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How can an ecosystem approach support integrated management of marine renewable energy? An initial assessment from an environmental point of view

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ABSTRACT

With the increasing installation of marine renewable energy (MRE) devices in areas already subject to multiple anthropogenic activities and environmental changes, it is necessary to develop tools and methods for the integrated management of marine ecosystems. The ecosystem approach is a holistic environmental management method that considers all components of an ecosystem. The ecosystem approach has demonstrated utility in the application to various anthropogenic activities and is relevant for consideration within the context of MRE. Indeed, many of the effects observed on marine ecosystems from those other activities are also applicable to MRE development. This review is an initial assessment where we summarize the potential effects of MRE development on marine ecosystems and propose schematic frameworks for applying the ecosystem approach to MRE. We also provide a non-exhaustive list of commonly used models pertinent to the ecosystem approach and associated with several reference studies. An outline of core questions that can currently be answered using available modeling tools central to the ecosystem approach is provided, along with recommendations for the application of this approach to the MRE context. Further, we identify key knowledge gaps and areas that require additional investigation for meaningful application of the ecosystem approach to MRE development. Our recommendations mainly concern the current limitations of applying the ecosystem approach to concrete cases, such as consolidating knowledge of the effects of MRE on the local environment, the need to obtain fine-scale data, considering effects at different spatiotemporal scales, and, finally, the need for an interdisciplinary vision.

1. Introduction

Human population growth is projected to reach 10 billion by 2050 [1] and with it comes elevated demands for energy. With the large surface area covered by the world's oceans, the development of marine renewable energy (MRE) is becoming increasingly important to meet this demand along with the ambitious challenges of sustainable development. MRE is derived from five sources: (1) tidal stream energy conversion (TEC; generated by tides), (2) ocean currents (generated by water volume displacement from large ocean currents), (3) wave energy

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conversion (WEC; produced by the movement of the water surface), (4) ocean thermal energy conversion (OTEC; resulting from the thermal difference between surface and deep waters), and (5) salinity gradient (produced by the difference in salt concentration in estuaries). Offshore wind is excluded from MRE because the source of power is atmospheric, not oceanic. MRE sources require technologies that will interact with marine ecosystems [2]; the nature and magnitude of these effects depend on the attributes of the MRE devices used and the spatial scale of development, as well as the environment in which they are deployed [3].

The international community studying the environmental effects of MRE has recognized seven main interactions of concern that often need to be addressed in environmental impact assessments and monitored at an MRE project site following dedicated survey plans [4–6]((Table 1):

- The risk of collision between marine animals and moving parts of turbines (e.g., rotating blades), potentially leading to injury or death, is the greatest interaction of concern for tidal and ocean current turbines.
- Underwater noise emitted by all MRE technologies during construction, operation, and decommissioning may lead to effects on marine animals' health and behavior.
- All MRE technologies with power export cables and other energized components in the water may emit electromagnetic fields (EMFs) and trigger effects on sensitive species, especially those that may use EMFs for navigation or prey detection.
- MRE devices may cause changes in benthic and pelagic habitats because of the presence of artificial structures in the water.
- Large arrays of MRE devices, especially wave, tidal, and ocean current energy, may lead to changes in oceanographic systems due to the operation of the devices and removal of energy from the system.
- Mooring lines and draped cables of floating MRE devices (e.g., wave, tidal, ocean current, OTEC) may present a risk of animal entanglement, with consequences such as injury or death.
- Large-scale arrays of MRE devices may lead to displacement of marine animals in the form of attraction to, avoidance of, or exclusion from the project area, with consequences from the individual to the population level.

Beyond the direct effects on marine species, habitats, and ecosystem processes, there is the possibility of indirect effects that can have broader implications. For example, environmental effects such as the attraction of biofouling assemblages, or beach replenishment or erosion from dampened wave action, may affect entire food webs and ecosystems in ways not yet anticipated, and are potentially greater at the scale of large commercial arrays [7].

The ecosystem approach (EA) is defined by the Convention on Biological Diversity (CBD) as “a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way” (https://www.cbd.int/ecosystem/description.shtml). Indeed, undertaking a science-based integrated ecosystem approach is a pre-requisite for a successful management of human activities [8]. The EA is based on a holistic vision of ecosystem functioning, intended to consider processes over a range of spatiotemporal scales. EA is particularly well-suited to the sustainable management of coastal areas, as it makes possible the anticipation of all direct and indirect effects of one or more pressures on the environment. The EA may enable stakeholders (especially policy makers, regulators, project opponents, holders of rights to the area covered and project proponents) to comprehensively assess various options available for sustainable development of technologies, including environmental effects, and to anticipate associated ecosystem-level consequences that would require consideration [9]. Guidance about the application of the EA is outlined in 12 principles provided by the CBD in 2000 (https://www.cbd.int/ecosystem/principles.shtml) that aim to fulfill three objectives: (1) conservation of ecosystems, (2) sustainable uses of ecosystems, and (3) equitable sharing of resources [10]. This review focuses on ecological environmental issues, corresponding to principles 5 (conservation of ecosystem structure and functioning), 7 (appropriate spatial and temporal scales), 8 (objectives should be set for the long term), 9 (recognize that change is inevitable), 10 (appropriate balance between conservation and use of biodiversity) and 11 (consider all forms of relevant information).

Ecosystem models are among the main tools of the EA and are used to represent the inherent complexity of ecosystem functions and fluxes, including consideration of interspecific interactions and defining indicators. Ultimately, the models contribute to the implementation of management plans developed in partnership with decision-makers [11], including a broader context of multiple-use management with potential for cumulative environmental effects [12]. Systematic approaches are important because the marine environment is dynamic and subject to multiple global pressures (e.g., climate change, diffuse and point-source pollution, multi-decadal atmospheric forcings, etc.). Integrated approaches combine qualitative and quantitative data and provide relevance to the causal linkages between complex ecological and socioeconomic processes that underpin the relationship between societies and ecosystems.

While the EA has been successfully applied to the context of offshore wind development in recent years, implementations in the MRE context remain scarce, if any. Leveraging experience from other sectors, the main objective of this study is to identify the challenges of implementing an EA in the MRE context by reviewing existing studies on MRE, and other relevant industries, whose methodology could be integrated in an ecosystem approach.

2. Methods

A combined approach of online working group discussions (hereafter “workshops”), literature review, and subject matter expert feedback was employed to assess the current state of knowledge on applying the EA to

Table 1
Pressures exerted by each of the five marine renewable energy (MRE) types on marine species, habitats and ecosystem processes. The question marks refer to a suspected but currently undocumented effect.

