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'*Horses for courses*' – an interrogation of tools for marine ecosystem-based management

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Marine Ecosystem-Based Management (EBM) approaches are a well-established and fundamental component of international agreements and treaties, regional seas conventions, assessment strategies, European Directives and national and regional instruments. However, there is the need to interrogate and clarify the implementation of EBM approaches under current marine management. Although particular focus here is within the European Union Marine Strategy Framework Directive (MSFD), all lessons learned are applicable to marine assessments and management in seas worldwide given that all marine management instruments aim to ensure sustainability in marine ecosystems and human uses. Notably, the MSFD aims to ensure that Good Environmental Status (GES) will be achieved thereby enabling the sustainability of coastal and marine ecosystems to deliver ecosystem services and societal goods and benefits while at the same time being adaptive to rapid climate and environmental changes. As a clear understanding of EBM and the tools available to achieve it is needed for practitioners, regulators and their advisors, the analysis here firstly presents the current understanding of EBM (including its origin and application) and the wider 26 principles on which it is based. Secondly, we identify the key elements that are addressed by those principles (18 key EBM elements). Thirdly, we identify the types of tools available for use in the EBM context (19 tool groups). Fourthly we analyze the suitability of tool types to deliver the key EBM elements using an expert judgement approach. Finally, we conclude with the lessons learned from the use of those tools and briefly indicate how they could be combined to help achieve EBM in the most effective way. It is emphasized that no single tool is likely to satisfy all aspects of EBM and therefore employing a complementary suite of tools as part of a toolbox is recommended.

KEYWORDS

Ecosystem-Based-Management, EBM elements, assessment tools, marine policies, Marine Strategy Framework Directive

1 Introduction

Managing human activities impacting marine systems focuses 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 delivers the ecosystem services from which society gains goods and benefits after inputting human capital and complementary assets (Elliott, 2013, 2023). For example, in 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 and the ability to be sentient are required to ensure that society benefits from those fish (Haines-Young and Potschin, 2018). 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 rely on an adequate understanding of the complex interplay of science, technology, and management skills (Borja et al., 2024). However, there are 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 summarized as managing the ecosystem in which humans are regarded as an integral part. The 'Ecosystem Approach' (EA or EcAp), 'Ecosystem-Based Approach' (EBA) and/or 'Ecosystem-Based Management' (EBM), and their variants are the terms commonly used for this philosophy (Kirkfeldt, 2019). However, it can be argued that the term 'based' is redundant as 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 analyzed (e.g., Kirkfeldt, 2019); here, the term EBM is taken to include all variants of the concept.

Given this implied uncertainty, the research here uses a structured expert evaluation to identify and interrogate current EBM approaches and policy measures to reduce the adverse effects of human activities; in doing so, it provides the best assessment of the most appropriate approaches/tools to reach policy objectives. The particular focus is within the European Union (EU) Marine Strategy Framework Directive (MSFD; EC, 2008) to ensure that Good Environmental Status (GES) can be achieved thereby enabling the sustainability of coastal and marine ecosystems to deliver ecosystem services and societal goods and benefits while at the same time being adaptive to rapid climate and other environmental changes (Borja et al., 2013). Despite that EU focus, this interrogation is relevant to all marine areas where similar policies/legislation are applied and marine ecosystem assessments are required; for example, Cormier et al. (2022) indicated that Canada has also followed large elements of the MSFD.

The analysis here is structured to firstly present the current understanding and context of EBM and the wider principles on which it is based. Secondly, we identify the key elements that are addressed by the EBM principles. Thirdly, we identify the types of assessment tools available to support EBM. Fourthly, we analyze the suitability of tool types to deliver the key EBM elements. Finally, the paper presents conclusions regarding the use of those tools and briefly indicates the way in which they could be combined to achieve EBM.

2 Ecosystem-Based Management in theory: the concept and principles

The term EBM has several definitions although these are not always very clear and unambiguous (Kirkfeldt, 2019; Delacámara et al., 2020); however, with respect to the MSFD, the following is used:

> *"Ecosystem-based approach (to management), aka 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"* (modified slightly from CSWD, 2020).

Ecosystem-Based Management recognizes the full array of interactions within a marine ecosystem, including humans, rather than considering single issues, species, or ecosystem services in isolation (see also McLeod et al., 2005). It encompasses the comprehensive integrated management of human activities based on the best available scientific knowledge about the ecosystem and its dynamics, helping to ensure activities are monitored and managed accordingly with the relevant legislation (ICES, 2020). It aims to identify and act on influences which are critical to the health of marine ecosystems, thereby achieving the sustainable use of goods and services and maintenance of ecosystem integrity (ICES, 2003).

Ecosystem-Based Management is under-pinned by several fundamental or key principles required for its operationalization and implementation. Using literature up to 2010, Long et al. (2015) reviewed the evolution of the concept of the set of EBM principles in their definition of EBM, which adds a spatial connotation compared to the previous definitions: *"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). That study selected the 15 most important/commonly cited EBM principles from a list of 26 principles. They noted three emerging Key Principles such as 'Consider Cumulative Impacts', 'Apply the Precautionary Approach' and 'Explicitly Acknowledge Trade Offs' that could help to shape and successfully apply EBM.

Other projects and expert working groups globally have since further considered this list of principles and consequently chosen the EBM principles that most fit their aims/mandate. For example, a United States, EU and Canadian working group on the ecosystem approach to ocean health and stressors was established in 2016 under the Atlantic Ocean Research Alliance (AORA) to investigate the implementation of EBM in the North Atlantic. They reviewed and contrasted 20 Principles for implementation (Dickey-Collas et al., 2022), including those 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'*. As a further example, to clarify and codify the priorities for EBM in New Zealand, a set of narratives and EBM principles were developed around seven themes including recognition 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, recognizing 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 Areas Beyond National Jurisdiction and deep-sea mining (DSM), grouped EBM principles into 8 categories: core, ecological, impacts, knowledge, management, participation, socio-economic and spatial-temporal scales. The inclusion of the words 'tailored' and 'management' in this definition implies that EBM must be an adaptive system to accommodate changing circumstances. Similarly, by necessity it should have feedback loops so that lessons learned can be incorporated into future management actions (Elliott et al., 2020a; Roux and Pedreschi, 2024; Smith et al., 2025).

3 Ecosystem-Based Management in practice: application from global to local scales

3.1 At the global level

Although previous regional approaches, such as the North Sea Conferences (e.g. NSC, 2002) mention the Ecosystem Approach, it was first codified by the UN Convention for Biological Diversity (CBD, 2000, 2004) as a set of 12 principles (CBD 1992, 2007). This defined it as *'a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way'* and so its application aims to achieve 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.

At a global level, EBM is not explicitly stated in the CBD although it is implicit in the original 12 principles and, at the 5th Conference of Parties (COP) meeting in 2000, the EBA was set as the primary framework for action under the Biodiversity Convention (CBD, 2000, COP 5, Decision V/6). The recent (12/2022) 15th CBD COP adopted the "Kunming-Montreal Global Biodiversity Framework" (GBF) in which three of 23 targets express the need to apply EBAs and nature-based solutions (CBD, 2022).

The UN Convention on the Law of the Sea (UNCLOS) defines the rights and responsibilities of nations concerning their use of the world's oceans as well as the management of marine resources (Cormier et al., 2022). At present, the concept of the Ecosystem Approach is only implicit in the Convention, through a reference to a clear obligation to protect and preserve the marine environment (Article 192). Similarly, the use of measures is included 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)).

3.2 At the regional level

Regional Sea Conventions, together with various organizations, such as the European Environment Agency (EEA), have included

EBM in their science and evidence planning and have included its principles in their data, science and advisory programs. EBM is therefore an approach for addressing 'wicked' environmental problems, i.e., complex problems that involve many interdependent factors and strong links between the socio-economic and ecological spheres (Termeer et al., 2019). As such, it recognizes the need to incorporate systems thinking into natural resource management (O'Higgins et al., 2020; Elliott et al., 2020a; Smith et al., 2025). It is important to acknowledge that due to the complexities involved in marine and aquatic social-ecological systems, there is neither a one-size-fits-all EBM approach nor only one EBM implementation path (Delacámara et al., 2020; Roux and Pedreschi, 2024). Indeed, progress towards EBM is more likely to proceed incrementally; it is essential therefore that approaches are regularly reviewed and that any produced EBM toolbox includes new tools and tool combinations to improve and support the process. This also ensures that EBM is an adaptive management approach which can accommodate changing conditions and the results of previous management actions.

