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Beyond Single Marine Renewable Energy Devices: A System-wide Effects Approach

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Global expansion of renewable energy, including marine renewable energy (MRE) technology development is necessary to mitigate the effects of climate change, facilitate a sustainable transition from carbon-based energy sources, and satisfy national energy security needs using locally produced electricity (European Commission 2022; IPCC 2023; IRENA 2020). As MRE engineering and research continue to focus on designing devices for deployment in nearshore and offshore waters around the world, researchers are also examining potential environmental effects on marine animals, habitats, and ecosystem processes. To date, the focus has been on interactions between small numbers of MRE devices (1–6) and the environment, such as collisions between animals and turbine blades, the effects of underwater noise and electromagnetic field (EMF) emissions, changes in habitats and oceanographic processes, risk of entanglement of animals, and displacement of animals (Boehlert & Gill 2010; Copping & Hemery 2020) (see Chapter 3).

Most of the knowledge of environmental effects has focused on potential outcomes of single (or a few) operational devices, especially in temperate areas. As MRE arrays and larger projects develop in the coming years, it is vital to understand how our knowledge of potential environmental effects might increase in scale, how they may translate to changes in ecosystems, and how they may interact with ongoing and future uses of the oceans. Potential effects of an expanding MRE industry must be placed within the context of other offshore developments. Through international collaborations, Ocean Energy Systems (OES)-Environmental is expanding its view of potential environmental and ecological effects of MRE development to include a broader look at higher level, system-wide effects. This broader perspective consists of investigating how to 1) increase the understanding of environmental effects of MRE from single devices to arrays, 2) apply an ecosystem approach to the integrated management of MRE, and 3) assess the cumulative effects of MRE with other anthropogenic activities at sea.

Future large-scale commercial MRE arrays will be in operation for decades. It is crucial to increase our understanding of environmental effects on marine animals and habitats to comprehend the full effect of this new low carbon energy generation and help facilitate sector growth, aid the transition of energy systems to renewable sources, and address the effects of climate change. Although our knowledge about stressor-receptor interactions for single devices and small arrays continues to improve (Copping & Hemery 2020), remaining uncertainties complicate the task of predicting how marine animals and habitats will interact with, and be affected by, large-scale arrays (Onoufriou et al. 2021). Research and monitoring around small deployments have provided substantial information to better understand the potential environmental effects of large-scale arrays. These effects are unlikely to scale linearly with the number of devices (Zhang et al. 2022), but rather in complex and nuanced ways. For this topic, OES-Environmental has examined how to apply the knowledge of stressor-receptor interactions from single devices to arrays. It also required exploring interactions that are not significant around single devices but that may become important around large-scale arrays, such as changes in oceanographic systems or displacement of animals around MRE developments.

To evaluate the potential effects of MRE development on the broader marine ecosystem, OES-Environmental has assessed the application of an ecosystem approach as defined by the international Convention on Biological Diversity, which currently does not address MRE. The approach follows an integrated strategy to manage land, water, and living resources while equitably promoting conservation and sustainable use. Scientific methods are applied to characterize the fundamental processes, functions, and interactions among organisms and their environment. While the ecosystem approach is a complex concept that integrates environmental, economic, and social sciences, OES-Environmental has initially focused on the environmental aspects of the approach. This topic used conceptual frameworks to explore how MRE development and operation may affect local ecosystems and associated food webs, and to describe how ecosystem services may be influenced by MRE. The development of such frameworks aids qualitative and quantitative descriptions of the interactions between ecosystem components (both biotic and abiotic) and MRE systems.

Cumulative environmental effects result from interacting activities across space and/or through time in one location, due to sequential or overlapping anthropogenic activities. The most complicated cumulative effects arise from combinations of both direct and indirect effects of the many activities that occur within a region over time. As MRE development approaches the state of commercial-scale deployment, projects will be installed in areas where other anthropogenic activities already exist, and environmental interactions between activities are likely. The understanding of environmental effects of MRE has matured to a point where there is sufficient information to begin assessing the potential cumulative effects of MRE development, even though many knowledge gaps remain. With this topic, OES-Environmental investigated how to define the cumulative effects of MRE developments, how these effects combine with or affect those of other human uses of marine environments, and the tools and research studies that can be used to best assess these effects.

Projections of potential future effects and the state of the environment into which MRE will be developed will assist planners, funders of projects, and decision-makers in determining their feasibility, smoothing the way for large-scale array deployment. By taking this system-wide effects integrated perspective, OES-Environmental lays out a pathway to expand the understanding of the environmental and ecological effects of MRE development across the appropriate spatial and temporal scales, based on existing research, leveraging information on MRE devices, and highlighting gaps in scientific knowledge. The following sections also identify the main knowledge gaps, limitations, and future research needs. In addition, they each lay out a robust scientific approach for testing hypotheses that can be applied to increase understanding of the environmental effects of MRE development at greater spatial, temporal, and technological scales.

9.1. 'SCALING UP' OUR UNDERSTANDING OF ENVIRONMENTAL EFFECTS OF MRE DEVELOPMENT FROM SINGLE DEVICES TO LARGE-SCALE COMMERCIAL ARRAYS

This section is a summary of a study published as a journal article (Hasselman et al. 2023) in which the authors adapted and applied cumulative environmental-effects terminology to the stressor-receptor interaction approach, in order to conceptualize how effects may scale up with large-scale MRE arrays.

9.1.1. THE NEED TO UNDERSTAND HOW ENVIRONMENTAL EFFECTS SCALE UP

A variety of obstacles impede the global expansion of the MRE sector, including difficulties in obtaining regulatory approvals required for project development due to uncertainty about environmental effects. Despite our growing understanding of the effects of various stressor-receptor interactions for single devices and small pre-commercial arrays, predicting the potential effects of large-scale commercial arrays on marine animals, habitats, and ecosystems is made more difficult by the uncertainties that still exist (Copping et al. 2016; Copping & Hemery 2020).

As stated above, it is unlikely that environmental effects will scale linearly with the number of operational devices deployed (Copping et al. 2016; Zhang et al. 2022). Environmental effects of large-scale arrays are anticipated to be site-specific, nuanced, contingent on array configuration, cumulative, and may exhibit non-linear environmental responses. Therefore, Hasselman et al. (2023) established generalized concepts about how effects for key stressor-receptor interactions might manifest with the development of large-scale arrays. These generalized concepts provide a basis for the development and testing of hypotheses that will help enhance predictions and comprehension of potential risks associated with expanding MRE deployments to large-scale commercial arrays. Consequently, the development of these generalized concepts informs MRE project siting and reduces barriers to project consenting by providing a robust scientific approach for developing and testing hypotheses that can be applied to increase our knowledge of the effects of arrays. This information is crucial for understanding potential risks of MRE expansion and developing effective mitigation strategies (as required). It is also needed to facilitate the development of MRE projects at scales that can make meaningful contributions to addressing the impacts of climate change, ensuring a sustainable transition of global energy sources, and safeguarding energy security.

9.1.2. APPROACH APPLIED TO INVESTIGATE THE SCALING-UP OF ENVIRONMENTAL EFFECTS OF MRE

Hasselman et al. (2023) developed and applied a structured approach (i.e., a multi-step framework) for conceptualizing how environmental effects might scale up to arrays for seven key stressor-receptor interactions (i.e., collision risk, underwater noise, EMFs, changes in habitats, changes in oceanographic systems, entanglement, and displacement). The framework included: i) a description of the interaction, ii) a summary of existing knowledge about the interaction based on available literature and relevant information from surrogate industries, iii) defining how effects of the interaction might manifest for arrays and identifying any caveats that need to be considered that could influence this perception, and iv) identifying the type(s) of research required to improve our understanding of the effects of the interaction for large-scale commercial arrays (Figure 9.1). Much of the information available about stressor-receptor interactions from single MRE device deployments and from surrogate industries was suitable for assessing how environmental effects might scale up and facilitated the implementation of this structured approach.