	Pressures \ MRE	Tidal stream	Wave energy	Ocean Current	Thermal conversion	Salinity gradient
Behavior	Collision	x		x		
	Noise	x	x	x	x	x
	EMF	x	x	x	x	x
	Entanglement	x	x	x	x	
	Avoidance/Displacement	x	x	x	?	?
Habitat	Reef effect	x	x	x	x	x
	Attraction/Aggregation	x	x	x	?	?
	Reserve effect	x	x	x	x	x
Oceanographic systems	Water circulation	x	x	x	?	?
	Sediment transport	x	x	x		
	Plume discharge				x	

MRE development. A series of five virtual workshops was conducted with international representatives from Ocean Energy Systems-Environmental (OES-Environmental) between August 2021 and August 2022. OES-Environmental is an International Energy Agency initiative that brings together experts in environmental effects of MRE from the 16 participating nations to advance the knowledge on the topic (https://tethys.pnnl.gov/about-oes-environmental). The OES-Environmental representatives participating in the workshops were all marine ecologists with a deep knowledge of environmental effects of MRE, but not necessarily expertise in the EA. The workshops consisted of a discussion of the various issues associated with MREs that the EA can help address, and the limits and uncertainties it may face. The workshops were complemented by an in-depth literature review. The literature review was conducted mainly via the Tethys platform, which is a knowledge base on the environmental effects of MRE and offshore wind, by filtering the research to obtain only journal articles dealing with MRE technologies. The stressors and receptors were then cross-referenced to retrieve all the papers associated with each stressor-receptor pair. Only articles highlighting a study that could be used as part of an EA were saved for this review. The review was completed with articles describing the application of the EA in other contexts, like offshore wind or fisheries. Once potential applications of the EA to MRE were drafted (see Section 4), EA experts who have applied the approach to the offshore wind or fisheries contexts, were consulted to gather their feedback on the proposed conceptual frameworks.

The combined approach (i.e., workshops, literature review, expert feedback) had three objectives.

The first objective was to review the numerical tools frequently used in marine EA implementations (whether in MRE, offshore wind or other sectors, such as fisheries), and identify the specific questions these tools can address. The review highlighted whether the tools were simply proposed (i.e., the product of an academic exercise but has yet to be applied) or were already in use, and if so whether it was in an MRE context, for an offshore wind farm (OWF), or for another sector such as fisheries, marine protected areas, or climate change.

The second objective was to assess the applicability of the EA to the MRE context; in particular to identify various uses related to the known environmental effects of MRE. Knowledge from other fields (mainly OWF) was used where relevant. For the purpose of the exercise, any ecological change was considered as *effect* on the ecosystem, caused by *stressors* (i.e., the factors associated with the exploration, construction, operation, or decommissioning of an MRE device). If these effects are of sufficient intensity, duration, and/or severity to cause significant changes to *receptors* (i.e., marine animals, habitats, or ecosystem processes), then they are termed *impacts* [13,14].

The third objective of the combined approach was to identify knowledge gaps and prioritize future research needs to support the development of MREs. Given that the EA applied to MRE is in its infancy (the sector is itself just developing), this paper presents a launch point for addressing these gaps, by providing a synthesis of available methods that could be employed and reviewing how to address the main issues raised during the installation and operation of MRE devices.

The subsequent work presented here is an in-depth study, confronted and discussed in the workshops and feedback chats with developers and users of the EA who are familiar with MREs.

3. Commonly used numerical tools in the marine ecosystem approach

Managing marine ecosystems requires both a qualitative and quantitative understanding of community structure, species composition, and ecological functions [15]. This can be achieved through observations, measurements, modeling, or (more commonly) a combination of all three. Operational and strategic planning increasingly relies on quantitative models, driving the societal goal of predicting the responses of the ocean to perturbations [16]. The observations can be integrated into ecosystem model to improve the understanding of ecosystem function [17].

3.1. Qualitative models

Qualitative models study the complexity of phenomena leading to ecosystem impacts without necessarily quantifying them. These approaches are particularly useful when scientific evidence is unavailable or conflicting, or for quickly gaining a conceptual understanding of MRE impacts on ecosystems. Qualitative models are a widely accepted type of ecosystem models, used in many contexts, including OWF development [18], but not yet in the context of MRE.

A qualitative mathematical model is based on a qualitative representation of the relationships between system variables. It is represented by a signed directed graph or signed digraph [19] that describes the neutral, positive, or negative direct effects (0, +, −) of variables in a system [20]. Qualitative assessments of model stability involve the analysis of all feedback cycles in the system and are examined by applying two Routh-Hurwitz criteria [21]: (1) the system is dominated by negative feedback at all levels of the system, and (2) feedback at lower levels in the system is stronger than feedback at higher levels. These models can also be analyzed to predict the likely direction of change that a population variable can have in response to a perturbation to the system and how that pressure flows through the system. Finally, where system feedback creates uncertainty about potential responses, sensitivity analysis allows for identification of the variables most likely to be affected by a change.

The variables included in these models can be natural or anthropogenic. One of the main issues with these models is the need to maintain a balance between the social and ecological components, with comparable numbers and quality of variables in the two constitutive subsystems [18,22,23]. Used in this way, qualitative mathematical models are helpful tools for rapidly conceptualizing ecosystem structure, and accounting for ecosystem components and processes that are difficult to quantify [24]. The speed of application also makes the method attractive, because model development can be completed on the order of hours and subsequent analysis completed in days. All of this makes qualitative mathematical modeling a powerful tool for projecting and analyzing different management options for MRE during the planning phase and for investigating the direct and indirect effects of multiple anthropogenic pressures on a system [18], as demonstrated below in Section 4.

3.2. Numerical models

Numerical ecosystem models are employed to characterize ecosystems and their complexity, considering interspecific interactions. They help define indicators, and support decision-makers in implementing effective management plans. To date, very few numerical ecosystem models have been applied to the MRE context [25], but there are relevant examples for OWFs [26], management of coastal systems [12], fisheries [27], climate change [28], and coupled effects of both climate change and fisheries [29,30]. These modeling approaches have most typically been applied to gain ecosystem understanding, or to support management of marine ecosystems and food webs to ensure their long-term sustainability, in the larger context of multiple-use management. Thus, ecosystem models can be used to address a wide range of questions and scenarios.

The system scale and quantitative form of these models mean they can be data intensive. A number of these different numerical modeling approaches could be applied to the MRE context (Table 2):

- *Minimum Realistic Models* are restricted to ecosystem components with significant interactions with the species or activities under study.

Table 2
Numerical ecosystem models broadly used in marine systems that can be applied to assess issues regularly raised in the marine renewable energy (MRE) context. The list of models and the associated references are not exhaustive.

Model	Type	Main Refs.	Main Applications	Advantages and Caveats
MICE: Model of Intermediate Complexity of Ecosystems	Minimum Realistic	[27,31]	Fisheries River management	Low data requirements (due to focused scope), however does require time series to be available for the key species or activities at the year of the model).
Bayesian models	Minimum Realistic	[32–34]	Generating technology Fisheries Conservation Wind energy	Gather information from disparate sources. The structure can be straightforwardly generated for qualitative mathematical models.
Mizer	Size-based	[35–37]	Fisheries Cumulative impacts Climate change	Low data requirements (though data needs are likely to increase when applied spatially).
Osmose	Size-structured individual-based	[30, 38–43]	Fisheries Ecosystem indicators Marine protected areas Climate change	Output indicators are spatially, temporally, size, age and species resolved. Detailed only for fish and cephalopods.
EwE: Ecopath with Ecosim Ecospace	Trophic-based	[25,26, 44–48]	Fisheries Climate change Wind energy Platforms Coastal development	Easy to use and versatile.
LIM: Linear Inverse Model	Trophic-based	[49]	Plankton communities	Powerful to model changes in low trophic levels. Exploration of uncertainty. Not dynamic.
Atlantis	End-to-End	[50–54]	Fisheries Conservation Climate change Coastal development	Flexible approach including many biological processes (however it has high data and resource requirements).
Strath2E2	End-to-End	[55,56]	Fisheries Climate change	Integrative approach (would need modification to allow for representation of non-fishing activities).