The monitoring and assessment strategy of the Baltic Sea Marine Environment Protection Commission (HELCOM) is built on the ecosystem approach concept (HELCOM, 2013). This strategy covers all the components of a marine ecosystem and the pressures impacting it, and more recently includes climate change. The HELCOM integrated assessments are based on a few key features: (i) commonly agreed assessment areas, which are defined in a nested way for each assessment indicator; (ii) quantitative core indicators which have been developed following commonly agreed criteria; (iii) indicator threshold values, which define good environmental status, and (iv) multi-metric indicator-based assessment tools.

The HELCOM assessment strategy not only covers the state of the environment but also gives due focus to human activities, pressures and their impacts on the ecosystem and society. In 2010, the HELCOM holistic assessment introduced the cumulative impact assessment of anthropogenic pressures (see Korpinen et al., 2012), following the global assessment method by Halpern et al. (2008). Since then, this includes the HELCOM multi-metric indicator-based assessment tools (HEAT, BEAT and CHASE), cumulative impact assessment (CIA) and a tool to estimate the effectiveness of measures (Ahtiainen et al., 2024).

The Barcelona Convention for the Mediterranean adopted the EcAp in 2008 as the guiding principle to all policy implementation for healthy marine and biological ecosystems that are productive and biologically diverse for the benefit of present and future generations (UNEP, 2008). The Integrated Monitoring and Assessment Program (IMAP) was adopted in 2016, as part of the implementation of the EcAp Roadmap. The current EcAp contributes to Sustainable Development Goal 14 (Cormier et al., 2021), the achievement of CBD Aichi Biodiversity Target 11 and the implementation of the MSFD (see below). The EcAp includes ecological objectives that mirror the MSFD descriptors and also aims towards operational objectives with indicators and target levels through regular monitoring programs.

For the Black Sea, although the Bucharest Convention (http://www.blacksea-commission.org/_convention.asp) does not explicitly mention EBM and the EcAp, the main actions are linked to combating pollution from land-based sources and maritime transport, achieving sustainable management of marine living resources, and pursuing sustainable human development, i.e. by definition an EcAp. Black Sea action plans require a holistic approach to the ecosystem, which has led to the development of the Black Sea Integrated Monitoring and Assessment Program (BSIMAP). Integrated evaluation tools are still generally missing from BSIMAP with the exception of eutrophication assessment tools, TRIX (Trophic Status Index; Vollenweider et al., 1998) and BEAST (Black Sea Eutrophication Assessment Tool; Slobodnik et al., 2017).

In the North-East Atlantic Ocean, the Oslo and Paris (OSPAR) Convention (https://www.ospar.org/convention) considers a framework for the regulation of most human activities, which are likely to influence marine ecosystems and the overall biodiversity. Both, the HELCOM and OSPAR Commissions have in their vision and mission the need to consider the concept of a defined Ecosystem Approach (given as "*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 OSPAR North-East Atlantic Environment Strategy 2030 provides further detail to this definition of the Ecosystem Approach to incorporate reference to "*drivers, activities and pressures that adversely affect the health of marine ecosystems*" in place of "*on influences which are critical to the health of marine ecosystems*" (OSPAR, 2021). Applying the ecosystem approach integrates conservation and management approaches, such as marine protected areas or measures targeted at single species and habitats, as well as other approaches, including cumulative effects.

In the case of the EEA, under its high level policy objective of achieving sustainability in Europe, its multifaceted work addresses key EBM principles. These include Ecological integrity and biodiversity, and Cumulative effects and support EU policies and strategies with evidence-based knowledge to help the EEA member countries and the EU to assess progress towards achieving their vision. The EEA outputs include the State of Environment reports. The EEA Marine Messages III addressing key EBM elements (as with marine Messages II, European Environment Agency, 2019), is being prepared for 2026.

3.3 At the European Union level

The EU, in policy, legal instruments (such as Directives), strategies and with support from numerous research projects, focuses on understanding marine ecosystems, their interactions and pressures. Therefore, this implicitly requires applying EBM as an iterative process (Haugen et al., 2024) although there is no definition of EBM embedded in EU law (O'Hagan, 2020). The EU Integrated Maritime Policy contains the fundamental pillars of the MSFD (EC, 2008) and the Maritime Spatial Planning Directive

(MSPD; EU, 2014). The MSFD text (EC, 2008) does not provide a definition (see also CSWD, 2020 and Section 4) of an EBA to management but requires its application. The 11 descriptors of the MSFD form the different sectors of the EBA 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 effects (Berg et al., 2015).

While the MSFD is the first piece of EU legislation to adopt an EBA aiming at the protection of the full range of marine biodiversity, the European Commission considers the Natura 2000-regime (the network of sites to safeguard the habitats and species of community interest) as one of the legal components of the implementation of this approach for the marine environment. This EBA considers the concepts of favorable conservation status and good ecological status as required respectively by the Habitats Directive (HD) and the Water Framework Directive (WFD) (Bastmeijer, 2018; Elliott and Wither, 2024). Both Natura 2000 and WFD objectives are in line with some of the EBM principles (e.g., ecosystems must be managed within the limits of their functioning, assess cumulative impacts, conserve ecosystem structure and functioning to maintain ecosystem services) and therefore the Ecosystem Approach is considered appropriate to aid their implementation (Vlachopoulou et al., 2014; Bastmeijer, 2018).

The MSPD (EU, 2014) explicitly acknowledges that an EBA will contribute to promoting the sustainable development and growth of the maritime and coastal economies and the sustainable use of marine and coastal resources, supported by maritime spatial planning. The MSPD is increasingly regarded as the mechanism for the Program of Measures needed to achieve Favorable Conservation Status, for HD, and GES, for the MSFD (Elliott and Wither, 2024).

The EU Common Fisheries Policy (CFP) (EU, 2013), whilst focused on fisheries, implements an EBA to fisheries management within ecologically meaningful boundaries. This aims to ensure that negative impacts of fishing activities on the marine ecosystem are minimized, and ensures that activities avoid the degradation of the marine environment.

The more recent EU Biodiversity Strategy 2030 (EC, 2020) again does not define EBM but reiterates the benefits of its application. It also introduces the EU Nature Restoration Law (EC, 2022; Hering et al., 2023; now adopted as EU, 2024) and the Action Plan to conserve fisheries resources and protect marine ecosystems (EC, 2023). With this action plan, the EC aims to achieve a more consistent implementation of the EU environmental policy and the Common Fisheries Policy with its three – environmental, economic and social - sustainability pillars.

4 Sector, single activity or single-policy EBM applications

Marine management has to address the full range of human activities and their resulting pressures and effects on both the natural and human systems (Elliott et al., 2020b). A key aspect of EBM is in recognizing the full array of marine ecosystem interactions (including humans) rather than focusing on specific sectors in isolation hence only on a subset of related activities and pressures to be managed. An early example of this is the adoption of Ecosystem Approach to Fisheries (EAF) management (EAFM) (FAO, 2003). 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 (FAO, 2021). Although the EAF concept has been introduced in the European CFP (e.g. see Garcia et al., 2003; Morishita, 2008; Jennings and Rice, 2011), its operationalization and implementation in European fisheries management so far have been limited (Wakefield, 2018; FAO, 2021).

The application of the EBM to a single sector (e.g. offshore energy) and activity (e.g. monopile and turbine placement) is also seen in the development of offshore wind farms (OWF) in line with conservation objectives (Pezy et al., 2020; Copping et al., 2020; Galparsoro et al., 2022; Maldonado et al., 2022). Similarly, 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 their 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 its activities within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems (FAO, 2010).

