Science of the Total Environment 904 (2023) 166801

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

‘Scaling up’ our understanding of environmental effects of marine renewable energy development from single devices to large-scale commercial arrays

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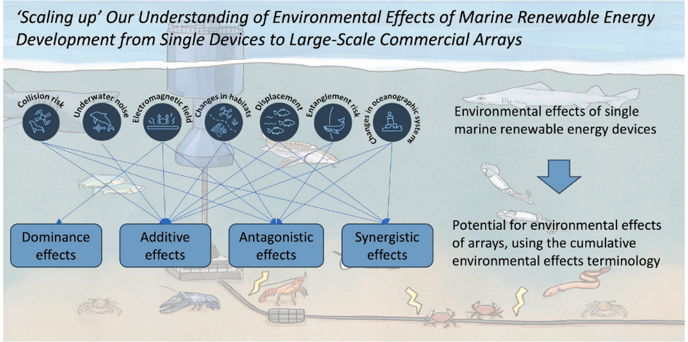
HIGHLIGHTS

- Marine renewable energy (MRE) growth is needed to help address impacts of climate change.
- MRE growth is impeded by uncertainty about how environmental effects manifest for arrays.
- We adapt and apply cumulative environmental effects terminology to stressors to conceptualize how effects ‘scale up’.
- Environmental effects of a stressor may be dominant, additive, antagonistic or synergistic.
- How effects manifest is dependent on various factors (e.g., environmental heterogeneity, array location and configuration).

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Martin Drews

Keywords:
Marine renewable energy
Commercial scale arrays
Stressor-receptor interactions
Environmental effects

ABSTRACT

Global expansion of marine renewable energy (MRE) technologies is needed to help address the impacts of climate change, to ensure a sustainable transition from carbon-based energy sources, and to meet national energy security needs using locally-generated electricity. However, the MRE sector has yet to realize its full potential due to the limited scale of device deployments (i.e., single devices or small demonstration-scale arrays), and is hampered by various factors including uncertainty about environmental effects and how the magnitude of these effects scale with an increasing number of devices. This paper seeks to expand our understanding of the environmental effects of MRE arrays using existing frameworks and through the adaptation and application of

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https://doi.org/10.1016/j.scitotenv.2023.166801
Received 31 May 2023; Received in revised form 8 August 2023; Accepted 2 September 2023

Environmental monitoring
Marine ecosystems

cumulative environmental effects terminology to key stressor-receptor interactions. This approach facilitates the development of generalized concepts for the scaling of environmental effects for key stressor-receptor interactions, identifying high priority risks and revealing knowledge gaps that require investigation to aid expansion of the MRE sector. Results suggest that effects of collision risk for an array may be additive, antagonistic, or synergistic, but are likely dependent on array location and configuration. Effects of underwater noise are likely additive as additional devices are deployed in an array, while the effects of electromagnetic fields may be dominant, additive, or antagonistic. Changes to benthic habitats are likely additive, but may be dependent on array configuration and could be antagonistic or synergistic at the ecosystem scale. Effects of displacement, entanglement, and changes to oceanographic systems for arrays are less certain because little information is available about effects at the current scale of MRE development.

1. Introduction

Persistent development and global adoption of renewable energy systems, including marine renewable energy (MRE) technologies (e.g., tidal stream and riverine turbines, wave energy converters), is a crucial component in addressing the impacts of climate change (IPCC, 2019, 2022; IRENA, 2020), ensuring a sustainable transition from carbon-based energy sources, and for meeting national energy security needs using locally-generated electricity (e.g., European Commission, 2022). Globally, the amount of potentially harvestable tidal stream power is estimated to be 1200 TWh yr^{-1}, while that for wave power is estimated to be 29,500 TWh yr^{-1}; sufficient to meet current global electricity demand (Mørk et al., 2010; IRENA, 2020). However, the share of MRE in global electricity generation has remained low at approximately 1 TWh yr^{-1} since 2015 (IPCC, 2022); falling well short of its potential due to the relatively small number of MRE devices deployed to date (i.e., single devices, small demonstration-scale arrays). To meaningfully contribute to addressing the impacts of climate change, the scale of device deployments must increase to large-scale commercial arrays (hereafter 'arrays') for ensuring a sustainable transition from carbon-based energy sources (Vennell, 2012; Malki et al., 2014).