- *Sized-Based Models* can explore anthropogenic effects on marine ecosystems by exploiting the role of size structure in marine ecological processes.
- *Trophic-Based Models* represent the food web in an ecosystem, from low trophic levels to top predators. Their design, based on the relationship between prey and predator, makes them one of the most widely used modeling approaches. Significant enhancements to the models have enabled the incorporation of more sophisticated representations of environmental dependencies and impact-response functions.
- *End-to-End Models* are a holistic representation of the ecosystem, integrating both biological compartments (low and high trophic levels) and physical processes, as well as anthropogenic aspects.

Numerical models offer a wide range of possible uses, and can therefore be applied to a large number of MRE-related issues, at every stage of the life cycle of an MRE project development. Models can be used to describe an initial state of the ecosystem, generate management scenarios, delimit the areas with the least impact, and assess the cumulative effects of MRE on the ecosystem structure and functioning. The large variety of models enables the study of issues at different spatial and temporal scales, looking at the ecosystem as a whole, or focusing on a particular species or components of interest.

3.3. Ecological indicators

The EA is best driven by the use of indicators to translate effects and changes in ecosystem structure and functioning into management measures. The choice of effective ecological indicators must consider both the degree to which the selected indicator is understandable to all stakeholders, and its capacity to reliably capture ecosystem properties and their responses to specific pressures [57]. No single indicator describes all aspects of ecosystem dynamics, and it is always preferable to use a suite of indicators covering different data, ecosystem components, and processes.

As ecological indicators measure the effects of a stressor on a group, they can therefore be used to make comparisons before and after the deployment of MRE devices, or after some time of operation. These indicators include presence/absence and/or density of schools of fishes around MRE devices [58], but also physiological indicators. For example, Furness et al. [59] identified a series of biological indicators to determine the vulnerability of diving seabirds (Vulnerability index), based on ecology and conservation, to TEC, considered to be the MRE with the greatest impact of collisions for diving seabirds. Behavioral indicators can also be used to assess the reactions of mobile organisms, such as fish, around structures [60].

There are several forms of ecological indicators, each highlighting different aspects of the ecosystem and identifying or responding to effects in different ways:

- *Species-based indicators* relate to species (or functional group) composition, biomass, production, or consumption ratios. These types of indicators are easy to interpret by stakeholders. Some species indicators, such as biomass, keystone, endemic or threatened species, are sensitive to different environmental stressors [57], and users need to be conscious of the specificity of the indicator to the activity of interest. In the case of MRE and as demonstrated by OWF applications, potential species-oriented indicators may be subject to the reef effect [22] or aggregating effect [61] of the artificial structures.
- *Size-based indicators*—such as the Large Fish Indicator [62] and the Typical Length [63] — correspond to changes in the structure of fish communities that could be induced, for example, by size-selective harvesting [38]. These indicators may be useful in the event of a

reserve effect induced by the ban or reduction of fishery activities within MRE arrays, leading to an increase in the size of targeted organisms, as may be the case in marine protected areas [61,64,65].

- *Functional indicators* relate to the functioning of the ecosystem and the food web and the role of species within the ecosystem. *Trophic level-based indicators* are at the frontier between structural and functional indicators. They both inform the role of species (or groups) through their trophic level, but also their relative influence based on their biomass. Nonetheless, trophic indicators could be pertinent in the MRE context, where species at different trophic levels are affected differently.
- *Ecological Network Analysis (ENA)* are purely functional indicators, designed to investigate interactions in the ecosystem to identify and characterize emergent properties, integrating complexities, dynamics, and natural variations of the ecosystem [66]. They allow for (1) the evaluation of the functioning of food webs; (2) the identification of important relationships between compartments, limiting resources, and keystone species; (3) the analysis of the main energy flows within the food web; and (4) the analysis of the effect of specific pressures on biomass distribution. Although more complex than structural indicators, and thus harder to interpret by stakeholders, they provide deep knowledge about the ecosystem and its properties, as well as the effects of ecological drivers [11,67].

4. Applicability of the ecosystem approach to the marine renewable energy context

The EA is recommended by the Convention on Biological Diversity and is increasingly used to address various issues, such as fisheries or climate change. In the context of MRE, this approach can address many questions often raised by stakeholders by providing a broader perspective on MRE and the ecosystem within which they are deployed. The discussion below is structured as a series of questions addressing the main ecological challenges related to the implementation of MRE. It leverages literature from offshore wind and other relevant sectors when applicable. The aim of this section is to highlight the potential effects of MRE on the components of the environment, as discussed by the workshop participants, and to point whether these effects have already been studied at local level, using examples from the literature. The aim is to demonstrate that these major issues could be studied following an EA, using the models listed above and methodologies that have already been published.

4.1. Can the ecosystem approach assess changes in behavior in megafauna?

Various interactions between stressors and receptors [5] may affect the behavior of marine organisms and can affect the way they interact with their environment. The main stressors that alter species behavior include underwater noise generated by a TEC, WEC, or ocean current turbine [68], as well as changes in naturally occurring EMFs from power generation and export through subsea cables [69], and animals' responses to a risk of collision with the moving parts of turbines [70]. The schematic representation (Fig. 1) of the changes in behavior caused by these three stressors illustrate how potential changes in several taxa—such as marine mammals, elasmobranchs or benthic invertebrates—can affect the rest of the ecosystem and associated functions. Although collision risk between marine animals and the moving parts of TECs or ocean current turbines is commonly perceived as the greatest risk of these two types of MRE [70,71], few cases of collisions have been recorded to date. This is due, in part, to the ability of marine animals to exhibit behaviors (avoidance and evasion) to prevent being struck by turbine blades [72–75]. In addition, collision risk models and laboratory experiments suggest that collision events are unlikely to be lethal to the