Ecosystem-based marine spatial planning (EB-MSP) is a relatively recent practice (see Andersen et al., 2020). EB-MSP has been extensively researched and reviewed in its concepts, tools and critical issues for its implementation (Katsanevakis et al., 2011, 2020; Kirkfeldt, 2019; Stelzenmueller et al., 2013, 2018, 2020). EBA is often presented as a concept or broad implementation philosophy to 'give space to ecology' within the MSP process and decisions. The guidance of the main steps of the MSP process (EC et al., 2021) presents a set of key actions to operationalize EBA.

Other EBM applications include approaches linked to Integrated Ecosystem Assessments (IEAs). First developed by the US National Oceanic and Atmospheric Administration (NOAA), IEAs are seen as an approach to operationalizing EBM (Levin et al., 2009, 2014; Samhouri et al., 2014; Dickey-Collas, 2014), and have been adopted by ICES as a key tool to achieve EBM (ICES, 2023) along with fisheries assessments and ecosystem overviews (ICES, 2021a; 2022).

5 Key EBM principles, elements and tools

Having defined EBM, it is then important to determine and interrogate the tools available for achieving it and its outcomes. To this end, the 26 EBM principles from Long et al. (2015) were reviewed together with more recent literature (Rudd et al., 2018; Hewitt et al., 2018; Clark et al., 2021; Dickey-Collas et al., 2022). The principles were reworded to add clarity and to aid their operationalization (Table 1). To make the analysis more manageable, only 16 of the 26 EBM principles were selected here as this study primarily focused on the assessment of environmental state change and pressures and Good Environmental Status in the marine environment. Accordingly, the current analysis omitted principles that apply exclusively to the management implementation part of the system, e.g., acknowledging trade-offs (principle 21), use of incentives (principle 26) and applying the precautionary approach to management (principle 18) (Table 1). Trade-off analysis can be used to advice on potential fisheries closures based on fisheries data and bioeconomic modelling (ICES, 2021b). Trade-offs between small-scale fisheries and aquaculture can be studied using a mixed methods approach (including literature reviews, conceptual models, quantitative and qualitative data and insights) to meet social and environmental goals (Mansfield et al., 2024). Trade-off scenarios between fisheries, offshore wind farms and MPAs, based on spatially-explicit trophic models, can also be used to advise on future sea space e.g. for planned offshore wind farms and new MPAs (Püts et al., 2023). However, whether trade-offs are actually considered formally, consistently and transparently by decision makers and national authorities when designing their management measures, i.e. the

TABLE 1 Ecosystem-Based Management (EBM) Principles (Long et al., 2015) and reworded as instructions.

No	EBM Principles	Reworded principles
1	Consider ecosystem connections*	Determine and ensure connectivity within and between areas
2	Appropriate spatial and temporal Scales*	Assess at temporal and spatial scales, appropriate to the ecosystem components of concern
3	Adaptive management*	Use adaptive management in employing measures
4	Use of scientific knowledge*	Use best and fit-for-purpose scientific knowledge
5	Integrated management*	Ensure integrated management is carried out
6	Stakeholder involvement*	Ensure a fair and transparent stakeholder involvement at all stages
7	Account for dynamic nature of ecosystem*	Ensure ecosystem functioning is assessed at relevant spatial and temporal scales accounting for change
8	Ecological integrity and biodiversity*	Determine ecological integrity and biodiversity
9	Sustainability*	Ensure the managed systems are sustainable in the long-term
10	Recognise coupled social-ecological systems*	Include and integrate both ecological and social systems (humans are part of the marine system)
11	Decisions reflect Societal Choice	Ensure the outcomes respect societal choice
12	Distinct boundaries*	Consider ecosystem and jurisdictional boundaries. Include spatial and temporal boundaries in the assessments.
13	Inter-disciplinarity*	Ensure the assessments are multidisciplinary, including social and natural scientists
14	Appropriate monitoring*	Perform appropriate and fit-for-purpose monitoring
15	Acknowledge uncertainty*	Measure and record uncertainty in the assessments
16	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	Consider economic context	Determine the economic repercussions of action and non-action
18	Apply the Precautionary Approach	Apply the precautionary approach in management
19	Consider cumulative impacts*	Assess the risk, identify and measure the cumulative impacts/effects (on both natural and social systems)
20	Organizational change	Identify if organizational change is required in management and make recommendations
21	Explicitly acknowledge Trade-offs	Determine whether and what are the trade-offs in management measures
22	Consider effects on adjacent ecosystems	Determine the effects and connectivity of an area on adjacent systems and vice versa
23	Commit to principles of equity	Ensure that actions and outcomes are just and equitable to nature and society
24	Develop long term objectives	Record the long-term vision and ensure objectives are SMART: Specific, Measurable, Achievable, Relevant, and Time-Bound and link to indicators
25	Use of all forms of knowledge*	Use best-available natural and social sciences, including indigenous knowledge
26	Use of incentives	Use economic, societal and ecological incentives to achieve outcomes

Principles marked with an asterisk (*) are the most relevant to this study focus on assessing Good Environmental Status under the Marine Strategy Framework Directive.

suggestion of the omitted EBM principle 21, is questionable (Howe et al., 2014; Fortnam et al., 2023) and not the focus of this work. Similarly, EBM principle 23 suggests that managers and decision makers should be committing to principles of equity ensuring that measures and outcomes are just for nature and society, while EBM 26 suggests the use of economic, societal and ecological objectives to achieve outcomes.

The current assessment identified key elements of EBM relevant to the selected 16 principles (as the operations to undertake and aspects to be considered and assessed to satisfy each principle as part of the overall EBM process; Table 2). It considers these together with the appropriate assessment approaches and tools that can be used to deliver, singly or in combination with others, these different EBM elements (Table 3). The selection of EBM principles, EBM elements and associated assessment tools was based on the judgement of 20 experts who were researchers with direct experience of GES assessment, EBM and use of the tools to deliver it; these experts were taken from the partners and advisors in the GES4SEAS project (www.ges4seas.eu) and are included as authors here. The experts (with an estimated >150,000 citations) were chosen based on their wide and documented experience working on major relevant marine policies (e.g. MSFD, WFD, MSP), on thematic assessments (e.g. non-indigenous species, benthic seafloor assessments, eutrophication, ecosystem services), tool development or use (e.g. AMBI, CIMPAL, NEAT, MARXAN, various models, risk based and cumulative impact assessment tools) and all the relevant EBM aspects and principles (e.g. assessing ecological integrity and biodiversity, cumulative impacts, distinct boundaries, appropriate spatial and temporal scales).

The experts deconstructed and matched the principles into elements (i.e., all those essential topics that need to be addressed/assessed to satisfy a principle) following a co-creation and consensus approach. For the next step, the experts matched the elements to tools/tool types/methodological approaches required to address/satisfy the elements based on expert knowledge and literature checks by subject focusing on marine applications. An example matching the principles to elements and corresponding tool groups/assessment methodologies is given in S1. The tools were then grouped in relevant tool groups following a co-creation with key stakeholders and a consensus approach based on their main characteristics (e.g. from conceptualizing to modelling, from assessing state to addressing risk, and within modelling from

TABLE 2 Elements of Ecosystem-Based Management (EBM) (and their applications) relevant to Ecosystem Assessments (full descriptions in Supplementary Materials S2).

