecosystem accounts (e.g., with more carbon accounts being developed than biodiversity accounts) a significant increase in completed ecosystem accounts is expected in the foreseeable future (Lange et al., 2022). Ecosystem accounts are needed to provide consistent information on extent and condition of ecosystems and on the flows of services from these ecosystems to society, and to monitor progress towards a green economy in line with the EU Green Deal (EC, 2019) and towards the Sustainable Development Goals in a Union context (EC, 2022b).

Tables 19 and 20 include a comprehensive description and examples of tools and methods for natural capital accounting, ecosystem services valuation and societal goods and benefits valuation, some of which will be applied by the ongoing EU project MARBEFES (MARine Biodiversity and Ecosystem Functioning leading to Ecosystem Services). MARBEFES has the ES in its core objectives along with understanding the causes and consequences of the maintenance, loss and gain of biodiversity and ecological and economic value and the repercussions of this for the management of European seas (https://marbefes.eu/).

Special biotic effects/impacts: include multiple examples, a major one being the sex segregation i.e., when sexes of a species live apart, either singly or in single-sex groups.

Various forms of sexual segregation, due to multiple factors involving natural but also anthropogenic pressures, have been documented for cetaceans, marine pinnipeds, marine birds, marine reptiles, marine birds, and marine teleost and elasmobranch fish (for a review see Wearmouth and Sims, 2008). Documenting the underlying causes of sexual segregation is important for management and conservation reasons as differential exploitation of the sexes by humans (e.g., by spatially focused fishing in key areas or hunting) can lead to population declines (Wearmouth and Sims, 2008; Mucientes et al., 2009). Understanding the factors that influence the distributions of species is also crucial for implementing effective EBM and conservation practices. Many shark species for example exhibit either spatial and/or temporal sexual segregation, requiring sex-specific habitat suitability modeling (Drymon et al., 2020). Habitats may be selected differentially by the sexes for social, foraging or thermal related reasons (Wearmouth and Sims, 2008).

For example, in a recent study, the impacts from climate change in the Mediterranean turtles, that received the highest scores from experts, included: (i) risk to the sex ratios of hatchlings and (ii) risk of current nesting sites becoming unviable in the future (i.e. location of nesting sites), which are very important in conservation decisions for these species (Mazaris et al., 2023). This is because it is well-known that turtles are species with temperature-dependent sex determination (i.e., the sand temperature determines whether male or female offspring are produced) (Hays et al., 2014). Hence, with increasing temperatures under climate change, populations are under threat as existing incubation temperatures are leading to predominantly female-skewed hatchling sex ratios (Patrício et al., 2021).

On the other hand, many studies have highlighted that pollution can alter population sex ratios or the female intersex condition in certain species, e.g., the Tributyltin (TBT) effect on imposex in gastropods (Gibbs et al., 1988; Bauer et al., 1995; Sousa et al., 2005). Similar sex ratio changes have been described for PAHs, PCBs and other pollutants.

More subtle effects have been described in the case of fishing on the demography and population ecology of sex-changing fishes. Hence, species with female-first sex change often have naturally skewed sex ratios in the adult population, and fishing pressure can alter this natural bias, limiting egg production and fertilization success (Chong-Montenegro and Kindsvater, 2022). For two species of groupers (*Epinephelus quinquefasciatus* and *Mycteroperca olfax*), these authors consider how variation in growth rates and fertilization rates interact with fishing selectivity to affect age structure and sex ratios, predicting a decrease both in spawning potential and biomass, causing rapid depletion of sex-changing species.

Changes in temperature at critical developmental stages can induce biases in primary sex ratios in some fish species. Hence, most studies under controlled conditions, conclude that if temperature affects sex ratios, elevated temperatures under climate change warning mostly led to a male bias (Geffroy and Wedekind, 2020). Extreme sex ratios resulting from high rates of environmental sex reversal (either due to climate change, pollution or other human pressure) reduce effective population sizes considerably. This may limit any evolutionary response to the deleterious effects of sex reversal and populations losing genetic sex determination may quickly go extinct if the environmental forces that cause sex reversal cease (Cotton and Wedekind, 2008).

Specific Ecosystem functions (and impacts on functions) this includes a very wide range of ecosystem functions with varied research and management interests.

The biotic and abiotic assets of the marine environment constitute the natural capital held in Europe's seas, i.e., 'marine natural capital'. Part of this capital is depletable, such as marine ecosystems and the services they can supply to people. Ecosystem structures (such as biotic elements as species and habitats and light, dissolved carbon and other physico-chemical elements), processes (such as nutrient uptake, photosynthesis, respiration, excretion, decomposition, biological/ecological and food web interactions) and functions (such as primary production, carbon sequestration, nutrient cycling, ecosystem metabolism, physical engineering; see Strong et al. (2015) for a comprehensive review of functions and their relation to biodiversity) are the foundation of ecosystem services (Costanza et al., 1997; EEA, 2019). The MSFD (EU, 2008) in line with its requirement for ‘good environmental status’ and ‘clean, healthy and productive oceans and seas within their intrinsic conditions', additionally requires that 'the structure, functions and processes of the constituent marine ecosystems allow those ecosystems to function fully and to maintain their resilience to human-induced environmental change'. More specifically it dictates for D6: 'sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected' (EU, 2017a), and for criterion D6C5: *'the extent of adverse effects from anthropogenic pressures on the condition of the habitat type, including alteration to its biotic and abiotic structure and its functions (e.g. its typical species composition and their relative abundance, absence of particularly sensitive or fragile species or species providing a key function, size structure of species), does not exceed a specified proportion of the natural extent of the habitat type in the assessment area.'* A key functional role within the component (e.g., high or specific biodiversity, productivity, trophic link, specific resource or service) or certain life history traits (age and size at breeding, longevity, migratory trait) is noted of particular ecological relevance for the choice of habitats and species for the assessments is (EU, 2017a). In terms of policy relevance (e.g., EU Green Deal, EU Nature Restoration Law) carbon sequestration by blue habitats is a major topic (for restoration and as natural climate solution) and drive for research and assessments (Macreadie et al., 2021; Duarte et al., 2020).

Pressures-Activities footprint: this category includes assessments of spatial footprints of pressures and activities operating in the study area. Pressure and activities footprints are used to demonstrate the extent of an activity (e.g., Eigaard et al., 2017; Amoroso et al., 2018; showing the extent of the towed gears footprint in European and world shelf and slope areas; Galparsoro et al., 2022; Gușatu et al., 2021, showing the extent of offshore wind sector; Korpinen et al., 2019, showing the extent of multiple activities and pressures across Europe; the overlap of an activity with a sensitive or important ecosystem components (offshore wind and birds of high conservation concern: Garthe et al., 2023; cetacean distributions overlap with maritime traffic: Awbery et al., 2022; Pennino et al., 2017) and consequently the risk from this interaction (depending on its extent and severity, Knights et al., 2015). A review article by Elliott et al. (2020a) discusses the differences between the Activity-footprints, the pressures-footprints and the effects-footprints (see also the EBM element below). Determining the overall effects of human activities on the estuaries, seas and coasts, as a precursor to marine management, requires quantifying three aspects: (i) the area in which the human activities take place, (ii) the area covered by the pressures generated by the activities on the prevailing habitats and species, and (iii) the area over which any adverse effects occur. These three features correspond to the activities-footprints, the pressures-footprints and the effects-footprints. The first two might or might not have the same footprint (e.g., fishing or aquaculture can cause localised near field effects such as mortality or physical habitat changes within the activity's footprint but they can also cause effects some distance away from operations by extensive resuspended sediment clouds, increased nutrient and carbon loads, biogeochemistry changes, spread of aliens and disease; Puig et al., 2012; Bradshaw et al., 2021; Weitzman et al., 2019). The effects footprints in turn incorporate both the effects on the natural system and the effects on ecosystem services from which society extracts goods and benefits. Quantifying the three footprints has repercussions for marine governance, is essential for EBM at national and regional levels and for cumulative and transboundary assessments. Cormier et al. (2022) discuss further the difference in scales and the links of these footprints with the management response footprints.

GES4SEAS Term 3, Activity Footprint: *"The area, and/or time, based on the duration, intensity and frequency of an activity which ideally, has been legally sanctioned by a regulator in an authorisation, license, permit or consent, and which should be so clearly defined and mapped in order to be legally-defendable; it should be both easily observed and monitored and attributable to the proponent of the activity"* Cormier et al. (2020). And Term 9 Pressures Footprint: *"The area and time covered by the mechanism(s) of change resulting from a given activity or all the activities in an area once avoidance and mitigation measures have been employed (the endogenic managed pressures)".* It does not necessarily coincide with the activity footprint and may be larger or smaller. It also needs to include the influence and consequences of pressures emanating from outside the management area (the exogenic unmanaged pressures); given that these are caused by widescale events (and even global developments) these are likely to have larger scale (spatial and temporal) consequences (Cormier et al., 2020). Important considerations for the pressures-footprint include the frequency of the activity as well as the spatial extent and temporal duration.

Related GES4SEAS terms. Term 2: *"Activities Actions (potentially positive or negative) by society in an area or globally - what we do in the natural and built environment to give us the Drivers; actions throughout all stages including creating, operating, using, removing infrastructure; creating an energy supply; obtaining food and water; being cognitive; using material by our presence (air), etc."* (Elliott et al., 2022a). Term 4: *"Pressure Resulting from [human] activities - defined as the mechanisms (as rate processes) of change, in the way in which an activity will change the natural and societal systems, by modifying the structure and functioning of the systems"* (Elliott et al., 2022a).

Effects (and impacts) footprints: As with the category Activity-pressure footprint this category brings in a spatial element in the assessments of impacts and effects which is an essential part of EBM and EU conservation policies (e.g., HD and MSFD). As effects and impacts are more difficult to identify and assess activity and pressure footprints are often used as proxies. For example, in simple regional risk screening exercises, the spatial extent of trawling is often used as a proxy for the extent of the pressure seabed abrasion which then is assumed to represent the extent of the fishing impacts on the benthic communities as accounting for other impacts (e.g., smothering sub-lethal effects on growth) is more difficult (ICES, 2019b, c). Spatial distribution (extent) in combination with fishing intensity layers are used to assess benthic impacts footprint for example underpinning the OSPAR 'Extent of Physical damage indicator' (BH3) (OSPAR, 2017b; ICES, 2021b). Specific impacts such as macrofauna depletion or impacts on mean benthic longevity or changes in biological traits are also investigated closely linked with the spatial extent of fishing (de Juan et al., 2009, 2020; Hiddink et al., 2017, 2018; Jac et al., 2020; Mazor et al., 2021; Pitcher et al., 2022; Smith et al., 2023). HELCOM and OSPAR are also developing indicator and risk-based assessment approaches based on species and habitats sensitivities and various disturbance layers (Elliott et al., 2018; González-Irusta et al., 2018, Serrano et al., 2022).

According to GES4SEAS Term 43 the effects footprint is defined as: The spatial (extent), temporal (duration), intensity, persistence and frequency characteristics resulting from (i) a single pressure from a marine activity, (ii) all the pressures from that activity, (iii) all the pressures from all activities in an area, or (iv) all pressures from all activities in an area or emanating from outside the management area. They will have adverse consequences on the natural ecosystem components, but also are likely to affect the ecosystem services from which society gains goods and benefits. Hence, the determination of the effects-footprint needs to include the near-field and far-field effects and near- and far-time effects because of the dynamics and characteristics of marine areas and the uses and users of the area. Similarly, the effects footprints may be larger in extent and more persistent than the causing activity-footprint and the resulting pressures-footprints. They also need to encompass the effects of both endogenic and exogenic pressures operating in that area (Cormier et al., 2020). Beyond the spatial and temporal extent of the effects of pressures arising from an activity, their magnitude may also be considered (ICES, 2019a). The activity and effect footprints might differ as the effects may be near-field (within the immediate vicinity of the pressure) or far-field (at distance as the result of physico-chemical dispersion or biological migration).

Related terms: 37 Impact, Impact for the MSFD refers to adverse effects on the environment caused by pressures from human activities. CSWD (2020). A possible adverse change, influencing or affecting an environmental component, caused by a pressure related to one or more anthropogenic activities. ICES (2019b). Term 38 Effect, Human activities exert pressures which have effects which may lead to impacts on receptors. So, pressure and effect are always coupled so that every pressure has an effect, but not every pressure necessarily leads to an impact (Judd et al., 2015). Impact is also defined as: The change in an ecosystem receptor resulting from the application of a pressure (ICES, 2019a). An effect can be on the natural or human features of the ecosystem. Term 39 Adverse effect refers to Environmental impacts that need to be avoided or reduced to achieve or maintain GES (CSWD, 2020).

Linking activities, pressures and impacts: linking activities, pressures and impacts is an essential part of the MSFD (EC, 2008) and a crucial element of EBM. Numerous variants of the original DPSIR frameworks exist (Patrício et al., 2016; Smith et al., 2016) covering multi-space cycles, from the original simple P-S-R chains (e.g., as used by OECD, 2003 and required as a minimum by the MSFD) to tetrahedral DPSIR and addressing various issues or actions relevant to EBM. Two such examples include Ecosystem Goods and Services being directly linked to EBM (through EBM-DPSER: EBM-Driver-Pressure-State-Ecosystem Service-Response (Kelble et al., 2013) or the Ecosystem Services and Societal Benefits (ES&SB) linked-DPSIR approach (Atkins et al, 2011). A recent variant offering more clarity on aspects of the EBM cycle is DAPSI(W)R(M) (Drivers, Activities, Pressures, State change, Impacts on human Welfare, Responses by Measures). This framework explicitly refers to human activities and separates these from both drivers (i.e., basic human needs such as food, shelter, security, and goods) and pressures resulting from human activities (Elliott et al., 2017).

The EC is using the similar DAPSES-MMM (socio-economic Drivers, human Activities, Pressures, State of environment, Ecosystem Services – Management (policies and governance), Measures, Monitoring) (CSWD, 2020) framework for the MSFD linking not only activities pressures and impacts but also relating to the various EBM elements and selected articles of the MSFD (especially Article 8: Assessments; Article 11: Monitoring programmes; and Article 13: Programmes of measures). Whilst the ecosystem-based approach has several facets, its relevance in relation to the determination, assessment and achievement of GES in MSFD is focused as shown in Figure 8.

OSPAR (OSPAR, 2019) is using the DAPSIR (drivers, activities, pressures, state, impacts, response) framework. For the QSR 2023 a suite of Thematic Assessments is being produced describing human activities, pressures and biodiversity in the context of, an adapted from Elliot et al. (2017) and Judd and Lonsdale (2021), DAPSIR framework embodying all the components of the ecosystem approach. This framework incorporates the Bow tie analyses undertaken for risk management and is fully compatible with the DAPSES-MMM framework (OSPAR 2019). HELCOM is using the DAPSIM framework (drivers, activities, pressures, state, impact, measures) and its Spatial distribution of Pressures and Impacts Assessment (SPIA) addresses the cumulative burden on the environment caused by human activities in the Baltic Sea region (HELCOM, 2023). In addition, HELCOM is using the ACTION tool (Ahtiainen et al., 2021), which is a probabilistic tool to estimate the effectiveness of actions in reducing pressures (or improving directly the ecosystem) and ultimately leading to improved ecosystem state (and the agreed environmental policy targets). This way, sectorial outlook assessments were used to predict changes in human activities for a near future ("D"), reduced pressures were estimated on the basis of measure impacts ("R") on human activities exerting them ("P"), the reduced pressures improved the state ("S") or the measures improved this directly, the measures had costs for the society ("I").

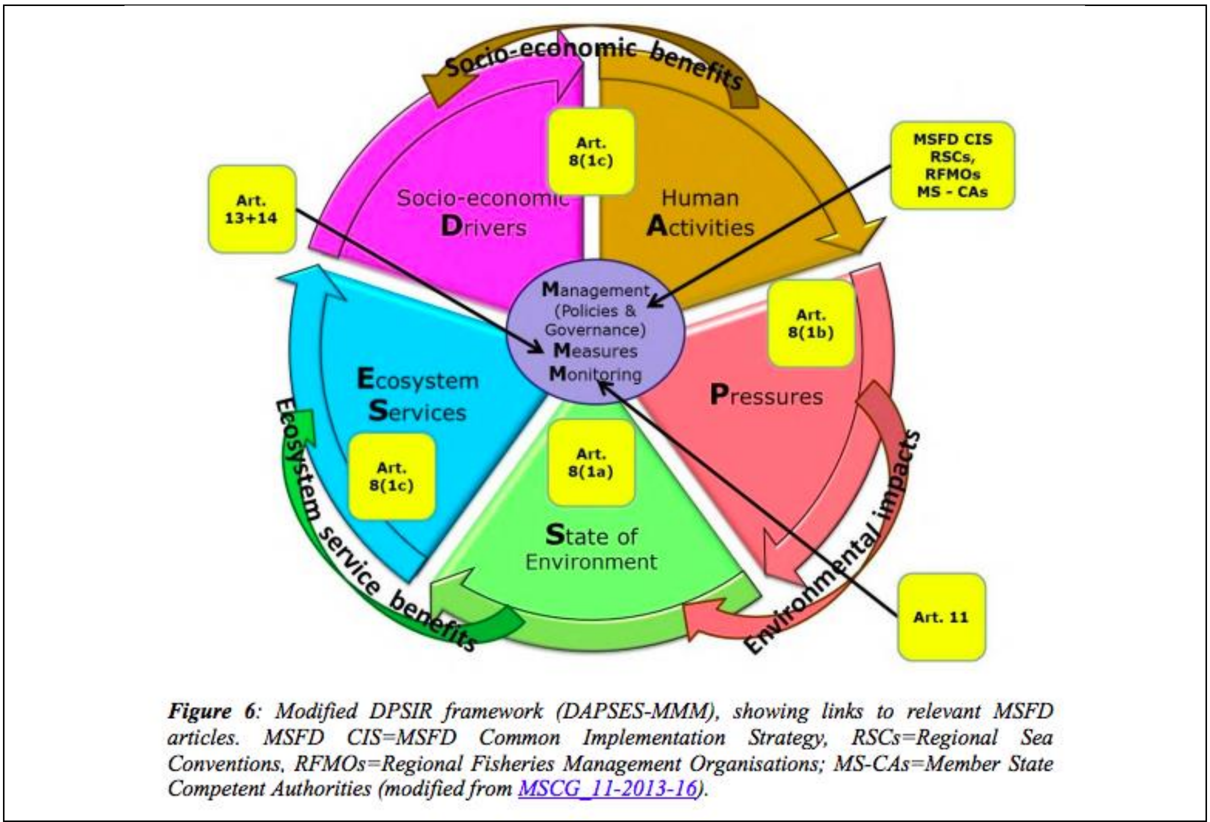


Figure 8. DAPSES-MMM framework used by European Commission for Marine Strategy Framework Directive purposes (from: CSWD, 2020)

All of these EBM approaches and related DPSIR derivatives (DAPSIWRM, DAPSES-MMM, DAPSISR and DAPSIM), aim to link activity/pressures (e.g., in single and cumulative assessments), to environmental impacts/effects (e.g., addressing key structures and functions and effects on selected species/habitats), and to adverse effects impairing the capacity of ecosystems to function properly (i.e. below GES) and deliver the ecosystem services linked to societal goods and benefits. Importantly these include human health and human survival and welfare and as such there is an urgent need to close the gap in assessing them and to quantify the relationship between compromised and degraded ecosystems and the delivery of services (EEA, 2019; Liquete et al., 2013a, b).

To track and assess the impacts of all the human activities on the ecosystem and its components use can be made of a linkage framework (Knights et al., 2015). The basic elements of the linkage framework are activities (note: sectors in the original, but conceptually closer to human activities) pressures and ecosystem components and how these are connected: activities can cause a range of pressures which, in turn, may impact one or more ecosystem components (Knights et al., 2013; Tamis et al., 2016; Piet et al., 2017). Knights et al. (2015) referred to this linear interaction between a "sector, pressure, and ecological component" (e.g., species or habitats) as an "impact chain".

Within the EU project ODEMM, impact chains were defined following an extensive review of the peer-reviewed scientific literature and published reports (Knights et al., 2013) resulting in a pre-pressure assessment matrix of 4,320 potential impact chains. Knights et al. (2015) identified and evaluated 3,347 sector – pressures linkages that can affect the ecological components of Europe's four regional seas noting that the number of impact chains varied between regions as a result of differences in the types of economic activities operating in each sea, the spatial extent of their operations (e.g. over a different range of habitats) and the type and number of pressures introduced.

In a following EU project AQUACROSS, Borgwardt et al. (2019) identified impact chains that link 45 human activities through 31 pressures to 82 ecosystem components. In this linkage framework >22,000 activity-pressure-ecosystem component interactions were found across seven European case studies (Borgwardt et al., 2019). Pedreschi et al. (2023) working in the Irish Sea have identified 1,592 impact chains while Paramana et al. (2023 submitted) working in the EU project ABIOMMED with 4 Mediterranean countries and 5 pressures linked to Descriptor 6 identified 1,680 impact chains linked to 24 activities and 14 habitats. These linkage frameworks go beyond the total risk as seen by the number of impact chains and working with 5 criteria and risk scores (see Table 13 in the following section) can inform on risk to specific ecosystem components (e.g., species groups or habitat types or bathymetric zones) by activity and pressure helping thus management measure prioritization. The framework is used by ICES (ICES, 2021a) to produce standardised comprehensive ecosystem overviews for the ICES areas using 3 criteria: spatial extent, and degree of impact with a slightly modified risk scoring (e.g., including future threats).

Sustaining the supply of ecosystem services requires understanding the activity-pressures-impacts chains and how these can lead to changes in the supply of services. A way to assess this is by assessing the total potential for ecosystem service (ES) supply by an ecosystem component (EC) based on EC-ES linkage matrices (working with expert judgement on presence-absence of a link and strength of a link) and the 'risk to ecosystem service supply' approach developed by the EU project Aquacross (Culhane et al., 2019b; Teixera et al., 2019).

The application of the linkage frameworks requires extensive expert judgement (especially when determining the sensitivity to impacts and the resilience/time to recovery to pre-impact conditions), and comparability between studies is not guaranteed as is dependent on the categorization of pressures and activities. Steps are taken however in the most recent applications (Pedreschi et al., 2023; Paramana et al., 2023 submitted) to refine and align the approach with the revised MSFD criteria and by using the MSFD elements and pressure lists (EU, 2017a, b). Other refinements are being made to reconcile the use of accurate geospatial data with expert knowledge (Piet et al., 2023a submitted).

Single MSFD Descriptors/single issues: this includes primarily assessments on major regional issues such as IAS, HABs, jellyfish blooms and eutrophication.

Invasive alien species (IAS) are non-native organisms that cause significant harm to the ecosystems they invade, their ecosystem services, and human health (Tsirintanis et al., 2022). These species can disrupt native ecosystems by outcompeting native species for resources, altering food chains, and degrading habitats. Invasive species can also cause economic and social damage by impacting fisheries and aquaculture, spreading diseases, and interfering with human activities such as recreation and tourism. In addition, invasive species can threaten biodiversity by causing the local extinction of native species, altering genetic diversity, and reducing the overall resilience of ecosystems. Overall, the impacts of invasive alien species can be severe and long-lasting, making their prevention and management critical for the health and well-being of both natural and human systems. The ecological and social impacts of IAS have been reviewed at the European level by Katsanevakis et al. (2014) and recently in the Mediterranean Sea by Tsirintanis et al. (2022). Horizon scanning can be conducted to identify emerging IAS, e.g., Tsiamis et al. (2020) developed a scoring tool that aims at identifying the most likely invasive species in European waters. Katsanevakis et al. (2016) developed a standardized, quantitative method for mapping cumulative impacts of invasive alien species on marine ecosystems, based on a conservative additive model; their model is called CIMPAL ('Cumulative IMPacts of invasive ALien species') and has been applied in the Mediterranean Sea (Katsanevakis et al., 2016), all European Seas (Korpinen et al., 2019; but also in the freshwater environment for all European catchments (Magliozzi et al., 2020).

Jellyfish blooms can have significant impacts on marine ecosystems, as well as on human activities such as fishing and tourism. When jellyfish populations increase rapidly and uncontrollably, they can consume large amounts of plankton and fish eggs, which can lead to a decline in fish populations and affect the entire food chain. Moreover, large blooms of jellyfish can clog fishing nets, damaging fishing equipment and reducing the catch. Jellyfish can also sting swimmers and beachgoers, which can lead to discomfort and allergic reactions. The economic impacts of jellyfish blooms can be substantial, particularly in areas where tourism and fisheries are important industries. Jellyfish is a key group for the evaluation of the ecological condition of marine waters, as it is considered as an indicator taxon for the health of marine ecosystems. Jellyfish have been proposed by OSPAR for inclusion in the indicator “Changes in Phytoplankton and Zooplankton Communities” that was used towards the assessments of pelagic habitats and food webs in the Intermediate Assessment of 2017 (OSPAR, 2017a). The Black Sea Commission includes a section on the “State of Gelatinous Plankton” within their “Chapter 1: State and Dynamics of The Black Sea Ecosystem” (BSC, 2019). Jellyfish blooms are attributed to several natural and anthropogenic causes. The latter were reviewed by Purcell et al. (2007), who examined cases where jellyfish blooms have increased and analyzed how several human activities may have contributed to that.

Harmful Algal Blooms (HABs) occur when certain species of algae grow rapidly, often producing toxins that can harm aquatic animals and humans. These blooms can have significant impacts on the environment, fisheries, and public health. For example, HABs can cause mass mortalities of many wild or farmed species (Hsia et al., 2006; Katsanevakis et al., 2014). HABs render coastal waters unsuitable for recreational activities due to health risks and may cause the temporary closure of beaches (e.g., Figgatt et al., 2017). HAB-related mucilage outbreaks may have serious impacts on maritime operations by clogging sea chest filters and causing overheating and damages to the main engine, generators, compressors, or the cooling systems, and increasing operational costs (Uflaz et al., 2021). Many HAB-causing species produce toxins, which accumulate in shellfish and other invertebrates and may then be transmitted to other commercial species through the food chain (Costa et al., 2009; Lage and Costa, 2013), and eventually to humans (Pérez Linares et al., 2009; Katsanevakis et al., 2014). Understanding the causes and effects of HABs is critical for managing and mitigating their impacts on aquatic ecosystems and human activities. So far, HABs are primarily managed as a public health problem (Food Hygiene Regulations (EC) No. 853/2004 and (EC) No. 854/2004) to address their toxicity hazards. Nevertheless, HABs are linked to various MSFD descriptors, such as Descriptor 1 - Biodiversity is maintained, Descriptor 4 - Elements of food webs ensure long-term abundance and reproduction, Descriptor 5 - Eutrophication is minimized, Descriptor 6 - The sea floor integrity ensures functioning of the ecosystem, and Descriptor 9 - Contaminants in seafood are below safe levels.

Guérin and Lizińska (2022), working for the NEA PANACEA EU project review MSFD Descriptor 6 (sea floor integrity) EU Member States assessments on physical disturbance and physical loss as well as comparing and linking methodological approaches (e.g. choice of indicators) used by the Regional Seas Conventions assessments. Due to the complex nature of Descriptor 6, they acknowledge the need for both single activity/single pressure and multiple activity/multiple pressures CEA under D6. HELCOM (2023) presents the thematic Baltic Sea assessments, the spatial maps of potential impacts of physical disturbance on sea floor (based on the 'CumI tool'), NIS and hazardous substances, the potential effect of continuous noise to mobile species and their habitats, and various single pressures maps and human activities distribution maps. Essentially the CumI tool is a spatial sea-floor specific CEA tool estimating potential cumulative impacts from physical pressures on benthic habitats (HELCOM, 2021), and not a full CEA (sensu Halpern et al., 2008).

The perhaps best assessed and mapped single issue is eutrophication, where HELCOM and OSPAR regularly have published indicator- and tool-based assessment (HEAT and OSPAR COMP; see EEA, 2019a for summary). Another single issue is contamination and indicator- and tool-based assessments (e.g., CHASE) have also been published regularly by HELCOM and OSPAR (see EEA, 2019b for summary.

Single species, ecosystem components state change: this includes assessments of single species status (e.g., under CFP for commercial species, under MSFD for descriptor D1 Biodiversity or D3 Commercial species) or assessments of a habitat (e.g., for reporting for HD or within an MPA or within a region) and looking at changes of status due to pressures.

Related GES4SEAS term 21: ecosystem components are constituent elements of an ecosystem, particularly its biological elements (species, habitats and their communities), or of marine waters (CSWD, 2020). An ecosystem component can also be defined as an attribute or set of attributes of the natural environment (Cooper, 2013). Alternative terms used may be valued ecosystem component (VEC), ecological component, receptor, indicator (Tamis et al., 2016). Ecosystem components should be comprehensive in the sense that they are expected to represent biodiversity and all its different life forms and should thus cover all the biota of the ecosystem. At the most basic structural level ecosystem components include species groups (e.g., birds, mammals) and habitat types including their pelagic and benthic biota (see EU, 2017a, for the MSFD groups of ecosystem components). Each of these may be split up into increasingly smaller ecosystem components depending on the aim of the assessment (e.g., MSFD, CEA), as identified in a scoping exercise (MacDonald, 2000; Therivel and Ross, 2007; Tamis et al., 2016). The likelihood of change of state of an ecosystem component when a pressure is applied can be referred to as sensitivity or effect potential, and is a function of the ability of that receptor to avoid interaction, tolerate or resist change (resistance), and/or its ability to recover from impact (resilience) (Tillin et al., 2010; Piet et al., 2023a submitted).

Threatened habitats and species: this includes documenting status and distributions of species and habitats at risk at global (e.g., O' Hara et al., 2019, for species; Gubbay et al., 2016, for habitats), regional (see OSPAR 2020 threatened habitats and species list and spatial dataset now available in EMODNET: https://emodnet.ec.europa.eu/en/ospar-threatened-andor-declining-habitats-spatial-dataset, the IUCN red list: https://www.iucnredlist.org/regions/europe) or local levels (Nebot-Colomer et al., 2021; Zotou et al., 2020).

Pressure and impact reduction/mitigation: this includes targeted and specific pressure and impact reduction or mitigation measures.

For example, for mitigating the impacts of IAS in the marine environment a variety of options have been proposed and assessed (Thresher and Kuris, 2004; Giakoumi et al., 2019). Management options ranked high by experts and stakeholders include physical removal, promotion of commercial exploitation, and environmental rehabilitation. On the other hand, biological control, with alien agents or genetically modified pathogens, generally ranked the lowest. The only two species for which large-scale control efforts in the EU have been implemented are the lionfish *Pterois miles* and the silver-cheeked toadfish *Lagocephalus sceleratus.* In Cyprus, to control the population of *L. sceleratus*, targeted, intense fishing pressure on the species by the coastal professional fleet has been promoted by a bounty (3 €/kg) since 2012; there is anecdotal information by fishers of effective reduction of its population and mitigation of its socio-economic impacts (A. Petrou, pers. comm). For the lionfish, physical removal methods have been extensively applied in the western Atlantic and the Mediterranean, based on culling by divers, often with public participation (e.g. by organizing lionfish tournaments), physical removals involving fishers, promoting the targeted fisheries of the species and human consumption (or other uses), developing specific fishing gear such as the 'Gittings' traps (Harris et al., 2020), and recently developing UW robots, which may harvest lionfish (Sutherland et al., 2017).

Other pressure and impact reduction methods include rebuilding fish stocks to Maximum Sustainable Yield levels (in line with CFP and EU SDG goals) and above to reduce negative impacts on marine ecosystems; increasing the selectivity of the fishing gears (e.g., with technical measures increasing the net mesh size, fitting escape panels or with various technical modifications and devices: Mytilineou et al., 2021, 2021; Squires et al., 2021) and implementing the landing obligation to reduce bycatch and unwanted catches contributing to the decline of marine resources and of protected species (Lucchetti et al. 2019; Fauconnet et al., 2023); improving the CFP governance, ensuring compliance with the obligations stemming from the EU environmental legislation and the Technical Measures Regulation and by Strengthening the ecosystem-based approach through better science taking into account the various types of human impacts and management systems on the use of natural resources and the marine environment, and, vice versa, the impacts of the state of natural resources on the fisheries sector (EC, 2023b). McConnaughey et al. (2020) review nine measures and industry actions under four classes: (i) *technical measures* (e.g., changes in gear design and operations), (ii) *spatial controls* (e.g. gear-specific prohibitions, freezing the trawling footprint, nearshore restrictions and coastal zoning, prohibitions by habitat type including real time (i.e. 'move-on rules') and multipurpose habitat management, (iii) *impact quotas* (i.e., output controls that include invertebrate bycatch or habitat-impact quotas) and (iv) *effort controls* that affect the overall amount and distribution of trawling. Based on this review they offer insights on best practices for managing impacts of trawl fishing on seabed habitats and biota. Area-based fisheries management measures ABFMs) can be related to the sustainable use of resources but are increasingly considered broader conservation measures and include the placement of Vulnerable Marine Ecosystems (VMEs) closures, fisheries closures, species-specific closures, fishing bans and conservation areas among others (Petza et al., 2023).

Inputs of contaminants, substances and of energy and litter may require pressure and impact reduction measures to levels that do not adversely affect the marine environment and are or remain in line with levels established by Union legislation or other relevant standards (EU, 2017a, Descriptors D8-D11). In the case of marine litter (descriptor D10) relevant measures include preventive measures by reducing the occurrence or reducing at source (e.g., production, waste management and recycling, establishment of port reception facilities, gear marking to tackle lost and discarded gears, EU policies such as the MSFD establishing threshold values for litter, the EU Single use plastics directive introducing several bans and restrictions on different uses and materials including for plastics and derelict fishing gear, the EU Green Deal and Zero pollution ambitions); mitigating measures through reducing debris disposal and dumping regulations; and curative measures to remove litter from the marine environment through clean up technologies and actions and fishing for litter campaigns (Gallo et al., 2018; Madricardo et al., 2020; Van Loon et al., 2020; Gilman et al., 2021). Various mitigation measures depending on affected species groups (e.g., mammals, birds or fish) and the phase of operation (e.g., construction, installation, operation, maintenance, decommissioning) are given in relation to type of impact (e.g., from noise, electromagnetic fields) and the offshore renewable energy generation sector by Soukissian et al. (2023).

As with marine litter, thresholds values are also introduced, through cooperation at Union level, for D6 Seafloor integrity restricting the extent of physical loss allowed but also the maximum allowed adverse effects from anthropogenic pressures on the condition of the habitat type, including alteration to its biotic and abiotic structure and its functions (e.g. its typical species composition and their relative abundance, absence of particularly sensitive or fragile species or species providing a key function, size structure of species) (EU, 2017a). These thresholds will require additional measures to attain GES including by reducing both the extent (e.g., by closures, exclusion zones, protected areas) and the severity of operations (to remain within the light impact categories by lighter operations or through stricter licensing) and will work in synergy with the EU Biodiversity Strategy and the proposed EU Nature restoration Law aims for both increased protection and restoration of degraded habitats. Pressure and impact criteria are set out in the MSFD conceptually linked to GES as an EBM to assessment of GES follows the main elements of the system: the state-based Descriptors (such as D1 Biodiversity and D6 Seafloor integrity) and the adverse effects of pressures from human activities via their environmental impacts (e.g., by the pressure-based descriptors such as D2 alien species, D6 seafloor integrity and D10 litter) (EC, 2022c; CSWD, 2020).

Spatial and other measures: this includes spatial and other measures related to the management response and management footprint. Well known spatial measures include the ban of trawling in the deep habitats in the Mediterranean (with a depth operations limit to 1000 m although the GFCM is currently discussing proposals to revise this to depths between 600-800 m depth) and the North East Atlantic (with a depth limit of trawl operations at 800); the ban of trawling within 3 nm- 1.5 nm distance from coast/shallower than 50 m depth and over protected habitats like *Posidonia oceanica* beds, coralligenous habitat, and maërl beds in Mediterranean (EU Mediterranean Regulation (EC) No 1967/2006); and various regional 'Fisheries Restricted Areas' (FRA) that aim to protect Essential Fish Habitats (EFH) and/or sensitive habitats of high ecological value, such as Vulnerable Marine Ecosystems (VME) such as the recent Jabuka/Pomo Pit FRA in the Adriatic with different measures implemented by one or both of the two main countries, Croatia and Italy (FAO, 2020). Giménez et al. (2020) build on a spatial planning approach with MARXAN to design a proactive area-based protection strategy towards elasmobranch conservation in the Western Mediterranean.

Various spatial measures and move on rules are implemented in the NEA and other regions to protect VMEs from fishing operations (e.g., as set out at the EU Regulation (EU) 2016/2336, the so-called the "Deep-sea Access Regulation" (DSAR); Auster et al., 2011; Geange et al., 2020; Walmsley et al., 2021). Various networks of MPAs (e.g. SPAMIs in the Mediterranean) and numerous national MPAs, marine reserves and local spatial closures (and temporal closures) also fall within this category aiming to protect species and habitats particularly important in terms of biodiversity or services and/or threatened/protected habitats and species (e.g. mammals and sea turtles; typically MPAs such as the international Sanctuary PELAGOS combine spatial measures with maritime speed limitations for passing vessels, https://www.sanctuaire-pelagos.org/en/). Other spatial measures are related to licensing and restricting the footprint of certain human activities for example by designating areas for offshore wind farm development, for aquaculture development, for aggregate extraction (e.g., the Belgian MSP at the EU MSP platform at https://maritime-spatial-planning.ec.europa.eu/countries/belgium, and the EMODNET portal of Human activities https://emodnet.ec.europa.eu/en/human-activities). The effectiveness of these protected areas is as important as their extension (Arneth et al., 2023) and currently no-take areas or highly protected areas cover very small areas of European regional seas, such as the Mediterranean (Claudet et al., 2020).

Related GES4SEAS Terms for both EBM elements, Term 51 Response (using management Measures): Using management measures (ecology/environment, technological, economic, societal behaviour, governance (politics/policies, administration, legislation), culture, ethics/morals and communication, using stakeholders) as ways of influencing the Drivers and controlling the activities and pressures as the causes of change in order to prevent the consequences of state changes and impacts on welfare; to respond to both the exogenic and endogenic causes and consequences. Elliott et al. (2017, 2022a). Term 52 Management Response Footprint: The area and time covered by the governance means of monitoring, assessing and controlling the causes and consequences involved in the use of the marine environment through public policymaking, marine planning and regulatory processes. The policies, marine plans and technical measures produced by these processes indicate the means of determining if legal controls are satisfied, and of providing information and data to national and supra-national bodies. They focus on the area and/or time covered by the marine management actions and measures (e.g., programme of measures), including the distribution and range of a species (Elliott et al., 2022a), Term 54 Programme of Measures (PoMs): PoMs which need to be taken by Member States in order to achieve or maintain GES. These include input controls, output controls, spatial and distribution controls, measures to improve traceability, economic incentives, mitigation and remediation tools, communication, stakeholder involvement and raising public awareness (EC, 2008). Gorjanc et al. (2020, 2022) review the Mediterranean MS PoMS (e.g., the types of meaures they include) and their contributions to GES while Murillas-Maza et al. (2022) propose a methodology to assess the effectiveness of PoMs.

Climate change: is relevant to EBM to both planning mitigation and adaptation actions and evaluation phases from both a managers' and a scientists' point of view. Modelling tools can address changes in species distributions due to climatic effects (e.g., Fabbrizzi et al., 2023; Antão et al., 2020; Hodapp et al., 2023; Pennino et al., 2020) and these insights are relevant to the planning phase to conservation spatial planning and restoration prioritization. For the evaluation and assessment phase it would be useful to know whether the outcome of the evaluation is affected by (an unmanageable exogenic P like) climate change as well as the trajectory of change. Recent works investigate the combined effects of climate change and other human pressures (Gissi et al., 2021; Korpinen et al., 2021; Vilas et al., 2021).

Doxa et al. (2022) developed a depth-specific prioritization analysis to inform the design of networks of protected areas, further including metrics of climate-driven changes in the ocean (planning phase). Climate change was captured in this analysis by considering the projected future distribution of >2000 benthic and pelagic species inhabiting the Mediterranean Sea, combined with climatic stability and heterogeneity metrics of the seascape to identify climatic refugia.

Uncertainty: uncertainty applies to all PACE phases in that the managers prefer to get advice that includes uncertainty/confidence both in terms of consequences of planning scenarios or management plans and in assessment outcomes. However not all tools address the issue; some examples are given in the tools' narratives section (5.3. below).

Risks: different tools address different aspects of risk. This includes risk from action or inaction (see below Bow-Tie section), risks to ecosystem components due to spatial overlap with activities and pressures (e.g., EU ODEMM and AQUACROSS projects approaches, see Table 13 below), risks related to specific biotic effects (e.g., sex related fishing impacts or fishing impacts on nesting or nursery areas; UNEP-MAP-RAC/SPA 2010; Ogburn, 2019). Some examples can be seen in the tools' narratives section (5.3. below).

Other Policy Requirements e.g., MSPD, BHD, Biodiversity Strategy: different tools will address different policy needs, e.g., MARXAN and HSM will be providing outputs relevant for the MSPD or the Biodiversity Strategy and the proposed EU Nature Restoration Law (Michelli et al., 2013b; Korpinen et al., 2021; Fabbrizzi et al., 2022) while threatened species and habitats assessments will support the BHD or the needs of RSC (e.g., OSPAR, HELCOM). Food web models can support the assessment of nutrient reduction policies (Piroddi et al., 2021).

5.3. Narrative of the tools

Following the procedure noted above (section 5.1), the group identified and chose the methodological approaches/tool groups shown in Table 4. For each of the 19 tools (Table 5) a tool narrative was built following a concise template format (see Table 6) and given for each tool below in Tables 7-25.

Table 5. Methodologies/tool groups
Conceptual models
Semi-quantitative mental models - Fuzzy Cognitive Mapping
Knowledge Graph
BBN probabilistic
Risk based approaches exposure-effect-hazard-vulnerability (e.g., Bow-Tie)
Cumulative impact spatial mapping (Halpern et al., 2008)
Impact risk ranking through linkage-chain-frameworks (e.g., ODEMM)
Single spp. model (life cycle, stock assessment)
Biogeochemical models
Food web models (e.g., multispecies models, EWE)
Ecosystem models (e.g., End2End)
HSM models (spp. predictive distribution)
Natural capital accounting, ecosystem services valuation
Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation
Spatial planning models (e.g., GIS, VAPEM, related to use)
Conservation planning models (e.g., MARXAN)
Simple assessment index (e.g., M-AMBI)
Descriptor or theme-specific combination of indices and models (e.g., HEAT, BEAT and CHASE)
Overarching assessment tools (e.g., NEAT and OHI)

Table 6. Tool narrative template
A. Description of the methodological approach:
• What it is: name, concept • What it does: how is the tool used • About the tool: software, ready-made, free, purchased
B. Application of the tool:
• How can it be useful towards environmental assessments: in what way can it be applied to environmental assessments • What has it been used for: any examples of how it has been used, type of assessment it has been used for and, to what level
C. Tool requirements:

- Data: what are the data requirements – briefly, kind of data, numerical, measurements, mix or other, any background data (e.g., linkage tables, sensitivity scores)
- Rich/poor data/skills needs

D. Key example References or Resources

- Some key references either on the methodology or an application
- screenshot/figure from publication/application

Table 7. Conceptual models (including argument mapping, mind-mapping, horrendograms, organograms, etc)

A. Description of the methodological approach:

EBM relies on an ability to structure the analysis of the ecosystem in relation to the ecological, cultural and social systems that drive governance and management processes to ultimately gain a better understanding of their interplay. Addressing any problem should start by creating an actual or virtual conceptual model (analogous to argument mapping, mind mapping, horrendograms and organograms) which are graphical representations and as such, they are used extensively for defining, interrogating and communicating cause, consequence and response sequences (see below an example schematic of a horrendogram by Elliott et al., 2014. They are of particular value in representing the continuum from ecosystem physical and chemical attributes to ecological structure and functioning, to ecosystem services flow and to societal goods and benefits provision; they can include the pathways whereby each of these elements get degraded and recovered through human actions. Hence, they show components, processes, and linkages that form a social–ecological system.

Their use encompasses the following definitions: a system is a set of things working together as parts of a mechanism or an interconnecting network; a set of principles or procedures according to which something is done; an organized scheme or method. A process is a series of actions or steps taken in order to achieve a particular end. Management is the process of dealing with or controlling things or people, and governance is the action or manner of governing through authority, decision-making and accountability.

The term framework is used as a basic structure underlying a system, concept, or text and approaches can be separated into frameworks, theories and models – hence EBM requires a framework that aims to identify the necessary components and the links between them prior to analysing, interrogating and then using the framework. This also allows the questions and hypotheses in sustainable resource management to be defined and addressed (see Elliott et al., 2020b for a discussion of systems analysis).

Systems analysis relies heavily on diagrams to show the complexity of the natural and human systems and its management; this could be taken further as there are possible mapping approaches of the system to represent system elements and connections, e.g.: Actor maps – covering which individuals and/or organizations are key players in the space and how they are connected; Mind-maps – which highlight various trends in the external environment that influence issues; Issue maps – covering the political, social, or economic issues affecting a given geography or constituency (often used by advocacy groups), and Causal-loop diagrams – interrogating the feedback loops (positive and negative) that lead to system behaviour or functioning.

Mind-mapping or conceptual models are regarded as an integral part of summarizing complex relationships within a system, what social scientists may call 'wicked problems' (Rittel & Webber, 1973). They aim to present graphically (visually) the main components (nodes) of a system, the pathways (vectors) linking those components and thus the nature of changes in one part of the system having repercussions for other parts of the system. While these are often qualitative diagrams, they form the basis of a quantitative assessment and thus future mathematical descriptions and predictive models; for example, conceptual models combined with Bayesian Belief Network Modelling can create descriptive and predictive systems. The boxes or nodes in a model may be regarded as the structural elements whereas the arrows (vectors) connecting these are functioning (rate processes) or cause-and-effect relationships.

Owing to their inevitable complexity they have often been referred to as 'horrendograms' which may be regarded as being of greater value for the constructor than the reader (e.g., see example below, schematic from Elliott et al., 2014). It is often more illustrative to present individual parts to the reader than to present the whole, for example to create a composite diagram showing all features and hence the complexity, but then deconstruct this in order to discuss, explain and tackle the individual parts. As a related technique, the use of 'Rich Pictures', a branch of Soft System Methodology (Avison et al., 1992), is increasingly used both as a tool for communicating complex ideas to stakeholders and the public but also for determining, interrogating and summarizing those ideas in a pictorial/semi-pictorial form. Similarly, there is an increasing amount of software to allow complex problem visualization leading to solving a problem, for example bCisive (http://bcisive.austhink.com/).

Argument mapping is a method of producing a diagram of an argument, in the form of reasoning, inferences, debates or cases. Pictures and diagrams (infographics) are thought to be a clearer way to illustrate and understand complex themes, and Davies (2010) gives a summary of research and development into the visual representation of information, while Farnham Street (2019) focusses on mind mapping and conceptual mapping across the natural and social sciences. There are various systems of mapping, such as concept mapping, mind mapping and argument mapping, which are sometimes used interchangeably but which Davies (2010) differentiates between; argument mapping allows the display of inferential connections and evaluation of the structure and basis of the argument.

B. Application of the tool:

Conceptual models are usually created merely using drawing packages (in WORD or Powerpoint) although there are more sophisticated techniques. Various software packages are available for computer-aided argument mapping (CAAM), e.g., KUMU (https://kumu.io/). See below example schematic using software Rational (after Davies, 2010) demonstrating the structure of an argument map; at the top, there is a contention, followed by a supporting claim and an objection. Further claims, objections and rebuttals follow these, and the terminal boxes require evidence.

A further example (below) of argument mapping is using the software bCisive™ to keep track of arguments used in environmental case-making. It allows all the threads of a case to be tracked and provides an audit-trail for any environmental position adopted in the power station planning process of how it has been used, type of assessment it has been used for and, to what level.