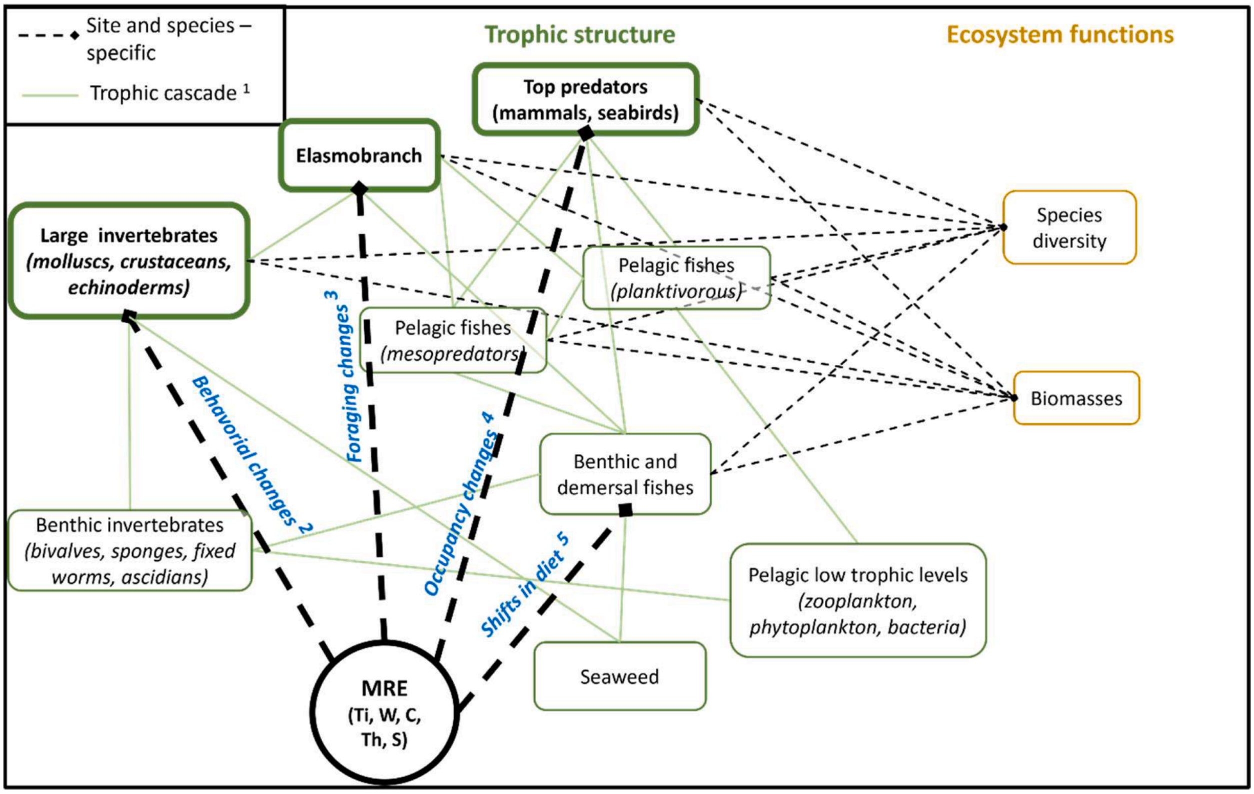

Fig. 1. Schematic representation of changes in megafauna behavior during the MRE exploitation phase. The letters correspond to the main MREs affected by these pressures (Table 1): tidal (Ti), waves (W), ocean current (C), thermal (Th), and salinity (S). The effects are represented by arrows and illustrated by a bibliographic reference: 1: [77]; 2: [69]; 3: [69]; 4: [68]; 5: [78]. Direct effects and compartments directly affected are shown in bold. The trophic cascade is presented in a different color than the responses for ease of interpretation.

animals [76] because of the typically slow speeds of turbine rotation. Therefore, population-level consequences from individual collisions remain poorly understood, making it difficult to incorporate into an EA. More research is needed to understand potential impacts but potential changes in behavior, due to the presence of MRE devices, could propagate up and down the food web (Fig. 1). At present, however, integrating the effects from avoidance of the area due to a potential collision risk into the models used in the EA remains a challenge.

Sound is an important interaction modality for marine organisms and their interaction with their environment. Underwater noise can be generated at various phases of an MRE device's life cycle, and in particular mechanical and electrical noises of operating TECs and WECs generators [79,80]. MRE installations usually do not require pile driving, which is considered as the main noise source of offshore structures [81]. However, the increased vessel activity necessary for the installation of MRE devices can lead to heightened noise emissions, causing certain highly mobile organisms such as cetaceans to temporarily avoid the area [6,82]. During the operational phase, the longest period of a MRE life cycle, emitted noise is not expected to exceed those of other human activities, such as vessel activities or sonar emissions [79,83]. Buscaino et al. [84] recorded louder noise in the marine environment during operation of a WEC in the Mediterranean Sea, especially during high waves. However, the noise was less than that emitted by passing boats. The noise emitted could induce animal behavioral responses, such as avoidance, possibly affecting areas of occupancy ([85]—Reference 4 in Fig. 1). In their study, Harding et al. [86] modeled the noise propagation of a 28-WEC array in the Pacific. The results were used to determine the acoustic impact metrics of several marine mammals. From this, the authors modeled the “effective signal level”, which can be used to predict and quantify the effects of WEC noise on marine mammals' health and behavior. This type of model could be used as a forcing function in an ecosystem model by estimating the avoidance of an area by these animals and therefore the reduction in species biomass and its consequences on the food web. Although many factors can influence the significance of impacts, making definitive statements about effects of device generated underwater noise at any particular site remains difficult. For example, Hastie et al. [75] observed localized avoidance of TEC by harbor seals, but Robertson et al. [87] did not report any noticeable change in harbor seal or porpoise behavior. Furthermore, the avoidance and risk-taking capacity of animals is highly variable. For example, Hastie et al. [88] recommend considering foraging behavior when estimating noise avoidance. In their study, seals exhibited different foraging success in the presence of pile-driving or TEC noise when offered large vs. small numbers of fish. Some animals, like seals, seem able to balance the benefits of successful foraging in the presence of anthropogenic noise with the risks associated with less foraging opportunity because of area avoidance.

EMFs emitted by MRE power export cables or the devices themselves can potentially alter the behavior of sensitive marine animals (i.e., some species of elasmobranchs, fish, and benthic invertebrates) that use natural geomagnetic fields ([89,90]—Reference 2 in Fig. 1). Increased levels of EMF may interfere with migratory movements [91] and may influence feeding behavior. Changes in elasmobranch foraging behavior related to EMFs (Reference 3 in Fig. 1) could alter predation pressure on benthic and demersal fishes, because some species cannot differentiate electrical fields generated by prey from anthropogenic sources [92]. The attraction of some species, like lesser spotted dogfish (*Scyliorhinus canicula*), to the vicinity of alternating current power cables may increase localized foraging behavior and predation pressure [93]. Additionally, this attraction may be confounded by the attraction caused by the reef and/or reserve effects, possibly exacerbating the presence of predators. It is worth noting that floating MRE devices at the water surface, like floating tidal or ocean current turbines, surface attenuator WECs, or floating OTEC plants, will have export cables emitting EMFs in the water column, potentially affecting pelagic species. However, it is important to consider that levels of EMF generated by MRE devices of any kind are considerably lower than those of OWF export cables [94].

Behavioral effects related to underwater noise and EMFs are not always consistent across diverse marine species, location, or MRE device emission signature. For instance, some benthic invertebrates exhibit varying responses to EMFs (Reference 3 in Fig. 1), ranging from no significant response [95] to exploratory movement [69] and attraction [96]. Changes in perception or differences in sensitivity throughout life cycle phases may also play an important role [69,97]. Consequently, in the schematic representation (Fig. 1), dotted lines were chosen to emphasize the uncertainty in the species response, generalizations being precluded. Even though the changes in behavior related to underwater noise and EMFs may be limited, the impacts through a trophic cascade (Reference 1 in Fig. 1) could have implications for the ecosystem structure and function. This should be addressed because the changes in diet or in distribution can affect important ecosystem functions like species diversity and secondary production.