#	EBM element	Brief description
1	Cumulative effects assessments -CEA	Cumulative Effects Assessment (CEA) is the assessment of ecosystem changes that accumulate from multiple stressors, both natural and human made (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.
2	GES MSFD assessments	The assessment undertaken for the purposes of the MSFD. It is a formal procedure by which information is collected and evaluated following agreed methods, rules and guidance. It is carried out periodically to determine the level of available knowledge and to evaluate the environmental status. The resulting output is a report that synthesizes the findings, and leading to a classification of status in relation to the determination of GES (CSWD, 2020).
3	Whole ecosystem assessments	Whole ecosystem assessments are similar to the previous but without the same strict structure and requirements of the MSFD. These include regional assessments, e.g., in the Baltic Sea (HELCOM), Atlantic Ocean (OSPAR Commission), Mediterranean (UNEP-MAP), or in the Black Sea (Todorova et al., 2019) and ICES ecoregions (ICES, 2023).
4	Ecosystem services (delivery, impacts, valuation)	This includes assessments of ecosystem services (ES) in terms of delivery and impacts as well as of value. Ecosystem services are the final outputs or products from ecosystems that lead to societal goods and benefits that are directly consumed, used (actively or passively) or enjoyed by people.
5	Special biotic effects/impacts	Examples include sex-changing and sex segregation (i.e., when sexes of a species live apart, either singly or in single-sex groups). Documenting the underlying causes of sexual segregation is important for management and conservation reasons as differential exploitation of the sexes (e.g., by spatially focused fishing in key areas) can lead to population decline.
6	Specific ecosystem functions (and impacts on functions)	The MSFD 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* (EC, 2008).
7	Pressures-activities footprint	Determining the overall effects of human activities as a precursor to management, requires quantifying: (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 activities-footprints, pressures-footprints and effects-footprint (Elliott et al., 2020b).
8	Effects or Impacts footprints	As with the category Pressure-Activities 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.

(Continued)

TABLE 2 Continued

#	EBM element	Brief description
9	Links activities pressures impacts	Linking activities, pressures and impacts is an essential part of the MSFD and a crucial element of EBM. DAPSI(W)R(M) (Drivers, Activities, Pressures, State change, Impacts on human Welfare, Responses by Measures) or DAPSES-MMM (socio-economic Drivers, human Activities, Pressures, State of environment, Ecosystem Services – Management (policies and governance), Measures, Monitoring) are examples of the conceptual frameworks mapping these links.
10	Single MSFD descriptors/single issues	This includes primarily assessments on major issues such as Invasive alien species (IAS), Harmful Algal Blooms (HABs), jellyfish blooms and eutrophication.
11	Single species, ecosystem components state change	This includes assessments of single species status (e.g., under CFP and MSFD for commercial species) or assessments of a habitat (e.g., for reporting for HD or within an MPA) and looking at changes of status due to pressures.
12	Threatened habitats and species	This includes documenting status and distributions of species and habitats at risk at global, regional or local scales.
13	Pressure and impact reduction/mitigation	This includes targeted and specific pressure and impact reduction or mitigation measures. For example measures mitigating the impacts of marine IAS include physical removal, promotion of commercial exploitation, and environmental rehabilitation. Other examples include increasing the selectivity of the fishing gears and implementing the landing obligation to reduce bycatch and unwanted catches.
14	Spatial and other measures	This includes spatial and other measures related to the management response and management footprint. Well known spatial measures include, for example, the ban of trawling in the deep habitats in the Mediterranean and the North East Atlantic, or in particular areas (e.g., over protected habitats).
15	Climate change	Modelling tools can address changes in species distributions due to climatic effects and these insights are relevant to the planning phase to conservation spatial planning and restoration prioritization. In the evaluation and assessment phase it can inform on whether the outcomes are affected by climate change as well as the trajectory of change.
16	Uncertainty	Uncertainty applies to all the EBM process 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.
17	Risks	This includes risk from action or inaction, risks to ecosystem components due to spatial overlap with activities and pressures, risks related to specific biotic effects (e.g., sex related fishing impacts or fishing impacts on nesting or nursery areas).
18	Other policy requirements e.g., MSPD, BHD, Biodiversity Strategy	This EBM element addressed the ability of satisfying different policy needs (other than MSFD), e.g., by providing outputs relevant for the MSPD, the Biodiversity Strategy, the EU Nature Restoration Law, the BHD or the needs of RSC (e.g., OSPAR, HELCOM).

MSFD, Marine Strategy Framework Directive; GES, Good Environmental Status; HD, Habitats Directive; BHD, Birds and Habitats Directives; CFP, Common Fisheries Policy.

single species life cycle or stock assessment modeling to predictive species distribution models, multi species food web modeling, bioeconomic modelling and so on; they excluded approaches used in the ecohydrology/other coastal/terrestrial fields).

In total, 18 individual key EBM elements were identified (Table 2; full descriptions in S2). They relate to all aspects of conceptual management cycle frameworks around adaptive EBM strategy, including the PACE [plan, act, check, evaluate (BSPC, 2006)] and cause-consequence-response frameworks such as the modified DPSIR-related (Drivers, Pressures, State, Impacts, Response) frameworks DAPSES-MMM (Drivers-Activity-Pressures-State-Ecosystem Services-Management (Policies and Governance)- Measures-Monitoring; CSWD, 2020) and DAPSI(W)R(M) (Drivers-Activities-Pressures-State change-Impacts (on human Welfare)-Responses (using management Measures; Elliott et al., 2017); the cause-consequence-response frameworks are typically used as problem-solving approaches by the European Commission, Regional Seas Conventions and EU research projects.

Assessment methodological approaches and tools addressing the 18 EBM elements were identified as 19 tool groups (categories) (Table 3; full descriptions including examples of applications and required data and resources are given in S3). Scoring of the tools by the experts is given in section 6.1.

6 Assessment of tools used in EBM

6.1 Assessment method

The relevance and usefulness of the tool groups was assessed by the team of 20 experts by scoring the tool group ability to deliver on the specific elements of EBM according to a set of questions. Specifically, "can these tool groups 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 insufficient knowledge).

TABLE 3 Types of tools used to support delivery of the elements of Ecosystem-Based Management (EBM).

#	Tool group	Brief description
1	Conceptual models	Conceptual models (including mental models, mind maps, argument mapping, horrendograms, organograms, etc.) are a graphical representation of a system (e.g., natural, socio-economic or socio-ecological system). They visually summarize the complex relationships within a system through a network of nodes (the main components of a system) and vectors/links (the pathways linking those components).
2	Semi-quantitative mental models - Fuzzy cognitive mapping	Semi-quantitative mental models are an advance on conceptual models in that the linkages between nodes (the system's main components) are not just documented, but the direction and strength of interaction is specified, allowing for simple scenario investigation. Perhaps the most used Fuzzy cognitive mapping (FCM) tool is Mental modeler.
3	Knowledge graphs	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. 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.
4	BBN probabilistic models	Bayesian Belief Networks (BBNs) are models that graphically and probabilistically represent correlative and causal relationships among variables and which account for uncertainty. BBNs operationalize conceptual models by quantifying the linkages and the strengths of the links (the dependencies and interdependencies) between nodes (the model's variables) through conditional probability tables or distributions.
5	Risk based approaches exposure-effect-hazard-vulnerability (e.g., Bow-Tie)	Bow-Tie is an ISO and industry-standard method for producing conceptual models (Cormier et al., 2019). It addresses a risk or problem (as the central knot of the Bow-Tie) and indicates the causes of that problem (to the left of the knot) and the consequences that occur because of the problem (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.
6	Cumulative impact spatial mapping	The global human impact assessment (Halpern et al., 2008) is a spatial assessment where layers of pressures and of ecosystem components (e.g., species, species groups, habitats), spatialized across a grid of selected resolution, are combined. Their spatial overlap and weight scores representing the sensitivity of the ecosystem components to each of the pressures are used to derive an index expressing cumulative impacts/effects.
7	Impact risk ranking through linkage-chain-frameworks (e.g., ODEMM)	A risk assessment methodology which traces sector–pressure–ecosystem component pathways (also known as 'linkage chains') and scores them through expert judgement and data where available. Each link is scored for a number of attributes (e.g., spatial overlap, temporal overlap, degree of impact, resilience or resistance), giving total impact risk scores in a variety of ways depending on complexity (ODEMM: Knights et al., 2015; Pedreschi et al., 2023; SCAIRM: Piet et al., 2023).
8	Single spp. model (life cycle, stock assessment)	Single-species models are mathematical representations used to study and understand the dynamics of a particular species within an ecosystem. The models focus on population size, growth, and interactions of a single species, while often considering the species interactions with its environment and other influencing factors. These models can incorporate limited ecosystem or multispecies information.
9	Biogeochemical models	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.
10	Food web models (e.g., multispecies models, EWE)	Food-web models are a particular type of ecosystem models, which simulate the structure and flow of energy and nutrients between ecosystem components. Food web models aim to understand the trophic patterns, population dynamics among predators and prey, and implications for system stability. Examples include Ecopath with Ecosim (EwE) and Ecological Network Analysis (ENA).
11	Ecosystem models (e.g., End2End)	Ecosystem models are models that 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). They are a mathematical representation of an entire ecosystem, which integrates physico-chemical oceanographic descriptors and organisms ranging from microbes to higher-trophic-level organisms (including humans).
12	Species distribution models	Species distribution models (SDM, also known as habitat suitability models or predictive habitat distribution models) are used to predict the spatial distribution of a species (e.g. the likelihood of its presence or density) based on its observed relationship with environmental conditions. Different modelling techniques can be used (e.g., generalized linear or additive regression models, classification and regression trees, Random Forest, maximum entropy algorithm).