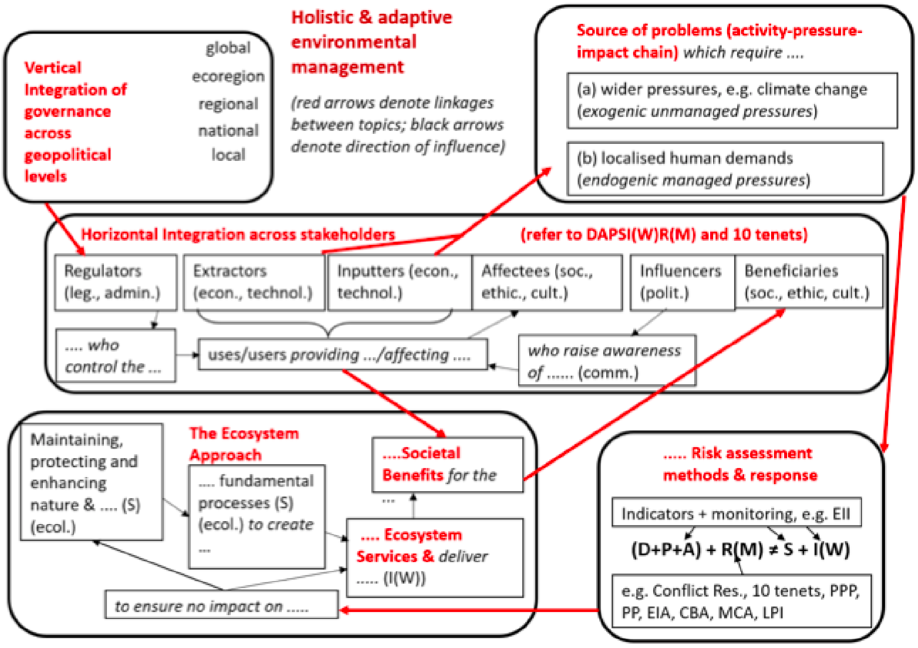
C. Tool requirements:

- The data requirements are low in preparing the conceptual models but they require either a high individual or collective knowledge. They can address single chains of cause-consequence-response or they can address cumulative effects/impacts. They do not explicitly consider uncertainty (potentially giving a false sense of precision). They either do not produce spatially-dependent outputs or temporal trends or at least give these in general terms for a particular area. They can be designed to apply both to data rich/skill rich and data poor/skills poor areas.

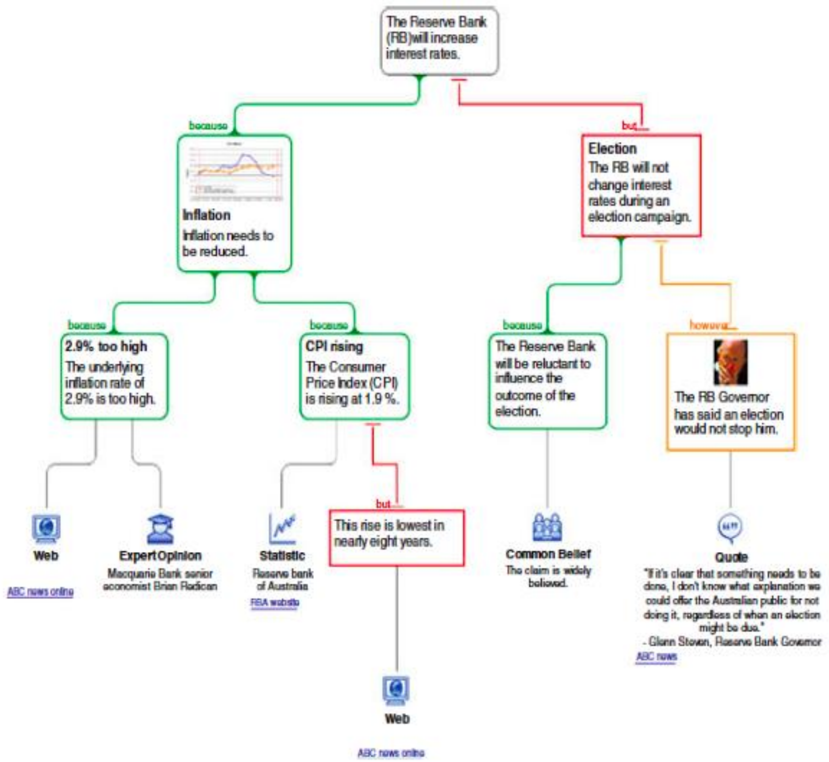
D. Key example References or Resources

- Avison et al., 1992; Broszeit et al., 2019; Davies, 2010; DePiper et al., 2021.; Elliott, 2012, 2014; Farnham Street, 2019; Gray and Elliott, 2009; McLusky and Elliott, 2004; Twardy, 2003.

- Example of a horrendogram for integrated marine governance (from Elliott, 2014):



- Example of an Argument map using software Rationale (Davies, 2010):



- Example of a bCisive™ Argument map for consideration of entrainment impacts caused by cooling water abstraction:

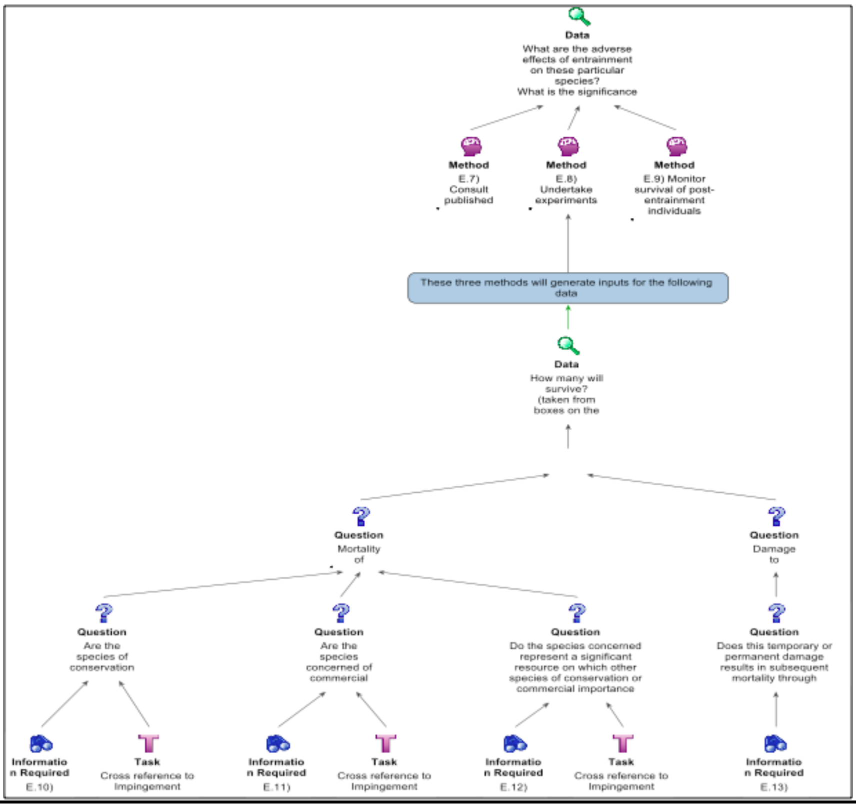


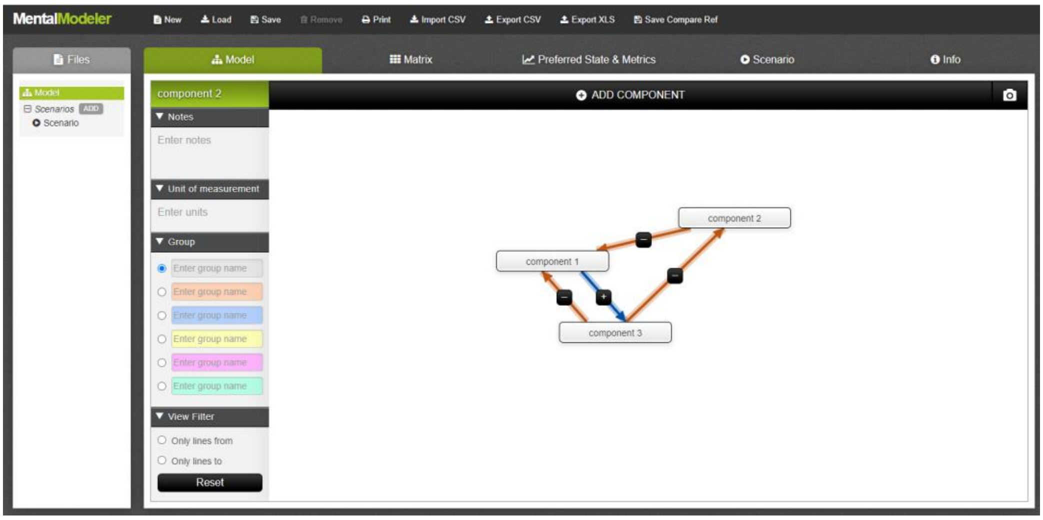
Table 8. Semi-quantitative mental models – Fuzzy Cognitive mapping
A. Description of the methodological approach:
Mental models are another name for a conceptual model (see above for conceptual models). Both consist of a graphical representation of a system (e.g., natural ecosystem, socio-economic system, socio-ecological system). Because these systems are so complex, these models reflect simplifications that can be useful for improving common understanding and communication tool, particularly when working with stakeholders, helping to identify common understanding, goals and objectives, and highlighting differences in perspective, values and priorities. The main difference with this approach is that linkages are not just documented, but the direction and strength of interaction should be specified, allowing for simple scenario investigation. Perhaps the most used Fuzzy Cognitive Mapping (FCM) tool is Mental Modeler (Gray et al., 2012, 2013a, 2013b) which is freely available at: https://www.mentalmodeler.com/ (with registration). Another type of qualitative mathematical model in this category would be the sign-directed graph model (Dambacher et al., 2009 and 2015).
B. Application of the tool:
As outlined for conceptual models, this process can be extremely useful for identifying what elements are relevant/should be included/prioritised in an otherwise extremely complex system. It highlights which elements are related to each other, and how they are connected. It is an incredibly useful first step in processes such as Integrated Ecosystem Assessments, where it can be useful to identify key questions to be answered by such an assessment, and to build up the socio-economic understanding around the identified ecological issues.
C. Tool requirements:
There are no data requirements. This extremely adaptable tool can be built by an individual or a group, and completely sourced from their innate knowledge, similarly, what

results will be influenced by who contributes, and limited by their knowledge (although data can be used to inform decisions if/when relevant). It can also be used to enhance understanding around a specific issue (e.g., core elements can be specified a priori) and for a range of uses, purposes and potential outcomes (see WKCCMM report; ICES 2022b). They are limited in the outputs (e.g., if scenarios are investigated), and it does not allow self-looping, nor calculate uncertainty. Thus, FCM represents knowledge by defining three characteristics of a system: the components of the system, the positive or negative relationships between the components, and the degree of influence that one component can have on another, defined using qualitative weightings (e.g., high, medium, or low influence).

Almost no skills are needed to operate the tool – it is a simple click and place interface which can be quickly mastered in an afternoon. However, skills are needed to facilitate discussion, manage group interactions, and focus the exercise on the task at hand (including keeping the model manageable!). Additionally, outcomes rely on the level of expert judgement or data available to quantify relationships (see Lazăr et al. 2018).

D. Key example References or Resources

- Gray et al., 2012, 2013a, b; ICES, 2020, 2022; Lazar et al., 2018
- Mental Modeler, the user interface:



- A mental model (FCM) example from WKIRISH (ICES, 2020b):

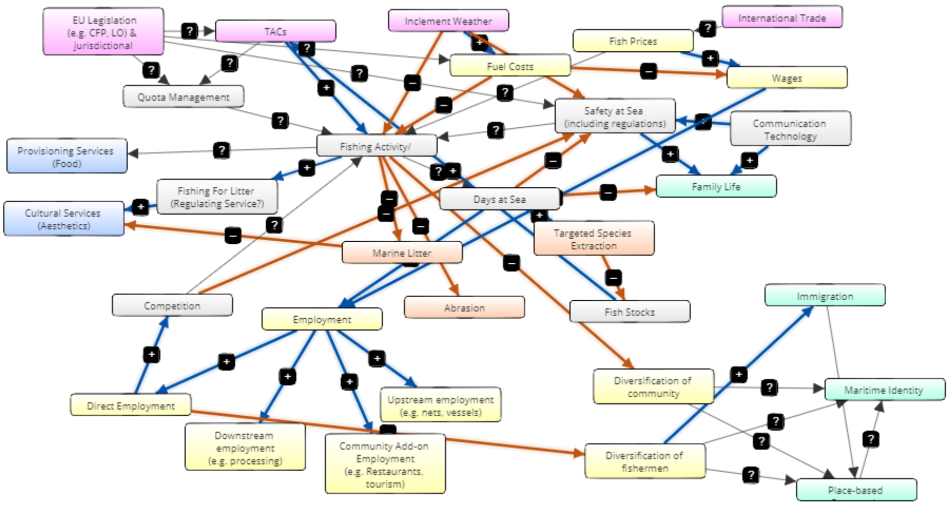


Table 9. Knowledge Graph
A. Description of the methodological approach:
Knowledge graph: A knowledge graph is a structured representation of knowledge that encapsulates information on entities, their attributes, and the relationships between them. It consists of 'nodes' (representing entities) and 'edges' (representing the relationships between them), and can be visualized as a network or a graph. It is a type of information source that is used by search engines and other applications to provide more relevant and accurate information to users. A knowledge graph might be usefully viewed as a combination of a graphical network diagram, allied to a database providing information on each of the nodes and links. Knowledge graphs are useful in a variety of applications (e.g., search engines, recommendation systems, virtual assistants). By capturing the relationships between entities, knowledge graphs can provide a more comprehensive understanding of a topic, and enable more sophisticated reasoning and decision-making. There are many options for software to develop and apply a Knowledge Graph approach – e.g., Neo4j, TigerGraph, GraphDB – with a variety of subscription levels (and costs) dependent on the user's specific needs.
B. Application of the tool:
A causal loop network (CLN) is a type of system dynamics model that represents the feedback loops and causal relationships between variables in a complex system, and a CLN-based approach is often used to understand the behaviour of complex systems (e.g., social, economic, or environmental systems). A knowledge graph can be used to represent the entities and relationships within a system, including the variables and feedback loops that are modelled as part of a causal loop network (CLN). Hence, by representing the knowledge about the system in a structured and standardized format, a knowledge graph can facilitate the development of a CLN by providing a clear and comprehensive view of the system's components and relationships. For example, a knowledge graph could be used to represent the entities and relationships in a cause-effect-consequence chain, such as the causal links between human Activities, the resulting Pressures that are generated and that cause State changes in the environmental system and consequential Impacts (on societal welfare) – i.e. an A-P-S-I(W) chain. Such a knowledge graph could then be used to develop a detailed CLN model representing the feedback loops and causal relationships between these entities, facilitating analysis of the system's behaviour under different scenarios.

Knowledge graphs are commonly used across a variety of IT system applications, including internet search engines, recommendation systems, chatbots, and virtual assistants. By capturing the relationships between entities, knowledge graphs can provide a comprehensive understanding of a topic, and so enable more sophisticated reasoning and decision-making.

The knowledge graph approach is primarily a means of organising and presenting information, and is not a statistical model per se. In this sense, whilst a knowledge graph approach may provide valuable insights into an environmental system's behaviour (for example, supporting a CLN analysis), it does not represent a means by which a parameterised analytical or predictive model of aspects of the system might be developed.

Knowledge graphs have been used in environmental science for data integration, biodiversity assessment, and environmental monitoring (Page 2016; Babalou et al., 2022). Knowledge graphs can provide a powerful tool for organizing and integrating diverse environmental data sources, enabling more comprehensive analysis and understanding of complex environmental systems, but are not applicable as parameterised analytical or predictive models

C. Tool requirements:

A knowledge graph application is, by its nature, data-rich and therefore places a considerable demand on data availability. However, the knowledge graph approach is able to accommodate a wide variety and combination of data types (quantitative numerical, qualitative, graphical) that apply to each of the entities (nodes) that make up its structure.

D. Key example References or Resources

- Page, 2016; Penev et al., 2019; Sachs et al., 2019; Babalou et al., 2022
- Example: Knowledge graph OpenBiodiv: A Knowledge Graph for Literature-Extracted Linked Open Data in Biodiversity Science from Penev et al., 2019:

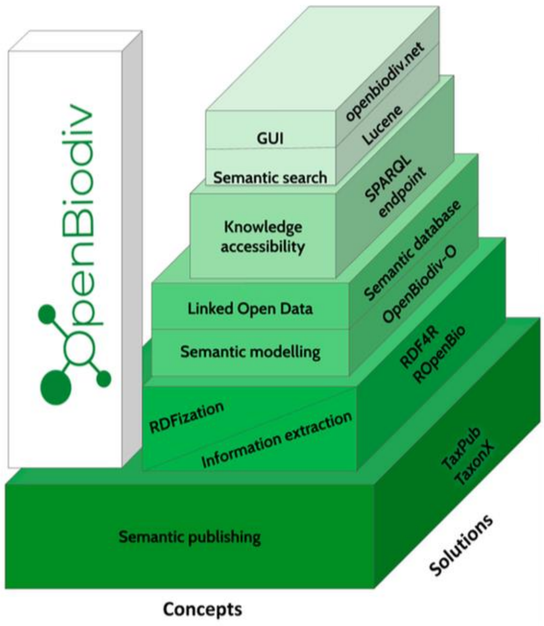


Figure 1. Architectural model of OpenBiodiv.

Table 10. Bayesian belief networks

A. Description of the methodological approach:

Bayesian Belief Networks (BBNs) are models that graphically and probabilistically represent correlative and causal relationships among variables and which account for uncertainty (McCann et al. 2006). Hence, BBNs are based on two structural model components: (1) a directed acyclic graph (DAG) that denotes dependencies and independencies between the model's variables (referred to as nodes); and (2) conditional probability tables or distributions (CPTs/CPDs) denoting the strengths of the links in the graph. The DAG consists of a structured set of variables or nodes that represent the modeled system. Directed arrows that are often designed to represent cause effect relations between the system's variables indicate the statistical dependencies between the different nodes. Each arrow starts in a parent node and ends in a child node. The absence of a link between two variables indicates statistical independence between them. The graph is acyclic and therefore no feedback paths from child nodes to parent nodes exist. The DAG can be developed by experts and based on system understanding or can be learned by empirical observation. The resulting BN structure forms the basis for developing operational BNs. Each node has a probability distribution that encodes the current belief in its state; i.e., it shows the uncertainty there is about the value of the variable. The probability distribution can be either continuous or discrete, consisting of several mutually exclusive states, which each have a certain probability of occurrence. Since they denote a probability distribution, the sum of state values makes a total of 1. BBNs allow for the integration of different data types and are a valuable tool for modelling complex systems with many uncertain variables (Marcot and Penman, 2019; McCann et al., 2006). BBNs are probabilistic models that are defined in relation to the problems or question at hand. There are commercial software products like Netica (www.norsys.com), HugIn (www.hugin.com) or GeNIe (https://www.bayesfusion.com/genie/) as well as numerous R libraries such as e.g., bnlearn (www.bnlearn.com).
B. Application of the tool:
BBNs have been successfully applied to natural resource management to address environmental management problems and to assess the impact of alternative management measures (Marcot et al., 2019; Coccoli et al., 2018). Thus, BBNs can be used for probabilistic scenario analysis (Hosack et al., 2008; Coll et al., 2019; Kaikkonen et al., 2021; Pihlajamäki et al., 2020). One of their strengths lies in their ability to transparently integrate different types of data sources such as expert judgement, data, or modelling results (Uusitalo, 2007) and even encode expert knowledge into numeric form (Uusitalo et al., 2005). This allows the development of BBN models even in data-poor cases if theoretical understanding of the phenomenon exists. Marine BBN applications have primarily addressed the assessment of alternative management options and choices (Naranjo-Madrigal et al., 2015; van Putten et al., 2013; Rambo et al., 2022) or the risk of not achieving management targets (Stelzenmüller et al., 2010; Stelzenmüller et al., 2011; Bastardie and Brown, 2021). More recently BBNs have been used to integrate complex models into a decision-support system in the context of evaluation of the attainment of different MSFD goals (eutrophication, Descriptor 5, and fisheries, Descriptor 3) under different scenarios (Uusitalo et al., 2022) or to identify suitable areas for offshore wave energy farms, in the framework of ecosystem approach to marine spatial planning (Maldonado et al., 2022). BBN can easily integrate new knowledge as new evidence becomes available (belief updating) allowing for an evaluation of existing management measures and their adaptations (McCann et al., 2006).
C. Tool requirements:
One of the strengths of BBN lies in their ability to transparently integrate different types of data sources such as expert judgement, data, or modelling results (Uusitalo, 2007) and even encode expert knowledge into numeric form (Uusitalo et al., 2005), and different data qualities, as long as there are reasonable estimates of the related uncertainties. BNs can be built based on rich data alone, or scarce data together with domain knowledge. This allows the development of

BBN models even in data-poor cases if theoretical understanding of the phenomenon exists. As described above, the quantitative information is expressed in the form of (conditional) probability distributions, reflecting the current level of knowledge about the state of the variable under each set of conditions. Acquiring this uncertainty information may be tricky, but there are possible ways of doing it (Uusitalo et al., 2015).

The available commercial BBN packages are easy to use and require only moderate skills to use. Building BBN models that are theoretically solid and describe the phenomenon in the intended way requires some theoretical understanding on BBN modelling.

D. Key example References or Resources

- Bastardie and Brown, 2021; Kaikkonen et al., 2021; Marcot and Penman, 2019; McCann et al., 2006; Naranjo-Madrigal et al., 2015; Pihlajamäki et al., 2020; Rambo et al., 2022; Stelzenmüller et al., 2010, 2011; Uusitalo, 2007; Uusitalo et al., 2005, 2015, 2022; van Putten et al., 2013.
- Example of BBN illustration taken from Rambo et al., 2022:

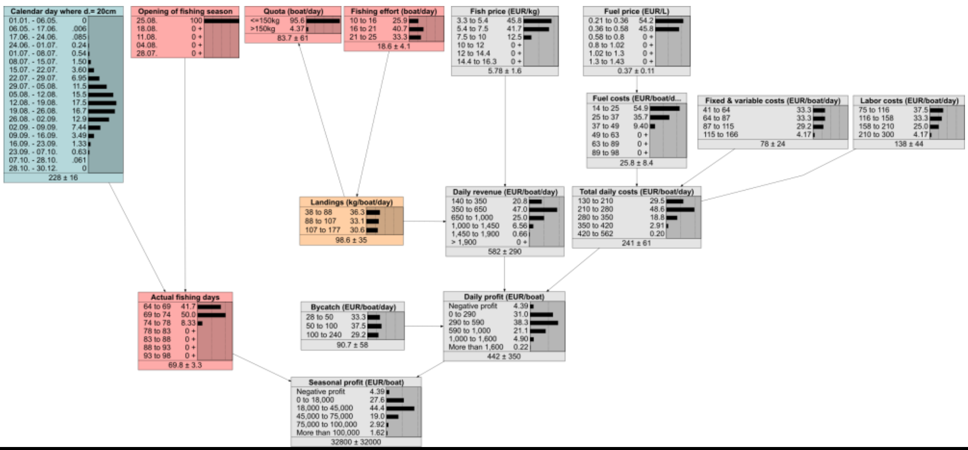


Table 11. Risk based approaches exposure-effect-hazard-vulnerability (e.g., Bow-Tie)

A. Description of the methodological approach:

Seas and coasts are subject to and may contribute to many hazards, each of which has causes and consequences. In essence, hazards may occur either naturally or by human actions and they become risks when they adversely affect something valued by humans such as health, welfare or property; in some cases, human responses to one hazard may make the consequences even more severe. Hazard is the cause of an adverse effect compared to risk which in contrast is the probability of effect (i.e., the likely consequences) potentially leading to even more severe consequences to humans. Natural risk can be defined as the damage expected from an actual or hypothetical scenario triggered by phenomena or events following natural events (Smith and Petley, 2009). Hazards may be natural or anthropogenic (Elliott et al., 2019) and require to be tackled using a rigorous approach covering technological, governance and economic approaches.

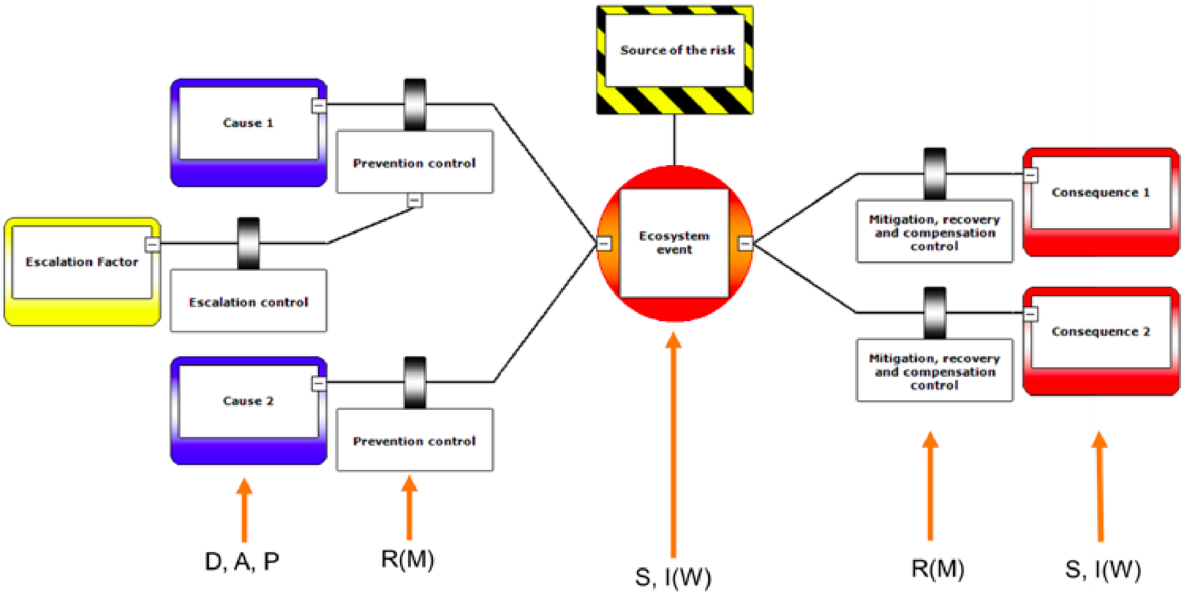
Bow-Tie diagrams (examples 1-3 below) are a visual tool describing and analysing the pathways of a risk, from hazards to outcomes and reviewing controls (preventative and mitigation/compensation methods, the so-called Programmes of Measures). The approach shows the causes of a problem (to the left of the knot of a Bow-Tie), the hazard and element of main concern (the knot of a Bow-Tie) and the consequences of a hazard happening (to the right of the knot). Various controls can be placed on the left of the hazard to prevent the hazard from occurring, or on the right to reduce/mitigate/compensate for the magnitude of any consequences.

Bow-Tie is an analytical approach for risk assessment and management, which can be adapted for opportunity assessment and management (see Cormier et al., 2019; Elliott et al.,

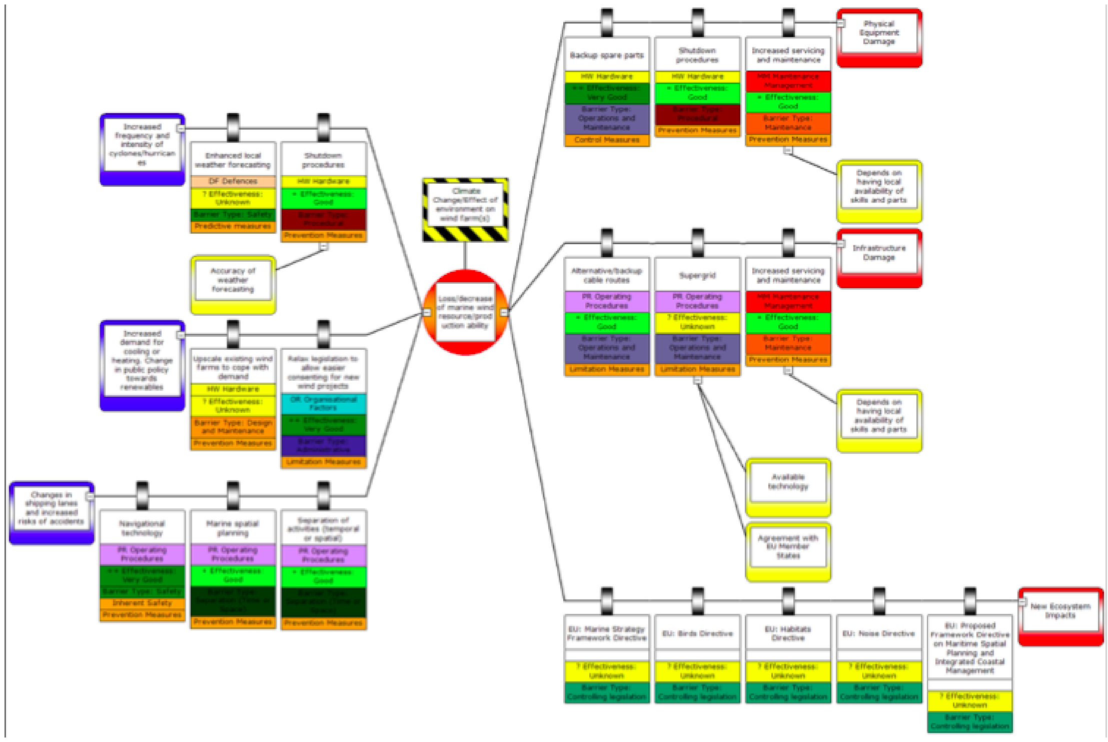
2020b). It is an industry-standard ISO-31000 compliant method for producing conceptual models. It addresses a risk or problem and indicates the causes of that problem, ways to mitigate and prevent these causes, and then consequences that occur because of the problem, and again, ways to prevent or mitigate the consequences. The central knot of the Bow-Tie represents a particular risk (e.g., loss of profits for a specific fishery due to climate change). The left side lists pathways of potential causes (Figure 1 – generic model) whereas the right-side lists consequences (and even opportunities) resulting from the event. Controls (as prevention in a Programme of Measures) are positioned along the pathways of risks on the left (solutions to prevent the central event) and, on the right are placed, other aspects of the Programme of Measures involving mitigation/compensation and recovery from the central event. Escalation factors which undermine or enhance the effectiveness of a given control, can also be added with additional barriers. Hence, the scheme accommodates uncertainty in risk management. The performance of a management control in managing or reducing these uncertainties relies on a suite of barriers that eliminate, avoid, or control the likelihood of a given risk to occur or mitigate or recover from the consequences of a given risk. Barriers implemented closest to the sources of the risk provide the greatest assurance in reducing uncertainty in achieving objectives. At the same time, determining the prevention or response to risk, allows the opportunities to be defined for the sector in question to successfully accommodate impacts and enhance growth. A key advantage of this method is that the Bow-Tie concept visualises the risks being considered in one, clear and easy to read picture (see examples 1-3 below). Shaped like a bow tie, the diagram creates a clear differentiation between preventative and mitigation/compensation/adaptation measures – effectively ways to prevent an event from happening, and if it does, ways to mitigate any effects; the latter step will also include any compensation, adaptation and control measures. The power of a Bow-Tie analysis is that it shows a summary of numerous risk scenarios, in a single, easy to follow picture that can be understood by all levels of an organisation, as well as the general public. In short, it provides a simple, visual explanation of a risk that would be much more difficult to explain otherwise.
B. Application of the tool:
Risk assessment and risk management techniques (for example using the ISO standard Bow-Tie analysis) such as IEC/ISO 31010 (IEC/ISO, 2009) are fundamental to industrial and commercial applications and have only since 2010 been applied to environmental challenges. The environmental manager will be responsible for carrying out operational controls to reach operational outcomes which in turn are required for fulfilling the management objectives and the higher national and international development goals (see diagrams in Cormier et al., 2019). The risk assessment technique of the ISO 31000 risk management standard (ISO, 2018) is an efficient method well-suited to this role. Here it is emphasised the value to marine environmental managers of the risk management process of ISO 31000 given that an analysis of the measures and actions is needed both to reduce the risks and horizontally to integrate operational controls and conservation measures. Bow-Tie analysis has been used in many industrial applications and recently used in relation to fisheries and aquaculture (Elliott et al., 2020b) and offshore windfarms (Burdon et al., 2018).
C. Tool requirements:
Bow-Tie analysis can be carried out either using proprietary software (see Bow-Tie XP and Bow-Tie Master in references, examples 1 and 2) or using a simple WORD drawing or Powerpoint technique; the latter was used as a stakeholder-led process in the CERES project (see Elliott et al., 2020b, example 3). In the latter, generic conceptual models were generated which were then made case-specific using stakeholder engagement.
D. Key example References or Resources
• Bowtie Master –

https://bowtiemaster.com/?gclid=CjwKCAjwitShBhA6EiwAq3RqA8SiNmfBeYGxchMPGzXZhSWK2iAmqBlZtIfHCbTJFZGmbjznRSkpDBoCRFgQAvD_BwE

- Bow-Tie XP - https://www.wolterskluwer.com/en-gb/solutions/enablon/bowtie/bowtiexp
- Burdon et al., 2018; Camposet al., 2015; Cormier et al., 2013 (eds); Cormier et al., 2015, 2019; Elliott et al., 2014, 2019, 2020; IEC/ISO, 2009; ISO, 2018; Smith and Petley, 2009.
- www.decisionsciences.org/decisionline/vol30/30_3/pom30_3.pd
- www.iso14000-iso14001-environmental-management.com/
- Example 1: Simplified Bow-Tie with DAPSI(W)R(M) overlain – to determine causes and consequences and to agree the responses throughout the sequence (Cormier et al., 2019)



- Example 2: Bow-Tie application – from Burdon et al. (2018).



- Example 3: Powerpoint and stakeholder-based Bow-Tie analysis (from Elliott et al., 2020b, CERES project).

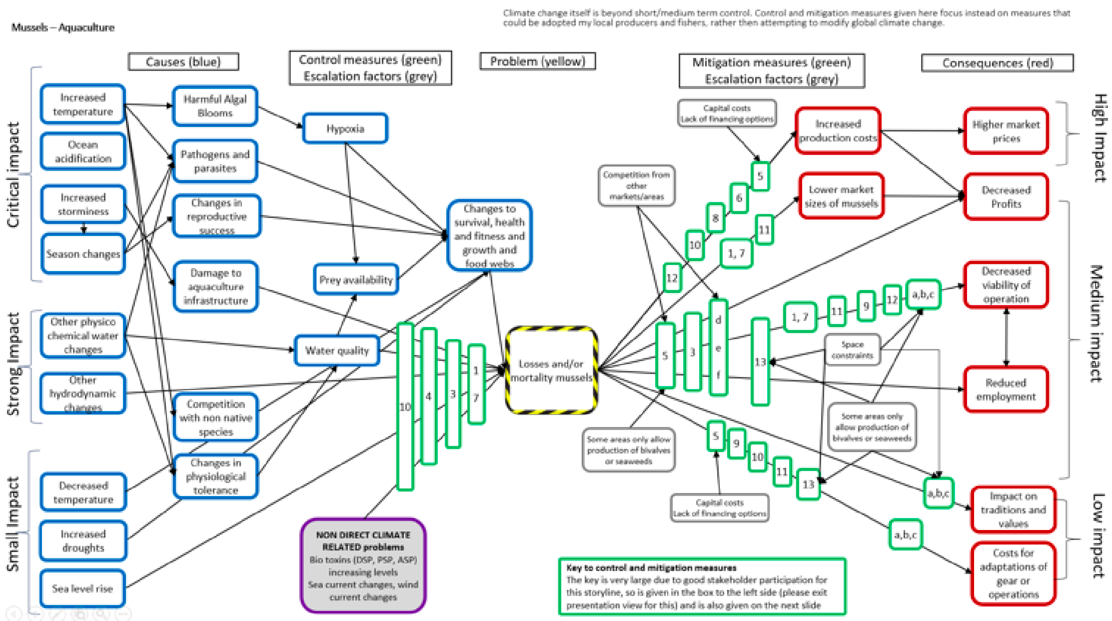


Table 12. Cumulative impact spatial mapping (e.g., Halpern et al., 2008)
A. Description of the methodological approach:

The main features of the global human impact assessment (Halpern et al., 2008) are (i) a grid of selected resolution for all the spatial data, (ii) spatial layers of pressures which are quantified and then normalized between 0-1 inside a grid cell, (iii) spatial layers of ecosystem components (e.g. species, species groups, habitats) which are similarly quantified and then normalized between 0-1 inside a grid cell, and (iv) weight scores representing the sensitivity of the ecosystem components to each of the pressures. Depending on the application, the three scores are summed, or a mean of impacted ecosystem components is taken (e.g., Stock and Micheli, 2018). There are also various ways in determining the weight scores (Halpern et al., 2007; Korpinen and Andersen, 2016).

The global method is simple to use, a free software EcoImpactMapper is available to calculate it (Stock, 2016) and it is easily modifiable (Stock and Micheli, 2018). Simplicity, however, also makes it vulnerable to simplifications of reality which was first warned by Halpern and Fujita (2013) and later confirmed by many studies (e.g., Korpinen et al., 2021). While the use of expert judgment in determining the weight scores often receives the most critical comments, it is a relatively robust component (e.g., Korpinen et al., 2012), and the real caveats are in the selection of ecosystem components, data availability, the assumption of linear ecosystem response to pressures and the additive model of cumulative impacts (Halpern and Fujita 2013; Quemmerais-Amice et al., 2020).

B. Application of the tool:

Following the first global assessment (Halpern et al., 2008), several regional and pan-European development processes were established and published in a couple of years' time span. The HELCOM holistic assessment in 2010 was the first regional cumulative effect assessment (CEA; HELCOM, 2010; Korpinen et al., 2012), followed by the Mediterranean and the Black Sea (Micheli et al., 2013a) and the North Sea (Andersen and Stock 2013). Korpinen and Andersen (2016) reviewed the use of this (and similar) methods worldwide and recognized the main similarities and differences among the tens of studies.

Despite the simplifications, the global CEA method seems to reflect the human impacts, at least in large spatial scales. Using the large-scale biodiversity status of the Baltic Sea sub-basins and the mean cumulative impacts in the same scale, Andersen et al. (2015) were able to show a clear dependency. In the pan-European scale, the Marine Messages II showed a similar dependency of the integrated ecosystem health on cumulative impacts (Reker et al., 2019) and this was also shown for the coastal waters between the ecological status and CEAs (Korpinen et al., 2021; HELCOM, 2023). Research is going on to establish more sophisticated models for cumulative impacts to predict risks for the ecosystem state than the pressure data alone.

C. Tool requirements:

The tool requires numerical and spatial datasets, expert knowledge and computational and analytics skills. As such it is a data-rich tool with specialised skills needs.

D. Key example References or Resources

- Halpern et al., 2008, 2015; Stock 2016; Stock and Micheli, 2018; Korpinen and Andersen, 2016; Reker et al., 2019; Korpinen et al., 2021; HELCOM, 2023
- Baltic Sea potential cumulative impact from HELCOM 2023:

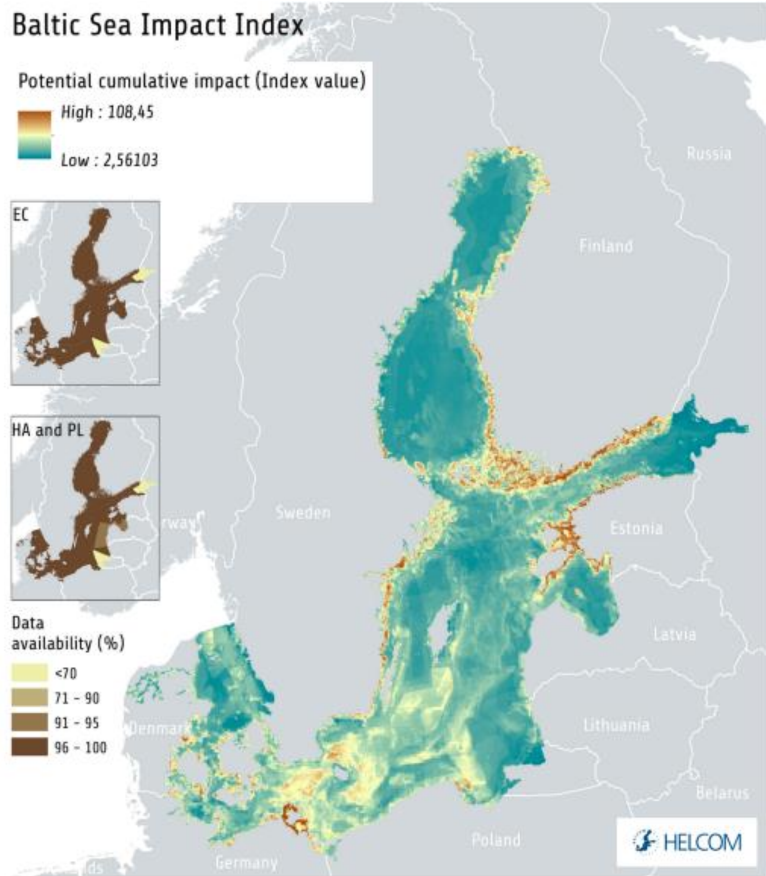


Figure 18. Distribution of potential cumulative impact from human activities on the Baltic Sea environment, based on the Baltic Sea Impact Index. The analysis is based on currently best available regional data, but spatial gaps may occur in some underlying datasets, as described by the data availability maps, showing available data for human activities/pressures (HA and PL) and ecosystem components (EC).

Table 13. Impact risk assessment through linkage-chain frameworks (e.g., ODEMM)
A. Description of the methodological approach:
The EU ODEMM and AQUACROSS projects provide an assessment methodology tracing sector–pressure–ecosystem component pressure pathways (also known as 'linkage chains') and scoring them through expert judgement and data where available. The methodology has been adapted and evolved since in several ways, including for use in ICES Ecosystem Overviews, for use in Integrated Ecosystem Assessment in the Mission Atlantic project, linking to management objectives (such as MSFD descriptors and criteria) and to better account for cumulative impacts (ICES WGCEAM, ICES 2019a). There is much documentation on how to use the tool in the project websites and papers (resources below), but in general the approach consists of two main steps, identifying where linkages exist (mapping in a 'linkage matrix') and then scoring each linkage that does occur for a number of attributes (e.g., spatial overlap, temporal overlap, degree of impact, resilience or resistance, although there are variations on these). The templates are free, most analysis can be carried out in excel, but the Mission Atlantic project has developed an R script with a standardised list of outputs which is freely available: https://github.com/missionatlantic/MissionAtlantic-RISK-Analysis
B. Application of the tool:
The benefits of such an approach lie in its comprehensiveness; all relevant sectors and pressures are considered, and the ecological components can be specified at a resolution that is relevant for your purposes. It is very useful for providing context (avoiding tunnel-vision and

focusing only on where there is data available), and its key output is a prioritisation of the top risks for the region. The approach is limited in that there are currently few ways to incorporate quantitative knowledge where it does exist, it relies on expert and/or stakeholder judgement (which is fallible and dependent on who is present), and it is often limited to the three components detailed above, limiting the connection to the social system. As such, it is best used in tandem with a few other tools detailed here (e.g., mental models and BBNs) and used to identify key areas of focus for further investigation (as in the case of scoping in IEAs). Recently, Piet et al. (2023a submitted) introduced SCAIRM (Spatial Cumulative Impact Risk Assessment for Management) that builds on the ODEMM/AQUACROSS approach (Knights et al., 2015; Piet et al., 2015; Piet et al., 2017; Borgwardt et al., 2019; Culhane et al., 2019a; Piet et al., 2019). The method is modified to address several shortcomings of those approaches. SCAIRM can be used in data-poor situations while allowing the use of available quantitative information in more data-rich situations resulting in an improved capacity to inform policy or guide EBM. Human activities are included at their basic sectoral level, allowing a straightforward link to the socio-economic system and its relevant data, scenarios or stakeholders. In addition, the linkage framework that is at the basis of SCAIRM has been extended by incorporating Ecosystem Services (Piet et al. 2023b submitted).
C. Tool requirements:
The method can be carried out with nothing but expert/stakeholder knowledge and refined as data is identified/becomes available. However, building the linkage tables can be a time consuming and difficult process. There are several existing assessments (e.g., for four European regional seas: Knights et al., 2015; for Irish sea: Pedreschi et al., 2019) that can be used as a strawman, which often makes progress much faster. Current efforts often result in an initial expert assessment by the assessment team (reaching out to specialists where knowledge is lacking) which is then ground-truthed with stakeholders. This greatly cuts down on the time requirements. It can be carried out with very basic data and analysis skills – however strong facilitation skills and knowledge of the scoring rules are essential to ensure consistency in application.
D. Key example References or Resources
• ODEMM: https://odemm.com/ (and references therein) • AQUACROSS: https://aquacross.eu/ (and references therein) • ICES 2021a (WKTRANSPARENT) • WGCEAM Working Group on Cumulative Effects Assessment Approaches in Management: https://www.ices.dk/community/groups/Pages/wgceam.aspx • Mission Atlantic Analysis Script: https://github.com/missionatlantic/MissionAtlantic-RISK-Analysis • Pedreschi et al., 2019, 2023; Knights et al., 2015 • Example of Risk and Pressure assessment criteria (schematic) from Robinson et al. (2014):

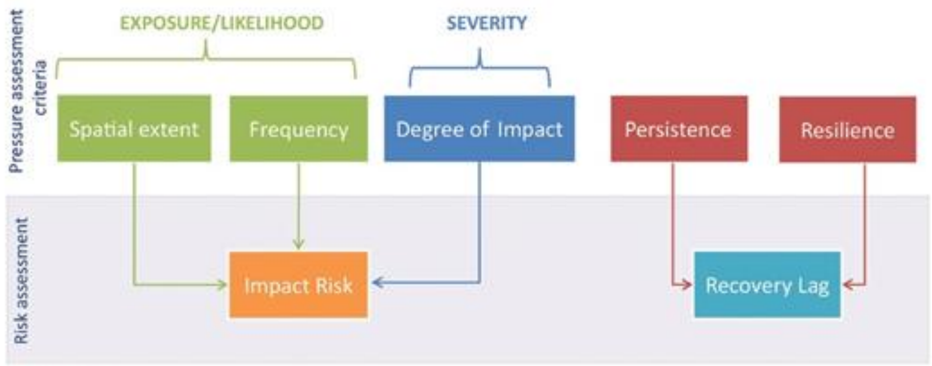


Figure 5.2 Pressure assessment criteria are grouped to assess *Impact Risk* and *Recovery Lag* under the risk assessment framework.

Table 14. Single-species models (e.g., life cycle, stock assessment)
A. Description of the methodological approach:
Single-species models are mathematical representations used to study and understand the dynamics of a particular species within an ecosystem. The models focus on the population size, growth, and interactions of a single species, while often considering the species' interactions with its environment and other factors that influence its population dynamics. These models can incorporate limited ecosystem or multispecies information. Examples of types of single-species models are dynamic energy budget (DEB) models, metapopulation models, dynamic population models and individual-based models (IBM). DEB models are mechanistic models that integrate the dynamics of individual metabolism, simulating energy allocation, growth, reproduction, and other physiological processes based on the principles of mass and energy conservation. These models are extensively used as basic components of complex models of marine ecosystems. Metapopulation models investigate the dynamics of a network of interconnected subpopulations within a larger population and therefore explicitly consider the spatial structure of populations. Dynamic population models describe the changes in size and structure of a single population through time. These models incorporate various factors that influence population dynamics, such as new individuals, mortality, migrations and interactions with the environment. The results of these models are also often used as input for more general models, such as ecosystem end-to-end models. IBMs, or agent-based models, are a population and community modelling approach that accounts for a high degree of complexity or interactions between individuals. IBMs simulate populations or systems of populations as being composed of discrete individual organisms and explore the mechanisms through which population and ecosystem ecology are affected by the way individuals interact with each other and their environment. A wide range of software packages are available to apply the different types of single-species models. For example, NicheMapR is a package to implement DEB using R (Kearney and Porter, 2020). The Fisheries Library in R is a collection of tools that include Dynamic population models also developed for R (Kell et al, 2007). RAMAS Metapop RAMAS-METAPOP (Applied Biomathematics, Setauket, NY, USA) is a software package specifically designed for studying metapopulation dynamics. Ichthyop is a free Java tool that applies an IBM designed to study the effects of physical and biological factors on ichthyoplankton dynamics (Lett et al., 2008).
B. Application of the tool:

Single-species models are useful to understand factors influencing the abundance, distribution, and sustainability of marine organisms, by for example elucidating causal processes underpinning declines of individual species. The models can provide useful information for policy and management, especially for threatened species, keystone species and invasive species (Lindenmayer et al, 2007). Single-species models have also been traditionally used in fisheries management for estimating stock status and fluctuations over time and providing management advice (Burgess et al., 2017).