4.2. *How to study the local changes in habitat associated with MRE?*

One of the main effects of offshore structure installations such as MRE devices is that they can modify marine habitats (Fig. 2). The effects of these modifications and the interactions they promote may be observed throughout the food web [98]. MRE devices can be deployed nearshore (e.g., Mutriku wave energy project in Spain or Wave Swell project in Australia), on the seafloor in subtidal areas (e.g., MeyGen tidal turbines in Scotland or the WaveRoller WEC in Portugal), or floating at the surface but secured to the seafloor with mooring lines (e.g., CalWave xWave WEC in California, the Orbital O2 tidal platform in Scotland, or the upcoming Dominique OTEC platform in São Tomé and Príncipe). This means MRE devices may affect benthic and pelagic habitats, in many different ways [99].

The artificial reef effect (which includes biofouling; Reference 3 in Fig. 2) is characterized by the colonization of all immersed surfaces [100] by benthic flora and fauna. This effect is well studied in the MRE sector (e.g., [101]) because it has the potential to affect the functioning of devices by reducing efficiencies in power production, increasing their weight and drag, hindering the movement of mobile parts such as rotors and turbine blades, and affecting the ability to maintain devices and systems [102]. For example, Want et al. [101] noted that the ability of *Chirona hameri* to settle in a wide variety of areas, as well as its very rapid growth and heavy weight, can hamper the operation of tidal turbines. The artificial reef effect caused by immersed structures can measurably increase the species richness of a site [103,104] and attract different types of organisms like benthic predators that come to feed on biofouling (e.g., crustaceans, carnivorous gastropods, and echinoderms), detritus feeders (e.g., shrimp species), or organisms that seek refuge in these habitats (e.g., juvenile fishes) [105–107]. In Sweden, monitoring 21 WEC foundations over 12 years identified an attraction characterized by a greater number of individuals and greater species richness, especially by the foundations with more complex structure [108]. Besides benefiting species richness and biomass, the artificial reef effect can lead to enrichment of organic matter in the ecosystem, especially from the fall of feces and decaying organisms on the seafloor around device foundations and anchors ([109]—References 6a and 6b in Fig. 2). The alteration of food webs due to species benefiting from biofouling were investigated in a study of an OWF in the English Channel by Raoux et al. [110]. Structural and functional group-based indices and ENA were used, which highlighted a change in the local food web following the increase in biomass of filter-feeding species. For example, an increase in the organic carbon cycling process has been found (Reference 7 in Fig. 2). It is worth noting that impacts related to the artificial reef effect are complex to study due to the high variability of sessile and motile species assemblages and abundance depending on the site, season, and depth [101,111,112]. For example, Nall et al. [113] sampled 115 species attached to a WEC in a temperate zone and found vertical and horizontal zonation, as well as temporal variations.

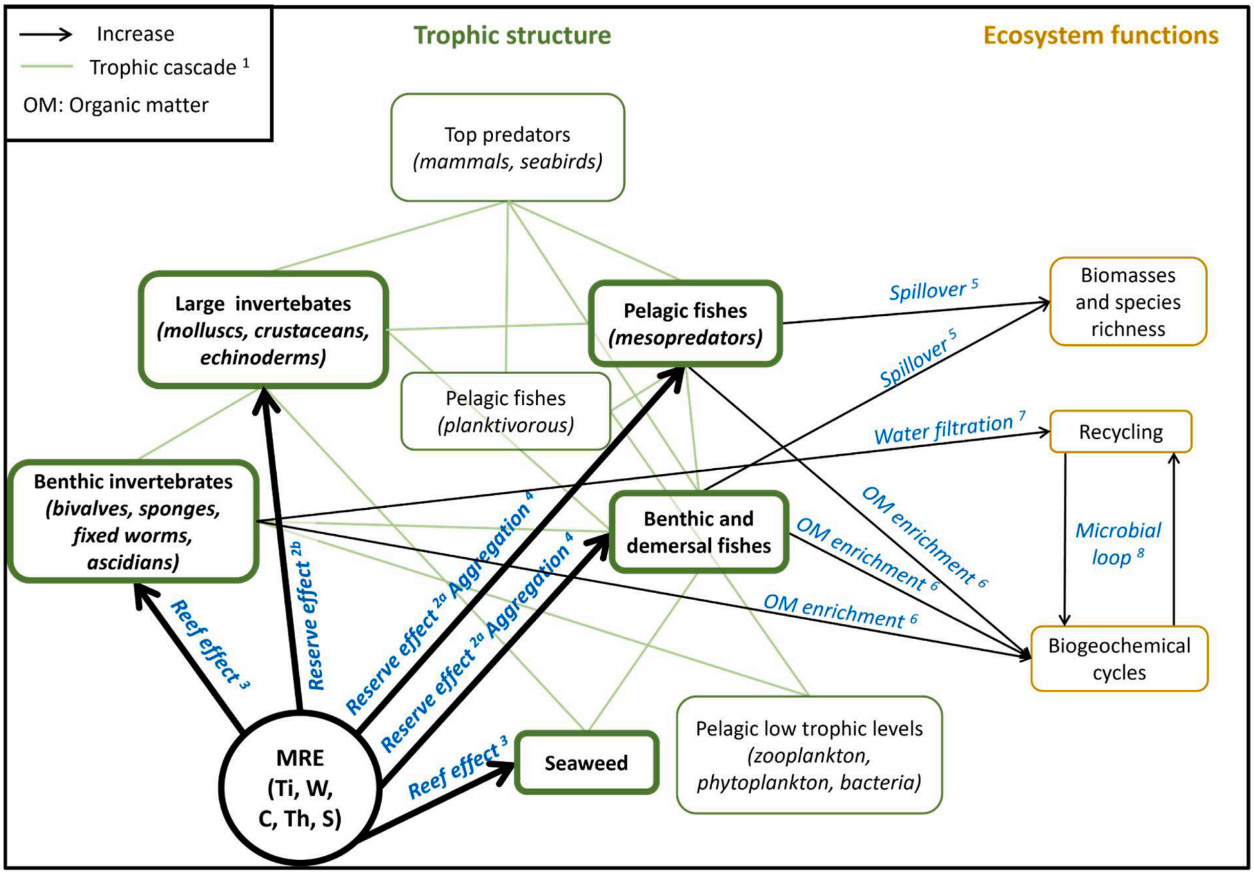

Fig. 2. Schematic representation of changes in habitats during the marine renewable energy (MRE) exploitation phase. The letters correspond to the main MREs affected by these pressures: tidal (Ti), waves (W), ocean current (C), thermal (Th), and salinity (S). OM stands for organic matter. The effects are represented by arrows and illustrated by a bibliographic reference: 1: [77]; 2a: [114]; 2b: [65]; 3: [110]; 4: [115]; 5: [26]; 6: [98]; 7: [110]; 8: [116]. Direct effects and compartments directly affected are shown in bold. The trophic cascade is presented in a different color than the responses for ease of interpretation.