(Continued)

TABLE 3 Continued

#	Tool group	Brief description
13	Natural capital accounting, ecosystem services valuation	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. Natural capital accounts are developed to assess and monitor the contribution of natural resources to economic activity.
14	Bioeconomic models, socioeconomic models (CBA), societal goods and benefits valuation	This tool group includes tools such as: (i) Bio-economic models, i.e. integrated economic-ecological models used for resource management; (ii) Valuation of Societal Benefits, which determines the 'total social value' (comprising of ecological value, economic value, and socio-cultural value) of marine ecosystem services leading to benefits for society; (iii) Cost-benefit analysis (CBA), a core tool of public policy consisting of the systematic process of calculating the benefits and costs, expressed in monetary units, of policy options and projects.
15	Spatial planning models (e.g., GIS, VAPEM, related to use)	Spatial planning models 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. Examples include Geographic Information Systems (GIS, computer-based tools used to store, analyze, and visualize spatial or geographic data) and VAPEM tool (Ecological Assessment and Marine Spatial Planning Tool, which integrates environmental risk information and with technical and socio-ecological information).
16	Conservation planning models (e.g., MARXAN)	Conservation planning is the process of locating, configuring and implementing areas that are managed to promote the persistence of biodiversity and other natural values. Systematic conservation planning (SCP) based on clear goals and targets, locates and designs new reserves. Common decision support tools to facilitate SCP include MARXAN (a suite of spatial prioritization decision support tools to design networks of protected areas) and ZONATION (operating on spatial data about ecological features, costs, and threats, also utilizing information about uncertainty and connectivity).
17	Simple assessment index (e.g., M-AMBI)	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 (e.g., diversity indices). Examples include numerous biotic indices, covering different biological elements from phytoplankton to macroinvertebrates and fishes. M-AMBI (Multivariate AZTI's Marine Biotic Index) is an example of multivariate index for macroinvertebrates (Borja et al., 2019).
18	Descriptor or theme-specific combination of indices and models (e.g., HEAT, BEAT and CHASE)	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) and 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.
19	Overarching assessment tools (e.g., NEAT and OHI)	NEAT (Nested Environmental status Assessment Tool) is a tool primarily developed for biodiversity assessment. The tool is usually applied to status assessment, describing the status of an ecosystem using target, thresholds and values of state indicators for various ecosystem components, divided into separate values for specific habitats inside a spatial assessment unit. OHI (Ocean Health Index) is a framework for assessing ocean health based on the sustainable provisioning of benefits and services people expect from healthy oceans, such as food, cultural and social value, and jobs.

Full descriptions in Supplementary Materials S3.

The scores were reported in a matrix format crossing tool groups (19 rows; Table 3) against EBM elements (18 columns; Table 2). Each expert contributed to scoring individual or multiple tools depending on their knowledge of the tools, and the confidence the experts had in this knowledge was also recorded (as high, moderate or low) for each of the tool groups they scored.

In addition, each tool was assessed for its place within the four management cycle phases based on the PACE framework (plan, act, check, evaluate) (BSPC, 2006; Andersen, 2012). PACE is compatible with 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, in the MSFD) are set by management and all the main threats to the system are identified. In the Evaluation and Check phases, the main focus of this work, status assessments are performed and distance to goals is evaluated (e.g., is GES reached? Why GES is not achieved? Is monitoring fit-for-purpose? Are additional measures needed)?.

Score matrices were collated and averaged across contributors. Scores allocated by the contributors to tool groups with high or moderate confidence were only considered further in the analysis. Due to blanks in the matrix, the number of responses contributing to the average varied according to the tool-by-element pair. The number of responses considered in the average calculation was recorded, together with estimates of the standard deviation (SD) and range (minimum and maximum) of the scores across participants. The minimum and maximum number of entries per tool were also recorded.

A Group average algorithm cluster analysis, based on Euclidean distance, was applied to the matrix data (average of scores across contributors) to identify groupings of (i) elements of EBM based on the similarity of tools used, and (ii) the tool abilities to deliver the specific element of EBM, i.e. Q and R-mode analyses (respectively analyzing attributes by cases and vice versa, Southwood and Henderson (2000)). A SIMPROF test was applied to identify clusters of elements that do not significantly (P>0.05) differentiate based on the tools used to deliver them. 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* categorization based on the EBM process phases (PACE) was also considered as a means to interpret the data-based clusters. The analyses were undertaken in PRIMER v6 (Clarke and Gorley, 2006).

6.2 Assessment results

On average, there were 11 entries per methodological tool group across all contributors, ranging from 7 (Knowledge Graphs) to 15 (Overarching Assessment Tools). The mean scores attributed to the tool groups according to their ability to deliver on the specific elements of EBM are shown in Table 4. The EBM elements (columns) and tool groups (rows) in Table 4 are grouped with separators according to the results of the cluster analysis undertaken between EBM elements (Figure 1 shows 5 groups differentiated at Euclidean distance 5) and tool groups (Figure 2 shows 5 groups differentiated at Euclidean distance 5). The cells in Table 4 are colored to reflect the variability of the mean score of tool groups within each column (the lowest score in the column is white, highest score in the column is dark blue).

All tool groups are noted in italics and all EBM elements are in bold in the following sections. *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) together 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. *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 4.7 (Table 4). This tool group 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; #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), together with

TABLE 4 Mean scores assigned to each tool group (rows) based on their ability to deliver on a specific element of Ecosystem-Based Management (EBM) (columns).

Main group		EBM elements																	
Tool No.	Tool Group	4 ES (delivery, impacts, valuation)	9 Links activities pressures impacts	15 Spatial and other measures	3 Whole ecosystem assessments	2 GES MSFD assessments	10 Single MSFD Descriptors/ single issues	13 Climate change	14 Pressure and impact reduction/ mitigation	15 Other Policy Requirements	5 Specific biotic effects	6 Specific functions	16 Uncertainty	11 Single species, State change	12 Threatened habitats and species	17 Risks	1 Cumulative assessments	7 Pressures-Activities footprint	8 Impacts footprints
13	Natural capital accounting, ES valuation	4.7	0.7	1.3	0.8	0.0	0.3	0.8	1.3	1.8	1.2	2.7	1.5	0.5	1.0	1.2	0.3	1.0	1.0
14	Bioecon., socioec. models, SG&B valuation	5.0	1.5	0.0	1.5	0.0	0.0	0.5	0.5	1.5	0.5	0.5	0.0	0.0	0.0	0.5	2.0	0.5	1.5
9	Biogeochemical models	0.3	0.0	0.7	1.3	0.7	1.3	2.0	1.0	1.0	1.0	0.7	1.5	1.3	1.0	0.5	0.3	0.0	0.0
17	Simple assessment index	0.8	1.2	1.4	1.3	3.0	2.5	0.7	1.6	2.4	3.1	2.2	1.3	1.9	2.4	0.9	1.1	0.8	1.0
8	Single spp. models	0.6	1.0	1.9	0.9	1.3	2.0	1.7	1.3	1.6	2.6	1.4	2.1	3.3	2.4	1.7	0.1	0.9	0.5
12	SDM models	1.7	1.2	2.1	1.2	2.0	1.9	2.4	1.3	2.0	2.5	1.7	1.9	2.8	3.2	1.8	1.8	1.1	1.2

(Continued)