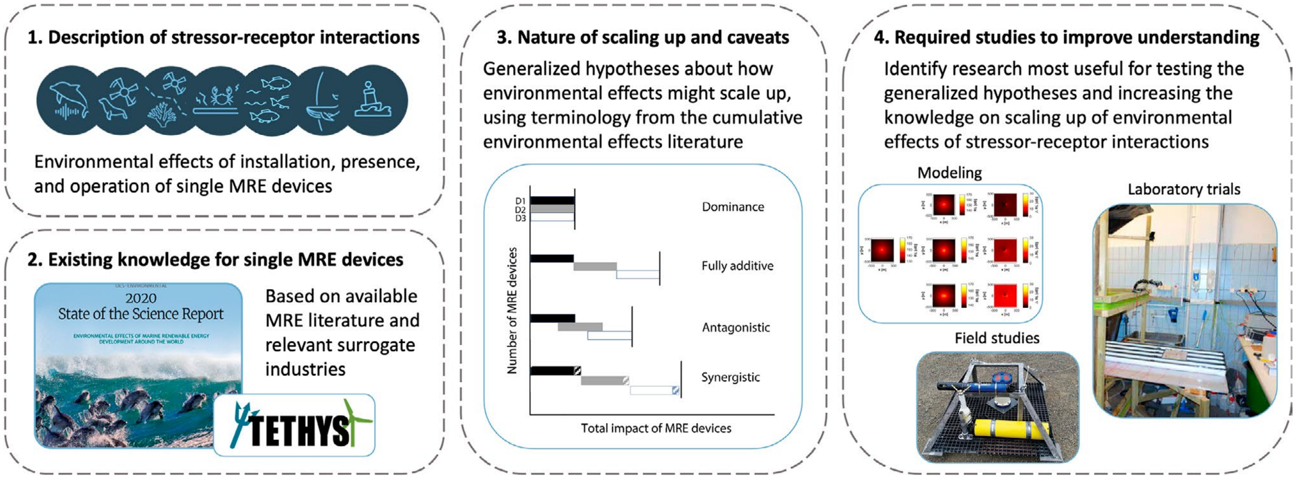

Figure 9.1. Summary of the four-step framework developed for assessing how the environmental effects from seven stressor-receptor interactions may scale up from single marine renewable energy (MRE) devices to arrays. (From Hasselman et al. 2023)

Generalized concepts for how the effects of stressor-receptor interactions might scale up (i.e., step 3 of the framework) were developed using terminology adapted from the cumulative environmental effects literature, providing an informative framework for developing this nomenclature. While the field of cumulative environmental effects typically focuses on describing the nature of interactions between different stressors (e.g., habitat loss, invasive species, climate change, etc.) (Carrier-Belleau et al. 2021; Halpern et al. 2008a), Hasselman et al. (2023) were concerned with understanding how the effects of the same stressor-receptor interaction might change with an increasing number of MRE devices. This required adaptation of existing terminology to reflect comparatively simple additive or more complex non-linear (e.g., multiplicative) effects, and generated four broad classification categories (i.e., dominance, additive, antagonistic, and synergistic effects):

- Dominance effects describe a scenario where the effect of one MRE device overwhelms the effect of other devices in an array.
- Additive effects describe a scenario where the effects of each MRE device add up to those of the other devices in an array. In other words, it reflects the sum of effects for each device in an array.
- Antagonistic effects describe a scenario where the effects do not fully add up but somewhat partially cancel each other out. The sum of effects for each device in an array is scaled to reflect a diminished effect as the number of devices increases.
- Synergistic effects describe a scenario where the combined effect of all devices in the array is greater than the sum of their individual effects. It arises from a scalar applied to each device's individual effects resulting from the interactions among each other.

9.1.3. APPLICATION OF THE SCALING-UP FRAMEWORK TO THE MRE CONTEXT

Hasselman et al. (2023) generated a series of hypotheses for how environmental effects from seven key stressor-receptor interactions may scale up with the development of large-scale commercial arrays (Table 9.1).

Current knowledge about the environmental effects of stressor-receptor interactions from single MRE devices is relevant and important for developing hypotheses about the potential effects of arrays. For instance, knowledge about how underwater sound propagates over space generated the expectation that the effects of underwater noise would scale in an additive manner with an increasing number of operational devices. This, in turn, led to the hypothesis that the area over which noise would be higher than baseline levels would increase commensurate with array size, but that elevation in received levels would increase in a non-linear fashion. Conversely, comparatively little information is currently available about the environmental effects of some other stressor-receptor interactions (i.e., displacement, entanglement, changes in oceanographic systems) because an unknown threshold number of operational devices is required before such effects can manifest and become detectable. As such, this work highlights the value of existing post-installation programs for collecting environmental effects data for

Table 9.1. Summary of hypotheses for how environmental effects from stressor-receptor interactions may scale up with large-scale marine renewable energy (MRE) commercial arrays. (Modified from Hasselman et al., 2023)

Stressor-receptor Interactions	Environmental Effects				Notes
	Dominance	Additive	Antagonistic	Synergistic	
Collision risk		×	×	×	Dependent on array layout, configuration (e.g., 'in parallel' vs. 'in series'), MRE technology type, site location, and species' ability to detect devices and avoid/evade collisions
Underwater noise		×		×	Area over which sound will be elevated will increase with array size; elevation in received levels will increase non-linearly
Electromagnetic fields	×	×	×		Electromagnetic fields increase linearly with additional electrical current; effects may be influenced by spatial arrangement of subsea cables
Changes in habitats		×	×	×	Complex effects that may vary across spatiotemporal scales, with array geometry, and equivalency of effects for individual devices within an array
Changes in oceanographic systems		×	×	×	Effects observed at some threshold number of devices; dependent on MRE technology, number of devices, array configuration, and site-specific hydrodynamics
Entanglement		×	×		Risk increases with number of MRE devices, but dependent on scale and configuration of mooring lines/cables, depth at MRE site, and animal behavior/movement
Displacement		×		×	Effects observed at some threshold number of devices; no single threshold applicable across species or MRE technology type

facilitating MRE expansion, such as adaptive management (Le Lièvre 2020), but sets realistic expectations for understanding the effects of some stressor-receptor interactions until more operational MRE devices are deployed.

Results from this work suggest that while the environmental effects for some stressor-receptor interactions may scale up in a predictive manner (i.e., additive effects for underwater noise), the effects for some other interactions (e.g., collision risk, changes in habitats, etc.) may be influenced by a variety of compounding factors that need to be considered (e.g., environmental heterogeneity, physical habitat characteristics, biological constituents of the environment, spatial arrangement of an array, etc.). Consequently, these factors may generate a variety of context-specific expressions for environmental effects (i.e., dominance, additive, antagonistic, or synergistic effects) as the number of devices in an array increases and is based on the arrangement of devices in an array. This highlights the inherent complexity of understanding environmental effects and suggests that effects observed for an array in one location may not necessarily be indicative of the effects of an array in a different area. The further development of standardized methodologies for assessing environmental effects of arrays will be important for determining the extent to which the various factors influence the effects of arrays.

Finally, Hasselman et al. (2023) identified a suite of research efforts that are required to help fill knowledge gaps, several of which could be undertaken in the near term, in order to improve our understanding of environmental effects for single MRE devices and large-scale commercial arrays. For some interactions (e.g., EMFs), improved knowledge about effects first requires the development of sufficiently robust sensors to collect in situ measurements around operational devices, followed by systematic measurements over a range of power outputs from operational devices. For others (e.g., changes in habitats), a deeper understanding of effects requires the consistent collection of high-quality baseline habitat data using standardized approaches prior to device deployments. A recurrent theme across several stressor-receptor interactions (i.e., collision risk, displacement, entanglement, changes in oceanographic systems) was the need for numerical simulations and new, or improved, modeling approaches to advance our understanding of effects, which are supported by empirical data collected using standardized and appropriate methods to validate (or refute) model predictions. Importantly, future modeling endeavors ought to take into account practical array configurations that are restricted by the physical constraints of the environment, such as geography, water depth, hydrodynamic complexities, bathymetric constraints, etc., as opposed to the theoretical configurations used most commonly to model and optimize energy extraction efficiency (e.g., Bryden et al. 2007; Turnock et al. 2011).