Numerous obstacles to MRE expansion exist (e.g., high capital cost of technology development, lack of infrastructure for device deployment/maintenance, etc.), including difficulty obtaining regulatory approvals due to uncertain environmental effects (hereafter 'effects') of arrays (Neill et al., 2012; Kempener and Neumann, 2014a, 2014b; Copping et al., 2016). The limited scale of deployments to date has generated a paucity of post-installation data on effects that has generated uncertainty about their impacts on marine animals and habitats, and confounds our ability to differentiate between unknown (but perceived) and realized risks of MRE development for marine ecosystems (Copping et al., 2016; Copping and Hemery, 2020). A long-established framework for assessing the effects of MRE development focuses on understanding the interactions between 'stressors' (i.e., those parts of a device or system that may cause harm) and 'receptors' (i.e., those components of the ecosystem that may elicit some response to the stressor) (Boehlert et al., 2008; Boehlert and Gill, 2010; Copping and Hemery, 2020). Seven stressor-receptor interactions have been collectively recognized by regulators, stakeholders, developers, and researchers as key concerns post-installation (Copping and Hemery, 2020), and include:

- Collision risk for marine animals with tidal turbine blades or other device components,
- Effects of underwater noise on marine animal behavior and health from device operation,
- Effects of electromagnetic fields (EMFs) on marine species from cables and energized devices,
- Changes in benthic and pelagic habitats from anchors, foundations, and mooring lines,
- Displacement (i.e., attraction, avoidance, or exclusion) of marine animal populations from arrays of devices,
- Risk of entanglement of marine animals in mooring lines of floating devices, and
- Changes in oceanographic systems (e.g., water circulation, changes in wave heights, and sediment transport) from device operation and effects of energy removal from the system.

Our understanding of effects for these stressor-receptor interactions continues to improve for single devices and small pre-commercial arrays (Copping and Hemery, 2020; Copping et al., 2021; Gillespie et al., 2021). However, remaining uncertainties complicate the task of predicting how marine animals, habitats, and ecosystems will be impacted by arrays, and it is not realistic to assume that effects would scale linearly with the number of operational devices (Copping et al., 2016; Zhang et al., 2022). Effects of arrays are likely to be complex and nuanced, site specific and dependent on array configuration, cumulative in some form, and have potential for non-linear environmental responses. Thus, establishing generalized concepts for how effects may manifest with the development of arrays provides a foundation from which hypotheses can be formulated and tested to refine predictions and improve our understanding of the potential risks of 'scaling up'.

Informed development of such generalized concepts requires a multitiered approach incorporating modeling, experiments in controlled laboratory conditions and field settings, and the collection of empirical data to support (or refute) predictions and experimental results. This paper focuses on the development of generalized concepts for the seven stressor-receptor interactions, so that a robust scientific approach for developing and testing hypotheses can be applied to increase our knowledge of effects for arrays. This information is crucial for understanding risks and developing effective mitigation measures (as necessary) and is needed to facilitate the deployment of MRE technologies at scales that can make meaningful contributions for climate change, energy system transition and security. A brief overview of MRE technologies that are likely to comprise large-scale commercial arrays, and some of the previous work that has been conducted in support of establishing arrays is provided in the Appendix.

2. Methods

2.1. Defining 'large-scale commercial array'

No consistent definition exists in the literature about how many devices constitute a 'large-scale commercial array'. For the purposes of this study, we define this as 10–30 devices. We do not consider power generation capacity (e.g., megawatts of rated generation) in this definition, but rather the number of individual devices (wave energy converters, turbine rotors) that independently contribute to increasing the magnitude of effects for a given stressor. Under this definition, MRE technologies with multiple converters/rotors may be classified as arrays (albeit, typically small) and have intrinsic value for in situ testing of hypotheses and empirical data collection about how effects scale up.