TABLE 4 Continued

	Main group	EBM elements																	
Tool No.	Tool Group	4 ES (delivery, impacts, valuation)	9 Links activities pressures impacts	15 Spatial and other measures	3 Whole ecosystem assessments	2 GES MSFD assessments	10 Single MSFD Descriptors/ single issues	13 Climate change	14 Pressure and impact reduction/ mitigation	15 Other Policy Requirements	5 Specific biotic effects	6 Specific functions	16 Uncertainty	11 Single species, State change	12 Threatened habitats and species	17 Risks	1 Cumulative assessments	7 Pressures-Activities footprint	8 Impacts footprints
6	Cumulative impact spatial mapping	1.7	3.1	2.6	2.7	2.6	2.3	1.9	2.1	2.6	1.7	1.8	1.5	0.9	1.9	2.5	4.7	4.0	3.8
15	Spatial planning models	1.7	2.7	4.3	1.3	1.5	1.4	1.2	1.9	2.5	1.7	1.2	1.5	1.0	1.5	2.1	2.8	2.9	2.5
16	Conservation planning models	0.8	1.9	4.6	0.8	0.7	0.7	1.6	2.3	3.1	0.9	0.8	2.0	1.0	2.7	1.6	1.8	2.2	1.8
18	Descriptor or theme-specific combination of indices & models	1.9	2.6	2.6	3.3	4.8	4.8	1.7	2.1	2.9	2.3	2.5	3.1	2.5	2.6	1.4	2.4	1.5	1.6
19	Overarching assessment tools	1.5	2.5	3.7	4.5	4.5	3.3	1.9	2.5	3.0	1.5	1.4	4.0	2.9	3.1	0.7	2.7	2.7	2.8
7	Impact risk - linkage-chain-frameworks	2.0	4.8	1.3	3.2	1.9	2.8	1.6	3.3	2.8	2.3	3.0	1.6	2.2	1.7	3.9	4.1	3.1	2.9
4	BBN probabilistic	2.4	4.6	1.6	2.6	1.9	3.0	2.9	3.2	2.6	3.0	3.2	3.8	2.7	3.3	3.6	3.4	1.8	2.0
5	Risk based approaches	2.4	4.5	1.9	2.3	2.1	3.5	2.7	4.3	3.8	3.3	3.0	2.6	2.5	2.8	4.7	3.8	1.9	1.9
3	Knowledge Graphs	1.2	4.6	1.0	1.4	1.2	2.6	3.4	3.0	2.8	1.8	1.6	0.8	1.0	2.6	1.2	1.4	1.0	1.0
1	Conceptual models	2.6	4.2	2.0	2.5	2.0	2.6	2.9	2.8	2.1	2.7	3.0	1.8	2.2	2.4	1.9	2.6	2.6	2.3
2	Semi-quantitative mental models	2.0	3.5	1.4	2.1	1.4	2.6	2.6	2.5	2.1	2.0	2.0	1.3	2.0	2.3	1.9	2.3	1.7	1.6
10	Food web models	1.7	2.0	2.5	3.0	2.3	3.0	2.6	2.7	1.9	3.6	4.0	2.6	3.1	2.6	1.8	2.1	1.3	2.0
11	Ecosystem models	2.1	2.4	2.0	3.5	2.0	2.4	2.3	2.0	2.1	2.5	3.3	1.7	2.4	2.4	1.8	2.3	1.0	1.1
	ProcessPhase	PA	PA	PA	CE	CE	PA	Gen	PA	Gen	CE	PA	Gen	CE	CE	Gen	PA/CE	PA	PA

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 1) and tools (Figure 2), 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 (P, Plan; A, Act; C, Check; E, Evaluate; Gen, General relevance). Cells in the table are colored in a monochrome gradient to reflect the 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.

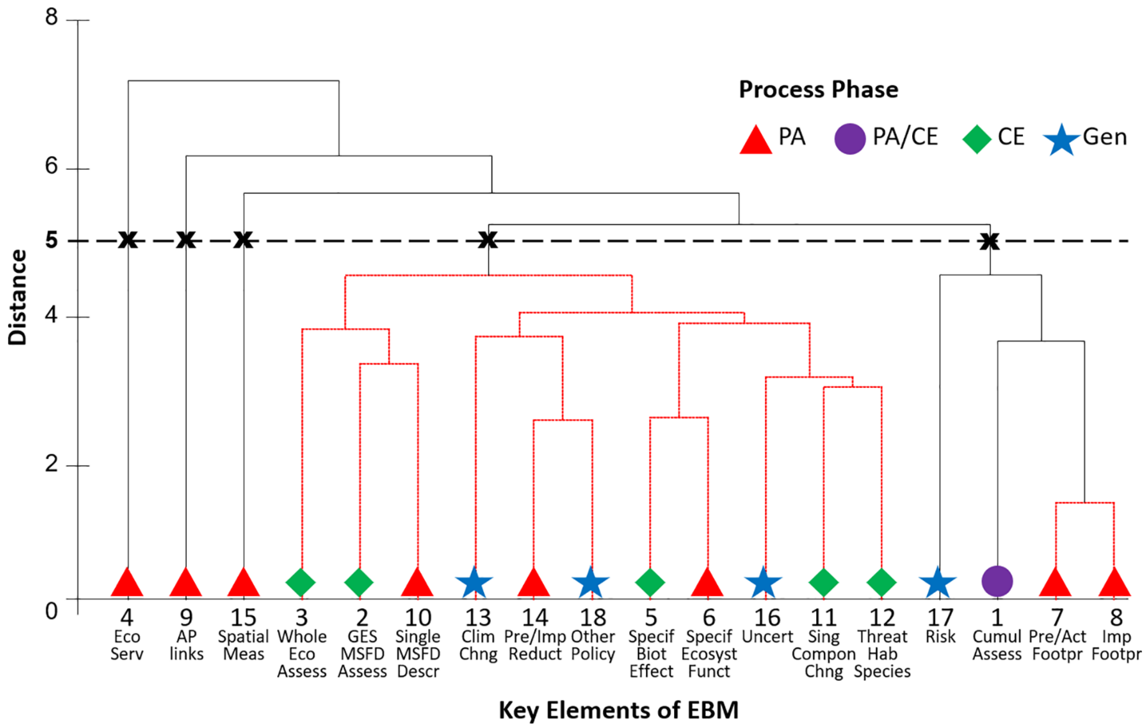

FIGURE 1
Cluster analysis of the elements of Ecosystem-Based Management (EBM) based on similarity of tools used and their ability to deliver the specific element of EBM (mean of scores with high or medium confidence). See Table 2 for full name and reference number of the EBM elements. Symbols indicate EBM process phases: P, Plan; A, Act; C, Check; E, Evaluate; Gen, General relevance. Group average algorithm was applied for the cluster analysis, based on Euclidean distance. Elements connected by red lines do not significantly differentiate based on the tools used to deliver them (SIMPROF test, P>0.05). Bold crosses identify the cluster groups differentiated at Euclidean Distance of 5 (black dotted line), as reported in Table 4).