DEB models have been widely used to analyse and predict the dynamics of marine organisms, and to understand their life history strategies and responses to environmental changes. DEB models can be valuable tools in assessing the potential impacts of environmental change, habitat degradation, or fishing on population dynamics (e.g., Jager et al., 2016; Mangano et al., 2019).

Metapopulation models are relevant for species that exhibit spatially structured populations, such as coral reef fish or bird populations that use multiple habitats or breeding sites. By modeling the dynamics of subpopulations in fragmented landscapes, these models can estimate the impacts of habitat loss, fragmentation, or degradation on the overall metapopulation viability (e.g., Guizien et al., 2014; Mari et al., 2021).

Dynamic population models are mainly applied to commercially exploited fish species for stock assessment and management purposes (e.g., Szuwalski, 2022). By integrating the available data, projecting future population dynamics, and considering various management scenarios, these models provide insights into the sustainability and productivity of fisheries resources.

IBM are a useful tool for understanding the dynamics of marine ecosystems, studying species interactions, assessing human impacts, exploring management strategies, predicting species responses to environmental change, and integrating diverse data sources (e.g., Marzloff et al., 2009, Xuareb et al., 2021)

C. Tool requirements:

Single-species models encompass a large variety of models that differ in the level of complexity and the amount of data required. Among the single species models indicated above IBM have highest computational demands. DEB models need parameterizations based on literature, but there is large database collecting data for hundreds of species (Marques et al., 2018).

D. Key example References or Resources

- Burgess et al., 2017; Guizien et al., 2014; Jager et al., 2016; Kearney et al., 2020; Kell et al., 2007; Lett et al., 2008; Lindenmayer et al., 2007; Mangano et al., 2019; Mari et al., 2021; Marques et al., 2018; Marzloff et al., 2009; Stelfox et al., 2020; Szuwalski, 2022; Talbot et al., 2019; Xuareb et al., 2021.
- Dynamic Energy Budget Model in the Sea: http://bioforecasts.science.unimelb.edu.au/app_direct/deb_sea/
- Icthyop: https://ichthyop.org/
- Example: Schematic diagram of the standard DEB model (Talbot et al, 2019).

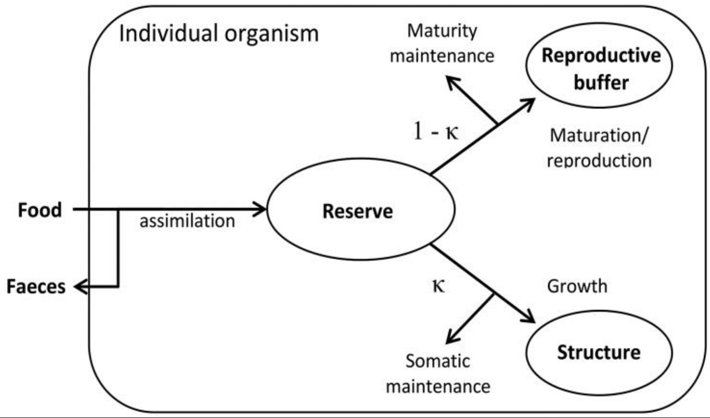


Table 15. Biogeochemical models
A. Description of the methodological approach:
Biogeochemical models capture two-way interactions between the biology and chemistry of ecosystems. They are used to simulate how abiotic and biotic variables interact through time and across space and provide a means to explore management scenarios in relation to climate change and change in the flow of nutrients from land into the ocean. Typically, biogeochemical models are used to study nutrient cycling (nitrogen, phosphorus, oxygen, silicon, and iron) and impacts on planktonic communities due to events such as eutrophication and oxygen depletion.
B. Application of the tool:
A range of tools exist, a few key examples are: • The European Regional Seas Ecosystem Model (ERSEM) is a plankton functional type model, developed from a NPZD model, which describes the biogeochemical and plankton cycles (Baretta et al., 1995). BFM is a numerical model designed to study stoichiometric relationships in the biogeochemistry of marine ecosystems by describing the dynamics of major marine biogeochemical processes (Vichi et al., 2007). The model extends and advances the original philosophy of ERSEM. Petihakis et al. (2007) used a high resolution coupled Princeton Ocean Model (providing the physics) and ERSEM (providing the biogeochemical processes) ecosystem model for scenario testing of fisheries management strategies. • ECOSMO ('ECOSystem MOdel') is a coupled physical-biogeochemical model (Schrum et al., 2006a, 2006b), with the hydrodynamics based on the HAMSOM ('HAMburg Shelf Ocean Model'; Schrum and Backhaus, 1999), a free-surface 3D baroclinic coupled sea-ice model. The prognostic variables of HAMSOM include temperature, salinity, relative sea surface elevation, 3D-transports, vertical exchange coefficients and turbulent air–sea exchange. • BALTSEM, the 'Baltic Sea Long-Term Large-Scale Eutrophication Model', which divides the Baltic Sea into multiple interconnected marine basins each of which is assumed to be horizontally homogeneous but with high vertical resolution (Savchuk et al. 2012).
C. Tool requirements:
Biochemical models are data rich tools with various data requirements for biotic and abiotic parameters. Specialised skills and computer power are also required.
D. Key example References or Resources
• Baretta et al., 1995; Vichi et al., 2007; Savchuk et al., 2012; Schrum et al., 1999, 2006a, b; Butenschön et al., 2016. • ERSEM schematic from https://www.pml.ac.uk/science/projects/ERSEM-(European-

Regional-Seas-Ecosystem-Model):

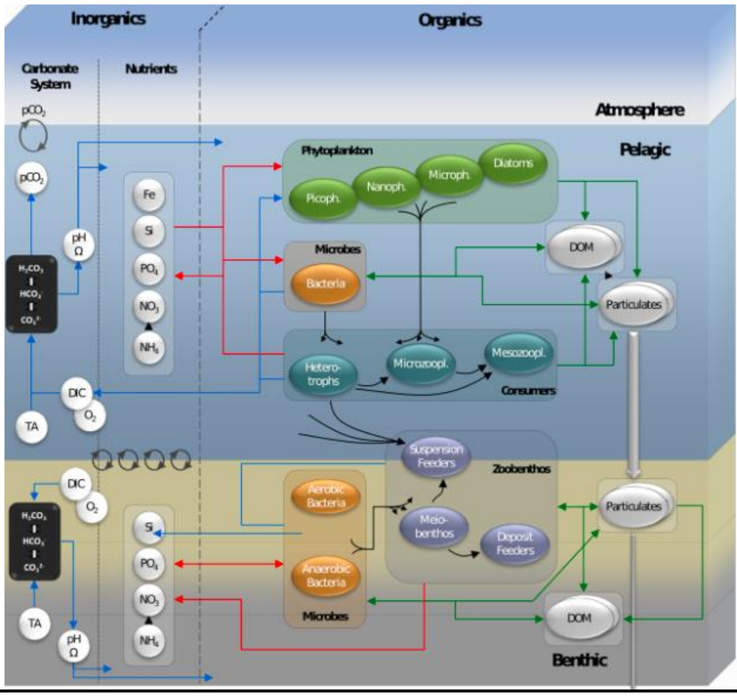


Table 16. Food web models (e.g., multispecies models EwE)
A. Description of the methodological approach:
Marine Ecosystem Models (MEMs) are of different types and include a variety of assumptions (Tittensor et al., 2018), including as size based, food-web based and individual based processes. Ecosystem models frequently describe the interactions between at least two ecosystem components (e.g., populations, species, functional groups), whereby the interactions are real ecological processes (e.g., predator–prey interactions, mediation, size relationships) and are driven by ecological dynamics, including movement, and perturbations (both natural and anthropogenic). Some of the most used MEMs are food web models, which are often visualized as networks, where nodes denote interacting ecological components, and the causal relationships between them are shown by edges (Geary et al., 2020). Food-web models are a particular type of ecosystem models. They simulate the structure and flow of energy and nutrients between ecosystem components and are commonly used for quantifying food web interactions in a whole-ecosystem context. Generally, for modelling, multiple species are aggregated according to a certain criterion and represent a single species, groups of species or orthogenic phases of a species (juveniles and adults) which are different compartment in the directed network. Food web models aim to the understand the population dynamics among predators and prey, the stability of communities and the implications of change for ecosystem structure, functioning and stability, as well as the flow of matter/energy among the nodes as an ecosystem or ecological network. Food web dynamic models can be used to forecast/hindcast scenarios, and often to describe and understand the current ecosystem. They are often able to account for temporal dynamics and sometimes to incorporate multiple spatial scales, and regularly represent ecosystem components at the level of aggregates/groups of taxa and ecosystem condition/state, but often also at the level of population (size, stage) structure and individual species They model ecosystem processes such as species interactions as well as various perturbations (Geary et al.,

2020).

Examples of such type of models are Ecopath with Ecosim (EwE) and Ecological Network Analysis (ENA). EwE is a whole ecosystem model that quantifies food-web and fishery interactions and can include the impact of environmental change and human activities, including the effect of spatial management options such as the placement of marine protected areas and conservation measures (Christensen and Walters 2004; Heymans et al., 2016). EwE has been widely applied in several marine ecosystem types and regions (Colleter et al., 2015; Stock et al., 2023). The EwE modelling approach and software consists of a suite of three main sub-models (or routines): (i) Ecopath, a static model, representing a mass-balanced snapshot of the food web; (ii) Ecosim, a temporal dynamic model, producing time-dynamic simulations for exploring alternative scenarios (e.g. past and future impacts of fishing and environmental disturbances); and (iii) Ecospace, a spatially-explicit time dynamic 2D model. The last version of Ecospace has been substantially improved with the Habitat Capacity Model, which bring in the capacity to incorporate a niche model within the food web model dynamics (Christensen et al., 2014). This capability has allowed to incorporate a diversity of climate and human activities changing in time and space (de Mutsert et al., 2023).

ENA combines modelling and analysis used to investigate the structure, function, and evolution of ecosystems and other complex systems. ENA is applied to network models that follow the flow of energy or nutrients through the ecosystem by tracing the movement of thermodynamically conserved energy or matter through the system, so that the networks function like resource-distribution maps. Network nodes represent species, functional groups, or non-living resource pools, and the directed edges indicate the transfer of the resources between nodes (e.g., eating, excretion, death). Multiple methods exist to build this type of model, including for example a phenomenological energy or nutrient budget approach, linear inverse modelling methods, dynamic simulation models, and bioenergetics modelling as implemented in EwE. ENA indices can quantify emerging properties of ecosystems and monitor their evolution and offers a quantitative assessment of marine ecosystem functioning.

Food web models may be used to quantify changes in ecosystem indicators, including GES indicators relevant to MSFD Descriptor 3 (D3: Commercially exploited species) and Descriptor 4 (D4: Food webs) (Lynam et al. 2016; Piroddi et al. 2021; Korpinen et al., 2022), and other ecological indicators (Coll and Steenbeek 2017).

B. Application of the tool:

The Ecopath mass-balance model can be calibrated using the time dynamic version (Ecosim) by comparing model predictions with data of historical changes in populations and fisheries. Inputs from other models (such as stock assessments) and data sources (e.g., from scientific surveys) are used for the fitting procedure, and outputs from EwE include sea estimates of biomass, production and other ecological indicators for functional groups (ranging from mammals, seabirds, reptiles, fish, invertebrates, seaweeds and primary producers, from both and benthic and pelagic habitats) and ecosystem indicators. The 'EcoBase' model repository, which was developed to gather EwE models published worldwide, includes hundreds of unique models. EwE models have been used to analyse, among others, the ecosystem functioning and the impacts of fisheries, ; trophic functioning in marine systems; the effects of pollution, aquaculture and Marine Protected Areas on a wide variety of ecosystems (including polar regions and terrestrial systems), and the impacts of climate change or cumulative impacts (Colleter et al., 2015; Stock et al., 2023).

Within the scope of GES4SEAS, other specific examples include evaluating the trade-offs among alternative fishing strategies (e.g., discard policy, North Sea, Mediterranean Sea); evaluating relative impacts of fisheries and climate effects (North Sea, Irish Sea, Celtic Sea, Mediterranean Sea); evaluation of closed area management (North Sea, Mediterranean Sea);

evaluation of impact of aggregate extraction (Eastern Channel); dynamics of the gadoid and demersal fisheries (West Scotland); feasibility for ecosystem-based management (Clyde Sea). EwE has also been used as part of overarching ensemble models, as developed for example within the Marine Ecosystems Research Programme (MERP) to provide a more holistic and representative assessment of marine ecosystems than could be achieved through the application of a single model or as part of FishMIP the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP) (Tittensor et al., 2018). In MERP it was used as a West coast of Scotland model, an area covering 110,000 km2, and a Celtic Sea model. The joint research centre of the EU lists EwE as an important tool in its modelling suite.

ENA techniques have been applied to characterize food web organization, assess ecosystem maturity or status, trace biogeochemical cycling in ecosystems, and characterize the sustainability of urban metabolisms and other socio-ecological systems. ENA indices have been proved useful to evaluate the impacts of human pressures on ecosystem functioning and to simulate likely impacts given climatic change scenarios (Lynam et al., 2016). Due to the ability of ENA to characterize the whole ecosystem, and its suitability to answer the need for ecosystem-based management, the use of ENA has been suggested to guide ecosystem assessment and management, including the use of ENA system metrics as GES indicators in the MSFD.

C. Tool requirements:

Food web models are data rich tools. They require data from biological surveys and assessments to specify the abundance, productivity of groups and who eats (or catches) whom, and how much. Fishing fleets can be described at any level of detail including landings, discards and economics.

D. Key example References or Resources

- Borrett et al., 2018; Christensen and Walters, 2004; Colléter et al., 2015; D'Alelio et al., 2016; Fath et al., 2019; Funes et al., 2022; Geary et al., 2020; Korpinen et al., 2022; Lynam et al., 2016; MERP 2019; Nogues et al., 2022; Piroddi et al., 2021; Heymans et al., 2016; Tittensor et al., 2018; Christensen et al., 2014; Stock et al; 2023; De Mutsert et al., 2023; Coll and Steenbeek 2017;
- https://www.masts.ac.uk/media/4706/ecopath_with_ecosim.pdf
- http://ecopath.org/
- Example: Ecopath food web model of the northern North Sea. The diagram shows energy flow (lines) and biomass (nodes). From Hill et al. 2021.

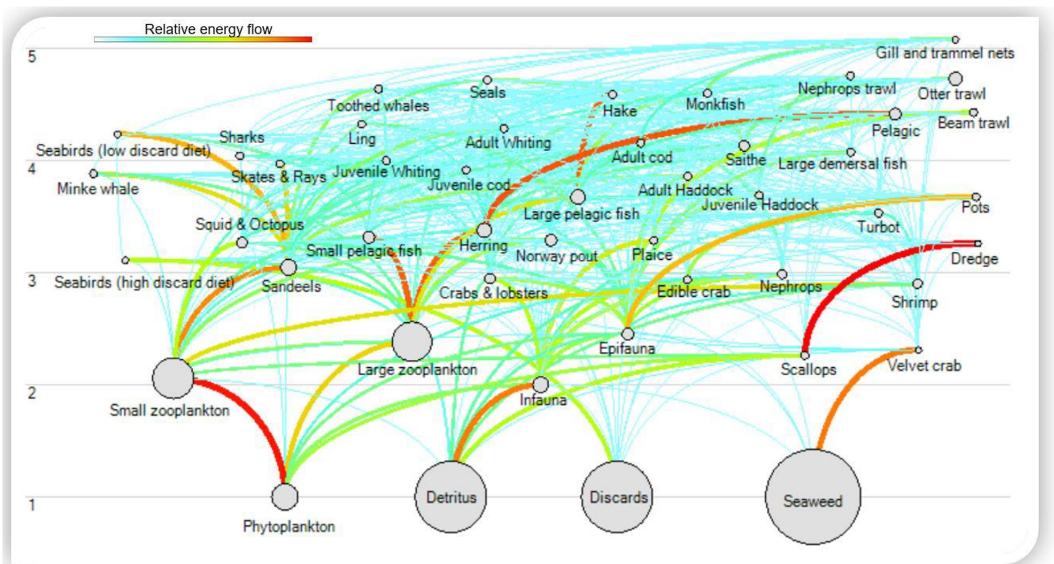


Table 17. Ecosystem models (e.g., E2E)
A. Description of the methodological approach:
End-to-end (E2E) models are one type of ecosystem models. They are a mathematical representation of an entire ecosystem, a single modelling framework that integrates physico-chemical oceanographic descriptors and organisms ranging from microbes to higher-trophic-level organisms (including humans) and that links to the marine socio-economic aspects. This approach was developed from the need for quantitative tools for Ecosystem-Based Management, particularly models that can deal with bottom-up and top-down controls that operate simultaneously and vary in time and space and that are capable of handling multiple impacts. E2E models are used to describe and understand the current ecosystem and forecast/hindcast scenarios, and often also to make decisions on management actions. They are able to incorporate multiple spatial scales and account for temporally dynamics, and regularly represent ecosystem components at the level of aggregates/groups of taxa and ecosystem condition/state, but often also at the level of population (size, stage) structure and individual species. They model ecosystem processes such as species interactions as well as perturbations (to a single node or to the whole ecosystem) and may also account for dispersal processes. Owing to the complexity of such models, they are generally inappropriate for use as tools for setting tactical management measures such as quotas, as absolute values are far less reliable than the patterns and relative distributions produced (Geary et al., 2020). Examples of E2E models are Atlantis and STRATH E2E. Atlantis is an E2E ecosystem model that considers all parts of marine ecosystems including the biophysical, economic and social systems (Fulton 2010; Fulton et al., 2011). Originally focused on the biophysical world, Atlantis was further developed to investigate fisheries and more recently for multiple use and climate questions. A summary of Atlantis is provided by Pinnegar (2019) and Geary et al. (2020): Atlantis is a deterministic biogeochemical whole-of-ecosystem model. At the core of Atlantis is a biophysical sub-model that tracks nutrient flows through the biological groups. The primary ecological processes modelled are consumption, production, migration, predation, recruitment, habitat dependency, and mortality. The trophic resolution is typically at the functional group level and the physical environment is spatially represented through a series of irregular polygons. Atlantis includes a detailed exploitation model that is able to examine the impact of pollution, coastal development and broad-scale environmental change. The dynamics of multiple fishing fleets can also be examined each with its own characteristics of gear selectivity, habitat association, targeting, effort allocation, and management structures. Atlantis can be used to assess economic consequences, the result of compliance decisions, exploratory fishing and fishery management instruments including gear restrictions, days at sea, quotas, spatial and temporal zoning, discarding restrictions, size limits, bycatch mitigation, and biomass reference points. The complexity of Atlantis models does make them potentially unwieldy, and they are often used for strategic (what) but not tactical (how) decisions (Peck et al., 2018; https://www.masts.ac.uk/media/4695/atlantis.pdf). STRATH E2E is geared towards marine ecosystem-based management. The model couples an ecological model with either a fishing fleet model or a fishers' behaviour model, so creating feedback between ecological state and properties of the fishing fleet. The model is designed for application in the North Sea, West of Scotland, Celtic Sea and English Channel. It works on two vertical layers in the water column and two horizontal components (inshore and offshore waters); it uses three inshore and three offshore habitats based on sediment properties. STRATH E2E is ready for use for carnivorous and omnivorous zooplankton and fish, while there is growing confidence in outputs for nutrients, phytoplankton, benthos and seabirds and mammals. Fish are represented by three types, including the external input from fish that migrate in at a set time of year, feeding, growing, being eaten or dying. STRATH E2E includes horizontal transport, vertical

mixing, and sediment resuspension by waves and currents as 'physical' inputs. Suspended and sediment detritus and bacteria are combined as detritus in STRATH E2E, sediment detritus is fixed in each seabed habitat from observational data. The outputs can be processed into other variables such as landings and discards for an individual fleet. Results of a model run can be converted into a range of graphs, spreadsheets, maps etc. At the current time STRATH E2E is best suited to annual projections. This model is also part of a suite of models integrated within an overarching ensemble model as developed within the Marine Ecosystems Research Programme (MERP) to provide a more holistic and representative assessment of marine ecosystems than could be achieved through the application of a single model (MERP, 2019). E2E modelling which represents large parts of the marine ecosystem by including the most relevant processes in the system, from physics to chemistry, and plankton to fish has been developed with explicit links to MSFD Descriptor 3 (D3: Commercially exploited species) and Descriptor 4 (D4: Food webs) (JRC, 2021; Piroddi et al., 2021). Most often, E2E models are used for strategic insight into system function and the consequences and potential trade-offs associated with different combinations of management strategies, providing information for strategic planning and decision support towards achieving GES (e.g., Bossier et al., 2018).
B. Application of the tool:
The Atlantis modelling framework is very flexible and can be applied to any situation world-wide using the many alternative model formulations. Atlantis has been used in 30+ systems round the world, from small estuaries to large ocean regions. Atlantis models have been developed for the North Sea and the English Channel (Pinnegar, 2019). The North Sea model has been used to explore interactions between fisheries, windfarms, and MPAs (calibration of the model is still ongoing). The English Channel model has been coupled to a fishing fleet behaviour model and used to explore interactions between fisheries (French and English) targeting sole and plaice, as well as the influence of riverine inputs. A Baltic implementation of the spatially-explicit E2E Atlantis ecosystem model has also been developed to explore the different pressures (e.g., eutrophication, climate change and fishing pressure) on the marine ecosystem on the medium to long term, and to support strategic management evaluations (Bosser et al., 2018). This links the Baltic Atlantis model to two external models: the HBM-ERGOM, which initialises the Atlantis model with high-resolution physical-chemical-biological and hydrodynamic information while the FISHRENT model analyses the fisheries economics of the output of commercial fish biomass for the Atlantis terminal projection year. The Baltic Atlantis model composes 29 subareas, 9 vertical layers and 30 biological functional groups. The balanced calibration provides realistic levels of biomass for, among others, known stock sizes of top predators and of key fish species. Furthermore, it gives realistic levels of phytoplankton biomass and shows reasonable diet compositions and geographical distribution patterns for the functional groups. Several scenarios of nutrient load reductions on the ecosystem were simulated and the model sensitivity to different fishing pressures tested, allowing to evaluate the impacts on different trophic levels, fish stocks, and fisheries associated with changed benthic oxygen conditions. Another example is shown by Geary et al. (2020) for the application of Atlantis for a whole-of-ecosystem management strategy evaluation (MSE) in support of a strategic restructuring of southeast Australian federal fisheries (model Atlantis-SE44). Ecosystem-based management solutions were developed and tested for a complex of multispecies and multi-gear fisheries to predict ecosystem-scale responses to the consequences of alternative management scenarios. Strategies focused on different types and combinations of management including alternative quota management, spatial management and gear controls. Different future management scenarios were quantitatively compared, and outputs showed that trade-offs are required for the successful management of such large and complex fisheries, so that various input, output and technical management options may be balanced. MSE outputs were used as a decision-support for

understanding potential futures of the ecosystem given different scenarios, rather than providing prescriptive management advice. The model is one of the most complex dynamic ecosystem models for fisheries ever developed, with uncertainty a crucial consideration (including structural uncertainty and human behavioural uncertainty).

STRATH E2E is designed for application in the North Sea, West of Scotland, Celtic Sea and English Channel. Examples of its application include:

- Simulation of fishery yields and maximum sustainable yield (MSY) in relation to the combination of pelagic and demersal harvesting rates (Heath, 2012).
- Simulation of trophic cascades and the sensitivity to top-down and bottom-up drivers (fishing and river nutrient inputs (Heath et al., 2014a)
- Sensitivity of fishery yields to environmental drivers and biological parameters (Morris et al., 2014)
- Cascading trophic effects of scenarios for implementing a discard ban (Heath et al., 2014b)

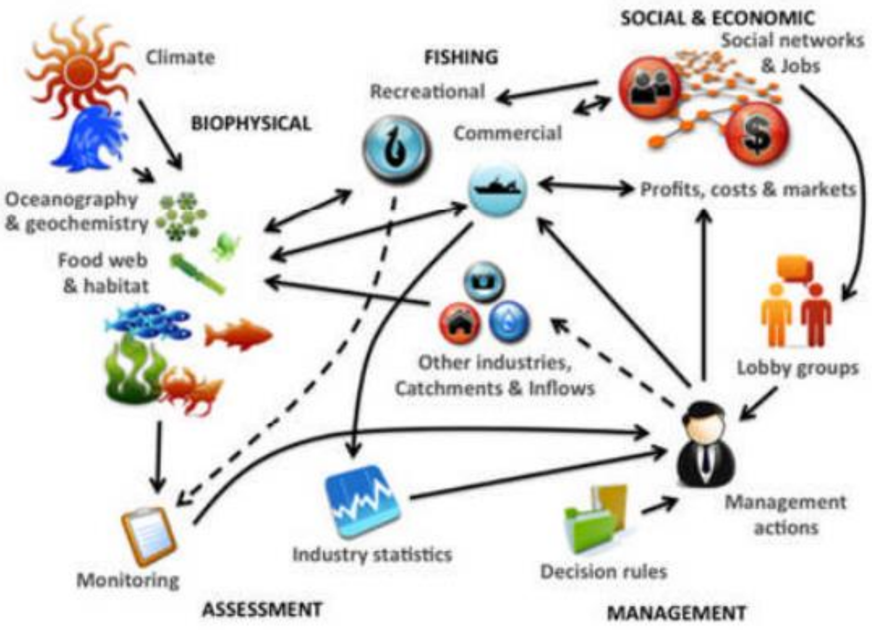
C. Tool requirements:

Ecosystem models are parametrized using field-collected, experimental and/or expert-elicited data to make inferences about specific components (for example, individual species), the entire ecosystem, or even a large part of the coupled socio-ecological system. As such they are data rich tools.

Parameterisation of ATLANTIS models requires significant effort including many iterations of validation, calibration and data manipulation. Larger E2E models allow to account for feedbacks as well as multiple ecosystem states and scales but are computationally expensive. They need considerable effort, data and computing power to be implemented. Highly specialised skills and training are also required for users

D. Key example References or Resources

- Bossier et al., 2018; Fulton 2010; Fulton et al., 2011; Geary et al., 2020; Fulton et al., 2011; Heath, 2012; Heath and Steele, 2009; Heath et al., 2014a, b; JRC, 2021; MERP, 2019; Morris et al., 2014; Peck et al., 2018; Pinnegar, 2019; Piroddi et al., 2021;
- http://www.mathstat.strath.ac.uk/outreach/e2e
- Example: graphical representation of a generic Atlantis model with specifications of examples of models for UK shelf areas (from https://www.masts.ac.uk/media/4695/atlantis.pdf)



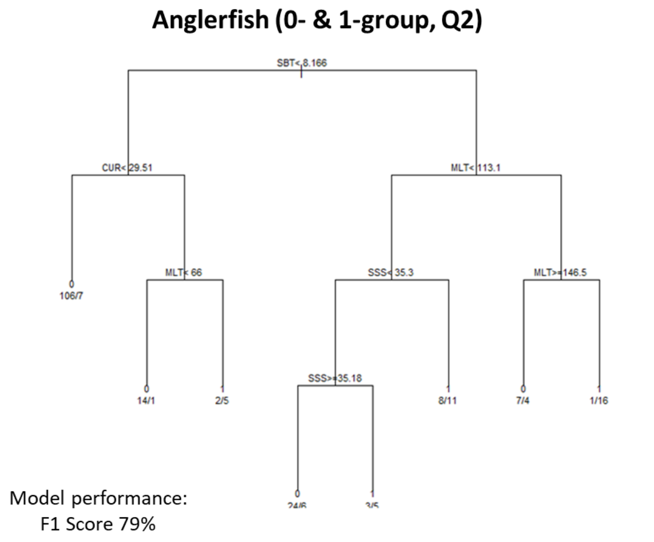
Existing Models for UK shelf seas:

Area Modelled	Includes: M[1] B[2] F[3] I[4] P[5]	Spatial Scale	Quality (data used)
North Sea	53 functional groups (M = 3, B = 1, F = 26, I = 16, P = 3, detritus groups = 4)	25 polygons	Parameterised with EU landings data & outputs from the hydrodynamic model ECOHAM
English Channel	40 functional groups (M = 2, B = 1, F = 18, I = 13, P = 3, detritus groups = 3	37 polygons	Parameterised with EU landings data & outputs from the hydrodynamic model ECOMARS3D

1 M = mammals, 2 B = birds, 3 F = fish, 4 I = invertebrates, 5 P = primary producers

Table 18. Habitat suitability models/species distribution models
A. Description of the methodological approach:
Habitat suitability models (HSM) are predictive models used to predict the spatial distribution of species based on their observed relationship with environmental conditions. These are also referred in the literature as species distribution models (SDM) or predictive habitat distribution models (Guisan and Zimmermann, 2000). On calibration of the model, the species-environment relationship is established based on data on the species distribution and the environmental conditions where it occurs. It is used to identify the key environmental predictors which determine the suitability of a location for the species. On prediction, the environmental conditions are used as predictors of the likelihood of presence or density of the species throughout a study area. As such, this modelling approach can be seen as an operational application of the potential ecological niche. Different techniques can be applied for the modelling (e.g., generalized linear or additive regression models, classification and regression trees, Random Forest, maximum entropy algorithm), which may rely solely on presence/absence, presence or on density data from surveys. Several of these techniques may be applied using the open-source programming language R, but other statistical software may be available for the individual techniques. A Geographic Information System (GIS) interface is very useful to extract environmental variables from relevant data layers for the model calibration, and to spatialise the resulting model predictions.
B. Application of the tool:
HSM are commonly applied to individual species, to identify areas with environmental

characteristics that may support the species as a whole, or sensitive stages or processes of the species' life cycle (e.g., nursery habitats for juveniles, spawning grounds). Examples of this application are the mapping of Essential Fish Habitats for fish and shellfish species in the marine environment. Habitat suitability models have also been used to identify geographical regions suitable for different cetacean species, seabirds, and elasmobranchs. These models may be applied to identify potential important marine areas where to prioritise conservation, restoration or to support spatial planning and project level assessment (e.g., by highlighting possible sensitive areas during the environmental impact assessment of marine developments). When applied to multiple species, these models can be used to identify coexisting species and to characterize interaction networks.
C. Tool requirements:
The application of HSM is data-rich and therefore places a considerable demand on data availability. To calibrate HSM, monitoring data are required recording either the presence/absence or the abundance (e.g., as density) of a species at survey locations. Where specific life stages are modelled, additional data on body size, age or life stage are needed to differentiate the presence or abundance of the selected life stage from the rest of the population. Environmental variables (e.g., depth temperature, salinity, habitat type, etc.) at the sample locations are also required, either measured during the survey, or derived from correspondent environmental spatial layers. The wider the environmental ranges covered by the survey, the wider is the validity of application of the model hence its spatial coverage.
D. Key example References or Resources
• Aires et al., 2014; Chavez-Rosales *et al.,* 2019; Fabbrizzi et al., 2020, 2023; Franco et al., 2022; Frederiksen et al., 2013; González-Irusta and Wright, 2016a, b; Guisan and Zimmermann, 2000; Hirzel and Le Lay, 2008; Katara et al., 2021; Lauria et al., 2015; Oppel et al., 2012; Ramírez-León et al., 2021. • Example: Habitat suitability model (classification tree) and resulting prediction map for juvenile aggregations of anglerfish (*Lophius piscatorius*) around the UK (from Franco et al. 2022). The classification tree model identifies environmental conditions at which aggregations of juvenile anglerfish (age groups 0 and 1) are predicted as present (1 at the end of a tree branch) or absent (0). Environmental predictors in the model are: SBT = Sea Bottom Temperature; CUR = Energy of the currents at the seabed; MLT = depth of the mixed water column layer; SSS = sea surface salinity. Model predictions in the map are (coloured sea areas) are based on the environmental conditions in the spring 2015.



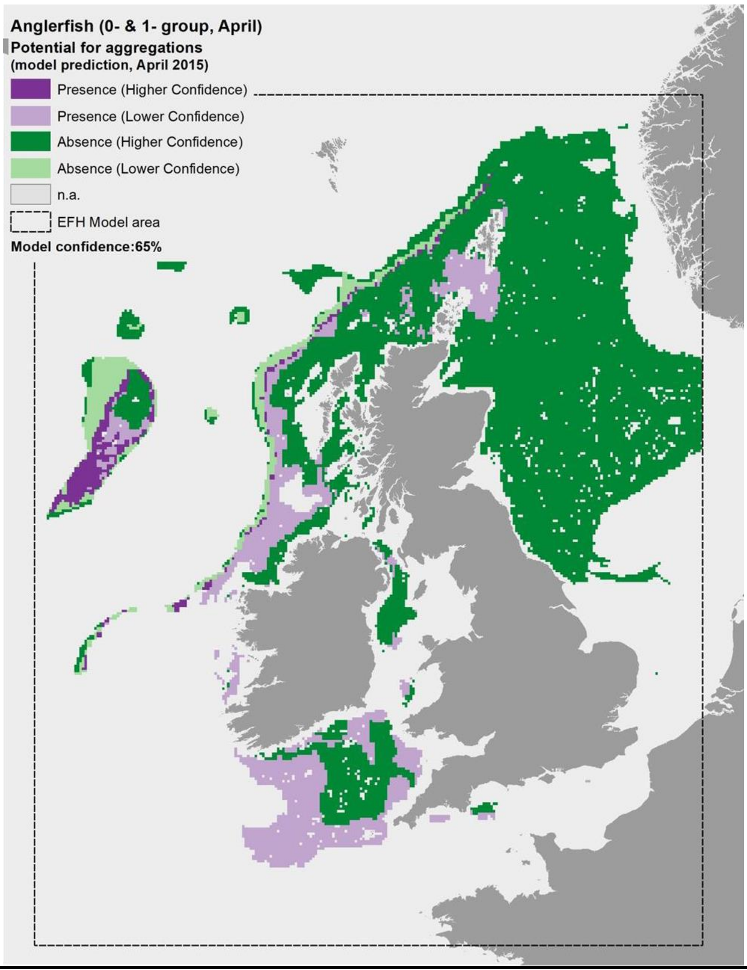


Table 19. Natural capital accounting, ecosystem services valuation
A. Description of the methodological approach:
The natural capital approach to policy and decision-making considers the value of the natural environment for people and the economy, providing a tool to support the protection and management of the natural environment and to facilitate the engagement of stakeholders within

management decisions. The UN System of Environmental-Economic Accounting Ecosystem Accounting (SEEA EA) is the globally adopted statistical standard on ecosystem accounts used to map, assess and achieve good condition of ecosystems (Vallecillo et al., 2022). The reference framework is used to assess the condition of EU ecosystems, so they continue delivering societal benefits, as required by the EU Biodiversity Strategy for 2030. SEEA EA is a spatially based, integrated statistical framework for organizing biophysical information about ecosystems, measuring ecosystem services, tracking changes in ecosystem extent and condition, valuing ecosystem services and assets and linking this information to measures of economic and human activity (United Nations et al., 2021). The SEEA EA is built on five core accounts (see example below) which are compiled using spatially explicit data and information about the functions of ecosystem assets and the ecosystem services they produce.
B. Application of the tool:
Natural capital accounts are developed to assess and monitor the contribution of natural resources to economic activity. Physical accounts tables provide basic information on the state of the environment (the stock and the flows of the natural capital, analogous to ecological structure and functioning) in a specific geographical area. When a condition table is also populated, this information can indicate at what level of the ecosystem an impact of economic activities is occurring. However, given the complexity of the marine environment, and the fact that in the SEEA EA only the societal benefits for which a market value exists are reported, for policy and project decision making there might be the need to go beyond SEEA EA accounts. This is currently being addressed in the Horizon Europe MARBEFES project. Examples of applications of natural capital accounting include: the study by Blazquez (2021) which provides preliminary results and first estimates of natural capital accounts for the NE Atlantic area, the work associated with the first marine natural capital accounts for the United Kingdom by the UK Office for National Statistics (2021a, b) and Grilli et al. (2021) which reviews the limitations, opportunities and lessons learned from the United Kingdom experience.
C. Tool requirements:
The following data are required to populate the five ecosystem accounts: 1. ECOSYSTEM EXTENT accounts record the total area of each ecosystem, classified by type within a specified area (ecosystem accounting area). Ecosystem extent accounts are measured over time in ecosystem accounting areas (e.g., nation, province, river basin, protected area, etc.) by ecosystem type, thus illustrating the changes in extent from one ecosystem type to another over the accounting period; 2. ECOSYSTEM CONDITION accounts record the condition of ecosystem assets in terms of selected characteristics at specific points in time. Over time, they record the changes to their condition and provide valuable information on the health of ecosystems; 3. and 4. ECOSYSTEM SERVICES flow accounts (physical and monetary) record the supply of ecosystem services by ecosystem assets in physical units and the use of those services by economic units, including households, in monetary units; and 5. MONETARY ECOSYSTEM ASSET accounts record information on stocks and changes in stocks (additions and reductions) of ecosystem assets in monetary units. This includes accounting for ecosystem degradation and enhancement.
D. Key example References or Resources
• Blazquez, 2021; Gacutan et al., 2022a, b, Grilli et al., 2021; ONS, 2021a, b; United Nations et al., 2021; Vallecillo et al., 2022. • The SEEA EA Framework for natural capital accounting (United Nations et al., 2021):

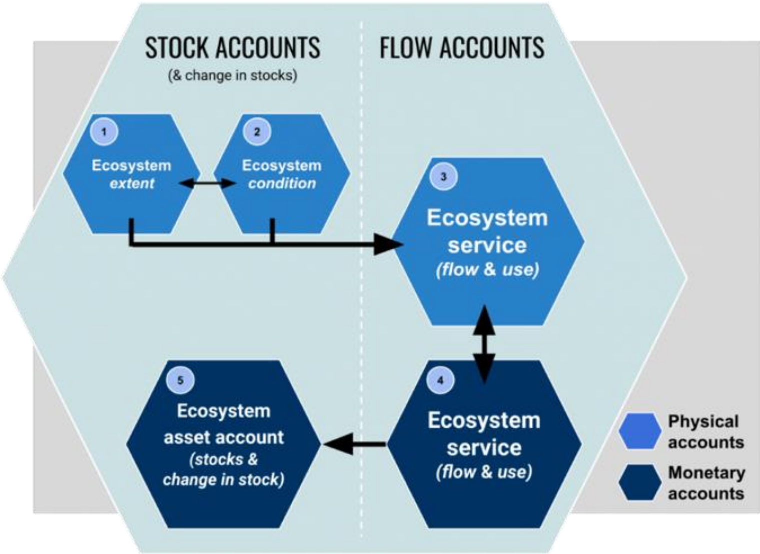


Table 20. Bioeconomic models, socioeconomic models, CBA, societal goods and benefits valuation
A. Description of the methodological approach:
• **Bio-economic modelling:** Bio-economic models are integrated economic-ecological models. Among the important fields of application for bio-economic modelling are resource management and sustainable resource use. For example, bioeconomic theory and models in fisheries combine the biological and economic aspects of a fishery to explain stock, catch, and effort dynamics under different regimes, and provide insights on the optimal management of the stock (Christensen et al., 2011, Sola et al., 2020). • **Valuation of Societal Benefits:** Since marine ecosystem services have the potential to lead to benefits for society it is appropriate to consider and determine their value (Atkins et al., 2011). Value can be defined in terms of ecological value, economic value, and socio-cultural value (MA, 2003). The concept of 'total social value', which comprises these three definitions, can be used to incorporate value preferences of society associated with natural capital into the decision-making process to inform policy options and management measures (see figure below). Whilst ecological valuation does not directly contribute to total social value, its contribution is indirect in that it provides the basis for both assessments of economic value and socio-cultural value (Burdon et al., 2018). • **Cost Benefit Analysis:** Cost-benefit analysis (CBA) is a core tool of public policy. The systematic process of calculating the benefits and costs, expressed in monetary units, of policy options and projects is now widely regarded as an essential step in the policy process as it helps decision makers to have a clear picture of how society would fare under a range of policy options for achieving goals (OECD, 2018). Environmental CBA is the application of CBA to projects or policies that have the deliberate aim of environmental improvement or actions that somehow affect the natural environment as an indirect consequence. In the UK, the Green Book (HM Treasury, 2022) offers detailed guidance issued by HM Treasury on how to appraise public policies, programmes and projects, including those involving the natural environment.
B. Application of the tool:

• **Bio-economic data:** The data required for bio-economic models is dependent on the focus of the model, but in general requires the input of both ecological and economic data. For example, Bartellings et al. (2015) present the Spatial Integrated bio-economic Model for FISHeries (SIMFISH). In this model fishers' behaviour is simulated based on optimal effort allocation. The added value of this model compared to other existing spatial management tools lies in the presence of (i) short- and long-term fishers' behaviour (ii) spatial explicit stock and fleet dynamics and (iii) relatively low data requirements. As an illustration, SIMFISH is applied in this paper to estimate the impact of area closures in the North Sea. In a second example, Cisse et al. (2013) developed and applied a bio-economic model for the ecosystem-based management of the coastal fishery in French Guiana. • **Valuation data** can be used to monitor changes in the provision of ecosystem services, and their associated societal benefits, over time. Such assessments can be used to assess natural changes in the system or the impact of existing or proposed management interventions (e.g., the designation of an extended MPA network – Hussain et al., 2010). Valuation data can be incorporated into natural capital accounts (e.g., ONS, 2021 - see Table X15), can be used to support Economic Impacts Assessments (e.g. in the case of the designation of new Marine Conservation Zones – Fletcher et al., 2012) or can feed into **Cost Benefit Analyses** e.g. Cooper et al. (2013) assessed the costs and benefits associated with seabed restoration following the cessation of dredging activities in the North Sea and Davis et al. (2019) estimated the economic benefits and costs of highly-protected marine protected areas.
C. Tool requirements:
• **Bio-Economic Models**: In the case of the fisheries models, these require data on biological, economic and transversal variables (catch and effort). Biological data requirements include (age structured) assessment outputs and biological parameters (such as natural mortality, maturity and weight at age). Economic data requirements include costs and earnings at the fleet segment level. Transversal variables should match both the biological and economic levels of disaggregation. Currently there is typically a mismatch across the different data sources. • **Valuation of Societal Benefits:** Regarding economic valuation, for some marine ecosystem benefits market prices may reflect their value (e.g., fish landed for human consumption), but for others a market price either does not exist (e.g., spiritual and cultural well-being) or does not reflect the social value of that benefit. It is not appropriate to value basic marine processes without identifying explicitly the associated ecosystem services and societal benefits which have human welfare implications (Turner et al., 2015). Therefore, valuation focusses on societal benefits only, to avoid double counting of values from natural capital and/or ecosystem services. A suite of economic valuation methods, including market and non-market approaches, are available which can be applied to value the flow and changes in the flow of ecosystem services (see example below). Primary data collection can be costly with respect to time and resources. Therefore, where valuation data are not available for a specific location/region, management decisions may need to be based upon value (or benefit) transfer methods. This approach uses primary valuation research results from one area (a study site) to make secondary predictions about values at a different area (the policy site) (Atkins et al., 2013). There is currently a paucity of valuation data for the broad range of societal benefits associated with the marine environment. Much of the valuation data available within the literature relates to a limited number of societal benefits, largely those which have widely recognised unit prices such as food provision (e.g., Cooper et al., 2013), tourism and nature watching (e.g., Luisetti et al., 2014), and carbon sequestration resulting in a healthy climate (e.g., Luisetti et al., 2015;

Watson et al., 2020). Such valuation data are often obtained at the local level through case studies, with few such studies collecting time series data, which is valuable for identifying changes in benefit delivery over time or collecting data at the national level. The ensuing data gaps make valuing the marine environment challenging.

- **Cost Benefit Analysis:** The approach to the monetary valuation of costs and benefits includes assessment based on opportunity costs (defined by the value which reflects the best alternative use a good or service could be put to), and valuation may include data based on market prices and non-market monetary valuation where market prices are not available. Data on all relevant costs and benefits implies a requirement for data on a range of variable including those associated with natural capital, health and risks to life. Significant benefits and risks that are beyond direct monetisation can be considered by comparing alternative scenarios with and without their inclusion, which can be used to reveal their costs. This informs choice by considering whether these cost differences are worth paying.
- All three are data and skills rich tools/approaches.

D. Key example References or Resources

- Atkins et al., 2011, 2013; Bartelings et al., 2015; Burdon et al., 2018, 2022; Cissé et al., 2013; Davis et al., 2019; Fletcher et al., 2012; Hussain et al., 2010; Luisetti et al., 2011, 2019; OECD, 2018; HM Treasury, 2022; Watsonet al., 2020; Turner et al. 2015; MA, 2003.
- Example of a conceptual framework linking natural capital, ecosystem services and societal benefits with Total Social Value and valuation methods (Burdon et al., 2022 and references therein):

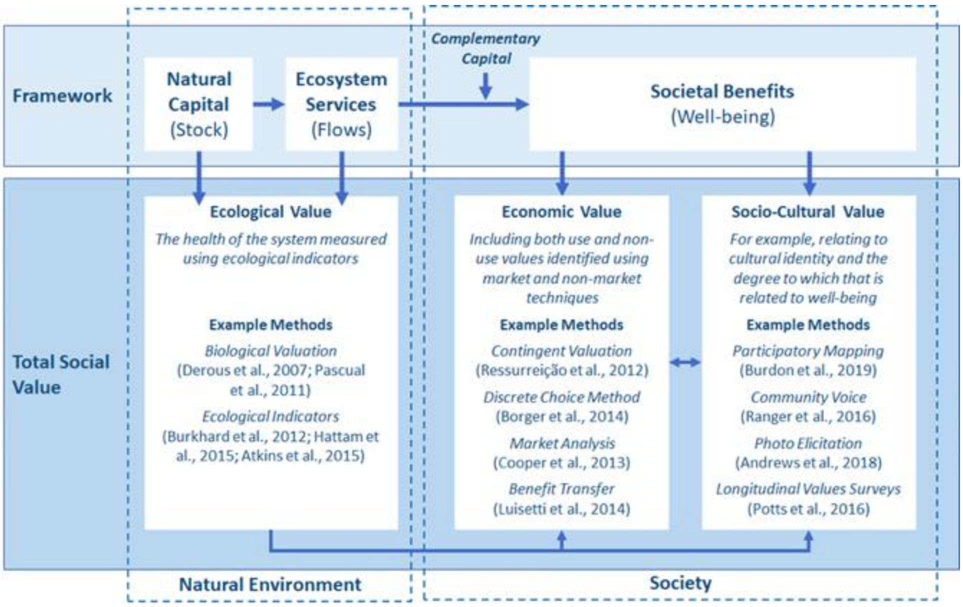


Table 21. Spatial planning models (e.g., GIS, VAPEM)

A. Description of the methodological approach:

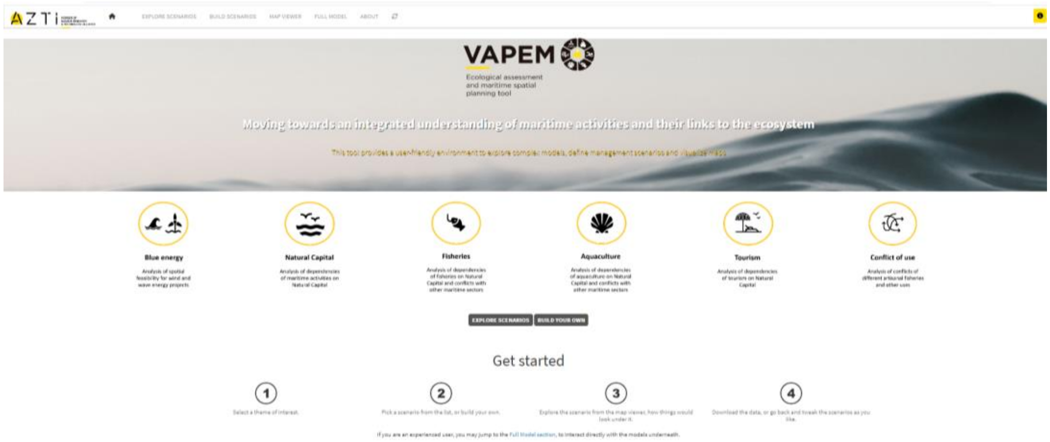
Spatial planning models, adapted to marine realm, are tools used to help planners and policymakers make informed decisions about the use of marine space and resources. The models are designed to provide insights into the potential impacts of different planning scenarios, and to help identify the most effective strategies for achieving specific planning goals. There are several different types of spatial planning models, each of which is suited to different types of planning challenges. Overall, spatial planning models are valuable tools for helping planners and policymakers make informed decisions about how to manage and develop the built environment in a way that promotes social, economic, and environmental sustainability. They are used to assess the impact of different land-use and development scenarios on environmental quality and natural resources. They can help planners identify areas of the city or region that are most vulnerable to pollution, habitat loss, or other environmental hazards, and evaluate the effectiveness of different conservation strategies.