2.2. Framework for understanding the scaling of environmental effects

In consultation with Ocean Energy Systems-Environmental (OES-E) analysts from around the world (experts in the environmental effects of MRE devices), we developed and applied a structured approach (i.e., multi-step framework outlined below; Fig. 1) for evaluating each of the seven stressor-receptor interactions, and conceptualizing how effects may scale up for arrays:

1. **Describe the stressor-receptor interaction.** Device deployment and operation can trigger various effects; the goal of this step was to describe the interaction.
2. **Summarize existing knowledge.** Existing knowledge about effects of the interaction for single MRE devices was summarized based on available literature (e.g., Copping and Hemery, 2020) and relevant surrogate industries.
3. **Define the nature of scaling up and identify any caveats that could influence how effects might manifest.** Generalized concepts about how effects of the interaction might scale up were developed using terminology adapted from the cumulative environmental effects literature (see below) and considering knowledge gaps that could influence our understanding.
4. **Identify the research required to improve our understanding of effects for arrays.** The most beneficial research (e.g., modeling exercises, laboratory trials, field studies) for testing the generalized concepts to increase our knowledge of how effects of the interaction scale were identified.

2.3. *Environmental effects terminology for MRE arrays*

Terminology does not exist to describe how effects of stressor-receptor interactions may scale with an increasing number of devices. While the cumulative environmental effects literature provides an informative framework for developing such nomenclature, that terminology is not easily or directly transferable because much of that research focuses on describing the nature of interactions *between* different stressors (e.g., habitat loss, invasive species, climate change, etc.) (Folt et al., 1999; Halpern et al., 2008; Carrier-Belleau et al., 2021). Here, we are specifically interested in understanding how the effects of the *same* stressor changes with the number of devices, and have adapted cumulative effects terminology for that purpose. Earlier work associated with Environmental Impact Assessments does consider different activities (e.g., construction, operation, decommissioning) of a single development or the implications of multiple developments of a similar type within a general region. The latter, in particular, is relevant but typically relies on expert opinion, and does not have the desired rigor around the terminology that we seek to establish. However, we can take lessons from prior discourse on cumulative effects from an ecotoxicological perspective that has its foundations in human health (Suter et al., 2003). There are some parallels in the experience of the U.S. Environmental Protection Agency (2002) in going from considering a single exposure to increasing (intensifying) exposure from a single source, to exposure from multiple concurrent pathways that are useful in this context.

To help illustrate how effects may scale up, let us denote an individual device by D_i. As the number of devices increases (i.e., D_1, D_2, …, D_i…, D_n), the effects for a stressor may be characterized by comparatively simple additive or more complex non-linear (e.g., multiplicative) effects due to synergistic and antagonistic interactions (Coors and De Meester, 2008). We outline several scenarios to describe these effects below, and provide definitions for this terminology in an associated glossary (Table 1).

2.3.1. *Scenario 1 – dominance effects*

Albeit unlikely, for some stressors the effect may not scale with the number of devices (Fig. 2; Folt et al., 1999; Halpern et al., 2008; Côté et al., 2016; Carrier-Belleau et al., 2021), and the effect from one device may overwhelm the effect from other devices in an array.