9.1.4. CONTRIBUTION TO UNDERSTANDING SYSTEM-WIDE EFFECTS

Hasselman et al. (2023) outlined an approach and provided guidance to improve our ability to differentiate between unknown and actual risks of MRE development, identify critical knowledge gaps, and facilitate the global expansion of the MRE sector in the near term. The generalized concepts established in this study provide a basis for developing testable hypotheses so that a robust scientific approach can be used to improve our understanding of the effects of large-scale commercial MRE arrays. Importantly, this study identifies how various factors (e.g., environmental heterogeneity, physical habitat characteristics, array configuration, etc.) could influence how effects from different stressor-receptor interactions manifest. In addition, it cautions against the indiscriminate application of monitoring results across differing marine ecosystems without an appropriate level of empirical data collection using standardized methodologies to validate assumptions and confirm expectations.

While much of the work outlined above can be undertaken in the near term to improve our understanding of the potential effects of arrays, it is crucial to remember that ecosystem components and stressors do not exist in isolation, and as the MRE sector grows, relationships between stressor-receptor interactions may amplify impacts at wider spatiotemporal scales (see below). Research on this subject may become important in the future and could be conducted alongside efforts to understand ecosystem-level effects and cumulative environmental impacts of MRE development (see Sections 9.2 and 9.3).

9.2. HOW CAN ECOSYSTEM APPROACHES SUPPORT INTEGRATED MANAGEMENT OF MRE?

This section is a summary of a study in preparation (Le Marchand et al. pers. comm.) in which the authors assessed the application of the ecosystem approach to the MRE context, especially by leveraging the lessons learned from its application to other marine sectors.

9.2.1. THE NEED FOR AN ECOSYSTEM APPROACH

The coastal ecosystems into which MRE is developed are already subject to numerous pressures such as climate change, fisheries, extraction of raw materials, maritime transport, tourism activities, contamination, and underwater noise from diverse sources. Marine ecosystems are based on complex networks, linking biological components and environmental parameters in a dynamic balance. Any additional pressure from the installation and operation of MRE devices can therefore have direct effects on one or more components of the ecosystem, and indirect effects on other, related components. However, the current approach of investigating environmental effects of MRE looks at effects of each stressor-receptor interaction on individual species and in isolation, even though species are parts of an ecosystem and linked by food web interactions.

The ecosystem approach is a technique for environmental management that incorporates both natural and human-made components into the biotic and abiotic aspects of ecosystems within a comprehensive framework, founded on an all-encompassing understanding of how ecosystems function (Borja et al. 2016). With the use of the ecosystem approach, stakeholders can thoroughly evaluate a range of choices for the sustainable development of MRE technologies, taking into account their effects on the environment and any potential ecosystem-level ramifications (Hammer 2023). Supporting a systematic understanding of ecosystem-level effects and coordinated management of marine environments is an ongoing challenge. Using both qualitative and quantitative data, integrated approaches provide relevance to the causal linkages between complex ecological and socioeconomic processes that support the coexistence of societies and ecosystems (Isaksson et al. 2023).

To support an integrated management of MRE development worldwide and minimize impacts on ecosystem processes, an ecosystem approach must be applied to: (1) identify any resulting disruptions to ecosystem functioning and services; (2) quantify and contextualize the magnitude of any such disruptions; (3) track the efficiency of management responses; and (4) model changes to the structure and function of the ecological processes.

9.2.2. APPROACHES AVAILABLE FOR APPLYING AN ECOSYSTEM APPROACH TO THE MRE CONTEXT

Le Marchand et al. (pers. comm.) reviewed the ecosystem approach numerical tools that are commonly implemented in various marine studies and assessed how they might be applied to the MRE context. Understanding community structure, species composition, and ecological roles on a qualitative and quantitative level is necessary for managing marine ecosystems. The increasing reliance of operational and strategic planning on quantitative models is driving society's goal of predicting how the ocean will respond to disruptions. However, such methods can be prohibitively resource intensive, or inconclusive when available data is poor. Qualitative models can provide a rigorous alternative. According to Dambacher et al. (2003), qualitative models offer an unweighted perspective on the direct and indirect impacts that may result from the addition of pressures such as MRE devices.

The ecosystem approach extensively relies on ecosystem models that can be used to address a wide range of issues and situations. They can be employed to characterize ecosystems and their complexity, consider interspecific interactions, define indicators, and contribute to the implementation of management plans by decision-makers. These models can be data-intensive due to their quantitative structure and the size and complexity of some ecosystems; each model has its own scope, emphasis, data needs, mathematical foundations, and ecological assumptions. The most promising numerical modeling techniques in the MRE context are listed below.

Minimum Realistic Models are limited to elements of an ecosystem that significantly interact with the species or activity being studied. In the MRE context, these models might be helpful in places where species of particular concern are expected to be impacted by MRE devices. The Models of Intermediate Complexity for Ecosystem assessments (MICE) consider the dynamics of key components of ecosystems and the factors influencing them, and have been primarily used in fisheries and river management (Plagányi et al. 2014). Bayesian models are based on conditional probabilities and a network of nodes that represent the cause and effect relationships within a system, and are mostly used in the context of energy-generating technologies, fisheries, conservation, and offshore wind energy (Adedipe et al. 2020; Trifonova et al. 2021).

Size-Based Models explore the role of size structure in marine ecological processes. These modeling approaches have been most frequently used to examine the effects of fisheries and climate change on pelagic ecosystems. Because of their efficiency, they can also be applied to questions around MRE development. Mizer is a dynamic multispecies size-spectrum model that tracks individual sizes and uses individual physiological rates and predation preferences to infer population-level dynamics (Woodworth-Jefcoats et al. 2019). Mizer is computationally efficient and easy to implement, but not inherently spatial. In contrast, the Object-oriented Simulator of Marine ecOSystem Exploitation (OSMOSE) is a multispecies individual-based model, which assumes opportunistic predation based on size adequacy and spatio-temporal co-occurrence between a predator and its prey (Halouani et al. 2016). Both models have been used to explore fisheries and climate change questions and could easily be extended to MRE.

Trophic-Based Models represent the food web in an ecosystem, from low trophic levels (e.g., phytoplankton) to top predators. These models may help address a variety of potential MRE impacts, such as artificial reef or reserve effects, since they are based on the interaction between prey and predator and include intricate representations of environmental dependencies and impact-response functions. Ecopath with Ecosim (EwE) use spatial-temporal dynamic simulations to study the energy transfer throughout the food web (Christensen & Walters 2004). The interface can dynamically depict human causes of disturbance as well as environmental forces. EwE is largely used in fisheries, climate change, offshore wind energy, and coastal development (Serpetti et al. 2021). An alternative approach, Linear Inverse Models (LIM), calculates the flow of the food web from empirical data using inverse modeling. This approach is most often used to model questions related to plankton communities (van Oevelen et al. 2010).

End-to-End Models provide a holistic representation of the ecosystem, integrating both biological compartments (low and high trophic levels) and physical processes, as well as anthropogenic aspects, which could make them relatively straightforward for application to the MRE context. Atlantis includes physical environmental drivers and biogeochemical processes spanning food web- and habitat-mediated interactions, as well as human uses of marine and coastal areas and their management arrangements (Pethybridge et al. 2020). StrathE2E2 is an ecological mass-conserving dynamic model coupled with a fishing fleet model (Thorpe et al. 2022). Both models are employed for fisheries- and climate change-related issues, as well as conservation and coastal development topics.