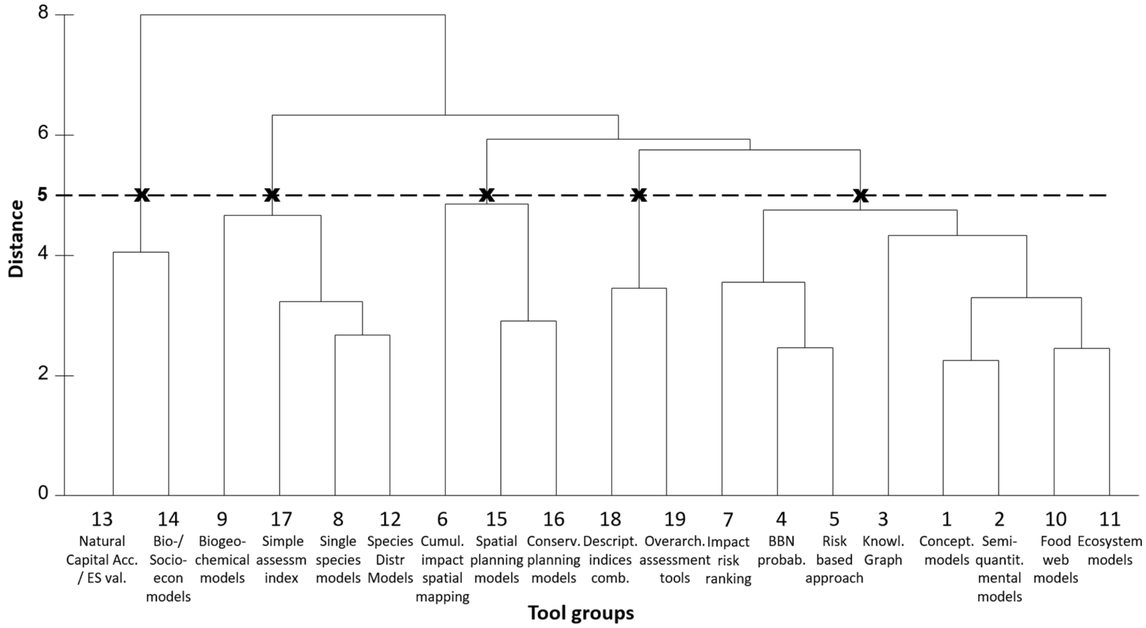

FIGURE 2
Cluster analysis of the tool groups based on similarity in the Ecosystem-Based Management (EBM) elements they can deliver (mean of scores with high or medium confidence). See Table 3 for full name and reference number of the tool groups. Group average algorithm was applied for the cluster analysis, based on Euclidean distance. Bold crosses identify the cluster groups differentiated at Euclidean Distance of 5 (black dotted line), as reported in Table 4).

Ecosystem end-to-end models (#11), and for **Uncertainty assessments** (score 4.0), along with *BBN probabilistic methods* (score 3.8) (Table 5).

Spatial-based tools were best suited to deliver elements at the Planning phase of the EBM process. *Cumulative impact spatial mapping* (#6) was identified as the best option to undertake **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* (#15 and #16, respectively) were the most suitable option to deliver on **Spatial and other measures**.

Food web models (#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) scored moderately 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 in the mid-range (score 3.3). *SDM models* (#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

TABLE 5 Three top-scoring tool groups for each Ecosystem-Based Management (EBM) element.

EBM element	First place	Second place	Third place
Cumulative assessments	Cumulative impact spatial mapping (e.g., Halpern et al.) [4.7]	Impact risk ranking through linkage-chain-frameworks (e.g., ODEMM) [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]	SDM models[3.2]	Overarching assessment tools (e.g., NEAT and OHI) [3.1]
Climate change	Knowledge graph [3.4]		
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, Biodiversity 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]

Only tools with average score ≥4 are included, where present. 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. MSFD, Marine Strategy Framework Directive; GES, Good Environmental Status.

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)** (including societal goods and benefits) 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 4). 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.

The three top-scoring tool groups for each EBM element are summarized in Table 5. When tools with an average score ≥4 are considered, 12 tools are selected, but these only deliver 12 of the 18 EBM elements, as some EBM elements have only tools scoring lower than 4 (e.g., Specific biotic effects/impacts; Table 4). 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, Table 5 includes 15 out of the 19 tool groups analyzed. *Conceptual models*, *semi-quantitative mental models*, *biogeochemical models* and *ecosystem models* are not included as they did not fulfil the selection criteria.

6.3 Selecting tools for the EBM approaches

Each of the tools have different advantages and disadvantages but, as shown above, they also have different abilities to fully or partially deliver one or multiple EBM elements. *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 of 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).

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). Both the NEAT and OHI 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. Similarly, 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 *SDM models*). *Overarching assessment tools* also deliver well on **Uncertainty** and may be used to support **Other policy requirements** (together with *Conservation planning models*). These tools are sufficiently specific to support the strict requirements of the MSFD but also, in 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 appear to poorly deliver on other EBM elements, both being among the lowest ranking tools for **Risks** and **Climate change**.

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 (for *Natural capital accounting*) or equal to the maximum of 5 (for *Bio/Socio-economic models*). However, due to their very specific nature, 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, Single species/ecosystem components state change, Threatened habitats and species, Spatial and other measures**, and **Uncertainty** (*Bio/Socio-economic models*).

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.

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. 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., advising on the 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 ≤4). It also appears to be always within the top ten ranking tools for any of the other EBM elements. Furthermore, *Knowledge graphs* appear to be the best tool to account for **Climate change** (albeit with an average score ≤4 and most likely done in a qualitative way. This tool is also within the top 3 ranking (with score ≥4) in the delivery of **Links activities-pressures-impact**, together with *BBN probabilistic tools* and *impact risk ranking through linkage-chain-frameworks*.

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 tool cannot fully deliver all aspects of this element of EBM (scoring close to 3).

7 Discussion

The analysis here has shown that EBM is either explicit or implicit in all major policies for sustainable marine management. It is commonly regarded to be based on a set of accepted principles, presented here, and as shown here, it has been adopted widely by national, European, regional and global initiatives. Because of this, it requires tools and approaches for that adoption but is has become apparent that (i) EBM principles need to be disaggregated to all important associated EBM elements (e.g. example in S1) to be able to address them fully and correctly match them to necessary tools and methods, and (ii) not all tools are suitable for fulfilling all of those principles and thus the user needs guidance in choosing the most suitable tools – hence 'horses for courses'.

Marine EBM is essentially a risk-based process based on an understanding of natural and anthropogenic hazards, 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 essence, hazards occur in the environment (for example, by natural features such as tsunamis, and anthropogenic hazards such as contaminant inputs) and these become risks once they affect human health and welfare (Cormier et al., 2019). Hence, marine management and especially EBM is centered around cause-consequence-response frameworks (see above) relating to the human activities, their pressures, risks and effects on the natural and human systems and the management responses to prevent or mitigate those adverse consequences (e.g. CSWD, 2020; Elliott et al., 2017; Stelzenmüller et al., 2020). 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 (Borja et al., 2024). Key EBM elements in all these frameworks focus on ecosystem health and so identify: (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. The analysis here shows that two key tool group categories fit this purpose: Overarching assessment tools (for GES assessments through structured ecosystem component changes assessments) and Cumulative impact spatial mapping (Halpern et al., 2008: EcoImpactMapper). Improvements can be made to these tools to further their use, for example to the Halpern et al. (2008) approach, to provide a hierarchical (*vs.* flat) structure, values for ecosystem components (*vs.* only presence/absence), and proper (*vs.* no) weighting by importance or spatial distribution of ecosystem components) (see Borja et al., 2024).

The risk-based tools (e.g. Knights et al., 2015; Piet et al., 2021, 2023) using spatial overlap and sensitivity estimates specifically intended to guide EBM), can also be used more widely in assessments, where their outcomes can be compared with those of more quantitative tools (or perhaps alternatively in data-poor cases). They can also partly inform on spatial and other measures and be integrated into science and advice frameworks (Roux and Pedreschi, 2024). However highly specialized tools such as MARXAN, ZONATION, VAPEM (see Supplementary Materials S3 for skills/software links/references) may be needed to support decision-making (for placing and zoning activities including conservation) and maritime spatial planning (see, for example, applications by Maldonado et al., 2022; Doxa et al., 2022; Fabbrizzi et al., 2023). Beyond highly specialized tools for the valuation of natural capital and ecosystem services, only food web models can address the delivery of ecosystem services and some production-related societal goods and benefits (e.g. Elliott, 2023).

Despite the continued debate and semantics regarding the EBM terms used (Kirkfeldt, 2019), the analysis here has strongly confirmed that EBM is the central pillar of the understanding, interrogation and management of the marine environment. Hence, 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). As such, it is notable that the analysis here is the first in which the 26 EBM principles have been reworded as instructions and 16 of them have been assessed in relation to tools for their partial or full delivery (Table 2). Despite this, while Link and Haugen (2025) recently carried out a valuable assessment to quantify the monetary repercussions of using EBM compared to a Business-As-Usual (BAU) scenario, we contend that so many bodies and instruments are using EBM that it should be regarded as BAU. However, importantly, this work reinforces the point here that EBM is good for both the ecosystem structure, functioning and services, as well as delivering societal goods and benefits.