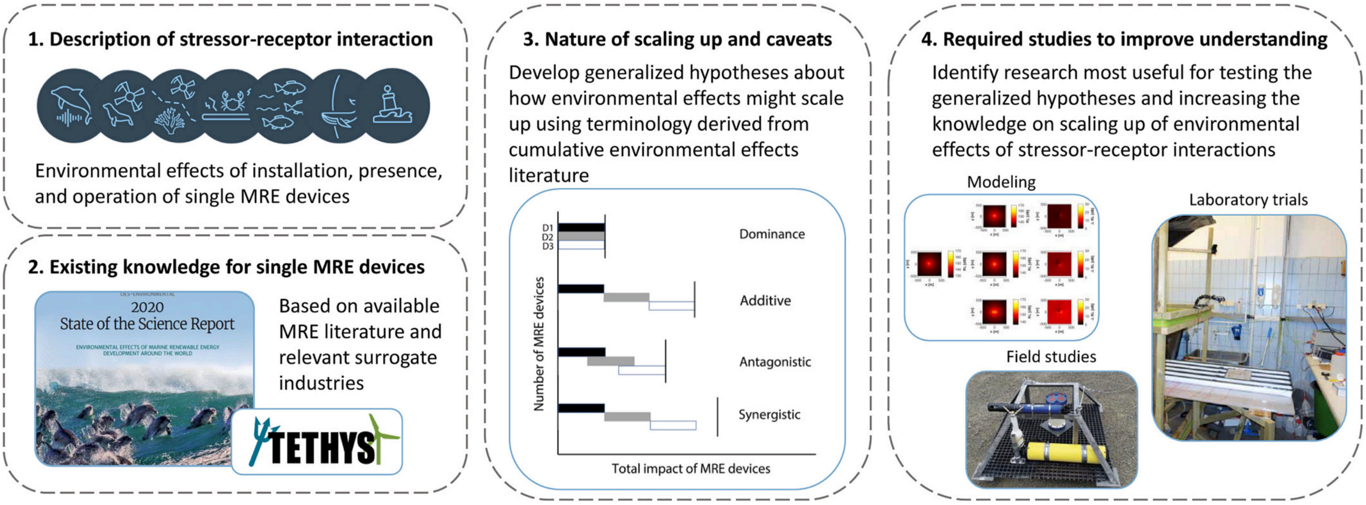

Fig. 1. Graphical representation of the multi-step framework developed for assessing each stressor-receptor interaction (icons from left to right: underwater noise, collision risk, changes in habitat, electromagnetic fields, displacement, entanglement, and changes to oceanographic systems) and conceptualizing how environmental effects may scale up from single marine renewable energy (MRE) devices to large-scale commercial arrays.

Table 1
Glossary of cumulative environmental effects terminology as applied to MRE arrays (derived from Folt et al., 1999; Halpern et al., 2008; Côté et al., 2016; Carrier-Belleau et al., 2021).

Term	Description
Dominance effects	The environmental effect from the first device (or its associated infrastructure) overwhelms the effect from additional devices added to an array so that only the signature/footprint of the first device/infrastructure can be detected.
Additive effects	The cumulative environmental effect for a stressor equals the sum of the individual effects for each device in an array.
Antagonistic effects	The cumulative environmental effect for a stressor with an increasing number of devices in an array is diminished relative to additive expectations; possibly due to interactions between the actions of individual devices.
Synergistic effects	The cumulative environmental effect for a stressor with an increasing number of devices in an array is amplified relative to additive expectations; possibly due to interactions between the actions of individual devices.