In addition to models, the ecosystem approach often employs indicators to express effects and changes in ecosystem structure and functioning in terms of management measures that can address them (Trifonova & Scott 2024). The indicators should ideally match the characteristics or services of the ecosystem in which stakeholders and policymakers are interested. A suite of indicators spanning various data, ecosystem components, and processes is ideal, as no single indicator can fully capture the dynamics of an ecosystem. Some examples of such indicators are listed below.

Species- or functional group-based indicators that pertain to the biomass, production, or consumption ratios of species, as well as the species and functional group composition. Stakeholders may easily comprehend these types of indicators, but users must be mindful of how specific an indicator is to the activity of interest, as some are sensitive to various environmental stressors. In the MRE context, potential species-oriented indicators may be used to evaluate the artificial reef effect of devices and associated infrastructures (Raoux et al. 2018).

Size-based indicators, that are traditionally used in a fishery context, correspond to changes in the structure of fish communities. These indicators, such as the Large Fish indicator and the Typical Length indicator, may be useful to evaluate whether the prohibition or restriction of fishing operations inside MRE arrays has created a potential reserve effect, similar to that of a marine protected area, consequently increasing the size of the targeted organisms (Roach et al. 2018). However, signals in size-based indicators may take a long period of time to become evident, based on the growth rate of the target species.

Functional indicators relate to the functioning of the ecosystem and food web, and the role of species within the ecosystem. Trophic-level based indicators are at the interface between structural and functional indicators. Both indicators inform the role played by individual species (or groups) considering their trophic level and biomass (Pauly 1998). These indicators could be pertinent to MRE, where species at different trophic levels may be affected differently.

Ecological network analysis indices are designed to integrate the intricacies, dynamics, and natural fluctuations of the ecosystem while examining interactions to discover and describe emergent characteristics. While they are more difficult for stakeholders to comprehend than structural indicators due to their complexity, they offer in-depth information on ecosystem dynamics and the impacts of ecological drivers. In addition, they are among the few indicators to consider ecosystem structure and functioning (Safi et al. 2019).

9.2.3. APPLICATION OF THE ECOSYSTEM APPROACH TO THE MRE CONTEXT

Although few studies to date have applied an ecosystem approach to MRE development (e.g., Alexander et al. 2016), the approach has been employed in the context of other anthropogenic marine activities (e.g., offshore wind, fisheries management) in ways that may be transferable to MRE. The ecosystem approach may provide answers to certain environmental questions that have been raised with the development of MRE.

The main effects that may occur as a result of MRE development on the behavior of megafauna (i.e., marine mammals, diving seabirds, elasmobranchs, fishes, and large invertebrates) are due to underwater noise and EMF emissions, as well as the risk of collision with moving parts of turbines. These effects can vary greatly among trophic groups, MRE technologies, and project sites. Each of these effects could lead to avoidance of an MRE development area by numerous individuals of multiple species from various trophic levels, ultimately resulting in a trophic cascade for the impacted ecosystem. Even though changes in animals' behavior related to various stressor-receptor interactions may be limited and more research is required, the impacts of a trophic cascade could have lasting consequences on ecosystem structure and function (Ripple et al. 2016). Integrating such intricate and dynamic changes into ecosystem approach models remains a challenge.

Submerged structures can create an artificial reef effect that may boost local species richness and attract a variety of animals, such as detritus feeders, benthic predators that come to feed on biofouling, and organisms that seek shelter in these habitats, such as juvenile fish aggregating on and around structures. The artificial reef effect can improve biomass and species richness while also enhancing the amount of organic matter in the ecosystem (Sheehan et al. 2020). Because of this income of new species and increase in biomass, fish aggregation around MRE infrastructure and the artificial reef effect may, directly or indirectly, cause a trophic cascade in ecosystem structure that is mediated by feeding interactions (Figure 9.2). Such changes in habitats caused by MRE devices could lead to changes in the structure and functioning of the entire food web within the area of an MRE array. Applying the ecosystem approach through an ecosystem model such as OSMOSE or EwE enables the inclusion of a diverse set of species or functional groups to assess their trophic interactions (Raoux et al. 2017).

When other human activities are completely or partially prohibited close to MRE devices as a safety precaution, a reserve effect may occur. Restricting access to the region and reducing fishing pressure can increase the biomasses of fish, crustaceans, and mollusks (Alexander et al. 2016). This may, in turn, lead to a spillover effect (Figure 9.2). Fisheries populations that have been overfished may be able to recover because of biomass increases facilitated by MRE infrastructure. The fishing industry has raised questions regarding the reserve effect and resulting potential for spillover. Consequently, it has been the subject of numerous ecosystem approach studies, using EwE models within the context of both MRE arrays and offshore wind farms (Alexander et al. 2016; Halouani et al. 2020).

Large-scale development of MRE arrays may influence physical oceanographic processes that control an ecosystem, like waves, tides, currents, temperature, or salinity (Whiting et al. 2023). For example, a change in turbulence could lead to changes in community patterns for fish, benthic invertebrates, and macroalgae (du Feu et al. 2019). However, site-specific differences are likely, and it may be challenging to generalize and extrapolate across locations. Biogeochemical models provide a connection between the ecosystem dynamics of lower trophic levels (e.g., phytoplankton and zooplankton) and marine biogeochemistry (e.g., water quality, nutrients) (van der Molen et al. 2016). Such models could be implemented with more realistic array sizes and configurations to consider the effects of changes in oceanographic systems around MRE arrays on lower trophic levels and their productivity. Additionally, physical-biogeochemical models could be coupled to trophic models in end-to-end modeling within the ecosystem approach to explore questions related to oceanographic changes due to the presence and operation of MRE arrays.

Lessons learned from applications of the ecosystem approach to other anthropogenic marine activities can be applied to assessing the potential ecosystem-wide effects of MRE development. For example, trophic interactions in an ecosystem modeling framework would be appropriate to study the potential MRE-related effects on predators as these interactions demonstrate how targeted species may respond to varying degrees of pressure (Kiyota et al. 2020). As such, models used in the fishery approach, such as OSMOSE, Mizer, EwE,