Most EA studies on the artificial reef effect have focused so far mainly on offshore wind turbines and oil-extraction platforms, which have a larger submerged surface area than most MRE devices, and cover the entire water column. While these studies showed that it is possible to integrate the artificial reef effect into an EA, it is necessary to consider its effects in the context of MRE devices, which have a smaller colonizable surface area. It is worth noting, however, that floating MRE devices like the OE-35 WEC, the O2 TEC, or an OTEC platform can provide very large surface areas to colonize in the top few meters of the water column and generalizations may be difficult from one device type to another.

These changes in habitat can lead to fish aggregation (Reference 4 in Fig. 2) around or under structures in search for shelter, in the newly created habitats (especially those made up of macroalgae growing on the MRE devices), or in search for food provided by the high biomass concentration resulting from the artificial reef effect [117]. Floating structures such as WECs can also act as fish aggregating devices for species subject to a thigmotactic effect [58]. Bottom structures like foundations and anchors have also been shown to attract demersal fishes, especially finding shelter in scour depressions underneath anchors [118]. These structures could therefore bring about a change in MRE device communities. For example, Couto et al. [119] highlighted the close link between the presence of a TEC and the availability of prey for diving seabirds.

Besides, a reserve effect (References 2a and 2b in Fig. 2) can occur when a partial or total restriction of other human activities near MRE devices, as a safety measure, is applied. For example, Roach et al. [65] noted an increase in lobster abundance on the construction site of a wind farm, following the ban on fishing activities during the installation phase. As a result, the first catches following the reopening of the site to fishing were marked by high abundances and larger than usual lobster sizes. Restricting access to the area can decrease the fishing pressure on species, leading to an increase in fish, crustacean, and mollusc biomass [25,26]. This may, in turn, lead to a spillover effect (Reference 5 in Fig. 2), imitating features of marine protected areas and thus benefiting neighboring ecosystems and local fisheries [120]. For instance, in the North Sea, Coates et al. [109] observed an increase in macroinvertebrate populations three years after an OWF was closed to fishing. However, the scale of OWFs is much larger than the current tidal or wave project sites and this effect will need to be assessed once large-scale arrays are deployed [7].

The artificial reef effect and fish aggregation around MRE infrastructure could induce a trophic cascade (Reference 1 in Fig. 2) in the ecosystem structure, directly or indirectly, that is mediated by feeding interactions [121]. Thus, the installation of MRE devices would induce a modification in the structure and the functioning of the food web around single MRE devices or within an MRE array. This effect can be simulated using an ecosystem model that includes a diverse set of species or functional groups and their trophic interactions—such as OSMOSE [39, 41] or Ecopath with Ecosim [25,122].

4.3. *How should changes in oceanographic systems due to MRE be included?*

Development of MRE devices in the marine environment may influence physical processes that help to form and maintain ecosystem processes. These physical processes include waves, tides, persistent ocean currents, temperature, salinity, density, and the processes that control sediment transport (Fig. 3). While small-scale MRE deployments

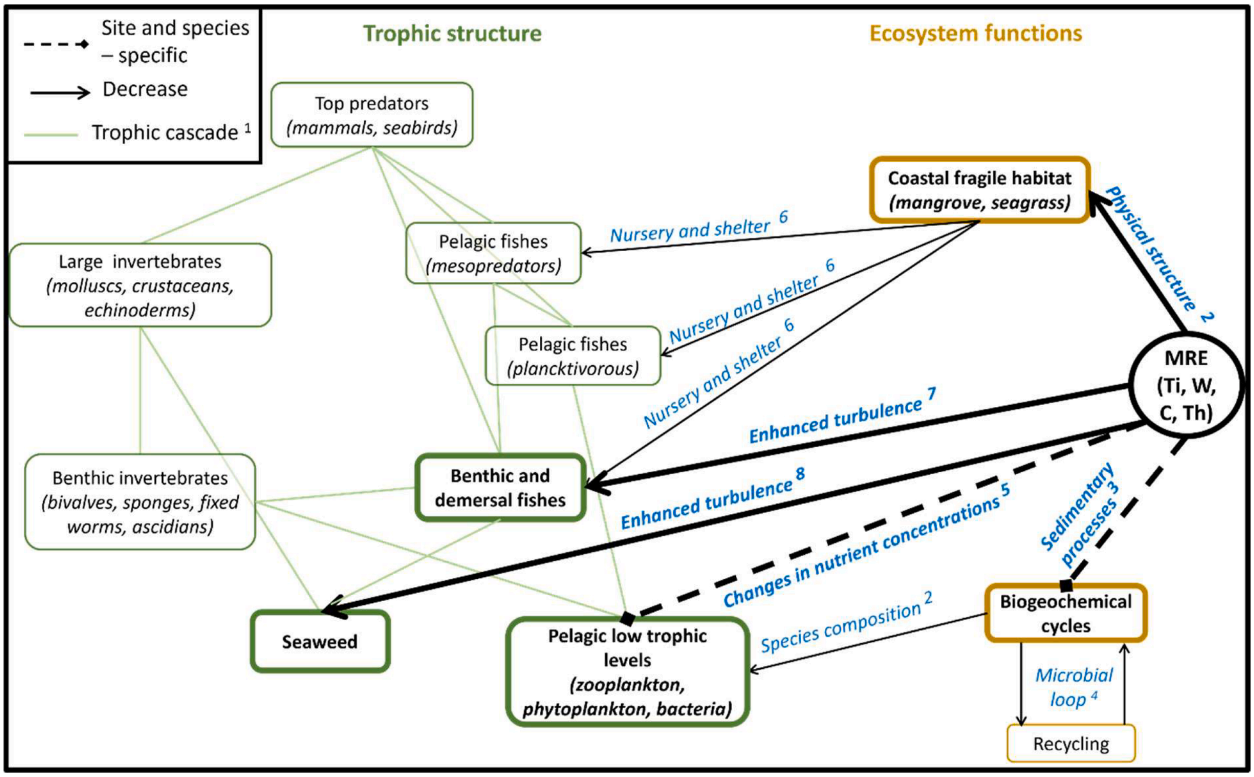

Fig. 3. Schematic representation of changes in oceanographic systems during the MRE exploitation phase. The letters correspond to the main MREs affected by these pressures: tidal (Ti), ocean current (C), and thermal (Th). The effects are represented by arrows and illustrated by a bibliographic reference: 1: [77]; 2: [129]; 3: [124]; 4: [116]; 5: [130]; 6: [131]; 7: [127]; 8: [128]. Direct effects and compartments directly affected are shown in bold. The trophic cascade is presented in a different color than the responses for ease of interpretation.

are unlikely to create measurable changes to oceanographic systems [123], large-scale commercial arrays could induce effects that may propagate through the broader ecosystem [7,124]. For example, the disruption of a tidal flow or ocean current around a turbine and foundation will cause faster flows to the sides and reduced flow in the immediate wake of the turbine ([125]—Reference 3 on Fig. 3). The change in flow can be seen as local scour around a foundation or anchor, but the flow returns to background rapidly. With the addition of many devices, the disruption in flow could be felt further afield [124,126]. This change may lead to changes in fish ([127]—Reference 7 in Fig. 3) and macroalgal ([128]—Reference 8 in Fig. 3) community patterns and benthic communities.