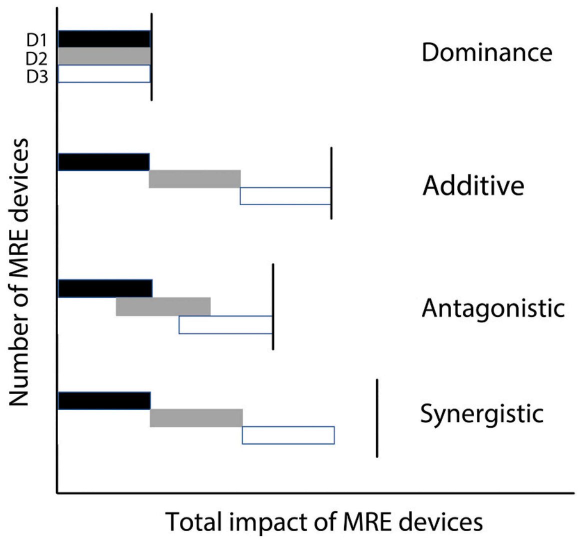

Fig. 2. Conceptual schematic for how environmental effects of a single stressor may scale with an increasing number of marine renewable energy (MRE) devices. Color bars represent the number of MRE devices (i.e., D1, D2, D3) and solid vertical lines represent the total environmental effect of the MRE devices for a given stressor. Conceptual design follows that outlined from the cumulative environmental effects literature (Halpern et al., 2008; Côté et al., 2016).

Quantitatively, this would be expressed as $D_{TOT} = \max(D_1, D_2, D_n)$. This could manifest if the installation of base infrastructure for devices was the dominant effect (e.g., common array infrastructure such as a power export cable to shore), and there was no increased footprint associated with additional devices.

2.3.2. *Scenario 2 – additive effects*

Additive effects are equal to the algebraic sum of the effect of a stressor for each device ($D_{TOT} = D_1 + D_2 + \ldots + D_i + \ldots + D_n$) (Fig. 2; Folt et al., 1999; Halpern et al., 2008; Côté et al., 2016). This could manifest with biofouling organisms independently colonizing all devices in an array, or with mobile organisms using all devices interchangeably as artificial reefs.

2.3.3. *Scenario 3 – antagonistic effects*

Under this scenario, the effect is equal to the sum of the effects for each additional device, but adjusted by some proportion that describes a diminished effect as the number of devices increases ($D_{TOT} = s_1D_1 + s_2D_2 + \ldots + s_nD_n$); where the individual s_i terms may all be identical or may vary with the device and where $s_i < 1$ (Fig. 2; Folt et al., 1999; Halpern et al., 2008; Côté et al., 2016). Where it is clear that the diminished effect is due to interactions between the actions of devices, this may also be represented as ($D_{TOT} = (D_1 + D_2 + \ldots + D_n) - (D_1 \times D_2 \times \ldots \times D_n)$). This scenario may arise for collision risk with tidal stream turbines, where the risk of collision for animals with each device may be equal, but they exhibit avoidance or evasion behaviors to prevent being struck by turbines (e.g., Gillespie et al., 2021); thereby decreasing the risk of collision as they navigate through (or past) an array.

2.3.4. *Scenario 4 – synergistic effects*

Synergistic effects can also originate from a scalar on the individual effects of a device or from multiplicative interactions, but in this case the effect from multiple devices exceeds the sum of the effects from individual devices (Fig. 2; Folt et al., 1999; Côté et al., 2016). This can be represented as either ($D_{TOT} = s_1D_1 + s_2D_2 + \ldots + s_nD_n$) where $s_i > 1$, or ($D_{TOT} = (D_1 + D_2 + \ldots + D_n) + (D_1 \times D_2 \times \ldots \times D_n)$) or simply ($D_{TOT} = D_1 \times D_2 \times \ldots \times D_n$), with the exact representation depending on the pathway of action. This scenario may be observed for displacement; while the presence of a single device may trigger some slight avoidance

Table 2
Summary of hypotheses for how environmental effects of seven key stressor-receptor interactions may scale up with the deployment of marine renewable energy (MRE) large-scale commercial arrays.

Stressor-receptor interaction	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, species' ability to detect device 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	✓	✓	✓		EMFs increase linearly with additional electrical current; effects may be influenced by spatial arrangement of subsea cables
Changes to habitat		✓	✓	✓	Complex effects that may vary across spatiotemporal scales, with array geometry, and equivalency of effects for individual devices within an array
Displacement		✓		✓	Effects observed at some threshold number of devices; no single threshold applicable across species or MRE device type
Risk of 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
Changes to oceanographic systems		✓	✓	✓	Effects observed at some threshold number of devices; dependent on MRE technology, number of devices, array configuration, and site specific hydrodynamics