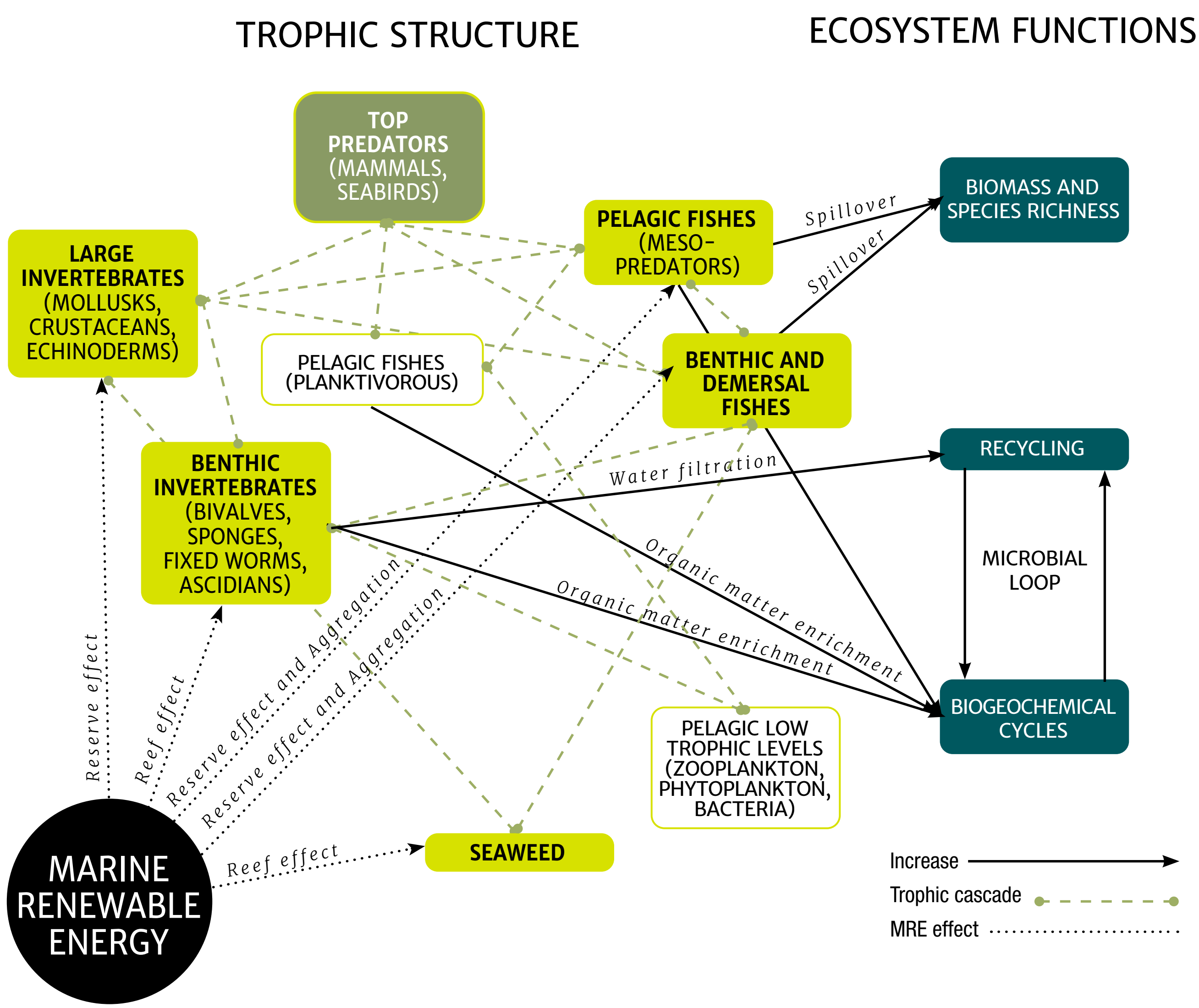

Figure 9.2. Schematic representation of changes in habitats from marine renewable energy (MRE). The effects are represented by arrows, with direct effects and ecosystem compartments directly affected shown in bold. The trophic cascade is presented in a different color than the responses for ease of interpretation.

or Atlantis, could be useful for answering questions around MRE (Shin and Cury 2004; Genner et al. 2010). In addition, MRE projects will be developed in coastal ecosystems that are already subject to pressures from climate change, such as rising seawater temperatures, ocean acidification, hypoxia, and disruption of nutrient cycling. In turn, such pressures contribute to changes in the physiology and fitness of organisms, and shifts in species abundance, distributions, and phenology (Poloczanska et al. 2016). These interacting pressures should be taken into account for future MRE planning, notably through adaptive management strategies that preserve the resilience of important species and the ecosystem as a whole (Engler 2020; see Chapter 6).

Many ecosystem models used to study the influence of climate change on marine communities and food webs (Tittensor et al. 2021), such as size-based and coupled physical-biogeochemical models, could be applied to MRE. Furthermore, MRE sites may be used for multiple purposes, such as aquaculture or tourism, which may enable the co-development of other activities along-side MRE projects (Garavelli et al. 2022). The ecosystem approach and associated tools can be used to study the combined effects of pressures from varying activities at the same site to help define the best management strategies (Le Marchand et al. pers. comm).

9.2.4. CONTRIBUTIONS TO UNDERSTANDING SYSTEM-WIDE EFFECTS

In many parts of the world, the application of an ecosystem approach to MRE has not yet been considered. However, the tools to support an ecosystem approach relevant to MRE already exist and are being used routinely for managing fisheries, offshore wind farms, climate change, and various other assessments of the marine environment, as described above (see 9.2.2). When MRE devices are installed in ecosystems already subjected to natural and/or various anthropogenic pressures, the cascading responses can be difficult to anticipate. The models developed in support of an ecosystem approach for other ocean uses recreate the local food web and environmental parameters to accurately model the effects of a set of pressures on a particular site. Because of this, they are particularly well suited for creating scenarios for the expansion and management of MRE, considering local issues specific to a project site. To facilitate the application of an ecosystem approach to the MRE context, five important points should be addressed in the near future: (1) continue the ongoing consolidation of knowledge on the potential effects of MRE devices and arrays on their surrounding environment to provide risk mitigation strategies (Copping & Hemery 2020); (2) improve the quality of the fine-scale and local data integrated into models; (3) consider differences in the spatial and temporal scales of impacts (Hasselman et al. 2023); (4) consider the uncertainty in ecosystem models (Geary et al. 2020); and (5) couple models and approaches to achieve a holistic ecosystem approach.

Ecosystem management involves understanding the complex interactions between organisms, processes, and scientific disciplines. By providing an overview of the system and its pressures, ecological models and indicators enable the development of scenarios and contribute to the execution of management plans created in collaboration with decision-makers, accounting for a larger context of multiple-use management with potential for cumulative environmental effects (Declerck et al. 2023; Fulton et al. 2019). Since the Convention on Biological Diversity defines human societies as an integral part of the ecosystem, the ecosystem approach considers that ecosystems and human societies are intricately linked and supports integrated studies. However, most applications of the ecosystem approach so far have been based solely on ecological components, due to a lack of knowledge regarding the consequences of ecosystem changes on societies through the relationship between people and the environment. A true ecosystem-based approach requires interdisciplinarity between ecological and social sciences, which can be lacking for the marine environment (Causon and Gill 2018), although this more rounded approach has been growing in application, particularly over the past couple of decades (Trifonova et al. 2022). Nevertheless, while many obstacles remain to be addressed and overcome, the ecosystem approach is a powerful tool for guiding decision-making related to MRE development with a broader view of the potential effects at the ecosystem level.

9.3. CUMULATIVE EFFECTS

This section is a summary of a study in preparation (Fulton et al. pers. comm.) in which the authors assessed the application of a cumulative effects approach to the MRE context by leveraging the lessons learned from its application to other marine sectors.

9.3.1. THE NEED FOR CUMULATIVE EFFECTS ASSESSMENTS

Changes to ecosystem components brought about by the combined influence of past and present human actions (including climate change) are referred to as cumulative effects. Sequential or overlapping activities cause interactions to occur over space or through time in a single location, leading to cumulative effects. These activities may result from various aspects of a single development, multiple developments of a single type (e.g., multiple independent MRE developments in a region, or the construction of an array), or they may result from interactions between various sectors (e.g., fisheries, tourism, shipping, MRE, conservation, etc.). Cumulative effects arise in a variety of forms and can be categorized as additive or nonlinear (i.e., not the same as the sum of the individual pressures added together). Most of the variation observed among the different types of cumulative effects is associated with how nonlinear effects can be expressed (Figure 9.3; see also Section 9.1.2): one pressure may be dominant (thereby masking other effects); pressures may have a synergistic effect, producing a result that exceeds the sum of the individual effects; or pressures may interact antagonistically, producing a result in which the total effect is less than the sum of the individual influences.