Geographic Information Systems (GIS) are computer-based tools used to store, analyse, and visualize spatial or geographic data. GIS systems allow users to capture, manipulate, analyse, and present geographic data in a variety of ways, including as maps, charts, and 3D models.

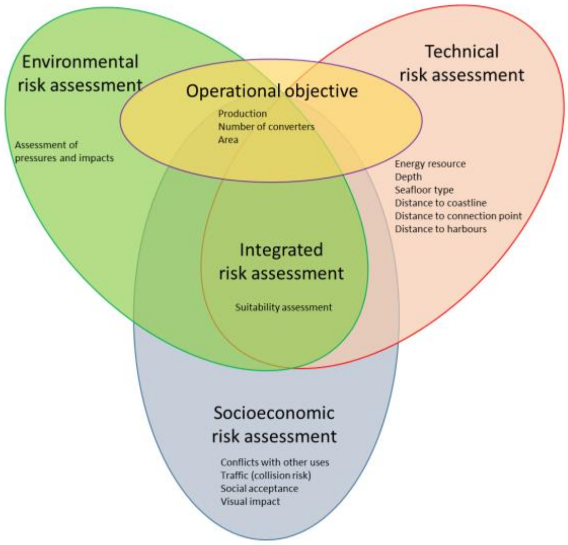
GIS applications can be used for a wide range of purposes, including environmental monitoring and management, urban planning, natural resource management, emergency response, and market analysis, among others. For example, a GIS system could be used to map the distribution of pollutants in an area, or to analyse the impact of proposed infrastructure projects on the natural environment.

GIS systems are powerful tools that allow users to integrate and analyse data from a variety of sources to gain insights into complex geographic phenomena. They have become an essential tool for decision-makers in a wide range of issues.

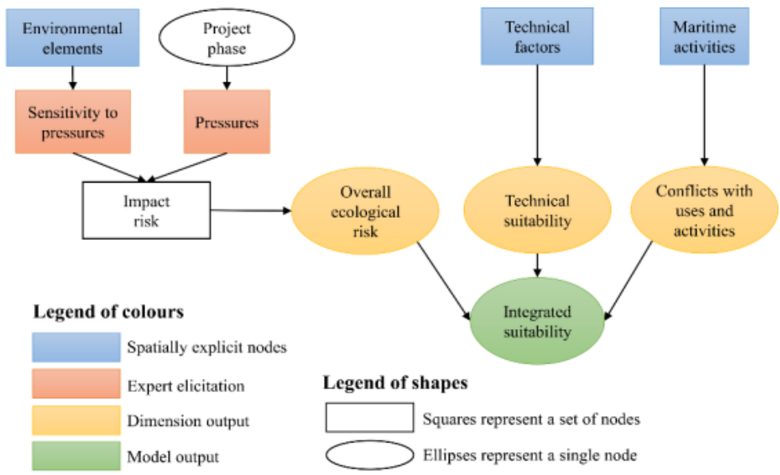
VAPEM tool (Ecological Assessment and Marine Spatial Planning Tool) is an open access web-based decision support tool (https://aztidata.es/vapem/) which integrates the environmental risk information (through WEC-ERA tool information, Galparsoro et al., 2021) together with the technical and socio-ecological information linked to wave energy projects, into a Bayesian model (Galparsoro et al., 2022b). The environmental dimension of the model is based on the integration of 16 pressure types and 27 ecosystem elements according to the MSFD.



Front page of the VAPEM tool



Conceptual model of VAPEM tool (Galparsoro et al., 2020)



Model structure and factors considered for the identification of suitable areas for the development of wave farms. Adapted from Maldonado et al. (2022)

B. Application of the tool:

The VAPEM tool permits the user the exploration of predefined scenarios or the generation of scenarios by the user. It provides information on the feasibility of wave energy projects development under different technical, environmental, and socio-economic conditions. The outcome of the assessment is also provided as a spatially explicit feasibility map. VAPEM tool is designed especially for managers and decision makers, but also for the industry or other kind of stakeholders, to inform about different options of development of wave energy projects under MSP framework. More details in Maldonado et al. (2022).

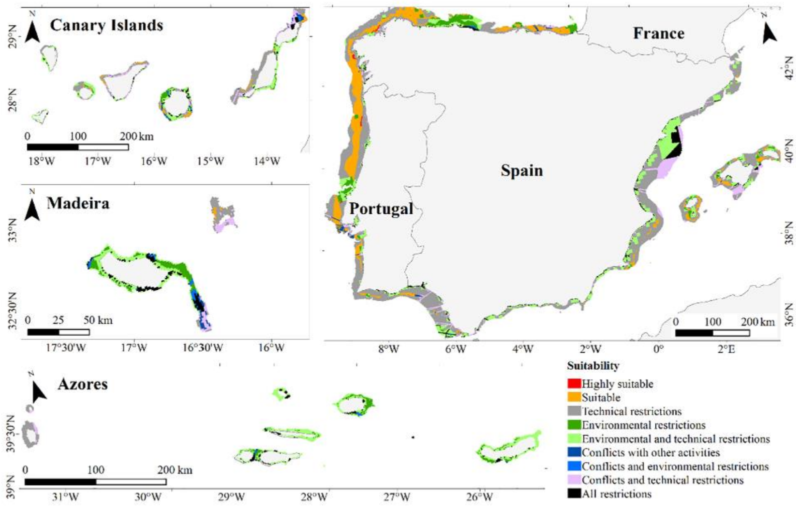
C. Tool requirements:

Technical information: seafloor score, wave resource, weather window, distance to the nearest port, and distance to the nearest electric substation. Environmental information: pressures produced by the wave converters, sensitivity of the ecosystem elements to the pressures, the spatial distribution of the ecosystem elements, the impact risk for each ecosystem element and the overall ecological risk. Socioeconomic information: activities that make use of marine space and that may be incompatible or cause limitations to the development of wave energy farms.

VAPEM is a rich data tool with many types of data layers needed (as detailed above) requiring a range of skills (e.g., in GIS and analytical skills).

D. Key example References or Resources

- VAPEM tool: https://aztidata.es/vapem/
- Maldonado et al., 2022.
- Example of spatial distribution of integrated suitability for the development of offshore wave energy farms in Spain and in Portugal adopted from Maldonado et al., 2022:



- Example of a Bayesian model defined for VAPEM tool adapted from Maldonado et al. (2022). In green "environmental dimension", the environmental pressures (stressors) that might be produced by wave energy converters, the ecosystem elements that are sensitive to those pressures (receptors), and corresponding ecological risk. In yellow nodes for which the model is fed with spatially explicit information. In green factors considered under "technical dimension"; and in orange the marine activities that potentially conflict with the establishment of wave farms.

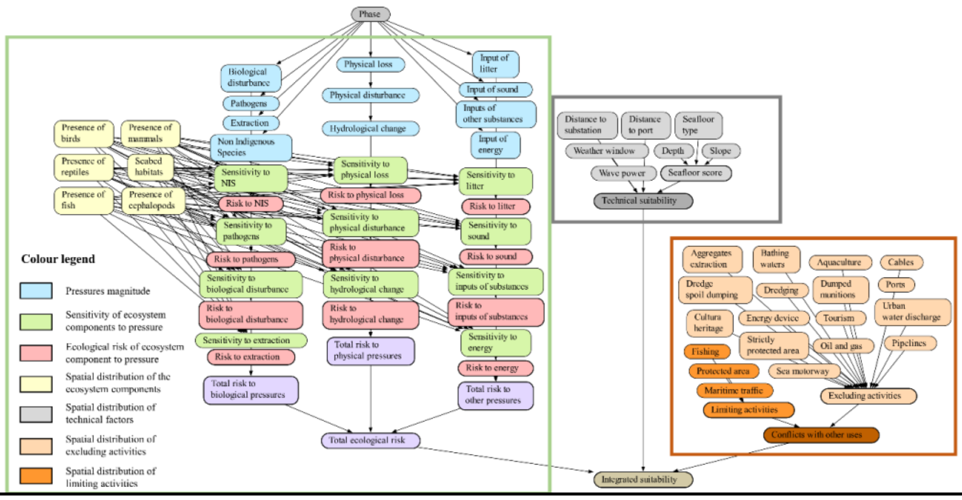


Table 22. Systematic conservation planning models (e.g., MARXAN, ZONATION)

A. Description of the methodological approach:

Conservation planning is "the process of locating, configuring, implementing and maintaining areas that are managed to promote the persistence of biodiversity and other natural values" (Pressey et al., 2007). Systematic conservation planning (SCP) has six distinctive characteristics (Margules and Pressey, 2000): (1) requirement for clear choices about the ecological features that will be used as surrogates for overall biodiversity; (2) it is based on clear goals, translated into operational targets; (3) it recognizes the level of achievement of conservation goals in the existing protected areas; (4) it uses an explicit and transparent methodology to locate and design new reserves complementing the existing network of protected areas; (5) it applies explicit criteria for implementing conservation actions; and (6) it adopts explicit objectives and mechanisms for maintaining the needed conditions in protected areas required to foster the persistence of the protected ecological features, as well as adequate monitoring schemes and adaptive management. SCP can implicitly account for the spatial variability of human uses and the associated cost of excluding human activities for the sake of protection, ideally expressed in monetary values (Naidoo et al., 2006). Hence, SCP approaches can account for trade offs between conservation and socio-economic priorities. The importance of SCP approaches for marine spatial prioritization in Europe has been repeatedly highlighted by experts (e.g., Giakoumi et al., 2012; Metcalfe et al., 2013; Mazor et al., 2014; Katsanevakis et al., 2020; Gimenez et al., 2020).

Decision support tools have been developed to facilitate systematic conservation planning, the most widely used being MARXAN and ZONATION. MARXAN attempts to solve the minimum set problem, i.e., design networks of protected areas that capture a set amount of biodiversity for the least cost (Ball et al., 2009). On the other hand, ZONATION attempts to solve the maximum coverage problem, i.e., design networks of protected areas that capture as much biodiversity as possible for a fixed budget/cost (Moilanen et al., 2009). This means the approaches underpinning MARXAN and Zonation are fundamentally different; nevertheless, comparisons between the two tools have not detected very different results (Delavenne et al., 2012).

MARXAN is a suite of spatial prioritization decision support tools that includes free software that can be used to solve conservation planning problems (https://marxansolutions.org/). The suite includes various variants of MARXAN (e.g., MARXAN with Zones, MARXAN with Connectivity) focusing on different applications. MARXAN uses a simulated annealing algorithm to find a suite of good near-optimal systems of priority areas that meet conservation targets while attempting to minimize socio-economic costs. MARXAN with Zones allows any parcel of land or sea to be allocated to a specific zone, not just reserved or unreserved. Then, each zone has discrete management actions, objectives, and constraints, with the flexibility to define the contribution of each zone to achieve targets for pre-specified features (e.g., species or habitats). The objective is to minimize the total cost of implementing the zoning plan while ensuring a set of conservation objectives are achieved. In 2018, through the Biodiversity and Protected Areas Management programme (BIOPAMA), the Joint Research Centre working with The Nature Conservancy managed to prototype a web-based MARXAN platform that improves accessibility to non-experts. In 2020, MARXAN developers partnered with Microsoft to bring the MARXAN platform to the cloud, scaling its infrastructure for global accessibility. MARXAN is currently a key application featured on Microsoft's Planetary Computer.

Zonation (https://zonationteam.github.io/Zonation5/) is a freely available decision support software tool, operating on spatial data about ecological features, costs, and threats, also utilizing information about uncertainty and connectivity. It is versatile, including a broad set of methods and analyses that can be used to address different types of spatial prioritization problems and analytical needs (Arponen et al., 2006; Moilanen et al., 2009).

The spatial dynamic module of EwE, Ecospace, includes an optimization routine which incorporates Marxan's principles linking them to the spatial prediction capabilities of Ecospace (Christensen et al., 2009). Ecospace modelling capabilities are also being used to assess the effects of different management options, such as the placement of MPAs and other management interventions (Gomei et al., 2022; de Mutsert et al., 2023).

B. Application of the tool:

SCP tools can be used in various ways, such as to design networks of marine protected areas to reach specific spatial targets, complement existing MPA networks with additional sites, create zones within an existing or expanded network of MPAs, prioritize management actions, assess and improve the connectivity of an existing network of MPAs, integrate terrestrial-freshwater-marine conservation planning, assess trade offs between ecological and socioeconomic priorities in maritime spatial planning, assess the cost-efficiency of an existing or proposed network of MPAs, and assess the outcomes of different scenarios affecting goals and operational targets. Such tools are very relevant for the implementation of the spatial targets of the Biodiversity Strategy for 2030 (30% protection – 10% strict protection).

Selected examples:

- [Giakoumi et al., 2012] MARXAN was used in the Greek Ionian Sea to identify priority areas for conservation of coastal and offshore biodiversity, under different scenarios, taking into account socio-economic factors expressed as a single cost metric, weighting different economic sectors in proportion to their contribution to the GDP of the region. The results were compared with the existing Natura 2000 sites in terms of goal achievement, area requirements, and cost. Existing Natura 2000 sites were found to fail in achieving conservation goals for some EU priority and other important coastal and offshore habitats and species.
- [Doxa et al., 2022] A framework for 4D conservation planning was developed, where the 3rd dimension is depth, and the 4th dimension is time (climate-driven predicted changes in the distribution of biodiversity). Spatial prioritization of marine areas in the Mediterranean Sea was based on both ecological and climatic criteria, considering the present and future distribution of >2000 benthic and pelagic species, using ZONATION.
- [Hermoso et al., 2021] An approach was developed to identify priority areas for conservation across three different realms (freshwater–terrestrial, estuary and marine) for multiple species, including species that inhabit or move across the three realms and accounting for different types of connectivity (longitudinal connectivity along rivers or multidimensional connectivity in the estuary and marine realms, guided by currents and depth similarity), using MARXAN.
- [Evans et al., 2015] MARXAN coupled with a biophysical habitat map was used to investigate representative MPA network scenarios and to assess the efficiency and representativeness of the existing High Seas MPA network in the Northeast Atlantic.

C. Tool requirements:

Data needed include:

- Spatial distribution of ecological features (habitats, species, geomorphological features, other surrogates of biodiversity), i.e., GIS layers.
- Spatial distribution of human uses, e.g., fishing effort, shipping, aquaculture, UW cables or pipes, offshore exploration, wind farms, port facilities, coastal infrastructure etc.
- Spatial distribution of existing management measures, sectoral or regional management plans, e.g., Fisheries Restricted Areas, OECMs, management plan for aquaculture, management plan for tourism, etc.
- Valuation of human uses or surrogates to estimate opportunity costs (i.e., loss of revenue by restricting human uses).
- Data on connectivity (e.g., based on oceanographic models, species molecular analyses, tagging etc.).

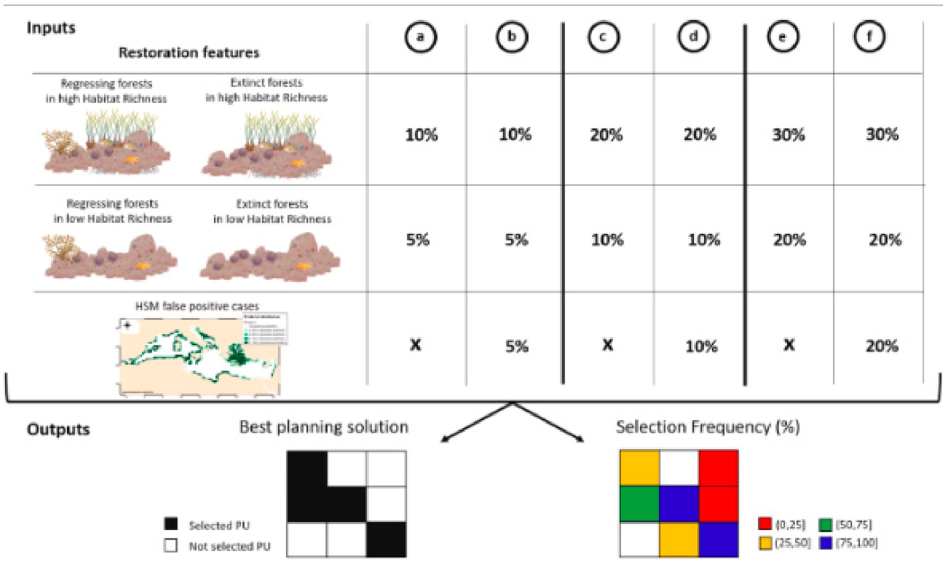
- Vulnerability data (linking the impact of human activities to ecological components).

Several approaches can be applied by using surrogates to cover data gaps.

Skills needed: GIS, use of SCP tools such as MARXAN or ZONATION, analytical skills

D. Key example References or Resources

- Arponen et al., 2007; Ball et al., 2009; Delavenne et al., 2012; Doxa et al., 2022; Evans et al., 2015; Giakoumi et al., 2012; Hermoso et al., 2021; Katsanevakis et al., 2020; Margules and Pressey, 2000; Mazor et al., 2014; Metcalfe et al., 2013; Moilanen et al., 2009; Naidoo et al., 2006; Pressey et al., 2007; Fabbrizzi et al., 2023.
- Example of MARXAN inputs and outputs from Fabbrizzi et al., 2023:

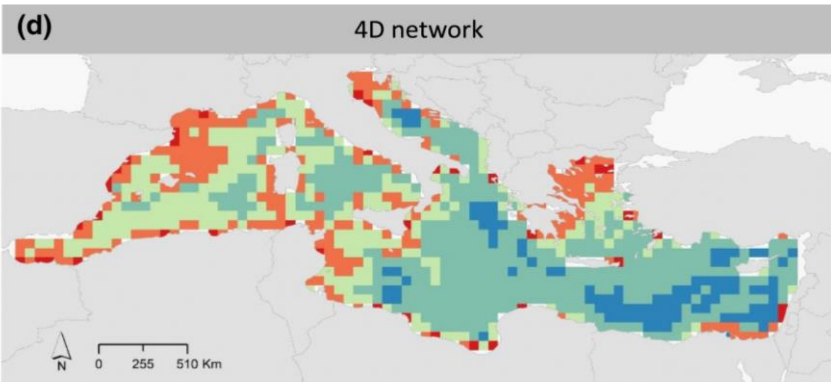


Download : Download high-res image (517KB)

Download : Download full-size image

Fig. 2. Graphical representation of Marxan inputs and outputs. Letters *a*, *b*, *c*, *d*, *e* and *f* correspond to the six scenarios while percentage numbers represent the targets set for each restoration feature in each scenario. In the scenarios *b*, *d*, and *f*, letter "x" means that the HSMf (i.e., the HSM false positive cases) were not taken into account.

- Example of outputs from Doxa et al. (2022) based on ZONATION



The 4D priority network in the Mediterranean Sea, proposed by Doxa et al. (2022). High-priority areas are indicated in dark red and medium-priority areas in orange. A depth-specific prioritization analysis was developed to inform the design of protected areas (three dimensions), further including metrics of climate-driven changes in the ocean (time: fourth dimension). Climate change was captured in this analysis by considering the projected future distribution of >2000 benthic and pelagic species inhabiting the Mediterranean Sea, combined with climatic stability and heterogeneity metrics of the seascape.

Table 23. Simple assessment index (e.g., M-AMBI)
A. Description of the methodological approach:
Simple assessment indices are methods for classifying marine systems according to human pressures and include those focusing on the primary community structural variables (abundance, species richness, and biomass) and derived community structural variables (such as diversity indices, abundance and biomass ratios, and evenness indices) (Gray and Elliott, 2009). These indices can also include functional analyses such as those involving feeding guilds (as in the Infaunal Trophic Index (ITI)) and their responses to organic matter inputs or other human pressures (such as the so-called 'biotic indices'). There are dozens, if not hundreds, of biotic indices, covering different biological elements, which include phytoplankton, zooplankton, macroalgae, seagrasses, macroinvertebrates and fishes (Borja et al., 2023). Well known examples of indices used by the RSC and EU MS for their MSFD assessments include: AZTI's Marine Biotic Index AMBI, Trawl Disturbance Index TDI, Benthic Ecosystem Quality Index BEQI, Danish quality index DKI, HELCOM State of the Soft-bottom macrofauna community BQI, HELCOM Cumulative Impact from physical pressures on benthic biotopes CumI, ICES PD median benthic longevity, OSPAR Benthic Indicator Species Index BISI, OSPAR Area of habitat loss BH4, OSPAR Extent of physical disturbance to benthic habitats BH3, OSPAR Sentinel of the Seabed SoS -BH1. Among the assessing biotic indices, those using several metrics (e.g., richness, diversity, proportion of opportunistic/sensitive species, etc.) and combined in different ways (e.g., multimetric, multivariate) have been very successful, especially after the Water Framework Directive requirements (Birk et al., 2012). One of the most successful indices, used for macroinvertebrates, is AMBI and its derivative Multivariate AMBI (M-AMBI), which have given place to multiple adaptations, changes, new indices and even applications to other biological elements, such as foraminifera or bacteria (Borja et al., 2019). M-AMBI is a multivariate index, which includes richness, diversity and AMBI, and is calculated comparing monitoring data and reference conditions of high and bad status, using a factor analysis (Muxika et al., 2007). The result of the calculation is a value between 0 (worst status) and 1 (best status), being the quality status classification divided into five quality classes, from bad to high. The thresholds between the different quality classes, and especially those between moderate and good, have been intercalibrated and agreed among the European countries, not only for this index, but also for all

used in the different regional seas (European Commission, 2018).
B. Application of the tool:
M-AMBI was developed to be used primarily in the ecological status assessment within the Water Framework Directive, where it is intercalibrated with other European indices (European Commission, 2018). In addition, it has been used in assessing the environmental status within the Marine Strategy Framework Directive, both in Descriptor 5 (eutrophication) and Descriptor 6 (seafloor integrity). Also, it has been used worldwide in assessing the impacts from different human pressures. Recently, it has been adopted by the US Environmental Protection Agency (EPA) as the official method to assess the status of all estuaries and coasts in USA (US EPA, 2021a, b). It has been used to assess the impacts produced by many different human pressures (e.g., 15 in the case of Borja et al., 2015), or in a meta-analysis of 834 references, including 6 human pressures, 11 biogeographical areas (covering from poles to equator), and 26 responsive variables, including nutrients, metals and organic compounds (Borja et al., 2019).
C. Tool requirements:
• Data: for the index calculation only the abundance or biomass per species and station/replicate is needed (also, it can be calculated at other taxonomical levels, e.g., genus, family). The most important is to set reference conditions for each type to be assessed i.e., community, defined by salinity, depth and sediment grain size. There is a free software tool allowing the calculation (https://ambi.azti.es) • It can be calculated with any number of stations, but it is true that a minimum number of 50 sampling stations is recommended, to reduce uncertainty (Borja et al., 2008)
D. Key example References or Resources
• Borja et al., 2008, 2015, 2019, 2023; EC, 2018; Muxika et al., 2007.

Table 24. Descriptor or theme specific combination of indices and models (e.g., HEAT, BEAT and CHASE)
A. Description of the methodological approach:
The indicator-based multi-metric assessment tools integrate quantitative indicators to inform of the integrated state of the assessment area. Tools have been developed for hazardous substances (CHASE), eutrophication (HEAT), biodiversity (BEAT). The indicators use a threshold value indicating acceptable state from the un-acceptable state and the indicators can be grouped within the tool to best reflect the assessment topic. For example, in the integrated biodiversity assessment, habitat-related indicators are assessed together while species population indicators are assessed in another group of indicators. The integration of the indicators is on two levels: (1) indicators within a group are first integrated by weighted averaging to derive a state of the group and then (2) each of the groups are compared: the group with the worst state is selected to represent the integrated state of the area, following the precautionary principle. As the tools function with relatively simple integration techniques, the major effort is put into using representative indicators, reliable thresholds and ecologically meaningful grouping of indicators. The tools also include a confidence assessment which informs of any shortcomings in meeting adequate standards in data, indicator representativeness or threshold setting.
B. Application of the tool:
The hazardous substances (CHASE), eutrophication (HEAT), biodiversity (BEAT) tools were developed first for the Baltic Sea region but have expanded to the NE Atlantic (HEAT and CHASE), Western Mediterranean Sea (HEAT), Black Sea (HEAT/BEAST) and the European Environment Agency's pan-European state assessments. The eutrophication tool has been indirectly accepted by the European Commission as a tool to be used for the descriptor 5 assessment under the MSFD. The D5 assessment guidance by the EC

was developed by taking into account the HEAT requirements.

While the Descriptor 8 assessment (contaminants) requires substance-specific results, the CHASE tool can assist in comparing the substances by using the tool's Contaminant Ratios (CR) as well as in presenting overall status of the areas.

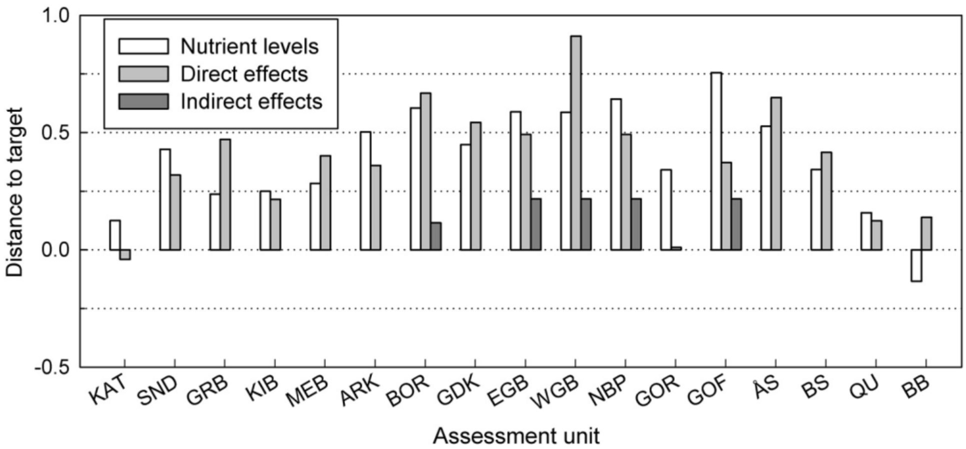
The BEAT tool is not directly applicable to the MSFD biodiversity assessments (descriptors 1, 3, 4 and 6) but is a good communication tool to illustrate the complicated multi-species/habitat results in a simple manner over large areas.

C. Tool requirements:

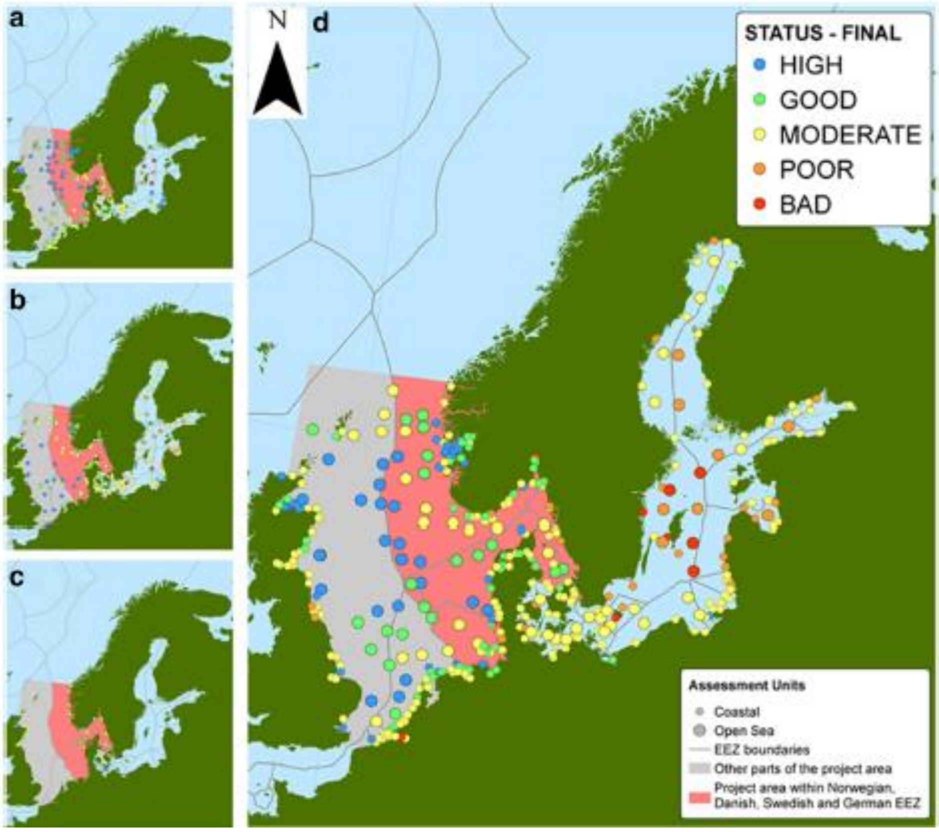
The HEAT, BEAT and CHASE assessment tools can be applied to any spatial level where data exists. HELCOM HOLAS III applies the HEAT tool into large assessment units (18 Baltic Sea sub-basins) where the underlying indicator data is aggregated over the assessment area whereas EEA is using the same tool in a grid where each grid cell calculates the HEAT result. The use of monitoring data which may restrict the spatial resolution of the assessment, but this has been recently improved by adding earth observation data. In principle, also modelled data could be used, but that should be validated against the indicator and its threshold. EEA has applied HEAT, BEAT and CHASE on a European-wide scale. The HEAT and CHASE tools have been used as analytical tools, e.g., focusing on long time series (Andersen et al., 2017) or on distance-to-target (Fleming-Lehtinen et al., 2015; see example below).

D. Key example References or Resources

- Andersen et al., 2011, 2014, 2016 a, b and 2017; Fleming-Lehtinen et al., 2015; Nygård et al. 2018;
- Example on distance-to-target from Fleming-Lehtinen et al., 2015:



- Example of CHASE assessment results from Andersen et al. 2016 b.



- Example of assessment result from Andersen et al., 2017

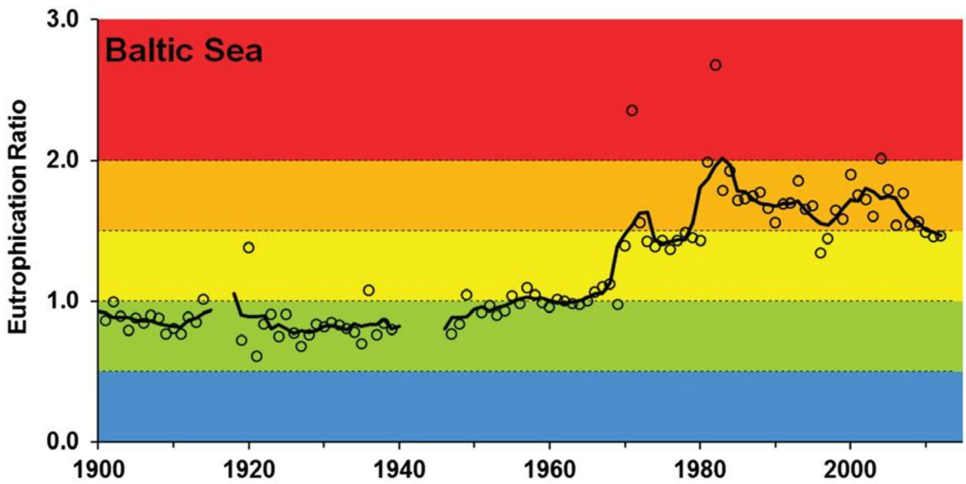


Table 25. Overarching assessment tools (e.g., NEAT and OHI)
A. Description of the methodological approach:
Two overarching assessment tools are well known, although addressing very different policy needs. Ocean Health Index (OHI) (Halpern et al. 2012) is an assessment tool customized by stakeholders to meet local management needs but also the comprehensive framework used to

measure ocean health from global to local scales, providing a measure of sustainability. A healthy ocean sustainably delivers a range of benefits to people now and in the future. The Ocean Health Index incorporates spatial data on cumulative impact of human activities, numerous single land and sea based human activities indicators (e.g. relative intensity of organic pollution due to pesticide runoff from land-based applications, relative intensity of nutrient pollution due to fertilizer runoff from land-based applications, relative magnitude of light pollution in coastal environments, magnitude of direct human interactions on coastal and near-coastal habitats, magnitude of increasing sea level due to increasing atmospheric CO2 levels from human influences, tonnes of demersal fisheries catch using non-destructive and low bycatch gear types, tonnes of catch using demersal destructive gear types, relative intensity of global shipping traffic) and reports on scores for 10 'goals': food provision, artisanal fishing opportunities, natural products, carbon storage, coastal protection, livelihoods and economies, tourism and recreation, sense of place, clean waters and biodiversity. The OHI 2023 global assessment includes scores from 2012 to 2023 for 220 coastal countries and territories (available from https://oceanhealthindex.org/). NEAT stands for "Nested Environmental status Assessment Tool". It is a tool primarily designed for (marine) environmental assessment but can in principle be used for other types of assessment too. The tool by Berg et al. (2018), in the context of DEVOTES, an EU funded project NEAT has a clean implementation of indicator aggregation through a hierarchy that is based on Spatial Assessment Units (SAUs). Due to a process of indicator normalization, NEAT can aggregate various indicators in such manner that all indicators within that SAU equals the same weight, unless indicated the opposite. Thus, NEAT avoids a bias from an uneven number of indicators per certain ecosystem component. The method is available with the free NEAT software, which is a desktop software for Windows and MacOS (current version 1.4). https://www.azti.es/en/productos/neat/
B. Application of the tool:
The tool is useful for environmental assessments as it has been designed for exactly that purpose. Usually, it is applied to marine environmental status assessment, and it allows describing the environmental status for the whole assessed area but it can also be visualized for the different spatial scales from the pre-defined SAU hierarchy, MSFD descriptors, ecosystem components (e.g., fish, phytoplankton, etc.), or habitat types. To reach this output, it uses state indicators that are assigned to a SAU, a habitat, a descriptor, and an ecosystem component. Each indicator has a unique value (and a standard error associated with it) for the MRUs for which information is available. In addition, each indicator requires defining the target value as well as the upper and lower thresholds. Prior to the aggregation of indicators within and across the different MRUs, indicators are normalized on a scale from 0 to 1, setting the boundary between no good and good environmental status at 0.6. The assessment outputs are accompanied with confidence assessment values, which are based on Monte Carlo permutations. It was first applied to 10 case studies across the European Seas (Uusitalo, 2016), ranging from smaller parts of e.g., the Dutch North Sea to larger areas such as the Norwegian Barents Sea. Subsequently, the method was applied to the Caspian Sea (Nemati et al., 2017, 2018) where impacted and non-impacted sites were compared and pressure indicators included into the assessment. Other applications include the Black Sea (Marin et al., 2020), Mediterranean Sea (Pavlidou et al., 2019, application in Greece covering 8 descriptors and 24 indicators), Malta (Borja et al., 2021, application covering seven descriptors), deep areas of the Atlantic (Kazanidis et al., 2020, application in 9 study areas in the North Atlantic focusing on five MSFD descriptors with 24 indicators), the Bay of Biscay (Menchaca et al., 2022; with 7 descriptors and 67 indicators) and in 26 Mediterranean MPAs (Fraschetti et al., 2022, application with an extensive dataset across five Mediterranean ecoregions).

C. Tool requirements:

The central principle in the NEAT method is a hierarchical, nested structure of spatial assessment units (called SAU) and habitats. These must be defined to run the assessment. The order of these hierarchies is such that the assessment begins with the hierarchically nested SAUs. For each of these, one or more habitats are assigned. These habitats are themselves nested and hierarchically structured so an indicator can be assigned to one individual habitat or to more than one habitat comprising all habitats from the hierarchical levels below. Each of the resulting SAU/habitat combinations is then used to assign the various indicators to. These indicators are typically designed around specific species or communities or functional groups, which spatially are in their own habitats, within a specific SAU. The method requires to know the value of each of the indicators and their corresponding assessment class boundaries (between high, good, moderate, poor and bad status) per SAU and habitats (these may vary). To run the assessment, the obtained indicator values are entered along with their standard error, so confidence assessments can also be obtained.

D. Key example References or Resources

- Berg et al., 2018; Borja et al., 2021; Fraschetti et al., 2022, Kazanidis et al., 2020; Marin et al., 2020; Menchaca et al., 2022; Nemati et al., 2017, 2018; Pavlidou et al., 2019; Uusitalo et al. 2016
- NEAT assessment results for Mediterranean MPAs, from Fraschetti et al., 2022

Table 2a	Sampled extent											Table 2b		Real extent – buffer 5 km								
SAU	Area (km²)	NEAT value	Status class	Confidence level (%)	Erect algae	Canopy algae	Fish	*P. oceanica*	Sea urchins	Turf	Barren	Area (km²)	NEAT value	Status class	Confidence level (%)	Erect algae	Canopy algae	Fish	*P. oceanica*	Sea urchins	Turf	Barren
MED	2.78	0.49	mod.	100	0.19	0.02	0.58	0.85	0.79	0.56	0.50	13558.79	0.47	mod.	100	0.23	0.16	0.38	0.77	0.87	0.55	0.53
PR	2.48	0.47	mod.	99.7	0.18	0.02	0.62	0.79	0.79	0.56	0.50	5073.14	0.53	mod.	100	0.17	0.10	0.51	0.85	0.86	0.56	0.50
Aegean	2.25	0.45	mod.	97	0.17	0.002	0.62		0.85	0.56	0.50	2481.48	0.45	mod.	98.3	0.16	0.002	0.59		0.87	0.56	0.49
Adriatic	0.01	0.55	mod.	100	0.52	0.38	0.46	0.66	1.00	0.59		118.27	0.48	mod.	99.9	0.52	0.38	0.39	0.69	1.00	0.51	
Ionian	0.01	0.35	poor	99.8	0.02	0.19	0.20	0.78	0.87	0.41	0.79	377.05	0.70	good	100	0.02	0.16	0.18	0.84	0.72	0.41	0.79
Western Med	0.21	0.65	good	98.7	0.83	0.68	0.67	0.80	0.54	0.64	0.97	2055.34	0.58	mod.	93.6	0.78	0.87	0.51	0.88	0.86	0.70	0.97
Tunisian Plateau	0.002	0.78	good	96.1	0.43	0.80	0.64		1.00			41.00	0.78	good	95.3	0.43	0.80	0.64		1.00		
Non-PR	0.30	0.64	good	100	0.45	0.17	0.39	0.87	0.78	0.54	0.58	8485.65	0.44	mod.	100	0.27	0.20	0.31	0.73	0.88	0.55	0.55
Aegean	0.04	0.41	mod.	99.9	0.16	0.03	0.23		0.94	0.53	0.54	3044.08	0.41	mod.	99.9	0.17	0.03	0.22		0.94	0.54	0.53
Adriatic	0.01	0.42	mod.	91.3	0.36	0.41	0.35	0.45	0.49	0.59		456.68	0.46	mod.	99.6	0.36	0.41	0.37	0.54	0.49	0.58	
Ionian	0.01	0.35	poor	100	0.01	0.22	0.15	0.67	0.96	0.45	0.57	934.14	0.53	mod.	100	0.01	0.41	0.16	0.67	0.96	0.45	0.57
Western Med	0.25	0.69	good	100	0.75	0.51	0.42	0.88	0.66	0.61	0.95	3823.88	0.43	mod.	99.7	0.80	0.67	0.33	0.89	0.79	0.66	0.96
Tunisian Plateau	0.002	0.76	good	96.2	1.00	0.52	0.47		0.90			226.87	0.76	good	97.7	1.00	0.52	0.47		0.98		

6. Tools Assessment

6.1. Workshop method

The groups (categories or types) of tools used in biodiversity and ecosystem assessment and planning, described in the previous section, were assessed against the elements of the EBM approach that are relevant to GES4SEAS work. A matrix scoring approach was used, whereby the tool groups (matrix rows, n=19, Table 5 in section 5.3) were assigned scores based on their ability to deliver on the specific elements of EBM (matrix columns, n=18, Table 4 in section 5.2). The score answered questions such as "Can these tool groups fully inform on the EBM element in question? Can they offer concrete advice alone or in combination with other tools?".

The scoring system used was as follows:

- Score 5 if the tool group fully delivers on the specific element of EBM;
- Score 3 if the tool group only delivers on some aspects of the specific element of EBM;
- Score 1 if the tool group only delivers on specific aspects of the EBM element and its use in combination with other tools is required to deliver the element of EBM;
- Score 0 if the tool group does not deliver on the EBM element (in full or partially).
- Leave blank if no score can be attributed (e.g., due to lack or insufficient knowledge).

The matrix was first circulated to the participants (GES4SEAS partners) of an in-person workshop undertaken on 2-3 March 2023 in The Hague, and subsequently to other experts amongst the GES4SEAS partners for input. The contributors were also asked to record their confidence (as high, medium or low) in their knowledge of the tool groups they scored.

The resulting data matrices were collated and averaged across contributors. Scores allocated by the contributors to tool groups with high or moderate confidence were only considered in the analysis. Due to blanks in the matrix, a variable number of responses contributed to the average depending on the tool-by-element pair. The number of responses considered in the average calculation was recorded, along with estimates of the standard deviation (SD) and range (min and max) of the scores across participants. The links of the EBM elements with the PACE management phases (see section 5.2 and Table 3) were also considered when interpreting the results.

A cluster analysis was applied to the matrix data (average of scores across contributors) to identify groupings of elements of EBM based on similarity of tools used and their ability to deliver the specific element of EBM. Group average algorithm was applied for the cluster analysis, based on

Euclidean distance. SIMPROF test applied to identify clusters of elements that do not significantly (P>0.05) differentiate based on tools used to deliver them. The cluster analysis was also undertaken between tool groups based on similarity of EBM elements they deliver. The contingency table from the clustering of both EBM elements and tools was explored and the score matrix rearranged accordingly to identify which tool groups better deliver for which EBM elements (or groups of elements within a cluster). The a priori categorisation based on the EBM process phases was also considered to interpret the data-based clusters.

6.2. Workshop Results

Input was obtained from 20 contributors amongst the GES4SEAS partners. Not all contributors scored all tool groups, and there was variable confidence according to the contributor's knowledge of the specific tool groups (Table 26).

Simple assessment indices (tool group #17), Overarching assessment tools (#19), Cumulative impact spatial mapping (#6) and Impact risk ranking through linkage-chain-frameworks (#7) were the tool groups that were most frequently scored and with higher confidence on average, compared to other tools (Table 26). This is likely a reflection of the expertise of the contributors which matches the main research aims of GES4SEAS. In turn, Bioeconomic/ socioeconomic models and societal goods and benefits valuation (#14), Biogeochemical models (#9) and Knowledge Graphs (#3) were the tool groups which received the lower number of scores and often with lower confidence (Table 26).

Some contributors prioritised the scoring of tool groups for which they had moderate to high confidence, whereas they did not score tool groups for which they felt they had poor or no knowledge. Due to this disparity in the recording of the scores with different confidence, the data entries were standardised by considering only scores with moderate and high confidence for the analysis.

Table 26. Number of contributors who scored each tool group with high, medium or low confidence.

Methodologies/tool groups		**Confidence in scoring**			**Total**
#	Tool group name	High	Medium	Low	
1	Conceptual models	3	7	1	11
2	Semi-quantitative mental models - Fuzzy Cognitive Mapping	1	9	2	12
3	Knowledge Graph	0	5	2	7
4	BBN probabilistic	3	6	1	10
5	Risk based approaches exposure-effect-hazard-vulnerability (e.g., Bow tie)	3	5	3	11
6	Cumulative impact spatial mapping (e.g., Halpern et al. 2008)	5	8	1	14
7	impact risk ranking through linkage-chain-frameworks (e.g., ODEMM)	5	4	1	10
8	Single spp. model (e.g., life cycle, stock assessment)	1	7	3	11
9	Biogeochemical models	0	3	6	9
10	Food web models (e.g., multispecies models, EWE)	1	9	1	11
11	Ecosystem models (e.g., End2End)	0	8	2	10
12	HSM models (spp. predictive distribution)	3	7	1	11
13	Natural capital accounting, ecosystem services valuation	2	4	5	11
14	Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation	0	2	6	8
15	Spatial planning models (e.g., GIS, VAPEM, related to use)	0	11	2	13
16	Conservation planning models (e.g., MARXAN)	2	7	3	12
17	Simple assessment index (e.g., M-AMBI)	6	4	2	12
18	Descriptor or theme-specific combination of indices and models (e.g., HEAT, BEAT and CHASE)	4	4	4	12
19	Overarching assessment tools (e.g., NEAT and OHI)	8	3	4	15

The mean scores attributed to the tool groups according to their ability to deliver on the specific elements of EBM are shown in Table 27. The EBM elements (columns) and tool groups (rows) in the table are grouped according to the results of the cluster analysis undertaken between EBM elements (Figure 9) and tool groups (Figure 10). The cells in the table are coloured to reflect the variability of the mean score of tool groups within each column (lowest score in the column is white, highest score in the column is dark blue). Additional information on the combined matrix scores across all contributors (number of scores assigned to each cell and their variability, as range and standard deviation) are given in Appendix 2.

Table 27. Mean scores assigned to each tool group (rows) based on their ability to deliver on a specific element of Ecosystem-Based Management (EBM) (columns). Scores assigned with high or medium confidence only were considered to calculate the mean values across all contributors. EBM elements and tool groups are grouped based on cluster analysis between EBM elements (Figure 9) and tools (Figure 10), respectively (gaps between columns and rows separate cluster groups at Euclidean Distance = 5). Links between EBM elements and the EBM process phases are also shown at the bottom of the table (see Figure 9 for an explanation of the codes). EBM elements in orange are those specifically addressed in GES4SEAS. Cells in the table are coloured in a monochrome gradient to reflect variability of the mean score from lowest (white) to highest (dark blue) value overall, indicating therefore the highest score-match between tool groups and EBM elements.