The maintenance of ecosystem structure and functions is significantly influenced by the physical oceanographic conditions within the ecosystem. As biogeochemical cycles form the base of ecosystems, changes in temperature, salinity, pH, oxygen or nutrient availability may alter the availability and diversity of primary producers (i.e., phytoplankton: [130]—References 2 and 5 in Fig. 3) and could alter the marine food web from the base (bottom-up effect), and reverberate throughout the system ([129]—Reference 2 in Fig. 3). Physical processes including nutrient supplies and sediment transport are also of great importance for maintaining certain sensitive habitats like seagrass meadows, fringing marshes, and other key habitats ([125,131]—Reference 6 in Fig. 3), and the overall population dynamics of many organisms (e.g., larval dispersal, recruitment, survival [132]). Lastly, one pressure specific to OTEC plants and linked to the movement of cold, deep water through the structure is the discharge plume (which can be of the order of several cubic meters per second) that could alter the accessibility of nutrients in surface and encourage eutrophication and toxic algae blooms [133,134]. Indeed, if the plume of deep water were to be released near the sea surface, it would have different properties such as temperature, salinity, nutrient, dissolved gasses or even pH, that may affect the phytoplankton communities [135]. Common mitigation for OTEC plants is to ensure the cold water is discharged at greater depth to allow for mixing with ambient water [136]. Biogeochemical models link the marine biogeochemistry (e.g., water quality, nutrients) and ecosystem dynamics of the lower trophic levels (e.g., phytoplankton, zooplankton) in a marine food web [137,138]. Coupled with physical models, they have been used for process studies [139,140], examining biogeochemical cycling ([141]—Reference 3 in Fig. 3), determining temporal scales of ecosystem variability [142], and investigating habitat alterations [143]. These coupled models could allow for the integration of low trophic level variations within models of effects of MRE arrays. For example, the Linear Inverse Model has most often been applied to plankton communities and can be applied to food webs more generally [144,145]. Schuchert et al. [146] developed a series of coupled hydrodynamic and biogeochemical models to define the influence of very large scale TEC arrays on variations in phytoplankton production. Coupling physical-biogeochemical models and ecosystem models could be used to conduct an EA [37] to explore questions related to oceanographic changes around MRE arrays and their potential consequences at the ecosystem scale. For example, Baker et al. [147] modeled the effects of the potential installation of a tidal barrage in a river in the UK, by combining species distribution and hydrodynamic models with the trophic relationships linking these species. This type of methodology could be applied as part of an ecosystem approach by modeling the effects of environmental changes on the distribution of local species, and forcing an ecosystem model with these results.

4.4. Can an ecosystem approach assess cumulative effects scenarios?

Coastal areas are increasingly occupied, and each human activities can result in spatial impacts and consequences for the environment. Cumulatively, these consequences can cancel each other out, dampen or even amplify each other. Added to this are the complex effects of climate change, which affects all trophic compartments. The study of cumulative effects means considering all the effects on the ecosystem at the same time, in order to anticipate, as far as possible, the consequences of heavy exploitation of the coastal area. The ecosystem approach is particularly well suited to the holistic study of cumulative effects of MRE, as the devices will be integrated into those complex ecosystems, and those pressures must be considered when planning MRE projects. For example, Borja et al. [9] have created a conceptual model showing how to maintain the use of marine ecosystem services while reducing the pressure of human activities on ecosystems.

The EA is now applied for managing many marine sectors, with the best-known being fishery resources [148,149]. As shown in Fig. 1, MRE devices are expected to influence the behavior of marine organisms, particularly high trophic level species. Direct effects of MRE (once characterized as impact-response functions) can be added to EA models or represented by forcing functions on mortality and production [150]. Together, this means that both the direct and indirect effects of MRE on the ecosystems surrounding an installation can be considered (e.g., to check for cascading impacts), just as the models have been used to examine different levels of fishing pressure on exploited species or technical, spatial and/or temporal management measures. Models used in the fishery approach, such as OSMOSE, MIZER, Ecopath with Ecosim, and Atlantis (e.g., [38,151]) could be usefully applied to the MRE context. For example, Fay et al. [152] developed a coupled ecological-economic modeling framework using Atlantis to assess the effects of fisheries management on a suite of ecological and economic indicators. This type of modeling tool could be developed in the context of MRE to address tradeoffs across ecological, economic, and social management objectives, especially where large-scale arrays of TECs or WECs, or large OTEC plants, are planned. Maldonado et al. [34] also built a Bayesian model to identify suitable sites for the installation of WEC in Spain and Portugal. This model integrates technical, environmental and socio-economic issues and could be integrated in an EA study prior to project discussions.

Climate change in marine systems results in increased seawater temperature, ocean acidification, deoxygenation, and disruption of nutrient cycles, which contribute to changes in the physiology and fitness of organisms, shifts in species distributions, abundance, size and composition and, ultimately, modifications of food web structure and function [153,154]. Future planning for MRE will need to take this set of interacting pressures into account, including through adaptive management approaches [155]. Many models are used to study the influence of climate change on marine communities (e.g., [156]), and could be applied to MRE. For example, coupled physical-biogeochemical models are particularly well adapted to considering ecosystem questions in the context of climate change, because they enable the linkage of environmental parameters to ecosystem components [157]. These climate change-focused models could be used to consider the ecosystem context MRE will face into the future, as they can integrate it via climate-induced species displacement [28,158,159] or changes in environmental suitability and/or trophic environment, affecting species predation, consumption, growth and production [122,160].

Additionally, the potential of using MRE sites for other purposes, such as aquaculture, is considered a potential approach to optimizing marine spatial zones - for example, as part of multi-purpose platforms or to use MRE energy to power the other activities [47], such as the cultivation of mussels or algae [161] or fish farms [162]. The use of the EA at the planning stage of a co-located MRE project enables the identification of the most suitable site for the co-located activities.

A wide range of indicators can be used to answer a large number of questions related to fisheries and climate change, such as changes in biomass and environmental variables [56] or landings, many of which are relevant to MRE. Notably, ENAs are computed to study the effects of fishing on marine communities [66] and have already been applied to study the projected cumulative effects of climate change for various species consumption and production rates, and the artificial reef and reserve effects of an OWF in France [163].