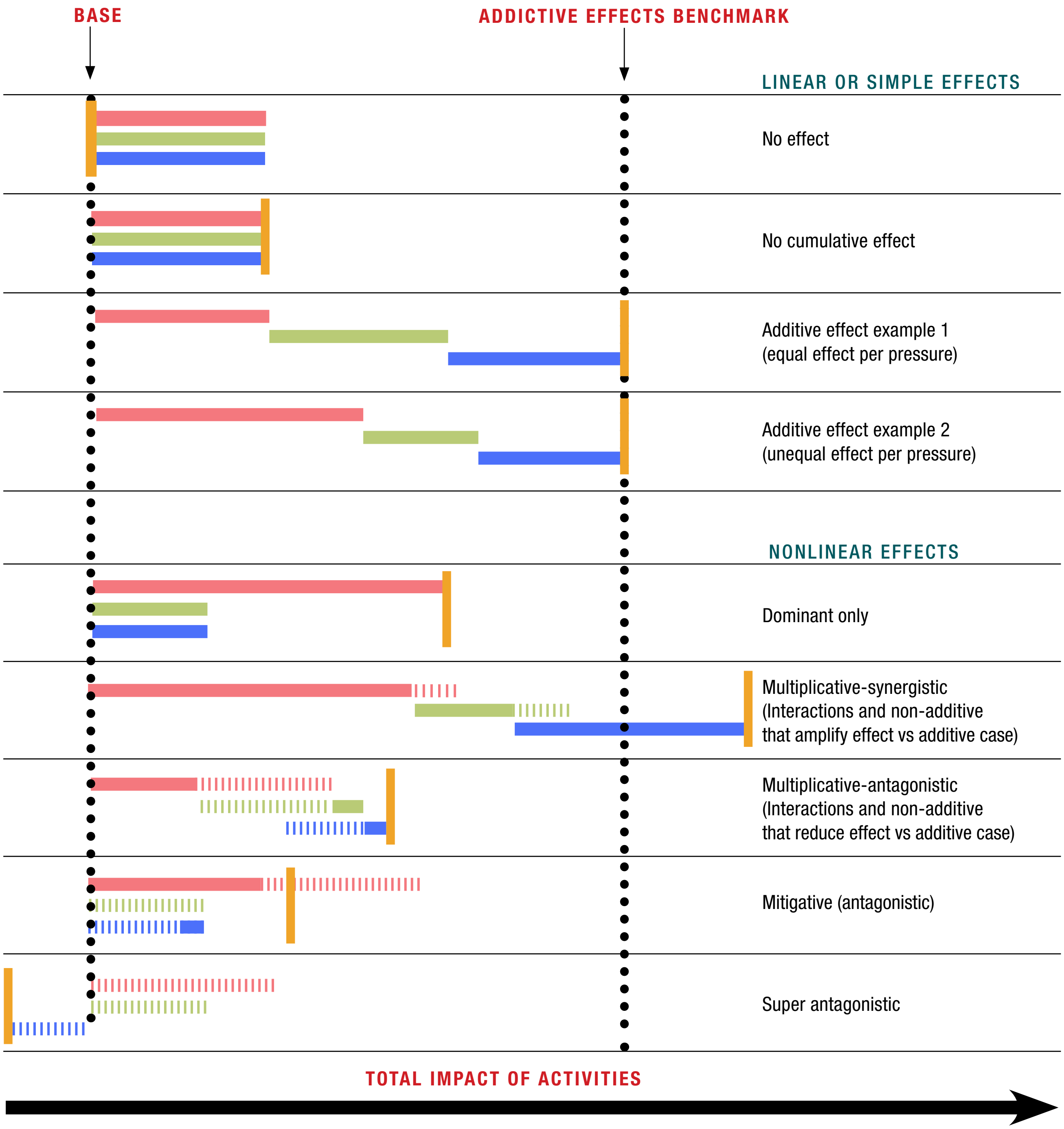

Figure 9.3. Schematic of the different types of non-cumulative and cumulative (additive and nonlinear) effects. Nonlinear effects are marked by interactions (hashed areas on each bar), meaning the outcomes do not simply add up to the linear sum of the individual effects. The no-effect and additive-effect benchmarks are shown as vertical black dotted lines where the levels resulting from other effects are cleared. (From Fulton et al. (2023) and modified from Halpern et al. (2008a))

A cumulative effects assessment (CEA), also called cumulative impacts assessment (CIA), is currently required in many countries for new offshore activities, including MRE development, as the maritime environment is increasingly utilized. In these jurisdictions, a project-level CEA is required as part of a consent application (i.e., as part of an environmental impact assessment [EIA]). Separately, researchers or government agencies may undertake a broad-scale CEA as part of a planning process, as multiple activities and phenomena of different kinds (e.g., MRE, offshore wind, fisheries, aquaculture, shipping, and climate change) can lead to compound (cumulative) effects, which means integrated strategic CEAs are necessary to assure marine use is sustainable in the long term.

Despite these demands for CEAs, there is typically a lack of guidance on the format and the critical role that a well-executed assessment may play in averting future conflict and issues. The benefits of a well-executed CEA are becoming increasingly recognized by regulators, practitioners, and researchers. Due to the absence of historical guidance on CEA content, practitioners have struggled to define what exactly constitutes a CEA. The issues surrounding and necessity for CEAs are increased by the dynamic character of marine ecosystems and the swift expansion of the maritime industries. Another complicating factor is that while the two different forms of CEAs (project scale and strategic scale) share fundamental concepts and workflow steps (e.g., scoping and hazard analysis, data gathering, consultation, analysis, management plans, and responses), they usually have vastly different scopes and use different tools.

Note that while academia (and some national jurisdictions) treat "cumulative impacts" and "cumulative effects" interchangeably—now more commonly using the term "cumulative effects", acknowledging that not all outcomes are necessarily deleterious—this is not universally the case. In some jurisdictions, particularly in the United Kingdom and the European Union, the terminology is not as interchangeable, with "impacts" resulting from the influence of an "effect" (i.e., an event or activity) on the receptor (e.g., ecosystem component). This is one of many instances where there are divergences around terminology and methodology between jurisdictions, practitioners, and academics.

9.3.2. APPROACHES AVAILABLE TO INVESTIGATE CUMULATIVE EFFECTS OF MRE

Expansion of urban and industrial developments on land in the 1970s and 1980s first drove a need to address cumulative effects (Cooper 1998). Between the 1980s and early 2000s, standardizing tiered-assessment approaches became the industry standard (Hope 2006). For example, CEA is a systematic method for identifying and evaluating the compound effects of multiple pressures or activities. Interest in marine CEAs rose sharply in the 2000s as compound pressures caused more conflict and as new analytical assessment methods were developed (Callahan & Sexton 2007; Samhouri & Levin 2012). Still, the broad scope demanded by such large-scale assessments resulted in data limitations that often precluded more quantitative approaches (Stelzenmüller et al. 2018).

Thus far, a portion of the techniques available for CEA have been used for MRE-relevant assessments, such as dynamic approaches, map-based methods, expert elicitation, and loop analysis. Map-based methods are most frequently used in industry applications, which overlay activities (and associated pressures) on ecosystem components, highlighting any potential hotspots (i.e., where multiple activities overlay multiple vulnerable species and habitats [Bergström et al. 2020; Garavelli et al. 2022]). These maps are a reasonably interpretable product that, when done well, can provide the transparent analyses increasingly demanded by the growing list of stakeholders interested in the true sustainability of the growth of marine industries.

Academia also makes use of geographic information system (GIS)-based approaches (e.g., Halpern et al. 2008b; O'Hara et al. 2021) because of their ease of use, even though it is widely acknowledged that these methods do not address a sizeable portion of known marine effects (Crain et al. 2008; Hodgson & Halpern 2019; MacDonald 2000).

A broader set of tools is used within academia, particularly within the analytical steps of a CEA. One of the most used approaches remains expert elicitation (also known as expert judgement). This may be the opening step of a larger process (i.e., the hazard analysis step) or it may be the entire analysis. In most instances, experts are asked to identify connections between activities or drivers and associated stressors, and then they may be asked to score aspects such as the likelihood of the stressor occurring, the level of exposure of each ecosystem component to the stressor, or the sensitivity of the components to the stressors (e.g., Singh et al. 2017).

Quantitative tools are becoming more commonly used. Among the most straightforward to apply are quasi-quantitative methods such as loop analysis, which uses network and flow diagrams to map the important connections and feedback in the system, especially around offshore energy generation or around ecosystem functioning (Niquil et al. 2021; Raoux et al. 2018). This is a very flexible approach that brings together different knowledge and information types and can project the possible effects of expansion or contraction of an activity (e.g., increase development of energy generation infrastructure) on other parts of the system.