	Main Group	**EBM elements**										
Tool Table No.	AVERAGE of SCORES	Whole ecosystem assessments	**GES MSFD assessments**	Single MSFD Descriptors/single issues	Climate change	Pressure and impact reduction/mitigation	Other Policy Requirements	Specific biotic effects	Specific functions	Uncertainty	Single species, State change	Threatened habitats and species
18	Natural capital accounting, ES valuation	0.8	0.0	0.3	0.8	1.3	1.8	1.2	2.7	1.5	0.5	1.0
19	Bioecon., socioec. models, G&B valuation	1.5	0.0	0.0	0.5	0.5	1.5	0.5	0.5	0.0	0.0	0.0
14	Biogeochemical models	1.3	0.7	1.3	2.0	1.0	1.0	1.0	0.7	1.5	1.3	1.0
22	Simple assessment index	1.3	3.0	2.5	0.7	1.6	2.4	3.1	2.2	1.3	1.9	2.4
13	Single spp. model	0.9	1.3	2.0	1.7	1.3	1.6	2.6	1.4	2.1	3.3	2.4
17	HSM models	1.2	2.0	1.9	2.4	1.3	2.0	2.5	1.7	1.9	2.8	3.2
11	Cumulative impact spatial mapping	2.7	2.6	2.3	1.9	2.1	2.6	1.7	1.8	1.5	0.9	1.9
20	Spatial planning models	1.3	1.5	1.4	1.2	1.9	2.5	1.7	1.2	1.5	1.0	1.5
21	Conservation planning models	0.8	0.7	0.7	1.6	2.3	3.1	0.9	0.8	2.0	1.0	2.7
23	Descriptor or theme-specific combination of indices & models	3.3	4.8	4.8	1.7	2.1	2.9	2.3	2.5	3.1	2.5	2.6
24	Overarching assessment tools	4.5	4.5	3.3	1.9	2.5	3.0	1.5	1.4	4.0	2.9	3.1
12	impact risk - linkage-chain-frameworks (ODEMM)	3.2	1.9	2.8	1.6	3.3	2.8	2.3	3.0	1.6	2.2	1.7
9	BBN probabilistic	2.6	1.9	3.0	2.9	3.2	2.6	3.0	3.2	3.8	2.7	3.3

10	Risk based approaches (Bow tie)	2.3	2.1	3.5	2.7	4.3	3.8	3.3	3.0	2.6	2.5	2.8
8	Knowledge Graph	1.4	1.2	2.6	3.4	3.0	2.8	1.8	1.6	0.8	1.0	2.6
6	Conceptual models	2.5	2.0	2.6	2.9	2.8	2.1	2.7	3.0	1.8	2.2	2.4
7	Semi-quantitative mental models	2.1	1.4	2.6	2.6	2.5	2.1	2.0	2.0	1.3	2.0	2.3
15	Food web models	3.0	2.3	3.0	2.6	2.7	1.9	3.6	4.0	2.6	3.1	2.6
16	Ecosystem models	3.5	2.0	2.4	2.3	2.0	2.1	2.5	3.3	1.7	2.4	2.4
	Element label	3WholeEco	2GES-MSFD	10single MSFD/issues	13CC	14PIreduct	18Other Policy	5SpecifBiot	6SpecifFunct	16Uncert	11SingleCompStateC	12ThreatHab/Sp
	ProcessPhase	CE	CE	PA	Gen	PA	Gen	CE	PA	Gen	CE	CE
	ProcessPhase+	CE	CE	PA1	Gen1	PA3	Gen2	CE	PA1	Gen2	CE	CE

	Other groups	**EBM elements**						
Tool Table No.	AVERAGE of SCORES	Risks	cumulative assessments	Pressures-Activities footprint	Impacts footprints	ES (delivery, impacts, valuation)	Links activities pressures impacts	Spatial and other measures
18	Natural capital accounting, ES valuation	1.2	0.3	1.0	1.0	4.7	0.7	1.3
19	Bioecon, socioecon. models, G&B valuation	0.5	2.0	0.5	1.5	5.0	1.5	0.0
14	Biogeochemical models	0.5	0.3	0.0	0.0	0.3	0.0	0.7
22	Simple assessment index	0.9	1.1	0.8	1.0	0.8	1.2	1.4
13	Single spp. model	1.7	0.1	0.9	0.5	0.6	1.0	1.9
17	HSM models	1.8	1.8	1.1	1.2	1.7	1.2	2.1
11	Cumulative impact spatial mapping	2.5	4.7	4.0	3.8	1.7	3.1	2.6
20	Spatial planning models	2.1	2.8	2.9	2.5	1.7	2.7	4.3
21	Conservation planning models	1.6	1.8	2.2	1.8	0.8	1.9	4.6
23	Descriptor or theme-specific combination of indices & models	1.4	2.4	1.5	1.6	1.9	2.6	2.6
24	Overarching assessment tools	0.7	2.7	2.7	2.8	1.5	2.5	3.7
12	impact risk - linkage-chain-frameworks (ODEMM)	3.9	4.1	3.1	2.9	2.0	4.8	1.3

9	BBN probabilistic	3.6	3.4	1.8	2.0		2.4		4.6		1.6
10	Risk based approaches (Bow tie)	4.7	3.8	1.9	1.9		2.4		4.5		1.9
8	Knowledge Graph	1.2	1.4	1.0	1.0		1.2		4.6		1.0
6	Conceptual models	1.9	2.6	2.6	2.3		2.6		4.2		2.0
7	Semi-quantitative mental models	1.9	2.3	1.7	1.6		2.0		3.5		1.4
15	Food web models	1.8	2.1	1.3	2.0		1.7		2.0		2.5
16	Ecosystem models	1.8	2.3	1.0	1.1		2.1		2.4		2.0
	Element label	17Risk	1CumulA	7PAfootpr	8IFootpr		4ES		9APIlinks		15SpatialM
	ProcessPhase	Gen	PA/CE	PA	PA		PA		PA		PA
	ProcessPhase+	Gen2	PA1/PA2/CE	PA2	PA2		PA1		PA1		PA3

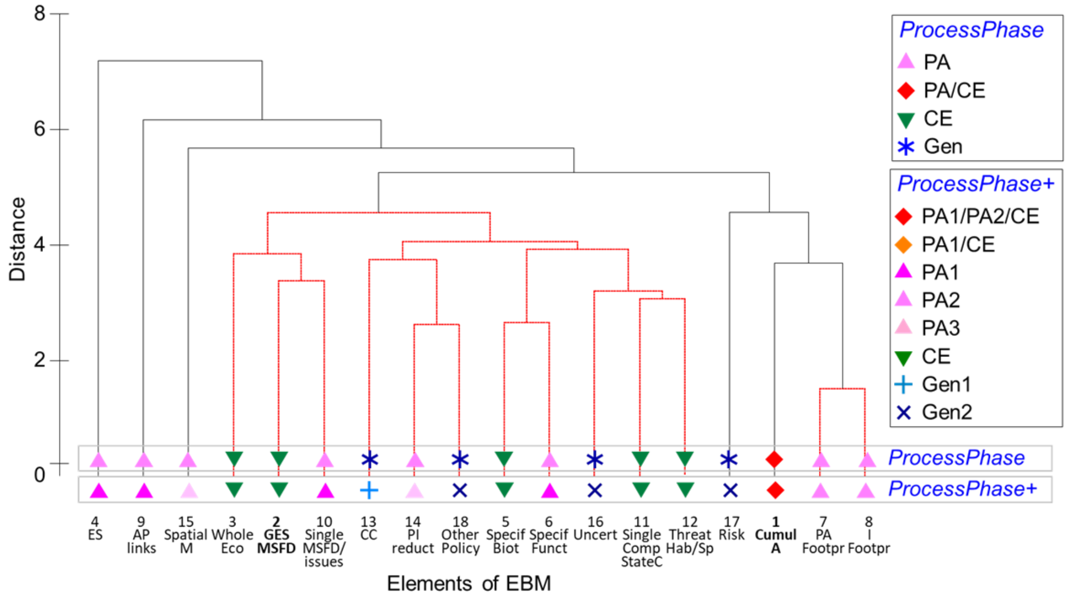


Figure 9. Cluster analysis of the elements of Ecosystem-Based Management (EBM) based on similarity of tools used and their ability to deliver the specific element of EBM (mean of scores with high or medium confidence). See Table 4 for EBM element labels. Symbols distinguish EBM elements according to the phase of the EBM process they are relevant to: for higher level process phases, elements used in the Planning phase (including assessment) (PA), in the Check-Evaluation phases (CE) or of general relevance (Gen); for detailed process phases, elements used in Planning are distinguished between elements for the application of CEA (and improvement along a cascade-effect approach) (PA1), including a spatial dimension (PA2) or to inform/guide Action phase (PA3), and elements of general relevance are further distinguished into those accounting for climate change (Gen1) and other elements (Gen2). Group average algorithm was applied for the cluster analysis, based on Euclidean distance. Elements connected by red lines do not significantly differentiate based on tools used to deliver them (SIMPROF test, P>0.05).

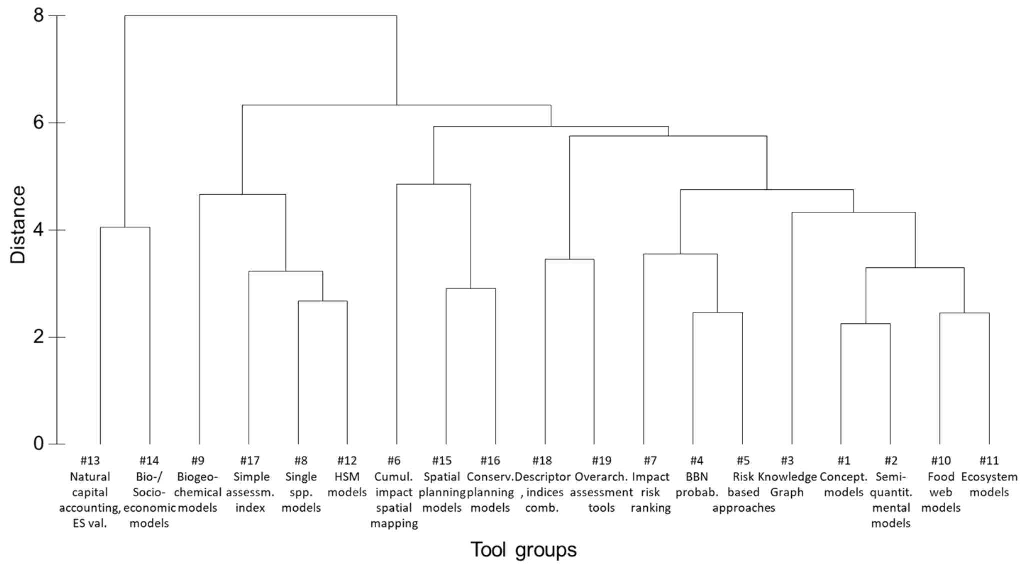


Figure 10. Cluster analysis of the tool groups based on similarity in the Ecosystem-Based Management (EBM) elements they can deliver (mean of scores with high or medium confidence). See Table 5 for full name and reference number of the tool groups. Group average algorithm was applied for the cluster analysis, based on Euclidean distance.

Risk based approaches accounting for exposure-effect-hazard-vulnerability (e.g., Bow-Tie; tool group #5), BBN probabilistic tools (#4) and Impact risk ranking through linkage-chain-frameworks (#7) were the top scoring tools overall. This set of tools, along with Knowledge graphs (#3) and Conceptual models (#1), were identified as the most suitable (with mean score values between 4.2-4.8 out of a maximum of 5) for the assessment of **Links between activities, pressures and impacts** during the planning phase of the EBM process (Table 3, Table 27).

Risk based approaches alone were also identified as the most suitable tool for the assessment of **Risks** and of **Pressure and impact reduction/mitigation**, with mean score values >4.2. This tool is also best suited to deliver the **requirements of other policies** (e.g., MSPD, BHD, Biodiversity Strategy), although the mean score in this case is lower (3.8) compared to the other EBM elements mentioned above.

The use of Descriptor or theme-specific combinations of indices and models (e.g., HEAT, BEAT and CHASE; tool group #18) and Overarching assessment tools (e.g., NEAT and OHI; #19) also scored high overall. They were considered the most suitable tools to deliver **GES MSFD assessments** during the Check/Evaluation phases of the EBM process (both tools scoring >4.5).

Descriptor or theme-specific combinations of indices and models (#18) were also the most suitable tool (score 4.8) to assess **Single MSFD Descriptors and single issues** (e.g., eutrophication, NIS, HABs), while the Overarching assessment tools (#19) were also the best option to undertake **Whole ecosystem assessments** (score 4.5), along with Ecosystem end-to-end models (#11), and for **Uncertainty assessments** (score 4.0), along with BBN probabilistic methods (score 3.8) (Table 27).

Spatial-based tools were best suited to deliver elements at the Planning phase of the EBM process. Cumulative impact spatial mapping (tool group #6) was identified as the best option to undertaken **Cumulative assessments** (score 4.7) and to assess the **footprints of pressures/activities** (score 4.0) **and of impacts** (score 3.8). Spatial and Conservation planning models (tool groups #15 and #16, respectively) were the most suitable option to deliver on **Spatial and other measures**.

Food web models (tool group #10) were identified as the best option to assess **Specific Ecosystem functions** (and impacts on functions) (score 4.0) and **Specific biotic effects/ impact** (score 3.6) during Planning and Check/Evaluation phases of the EBM process, respectively. Risk based approaches (#5) and Simple assessment indices (#17) were also relatively high scoring in the delivery of this latter EBM element.

Food web models were also amongst the top scoring tools (score 3.1) identified to deliver the assessment of **Single species, ecosystem Components State change**, although Single spp. Models (tool group #8) were identified as the best option for this element of the EBM Check/Evaluation phases, albeit with a score around the middle of the possible range (score 3.3).

HSM models (tool group #12) and Overarching assessment tools (#19) were also amongst the top scoring tools for the assessment of **Single species, ecosystem Components State change**, but their scores suggest a better suitability to deliver the assessment of **Threatened habitats and species**, along with BBN probabilistic methods (#4; top scoring for this EBM element, with a value of 3.3).

Tools such as Natural capital accounting, ecosystem services valuation (#13) and Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation (#14) are clearly the best option (scores >4.6) for the assessment of **Ecosystem Services (delivery, impacts, valuation)** during the Planning phase of the EBM process, while these tools are poorly suited to deliver other EBM elements (with almost all scores <2, and often 0; Table 27).

Finally, the best tool to account for **Climate change** in the EBM process appeared to be Knowledge Graphs (#3), followed by Conceptual models (#1) and BBN probabilistic methods (#4), albeit with scores only between 2.9-3.4.

Semi-quantitative mental models (tool group #2) never resulted among the best (top scoring) options to deliver any or the EBM elements considered, and a similar result was observed for Biogeochemical models (#9), although the latter tool was poorly covered in the present assessment, as mentioned before (Table 1).

A summary **table outlining the three top-scoring tool groups for each EBM element** is given below (Table 28). When only tools with average score ≥4 (on a scale 0-5) are considered in Table 28, 12 tools are selected as a result, but these only deliver on 12 of the 19 EBM elements, as some EBM elements have only tools scoring lower than 4 (e.g., Specific biotic effects/ impacts; Table 28). To account for these latter EBM elements, the top 3 scoring tools with scores between 3-4 were considered in these cases. As a result of these combined selection criteria, the table includes 15 out of the 19 tool groups analysed. Conceptual models, semi-quantitative mental models (Fuzzy Cognitive Mapping), biogeochemical models and ecosystem models are not included as they do not fulfil the selection criteria.

Table 28. Three top-scoring tool groups for each Ecosystem-Based Management (EBM) element. Only tools with average score ≥4 are included, where present (and indicated in bold along with the related EBM elements). Where not present the top 3 tools with average score between 3 and 4 were considered. The average score for each tool is shown between square brackets.

EBM element	Rank#1	Rank#2	Rank#3
Cumulative assessments	**Cumulative impact spatial mapping (e.g., Halpern et al.) [4.7]**	**Impact risk ranking through linkage-chain-frameworks (e.g., ODEMM et al.) [4.1]**	
GES MSFD assessments	**Descriptor or theme-specific combination of indices and models (e.g., HEAT, BEAT and CHASE) [4.8]**	**Overarching assessment tools (e.g., NEAT and OHI) [4.5]**	
Whole ecosystem assessments	**Overarching assessment tools (e.g., NEAT and OHI) [4.5]**		
Ecosystem Services (delivery, impacts, valuation)	**Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation [5.0]**	**Natural capital accounting, ecosystem services valuation [4.7]**	
Specific biotic effects/ impacts	Food web models (e.g., multispecies models, EWE) [3.6]	Risk based approaches exposure-effect-hazard-vulnerability (e.g., Bow tie) [3.3]	Simple assessment index (e.g., M-AMBI) [3.1]
Specific Ecosystem functions (and impacts on functions)	**Food web models (e.g., multispecies models, EWE) [4.0]**		
Pressures-Activities footprint	**Cumulative impact spatial mapping (e.g., Halpern et al.) [4.0]**		
Impacts footprints	Cumulative impact spatial mapping (e.g., Halpern et al.) [3.8]		
Links activities pressures impacts	**Impact risk ranking through linkage-chain-frameworks (e.g., ODEMM et al.) [4.8]**	**Knowledge Graph [4.6]**	**BBN probabilistic [4.6]**
Single MSFD Descriptors/ single issues (e.g., eutrophication, NIS, HABs)	**Descriptor or theme-specific combination of indices and models (e.g., HEAT, BEAT and CHASE) [4.8]**		
Single species, ecosystem Components State change	Single spp. model (e.g., life cycle, stock assessment) [3.3]	Food web models (e.g., multispecies models, EWE) [3.1]	
Threatened habitats and species	BBN probabilistic [3.3]	HSM models (spp. predictive distribution) [3.2]	Overarching assessment tools (e.g., NEAT and OHI) [3.1]
Climate change	Knowledge Graph [3.4]		

EBM element	Rank#1	Rank#2	Rank#3
Pressure and impact reduction/ mitigation	**Risk based approaches exposure-effect-hazard-vulnerability (e.g., Bow tie) [4.3]**		
Spatial and other measures	**Conservation planning models (e.g., MARXAN) [4.6]**	**Spatial planning models (e.g., GIS, VAPEM, related to use) [4.3]**	
Uncertainty	**Overarching assessment tools (e.g., NEAT and OHI) [4.0]**		
Risks	**Risk based approaches exposure-effect-hazard-vulnerability (e.g., Bow tie) [4.7]**		
Other Policy Requirements e.g., MSPD, BHD, Biod Strategy	Risk based approaches exposure-effect-hazard-vulnerability (e.g., Bow tie) [3.8]	Conservation planning models (e.g., MARXAN) [3.1]	Overarching assessment tools (e.g., NEAT and OHI) [3.0]

7. Conclusions and going forward

This section has two parts. A technical part provides insights and guidance on choosing tools for the EBM approaches e.g., which tools/tool groups deliver better each EBM element or which tool combinations offer best outcomes. A final conceptual part shows the position of this task within the GES4SEAS project, its links to other WPs and jointly delivering the project vision on practical implementations of EBM following a roadmap to achieve OUTCOME 4 of the call.

7.1. Choosing tools for the EBM approaches

At this section the pros and cons of the GES4SEAS Task 2.1. selected tools (Table 28, complemented by Table 27) are discussed based on their ability to deliver (fully or partially) one (or multiple) EBM elements. Further technical assessment of these tools, for example in relation to their practical implementation (e.g., data and skills required, spatial scales of the assessment etc.), will be undertaken in Task 2.3.

Cumulative impact spatial mapping and Impact risk ranking through linkage-chain-frameworks are the best suited tools to deliver **Cumulative assessments**, for which they both scored highly (≥4 on average, on a scale 0-5). The score closer to 5 attributed (on average) to Cumulative impact spatial mapping suggests that this tool alone is closer to fully deliver on this specific element of EBM at the plan and check phases. Either or both these two top tools also appear to support the delivery of five other EBM elements which specifically address **activities-pressures and impacts, through the assessment of their links or footprints** during the planning phase. In turn, the top-ranking tools for Cumulative assessments appear to be less suited for the other elements of EBM (e.g., on ecosystem services and specific biotic effects assessments), being able to only inform on specific aspects of the EBM element and therefore requiring the use of other tools in combination to fully deliver the element of EBM.

The best tools to deliver **GES MSFD assessments** during the Check-Evaluation phases of the EBM process are Descriptor or theme-specific combination of indices and models (e.g., HEAT, BEAT and CHASE) and Overarching assessment tools (e.g., NEAT and OHI). In this group, will be included the GES4SEAS toolbox to be developed in WP4 and tested and validated in WP5. Both tools scored ≥4 on average, but the use of Descriptor or theme-specific combination of indices and model alone appears to be closer to fully deliver on this specific element of EBM. Likewise, this tool group is also the best choice to undertake the assessment of **Single MSFD Descriptors/ single issues (e.g., eutrophication, contamination, NIS, HABs)** as may be required at the planning phase of the EBM process. Overarching assessment tools (e.g. NEAT and OHI) also inform other EBM elements at the Check-Evaluation phases, being well suited to deliver **Whole ecosystem assessments** and supporting the assessment of **Threatened habitats and species** (along with HSM models). Overarching assessment tools also deliver well on **Uncertainty** and may be used to support **Other Policy Requirements** (along with Conservation planning models). These tools are specific enough to support the strict requirements of the MSFD but also in fact being a combination of indices, models and integration tools can deliver to both topic related thematic and holistic assessments. In turn, the two top-ranking tools for GES MSFD assessments appears to poorly deliver on other EBM elements, both being among the lowest ranking tools for Risks and Climate change, with Overarching assessment tools also being particularly poor in informing the assessment of Ecosystem Services (delivery, impacts, valuation), Specific biotic effects/ impacts and Specific Ecosystem functions (and impacts on functions).

The top-ranking tools for the assessment of **Ecosystem Services (delivery, impacts, valuation)** during the planning phase of the EBM process (Natural capital accounting, ecosystem services valuation and Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation) are very well suited to deliver this specific EBM element, with scores close (Natural capital accounting) or equal to the maximum of 5 (Bio/Socio-economic models), whereas they are a very poor choice to inform all the other EBM elements, for which they are amongst the lowest ranking tools, and often with a value of 0 (no use) for example for GES MSFD assessments (both tools) and Single MSFD Descriptors/ single issues (e.g., eutrophication, NIS, HABs), Single species/ecosystem Components State change, Threatened habitats and species, Spatial and other measures, and Uncertainty (Bio/Socio-economic models). This outcome is related to their high specificity.

Food web models are the best tool choice for EBM elements of the planning phase such as the assessment of **Specific biotic effects/ impacts** (also informed by Simple assessment indices, e.g., M-AMBI) and **Specific Ecosystem functions (and impacts on functions)**, especially for the latter. Food web models may also inform the assessment of **Single species, ecosystem Components State change,** for which they are the top-ranking tool along with Single spp. model (e.g. life cycle, stock assessment), albeit both with scores close to 3, suggesting they, at best, deliver only on some aspects of this EBM elements (e.g. mainly informing on changes in stock size or mortality rates for commercial fish). In turn, this tool appears to be less suited for the other EMB elements, and especially for answering Other Policy Requirements (e.g., MSPD, BHD, Biodiversity Strategy) and addressing Links activities-pressures-impacts, for which food web models are amongst the lowest ranking tools.

The top-ranking tools to address **Spatial and other measures** during EBM planning (Spatial planning models (e.g., GIS, VAPEM, related to use) and Conservation planning models (e.g., MARXAN) are well suited for this EBM element, with scores ≥4. In turn, they do not appear to be of particular use for the other EBM elements, for which they are most often amongst the lowest ranking tools, with notable exceptions being the ability of Conservation planning models and of Spatial planning models to deliver on spatial planning aspects (e.g. spatial allocation and exclusion of activities, preferred locations for conservation and restoration) of, respectively, **Other Policy Requirements** (e.g., especially for MSPD, BHD, Biodiversity Strategy delivering on the MSP plans and advising on best ways to reach targets such as the 10 and 30% protection targets) or Pressures-Activities footprint (e.g. through the spatial mapping of these elements in an area).

The top-ranking tool for the general assessment of **Risks** is Risk based approaches exposure-effect-hazard-vulnerability (e.g., Bow tie), which appears to be well suited to deliver this EBM element. This latter tool is also the best option for the **Pressure and impact reduction/mitigation** during the planning and act phases of the EBM process and to address **Other Policy Requirements** (although with a score lower than 4 in this latter case)**.** It also appears to be always within the top ten ranking tools for any of the other EBM elements.

Knowledge graphs appear to be the best tool to address **Climate change** (albeit with an average score ≤4), although this is most likely done in a qualitative way (further assessment on how the EBM elements are delivered by the tools will be undertaken in GES4SEAS Task 2.3). This tool is also within the top 3 ranking (with score ≥4) in the delivery of **Links activities-pressures-impact**, along with BBN probabilistic tools and impact risk ranking through linkage-chain-frameworks. In turn, Knowledge graphs appear to be poorly suited to deliver other EBM elements, such as those addressing Uncertainty, Spatial and other measures, as well as cumulative assessments and GES MSFD assessments, among others.

BBN probabilistic tools are also the best suitable tool to assess **Threatened species and habitats** compared to other tools, and often are amongst the top ten ranking tools for any of the other EBM elements.

Finally, the best tool group for the assessment of **Single species/Ecosystem Components State change** at the planning stage of the EBM process includes Single spp. model (e.g., life cycle, stock assessment), although this type of tools appears to not be able to fully deliver all aspects of this element of EBM, as suggested by the score being close to 3, and food web models may also be used to integrate the delivery of this element.

The DAPSES-MMM (socio-economic Drivers, human Activities, Pressures, State of environment, Ecosystem Services – Management (policies and governance), Measures, Monitoring) used by the EC framework for the MSFD (CSWD, 2020), and variants such as DAPSI(W)R(M) and others used by RSC, have all an EBM focus, and all put an emphasis on linking activities pressures and impacts and identifying impacts of chains and combinations of risk. Key EBM elements in all these frameworks are identifying (i) the change in status of various ecosystem components due to single human activities or pressures and (ii) the cumulative effects of all the activities operating in the marine space, negatively but also positively e.g., through protection, conservation and restoration actions. Both elements look at the health of the natural system. There are two key tool group categories that fit this purpose, and these include NEAT (for GES assessments through structured ecosystem component changes assessments) and Halpern et al., 2008 EcoImpactMapper (for spatial extents and cumulative effects assessments). These will be taken forward in the LSs and in WP4 for the GES4SEAS tool development. Through the LSs work new and revised applications of the Halpern et al. (2008) approach are expected based on important advances/modifications planned by in WP4 (e.g., hierarchical (vs flat) structure, values for ecosystem components (vs only presence/absence), proper (vs no) weighting by importance or areal distribution of ecosystem components). NEAT will also support more functions and descriptor and issue specific assessments in the LSs (e.g., by incorporating CIMPAL tool assessments).

The risk-based tools (impact risk ranking through linkage-chain-frameworks and risk-based approaches working on exposure-effect-hazard-vulnerability, see also section 5.3. Tables 11 and 13) can also be used in the GES4SEAS LS work and WP5 and their outcomes can be compared with those of more quantitative tools (or perhaps instead in data poor cases). They can also partly support other policy requirements and can inform on spatial and other measures. However highly specialised tools such as MARXAN, ZONATION, VAPEM are needed to support decision making (for placing and zoning activities including conservation) and spatial planning.

Beyond highly specialised tools looking at valuation of natural capital and ecosystem services (out with the GES4SEAS core objectives), only food web models can address the capacity of ecosystem delivery and work in WP3 can advise on the relationships between the condition of the ecosystems and any tipping points in the delivery of the service. Food web models along with single species models and risk-based methods can also partly inform on specific ecosystem functions and biotic effects (as might be required in an assessment or a LS).

Based on this analysis and in line with the core objectives of GES4SEAS, from the 19 tool groups (presented and discussed above) and the 15 top scoring tools, all 19 will be taken forward in GES4SEAS for further analysis and 16 for use and testing in the Learning Sites.

Marine EBM is essentially a risk-based process, in order to determine what are the risks to the seas, how to assess and mitigate them, and how to manage the causes and consequences (Cormier et al., 2022). In order to be proactive, EBM should also enable an opportunity assessment and management process as a means to ensuring the wise and sustainable use of the seas while also maintaining and protecting the natural system.

The analysis here has shown that there is no doubt that EBM is the central pillar of the understanding, interrogation and management of the marine environment; this is despite the continued debate regarding the terms used and the semantics. It is of note that EBM or its variants are mentioned in all major marine policy instruments at local, national, regional (European) and international levels (see Dickey-Collas et al., 2022, for a list). It is notable that the analysis here is the first in which the 26 EBM principles have been assessed in relation to tools and in which those principles have been reworded as instructions (Table 2).

The EBM approaches have often been related to individual components, habitats, species, activities or sectors, but it is emphasised that such a deconstructing of the marine environment would not result in an 'ecosystem-based' approach which requires all natural and societal features to be included. For example, the FAO emphasised 'the ecosystem-based approach to fisheries management' but this is only for one sector and is likely to manage fisheries to the exclusion of other sectors. Similarly, it is cautioned that if the GES4SEAS would only consider the EBM in relation to HABs, NIS, top predators or any other individual component, no matter how important, then this would not constitute a true EBM.

When applied to disparate areas, the EBM and its tools would have the major challenge in having to cope with different types of information, both qualitative and quantitative. It also must be suitable for skills- and data-rich areas and skills- and data-poor areas. The analysis here has shown that the priorities from scientists are likely to differ from the priorities for managers as the 2 groups focus on different phases of the PACE process. Furthermore, the 19 tool groups interrogated here are not mutually exclusive and some have the same aims and outcomes, hence the rational for discussing tool groups in support of EBM.

Central to the task of managing marine areas is determining/assessing the footprints of activities, pressures and effects and then enacting and integrating the horizontal and vertical management response footprints (Cormier et al., 2022). A true EBM would have to encompass all of these aspects.

The tool groups show the importance of conceptual models as a starting point and frameworks such as DPSIR and its many variants including the recent DAPSI(W)R(M) created to eliminate confusion over the definition of its terms in previous variants (Elliott et al., 2017). It is not always needed or helpful for each management initiative (whether a Regional Sea Commission or any other group) to attempt to use a new DPSIR variant, especially when the differences between variants may be either insignificant or just semantics (for a recent review see Patrício et al., 2016). It should be noted however, that while some variants have been created for the sake of creating an individual/institutional variant others have been created to superimpose specific assessment elements or waypoints such as the DAPSES-MMM used by the EC for the MSFD (CSWD, 2020).

Given the complexity of the marine environment and the need for its management to cope with a multi-component, multi-functioning, multi-sectoral, multi-user, multi-agency and multi-legal jurisdiction environment then it is not surprising that several or many tools would be required to be used together to support and effect EBM. Here, as designed in this particular task, the EBM principles (Table 2) were matched to the GES4SEAS project core objectives (e.g., MSFD assessments, cumulative effects assessments, ecosystem services addressing uncertainty and acknowledging the importance of stakeholder engagement) for example the principles 'Determine Ecological Integrity and Biodiversity' (e.g., GES for MSFD) and 'Consider cumulative impacts' are at the core of the project work (based on keywords from the Description of Work, see also the project word cloud, Figure 5). The task also matched the EBM principles to four management cycle phases based on the PACE approach: the Plan-Act-Check-Evaluate- framework (BSPC, 2006). Importantly, the Evaluation and Check phases status assessments are preformed and the distance to the desired goals is evaluated (i.e., as questions - is GES reached? why is GES not achieved? is monitoring fit-for-purpose? are additional measures needed?). The core work of GES4SEAS is therefore related to the performance evaluation, review and assessment phases.

As a novel approach, a R and Q mode multivariate analysis was applied to the data elicited by expert judgement regarding the cases (experts) and attributes of the tools. The cluster analysis of matrix data (average of scores across contributors) aimed to identify groupings of elements of EBM based on similarity of tools used and their ability to support EBM by delivering the specific element of EBM. The cluster analysis also interrogated the tool groups based on similarity of EBM elements that they deliver.

The EBM tools analysed here appear to be grouped by cluster analysis according to their attributes relating to the principles of EBM. Figure 10 can be interpreted to show 5 groups of tools according to the elements to which they relate (Table 29): (i) socio-economic aspects, (ii) biochemical, species and habitat models; (iii) spatial mapping and planning models; (iv) indices and assessments for descriptors and wider assessment; and (v) conceptual, graphical and numerical ecosystem models encompassing natural and social features.

Table 29. Tool group clusters

Methodologies/tool groups	Cluster
Natural capital accounting, ecosystem services valuation	i
Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation	i
Single spp. model (life cycle, stock assessment)	ii
Biogeochemical models	ii
HSM models (spp. predictive distribution)	ii
Simple assessment index (e.g., M-AMBI)	ii
Cumulative impact spatial mapping (Halpern et al., 2008)	iii
Spatial planning models (e.g., GIS, VAPEM, related to use)	iii
Conservation planning models (e.g., MARXAN)	iii
Descriptor or theme-specific combination of indices and models (e.g., HEAT, BEAT and CHASE)	iv
Overarching assessment tools (e.g., NEAT and OHI)	iv
Conceptual models	v
Semi-quantitative mental models - Fuzzy Cognitive Mapping	v
Knowledge Graph	v
BBN probabilistic	v
Risk based approaches exposure-effect-hazard-vulnerability (e.g., Bow-Tie)	v
Impact risk ranking through linkage-chain-frameworks (e.g., ODEMM)	v
Food web models (e.g., multispecies models, EWE)	v
Ecosystem models (e.g., End2End)	v

Given that EBM is a risk and opportunity assessment and management process then it is not surprising that these tools scored highly. However, the analysis may be seen as indicating tautologies in that the overarching assessment tools are best as delivering an overall GES assessment. Similarly, descriptor and theme-based tools are good for descriptor and single issues. Other types of assessment tools are similarly appropriate for other assessments. Although assessment, and its monitoring, are not management measures do give an indication of the way in which management is deemed to be needed or deemed to have been successful. Several tools can help with planning (through activity placement, suggested measure types or closures/MPAs, and conservation prioritization) or by risk management informed through linkage chains or exposure-effect-hazard approaches. All these tools contribute to supporting EBM but not implement EBM. The act phase of

PACE and the Impact (Welfare) and Response (by Measures) phases of the DAPSIW)R(M) cycle (and Management and Measures part of the DAPSES-MMM framework) require additional tools. These include for example stakeholder involvement, consultation and co-creation of measures based on socio-economic tools, distance to accepted policy objectives and targets, elaborated scenarios and determination of social and economic repercussions of and need for management, completing thus the EBM cycle.

7.2. Going forward to practical implementations of EBM

The analysis here has shown that there must be a given complement of tools, i.e., a toolbox, to satisfy the many principles of EBM and that no single tool is likely to satisfy all aspects of EBM. Hence, as the result of the analysis, the EBM toolbox needs to include:

(i) The starting point of a good conceptual understanding linking the ecological features to their relevant management, policy and governance through a risk and opportunity assessment and management framework;

(ii) That conceptual model including the capability to create links (again conceptual or numerical) between the ecological structure and functioning, the resulting ecosystem services and the societal goods and benefits and their valuation.

(iii) A tool/suite of tools for a suitably weighted cumulative impacts assessment which is based on estimating the activity-, pressures- and effects-footprints for all aspects in an area and which can help define/evaluate/check the thresholds and identify tipping points of change and then link these to management actions;

(iv) A tool/suite of tools which covers the MSFD descriptors singly and in total, including the species and habitat components and their interlinkages.

Hence, it is emphasised that the information in this GES4SEAS task (Task 2.1, i.e. ‘to identify the existing EBM approaches’) needs to be merged with that for Task 2.2 (‘state of the art in support of EBM of specific and increasing problems such as HABs, jellyfish outbreaks, invasive species and the decline of top predators’) in order to inform Task 2.3 (‘best options for practical EBM approaches to fill gaps in understanding the effects of multiple and cumulative pressures’) and Task 2.4 (to design, through consultation, co-creation and iterative processes with WP1 and WP5, ‘a practical EBM using risk-based and opportunity assessment management’) (Figure 11). Once these concepts and guidelines have been delivered to the Learning Sites (WP5 – learning sites: testing and synthesis, Task 5.3. ‘testing and identification of information gaps’) in the project and then their conclusions, recommendations and lessons learned communicated onward to Task 5.4 ('integrating experiences from LSs') then those lessons can be integrated into an overarching toolbox. This toolbox will then also encompass the tool(s) created and/or further developed (e.g., with new functions or capabilities) in WP4 ('Linking pressure and status assessment with the capacity to supply ecosystem services into a unifying holistic framework and nested toolbox'). The following task in WP5, Task 5.5 can then make recommendations for improved monitoring, assessment and management for use in areas wider than the Learning Sites integral to the project. In summary, this then creates the links between this task and other WPs of the project thereby highlighting the roadmap to delivering the project vision on the practical implementations of EBM including developing an EBM approach guidance and recommendations from and for practitioners (WP1). In turn, this achieves the OUTCOME 4 of the call - i.e., EBM approaches and policy measures for activities to reduce pressures and lead to the achievement of GES. This again in turn enables the sustainability of coastal and marine ecosystems to deliver both ecosystem services and societal goods and benefits and hence allows the areas to be resilient to rapid climate and other environmental changes.

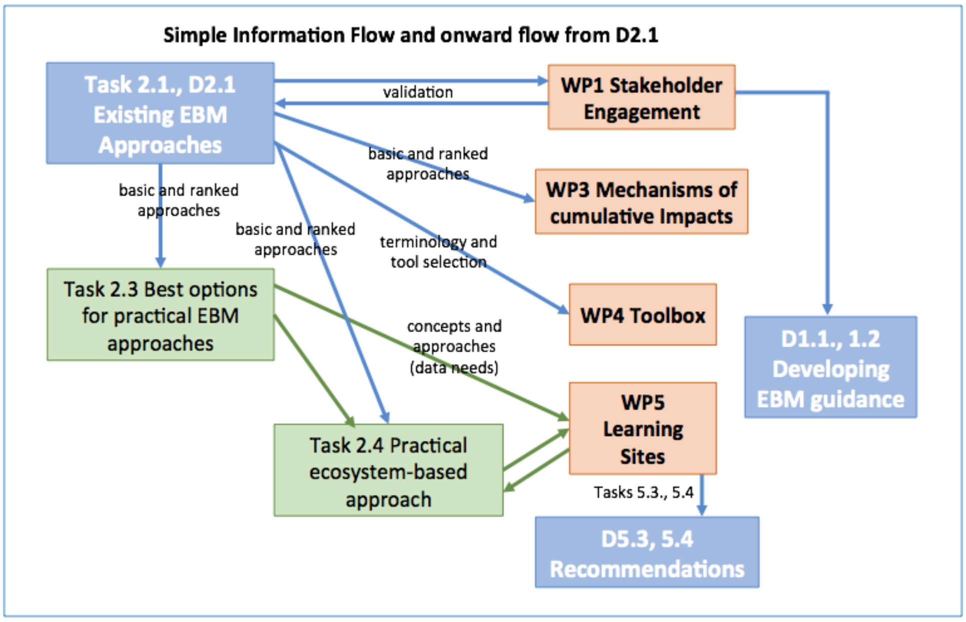


Figure 11. Schematic on flow of information from D2.1. and links between GES4SEAS WPs, tasks and deliverables contributing to the achievement of OUTCOME 4 of the call.

8. References

Ahtiainen H., Dodd L., Korpinen S., Pakalniete K., Saikkonen S., Estlander S., Hoikkala L., Vretborn M., 2021. Methodology for the sufficiency of measures analysis. HELCOM ACTION (2021), https://helcom.fi/helcom-at-work/projects/action/

Antão L.H., Bates A.E., Blowes S. A., Waldock C., Supp S.R., Magurran A. E., Dornelas M., Schipper A. M., 2020. Temperature-related biodiversity change across temperate marine and terrestrial systems. Nature Ecology & Evolution, 4(7), 927– 933. https://doi.org/10.1038/s41559-020-1185-7

Aires C., Gonzalez-Irusta J.M., Watret R., 2014. Updating Fisheries Sensitivity Maps in British Waters. Scottish Marine and Freshwater Science Report, Marine Scotland Science, 50(10), 88 pp.

Andersen J.H., Stock A. (Eds.), 2013. Human uses, Pressures and Impacts in the Eastern North Sea, Technical Report from DCE. Danish Centre for Environment and Energy, Aarhus

Andersen J.H., Axe P., Backer H., Carstensen J., Claussen U., Fleming-Lehtinen V., Järvinen M., Kaartokallio H., Knuuttila S., Korpinen S., Kubiliute A., Laamanen M., Lysiak-Pastuszak E., Martin G., Murray C., Møhlenberg F., Nausch G., Norkko A., Villnäs A. 2011. Getting the measure of eutrophication in the Baltic Sea: towards improved assessment principles and methods. Biogeochemistry 106: 137-156.

Andersen J.H., Dahl K., Göke C., Hartvig M., Murray C., Rindorf A., Skov H., Vinther M., Korpinen S., 2014. Integrated assessment of marine biodiversity status using a prototype indicator-based assessment tool. Frontiers in Marine Science 1:55 doi:10.3389/fmars.2014.00055.

Andersen J. H., Halpern B. S., Korpinen S., Murray C., Reker J., 2015. Baltic Sea biodiversity status vs. cumulative human pressures. Estuarine Coastal and Shelf Science 161:88-92. http://www.sciencedirect.com/science/article/pii/S0272771415001511

Andersen J.H., Korpinen S., Murray C., Larsen M.M., Green N., Høgåsen T., Gustavson K., Boalt E., Garnaga G., Haarich M., Mannio J., Strand J., 2016a. A tool for integrated assessment of chemical status. Marine Monitoring and Assessment 188:115, DOI 10.1007/s10661-016-5121-x.

Andersen J.H., Murray C., Larsen M.M., Green N., Høgåsen T., Dahlgren E., Garnaga-Budrė G., Gustavson K., Haarich M., Kallenbac E.M.F., Mannio J., Strand J., Korpinen S., 2016b. Development and testing of a prototype tool for integrated assessment of chemical status in marine environments. Environmental Monitoring and Assessment. 188, 115. https://doi.org/10.1007/s10661-016-5121-x

Andersen J.H., Carstensen J., Conley D.J., Dromph K., Fleming-Lehtinen V., Gustafsson B., Josefson A., Norkko A., Villnäs A., Murray C., 2017. Long-term temporal and spatial trends in eutrophication status of the Baltic Sea. Biological Reviews 92: 135–149

Andersen J. H., Bendtsen J., Hammer K. J., Harvey T., Knudsen S.W., Murray C. J., Carstensen J., Petersen I. K., Sveegaard S., Tougaard J., Edelvang K., Egekvist J., Olsen J., Vinther M., Al-Hamdani Z., Jensen J. B., Leth J. O., Kaae B. C., Olafsson A. S., McClintock W., Burt C., Yocum D. (2020a). ECOMAR: A data-driven framework for ecosystem-based Maritime Spatial Planning in Danish marine waters. NIVA. NIVA Denmark Report No. 7562-2020, 81 pp.

Andersen J.H., Z. Al-Hamdani E.T. Harvey, Kallenbach E., Murray C., Stock A., 2020b. Relative impacts of multiple human stressors in estuaries and coastal waters in the North Sea–Baltic Sea transition zone, Science of The Total Environment, 704, 2020,https://doi.org/10.1016/j.scitotenv.2019.135316.

AQUACROSS: https://aquacross.eu/ (and references therein)

Arneth, A., Leadley P. W., Claudet J., Coll M., Rondinini C., Rounsevell M., Shin Y.-J., Alexander P., Fuchs R., 2023. Making protected areas effective for biodiversity, climate and food. Global Change Biology. 05 March 2023, https://doi.org/10.1111/gcb.16664

Arponen A., Kondelin H., Moilanen A., 2007. Area‐Based Refinement for Selection of Reserve Sites with the Benefit‐Function Approach. Conservation biology, 21(2), 527-533.

Atkins J.P., Burdon D., Elliott M., Gregory A.J., 2011. Management of the marine environment: integrating ecosystem services and societal benefits with the DPSIR framework in a systems approach. Marine Pollution Bulletin, 62, pp. 215-226

Atkins J.P., Banks E., Burdon D., Greenhill L., Hastings E., Potts T., 2013. An analysis of methodologies for defining ecosystem services in the marine environment. JNCC Report 491 (Contract number: C12-0170-0612). https://data.jncc.gov.uk/data/00fef397-f5e3-4836-bcb9-26662aa500a2/JNCC-Report-491-FINAL-WEB.pdf

Auster P.J., K, Gjerde, Heupel E., Watling L., Grehan A., Rogers D., 2011. Definition and detection of vulnerable marine ecosystems on the high seas: problems with the “move-on” rule. ICES Journal of Marine Science, Volume 68, Issue 2, January 2011, Pages 254–264, https://doi.org/10.1093/icesjms/fsq074

Avison D.E., Golder P.A., Shah H.U., 1992. Towards an SSM toolkit: rich picture diagramming. European Journal of Information Systems 1: 397-408.

Awbery T., Akkaya A., Lyne P., Rudd L., Hoogenstrijd G., Nedelcu M., Kniha D., Erdoğan M.A., Persad C., Amaha Öztürk A., Öztürk B., 2022. Spatial distribution and encounter rates of delphinids and deep diving cetaceans in the eastern Mediterranean Sea of Turkey and the extent of overlap with areas of dense marine traffic. Frontiers in Marine Science, *9*, p.860242.

Babalou S., Zander F., Kleinsteuber E., El Haouni B., Schellenberger Costa D., Kattge J., König-Ries B., 2022. iKNOW- A Knowledge Graph Management Platform for the Biodiversity Domain, Biodiversity Information Science and Standards, 6: e93867. doi: 10.3897/biss.6.93867

Ball I.R., Possingham H.P., Watts, M., 2009. Marxan and relatives: software for spatial conservation prioritisation. Spatial conservation prioritisation: Quantitative methods and computational tools, 185, p.195.

Baretta J.W., Ebenhoh W., Ruardij P., 1995. The European regional seas ecosystem model, a complex marine ecosystem model. Netherlands Journal of Sea Research. 33, 233–246.

Bartelings H., Hamon K.G., Berkenhagen J., Buisman F.C., 2015. Bio-economic modelling for marine spatial planning application in North Sea shrimp and flatfish fisheries. Environmental Modelling & Software 74, 156-172.

Bastardie F., Brown E.J., 2021. Reverse the declining course: A risk assessment for marine and fisheries policy strategies in Europe from current knowledge synthesis. Marine Policy 126 (2021): 104409.

Bastmeijer K., 2018. The Ecosystem Approach for the Marine Environment and the Position of Humans: Lessons from the EU Natura 2000 Regime. Chapter 7. The Ecosystem Approach in Ocean Planning and Governance. Brill | Nijhoff Publ. (2018). https://doi.org/10.1163/9789004389984_008

Bauer B., Fioroni P., Ide I., Liebe S., Oehlmann J., Stroben E., Watermann B., 1995. TBT effects on the female genital system of Littorina littorea: a possible indicator of tributyltin pollution. Hydrobiologia, 309: 15-27.

Bentley J.W., Lundy M.G., Howell D., Beggs S.E., Bundy A., De Castro F., Fox C.J., Heymans J.J., Lynam C.P., Pedreschi D., Schuchert P., 2021. Refining fisheries advice with stock-specific ecosystem information. Frontiers in Marine Science, 8, p.602072.

Berg T., Fürhaupter K., Teixeira H., Uusitalo L., Zampoukas, N., 2015. The Marine Strategy Framework Directive and the ecosystem-based approach – pitfalls and solutions. Marine Pollution Bulletin,96 (2), 1-2, https://doi.org/10.1016/j.marpolbul.2015.04.050.

Berg T., Murray C., Carstensen J., Andersen J.H., 2018. NEAT – Nested Environmental status Assessment Tool. Manual version 1.4. 38pp. 10.5281/zenodo.1215771

Bevilacqua S., Guarnieri G., Farella G., Terlizzi A., Fraschetti S., 2018. A regional assessment of cumulative impact mapping on Mediterranean coralligenous outcrops. Scientific Reports, 8(1), 1–11. https://doi.org/10.1038/s41598-018-20297-1

Birk S., Bonne W., Borja A., Brucet S., Courrat A., Poikane S., Solimini A., van de Bund W., Zampoukas N., Hering D., 2012. Three hundred ways to assess Europe's surface waters: An almost complete overview of biological methods to implement the Water Framework Directive. Ecological Indicators, 18: 31-41.

Blazquez, M.A., 2021. Natural capital accounting for the North East Atlantic area – Preliminary results and first estimates. https://www.noordzeeloket.nl/publish/pages/193624/natural-capital-accounting-for-the-nort-east-atlantic-area.pdf

Borja A., Mader J., Muxika I., Rodríguez J. G., Bald J., 2008. Using M-AMBI in assessing benthic quality within the Water Framework Directive: Some remarks and recommendations. Marine Pollution Bulletin, 56: 1377-1379.

Borja Á., Elliott M., Carstensen J., Heiskanen A.-S., van de Bund W., 2010. Marine management - Towards an integrated implementation of the European Marine Strategy Framework and the Water Framework Directives. Marine Pollution Bulletin, 60: 2175-2186.

Borja A., Elliott M., Andersen J. H., Cardoso A. C., Carstensen J., Ferreira J. G., Heiskanen A.-S., Marques J. C., Neto J. M., Teixeira H., Uusitalo L., Uyarra M. C., Zampoukas N., 2013. Good Environmental Status of marine ecosystems: What is it and how do we know when we have attained it? Marine Pollution Bulletin, 76: 16-27.

Borja Á., Marín S. L., Muxika I., Pino L., Rodríguez J. G., 2015. Is there a possibility of ranking benthic quality assessment indices to select the most responsive to different human pressures? Marine Pollution Bulletin, 97: 85-94.

Borja A., Elliott M., Andersen J.H., Berg T., Carstensen J., Halpern B.S., Heiskanen A.-S., Korpinen S., Lowndes J.S.S., Martin G., Rodriguez-Ezpeleta N., 2016. Overview of integrative assessment of marine systems: the Ecosystem Approach in practice. Frontiers in Marine Science, doi: 10.3389/fmars.2016.00020.