4.5. *A note about social and economic components*

Although the first principle of the EA, as defined by the Convention on Biological Diversity, links ecosystem management with societal choices, most EAs are based only on ecological components. As new technologies for MRE production develop, it is necessary to assess the societal perception and acceptance of these new technologies [164]. Ignoring these is an error that could result in the opposition and interruption of these projects, even if they benefit the environment and society [165]. These vast and complex issues are only recently getting investigated in the context of MRE. For instance, [166] showed that social resistance to the deployment of new technologies may block the installation of the new devices. The resistance to changes in the environment results from previous experiences where project promoters did not adequately inform local inhabitants about renewable energies and local actors did not participate in the process. Indeed, failure to act distantly and without consideration of the local communities and not addressing meaningfully how local communities, indigenous users, and other stakeholders interact and will be affected by the installation of MRE devices will render an incomplete and potentially harmful deployment of renewable energy devices [167]. This approach requires a more complete approach, beyond merely mentioning the problem.

The EA considers that ecosystems and human societies are closely linked and supports integrated studies. Such approaches require an interdisciplinary approach between ecological and social sciences, which is lacking for the marine environment [168]. Two challenges limit the application of integrated and interdisciplinary approaches, especially in the MRE context: (1) the need to develop a common language that enables interactions between disciplines, and (2) the need to consider common spatial, temporal, and organizational scales of analysis. To address these issues, concepts and tools have emerged since the early 2000s, including the concepts of ecosystem services [169], the Nature Future Framework [170] and social-ecological systems [171]. Trifonova et al. [172] proposed a framework based on a dynamic Bayesian model that takes into account the relationships between the physical environment, biological indicators and uses of the sea. In addition, as part of their toolbox for stakeholders, Borja et al. (2024) [9] created a conceptual framework of the cumulative pressures of maritime activities in Europe, set in a socio-economic context.

The EA can be placed at the center of environmental impact studies by supporting a holistic added value to the ecological information obtained before and during implementation of MRE projects by developers. Ultimately, it is the responsibility of public policymakers and resource managers to maintain a comprehensive vision of how the ecosystems they manage will evolve in response to planned MRE developments. With this in mind, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has developed the Nature Futures Framework (NFF), to support the development of scenarios and models of desirable futures for people and nature. This framework was conceived to represent the plurality of value perspectives on human-nature relationships, with a focus on scenarios and models more centered on biodiversity and ecosystem services. Thus, the EA could be used within the NFF through quantitative models to develop indicators and pathways toward positive futures, in order to better inform policy making for nature and nature's contributions to people, especially in highly exploited marine ecosystems [170,173]. Furthermore, the application of the AE would provide considerable support to the NFF through the provision of cumulative effects scenarios, necessary for the expansion of MRE, integrating local environmental data from impact studies. Similarly in the United States, the Ocean Climate Action Plan developed by the White House proposes direct short-term action plans to tackle climate change and the loss of biodiversity.

5. Recommendations and conclusion

The purpose of this review was to provide insight into the current state of the application of the EA in the context of MRE development. The MRE sector is relatively young compared to other offshore industries, and the application of an EA to this sector is in its infancy. However, lessons learned from other applications in relevant sectors (e.g., fisheries, OWFs) provide a solid foundation for their application to MRE and can accelerate the implementation of an EA. Accounting for this complexity is fundamental to the understanding and management of ecosystems, especially when new human activities are being developed and introduced to the marine environment. To this end, the current work presents different categories of tools (i.e., qualitative and quantitative models) and associated ecological indicators that are commonly used to address the complexity of an EA. The recommendations below give an overview of the main future research needs. Currently, the recommendations are technology-independent and rather general, so that they can be applied to the entire context of MRE. Note that in the context of ecosystem models as a tool to support EA for MRE, general limitations exist due to the lack of experience and the need to adapt modeling approaches to MRE issues. These recommendations are the main limitations identified by the workshop participants that could hinder the proper implementation of an ecosystem approach in the context of MRE, and that should be the subject of more in-depth studies in the near future.

- Consolidate knowledge of the potential effects of MRE devices and arrays on their surrounding environment to provide risk mitigation strategies [5]. For instance, the consequences of collisions between MRE devices and marine animals, including how the risk would scale up from a single device to large commercial-scale arrays [7], must be examined [58,71,174]. Similar questions remain regarding the consequences of underwater noise [175] and EMFs [94] generated by MRE on sensitive animals, especially their behavior [58,174].
- Improve the quality of the fine-scale and local data integrated into models. An example might consider low trophic level compartments (e.g., plankton and meiofauna) or local trophic relationships (e.g., via stomach contents or stable isotopes analyses and estimated biomasses and catches for all the living compartments). This would allow the adaptation of the models to the specificities of the studied ecosystem and provide a firm basis for quantitative assessments to be used in scenario analyses and management.
- Consider differences in the spatio-temporal scales of impacts. Some interactions between MRE and the ecosystem may be localized with short-term impacts, while others may occupy more space around single MRE devices or arrays and may have longer-term effects. Currently, only single device or small-scale arrays (1–6 devices) have been deployed around the world, but changes in the ecosystems are more likely to be observed at the scale of large commercial arrays (10–30 devices; [7]).
- Recognize the need to take account of the specific effects of each type of MRE and each life phase. There are many different ways of extracting renewable energy from the sea. Five broad categories of MRE were presented in this review, to show that they may have different impacts, but each type of MRE can be harvested with a large diversity of device designs. It is therefore necessary to consider in an EA study the type of structures that will be put in place at a specific project site. Besides, the installation of MRE devices generally requires activities that may have direct impacts on benthic habitats (e.g., deployment of gravity bases and associated infrastructure). The decommissioning phase has not been studied extensively and the environmental effects remain uncertain.
- Couple models and approaches to achieve a more holistic EA. The ability of environmental modifications to alter physical and biological ecosystem processes requires the integration of biogeochemical models, particularly during the MRE operational phase. To capture the full complexity of EA, it is necessary to involve experts from many fields, such as oceanography, biogeochemistry, stock assessment, species interactions, physiology and behavior. It quickly expands into other disciplines, such as fisheries, economics, engineering, and social sciences, and to industry experts, NGOs, regulators, and indigenous peoples. All these groups have a valuable understanding of how the systems work, including their components and connections.

In many parts of the world, the application of an EA to MRE has not yet been considered. However, a major advantage for the adaptation of the EA to the MRE sector is that the existing EA tools already integrate ecosystem dynamics. This methodology has already been applied to the MRE context in France and Scotland [25,110].

While many obstacles still need to be addressed and overcome, the EA is a powerful tool for guiding decision-making with a broader view of the potential effects at the ecosystem level. Broad application of the EA could better guide and support decision-making for the evolving MRE sector globally, whether it is the development of a tidal energy array off the coast of Scotland, or a single WEC or small-scale OTEC plant to power a small community on a tropical island.

CRediT authorship contribution statement

M. Le Marchand: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **L. G. Hemery:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **E. Araignous:** Writing – review & editing, Writing – original draft, Conceptualization. **D. Bănaru:** Writing – review & editing. **F. Ben Rais Lasram:** Writing – review & editing. **A. Copping:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Funding acquisition, Conceptualization. **E.A. Fulton:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **D.J. Hasselman:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **F. Le Loc'h:** Writing – review & editing. **M. Luisa Martínez:** Writing – review & editing, Writing – original draft. **N. Niquil:** Writing – review & editing. **D. Rose:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **G. Safi:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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