Fully quantitative model-based approaches are also being used for a subset of consenting, construction, and development-related questions. For example, ecosystem models such as EwE (historically used to consider fisheries and conservation questions) are being applied to address question around multi-use platforms off Scotland that include both aquaculture and MRE (Serpetti et al. 2021). This method has been expanded upon to forecast possible future cumulative effects within the existing development timelines. These simulation-based approaches—or, alternatively, GIS-based approaches—enable to highlight trade-offs in terms of achieving environmental and other objectives. They can be used to explore co-designed (as in collaboratively defined) scenarios around alternative development and spatial planning options and the deployment of MRE within a multi-sector, multi-use waterway context.

As users of simulation models and other highly quantitative methods can struggle to find sufficient data to support the methods reliably, hierarchical methods that attempt to maintain ease of use, while incorporating a quantitative understanding of indirect effects and feedbacks, are under development (Fulton et al. 2023). More recently, the need for repeatability and transparency for planning purposes has also seen a growing number of research and assessment groups working on novel integrative methods. Many of the most easily accessible tools (e.g., Tools4MSP, Symphony, and the other tools listed in Casimiro et al. [2021]) are often aimed more at strategic CEAs rather than project-level CEAs.

The nascent nature of many MRE projects and the relative newness of more in-depth CEA in planning and EIAs mean few applications go beyond the hazard analysis step (i.e., identifying what may pose a cumulative risk) to evaluate actual risk or realized effect. This is partially because they are usually applied in proactive planning, before developments are approved, rather than in post-deployment assessments, which take place after a development is implemented and the footprint is monitored over time. Moreover, the relative youth of MRE has not allowed sufficient time to monitor changes over time.

Implementation of project-level CEAs has also been mixed. The most cursory of assessments use expert opinion and statements such as "no significant cumulative effects anticipated". In other jurisdictions (such as the Netherlands), clear mandates exist from regulatory agencies (and across sectors) requiring the nesting of project-level CEAs within regional CEA contexts. The quality and consistency of CEAs will improve for MRE and other offshore industries once more jurisdictions have consistent terms of reference, and terminology across assessments and sectors are routinely applied (Hague et al. 2022). Appropriately rigorous, standardized methods that fit naturally within a regional context would minimize poor public perception, legal frustration (e.g., when judicial reviews and lawsuits are put forward by interest groups dissatisfied with the rigor), and the potential for undesirable environmental outcomes witnessed as a result of variable quality of CEAs undertaken in the consenting processes of other industries.

Cross-scale problems that plague CEAs and the system-level evaluation of MRE could be addressed by standardized and coordinated data collection during assessments, with results widely shared. If not addressed, these problems will only get worse as multi-user marine spaces become more crowded and access contested. Such a system-level approach would assure that industry- and society-wide benefits arise from investment in monitoring data.

9.3.3. APPLICATION OF CUMULATIVE EFFECTS ASSESSMENT TO THE MRE CONTEXT

The paucity of detailed supporting knowledge on marine ecosystems and cumulative effects and the complicated nature of comprehensive CEA mean that the most commonly used approaches must simplify one or more dimensions of the assessment to make the task tractable, especially when data availability and accessibility are an issue (Verling et al. 2023). For example, they might concentrate on a smaller number of interacting sectors, a smaller spatial and temporal scope, or decide not to take nonlinear interactions or indirect effects into account (Korpinen & Andersen 2016). Few studies exploring MRE development also consider various other maritime sectors and their trade-offs and relationships, either during the hazard analysis stage or during the more quantitative assessment or planning stages (Turschwell et al. 2022; Turschwell et al. 2023).

Further development of MRE-specific considerations in CEAs is needed, along with addressing priority data gaps, refining assessments in a cost-effective manner, and learning from the greater body of integrated ocean management work. Recommendations stemming from reviews of MRE-relevant CEAs include:

- Multiple stressors from multiple MRE and non-MRE activities or sources need to be considered; this will require connecting project-level and strategic-level planning-oriented CEA processes.
- Relevant and proportionate approaches should be standardized across projects, sectors, and jurisdictions.
- Framing and context (e.g., scales, environmental drivers, human activities, pressures, and ecosystem components) must be transparent with clear documentation.
- Risk criteria need to be set in conjunction with stakeholders and decision-makers prior to any analyses, as well as be project- or plan-specific, based on the best available science, and proportionate to the project or plan to be assessed.
- Where possible, predictive models should be used to assess cumulative effects, acknowledging caveats and surrounding uncertainties for the chosen approach. If this is not possible and/or proportionate, professional judgment (or expert elicitation) should be based upon the best available science and transparently documented (i.e., there must be a clear description of the CEA method used).
- Assumptions made during the CEA and any uncertainties, knowledge gaps, and associated assessment confidence must be communicated clearly and transparently.

Despite progress made to date, significant knowledge gaps remain, most importantly how to assess nonlinear interactions clearly and cost-effectively, especially across drivers and sectors. This relates not only to the technical methods but also to who should participate in the assessments (e.g., extent of involvement with communities, traditional owners, other industries, etc.) and how the results—including the uncertainties—should be explained to non-technical audiences. Stelzenmüller et al. (2020) identified common factors that lead to uncertainty in assessing cumulative effects:

- **Context** – the policy drivers for the CEA (such as the problem framing stage and boundaries established by policies and legislation) and defined risk criteria against which the cumulative effects are judged (which may be established by project assessment terms of reference)
- **Cause-effect (impact-response)** – ambiguity regarding causal linkages and externalities outside the immediate CEA context
- **Inputs** – information on ecosystem components, the efficiency of any management methods being taken into consideration, or the pressures and their associated effects that constitute the basis of the assessment
- **Recognized ignorance (also known as structural uncertainty)** – a fundamental lack of clarity on the system's true relationships and mechanisms and how they are represented in the CEA
- **Knowledge** – this reflects uncertainty due to information gaps and might be resolved by focused research or data collection
- **Variability** – due to a system's inherent variability (e.g., seasonal, interannual, interdecadal)
- **Statistical (analytical) uncertainty (or parametric uncertainty)** – often addressed by sensitivity analysis
- **Scenario uncertainty** – around the variety of potential configurations and results of development, planning, and management that are taken into consideration

Although conveying uncertainty can be challenging, Stelzenmüller et al. (2020) offered strategies for handling it effectively and suggest a method similar to that of the Intergovernmental Panel on Climate Change (IPCC 2022), in which a confidence matrix is provided to represent the reliability of the process and the data that forms the foundation of the CEA. Following these recommendations and applying the lessons learned from other industries' CEAs will enable avoiding repeating past errors and make for a more efficient implementation of CEAs in the MRE context.

9.3.4. CONTRIBUTIONS TO UNDERSTANDING SYSTEM-WIDE EFFECTS

As MRE continues to expand and scale up, the number of project- and strategic-level CEAs is likely to grow. MRE-related assessments will benefit from CEAs in other sectors, including integrated ocean management.

CEAs are founded on understanding system connections, processes, and responses. Lessons from more established industries (e.g., fisheries, conservation) strongly suggest that such assessments have helped avoid outcomes and decisions that preclude future opportunities. CEA experience from other industries suggests that, while map-based methods are simple and rapid, more dynamic model-based analyses would be preferable for long-term, large-scale MRE projects. These analyses allow for more in-depth quantification and consideration of risks that are non-stationary and evolving across many system properties. These dynamic modeling platforms can consider indirect effects, but the effort is considerably more resource- and data-intensive than the additive assessments. Using system-scale models during the early planning stages and periodic review cycles based on more specialized and focused models can help manage resource demands without sacrificing the power of the modeling approaches, as demonstrated by long-term experience from other fields, such as fisheries (e.g., Plagányi et al. 2014). Using models in this way requires fewer resources to apply and means quantitative methods can be used more frequently within an adaptive process to update understanding or recommended responses for specific species or activities of concern.