Borja A., Chust G., Muxika I., 2019. Chapter Three - Forever young: The successful story of a marine biotic index. Advances in Marine Biology, 82: 93-127.

Borja, A., Menchaca I., Garmendia J.M., Franco J., Larreta J., Sagarminaga Y., Schembri Y., González R., Antón R., Micallef T., Camilleri S., Solaun O., Uriarte A., Uyarra M.C., 2021. Big insights from a small country: the added value of integrated assessment in the marine environmental status evaluation of Malta Frontiers in Marine Science, 8: 10.3389/fmars.2021.638232

Borja A., S. Bricker, Dauvin J.C., Elliott M., Harrison T., Marques J.C., Weisberg S. B., West R., 2023. Classifying ecological quality and integrity of estuaries. In: Wolanski E and McLusky DS (eds.) Treatise on Estuarine and Coastal Science. Waltham: Academic Press., 2nd edition.

Borgwardt F., Robinson L., Trauner D., Teixeira H., Nogueira A. J. A., Lillebø A. I., Piet G., et al. 2019. Exploring variability in environmental impact risk from human activities across aquatic ecosystems. In Science of The Environment 652, 2019; ISSN: 0048-9697. 2019.

Borrett S.A., Sheble L., Moody J., Anway E.C., 2018. Bibliometric review of ecological network analysis: 2010–2016. Ecological Modelling 382, 63-82. https://www.sciencedirect.com/science/article/abs/pii/S0304380018301431

Bossier S., Palacz A.P., Nielsen J.R., Christensen A., Hoff A., et al., 2018. The Baltic Sea Atlantis: An integrated end-to-end modelling framework evaluating ecosystem-wide effects of human-induced pressures. PLOS ONE 13(7): e0199168. https://doi.org/10.1371/journal.pone.0199168

Bowtie Master – https://bowtiemaster.com/?gclid=CjwKCAjwitShBhA6EiwAq3RqA8SiNmfBeYGxchMPGzXZhSWK2iAmqBlZtIfHCbTJFZGmbjznRSkpDBoCRFgQAvD_BwE

Bow-Tie XP - https://www.wolterskluwer.com/en-gb/solutions/enablon/bowtie/bowtiexp

Bradshaw C., Jakobsson M., Brüchert V., Bonaglia S., Mörth C.-M., Muchowski J., Stranne C., Sköld M., 2021. Physical Disturbance by Bottom Trawling Suspends Particulate Matter and Alters Biogeochemical Processes on and Near the Seafloor. Frontiers in Marine Science, 8, 2021, DOI=10.3389/fmars.2021.683331

Broszeit S., Beaumont N.J., Hooper T.L., Somerfield P.J., Austen M.C al., 2019. Developing conceptual models that link multiple ecosystem services to ecological research to aid management and policy, the UK Marine Example. Marine Pollution Bulletin 141: 236–43. https://doi.org/10.1016/j.marpolbul.2019.02.051

Brugère C., Aguilar-Manjarrez J., Beveridge M.C.M., Soto D., 2019. The ecosystem approach to aquaculture 10 years on – a critical review and consideration of its future role in blue growth. Rev Aquacult, 11: 493-514. https://doi.org/10.1111/raq.12242

BSC, 2019. State of the Environment of the Black Sea (2009-2014/5). Edited by Anatoly Krutov. Publications of the Commission on the Protection of the Black Sea Against Pollution (BSC) 2019, Istanbul, Turkey, 811 pp.

Burdon D., Boyes S.J., Elliott M., Smyth K., Atkin J.P., Barnes R.A., Wurzel R.K., 2018. Integrating natural and social marine science to sustainably manage vectors of change: Dogger Bank transnational case study. Estuarine, Coastal and Shelf Science 201: 234-247, http://dx.doi.org/10.1016/j.ecss.2015.09.012.

Burdon D., Potts T., Barnard S., Boyes S.J., Lannin A., 2022. Linking natural capital, benefits and beneficiaries: The role of participatory mapping and logic chains for community engagement. Environmental Science & Policy, 134, pp. 85-99.

Burgess M.G., Giacomini H.C., Szuwalski C.S., Costello C., Gaines S.D., 2017. Describing ecosystem contexts with single-species models: a theoretical synthesis for fisheries. Fish and Fisheries, 18: 264-284. https://doi.org/10.1111/faf.12179

Butenschön M., Clark J., Aldridge J.N., Allen J.I., Artioli Y., Blackford J., Bruggeman J., Cazenave P., Ciavatta S., Kay S., Lessin G., van Leeuwen S., van der Molen J., de Mora L., Polimene L., Sailley S., Stephens N., Torres R., 2016. ERSEM 15.06: a generic model for marine biogeochemistry and the ecosystem dynamics of the lower trophic levels. Geoscientific Model Development, 9(4), 1293–1339. doi: 10.5194/gmd-9-1293-2016.

Campos L.M.S., Aparecida de Melo Heizen D., Verdinelli M.A., Miguel P.A.C., 2015. Environmental performance indicators: a study on ISO 14001 certified companies. Journal of Cleaner Production, 99: 286-296 https://doi.org/10.1016/j.jclepro.2015.03.019

Carlucci R., Manea E., Ricci P., Cipriano G., Fanizza C., Maglietta R., Gissi, E., 2021. Managing multiple pressures for cetaceans' conservation with an Ecosystem-Based Marine Spatial Planning approach. Journal of Environmental Management, 287(112240), 112240. https://doi.org/10.1016/j.jenvman.2021.112240

CBD, 2000. Convention on Biological Diversity, COP5, Decision V/6, The Ecosystem Approach, https://www.cbd.int/decision/cop/?id=7148

CBD, 2004. Secretariat of the Convention on Biological Diversity (2004) The Ecosystem Approach, (CBD Guidelines) Montreal: Secretariat of the Convention on Biological Diversity 50 p. https://www.cbd.int/doc/publications/ea-text-en.pdf

CBD, 2022. COP15: Nations adopt four goals, 23 targets for 2030 in landmark UN Biodiversity Agreement. Official CBD Press Release - 19 December 2022, Montreal. https://www.cbd.int/article/cop15-cbd-press-release-final-19dec2022

Chavez-Rosales S., Palka D.L., Garrison, L.P., Josephson E.A., 2019. Environmental predictors of habitat suitability and occurrence of cetaceans in the western North Atlantic Ocean. Scientific Reports 9, 5833. https://doi.org/10.1038/s41598-019-42288-6

Chong-Montenegro C., Kindsvater H. K., 2022. Demographic Consequences of Small-Scale Fisheries for Two Sex-Changing Groupers of the Tropical Eastern Pacific. Frontiers in Ecology and Evolution, 10. DOI: 10.3389/fevo.2022.850006

Christensen, V., Walters, C.J., 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecological Modelling 172, 109–139. https://scholar.google.it/scholar_url?url=https://www.vliz.be/imisdocs/publications/55191.pdf.&hl=en&sa=X&ei=5KsqZPrLF6XGsQKJ6ZToCA&scisig=AJ9-iYvy8YqDXzCw7CzMU08MoMIW&oi=scholarr

Christensen V., Ferdaña Z., Steenbeek J., 2009. Spatial optimization of protected area placement incorporating ecological, social and economical criteria. Ecological Modelling, 220: 2583-2593.

Cissé A.A., Gourguet S., Doyen L., Blanchard F., Péreau J.C., 2013. A bio-economic model for the ecosystem-based management of the coastal fishery in French Guiana. Environment and Development Economics, Volume 18, Issue 3, June 2013, pp. 245 – 269. DOI: https://doi.org/10.1017/S1355770X13000065.

Claudet J., Loiseau C., Sostres M., Zupan M., 2020. Underprotected Marine Protected Areas in a Global Biodiversity Hotspot. One Earth 2:380-384.

Coccoli C., Galparsoro I., Murillas A., Pınarbaşı K., Fernandes J. A., 2018. Conflict analysis and reallocation opportunities in the framework of marine spatial planning: A novel, spatially explicit Bayesian belief network approach for artisanal fishing and aquaculture. Marine Policy, 94: 119-131 https://www.sciencedirect.com/science/article/pii/S0308597X18301635

Coll M., Steenbeek J., 2017. Standardized ecological indicators to assess aquatic food webs: the ECOIND software plug-in for Ecopath with Ecosim models. Environmental Modelling and Software 89:120-130.

Coll M., Piroddi C., Albouy C., Ben Rais Lasram F., Cheung W., Christensen V., Karpouzi V., Le Loc F., Mouillot D., Paleczny M., Palomares M. L., Steenbeek J., Trujillo P., Watson R., Pauly D., 2012.

The Mediterranean Sea under siege: spatial overlap between marine biodiversity, cumulative threats and marine reserves. Global Ecology and Biogeography 21:465-480.

Coll M., Steenbeek J., Ben Rais Lasram F., Mouillot D., Cury P., 2015. “Low hanging fruits” for conservation of marine vertebrate species at risk in the Mediterranean Sea. Global Ecology and Biogeography 24:226-239.

Coll M., Albo-Puigserver M., Navarro J., Palomera I., Dambacher J., 2019. Who is to blame? Plausible pressures on small pelagic fish population changes in the NW Mediterranean Sea. Marine Ecology Progress Series 617-618:277-294.

Colléter M., Valls A., Guitton J., Gascuel D., Pauly D., Christensen V., 2015. Global overview of the applications of the Ecopath with Ecosim modeling approach using the EcoBase models repository. Ecological Modelling 302: 42-53. https://www.sciencedirect.com/science/article/abs/pii/S0304380015000447?via%3Dihub

Cooper K., Burdon D., Atkins J.P., Weiss L., Somerfield P., Elliott M., Turner K., Ware S., Vivian C., 2013. Can the benefits of physical seabed restoration justify the costs? An assessment of a disused aggregate extraction site off the Thames Estuary, UK. Marine Pollution Bulletin, 75, pp. 33-45.

Copping A.E., Gorton A.M., May R., Bennet F., DeGeorge E., Repas Goncalves M., Rumes B., 2020. Enabling Renewable Energy While Protecting Wildlife: An Ecological Risk-Based Approach to Wind Energy Development Using Ecosystem-Based Management Values. Sustainability 2020, 12, 9352. https://doi.org/10.3390/su12229352

Cormier R., Kannen A., Elliott M., Hall P., Davies I.M. (Eds), 2013. Marine and Coastal Ecosystem-based Risk Management Handbook. ICES Cooperative Research Report, No. 317, March 2013, International Council for the Exploration of the Sea, Copenhagen, 60pp, ISBN 978-87-7472-115-1.

Cormier R., Kannen A., Elliott M., Hall P., 2015. Marine Spatial Planning Quality Management System. ICES Cooperative Research Report No. 327. 106 pp. https://doi.org/10.17895/ices.pub.5495

Cormier R., Elliott M., 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. Science of the Total Environment, 648: 293-305. https://doi.org/10.1016/j.scitotenv.2018.08.168.

Cormier R., Elliott M., Borja Á., 2022. Managing Marine Resources Sustainably – The ‘Management Response-Footprint Pyramid’ Covering Policy, Plans and Technical Measures. Frontiers in Marine Science 9, 2022, https://www.frontiersin.org/articles/10.3389/fmars.2022.869992, DOI=10.3389/fmars.2022.869992

Cornacchia, F., 2022. Impacts on ecosystem services due to changes in the state of the environment in the North-East Atlantic Ocean. PhD Thesis. Rijkswaterstaat Water Verkeer en Leefomgeving. Available at Rijkswaterstaat Publicatie Platform (rws.nl) https://open.rws.nl/open-overheid/onderzoeksrapporten/@142922/impacts-on-ecosystem-services-due-to/

Cotton S., Wedekind C., 2009. Population Consequences of Environmental Sex Reversal. Conservation Biology, 23: 196-206

Christensen V., Walters C., 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecological Modelling 72:109-139.

Christensen V., Steenbeek J., Failler P., 2011. A combined ecosystem and value chain modeling approach for evaluating societal cost and benefit of fishing. Ecological Modelling 222:857-864.

Christensen V., Coll M., Steenbeek J., Buszowski J., Chagaris D., Walters C. J., 2014. Representing variable habitat quality in a spatial food web model. Ecosystems 17:1397-1412.

CSWD, 2020. Commission Staff Working Document: Background document for the Marine Strategy Framework Directive on the determination of good environmental status and its links to assessments and the setting of environmental targets. Accompanying the Report from the Commission to the European Parliament and the Council on the implementation of the Marine Strategy Framework Directive (Directive 2008/56/EC). European Commission SWD(2020) 62 final.

Culhane F., Frid C., Royo Gelabert E., Robinson L., 2019a. 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.

Culhane F., Teixeira H., Nogueir, A. J. A., Borgwardt F., Trauner D., Lillebø A., Piet G., Kuemmerlen M., McDonald H., O'Higgins T., Barbosa A.L., Van Der Wal J. T., Iglesias-Campos A., Arevalo-Torres J., Barbiere J., Robinson L.A., 2019b. Risk to the supply of ecosystem services across aquatic ecosystems. In Science of The Total Environment 660, 611-621, https://doi.org/10.1016/j.scitotenv.2018.12.346

Culhane F.E., Frid C.L.J., Gelabert E. R., Piet G., White L., Robinson, L. A., 2020. Assessing the capacity of European regional seas to supply ecosystem services using marine status assessments. Ocean and Coastal Management, 190 (November 2019), 105154. https://doi.org/10.1016/j.ocecoaman.2020.105154

D'Alelio D., Libralato S., Wyatt T., Ribera d'Alcalà M., 2016. Ecological-network models link diversity, structure and function in the plankton food-web. Scientific Reports 6, 21806. https://doi.org/10.1038/srep21806

Dambacher J.M., Gaughan D.J., Rochet M.J., Rossignol P.A., Trenkel V.M., 2009. Qualitative modelling and indicators of exploited ecosystems. Fish and Fisheries 10:305-322.

Dambacher J.M., Rothlisberg P.C., Loneragan N.R., 2015. Qualitative mathematical models to support ecosystem-based management of Australia's Northern Prawn Fishery. Ecological Applications 25:278-298.

Davies M., 2010. Concept mapping, mind mapping and argument mapping: what are the differences and do they matter? Higher Education, 62(3), 279-301. doi:10.1007/s10734-010-9387-6

Davis K.J., Vianna G.M.S., Meeuwig J.J., Meekan M.G., Pannell D.J., 2019. Estimating the economic benefits and costs of highly protected marine protected areas. Ecospheres, First published: 22 October 2019 https://doi.org/10.1002/ecs2.2879

Delacámara G., O'Higgins T. G., Lago M., Langhans S., 2020. Ecosystem-Based Management: Moving from Concept to Practice. Chapter. In: O'Higgins, T., Lago, M., DeWitt, T. (eds) Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity. Theory, tools and practice. Springer, Amsterdam. https://link.springer.com/book/10.1007/978-3-030-45843-0 (eBook)

Delavenne J., Metcalfe K., Smith R.J., Vaz S., Martin C.S., Dupuis L., Coppin F., Carpentier A., 2012. Systematic conservation planning in the eastern English Channel: comparing the Marxan and Zonation decision-support tools. ICES Journal of Marine Science 69(1), 75-83.

de Mutsert K., Coll M., Steenbeek J., Ainsworth C.H., Buszowski J., Chagaris D., Christensen V., Heymans S.J.J., Lewis K. A., Libralato S., Oldford G., Piroddi C., Romagnoni G., Sepetti N., Spence M., Walters C., 2023. Advances in spatial-temporal coastal and marine ecosystem modeling using Ecopath with Ecosim and Ecospace.in U. B. Scharler, D., editor. 2nd Edition of the Treatise on Coastal Science.

DePiper G., Gaichas S., Muffley B., Ardini G., Brust J., Coakley J., Dancy K., Elliott G W., Leaning D. C., Lipton D., McNamee J., Perretti C., Rootes-Murdy K., Wilberg M. J., 2021. Learning by Doing: Collaborative Conceptual Modelling as a Path Forward in Ecosystem-Based Management. ICES Journal of Marine Science 78, no. 4: 1217–28. https://doi.org/10.1093/icesjms/fsab054

Dickey-Collas M., 2014. Why the complex nature of integrated ecosystem assessments requires a flexible and adaptive approach. ICES Journal of Marine Science, 71: 1174–1182.

Dickey-Collas M., Link J. S., Snelgrove P., Roberts J. M., Anderson M. R., Kenchington E., Bundy A., (Peg) Brady, M. M., Shuford R. L., Townsend H., Rindorf A., Rudd M.A., Johnson D., Johannesen E., 2022. Exploring ecosystem-based management in the North Atlantic. Journal of Fish Biology, 101(2), 342– 350. https://doi.org/10.1111/jfb.15168.

Doxa A., Almpanidou V., Katsanevakis S., Queirós A.M., Kaschner K., Garilao C., Kesner-Reyes K., Mazaris A.D., 2022. 4D marine conservation networks: Combining 3D prioritization of present and future biodiversity with climatic refugia. Global Change Biology, 28(15), pp.4577-4588.

Drymon J.M., Dedman S., Froeschke J.T., Seubert E.A., Jefferson A. E., Kroetz A.M., Mareska J.F., Powers S.P., 2020. Defining Sex-Specific Habitat Suitability for a Northern Gulf of Mexico Shark Assemblage. Frontiers in Marine Science 7, 2020, DOI=10.3389/fmars.2020.00035.

Duarte C.M., Agusti S., Barbier E., Britten G.L., Castilla J.C., Gattuso J.P., Fulweiler R.W., Hughes T.P., Knowlton N., Lovelock C.E., Lotze H.K., Predragovic M., Poloczanska E., Roberts C., Worm B., 2020. Rebuilding marine life. Nature. 580, 39–51. https://doi.org/10.1038/s41586-020-2146-7.

Dubé M.G., Duinker P., Greig L., Carver M., Servos M., McMaster M., Noble B., Schreier H., Jackson L., Munkittrick K. R., 2013. A framework for assessing cumulative effects in watersheds: an introduction to Canadian case studies: Watershed CEA Framework. Integrated Environmental Assessment and Management, 9(3), 363–369. https://doi.org/10.1002/ieam.1418

Elliott M., 2012. Preface – Setting the Scene and the Need for Integrated Science for the Operational and Environmental Consequences of Large Industrial Cooling Water Systems. In: S Rajagopal, HA Jenner and VP Venugopalan (Eds). Operational and Environmental Consequences of Large Industrial Cooling Water Systems. Springer, Heidelberg/New York.

Elliott M., 2013. The 10-tenets for integrated, successful and sustainable marine management. Marine Pollution Bulletin, 74: 1-5.

Elliott M., 2014. Integrated marine science and management: wading through the morass. Marine Pollution Bulletin, 86(1/2): 1-4. doi: https://doi.org/10.1016/j.marpolbul.2014.07.026

Elliott M., O'Higgins T.G., 2020. From DPSIR the DAPSI(W)R(M) Emerges… a Butterfly – 'protecting the natural stuff and delivering the human stuff'. Chapter. In: O'Higgins, T., Lago, M., DeWitt, T. (eds) Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity. Theory, tools and practice. Springer, Amsterdam. https://link.springer.com/book/10.1007/978-3-030-45843-0 (eBook)

Elliott M., Cutts N.D., Trono A., 2014. A typology of marine and estuarine hazards and risks as vectors of change: a review for vulnerable coasts and their management. Ocean & Coastal Management, 93: 88-99.

Elliott M., Burdon D., Atkins J.P., Borja A., Cormier R., de Jonge V.N., Turner R.K., 2017. "And DPSIR begat DAPSI(W)R(M)!" - A unifying framework for marine environmental management. Marine Pollution Bulletin, 118: 27-40.

Elliott M., Day J.W., Ramachandran R., Wolanski, E. 2019. Chapter 1 - A Synthesis: What Future for Coasts, Estuaries, Deltas, and other Transitional Habitats in 2050 and Beyond? In: Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. (Eds.), Coasts and Estuaries: The Future. Elsevier, Amsterdam, ISBN 978-0-12-814003-1, p1-28.

Elliott M., Borja A., Cormier R., 2020a. Activity-footprints, pressures-footprints and effects-footprints – Walking the pathway to determining and managing human impacts in the sea. Marine Pollution Bulletin, 155, 2020, 111201, https://doi.org/10.1016/j.marpolbul.2020.111201

Elliott M., Franco A., Smyth K., Cormier R., 2020b. Industry and policy-driven conceptual frameworks of climate change impacts on aquaculture and fisheries. Deliverable 5.1, CERES Project, Report, pp 41+ Appendices. Accessed https://www.ceresproject.eu

Elliott S.A.M., Guérin L., Pesch R., Schmitt P., Meakins B., Vina-Herbon C., González-Irusta J. M., de la Torriente A., Serrano A., 2018. Integrating benthic habitat indicators: Working towards an ecosystem approach, Marine Policy, 90, 2018, 88-94, https://doi.org/10.1016/j.marpol.2018.01.003

EU, 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for Community action in the field of marine environmental policy. Official Journal of the European Union 2008, 164, 25.

EU, 2013. REGULATION (EU) No 1380/2013 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC.

EU, 2014. Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning (EU MSP Directive). Official Journal of the European Union 2008, L257/135.

EU, 2016. Regulation (EU) 2016/2336 of the European Parliament and of the Council of 14 December 2016 establishing specific conditions for fishing for deep-sea stocks in the north-east Atlantic and provisions for fishing in international waters of the north-east Atlantic and repealing Council Regulation (EC) No 2347/2002.

EU, 2017a. 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. Official Journal of the European Union L125/43

EU, 2017b. Commission Decision (EU) 2017/845 of 17 May 2017 amending Directive 2008/56/EC of the European Parliament and of the Council as regards the indicative lists of elements to be taken into account for the preparation of marine strategies. Official Journal of the European Union L 125/27

EU, 2021. European Commission, Directorate-General for Environment, EU Biodiversity strategy for 2030 – Bringing nature back into our lives. Publications Office of the European Union, 2021, https://data.europa.eu/doi/10.2779/677548

European Commission, 2018. Commission Decision (EU) 2018/229 of 12 February 2018 establishing, pursuant to Directive 2000/60/EC of the European Parliament and of the Council, the values of the Member State monitoring system classifications as a result of the intercalibration exercise and repealing Commission Decision 2013/480/EU. Official Journal of the European Communities, L47: 1-91.

European Commission, 2019. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of The Regions. The European Green Deal. COM/2019/640 final.

European Commission, 2020. Communication from the Commission to 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, 20.5.2020 COM (2020) 380 final.

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: Forging a climate-resilient Europe — the new EU Strategy on Adaptation to Climate Change (COM(2021) 82 final).

European Commission, 2022a. Proposal for a Regulation of the European Parliament and of the Council on nature restoration. Brussels, 22.6.2022, COM (2022) 304 final, 2022/0195 (COD).

European Commission, 2022b. Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) No 691/2011 as regards introducing new environmental economic accounts modules. COM/2022/329 final.

European Commission, 2022c. MSFD CIS Guidance Document No. 19, Article 8 MSFD. May 2022.

European Commission, European Climate, Infrastructure and Environment Executive Agency, Ruskule A, Oulès L, Zamparutti T, Dworak T, Lieberknecht L, Strosser P, et al., 2021a. Guidelines for implementing an ecosystem-based approach in maritime spatial planning: including a method for the evaluation, monitoring and review of EBA in MSP. Publications Office; 2021. Available from: doi/10.2926/84261

European Commission, European Climate, Infrastructure and Environment Executive Agency, 2021b. Guiding the application of an ecosystem-based approach in maritime spatial planning, Publications Office, 2021, https://data.europa.eu/doi/10.2926/6587

European Commission, European Climate, Infrastructure and Environment Executive Agency, Lukacova, Z., Gea, G., Strosser, P., et al., 2021c. Study on integrating an ecosystem-based approach into maritime spatial planning: what are the lessons from current practice in applying ecosystem-based approaches in maritime spatial planning?: results from the literature review, Publications Office, 2021, https://data.europa.eu/doi/10.2926/13709

European Commission, European Climate, Infrastructure and Environment Executive Agency, Ruskule, A., Dworak, T., Zamparutti, T., et al., 2021d. Study on integrating an ecosystem-based approach into maritime spatial planning: project final report: summary of project activities, Publications Office, 2021, https://data.europa.eu/doi/10.2926/17446

European Commission, European Climate, Infrastructure and Environment Executive Agency, 2021e. Study on integrating an ecosystem-based approach into maritime spatial planning: Project case-study reports, Publications Office, 2021, https://data.europa.eu/doi/10.2926/181540

European Commission, 2023a. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of The Regions. EU Action Plan: Protecting and restoring marine ecosystems for sustainable and resilient fisheries. COM (2023) 102 final, Brussels, 21.2.2023.

European Commission, 2023b. Communication from the Commission to the European Parliament and the Council. The Common Fisheries Policy today and tomorrow: a Fisheries and Oceans Pact towards sustainable, science-based, innovative and inclusive fisheries management Brussels, 21.2.2023 COM(2023) 103 final.

European Environment Agency, 2019, Marine messages II, Navigating the course towards clean, healthy and productive seas through implementation of an ecosystem-based approach. EEA. https://www.eea.europa.eu/publications/marine-messages-2

Evans J.L., Peckett F., Howell K.L., 2015. Combined application of biophysical habitat mapping and systematic conservation planning to assess efficiency and representativeness of the existing High Seas MPA network in the Northeast Atlantic. ICES Journal of Marine Science, 72(5), pp.1483-1497.

Fabbrizzi E., Scardi M., Ballesteros E., Benedetti-Cecchi L., Emma C., Ceccherelli G., De Leo F., Deidun A., Guarnieri G., Falace,A., Fraissinet S., Giommi C., Mačić V., Mangialajo L., Mannino A.M., Piazzi L., Ramdani M., Rilov G., Rindi L., Rizzo. L., Sara G., Souissi J. B., Taskin E., Fraschetti S., 2020. Modeling macroalgal forest distribution at Mediterranean scale: Present status, drivers of changes and insights for conservation and management. Frontiers in Marine Science 7, 20. doi:10.3389/fmars.2020.00020.

Fabbrizzi E., Giakoum, S., De Leo F., Tamburello L., Chiarore A., Colletti A., Coppola M., Munari M., Musco L., Rindi F., Rizzo L., Savinelli B., Franzitta G., Grech D., Cebrian E., Verdura J., Bianchelli S., Mangialajo L., Nasto I., Sota D., Fraschetti S., 2023. The challenge of setting restoration targets for macroalgal forests under climate changes. Journal of Environmental Management 326, 116834. doi: 10.1016/j.jenvman.2022.116834

Fauconnet L., Catarino D., Das D., Giacomello E., Gonzalez-Irusta J. M., Afonso P., Morato T., 2023. Challenges in avoiding deep-water shark bycatch in Azorean hook-and-line fisheries, ICES Journal of Marine Science, Volume 80, Issue 3, April 2023, Pages 605–619, https://doi.org/10.1093/icesjms/fsac178

FAO, 2003. The ecosystem approach to fisheries. FAO Technical Guidelines for Responsible Fisheries. No. 4, Suppl. 2. Rome. 112 pp. (also available at http://www.fao.org/3/a-y4470e.pdf).

FAO, 2020. The State of Mediterranean and Black Sea Fisheries 2020. General Fisheries Commission for the Mediterranean. Rome.

FAO, 2021. Ecosystem approach to fisheries implementation monitoring tool – A tool to monitor implementation of the ecosystem approach to fisheries (EAF) management. User manual. Rome. https://doi.org/10.4060/cb3669en

Farnham Street, 2019. The Great Mental Models, Vols. I, II and III, Latticework Publishing Inc., Ottawa, ISBN 978-1-9994490-0-1.

Fath B., Asmus H., Asmus R., Baird D., Borrett S.R., de Jonge V. N., Ludovisi A., Niquil N., Scharler U.M., Schückel U., Wolff M., 2019. Ecological network analysis metrics: The need for an entire ecosystem approach in management and policy. Ocean and Coastal Management 174, 1-14. https://hal.science/hal-02152462/document

Fernandes M., Esteves T.C., Oliveira E.R., Alves F.L., 2017. How does the cumulative impacts approach support Maritime Spatial Planning?. Ecological Indicators, 73, https://doi.org/10.1016/j.ecolind.2016.09.014.

Figgatt M., Hyde J., Dziewulski D., Wiegert E., Kishbaugh S., Zelin G., Wilson L., 2017. Harmful algal bloom–associated illnesses in humans and dogs identified through a pilot surveillance system—New York, 2015. Morbidity and Mortality Weekly Report 66(43):1182.

Fleming-Lehtinen V., Andersen J.H., Carstensen J., Lysiak-Pastuszak E., Murray C., Pyhälä M., Laamanen M., 2015. Recent developments in assessment methodology reveal an expanding eutrophication problem area in the Baltic Sea. Ecological Indicators 48:380-388

Fletcher S., Rees S., Gall S. Jackson E., Friedrich L., Rodwell L., 2012. Securing the benefits of the Marine Conservation Zone Network. A report to The Wildlife Trusts by the Centre for Marine and Coastal Policy Research, Plymouth University.

Franco A., Smyth. K., Thomson S., 2022. Developing Essential Fish Habitat maps for fish and shellfish species in Scotland. A report to the Scottish Government, December 2022.

Fraschetti S., Fabbrizzi E., Tamburello L., Uyarra M. C., Micheli F., Sala E., Pipitone C., Badalamenti F., Bevilacqua S., Boada J., Cebrian E., Ceccherelli G., Chiantore M., D'Anna G., Di Franco A., Farina Si., Giakoumi S., Gissi E., Guala I., Guidetti P., Katsanevakis S., Manea E., Montefalcone M., Sini M., Asnaghi Va., Calò A., Di Lorenzo M., Garrabou J., Musco L., Oprandi A., Rilov G., Borja A., 2022. An integrated assessment of the Good Environmental Status of Mediterranean Marine Protected Areas, Journal of Environmental Management, 305, 114370, https://doi.org/10.1016/j.jenvman.2021.114370

Frederiksen M., Anker-Nilssen T., Beaugrand G., Wanless S., 2013. Climate, copepods and seabirds in the boreal Northeast Atlantic – current state and future outlook. Global Change Biology 19, 364-372.

Fulton E.A., 2010. Approaches to end-to-end ecosystem models. Journal of Marine Systems 81:171-183.

Fulton E.A., Link J., Kaplan I.C., Johnson P., Savina-Rolland M., Ainsworth C., Horne P., Gorton R., Gamble R.J., Smith T., Smith D.C., 2011. Lessons in modelling and management of marine ecosystems: The Atlantis experience. Fish and Fisheries, 12:171-188.

Funes M., Saravia L.A., Cordone G., Iribarne O.O., Galvan D.E., 2022. Network analysis suggests changes in food web stability produced by bottom trawl fishery in Patagonia. Scientific Reports 12, 10876. https://doi.org/10.1038/s41598-022-14363-y

Gacutan, J., Pınarbaşı K., Agbaglah M., Bradley C., Galparsoro I., Murillas A., Adewumi I., Praphotjanaporn T., Bordt M., Findlay K., Lantz C., Milligan B. M., 2022a. The emerging intersection between marine spatial planning and ocean accounting: A global review and case studies. Marine Policy, 140: 105055 https://www.sciencedirect.com/science/article/pii/S0308597X22001026

Gacutan, J., I. Galparsoro, K. Pınarbaşı, A. Murillas, I. J. Adewumi, T. Praphotjanaporn, E. L. Johnston, K. P. Findlay, B. M. Milligan, 2022b. Marine spatial planning and ocean accounting: Synergistic tools enhancing integration in ocean governance. Marine Policy, 136: 104936 https://www.sciencedirect.com/science/article/pii/S0308597X21005479

Gallo F., Fossi C., Weber R., Santillo D., Sousa J., Ingram I., Nadal A., Romano D., 2018. Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures. Environ Sci Eur 30, 13 (2018). https://doi.org/10.1186/s12302-018-0139-z

Galparsoro I., Korta M., Subirana I., Borja Á., Menchaca I., Solaun O., Muxika I., Iglesias G., Bald J., 2021. A new framework and tool for ecological risk assessment of wave energy converters projects. Renewable and Sustainable Energy Reviews, 151: 111539. https://doi.org/10.1016/j.scitotenv.2022.156037

Galparsoro I., Menchaca I., Garmendia J.M., Borja A., Maldonado A.D., Iglesias G., Bald J., 2022a. Reviewing the ecological impacts of offshore wind farms. npj Ocean Sustain 1, 1 (2022). https://doi.org/10.1038/s44183-022-00003-5

Galparsoro I., Mandiola G., Garnier R., de Santiago I., Villarín E., Iglesias G., Machado I., Soulard T., Le Bourhis E., Zubiate L., Menchaca I., Bald J., 2022b. Development of a model for the identification of suitable areas for the development of wave energy projects in the European Atlantic region in the context of maritime spatial planning and its implementation into a Decision Support Tool. The corporate deliverable of the SafeWAVE Project co-funded by the

European Climate, Infrastructure and Environment Executive Agency (CINEA), Call for Proposals EMFF-2019- 1.2.1.1 - Environmental monitoring of ocean energy devices. 50 pp + Annexes

Garcia S.M., Cochrane K.L., 2005. Ecosystem approach to fisheries: a review of implementation guidelines. ICES Journal of Marine Science, 62: 311e318.

Garcia S.M., Zerbi A., Aliaume C., Do Chi T., Lasserre G., 2003. The ecosystem approach to fisheries: issues, terminology, principles, institutional foundations, implementation and outlook. FAO Fisheries Technical Paper No. 443, Rome, FAO, 2003, 71 p

Garthe S., Schwemmer H., Peschko V., Markones N., Müller S., Schwemmer P., Mercker M., 2023. Large-scale effects of offshore wind farms on seabirds of high conservation concern. Scientific Reports 13, 4779 (2023). https://doi.org/10.1038/s41598-023-31601-z

Geange S.W., Rowden A.A., Nicol S., Bock T., Cryer M., 2020. A Data-Informed Approach for Identifying Move-on Encounter Thresholds for Vulnerable Marine Ecosystem Indicator Taxa. Frontiers in Marine Science 7, 2020, DOI=10.3389/fmars.2020.00155

Geary W.L., Bode M., Doherty T.S., Fulton E.A., Nimmo D.G., A.I.T. Tulloch, V.J.D. Tulloch, Ritchie E. G., 2020. A guide to ecosystem models and their environmental applications. Nature Ecology & Evolution 4, 1459–1471. https://doi.org/10.1038/s41559-020-01298-8

Geffroy B., Wedekind C., 2020. Effects of global warming on sex ratios in fishes. Journal of Fish Biology, 97: 596-606.

Giakoumi S., Katsanevakis S., Vassilopoulou V., Panayotidis P., Kavadas S., Issaris Y., Kokkali A., Frantzis A., Panou A., Mavrommati G., 2012. Could European conservation policy benefit from systematic conservation planning? Aquatic Conservation 22, 762–775.

Giakoumi S., Katsanevakis S., Albano P.G., Azzurro E., Cardoso A.C., Cebrian E., Deidun A., Edelist D., Francour P., Jimenez C., Mačić V., Occhipinti-Ambrogi A., Rilov G., Ramzi Sghaier Y., 2019. Management priorities for marine invasive species. Science of The Total Environment 688: 976-982.

Gilman E., Musyl M., Suuronen P., Chaloupka M., Gorgin S., Wilson J., Kuczenski B., 2021. Highest risk abandoned, lost and discarded fishing gear. Sci Rep 11, 7195 (2021). https://doi.org/10.1038/s41598-021-86123-3

Gibbs, P.E., Pascoe P.L., Burt G.R., 1988. Sex change in the female dogwhelk Nucella lapillus, induced by TBT from antifouling paints. J. Mar. Biol. Assoc. (U.K.) 68: 715–732.

Giménez J., Cardador L., Mazor T., Kark S., Bellido J.M., Coll M., Navarro J., 2020. Marine protected areas for demersal elasmobranchs in highly exploited Mediterranean ecosystems, Marine Environmental Research, 160, 2020, https://doi.org/10.1016/j.marenvres.2020.105033

Gissi E., Menegon S., Sarretta A., Appiotti F., Maragno D., Vianello A., Depellegrin D., Venier C., Barbanti A., 2017. Addressing uncertainty in modelling cumulative impacts within maritime spatial planning in the Adriatic and Ionian region. PloS One, 12(7), e0180501. https://doi.org/10.1371/journal.pone.0180501

Gissi E., Manea E., Mazaris A.D., Fraschetti S., Almpanidou V., Bevilacqua S., Coll M., Guarnieri G., Lloret-Lloret E., Pascual M., Petza D., Rilov G., Schonwald M., Stelzenmüller V., Katsanevakis S., 2021. A review of the combined effects of climate change and other local human stressors on the marine environment, Science of The Total Environment, Volume 755, Part 1,2021,142564, https://doi.org/10.1016/j.scitotenv.2020.142564.

Gomei M., Steenbeek J., Coll M., Claudet J., 2021. 30 by 30: Scenarios to recover biodiversity and rebuild fish stocks in the Mediterranean. WWF Mediterranean Marine Initiative, Rome, Italy, 29 pp. https://www.wwf.eu/?2248641/Scenarios-to-recover-biodiversity-and-rebuild-fish-stocks-in-the-Mediterranean-Sea.

González-Irusta J.M., Wright P.J., 2016a. Spawning grounds of Atlantic cod (*Gadus morhua*) in the North Sea. ICES Journal of Marine Science 73, 304–315.

González-Irusta J.M., Wright P.J., 2016b. Spawning grounds of haddock (Melanogrammus aeglefinus) in the North Sea and West of Scotland. Fisheries Research 183, 180–191.

González-Irusta J.M., De la Torriente A., Punzón A., Blanco M., Serrano A., 2018. Determining and mapping species sensitivity to trawling impacts: the BEnthos Sensitivity Index to Trawling Operations (BESITO). ICES Journal of Marine Science 75(5), 1710- 1721. https://doi.org/10.1093/icesjms/fsy030

Gorjanc S., Klancnik K., Murillas-Maza A., Uyarra M.C., Papadopoulou N.K., Paramanad Th., Smith C., Chalkiadaki O., Dassenakis M., Peterlin M. 2020. Coordination of pollution-related MSFD measures in the Mediterranean - Where we stand now and insights for the future. Marine Pollution Bulletin 159 (2020) 111476. https://doi.org/10.1016/j.marpolbul.2020.111476

Gorjanc S, K Klančnik, NK Papadopoulou, A Murillas-Maza, KJarni, T Paramana, M Pavičić, F Ronchi, MC Uyarra, Š Koren, M Dassenakis, O Vidjak, CJ Smith, S Skejić 2022. Evaluating the progress in achieving Good Environmental Status in the Mediterranean: A methodology to assess the effectiveness of Marine Strategy Framework Directive's Programmes of Measures. Marine Policy 136, February 2022, 104889

Gray J.S., Elliott M., 2009. Ecology of Marine Sediments; Science to Management. Oxford University Press, Oxford, 260 pp.

Gray S., Chan A., Clark D., Jordan R.C., 2012. Modeling the integration of stakeholder knowledge in social-ecological system decision-making: Benefits and limitations to knowledge diversity. Ecological Modeling 229, 88-96.

Gray S., Gray S., Cox L., Henly-Shepard S., 2013a. Mental modeler: A fuzzy-logic cognitive mapping modeling tool for adaptive environmental management. Proceedings of the 46th International Conference on Complex Systems. 963-973

Gray S., Zanre E., Gray S., 2013b. Fuzzy Cognitive Maps as representations of mental models and group beliefs: theoretical and technical issues. In Fuzzy Cognitive maps for Applied Sciences and Engineering - From fundamentals to extensions and learning algorithms Ed: Elpiniki I. Papageorgiou. Springer Publishing

Grilli G., Luisetti T., Thornton A., Donovan D., 2021. Developing ecosystem accounts for the marine and coastal environment: Limitations, opportunities and lessons learned from the United Kingdom experience. Journal of Ocean and Coastal Economics: Vol. 8: Iss. 2, Article 4. DOI: https://doi.org/10.15351/2373-8456.1145

Gubbay S., Sanders N., Haynes T., Janssen J.A.M., Rodwell J.R., Nieto A., García Criado M., Beal S., Borg J., Kennedy M., Micu D., Otero M., Saunders G., Calix M., 2016. European Red List of Habitats Part 1. Marine habitats. EU 2016. https://portals.iucn.org/library/sites/library/files/documents/2016-079-vol.1.pdf

Guérin L., Lizińska A., 2022. Analysis of the main elements of the “Good Environmental Status” from the 1st and 2nd MSFD cycles, reported by the European Member States for the Descriptor 6 (sea floor integrity) - links with Regional Seas’ Conventions and D4 (food webs integrity) and D5 (eutrophication). NEA PANACEA European project. PatriNat joint unit (OFB, MNHN, CNRS). Station marine de Dinard. 50 p. + annexes. https://www.researchgate.net/profile/Laurent-Guerin-3

Guisan A., Zimmermann N.E., 2000. Predictive habitat distribution models in ecology. Ecological Modelling, 135, 147– 186.

Guizien K., Belharet M., Moritz C., Guarini J. M., 2014. Vulnerability of Marine Benthic Metapopulations: Implications of Spatially Structured Connectivity for Conservation Practice in the Gulf of Lions (NW Mediterranean Sea). Diversity and Distributions 20, no. 12: 1392–1402. https://doi.org/10.1111/ddi.12254.

Gușatu L.F., Menegon S., Depellegrin D., Zuidema C., Faaij A, Yamu C., 2021. Spatial and temporal analysis of cumulative environmental effects of offshore wind farms in the North Sea basin. Scientific Reports 11, 10125 (2021). https://doi.org/10.1038/s41598-021-89537-1

Halpern B.S., Fujita R., 2013. Assumptions, challenges, and future directions in cumulative impact analysis. Ecosphere 4, art131. doi:10.1890/ES13-00181.1.

Halpern B.S., Longo C., Hardy D., McLeod K.L., Samhouri J.F., Katona S.K., Kleisner K., Lester S.E., O'Leary J., Ranelletti M., Rosenberg A.A., Scarborough C., Selig E.R., Best B. D., Brumbaugh D. R., Chapin F. S., Crowder L. B., Daly K. L., Doney S. C., Elfes C., Fogarty M. J., Gaines S. D., Jacobsen K. I., Karrer L. B., Leslie H. M., Neeley E., Pauly D., Polasky S., Ris B., St Martin K., Stone G. S., Sumaila U. R., Zeller D., 2012. An index to assess the health and benefits of the global ocean. Nature. 2012;488: 615–620. doi:10.1038/nature11397

Halpern B.S., Selkoe K.A., Micheli F., Kappel C.V., 2007. Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. Conserv. Biol. J. Soc. Conserv. Biol. 21, 1301–1315. https://doi.org/10.1111/j.1523- 1739.2007.00752.x.

Halpern B. S., Walbridge S., Selkoe K. A., Kappel C. V., Micheli F., D'Agrosa C., Bruno J.F., Casey K.S., Ebert C., Fox H.E., Fujita R., Heinemann D., Lenihan H.S., Madin E.M.P., Perry M.T., Selig E.R., Spalding M., Steneck R., Watson R., 2008. A global map of human impact on marine ecosystems. Science 319, 948–952

Halpern B.S., Frazier M., Potapenko J., Casey K.S., Koenig K., Longo C., Stewart Lowndes J., Cotton Rockwood R., Selig E. R., Selkoe K. A., Walbridge S., 2015. Spatial and temporal changes in cumulative human impacts on the world's ocean, Nature 6:7615, DOI: 10.1038/ncomms8615.

Hammar L., Molander S., Pålsson J., Schmidtbauer Crona J., Carneiro G., Johansson T., Hume D., Kågesten G., Mattsson D., Törnqvist O., Zillén L., Mattsson M., Bergström U., Perry D., Caldow C., Andersen J.H., 2020. Cumulative impact assessment for ecosystem-based marine spatial planning. Science of The Total Environment, 734, 139024. doi: 10.1016/j.scitotenv.2020.139024

Harris H.E., Fogg A.Q., Gittings S.R., Ahrens R.N.M., Allen M.S., Patterson III W.F., 2020. Testing the efficacy of lionfish traps in the northern Gulf of Mexico. PLoS ONE 15(8): e0230985.

Haugen J.B., Link J.S., Cribari K., Bundy A., Dickey-Collas M., Leslie H.M., Hall J., Fulton E.A., Levenson J.J., Parsons D.M., Hassellöv I.-M., Olsen E., DePiper G.S., Gentry R.R., Clark D. E, Brainard R.E., Mateos-Molina D., Borja, A., Gelcich S., Guilhon M., Ban N.C., Pedreschi D., Khan A., Chuenpagdee R., Large S.I., Defeo O., Shannon L., Bailey S.A., Jordan A., Agnalt A.L., 2023 (submitted). Marine ecosystem-based management: challenges remain, yet solutions exist, and progress is occurring.

Hays G.C., Mazaris A.D., Schofield G., 2014. Different male vs. female breeding periodicity helps mitigate offspring sex ratio skews in sea turtles. Frontiers in Marine Science. 1, 43. https://doi.org/10.3389/fmars.2014.00043

Heath M.R., 2012. Ecosystem limits to food web fluxes and fisheries yields in the North Sea simulated with an end-to-end food web model. Progress in Oceanography (Special issue: End-to-end modelling: Towards Comparative Analysis of Marine Ecosystem Organisation) 102, 42-66.

Heath M.R., Steele J.H., 2009. The relative roles of fishing (top-down) and climate-driven changes in productivity (bottom-up) on changes in the structure of the food web in the North Sea. Deliverable 3.5 Report to the EU-RECLAIM project (REsolving CLimAtic IMpacts on fish stocks, 044133 (SSP8)). http://www.climateandfish.eu/default.asp?ZNT=S0T1O-1P242

Heath M.R., Speirs D.C., Steele J.H., 2014a. Understanding patterns and processes in models of trophic cascades. Ecology Letters 17, 101-114.

Heath M.R., Cook R.M., Cameron A.I., Morris D.J., Speirs D.C., 2014b. Cascading ecological effects of eliminating fishery discards. Nature Communications http://www.nature.com/ncomms/2014/140513/ncomms4893/full/ncomms4893.html

Heymans J.J., Coll M., Link J.S., Mackinson S., Steenbeek J., Christensen V., 2016. Best practice in Ecopath with Ecosim food-web models for ecosystem-based management. Ecological Modelling 331:173–184.

Hiddink J.G., Jennings S., Sciberras M., Szostek C.L., Hughes K.M., Ellis N., Rijnsdorp A.D., McConnaughey R.A., Mazor T., Hilborn R., Collie J.S., Pitcher R., Amoroso R.O., Parma A.M., Suuronen P., Kaiser M.J., 2017. Global analysis of depletion and recovery of seabed biota following bottom trawling disturbance. Proceedings of the National Academy of Sciences, 114, 8301–8306.

Hiddink J.G., Jennings S., Sciberras M., Bolam S.G., Cambiè G., McConnaughey R.A., Mazor T., Hilborn R., Collie J.S., Pitcher R., Parma A.M., Suuronen P., Kaiser M.J., Rijnsdorp A.D., 2018. Assessing bottom-trawling impacts based on the longevity of benthic invertebrates. Journal of Applied Ecology, https://doi.org/10.1111/1365-2664.13278

Hill C. E., Bentley J. W., Serpetti N., Fox C., Angus C., Heymans J.J., 2021. Modelling the trophic interaction, structure, and function of the northern North Sea food web. Ecopath Technical Report. Scottish Association for Marine Science, Oban. U.K. Report no. 299, p.115

HELCOM, 2010. Ecosystem Health of the Baltic Sea: HELCOM Initial Holistic Assessment. Baltic Sea Environment Proceedings 122. Available at: http://www.helcom.fi/stc/files/Publications/Proceedings/bsep122.pdf

HELCOM, 2021a. Baltic Sea Action Plan 2021 Update. Available at: https://helcom.fi/baltic-sea-action-plan/2021-update-process/

HELCOM, 2021b. Cumulative impact from physical pressures on benthic biotopes. HELCOM. Working Group on the State of the Environment and Nature Conservation Online, 4-8 October 2021. https://portal.helcom.fi/meetings/STATE%20-%20CONSERVATION%2015-2021-843/MeetingDocuments/3J-23%20Cumulative%20impact%20on%20benthic%20biotopes.pdf

HELCOM, 2023. HELCOM Thematic assessment of spatial distribution of pressures and impacts 2016-2021. Baltic Sea Environment Proceedings No. 189. https://helcom.fi/wp-content/uploads/2023/03/HELCOM-Thematic-assessment-of-spatial-distribution-of-pressures-and-impacts-2016-2021.pdf

Hermoso V., Vasconcelos, R.P., Henriques S., Filipe A.F., Carvalho S.B., 2021. Conservation planning across realms: Enhancing connectivity for multi-realm species. Journal of Applied Ecology, 58(3), pp.644-654.