The EBM approaches have often been related to individual components, habitats, species, activities or sectors, but it is emphasized 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, while the FAO emphasized 'the ecosystem-based approach to fisheries management', this is only for one sector and its management is usually to the benefit of this sector and to the exclusion of other sectors (Dickey-Collas et al., 2022), thereby a misnomer not constituting EBM as defined here and elsewhere. Similarly, it is cautioned that if EBM is only considered in relation to HABs, NIS, top predators or any other individual component, no matter how important, then this would not constitute a true EBM

(Borja et al., 2024) as EBM is/should be a systematic holistic approach and the alternative to piecemeal and sectoral management (Sander, 2023).

When applied to disparate areas, EBM and its tools would have the major challenge in having to cope with different types of information, both qualitative and quantitative (Haugen et al., 2024). It also must be suitable for skills- and data-poor areas as well as skills- and data-rich areas (S3). The analysis here has shown that the priorities of scientists may differ from the priorities of managers as the two 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 rationale 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 (Elliott et al., 2020b) and then enacting and integrating the horizontal and vertical management response-footprints (Cormier et al., 2022); a true EBM approach should encompass all of these aspects. The tool groups interrogated here show the importance of conceptual models as a starting point and frameworks, especially for cause-consequence-response links, such as DPSIR and its variants (see above). Among these, the most recent and increasingly widely-used variant, DAPSI(W)R(M) overcomes the difficulties in other and earlier variants (Patrício et al., 2016; Elliott et al., 2017).

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 (Cormier et al., 2022), 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 study, the EBM principles (Table 1) were matched to assessment core objectives (e.g., quality status 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 EU Member State MSFD assessments (Borja et al., 2024).

The novel application used here of R and Q mode multivariate analyses, applied to the data elicited by expert judgement regarding the cases (experts) and attributes of the tools, has respectively grouped the most appropriate tools for EBM and the most relevant EBM principles for the tools. In summary, the analysis indicated five groups of tools according to the elements to which they relate (Figure 2): (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.

Given that EBM is essentially a risk and opportunity assessment and management process, this grouping is not surprising. However, the analysis could indicate a circular argument in that the overarching assessment tools (e.g. NEAT) are best at delivering an overall GES assessment. Similarly, descriptor and theme-based tools (e.g. HEAT) are good for descriptor and single issues whereas other types of assessment tools (such as single species or simple biotic indices) are appropriate for other assessments (Borja et al., 2016). Assessment, and its monitoring, are not management measures *per se*, but they are necessary to indicate what management is needed and/or whether management has been successful (Borja and Elliott, 2021; Elliott and Wither, 2024). 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 of 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 DAPSI(W)R(M) cycle (and Management and Measures part of the DAPSES-MMM framework) require additional approaches. 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, thereby completing the EBM cycle (Borja et al., 2024). EBM should be then at the forefront of approaches that could address the current nature crisis (Sander, 2023).

It is emphasized throughout this review that EBM should not only gather appropriate information covering both the natural and human realms but that it has to accommodate both the changes to the system and the effects and repercussions of management measures. This implies that the management actions can be revisited by the environmental managers (often the so-called 'competent authorities' such as an Environmental Protection Agency) at prescribed intervals. Those intervals may occur whenever there are notable changes to external events, ecosystem local and global (e.g. climate change) characteristics, and levels of activities and pressures. Conversely, they may follow the monitoring and reporting cycle stipulated in the legislation, for example the 6-year cycle in the case of the MSFD. It is of note, for example, that the MSFD requires that its indicators, targets and thresholds can be adapted/modified at each reporting cycle to adjust for the so-called shifting baselines caused by climate change (Elliott et al., 2015).

Given that many of the EBM principles relate to natural and anthropogenic changes in the marine system under management (e.g. EBM principle 7, account for dynamic nature of ecosystems) then it is imperative that any tool used should be sufficiently flexible to those changes and repeated easily with the input parameters being changed/modified. This argues for not only having one tool used flexibly but also for having a suite of tools (a toolbox) which can be used to accommodate changing conditions. For example, this response to changing circumstances should include feedback loops indicating new or revised management actions, hence the central and important feature that EBM has to be related to an adequate monitoring system in which the monitoring not only indicates what management is required but also whether that management has succeeded in its aims.

8 Conclusions and recommendations

The analysis here has shown that a given complement of tools, i.e., a toolbox, is needed to satisfy the many principles of EBM. EBM principles encompass high level concepts with many different or complementary aspects and deconstructing the principles to essential relevant EBM elements is vital for clarity and to be able to address them fully. No single tool is likely to satisfy all aspects of EBM and especially there is the need to ensure that the EBM can adapt to changing circumstances. 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 anchored in all essential principles and elements, policy and governance through a risk and opportunity assessment and management framework.
ii. The conceptual model should include the capability to create links (again conceptual or preferably 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 both covers the components and features of the ecosystem, such as the MSFD descriptors, both singly and in total, including the species and habitat components and their interlinkages, and which allows an adaptive capacity in management as marine conditions change.

Developing such an EBM toolbox and applying these tools requires appropriate and fit-for-purpose data and expertise (see Supplementary Material S3) and thus EBM processes should plan for the required resources in order to advance EBM implementation. Hence, it is emphasized that for wide use globally then the tools should be suitable for skills- and data-poor areas as well as skills- and data-rich ones.

For most EBM principles (even for some of the omitted ones, as we show above) there are suitable tools to address their essential elements, but data gaps remain and impede comprehensive full-scale assessments. For example, while natural capital valuation tools are available, not many valuation studies or data are available for deep sea habitats (Jobstvogt et al., 2014). Similarly, there are tools available for trade-off analysis to allow EBM principle 11 decisions respect societal choices e.g. on planning priorities in national marine spatial plans but again valuations or willingness-to-pay studies are few and focusing on a small range of issues (e.g. Addamo et al., 2024).

The framework presented here, could be applicable to any marine system, from estuaries, to coastal and offshore waters, as well as to shallow and deep-sea areas. While it is intended to serve as basis to be used under European marine directives (e.g. MSFD, MSPD), it is emphasized that the fundamental aspects are global and applicable anywhere, in taking management decisions and measures for achieving a healthy ocean.

Author contributions

NP: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. CS: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. AF: Conceptualization, Formal Analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. ME: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. AB: Investigation, Writing – original draft, Writing – review & editing. JHA: Investigation, Writing – original draft, Writing – review & editing. EA: Investigation, Writing – original draft, Writing – review & editing. JPA: Investigation, Writing – original draft, Writing – review & editing. StB: Formal Analysis, Investigation, Writing – original draft, Writing – review & editing. TB: Investigation, Writing – original draft, Writing – review & editing. SiB: Writing – original draft, Writing – review & editing. DB: Investigation, Writing – original draft, Writing – review & editing. JC: Writing – review & editing, Writing – original draft. RC: Writing – original draft, Writing – review & editing. IG: Investigation, Writing – original draft, Writing – review & editing. AJ: Writing – review & editing, Writing – original draft. StK: Investigation, Writing – original draft, Writing – review & editing. SaK: Writing – original draft, Writing – review & editing. LL: Writing – review & editing. CLo: Writing – review & editing, Writing – original draft. CLy: Writing – original draft, Writing – review & editing. IM: Investigation, Writing – original draft, Writing – review & editing. CO: Investigation, Writing – review & editing. DP: Investigation, Writing – original draft, Writing – review & editing. GP: Investigation, Writing – original draft, Writing – review & editing. DR: Investigation, Writing – review & editing. IS-A: Writing – review & editing, Writing – original draft. VS: Investigation, Writing – original draft, Writing – review & editing. JT: Writing – review & editing, Writing – original draft. LU: Writing – review & editing, Writing – original draft. MU: Investigation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors AF, ME, EA, JHA, StB, DB, are employed by IECS Ltd, TB by MariLim Aquatic Research GmbH and SiB by Environmental Resources Management Ltd.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1426971/full#supplementary-material

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