Although seldom used in the past, semi-quantitative or quantitative models can be used to examine indirect effects; for example, the most commonly used GIS-based methods assume additive but otherwise independent effects (Halpern et al. 2008b; Jones et al. 2018). This is partially due to the lack of observational data on the compound and cascading effects of the many stressor-receptor interactions associated with MRE and other uses of the marine environment. This will need to change in the near future as research on the shifts and consequences caused by climate change has revealed that not only may individual stressor-receptor interactions be non-linear, but that the existence of additional factors may alter a relationship and magnify outcomes (IPCC 2022).

9.4. CONCLUSION AND RECOMMENDATIONS

Marine ecosystems worldwide are facing growing pressures, especially from climate change and human activities at sea, and although the MRE industry has set out to reduce reliance on fossil fuels and therefore mitigate the impacts of climate change, the installation, operation, and decommissioning of MRE devices in the marine environment cannot be left out of the picture. As arrays of MRE devices are deployed in multi-user marine spaces, there will be a need to assess the environmental effects in the context of other anthropogenic activities (e.g., other MRE developments, other energy industries, fishing, shipping, tourism, etc.). The pressures from MRE single devices and large-scale commercial arrays on the marine environment can be placed in a system-wide context by using the ecosystem approach and CEA methods described in this chapter, as well as the framework established to investigate the environmental effects of scaling up to arrays. However, these approaches can be challenging to implement, especially due to the lack of necessary data, and some may not be cost-effective; thus, assessments need to be proportional and risk based.

While stressor-receptor interactions have, to date, been studied mostly in isolation from each other, MRE devices are installed within functioning ecosystems and food webs, where the effects of a single stressor-receptor interaction may impact other components of the system, through top-down and/or bottom-up cascading effects. However, there is currently little, if any, information available on compound and cascading effects from the different stressor-receptor interactions; desktop and field studies are needed to investigate these impact-responses. Future research endeavors need to focus on the associations between various stressor-receptor interactions and their cumulative effects, especially in the context of multiple anthropogenic activities within a region and/or over time. Applying the approaches and framework described herein would assist with determining these system-wide interactions and contribute toward a more comprehensive understanding of the environmental effects of MRE technologies.

Moreover, improvements are necessary regarding scientific knowledge and the quality of numerical models in order to efficiently apply a system-wide approach to the MRE context; however, different priorities should be given to the various improvements needed as laid out in Figure 9.4. As described in Chapter 3, numerous knowledge gaps remain in our basic understanding of the effects of the stressor-receptor interactions, especially on animal behavior, physiology, and fitness. Few stressor-receptor interactions to date have been investigated in the context of climate change; the effects of changes in habitat or oceanographic systems and of displacement due to MRE may become challenging to discern from those of climate change. Similarly, other activities at sea may enhance, override, or mask some of the environmental effects of MRE, such as those from the exposure to underwater noise or EMF emissions. Existing numerical models need improvement to be able to investigate these effects in a system-wide approach. In addition, it is crucial to strive for a complete understanding of an ecosystem's initial state, as well as the collection of fine-scale and local data to adequately represent all MRE-environment interactions with a modeling study. Numerical models must be able to account for these site and ecosystem specificities, which may come in the form of very large and complex datasets. Lastly, with the expansion to large-scale commercial arrays and MRE projects that will be operational over decades, it is essential to understand how environmental effects may encompass larger spatio-temporal scales. Therefore, numerical approaches and frameworks must be able to model the effects at different scales. Only then will the numerical tools provide a probabilistic approach to investigate the system-wide effects of MRE development.

Nonetheless, and despite these necessary improvements, tools are currently available for the MRE community to start applying a system-wide approach to existing and upcoming MRE projects, keeping in mind the caveats listed above. Most importantly, researchers and practitioners should be as transparent in their processes as possible, and share data, results, and uncertainties publicly, in order to facilitate more comprehensive and informed investigations, reduce duplication of efforts, and increase the overall confidence and trust in MRE research outcomes.

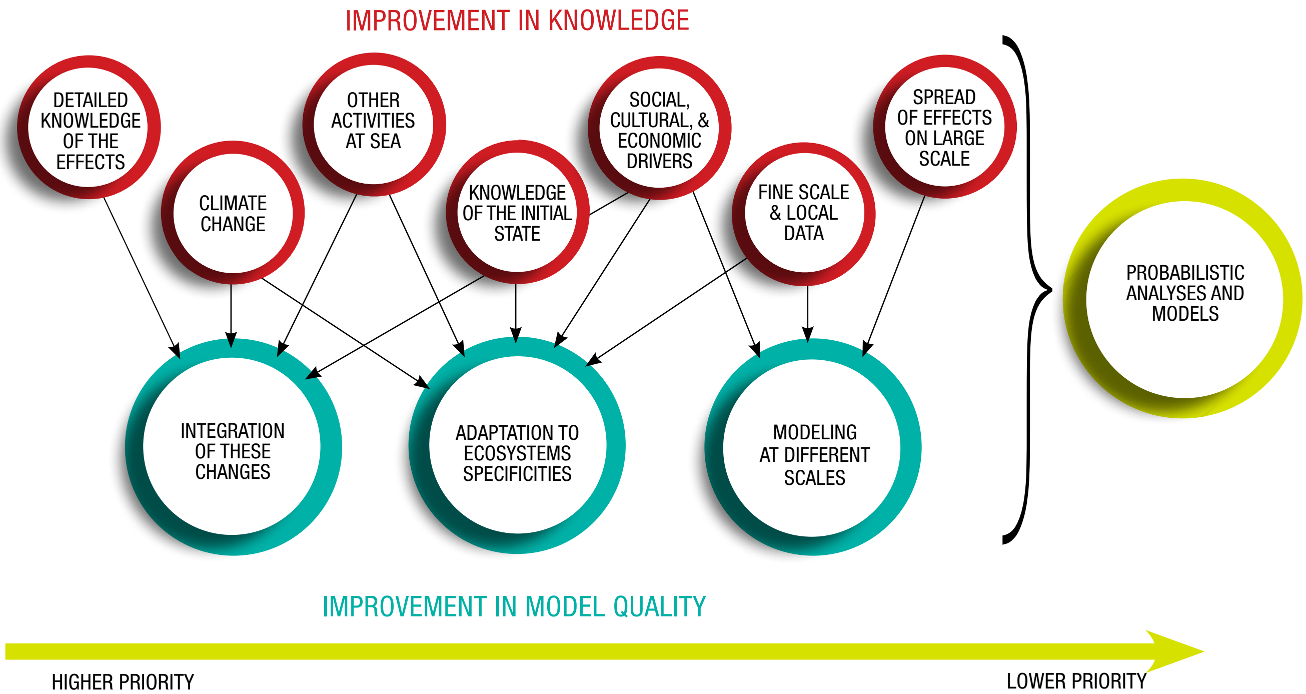

Figure 9.4. Different priorities should be given to improving knowledge and model quality, as they need to be carried out to model system-wide environmental effects of marine renewable energy.

Recommendations for advancing the implementation of a system-wide approach to understanding the environmental effects of MRE include:

- Improving the general understanding of physical and biological processes, ecosystems' characteristics, and social and economic factors in regions targeted for MRE development;
- Identifying MRE-specific data gaps that prevent applying a system-wide approach and a path toward collecting these data (e.g., laboratory experiments, field observations, etc.; see Chapter 3);
- Considering uncertainty in all modeling efforts for credible management decisions;
- Adapting system-wide investigations to MRE projects' lifecycle stages (e.g., construction, operation, decommissioning) and to specific scientific questions and management needs;
- Identifying thresholds in responses to the stressor-receptor interactions and tipping points past which system-wide effects may become irreversible; and
- Advocating for increased international cooperation and funding, which are essential to supporting data availability and science-led system-wide environmental effects assessments that can translate into lifting barriers to consenting MRE arrays.

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