Hirzel A.H., Le Lay G., 2008. Habitat suitability modelling and niche theory. Journal of Applied Ecology 45: 1372 – 1381.

HM Treasury, 2022. The Green Book (Updated 18 November 2022) https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent/the-green-book-2020.

Hodapp D., Roca I.T., Fiorentino D., Garilao C., Kaschner K., Kesner-Reyes K., Schneider B., Segschneider J., Kocsis Á. T., T. W. Kiessling, Brey R., 2023. Climate change disrupts core habitats of marine species. Global Change Biology, First published: 15 February 2023, https://doi.org/10.1111/gcb.16612

Holon F., Mouquet N., Boissery P., Bouchoucha M., Delaruelle G., Tribot A.-S., Deter J., 2015. Fine-scale cartography of human impacts along French Mediterranean coasts: A relevant map for the management of marine ecosystems. PloS One, 10(8), e0135473. https://doi.org/10.1371/journal.pone.0135473

Hosack G. R., Hayes K. R., Dambacher J. M., 2008. Assessing model structure uncertainty through an analysis of system feedback and Bayesian networks. Ecological Applications 18:1070-1082.

Howell D., Schueller A.M., Bentley J.W., Buchheister A., Chagaris D., Cieri M., Drew K., Lundy M.G., Pedreschi D., Reid D.G., Townsend H., 2021. Combining ecosystem and single-species modeling to provide ecosystem-based fisheries management advice within current management systems. Frontiers in Marine Science, 7, p.607831.

Hsia M.H., Morton S.L., Smith L.L., Beauchesne K.R., Huncik K.M., Moeller P.D.R., 2006. Production of goniodomin A by the planktonic, chainforming dinoflagellate Alexandrium monilatum (Howell) Balech isolated from the Gulf Coast of the United State. Harmful Algae 5(3): 290–299, http://dx.doi.org/10.1016/j.hal.2005.08.004

Hussain S.S., Winrow-Griffin A., Moran D., Robinson L., Fofana A., Paramor O.A.L., Frid C., 2010. An ex-ante ecological economic assessment of the benefits arising from marine protected areas designation in the UK. Ecological Economics, 69, pp. 828–838.

http://ecopath.org

https://www.masts.ac.uk/media/4706/ecopath_with_ecosim.pdf

ICES, 2012. Report of the Workshop on Benchmarking Integrated Ecosystem Assessments (WKBEMIA).

ICES, 2019a. Working Group on Cumulative Effects Assessment Approaches in Management (WGCEAM). ICES Scientific Reports. 1:92. 23 pp. http://doi.org/10.17895/ices.pub.5759

ICES, 2019b. Workshop on scoping for benthic pressure layers D6C2 - from methods to operational data product (WKBEDPRES1), 24–26 October 2018, ICES HQ, Copenhagen, Denmark. ICES CM 2018/ACOM:59. 69 pp.

ICES, 2019c. Workshop to evaluate and test operational assessment of human activities causing physical disturbance and loss to seabed habitats (MSFD D6 C1, C2 and C4) (WKBEDPRES2). ICES Scientific Reports. 1:69. http://doi.org/10.17895/ices.pub.5611

ICES, 2020a. Guide to ICES advisory framework and principles. ICES Technical Guidelines. Report. https://doi.org/10.17895/ices.advice.7648

ICES, 2020b. Workshop on an Ecosystem Based Approach to Fishery Management for the Irish Sea (WKIRISH6; outputs from 2019 meeting). ICES Scientific Reports. Report. https://doi.org/10.17895/ices.pub.5551

ICES, 2020c. Workshop on Challenges, Opportunities, Needs and Successes for Including Human Dimensions in Integrated Ecosystem Assessments (WKCONSERVE)). ICES Scientific Reports. Report. https://doi.org/10.17895/ices.pub.5950

ICES, 2021a. Workshop on methods and guidelines to link human activities, pressures and state of the ecosystem in Ecosystem Overviews (WKTRANSPARENT; outputs from 2020 meeting). ICES Scientific Reports. 3:17. 59 pp. https://doi.org/10.17895/ices.pub.7930

ICES, 2021b. OSPAR request on the production of spatial data layers of fishing intensity/pressure. In Report of the ICES Advisory Committee, 2021. ICES Advice 2021, ospar.2021.11. https://doi.org/10.17895/ices.advice.8297

ICES, 2022a. Advice on ecosystem services and effects. General ICES Advice guidelines. Report. https://doi.org/10.17895/ices.advice.19551433.v1

ICES, 2022b. Joint ICES EUROMARINE Workshop on Common Conceptual Mapping Methodologies (WKCCMM; Outputs from 2021 meeting). ICES Scientific Reports. Report. https://doi.org/10.17895/ices.pub.10095

ICES, 2022c. Workshop to evaluate proposed assessment methods and how to set thresholds for assessing adverse effects on seabed habitats (WKBENTH3). ICES Scientific Reports. 4:93. 102 pp. https://doi.org/10.17895/ices.pub.21666260

ICES, 2023. Advice on fishing opportunities (2023). General ICES Advice guidelines. Report. https://doi.org/10.17895/ices.advice.22240624.v1

IEC/ISO, 2009. Risk Management - Risk Assessment Techniques. International Organization for Standardization IEC/ISO 31010:2009.

ISO, 2018. Risk Management Principles and Guidelines. International Organization for Standardization ISO 31000:2018(E).

Jager T., Ravagnan E., Dupont S., 2016. Near-Future Ocean Acidification Impacts Maintenance Costs in Sea-Urchin Larvae: Identification of Stress Factors and Tipping Points Using a DEB Modelling Approach. Journal of Experimental Marine Biology and Ecology 474: 11–17. https://doi.org/10.1016/j.jembe.2015.09.016.

Jennings S., Rice J., 2011. Towards an ecosystem approach to fisheries in Europe: a perspective on existing progress and future directions. Fish and Fisheries. First published: 15 February 2011, https://doi.org/10.1111/j.1467-2979.2011.00409.x

Jones A. R., Doubleday Z. A., Prowse T. A. A., Wiltshire K. H., Deveney M. R., Ward T., Scrivens S. L., Cassey P., O'Connell L. G., Gillanders B. M., 2018. Capturing expert uncertainty in spatial cumulative impact assessments. Scientific Reports, 8(1), 1–13. https://doi.org/10.1038/s41598-018-19354-6

JRC, 2021. https://mcc.jrc.ec.europa.eu/main/dev.py?N=simple&O=11

Judd A., Lonsdale J.A., 2021. Applying systems thinking: The Ecosystem Approach and Natural Capital Approach – Convergent or divergent concepts in marine management? Marine Policy 129 (2021) 104517. https://doi.org/10.1016/j.marpol.2021.104517.

Kaikkonen L., Parviainen T., Rahikainen M., Uusitalo L., Lehikoinen A., 2021. Bayesian networks in environmental risk assessment: A review. Integrated environmental assessment and management, 17(1), 62-78.

Katara I., Peden J., Bannister H., Ribeiro J., Fronkova L., Scougal C., Martinez R., Downie A.-L., Sweeting C., 2021. Conservation hotspots for fish habitats: A case study from English and Welsh waters. Regional Studies in Marine Science 44, 101745.

Katsanevakis S., Stelzenmüller V., South A., Sorensen T.K., Jones P.J.S., Kerr S., Badalamenti F., Anagnostou C., Breen P., Chust G., D'Anna G., Duijn M., Filatova T., Fiorentino F., Hulsman H., Johnson K., Karageorgis A. P., Kröncke I., Mirto S., Pipitone C., Portelli S., Qiu W., Reiss H., Sakellariou D., Salomidi M., van Hoof L., Vassilopoulou V., Vega Fernández T., Vöge S., Weber A., Zenetos A., ter Hofstede R., 2011. Ecosystem-based marine spatial management: Review of concepts, policies, tools, and critical issues. Ocean & Coastal Management, 54: 807-820

Katsanevakis S., Wallentinus I., Zenetos A., Leppäkoski E., Çinar M.E., Oztürk B., Grabowski M., Golani D., Cardoso A.C., 2014. Impacts of invasive alien marine species on ecosystem services and biodiversity: a pan-European review. Aquatic Invasions, 9, 391–423, https://doi.org/10.3391/ai.2014.9.4.01

Katsanevakis S., Tempera F., Teixeira H., 2016. Mapping the impact of alien species on marine ecosystems: the Mediterranean Sea case study. Diversity and Distributions, 22, 694–707. https://doi.org/10.1111/ddi.12429

Katsanevakis S., Coll M., Fraschetti S., Giakoumi S., Goldsborough D., Mačić V., Mackelworth P., Rilov G., Stelzenmüller V., Albano P.G., Bates A.E., Bevilacqua S., Gissi E., Hermoso V., Mazaris A.D., Pita C., Rossi V., Teff-Seker Y., Yates K., 2020. Twelve Recommendations for Advancing Marine Conservation in European and Contiguous Seas. Frontiers in Marine Science, https://doi.org/10.3389/fmars.2020.565968

Kazanidis G., Orejas C., Borja A., Kenchington E., Henry L.-A., Callery O., Carreiro-Silva M., Egilsdottir H., Giacomello E., Grehan A., Menoth L., Morato T., Ragnarsson S.A., Rueda J.L., Stirling D., Stratmann T., van Oevelen D., Palialexis A., Roberts J.M., 2020. Assessing the environmental status of selected North Atlantic deep-sea ecosystems. Ecological Indicators, 119 (2020), p. 106624, 10.1016/j.ecolind.2020.106624

Kearney M. R., Porter W. P., 2020. NicheMapR – an R Package for Biophysical Modelling: The Ectotherm and Dynamic Energy Budget Models. Ecography 43, no. 1: 85–96. https://doi.org/10.1111/ecog.04680.

Kelble C. R., Loomis D. K., Lovelace S., Nuttle W. K., Ortner P. B., Fletcher P., Cook G.S., Lorenz J. J., Boyer J.N., 2013. The EBM-DPSER conceptual model: integrating ecosystem services into the DPSIR framework. PLoS ONE 8:e70766. doi: 10.1371/journal.pone.0070766

Kell L.T, Mosqueira I., Grosjean P., Fromentin J., Garcia D., Hillary R., Jardim E., Mardle S., Pastoors M.A., Poos J.J., 2007. FLR: An Open-Source Framework for the Evaluation and Development of Management Strategies. ICES Journal of Marine Science 64, no. 4: 640–46.

Kirkfeldt T. S., 2019. An ocean of concepts: Why choosing between ecosystem-based management, ecosystem-based approach and ecosystem approach makes a difference. Marine Policy, 106: 103541.

Knights A.M., Piet G.J., Jongbloed R.H., Tamis J.E., White L., Akoglu E., Boicenco L., Churilova T., Kryvenko O., Fleming-Lehtinen V., Leppanen J-M., Galil B.S., Goodsir F., Goren M., Margonski P., Moncheva S., Oguz T., Papadopoulou K.N., Setälä O., Smith C.J., Stefanova K., Timofte F., Robinson L.A., 2015. An exposure-effect approach for evaluating ecosystem-wide risks from human activities. ICES Journal of Marine Science, 72(3): 1105-1115

Korpinen S., Andersen J.H., 2016. A global review of cumulative pressure and impact assessments in marine environment. Frontiers in Marine Science, http://dx.doi.org/10.3389/fmars.2016.00153.

Korpinen S., Meski L., Andersen J.H., Laamanen M., 2012. Human pressures and their potential impact on the Baltic Sea ecosystem. Ecological Indicators 15: 105-114.

Korpinen S., Klancnik K., Peterlin M., Nurmi M., Laamanen L., Zupancic G., Murray C., Harvey T., Andersen J.H., Zenetos A., Stein U., Tunesi L., Abhold K., Piet G.J., Kallenbach E., Agnesi S., Bolman B.C., Vaughan D., Reker J., Gelabert E.R., 2019. Multiple pressures and their combined effects in Europe's seas. Report / ETC/ICM, No.4/2019. Available at: https://www.eionet.europa.eu/etcs/etc-icm/products/etc-icm- report-4-2019-multiple-pressures-and-their-combined-effects-in-europes-seas

Korpinen S., Laamanen L., Bergström L., Nurmi M., Andersen J.H., Haapaniemi J., Harvey E.T., Murray C.J., Peterlin M., Kallenbach E., Klančnic K., Stein U., Tunesi L., Vaughan D., Reker J., 2021. Combined effects of human pressures on Europe's marine ecosystems. Ambio https://doi.org/10.1007/s13280-020-01482-x

Korpinen S., Uusitalo L., Nordström M.C., Dierking J., Tomczak M.T., Haldin J., Opitz S., Bonsdorff E., Neuenfeldt S., 2022. Food web assessments in the Baltic Sea: Models bridging the gap between indicators and policy needs. Ambio 51, 1687–1697. https://doi.org/10.1007/s13280-021-01692-x

Lange S., Campagne C.S., Comte A., Bank E., Santos-Martín F., Maes J., Burkhard B., 2022. Progress on ecosystem accounting in Europe. Ecosystem Services, 57, 101473, https://doi.org/10.1016/j.ecoser.2022.101473.

Lauria V., Gristina M., Attrill M., Fiorentino F., Garofalo G., 2015. Predictive habitat suitability models to aid conservation of elasmobranch diversity in the central Mediterranean Sea. Scientific Reports 5, 13245. https://doi.org/10.1038/srep13245

Lazăr L., Boicenco L., Marin O., Culcea O., Pantea E., Bișinicu E., Timofte F., Mihailov M.E., 2018. Black Sea eutrophication dynamics from causes to effects. Revista Cercetări Marine-Revue Recherches Marines-Marine Research Journal, 48(1), pp.100-117.

Lett C., Verley P., Mullon C., Parada C., Brochier T., Penven P., Blanke B., 2008. A Lagrangian Tool for Modelling Ichthyoplankton Dynamics. Environmental Modelling & Software 23, no. 9: 1210–14. https://doi.org/10.1016/j.envsoft.2008.02.005.

Levin P.S., Fogarty M.J., Murawski S.A., Fluharty D., 2009. Integrated Ecosystem Assessments: Developing the Scientific Basis for Ecosystem-Based Management of the Ocean. PLoS Biology, 7: e1000014.

Levin P. S., Kelble C.R., Shuford R.L., Ainsworth C., DeReynier Y., Dunsmore R., Fogarty M. J., Holsman K., Howell E.A., Monaco M.E., Oakes S.A., Werner F., 2014. Guidance for implementation of integrated ecosystem assessments: a US perspective. ICES Journal of Marine Science, https://doi.org/doi:10.1093/icesjms/fst112

Lindenmayer B., Fischer J., Felton A., Montague-Drake R., Manning A.D.D., Simberloff D., Youngentob K., Saunders D., Wilson D., Felton A.M., 2007. The Complementarity of Single-species and Ecosystem-oriented Research in Conservation Research. Oikos 116, no. 7: 1220–26.

Liquete C., Piroddi C., Drakou E.G., Gurney L., Katsanevakis S., Charef A., Egoh B., 2013a. Current Status and Future Prospects for the Assessment of Marine and Coastal Ecosystem Services: A Systematic Review. PLoS ONE 8(7): e67737. https://doi.org/10.1371/journal.pone.0067737

Liquete C., Zulian G., Delgado I., Stips A., Maes J., 2013b. Assessment of coastal protection as an ecosystem service in Europe. Ecological Indicators, 30, 205-217, https://doi.org/10.1016/j.ecolind.2013.02.013

Loiseau C., Thiault L., Devillers R., Claudet J., 2021. Cumulative impact assessments highlight the benefits of integrating land-based management with marine spatial planning. The Science of The Total Environment, 787(147339), 147339.

Long, R. D., Charles, A., and Stephenson, R. L., 2015. Key principles of marine ecosystem-based management. Marine Policy. 57, 53–60. https://doi.org/10.1016/j.marpol.2015.01.

Lucchetti A., Bargione G., Petetta A., Vasapollo C., Virgili M., 2019. Reducing Sea Turtle Bycatch in the Mediterranean Mixed Demersal Fisheries. Frontiers in Marine Science 6, 2019, https://www.frontiersin.org/articles/10.3389/fmars.2019.00387

Luisetti T., Turner R.K., Bateman I.J., Morse-Jones S., Adams C., Fonseca L., 2011. Coastal and marine ecosystem services valuation for policy and management: Managed realignment case studies in England. Ocean & Coastal Management, 54(3), pp. 212–224.

Luisetti T., Turner R.K., Andrews J.E., Jickells T.D., Kröger S., Diesing M., Paltriguera L., Johnson M.T., Parker E.R., Bakker D.C.E., Weston K., 2019. Quantifying and valuing carbon flows and stores in coastal and shelf ecosystems in the UK. Ecosystem Services, 35, pp. 67–76.

Lynam C.P., Uusitalo L., Patrício J., Piroddi C., Queirós A.M., Teixeira H., Rossberg A.G., Sagarminaga Y., Hyder K., Niquil N., Möllmann C., Wilson C., Chust G., Galparsoro I., Forster R., Veríssimo H., Tedesco L., Revilla M., Neville S., 2016. Uses of Innovative Modeling Tools within the Implementation of the Marine Strategy Framework Directive. Frontiers in Marine Science 3, 2016. https://www.frontiersin.org/articles/10.3389/fmars.2016

MA, 2003. Ecosystems and human well-being: A framework for assessment. Island Press, Washington. http://pdf.wri.org/ecosystems_human_wellbeing.pdf

Macreadie P.I., Costa M.D.P., Atwood T.B., Kelleway J.J., Kennedy H, Lovelock C.E., Serrano O., Duarte C.M., 2021. Blue carbon as a natural climate solution. Nature Reviews Earth & Environment. Nat Rev Earth Environ 2, 826–839. https://doi.org/10.1038/s43017-021-00224-1

Madricardo F., Ghezzo M., Nesto N., Mc Kiver W. J., Faussone G. C., Fiorin R., Riccato F., Mackelworth P. C., Basta J., De Pascalis F., Kruss A., Petrizzo A., Moschino V., 2020. How to Deal with Seafloor Marine Litter: An Overview of the State-of-the-Art and Future Perspectives. Frontiers in Marine Science 7, 2020, https://www.frontiersin.org/articles/10.3389/fmars.2020.505134

Magliozzi C., Tsiamis K., Vigiak O., Deriu, I. Gervasini E., Cardoso A.C., 2020. Assessing invasive alien species in European catchments: Distribution and impacts. Science of The Total Environment, 732, 138677. https://doi.org/10.1016/j.scitotenv.2020.138677

Magliozzi C., Druon J.-N., Boschetti S.T., Palialexis A., 2021. Marine Strategy Framework Directive, Review and analysis of EU Member States' 2018 reports. Descriptor 1 Pelagic Habitats. EUR 30622 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-79-34199-4, doi:10.2760/09511, JRC124271: 38 pp.

Magliozzi C., Palma M., Druon J.-N., Palialexis A., McQuatters-Gollop A., Varkitzi I., González- Quirós R., Gorokhova E., Heyden B., Boicenco L. , Artigas L. F., 2023. Status of pelagic habitats within the EU-Marine Strategy Framework Directive: Proposals for improving consistency and representativeness of the assessment. Marine Policy, 148: 105467.

Maldonado A. D., Galparsoro I., Mandiola G., de Santiago I., Garnier R., Pouso S., Borja Á., Menchaca I., Marina D., Zubiate L., Bald J., 2022. A Bayesian Network model to identify suitable areas for offshore wave energy farms, in the framework of ecosystem approach to marine spatial planning. Science of The Total Environment, 838: 156037 https://doi.org/10.1016/j.scitotenv.2022.156037

Mangano M. C., Giacoletti A., Sarà G., 2019. Dynamic Energy Budget Provides Mechanistic Derived Quantities to Implement the Ecosystem Based Management Approach. Ecosystem Based Management and the Biosphere: A New Phase in DEB Research 143: 272–79. https://doi.org/10.1016/j.seares.2018.05.009.

Marcot B.G., Penman T.D., 2019. Advances in Bayesian network modelling: Integration of modelling technologies. Environmental Modelling & Software 111, 386–393. https://doi.org/10.1016/j.envsoft.2018.09.016

Margules C.R., Pressey R.L., 2000. Systematic conservation planning. Nature, 405(6783): 243-253.

Mari L., Melià P., Gatto M., Casagrandi R., 2021. Identification of Ecological Hotspots for the Seagrass Posidonia Oceanica via Metapopulation Modeling. Frontiers in Marine Science 8. https://www.frontiersin.org/articles/10.3389/fmars.2021.628976.

Marin O., Boicenco L., Abaza V., Bișinicu E., Coatu V., Galațchi M., Lazăr L., Oros A., Pantea E., Tabarcea C., Țiganov G., Vlas O.,2020. Performing First Integrative Evaluation of the Ecological Status of Romanian Black Sea Waters using Nested Environmental status Assessment Tool. Cercetări Marine, 50: 108-125.

Marques G. M., Augustine S., Lika K., Pecquerie L. Domingos T., Kooijman S. A.L.M., 2018. The AmP Project: Comparing Species on the Basis of Dynamic Energy Budget Parameters. PLOS Computational Biology 14, no. 5: e1006100. https://doi.org/10.1371/journal.pcbi.1006100.

Marzloff M., Shin Y., Tam J., Travers M., Bertrand A., 2009. Trophic Structure of the Peruvian Marine Ecosystem in 2000–2006: Insights on the Effects of Management Scenarios for the Hake Fishery Using the IBM Trophic Model Osmose. Journal of Marine Systems 75, no. 1: 290–304. https://doi.org/10.1016/j.jmarsys.2008.10.009.

Maxwell S.M., Hazen E.L., Bograd S.J., Halpern B.S., Breed G.A., Nickel B., Teutschel N.M., Crowder, L. B., Benson S., Dutton P. H., Bailey H., Kappes M. A., Kuhn C. E., Weise M. J., Mate B., Shaffer S. A., Hassrick J. L., Henry R. W., Irvine L., McDonald B.I., Robinson P.W., Block B.A., Costa D. P. (2013). Cumulative human impacts on marine predators. Nature Communications, 4(1), 2688. https://doi.org/10.1038/ncomms3688

Mazaris A. D., Dimitriadis C., Papazekou M., Schofield G., Doxa A., Chatzimentor A., Turkozan O., Katsanevakis S., Lioliou A., Abalo-Morla S., Aksissou M., Arcangeli A., Attard V., El Hili H.A., Atzori F., Belda E.J., Ben Nakhla L., Berbash A.A., Bjorndal K.A., Broderick A.C., Camiñas J.A., Candan O., Cardona L., Cetkovic I., Dakik N., de Lucia G. A., Dimitrakopoulos P. G., Diryaq S., Favilli C., Fortuna C.M., Fuller W.J., Gallon S., Hamza A., Jribi I., Ben Ismail M., Kamarianakis Y., Kaska Y., Korro K., Koutsoubas D., Lauriano G., Lazar B., March D., Marco A., Minotou C., Monsinjon J.R., Naguib N.M., Palialexis A., Piroli V., Sami K., Sönmez B., Sourbès L., Sözbilen D., Vandeperre F., Vignes P., Xanthakis M., Köpsel V., Peck M. A., 2023. Priorities for Mediterranean marine turtle conservation and management in the face of climate change. Journal of Environmental Management, 339: 117805.

Mazor T., Possingham H.P., Edelist D., Brokovich E., Kark S., 2014. The crowded sea: incorporating multiple marine activities in conservation plans can significantly alter spatial priorities. PLoS One 9(8):e104489.

Mazor T., Pitcher C.R., Rochester W., Kaiser M.J., Hiddink J.G., Jennings S., Amoroso R., McConnaughey R.A., Rijnsdorp A. D., Parma A. M., Suuronen P., Collie J., Sciberras M., Atkinson L., Durholtz D., Ellis J. R, Bolam S. G., Schratzberger M., Couce E., Eggleton J., Garcia C., Kainge P., Paulus S., Kathena J. N., Gogina M., van Denderen P. D., Keller A. A., Horness B. H., Hilborn R., 2021. Trawl fishing impacts on the status of seabed fauna in diverse regions of the globe. Fish and Fisheries 2021; 22: 72– 86. https://doi.org/10.1111/faf.12506

McConnaughey R.A., Hiddink J.G., Jennings S., Pitcher C.R., Kaiser M.J., Suuronen P., Sciberras M., Rijnsdorp A.D., Collie J.S., Mazor T., Amoroso R.O., Parma A.M., Hilborn R., 2020. Choosing best practices for managing impacts of trawl fishing on seabed habitats and biota. Fish and Fisheries 2020; 21: 319– 337. https://doi.org/10.1111/faf.12431

McCann R.K., Marcot B.G., Ellis R., 2006. Bayesian belief networks: applications in ecology and natural resource management. Canadian Journal of Forest Research 36, 3053–3062. https://doi.org/10.1139/x06-238

McLeod K.L., Lubchenco J., Palumbi S.R., Rosenberg A.A., 2005. Scientific Consensus Statement on Marine Ecosystem-Based Management. Signed by 217 academic scientists and policy experts with relevant expertise and published by the Communication Partnership for Science and the Sea at http://compassonline.org/?q=EBM, https://marineplanning.org/wp-content/uploads/2015/07/Consensusstatement.pdf

McLusky D.S., Elliott M., 2004. The Estuarine Ecosystem; ecology, threats and management, 3rd Edn. OUP, Oxford. Pp216.

Menchaca I., Borja Á., Galparsoro I., Franco J., Uyarra M.C., Uriarte A., Chust G., Ibaibarriaga L., Bald J., 2022. Multi-source and multi-scale data integration for the assessment of the marine environmental status of the Basque Coast (SE Bay of Biscay). Estuarine, Coastal and Shelf Science, 277: 108055.

Menegon S., Depellegrin D., Farella G., Gissi E., Ghezzo M., Sarretta A., Venier C., Barbanti A., 2018. A modelling framework for MSP-oriented cumulative effects assessment. Ecological Indicators, 91, 171–181. https://doi.org/10.1016/j.ecolind.2018.03.060

MERP, 2019. Dynamic Ecosystem Models. Plymouth Marine Laboratory. https://www.marine-ecosystems.org.uk/Research_outcomes/Model_Interactive

Metcalfe K., Roberts T., Smith R.J., Harrop S. R., 2013. Marine conservation science and governance in North–West Europe: conservation planning and international law and policy. Marine Policy 39, 289–295.

Micheli F., Halpern B.S., Walbridge S., Ciriaco S., Ferretti F., Fraschetti S., Lewison R., Nykjaer L., Rosenberg A.A., 2013a. Cumulative human impacts on Mediterranean and Black Sea marine ecosystems: assessing current pressures and opportunities. PLOS ONE 8,. https://doi.org/10.1371/journal.pone.0079889 e79889

Micheli F., Levin N., Giakoumi S., Katsanevakis S., Abdulla A., Coll M, Fraschetti S., Kark S., Koutsoubas D., Mackelworth P., Maiorano L., Possingham H.P., 2013b. Setting Priorities for Regional Conservation Planning in the Mediterranean Sea. PLoS ONE 8(4): e59038. https://doi.org/10.1371/journal.pone.0059038

Moilanen A., Kujala H., Leathwick J.R., 2009. The Zonation framework and software for conservation prioritization. Spatial conservation prioritization, 135, 196-210.

Morishita J. 2008. What is the ecosystem approach for fisheries management?. Marine Policy, 32, 1, 2008, 19-26, https://doi.org/10.1016/j.marpol.2007.04.004.

Morris D., Cameron A., Heath M., Speirs D., 2014. Global sensitivity analysis of an end-to-end marine ecosystem model of the North Sea: factors affecting the biomass of fish and benthos. Ecological Modelling 273, 251-263.

Mucientes G.R., Queiroz N., Sousa L.L., Tarroso P., Sims D.W., 2009. Sexual segregation of pelagic sharks and the potential threat from fisheries. Biology Letters doi:10.1098/rsbl.2008.0761

Murillas-Maza A., Uyarra M.C., Papadopoulou K.N., Smith C.J., Gorjanc S., Klancnik K., Paramana T., Chalkiadaki O., Dassenakis M, Pavicic, M. 2020. Programmes of measures of the marine strategy framework directive: Are they contributing to achieving good environmental status in the Mediterranean? Marine Pollution Bulletin 161 (2020). 111715. https://doi.org/10.1016/j.marpolbul.2020.111715

Mytilineou Ch., Herrmann B., Kavadas S., Smith C., Megalofonou P., 2020. Combining selection models and population structures to inform fisheries management: a case study on hake in the Mediterranean bottom trawl fishery. Mediterranean Marine Science 21/2, 360–371. https://doi.org/10.12681/mms.22191.

Mytilineou Ch., Herrmann B., Mantopoulou-Palouka D., Sala A., Megalofonou P., 2021. Escape, discard, and landing probability in multispecies Mediterranean bottom-trawl fishery. ICES Journal of Marine Science, doi:10.1093/icesjms/fsab048

Muxika I., Borja Á., Bald J., 2007. Using historical data, expert judgement and multivariate analysis in assessing reference conditions and benthic ecological status, according to the European Water Framework Directive. Marine Pollution Bulletin, 55: 16-29

Naidoo R., Balmford A., Ferraro P.J., Polasky S., Ricketts T.H., Rouget M., 2006. Integrating economic costs into conservation planning. Trends in Ecology & Evolution 21: 681–687.

Naranjo-Madrigal H., van Putten I., Norman-López A., 2015. Understanding socio-ecological drivers of spatial allocation choice in a multi-species artisanal fishery: A Bayesian network modeling approach. Marine Policy 62: 102-115.

Nebot-Colomer E., Álvarez E., Dolores Belando M., Deudero S., Catanese G., Bernardeau-Esteller J., García-Muñoz R., Ramos-Segura A., Ruiz J.M., Vázquez-Luis M., 2021. Living under threat: Will one of the last Pinna nobilis populations be able to survive? Aquatic Conservation, First published: 02 November 2021, https://doi.org/10.1002/aqc.3738

Nemati H., Shokri M.R., Ramezanpour Z., Ebrahimi Pour G.H., Muxika I., Borja Á., 2017. Using multiple indicators to assess the environmental status in impacted and non-impacted bathing waters in the Iranian Caspian Sea. Ecological Indicators, 82: 175-182.

Nemati H., Shokri M.R., Ramezanpour Z., Ebrahimi Pour G.H., Muxika I., Borja Á., 2018. Sensitivity of indicators matters when using aggregation methods to assess marine environmental status. Marine Pollution Bulletin 128:234–239.

Nogues Q., Araignous E., Bourdaud P., Halouani G., Raoux A., Foucher É., Le Loc'h F., Loew-Turbout F., Ben Rais Lasram F., Dauvin J.-C., Niquil N., 2022. Spatialized Ecological Network Analysis for Ecosystem-Based Management: Effects of Climate Change, Marine Renewable Energy, and Fishing on Ecosystem Functioning in the Bay of Seine. ICES Journal of Marine Science 79, no. 4: 1098–1112. https://doi.org/10.1093/icesjms/fsac026

Nygård H., Murray C., Andersen J.H., Martin G., Torn K., Korpinen S., 2018. BEAT 3.0 – a Tool for Integrated Biodiversity Assessments. Journal of Open Research Software, 6(1), p.19. DOI: http://doi.org/10.5334/jors.226

ODEMM: https://odemm.com/ (and references therein)

OECD, 2003. OECD Environmental Indicators. https://www.oecd.org/env/indicators-modelling-outlooks/24993546.pdf

OECD, 2018. Cost-Benefit Analysis and the Environment: Further Developments and Policy Use. OECD Publishing, Paris

Ogburn M. B., 2019. The effects of sex-biased fisheries on crustacean sex ratios and reproductive output, Invertebrate Reproduction & Development, 63:3, 200-207, DOI: 10.1080/07924259.2019.1612787

O'Hagan A. M., 2020. Ecosystem-Based Management (EBM) and Ecosystem Services in EU Law, Policy and Governance. Chapter. In: O'Higgins, T., Lago, M., DeWitt, T. (eds) Ecosystem-Based

Management, Ecosystem Services and Aquatic Biodiversity. Theory, tools and practice. Springer, Amsterdam. https://link.springer.com/book/10.1007/978-3-030-45843-0 (eBook)

O'Hara C.C, Villaseñor-Derbez J.C., Ralph G.M., Halpern B.S., 2019. Mapping status and conservation of global at-risk marine biodiversity. Conservation letters. First published: 06 May 2019, https://doi.org/10.1111/conl.12651

O'Higgins T.G., DeWitt T.H., Lago M., 2020. Using the Concepts and Tools of Social Ecological Systems and Ecosystem Services to Advance the Practice of Ecosystem-Based Management. Chapter. In: O'Higgins, T., Lago, M., DeWitt, T. (eds) Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity. Theory, tools and practice. Springer, Amsterdam. https://link.springer.com/book/10.1007/978-3-030-45843-0 (eBook)

ONS, 2021a. Marine accounts, natural capital, UK. https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/marineaccountsnaturalcapitaluk/2021

ONS, 2021b. Marine natural capital accounts, UK methodology guidance. https://www.ons.gov.uk/economy/environmentalaccounts/methodologies/marinenaturalcapitalaccountsukmethodologyguide

Oppel S., Meirinho A., Ramírez I., Gardner B., O'Connell A. F., Miller P. I., Louzao M., 2012. Comparison of five modelling techniques to predict the spatial distribution and abundance of seabirds. Biological Conservation, 156, 94–104. doi: 10.1016/j.biocon.2011.11.013

OSPAR, 2010. Quality Status Report 2010. OSPAR Commission, London: 176 pp.

OSPAR, 2017a. PH1/FW5: Changes in phytoplankton and zooplankton communities. In: OSPAR (Ed.), OSPAR Intermediate Assessment 2017. OSPAR, London, UK. Available at: https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/biodiversity-1359 status/habitats/changes-phytoplankton-and-zooplankton-communities/

OSPAR, 2017b. Extent of Physical Damage to Predominant and Special Habitats. OSPAR Intermediate Assessment 2017. https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/biodiversity-status/habitats/extent-physical-damage-predominant-and-special-habitats/

OSPAR, 2019. OSPAR QSR 2023 Guidance Document. OSPAR Commission OSPAR Agreement 2019-02. Available at: file:///Users/chreste/Downloads/19-02e-agreement_qsr2023-guidance.pdf

OSPAR, 2020. Threatened habitats and species list and spatial dataset. Available in EMODNET: https://emodnet.ec.europa.eu/en/ospar-threatened-andor-declining-habitats-spatial-dataset

OSPAR, 2021. Strategy of the OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic 2030 (Agreement 2021-01). North-East Atlantic Environment Strategy 2030 | OSPAR Commission, https://www.ospar.org/convention/strategy

Page R., 2016. Towards a biodiversity knowledge graph. Research Ideas and Outcomes, 2: e8767.

Palialexis A., Tornero V., Barbone E., Gonzalez D., Hanke G., Cardoso A.C., Hoepffner N., Katsanevakis S., Somma F., Zampoukas N., 2014. In-Depth Assessment of the EU Member States' Submissions for the Marine Strategy Framework Directive under articles 8, 9 and 10. JRC Scientific and Policy Reports, EUR 26473 EN: 153 pp.

Palialexis A., Kousteni V., Somma F., 2019. In-depth assessment of the Member States' reporting for the Marine Strategy's biodiversity monitoring. Publications Office of the European Union, Luxembourg, ISBN 978-92-76-07986-6, doi:10.2760/051785.: 44 pp.

Palialexis A., Kousteni V., Boicenco L., Enserink L., Pagou K., Zweifel U.L., Somma F., Cheilari A., Connor D., 2021. Monitoring biodiversity for the EU Marine Strategy Framework Directive: Lessons learnt from evaluating the official reports. Marine Policy, 128: 104473.

Paramana et al., 2023, submitted. Screening and assessing physical pressures compromising sea - floor integrity in the Mediterranean region.

Patrício J., Elliott M., Mazik K., Papadopoulou K.-N., Smith C. J., 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

Patrício A.R., Hawkes L.A., Monsinjon J.R., Godley B.J., Fuentes M.M.P.B., 2021. Climate change and marine turtles: recent advances and future directions. Endangered Species Research, 44, 363–395

Pavlidou A., Simboura N., Pagou K., Assimakopoulou G., Gerakaris V., Hatzianestis I., Panayotidis P., Pantazi M., Papadopoulou N., Reizopoulou S., Smith C., Triantaphyllou M., Uyarra M.C., Varkitzi I., Vassilopoulou V., Zeri C., Borja A., 2019. Using a holistic ecosystem-integrated approach to assess the environmental status of Saronikos Gulf, Eastern Mediterranean. Ecological indicators 96:336-350.

Peck M.A., Arvanitidis C., Butenschön M., Canu D.M., Chatzinikolaou E., Cucco A., Domenici P., Fernandes J.A., Gasche L., Huebert K.B., Hufnagl M., Jones M.C., Kempf A., Keyl F., Maar M., Mahévas S., Marchal P., Nicolas D., Pinnegar J.K., Rivot E., Rochette S., Sell A.F., Sinerchia M., Solidoro C., Somerfield P.J., Teal L.R., Travers-Trolet M., van de Wolfshaar K.E., 2018. Projecting changes in the distribution and productivity of living marine resources: A critical review of the suite of modelling approaches used in the large European project VECTORS. Estuarine, Coastal and Shelf Science, 201, pp. 40-55. https://doi.org/10.1016/j.ecss.2016.05.019

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

Pedreschi D., Niiranen S., Skern-Mauritzen M., Reid D.G., 2023. Operationalising ODEMM risk assessment for Integrated Ecosystem Assessment scoping: Complexity vs. manageability. Frontiers in Marine Science, 9, 2766. https://doi.org/10.3389/fmars.2022.1037878

Penev L., Dimitrova M., Senderov V., Zhelezov G., Georgiev T., Stoev P., Simov K., 2019. Openbiodiv: a knowledge graph for literature-extracted linked open data in biodiversity science, Publications, 7(2), 38. Doi: 10.3390/publications7020038

Pennino M.G., Arcangeli A., Prado Fonseca V., Campana I., Pierce G.J., Rotta A., J.M. Bellido, 2017. A spatially explicit risk assessment approach: Cetaceans and marine traffic in the Pelagos Sanctuary (Mediterranean Sea). PLoS ONE 12(6): e0179686. https://doi.org/10.1371/journal.pone.0179686

Pennino M.G., Coll M., Albo Puigserver M., Fernández Corredor E., Steenbeek J., González M., Esteban A., Bellido J. M., 2020. Current and future influence of environmental factors on small pelagic fish distributions in the Northwestern Mediterranean Sea. Frontiers in Marine Science, Marine Fisheries, Aquaculture and Living Resources 7.

Petihakis G., Smith C. J., Triantafyllou G., Sourlantzis G., Papadopoulou K-N., Pollani A., Korres G., 2007. Scenario testing of fisheries management strategies using a high resolution ERSEM–POM ecosystem model. – ICES Journal of Marine Science, 64: 1627–1640.

Petza D., Anastopoulos P., Kalogirou S., Coll M., Garzia S., Kaiser M., Koukourouvli N., Lourdi I., Rice J., Sciberras M., Katsanevakis S.. 2023. Contribution of Area-Based Fisheries Management

Measures to Fisheries Sustainability and Marine Conservation: a global scoping review. Reviews in Fish Biology and Fisheries. https://doi.org/10.1007/s11160-023-09780-9

Pezy J.-P., Raoux A., Dauvin J.-C., 2020. An ecosystem approach for studying the impact of offshore wind farms: a French case study, ICES Journal of Marine Science, Volume 77, Issue 3, May-June 2020, Pages 1238–1246, https://doi.org/10.1093/icesjms/fsy125

Piet G. J., Jongbloed R.H., Knights A. M., Tamis J.E., Paijmans A.J., van der Sluis M. T., de Vries P., Robinson L.A., 2015. Evaluation of ecosystem-based marine management strategies based on risk assessment. Biological Conservation, 186: 158-166.

Piet G.J., Knights A. M., Jongbloed R.H., Tamis J. E., de Vries P., Robinson L.A., 2017. Ecological risk assessments to guide decision-making: Methodology matters. Environmental Science & Policy, 68: 1-9.

Piet G.J., Culhane F., Jongbloed R., Robinson L., Rumes B., Tamis J., 2019. An integrated risk-based assessment of the North Sea to guide ecosystem-based management. Science of The Total Environment, 654: 694-704.

Piet G., Delacámara G., Kraan M., Röckmann C., Lago M., 2020. Advancing aquatic ecosystem-based management with full consideration of the social-ecological System. In: O'Higgins, T., Lago, M., DeWitt, T. (eds) Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity. Springer, Cham. https://doi.org/10.1007/978-3-030-45843-0_2

Piet G.J., Tamis J.E., Volwater J., de Vries P., van der Wal J.T., Jongbloed R. H., 2021. A roadmap towards quantitative cumulative impact assessments: Every step of the way. Science of The Total Environment, 784: 146847.

Piet et al., 2023a, submitted. A Cumulative Impact Assessment on the North Sea capacity to supply Ecosystem Services.

Piet et al., 2023b, submitted. SCAIRM: a Spatial Cumulative Assessment of Impact Risk for Management.

Pihlajamäki M., Helle I., Haapasaari P., Sarkki S., Kuikka S., Lehikoinen A., 2020. Catching the future: Applying Bayesian belief networks to exploratory scenario storylines to assess long-term changes in Baltic herring (Clupea harengus membras, Clupeidae) and salmon (Salmo salar, Salmonidae) fisheries. Fish and Fisheries 21, 797–812. https://doi.org/10.1111/faf.12461

Pinnegar J.K., 2019. Atlantis. https://www.masts.ac.uk/media/4695/atlantis.pdf

Piroddi C., Akoglu A.G., Andonegi E., Bentley J.W., Celic I., Coll M., Dimarchopoulou D., Friedland R., de Mutsert K., Girardin R., Garcia-Gorriz E., Grizzetti B., Hernvann P.-Y., Heymans J. J., Müller Karulis B., Libralato S., Lynam C. P., Macias D., Miladinova S., Moullec F., Palialexis A., Parn O., Serpetti N., Solidoro C., Steenbeek J., Stips A., Tomczak M., Travers-Trolet M., Tsikliras A., 2021. Effects of nutrient management scenarios on marine food webs: a Pan-European Assessment in support of the Marine Strategy Framework Directive. Frontiers in Marine Science 8:596797.

Pitcher C.R., Hiddink J.G., Jennings S., Collie J., Parma A.M., Amoroso R., Mazor T., Sciberras M., McConnaughey R.A., Rijnsdorp A.D., Kaiser M.J., Suuronen P., Hilborn R., 2022. Trawl impacts on the relative status of biotic communities of seabed sedimentary habitats in 24 regions worldwide. Proceedings of the National Academy of Sciences of the United States of America, PNAS. 119, 2 e2109449119. https://doi.org/10.1073/pnas.2109449119.

Pressey R. L., Cabeza M., Watts M. E., Cowling R. M., Wilson K. A., 2007. Conservation planning in a changing world. Trends in Ecology & Evolution, 22, 583–892

Puig P., Canals M., Company J. B., Martín J., Amblas D., Lastras G., Palanques A., Calafat A. M., 2012. Ploughing the deep sea floor. Nature 489:286-289.

Purcell J.E., 2005. Climate effects on formation of jellyfish and ctenophore blooms: a review. Journal of the Marine Biological Association of the United Kingdom, 85(3), pp.461-476.

Quemmerais-Amice F., Barrere J., La Rivière M., Contin G., Bailly D., 2020. A methodology and tool for mapping the risk of cumulative effects on benthic habitats. Frontiers in Marine Science, 7. https://doi.org/10.3389/fmars.2020.569205

Rambo H., Ospina-Alvarez A., Catalán I. A., Maynou F., Stelzenmüller V., 2022. Unravelling the combined effects of sociopolitical and climate change scenarios for an artisanal small-scale fishery in the Western Mediterranean. Ecology and Society 27(1): 43

Ramírez-León M.R., García-Aguilar M.C., Romo-Curiel A.E., Ramírez-Mendoza Z., Fajardo-Yamamoto A., Sosa-Nishizaki O., 2021. Habitat suitability of cetaceans in the Gulf of Mexico using an ecological niche modeling approach. PeerJ. March 17: e10834. doi: 10.7717/peerj.10834.

Reker J., Murray C., Royo-Gelabert E., Abhold K., Korpinen S., Peterlin M., Vaughan D., Andersen J.H., 2019. Marine messages II – Navigating the course towards clean, healthy and productive seas through implementation of an ecosystem-based approach. EEA Report No 17/2019

Rittel H.W., Webber M.M., 1973. Dilemmas in a general theory of planning. Policy Sciences, 4: 155–169.

Robinson L.A., White L.J., Culhane F.E., Knights A.M., 2013. ODEMM Pressure Assessment Userguide V.2. ODEMM Guidance Document Series No.4. EC FP7 project (244273) 'Options for Delivering Ecosystem-based Marine Management'. University of Liverpool. ISBN: 978-0-906370-86-5: 14 pp.

Robinson L.A., Culhane F.E., Baulcomb C., Bloomfield H., Boehnke-Henrichs A., Breen P., Goodsir F., Hussain S.S., Knights A.M., Piet G.J., Raakjaer J., van Tatenhove J., Frid, C.L.J., 2014. Towards delivering ecosystem-based marine management: The ODEMM Approach. Deliverable 17, EC FP7 Project (244273) 'Options for Delivering Ecosystem-based Marine Management'. University of Liverpool. ISBN: 978-0-906370-89-6: 96 pp.

Sachs J., Page R.D.M., Steven J., Baskauf S.J., Pender J., Lujan-Toro B., Macklin J., Comspon Z., 2019. Training and hackathon on building biodiversity knowledge graphs. Research Ideas and Outcomes, 5: e36152.

Samhouri J.F., Haupt A.J., Levin P. S., Link J.S., Shuford R., 2014. Lessons learned from developing integrated ecosystem assessments to inform marine ecosystem-based management in the USA. ICES Journal of Marine Science, 71: 1205–1215.

Savchuk O.P., Gustafsson B.G., Müller-Karulis B., 2012. BALTSEM – a marine model for decision support within the Baltic Sea Region. Technical Report No 7. Baltic Nest Institute. Stockholm.

Schrum C., Backhaus J.O., 1999. Sensitivity of atmosphere–ocean heat exchange and heat content in North Sea and Baltic Sea. A comparative assessment. Tellus 51, 526–549.

Schrum C., Alekseeva I., St. John M., 2006a. Development of a coupled physical–biological ecosystem model ECOSMO. Part I: Model description and validation for the North Sea. Journal of Marine Systems. 61: 79-99

Schrum C., St. John M., Alekseeva I. 2006b. Development of a coupled physical–biological ecosystem model ECOSMO. Part II: Spatial-seasonal characteristics. Journal of Marine Systems. 61: 100-113.

Serrano, A., de la Torriente A., Punzon A., Blanco A.M., Bellas J., Duran-Muniz P., Murillo F.J., Sacau M., Garcia-Alegre A., Antolinez A., Elliott S., Guerin L., Vina-Herbon G., Marra S., Gonzalez-Irusta J.M., 2022. Sentinels of Seabed (SoS) indicator: Assessing benthic habitats condition using typical sensitive species. Ecol. Indic. 140, 108979. https://doi.org/10.1016/j.ecolind.20220108979

Slobodnik J., Alexandrov B., Komorin V., Mikaelyan A., Guchmanidze A., Arabidze M., Korshenko A., Moncheva S., 2017. National Pilot Monitoring Studies and Joint Open Sea Surveys in Georgia, Russian Federation and Ukraine, 2016. Final Scientific Report EU/UNDP Project: Improving Environmental Monitoring in the Black Sea – Phase II (EMBLAS-II), ENPI/2013/313-169: 479 pp.

Smith, A.D.M., Fulton E. J., Hobday A. J., Smith D.C., Shoulder P., 2007. Scientific tools to support the practical implementation of ecosystem-based fisheries management. ICES Journal of Marine Science: Journal Du Conseil, 64(4), 633–639. https://doi.org/10.1093/icesjms/fsm041

Smith C.J., Papadopoulou K.-N., Barnard S., Mazik K., Elliott M., Patrício J., Solaun O., Little S., Bhatia N., Borja A., 2016. Managing the marine environment, conceptual models and assessment considerations for the European Marine Strategy Framework Directive. Frontiers in Marine Science, 3:144. doi: 10.3389/fmars.2016.00144

Smith C., Papadopoulou N., Elliott M., Franco A., Barnard A., Borja Á., Uyarra M.C., 2022. Marine Strategy Framework Directive Terminology Definitions and Lists. GES4SEAS Project. 29 pp.

Smith C.J., Papadopoulou N.K., Maina I., Kavadas S., P. van Denderen D., Katsiaras N., Reizopoulou S., Karakassis I., Tselepides A., Tsikopoulou I., 2023. Relating benthic sensitivity and status to spatial distribution and intensity of trawling in the Eastern Mediterranean. Ecological Indicators 150 (2023) 110286, https://doi.org/10.1016/j.ecolind.2023.110286

Smith K., Petley D.N., 2009. Environmental Hazards: assessing risk and reducing disaster. 5th Edition, Routledge, Oxford.

Sola I., Maynou F., Sánchez Lizaso J.L., 2020. Bioeconomic Analysis of the EU Multiannual Management Plan for demersal fisheries in the western Mediterranean. Spanish Fisheries as a Case Study. Frontiers in Marine Science 7. https://doi.org/10.3389/fmars.2020.00459

Soukissian T., O'Hagan A. M., Azzellino A., Boero F., Brito e Melo A., Comiskey P., Gao Z., Howell D., Le Boulluec M., Maisondieu C., Scott B.E., Tedeschi E., Maheri A., Pennock S. 2023. European offshore renewable energy: Towards a sustainable future. Heymans, J. J., Kellett, P., Alexander, B., Muñiz Piniella, Á., Rodriguez Perez, A., Van Elslander, J. [Eds.] Future Science Brief No. 9 of the European Marine Board, Ostend, Belgium. ISSN: 2593-5232. ISBN: 9789464206173. DOI: 10.5281/zenodo.7561906

Sousa A., Génio L., Mendo S., Barrosoi C., 2005. Comparison of the acute toxicity of tributyltin and copper to veliger larvae of Nassarius reticulatus (L.). Applied Organometallic Chemistry, 19: 324-328.

Squires D., Ballance L. T., Dagorn L., Dutton P. H., Lent R., 2021. Mitigating Bycatch: Novel Insights to Multidisciplinary Approaches. Frontiers in Marine Science, 8, 2021, https://www.frontiersin.org/articles/10.3389/fmars.2021.613285

Stelfox M., Lett C., Reid G., Souch G., Sweet M., 2020. Minimum Drift Times Infer Trajectories of Ghost Nets Found in the Maldives'. Marine Pollution Bulletin 154: 111037. https://doi.org/10.1016/j.marpolbul.2020.111037.

Stelzenmüller V., Lee J., Garnacho E., Rogers S.I., 2010. Assessment of a Bayesian Belief Network-GIS framework as a practical tool to support marine planning. Marine Pollution Bulletin 60: 1743-1754

Stelzenmüller V., Schulze T., Fock H.O., Berkenhagen J., 2011. Integrated modelling tools to support risk-based decision-making in marine spatial management. Marine Ecology Progress Series 441: 197-212.

Stelzenmüller V., Coll M., Mazaris A.D., Giakoumi S., Katsanevakis S., Portman M.E., Degen R., Mackelworth P., Gimpel A., Albano P. G., Almpanidou V., Claudet J., Essl F., Evagelopoulos T., Heymans J. J., Genov T., Kark S., Micheli F., Grazia Pennino M., Rilov G., Rumes B., Steenbeek J., Ojaveer H., 2018. A risk-based approach to cumulative effect assessments for marine management. Science of The Total Environment 612: 1132-1140. http://dx.doi.org/10.1016/j.scitotenv.2017.08.289

Stelzenmüller V., Coll M., Cormier R., Mazaris A.D., Pascual M., Loiseau C., Claudet J., Katsanevakis S., Gissi E., Evagelopoulos A., Rumes B., Degraer S., Ojaveer H., Moller T., Giménez J., Piroddi C., Markantonatou V., Dimitriadis C., 2020. Operationalizing risk-based cumulative effect assessments in the marine environment. Science of The Total Environment 724: 138118. https://doi.org/10.1016/j.scitotenv.2020.138118

Stock A., 2016. Open-source software for mapping human impacts on marine ecosystems with an additive model. Journal of Open Research Software, 4, 7. https://doi.org/ 10.5334/jors.88.

Stock A., Micheli F., 2016. Effects of model assumptions and data quality on spatial cumulative human impact assessments: uncertainty in human impact maps. Global Ecology and Biogeography. 25, 1321–1332. https://doi.org/10.1111/geb.12493

Stock A., Crowder L.B., Halpern B.S., Micheli F., 2018. Uncertainty analysis and robust areas of high and low modeled human impact on the global oceans. Conservation Biology: The Journal of the Society for Conservation Biology, 32(6), 1368–1379. https://doi.org/10.1111/cobi.13141

Stock A., Murray C.C., Gregr E., Steenbeek J., Woodburn E., Micheli F., Christensen V., Chan K.M., 2023. Exploring multiple stressor effects with Ecopath, Ecosim, and Ecospace: Research designs, modeling techniques, and future directions. Science of The Total Environment:161719.

Sutherland W.J., Barnard P., Broad S., Clout M., Connor B., Cote I.M., Dicks L.V., Doran H., Entwistle A.C., Fleishman E., Fox M., Gaston K.J., Gibbons D.W., Jiang Z., Keim B., Lickorish F.A., Markillie P., Monk K.A., Pearce-Higgins J.W., Peck L.S., Pretty J., Spalding M.D., Tonneijck F.H., Wintle B.C., Ockendon N., 2017. A 2017 horizon scan of emerging issues for global conservation and biological diversity. Trends in Ecology and Evolution 32: 31–40.

Szuwalski C., 2022. Estimating Time-Variation in Confounded Processes in Population Dynamics Modeling: A Case Study for Snow Crab in the Eastern Bering Sea. Fisheries Research 251: 106298. https://doi.org/10.1016/j.fishres.2022.106298.

Talbot S. E., Widdicombe S., Hauton C., Bruggeman J., 2019. Adapting the Dynamic Energy Budget (DEB) Approach to Include Non-Continuous Growth (Moulting) and Provide Better Predictions of Biological Performance in Crustaceans. ICES Journal of Marine Science 76, no. 1: 192–205. https://doi.org/10.1093/icesjms/fsy164.

Tamis J. E., Vries d. P., Jongbloed R. H., Lagerveld S., Jak R. G., Karman C. C., Wal v. d. J. T., Slijkerman D.M.E., Klok C., 2016. Toward a harmonized approach for environmental assessment of human activities in the marine environment. Integrated Environmental Assessment and Management, 12: 632-642.

Teixeira H., Lillebø A. I., Culhane F., Robinson L., Trauner D., Borgwardt F., Kummerlen M., Barbosa A., McDonald H., Funk A., O'Higgins T., Van der Wal J. T., Piet G., Hein T., Arévalo-Torres J., Iglesias-Campos A., Barbière J., Nogueira A.J.A., 2019. Linking biodiversity to ecosystem services supply: Patterns across aquatic ecosystems. Science of The Total Environment, 657(December 2018), 517–534. https://doi.org/10.1016/j.scitotenv.2018.11.440

Thresher R.E., Kuris A.M., 2004. Options for managing invasive marine species. Biological Invasions 6: 295–300.

Tittensor, D. P., Eddy T. D., Lotze H. K., Galbraith E. D., Cheung W., Barange M., Blanchard J., Bopp L., Bryndum-Buchholz A., Büchner M., C Bulman., Carozza D., Christensen V., Coll M., Dunne J., Fernandes J. A., Fulton B., Hobdayn A., Huber V., Jennings S., Jones M., Lehodey P., Link J.S., Mackinson S., Maury O., Niiranen S., Oliveros-Ramos R., Roy T., Schewe J., Shin Y.J., Silva T.A.M., Stock C.A., Steenbeek J., Underwood P., Volkholz J., Watson J., Walker N., 2018. A protocol for the intercomparison of marine fishery and ecosystem models: Fish-MIP v1.0 Geoscientific Model Development 11:1421–1442.

Todorova N., Alyomov S.V., Chiotoroiu B.C., Fach B., Osadchaya T.S., Rangelov M., Salihoglu B., Vasilev V., 2019. Chapter 8 – Black Sea. Pages 209-226 in C. Sheppard, editor. World Seas: an Environmental Evaluation (Second Edition). Academic Press.

Tsiamis K., Azzurro E., Bariche M., Çinar M.E., Crocetta F., De Clerck O., Galil B., Gómez F., Hoffman R., Jensen K.R., Kamburska L., Langeneck J., Langer M.R., Levitt-Barmats Y., Lezzi M., Marchini A., Occhipinti-Ambrogi A., Ojaveer H., Piraino S., Shenkar N., Yankova M., Zenetos A., Žuljević A., Cardoso A.C., 2020. Prioritizing marine invasive alien species in the European Union through horizon scanning. Aquatic Conservation: Marine and Freshwater Ecosystems 30: 794-845.

Tsirintanis K.; Azzurro, E.; Crocetta, F.; Dimiza, M.; Froglia, C.; Gerovasileiou, V.; Langeneck, J.; Mancinelli, G.; Rosso, A.; Stern, N.; et al., 2022. Bioinvasion impacts on biodiversity, ecosystem services, and human health in the Mediterranean Sea. Aquatic Invasions, 17, 308–352. https://doi.org/10.3391/ai.2022.17.3.01

Turner R.K., Schaafsma M., Mee L., Elliott M., Burdon D., Atkins J.P., Jickells T., 2015. Chapter 2. Conceptual framework. In: Turner, R.K., Schaafsma, M. (Eds.) Coastal zones ecosystem services: from science to values and decision making. Studies in Ecological Economics, Volume 9, Springer, Switzerland.

Twardy C. R., 2003. Argument Maps Improve Critical Thinking. Argument. Citeseer.

Uflaz E., Akyüz E., Bolat F., Bolat P., Arslan Ö., 2021. Investigation of the effects of mucilage on maritime operation. J. Black Sea/Mediterranean Environment 27: 140-153.

UNEP-MAP, 2017. 2017 Mediterranean Quality Status Report. Mediterranean Action Plan, Barcelona Convention: 539 pp.

UNEP-MAP-RAC/SPA, 2010. Fisheries conservation and vulnerable ecosystems in the Mediterranean open seas, including the deep seas. By de Juan, S. and Lleonart, J. Ed. RAC/SPA, Tunis: 103pp

United Nations et al. (2021). System of Environmental-Economic Accounting— Ecosystem Accounting (SEEA EA). White cover publication, pre-edited text subject to official editing. Available at: https://seea.un.org/ecosystem-accounting.

US EPA, 2021a. NCCA 2015 Technical Support Document. EPA/841/R-20/002. Office of Water and Office of Research and Development, Washington, DC.

US EPA, 2021b. National Coastal Condition Assessment: A Collaborative Survey of the Nation's Estuaries and Great Lakes Nearshore Waters. EPA/841/ R-21/001. Office of Water and Office of Research and Development, Washington, DC.

Uusitalo L. 2007. Advantages and challenges of Bayesian networks in environmental modelling. Ecological Modelling 203(3-4): 312-318. doi: 10.1016/j.ecolmodel.2006.11.033

Uusitalo L., Kuikka S., Romakkaniemi A., 2005. Estimation of Atlantic Salmon Smolt Carrying Capacity of Rivers Using Expert Knowledge. ICES Journal of Marine Science 62(4):708-722. doi: 10.1016/j.icesjms.2005.02.005

Uusitalo L., Lehikoinen A., Helle I., Myrberg K., 2015. An overview of methods to evaluate uncertainty of deterministic models in decision support. Environmental Modelling & Software 63:24-31. doi: 10.1016/j.envsoft.2014.09.017

Uusitalo L., Blanchet H., Andersen J.H., Beauchard O., Berg T., Bianchelli S., Cantafaro A., Carstensen J., Carugati L., Cochrane S., Danovaro R., Heiskanen A.-S., Karvinen V., Moncheva S., Murray C., Neto J.M., Nygård H., Pantazi M., Papadopoulou N., Simboura N., Srėbalienė G., Uyarra M.C., Borja A., 2016. Indicator-Based Assessment of Marine Biological Diversity–Lessons from 10 Case Studies across the European Seas. Frontiers in Marine Science 3:1–21.

Uusitalo L., Blenckner T., Puntila-Dodd R., Skyttä A., Jernberg S., Voss R., Peltonen H., 2022. Integrating diverse model results into decision support for good environmental status and blue growth. Science of The Total Environment, 806, 150450.

Vaher A., Kotta J., Szava-Kovats R., Kaasik A., Fetissov M., Aps R., Kõivupuu A., 2022. Assessing cumulative impacts of human-induced pressures on reef and sandbank habitats and associated biotopes in the northeastern Baltic Sea. Marine Pollution Bulletin, 183(114042), 114042. https://doi.org/10.1016/j.marpolbul.2022.114042

Vallecillo S., Maes J., Teller A., Babí Almenar J., Barredo J.I., Trombetti M., Abdul Malak D., Paracchini M.L., Carré A., Addamo A.M., Czúcz B., Zulian G., Marando F., Erhard M., Liquete C., Romao C., Polce C., Pardo Valle A., Jones A., Zurbaran-Nucci M., Nocita M., Vysna V., Cardoso A.C., Gervasini E., Magliozzi C., Baritz R., Barbero M., Andre V., Kokkoris I.P, Dimopoulos P., Kovacevic V., Gumbert A., 2022. EU-wide methodology to map and assess ecosystem condition: Towards a common approach consistent with a global statistical standard. Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/13048, JRC130782

van de Pol L., van der Biest K., Taelman S.E., de Luca Peña L., Everaert G., Hernandez, S., Culhane F., Borja A., Heymans J. J. , Van Hoey G. , Vanaverbeke J., Meire P., 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(3), e13589. https://doi.org/10.1016/j.heliyon.2023.e13589

Van Loon W., Hanke G., Fleet D., Werner S., Barry J., Strand J., Eriksson J., Galgani F., Gräwe D., Schulz M., Vlachogianni T., Press M., Blidberg E., Walvoort D., 2020. A European Threshold Value and Assessment Method for Macro Litter on Coastlines. Luxembourg, Publications Office of the European Union, 25pp. (EUR 30347 EN; JRC121707) DOI:10.2760/54369.

van Putten I., Lalancette A., Bayliss P., Dennis D., Hutton T., Norman-López A., Pascoe S., Plagányi E., Skewes T., 2013. A Bayesian model of factors influencing indigenous participation in the Torres Strait tropical rocklobster fishery. Marine Policy 37, 96–105. https://doi.org/10.1016/j.marpol.2012.04.001

Vichi M., Pinardi N., Masina S., 2007. A generalized model of pelagic biogeochemistry for the global ocean ecosystem. Part I: theory. Journal of Marine Systems, 64, 89-109.

Vilas D., Coll M., Pedersen T., Corrales X., Filbee-Dexter K., Wernberg T., 2021. Future trajectories of change for an Arctic deep ecosystem connected to coastal kelp forests. Restoration Ecology. Special Issue: Marine ecosystem restoration: theory, practice and future perspectives 29:e13327.

Vlachopoulou M., Coughlin D., Forrow D., Kirk S., Logan P., Voulvoulis N., 2014. The potential of using the Ecosystem Approach in the implementation of the EU Water Framework Directive, Science of The Total Environment, Vol. 470–471, 2014, Pages 684-694, https://doi.org/10.1016/j.scitotenv.2013.09.072.

Vollenweider R.A., Giovanardi F., Montanari G., Rinaldi A., 1998. Characterization of the trophic conditions of marine coastal waters with special reference to the NW Adriatic Sea: proposal for a trophic scale, turbidity and generalized water quality index. Environmetrics, 9: 329-357.

Watson S.C.L., Preston J., Beaumont N.J., Watson G.J., 2020. Assessing the natural capital value of water quality and climate regulation in temperate marine systems using a EUNIS biotope classification approach. Science of The Total Environment, 744, 140688

Wearmouth V.J., Sims D.W., 2008. Chapter 2 Sexual Segregation in Marine Fish, Reptiles, Birds and Mammals: Behaviour Patterns, Mechanisms and Conservation Implications, Advances in Marine Biology, Academic Press, Vol. 54, 2008, 107-170, https://doi.org/10.1016/S0065-2881(08)00002-3.

Weitzman J., Steeves L., Bradford J., Filgueira R., 2019. Chapter 11 - Far-Field and Near-Field Effects of Marine Aquaculture, Editor(s): Charles Sheppard, World Seas: An Environmental Evaluation (Second Edition), Academic Press, 2019, 197-220, https://doi.org/10.1016/B978-0-12-805052-1.00011-5.

Williams A., Dowdney J., Smith A.D.M., Hobday A.J., Fuller M., 2011. Evaluating impacts of fishing on benthic habitats: A risk assessment framework applied to Australian fisheries. Fisheries Research, 112(3), 154–167. https://doi.org/10.1016/j.fishres.2011.01.028

www.decisionsciences.org/decisionline/vol30/30_3/pom30_3.pd

www.iso14000-iso14001-environmental-management.com/

Xuereb A., Rougemont Q., Tiffin P., Xue H., Phifer-Rixey M., 2021. Individual-Based Eco-Evolutionary Models for Understanding Adaptation in Changing Seas. Proceedings of the Royal Society B: Biological Sciences 288, no. 1962: 20212006. https://doi.org/10.1098/rspb.2021.2006.

Zotou M., Gkrantounis P., Karadimou E., Tsirintanis K., Sini M., Poursanidis D., Azzolin M., Dailianis T., Kytinou E., Issaris Y., Gerakaris V., Salomidi M., Lardi P., Ramfos A., Akrivos V., Spinos E., Dimitriadis C., Papageorgiou D., Lattos A., Giantsis I. A., Michaelidis B., Vassilopoulou V., Miliou A., Katsanevakis S., 2020. Pinna nobilis in the Greek seas (NE Mediterranean): On the brink of extinction? Mediterranean Marine Science, 21(3), 558– 574. https://doi.org/10.12681/MMS.23777

9. Appendix 1 Terminology

https://www.ges4seas.eu/wp-content/uploads/2022/11/GES4SEAS__Report-Definitions-and-Lists-17112022final.pdf

10. Appendix 2. Tool assessment (additional information)

Table A2.1. Number of scores assigned across participants (out of total n=20) and contributing to the estimated average (considering only score assigned with High or Medium confidence. Cells are coloured according to range of number of scores overall (from lowest (white) to highest (dark blue), respectively). Ecosystem-Based Management (EBM) elements in orange are those specifically addressed in GES4SEAS.

# of SCORES assigned across participants (out of total n=20) and contributing to the estimated average (considering only score assigned with H or M confidence)	cumulative assessments	GES MSFD assessments	Whole ecosystem assessments	Ecosystem Services (delivery, impacts, valuation)	Specific biotic effects/ impacts	Specific Ecosystem functions (and impacts on functions)	Pressures-Activities footprint	Impacts footprints	Links activities pressures impacts	Single MSFD Descriptors/ single issues (e.g. eutrophication, NIS, HABs)	Single species, ecosystem Components State change	Threatened habitats and species	Climate change	Pressure and impact reduction/mitigation	Spatial and other measures	Uncertainty	Risks	Other Policy Requirements e.g. MSPD, BHD, Biod Strategy
Conceptual models	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10	9	9	10
Semi-quantitative mental models - Fuzzy Cognitive Mapping	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	8
Knowledge Graph	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
BBN probabilistic	9	9	9	9	9	9	9	9	9	9	9	9	8	9	9	8	8	8
Risk based approaches exposure-effect-hazard-vulnerability (e.g. Bow tie)	8	8	8	8	8	8	8	8	8	8	8	8	7	8	8	7	7	8
Cumulative impact spatial mapping (e.g. Halpern et al.)	12	12	12	12	12	12	12	11	12	12	12	12	11	11	12	11	11	13
impact risk ranking through linkage-chain-frameworks (e.g. ODEMM et al.)	9	9	9	9	9	9	9	9	9	9	9	9	8	9	9	7	8	9
Single spp. model (e.g. life cycle, stock assessment)	8	8	8	8	8	7	8	8	8	8	8	8	6	8	8	7	7	7
Biogeochemical models	3	3	3	3	3	3	3	3	3	3	3	3	2	3	3	2	2	3
Food web models (e.g. multispecies models, EWE)	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10	9	9	7
ecosystem models (e.g. End2End)	8	8	8	8	8	8	8	8	8	8	8	8	7	7	7	6	6	7
HSM models (spp. predictive distribution)	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10	9	9	10
Natural capital accounting, ecosystem services valuation	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Spatial planning models (e.g. GIS, VAPEM, related to use)	11	11	11	11	11	11	11	11	11	11	11	11	10	11	11	10	10	11
Conservation planning models (e.g. MARXAN)	9	9	9	9	9	9	9	9	9	9	9	9	8	9	9	8	8	9
Simple assessment index (e.g. M-AMBI)	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10	8	9	10
Descriptor or theme-specific combination of indices and models (e.g. HEAT, BEAT and CHASE)	8	8	8	8	8	8	8	8	8	8	8	8	7	8	8	7	7	8
Overarching assessment tools (e.g. NEAT and OHI)	11	11	11	11	11	11	11	11	11	11	11	11	10	11	11	10	10	9

Table A2.2. Mean scores assigned to each tool group (rows) based on their ability to deliver on a specific element of Ecosystem-Based Management (EBM) (columns). Scores assigned with high or medium confidence only were considered. Cells are coloured according to mean score in a column (from lowest (white) to highest (dark blue), respectively; note that the same shade of blue may have different meaning (mean score value) across different columns). EBM elements in orange are those specifically addressed in GES4SEAS.

AVERAGE of SCORES (calculated across scores assigned by participants with H or M confidence)	cumulative assessments	GES MSFD assessments	Whole ecosystem assessments	Ecosystem Services (delivery, impacts, valuation)	Specific biotic effects/ impacts	Specific Ecosystem functions (and impacts on functions)	Pressures-Activities footprint	Impacts footprints	Links activities pressures impacts	Single MSFD Descriptors/ single issues (e.g. eutrophication, NIS, HABs)	Single species, ecosystem Components State change	Threatened habitats and species	Climate change	Pressure and impact reduction/mitigation	Spatial and other measures	Uncertainty	Risks	Other Policy Requirements e.g. MSPD, BHD, Biod Strategy
Conceptual models	2.6	2.0	2.5	2.6	2.7	3.0	2.6	2.3	4.2	2.6	2.2	2.4	2.9	2.8	2.0	1.8	1.9	2.1
Semi-quantitative mental models - Fuzzy Cognitive Mapping	2.3	1.4	2.1	2.0	2.0	2.0	1.7	1.6	3.5	2.6	2.0	2.3	2.6	2.5	1.4	1.3	1.9	2.1
Knowledge Graph	1.4	1.2	1.4	1.2	1.8	1.6	1.0	1.0	4.6	2.6	1.0	2.6	3.4	3.0	1.0	0.8	1.2	2.8
BBN probabilistic	3.4	1.9	2.6	2.4	3.0	3.2	1.8	2.0	4.6	3.0	2.7	3.3	2.9	3.2	1.6	3.8	3.6	2.6
Risk based approaches exposure-effect-hazard-vulnerability (e.g. Bow tie)	3.8	2.1	2.3	2.4	3.3	3.0	1.9	1.9	4.5	3.5	2.5	2.8	2.7	4.3	1.9	2.6	4.7	3.8
Cumulative impact spatial mapping (e.g. Halpern et al.)	4.7	2.6	2.7	1.7	1.7	1.8	4.0	3.8	3.1	2.3	0.9	1.9	1.9	2.1	2.6	1.5	2.5	2.6
impact risk ranking through linkage-chain-frameworks (e.g. ODEMM et al.)	4.1	1.9	3.2	2.0	2.3	3.0	3.1	2.9	4.8	2.8	2.2	1.7	1.6	3.3	1.3	1.6	3.9	2.8
Single spp. model (e.g. life cycle, stock assessment)	0.1	1.3	0.9	0.6	2.6	1.4	0.9	0.5	1.0	2.0	3.3	2.4	1.7	1.3	1.9	2.1	1.7	1.6
Biogeochemical models	0.3	0.7	1.3	0.3	1.0	0.7	0.0	0.0	0.0	1.3	1.3	1.0	2.0	1.0	0.7	1.5	0.5	1.0
Food web models (e.g. multispecies models, EWE)	2.1	2.3	3.0	1.7	3.6	4.0	1.3	2.0	2.0	3.0	3.1	2.6	2.6	2.7	2.5	2.6	1.8	1.9
ecosystem models (e.g. End2End)	2.3	2.0	3.5	2.1	2.5	3.3	1.0	1.1	2.4	2.4	2.4	2.4	2.3	2.0	2.0	1.7	1.8	2.1
HSM models (spp. predictive distribution)	1.8	2.0	1.2	1.7	2.5	1.7	1.1	1.2	1.2	1.9	2.8	3.2	2.4	1.3	2.1	1.9	1.8	2.0
Natural capital accounting, ecosystem services valuation	0.3	0.0	0.8	4.7	1.2	2.7	1.0	1.0	0.7	0.3	0.5	1.0	0.8	1.3	1.3	1.5	1.2	1.8
Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation	2.0	0.0	1.5	5.0	0.5	0.5	0.5	1.5	1.5	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.5	1.5
Spatial planning models (e.g. GIS, VAPEM, related to use)	2.8	1.5	1.3	1.7	1.7	1.2	2.9	2.5	2.7	1.4	1.0	1.5	1.2	1.9	4.3	1.5	2.1	2.5
Conservation planning models (e.g. MARXAN)	1.8	0.7	0.8	0.8	0.9	0.8	2.2	1.8	1.9	0.7	1.0	2.7	1.6	2.3	4.6	2.0	1.6	3.1
Simple assessment index (e.g. M-AMBI)	1.1	3.0	1.3	0.8	3.1	2.2	0.8	1.0	1.2	2.5	1.9	2.4	0.7	1.6	1.4	1.3	0.9	2.4
Descriptor or theme-specific combination of indices and models (e.g. HEAT, BEAT and CHASE)	2.4	4.8	3.3	1.9	2.3	2.5	1.5	1.6	2.6	4.8	2.5	2.6	1.7	2.1	2.6	3.1	1.4	2.9
Overarching assessment tools (e.g. NEAT and OHI)	2.7	4.5	4.5	1.5	1.5	1.4	2.7	2.8	2.5	3.3	2.9	3.1	1.9	2.5	3.7	4.0	0.7	3.0
MeanScore_Average	2.2	1.9	2.1	2.0	2.1	2.1	1.7	1.7	2.6	2.3	1.9	2.2	2.0	2.2	2.0	1.9	1.9	2.3
MeanScore_Minimum	0.1	0.0	0.8	0.3	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.5	1.0
MeanScore_Maximum	4.7	4.8	4.5	5.0	3.6	4.0	4.0	3.8	4.8	4.8	3.3	3.3	3.4	4.3	4.6	4.0	4.7	3.8
Element label	1CumulA	2GES-MSFD	3WholeEco	4ES	5SpecifBiot	6SpecifFunct	7PAfootpr	8IFootpr	9APIlinks	10singleMSFD/iss	11SingleComp	12ThreatHab	13CC	14PIreduct	15SpatialM	16Uncert	17Risk	18OtherPolicy

Table A2.3. Standard Deviation (SD) of scores assigned across participants and contributing to the estimated average (considering only score assigned with High or Medium confidence). Cells are coloured according to SD range overall (from lowest (white) to highest (dark blue), respectively). Ecosystem-Based Management (EBM) elements in orange are those specifically addressed in GES4SEAS.

STANDARD DEVIATION (SD) of SCORES (calculated across scores assigned by participants with H or M confidence)	cumulative assessments	GES MSFD assessments	Whole ecosystem assessments	Ecosystem Services (delivery, impacts, valuation)	Specific biotic effects/impacts	Specific Ecosystem functions (and impacts on functions)	Pressures-Activities footprint	Impacts footprints	Links activities pressures impacts	Single MSFD Descriptors/ single issues (e.g. eutrophication, NIS, HABs)	Single species, ecosystem Components State change	Threatened habitats and species	Climate change	Pressure and impact reduction/mitigation	Spatial and other measures	Uncertainty	Risks	Other Policy Requirements e.g. MSPD, BHD, Biod Strategy
Conceptual models	1.6	1.9	2.0	1.6	1.6	1.3	1.8	1.9	1.4	2.0	1.9	2.1	2.1	1.5	1.9	2.0	2.0	1.8
Semi-quantitative mental models - Fuzzy Cognitive Mapping	1.5	1.2	1.0	1.1	1.3	1.1	1.4	1.3	1.6	1.3	1.2	1.3	1.6	1.7	1.4	1.3	1.2	1.6
Knowledge Graph	0.9	1.1	0.9	1.1	1.1	1.3	1.2	1.2	0.9	1.7	1.2	1.7	1.7	1.4	1.2	1.3	1.6	1.8
BBN probabilistic	1.3	1.4	1.2	1.5	1.0	1.6	2.0	2.3	0.9	1.4	1.4	1.6	1.4	1.6	1.7	1.5	1.4	1.8
Risk based approaches exposure-effect-hazard-vulnerability (e.g. Bow tie)	1.0	1.6	1.0	1.2	1.3	1.5	1.9	1.9	0.9	0.9	1.4	1.3	1.4	1.0	1.9	1.6	0.8	1.0
Cumulative impact spatial mapping (e.g. Halpern et al.)	0.8	1.6	1.4	1.2	1.1	1.5	1.0	1.3	1.6	1.8	1.1	1.4	1.4	1.6	2.0	1.8	1.6	1.7
impact risk ranking through linkage-chain-frameworks (e.g. ODEMM et al.)	1.1	1.5	1.2	1.2	2.2	1.4	1.9	1.8	0.7	1.2	1.6	1.0	1.2	1.6	1.3	1.4	1.8	1.6
Single spp. model (e.g. life cycle, stock assessment)	0.4	1.2	1.0	0.5	1.5	1.1	1.0	0.5	0.9	1.1	1.7	1.2	1.5	1.2	1.6	1.5	1.3	1.0
Biogeochemical models	0.6	0.6	1.5	0.6	1.7	0.6	0.0	0.0	0.0	1.5	1.5	1.7	1.4	0.0	0.6	2.1	0.7	0.0
Food web models (e.g. multispecies models, EWE)	1.8	1.2	0.9	1.5	1.3	1.1	1.3	1.9	1.6	1.6	1.9	1.6	1.9	1.6	1.7	1.9	1.7	1.1
ecosystem models (e.g. End2End)	1.0	1.1	1.4	1.2	1.4	0.7	1.3	1.2	1.6	1.2	1.6	1.6	1.3	1.3	1.3	1.5	1.3	1.1
HSM models (spp. predictive distribution)	1.3	1.1	0.6	1.8	1.4	1.2	1.1	1.0	1.0	1.2	1.1	1.1	1.8	1.3	1.5	1.4	1.2	1.1
Natural capital accounting, ecosystem services valuation	0.5	0.0	0.8	0.8	0.4	1.5	1.1	1.1	0.5	0.5	0.5	1.1	1.2	1.4	1.4	1.6	1.5	1.8
Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation	1.4	0.0	2.1	0.0	0.7	0.7	0.7	2.1	2.1	0.0	0.0	0.0	0.7	0.7	0.0	0.0	0.7	2.1
Spatial planning models (e.g. GIS, VAPEM, related to use)	1.4	1.0	0.9	1.6	1.8	1.3	1.7	1.6	1.8	1.1	0.8	1.2	1.0	1.3	1.0	1.6	1.2	1.6
Conservation planning models (e.g. MARXAN)	1.2	0.5	0.4	1.0	0.9	1.0	1.6	1.2	1.4	0.5	0.9	1.0	1.5	1.3	0.9	1.8	1.2	1.6
Simple assessment index (e.g. M-AMBI)	1.7	1.6	1.3	0.6	1.9	1.9	0.9	0.8	1.3	2.1	2.0	1.6	0.5	1.3	1.2	1.6	0.9	1.0
Descriptor or theme-specific combination of indices and models (e.g. HEAT, BEAT and CHASE)	1.6	0.7	1.7	1.6	1.4	1.4	1.3	1.2	1.5	0.7	1.4	1.5	1.3	1.2	1.5	1.5	1.1	1.4
Overarching assessment tools (e.g. NEAT and OHI)	0.9	0.8	0.9	0.9	1.8	1.4	1.6	1.4	1.0	2.1	2.1	2.0	1.4	1.0	1.3	1.4	1.3	0.0

Table A2.4. Minimum score assigned across participants (considering only score assigned with High or Medium confidence). Cells are coloured according to range on minimum scores overall (from lowest (white) to highest (dark blue), respectively). Ecosystem-Based Management (EBM) elements in orange are those specifically addressed in GES4SEAS.

MINIMUM SCORE across participants (calculated across scores assigned by participants with H or M confidence)	cumulative assessments	GES MSFD assessments	Whole ecosystem assessments	Ecosystem Services (delivery, impacts, valuation)	Specific biotic effects/impacts	Specific Ecosystem functions (and impacts on functions)	Pressures-Activities footprint	Impacts footprints	Links activities pressures impacts	Single MSFD Descriptors/ single issues (e.g. eutrophication, NIS, HABs)	Single species, ecosystem Components State change	Threatened habitats and species	Climate change	Pressure and impact reduction/mitigation	Spatial and other measures	Uncertainty	Risks	Other Policy Requirements e.g. MSPD, BHD, Biod Strategy	Overall MINIMUM Score across EBM elements
Conceptual models	1	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	0	0	**0**
Semi-quantitative mental models - Fuzzy Cognitive Mapping	1	0	1	1	0	1	0	0	1	1	0	1	0	1	0	0	0	0	**0**
Knowledge Graph	1	0	1	0	1	0	0	0	3	1	0	1	1	1	0	0	0	0	**0**
BBN probabilistic	1	0	0	0	1	1	0	0	3	1	1	1	1	1	0	1	1	0	**0**
Risk based approaches exposure-effect-hazard-vulnerability (e.g. Bow tie)	3	0	1	0	1	1	0	0	3	3	1	1	1	3	0	0	3	3	**0**
Cumulative impact spatial mapping (e.g. Halpern et al.)	3	0	1	0	0	0	3	1	1	0	0	0	0	1	0	0	1	0	**0**
impact risk ranking through linkage-chain-frameworks (e.g. ODEMM et al.)	3	1	1	0	0	1	1	1	3	1	0	1	0	0	0	0	0	1	**0**
Single spp. model (e.g. life cycle, stock assessment)	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0	0	0	1	**0**
Biogeochemical models	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	**0**
Food web models (e.g. multispecies models, EWE)	0	1	1	0	1	3	0	0	0	0	0	1	0	0	0	0	0	1	**0**
ecosystem models (e.g. End2End)	1	1	1	0	1	3	0	0	0	0	0	0	0	0	0	0	0	1	**0**
HSM models (spp. predictive distribution)	0	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	**0**
Natural capital accounting, ecosystem services valuation	0	0	0	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation	1	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Spatial planning models (e.g. GIS, VAPEM, related to use)	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	**0**
Conservation planning models (e.g. MARXAN)	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3	0	0	1	**0**
Simple assessment index (e.g. M-AMBI)	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**0**
Descriptor or theme-specific combination of indices and models (e.g. HEAT, BEAT and CHASE)	0	3	1	0	0	1	0	0	0	3	1	0	0	0	0	1	0	1	**0**
Overarching assessment tools (e.g. NEAT and OHI)	0	3	3	1	0	0	0	1	0	0	0	0	0	0	1	1	0	3	**0**
Overall MINIMUM Score across Tool groups	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table A2.5. Maximum score assigned across participants (considering only score assigned with High or Medium confidence). Cells are coloured according to range of maximum scores overall (from lowest (white) to highest (dark blue), respectively). Ecosystem-Based Management (EBM) elements in orange are those specifically addressed in GES4SEAS.

MAXIMUM SCORE across participants (calculated across scores assigned by participants with H or M confidence)	cumulative assessments	GES MSFD assessments	Whole ecosystem assessments	Ecosystem Services (delivery, impacts, valuation)	Specific biotic effects/ impacts	Specific Ecosystem functions (and impacts on functions)	Pressures-Activities footprint	Impacts footprints	Links activities pressures impacts	Single MSFD Descriptors/ single issues (e.g. eutrophication, NIS, HABs)	Single species, ecosystem Components State change	Threatened habitats and species	Climate change	Pressure and impact reduction/mitigation	Spatial and other measures	Uncertainty	Risks	Other Policy Requirements e.g. MSPD, BHD, Biod Strategy	Overall MAXIMUM Score across EBM elements
Conceptual models	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Semi-quantitative mental models - Fuzzy Cognitive Mapping	5	3	3	3	3	3	4	3	5	5	3	5	5	5	4	3	3	5	5
Knowledge Graph	3	3	3	3	3	3	3	3	5	5	3	5	5	5	3	3	3	5	5
BBN probabilistic	5	4	4	5	5	5	5	5	5	5	5	5	5	5	4	5	5	5	5
Risk based approaches exposure-effect-hazard-vulnerability (e.g. Bow tie)	5	5	3	3	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Cumulative impact spatial mapping (e.g. Halpern et al.)	5	5	5	3	3	5	5	5	5	5	3	5	5	5	5	5	5	5	5
impact risk ranking through linkage-chain-frameworks (e.g. ODEMM et al.)	5	5	5	3	5	5	5	5	5	5	5	3	3	5	3	3	5	5	5
Single spp. model (e.g. life cycle, stock assessment)	1	3	3	1	5	3	3	1	3	3	5	4	3	3	5	4	3	3	5
Biogeochemical models	1	1	3	1	3	1	0	0	0	3	3	3	3	1	1	3	1	1	3
Food web models (e.g. multispecies models, EWE)	5	4	5	5	5	5	3	5	5	5	5	5	5	5	5	5	4	3	5
ecosystem models (e.g. End2End)	3	3	5	3	5	5	3	3	5	3	5	5	3	3	3	3	3	3	5
HSM models (spp. predictive distribution)	3	3	3	5	5	3	3	3	3	3	5	5	5	3	5	3	3	3	5
Natural capital accounting, ecosystem services valuation	1	0	2	5	2	5	3	3	1	1	1	3	3	3	3	3	3	5	5
Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation	3	0	3	5	1	1	1	3	3	0	0	0	1	1	0	0	1	3	5
Spatial planning models (e.g. GIS, VAPEM, related to use)	5	3	3	5	5	3	5	5	5	3	3	3	3	3	5	5	3	5	5
Conservation planning models (e.g. MARXAN)	3	1	1	3	3	3	5	3	3	1	3	4	3	4	5	5	3	5	5
Simple assessment index (e.g. M-AMBI)	5	5	3	2	5	5	3	3	3	5	5	5	1	3	3	5	3	3	5
Descriptor or theme-specific combination of indices and models (e.g. HEAT, BEAT and CHASE)	5	5	5	5	3	5	3	3	5	5	5	5	3	3	5	5	3	5	5
Overarching assessment tools (e.g. NEAT and OHI)	3	5	5	3	5	5	5	5	3	5	5	5	3	3	5	5	3	3	5
Overall MAXIMUM Score across Tool groups	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

Table A2.6. As Table A2.2, but with Ecosystem-Based Management (EBM) elements (columns) sorted according to the EBM process phase they are relevant to: (a) Planning or Assessment phase, with elements indicating which are the main threats and reason why Good Environmental Status was not achieved, providing EBM guidance and/or assessing Ecosystem-Based Approach-Maritime Spatial Planning (EBA-MSP) scenarios; (b) Check-Evaluation (Follow-up) phase, with elements assessing the state of the environment; (c) Elements which apply to both planning/assessment and check/evaluation. EBM elements in orange are those specifically addressed in GES4SEAS.

(a) Planning-Assessment:	Elements relevant to Planning phase (including assessment) (PA)											
	Elements relevant to application CIA (and improvement along a cascade-effect approach) in Planning (PA1)							Elements including a spatial dimension relevant to Planning (PA2)			Elements used in Planning to inform/guide Action phase (PA3)	
AVERAGE of SCORES (calculated across scores assigned by participants with H or M confidence) (elements sorted by EBM process phase)	Cumulative assessments	Links activities pressures impacts	Single MSFD Descriptors/ single issues (e.g. eutrophication, NIS, HABs)	Specific biotic effects/ impacts	Single species, ecosystem Components State change	Specific Ecosystem functions (and impacts on functions)	Ecosystem Services (delivery, impacts, valuation)	Cumulative assessments	Pressures-Activities footprint	Impacts footprints	Pressure and impact reduction/ mitigation	Spatial and other measures
Conceptual models	2.6	4.2	2.6	2.7	2.2	3.0	2.6	2.6	2.6	2.3	2.8	2.0
Semi-quantitative mental models - Fuzzy Cognitive Mapping	2.3	3.5	2.6	2.0	2.0	2.0	2.0	2.3	1.7	1.6	2.5	1.4
Knowledge Graph	1.4	4.6	2.6	1.8	1.0	1.6	1.2	1.4	1.0	1.0	3.0	1.0
BBN probabilistic	3.4	4.6	3.0	3.0	2.7	3.2	2.4	3.4	1.8	2.0	3.2	1.6
Risk based approaches exposure-effect-hazard-vulnerability (e.g. Bow tie)	3.8	4.5	3.5	3.3	2.5	3.0	2.4	3.8	1.9	1.9	4.3	1.9
Cumulative impact spatial mapping (e.g. Halpern	4.7	3.1	2.3	1.7	0.9	1.8	1.7	4.7	4.0	3.8	2.1	2.6
impact risk ranking through linkage-chain-frameworks (e.g. ODEMM et al.)	4.1	4.8	2.8	2.3	2.2	3.0	2.0	4.1	3.1	2.9	3.3	1.3
Single spp. model (e.g. life cycle, stock assessment)	0.1	1.0	2.0	2.6	3.3	1.4	0.6	0.1	0.9	0.5	1.3	1.9
Biogeochemical models	0.3	0.0	1.3	1.0	1.3	0.7	0.3	0.3	0.0	0.0	1.0	0.7
Food web models (e.g. multispecies models, EWE)	2.1	2.0	3.0	3.6	3.1	4.0	1.7	2.1	1.3	2.0	2.7	2.5
ecosystem models (e.g. End2End)	2.3	2.4	2.4	2.5	2.4	3.3	2.1	2.3	1.0	1.1	2.0	2.0
HSM models (spp. predictive distribution)	1.8	1.2	1.9	2.5	2.8	1.7	1.7	1.8	1.1	1.2	1.3	2.1
Natural capital accounting, ecosystem services valuation	0.3	0.7	0.3	1.2	0.5	2.7	4.7	0.3	1.0	1.0	1.3	1.3
Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation	2.0	1.5	0.0	0.5	0.0	0.5	5.0	2.0	0.5	1.5	0.5	0.0
Spatial planning models (e.g. GIS, VAPEM, related to use)	2.8	2.7	1.4	1.7	1.0	1.2	1.7	2.8	2.9	2.5	1.9	4.3
Conservation planning models (e.g. MARXAN)	1.8	1.9	0.7	0.9	1.0	0.8	0.8	1.8	2.2	1.8	2.3	4.6
Simple assessment index (e.g. M-AMBI)	1.1	1.2	2.5	3.1	1.9	2.2	0.8	1.1	0.8	1.0	1.6	1.4
Descriptor or theme-specific combination of indices and models (e.g. HEAT, BEAT and CHASE)	2.4	2.6	4.8	2.3	2.5	2.5	1.9	2.4	1.5	1.6	2.1	2.6
Overarching assessment tools (e.g. NEAT and OHI)	2.7	2.5	3.3	1.5	2.9	1.4	1.5	2.7	2.7	2.8	2.5	3.7
MeanScore_Average	**2.2**	**2.6**	**2.3**	**2.1**	**1.9**	**2.1**	**2.0**	**2.2**	**1.7**	**1.7**	**2.2**	**2.0**
MeanScore_Minimum	**0.1**	**0.0**	**0.0**	**0.5**	**0.0**	**0.5**	**0.3**	**0.1**	**0.0**	**0.0**	**0.5**	**0.0**
MeanScore_Maximum	**4.7**	**4.8**	**4.8**	**3.6**	**3.3**	**4.0**	**5.0**	**4.7**	**4.0**	**3.8**	**4.3**	**4.6**

(b) Check-Evaluation and (c) Both phases	Elements relevant to Check-Evaluation phase (CE)					Elements relevant to both PA and CE phases (Gen)			
						Climate change (Gen1)	Other elements (Gen2)		
AVERAGE of SCORES (calculated across scores assigned by participants with H or M confidence) (elements sorted by EBM process phase)	**Cumulative assessments**	**Threatened habitats and species**	**Single MSFD Descriptors/ single issues (e.g. eutrophication, NIS, HABs)**	**GES MSFD assessments**	**Whole ecosystem assessments**	**Climate change**	**Uncertainty**	**Risks**	**Other Policy Requirements e.g. MSPD, BHD, Biod Strategy**
Conceptual models	2.6	2.4	2.6	2.0	2.5	2.9	1.8	1.9	2.1
Semi-quantitative mental models - Fuzzy Cognitive Mapping	2.3	2.3	2.6	1.4	2.1	2.6	1.3	1.9	2.1
Knowledge Graph	1.4	2.6	2.6	1.2	1.4	3.4	0.8	1.2	2.8
BBN probabilistic	3.4	3.3	3.0	1.9	2.6	2.9	3.8	3.6	2.6
Risk based approaches exposure-effect-hazard-vulnerability (e.g. Bow tie)	3.8	2.8	3.5	2.1	2.3	2.7	2.6	4.7	3.8
Cumulative impact spatial mapping (e.g. Halpern	4.7	1.9	2.3	2.6	2.7	1.9	1.5	2.5	2.6
impact risk ranking through linkage-chain-frameworks (e.g. ODEMM et al.)	4.1	1.7	2.8	1.9	3.2	1.6	1.6	3.9	2.8
Single spp. model (e.g. life cycle, stock assessment)	0.1	2.4	2.0	1.3	0.9	1.7	2.1	1.7	1.6
Biogeochemical models	0.3	1.0	1.3	0.7	1.3	2.0	1.5	0.5	1.0
Food web models (e.g. multispecies models, EWE)	2.1	2.6	3.0	2.3	3.0	2.6	2.6	1.8	1.9
ecosystem models (e.g. End2End)	2.3	2.4	2.4	2.0	3.5	2.3	1.7	1.8	2.1
HSM models (spp. predictive distribution)	1.8	3.2	1.9	2.0	1.2	2.4	1.9	1.8	2.0
Natural capital accounting, ecosystem services valuation	0.3	1.0	0.3	0.0	0.8	0.8	1.5	1.2	1.8
Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation	2.0	0.0	0.0	0.0	1.5	0.5	0.0	0.5	1.5
Spatial planning models (e.g. GIS, VAPEM, related to use)	2.8	1.5	1.4	1.5	1.3	1.2	1.5	2.1	2.5
Conservation planning models (e.g. MARXAN)	1.8	2.7	0.7	0.7	0.8	1.6	2.0	1.6	3.1
Simple assessment index (e.g. M-AMBI)	1.1	2.4	2.5	3.0	1.3	0.7	1.3	0.9	2.4
Descriptor or theme-specific combination of indices and models (e.g. HEAT, BEAT and CHASE)	2.4	2.6	4.8	4.8	3.3	1.7	3.1	1.4	2.9
Overarching assessment tools (e.g. NEAT and OHI)	2.7	3.1	3.3	4.5	4.5	1.9	4.0	0.7	3.0
MeanScore_Average	**2.2**	**2.2**	**2.3**	**1.9**	**2.1**	**2.0**	**1.9**	**1.9**	**2.3**
MeanScore_Minimum	**0.1**	**0.0**	**0.0**	**0.0**	**0.8**	**0.5**	**0.0**	**0.5**	**1.0**
MeanScore_Maximum	**4.7**	**3.3**	**4.8**	**4.8**	**4.5**	**3.4**	**4.0**	**4.7**	**3.8**

2023