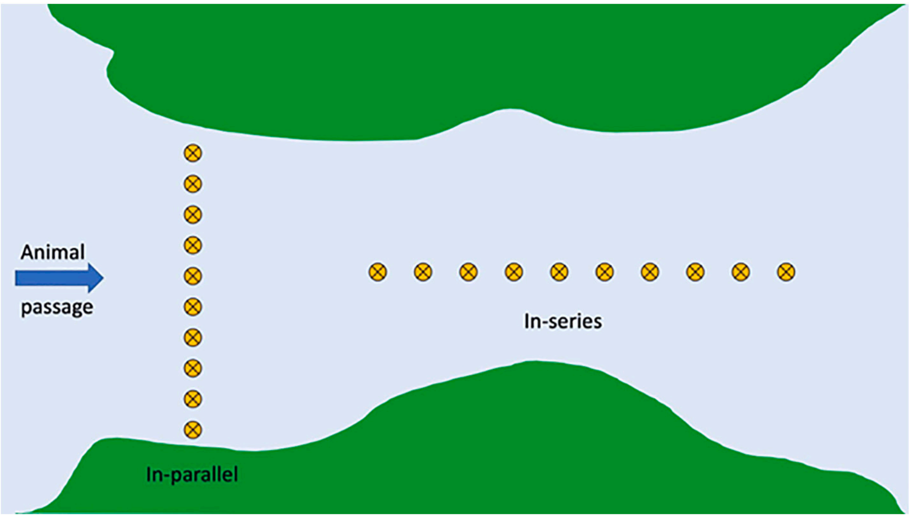

Fig. 3. Hypothetical ‘in-parallel’ and ‘in-series’ tidal turbine array configurations (redrawn from Wilson et al., 2006) relevant for considering the environmental effects of collision risk.

behavior with an animal swimming around the device, the presence of an array may result in complete exclusion from an area, particularly if the array spans a natural constriction in available habitat (e.g., tidal channels).

3. Results

Throughout this section, it is important to recognize that the scaling up of effects will be influenced by environmental heterogeneity, the characteristics of the environment that devices are deployed in (i.e., physical habitat, biological constituents), and the spatial arrangement of the array, among other factors. While understanding the effects of arrays requires a means for evaluating interactive effects among stressors and their cumulative impacts on marine ecosystems, that is beyond the scope of this paper.

3.1. *Collision risk*

3.1.1. *Description*

Collisions between animals and devices are thought to be the greatest risk of ocean current, river, and tidal stream turbine operations (Copping and Hemery, 2020). Collision risk describes the likelihood that animals might be harmed by coming into contact with moving parts of devices (Wilson et al., 2006), and applies most directly to components with a high velocity relative to the movement of water, such as turbine blades, tidal kites, or oscillating foils (Scottish Natural Heritage, 2016; Sparling et al., 2020a). Wave energy converters have no such components and are not thought to present much potential for collision risk (Copping et al., 2016; Greaves et al., 2016).

3.1.2. *Existing knowledge*

Collisions between marine animals and devices has been the focus of much research around single devices (Sparling et al., 2020a), and are expected to occur infrequently (Copping and Hemery, 2020). A recent synthesis of international research revealed no observations of collisions for marine mammals or seabirds (Sparling et al., 2020a), and the limited number of interactions with fish have not resulted in obvious harm (Matzner et al., 2017); although recent evidence suggests that fish passing through river turbines may become disoriented (Courtney et al., 2022). While it can be difficult to directly observe collisions in the field (Copping et al., 2021), mounting evidence suggests that when marine animals can detect turbines, they exhibit avoidance or evasion behaviors (Wilson et al., 2006; ABP Marine Environmental Research Ltd., 2010) to prevent being struck (Viehman and Zydlewski, 2015; Fraser et al., 2018; Joy et al., 2018; Williamson et al., 2019; Gillespie et al., 2021; Onoufriou et al., 2021; Palmer et al., 2021). Laboratory-based studies (i.e., flume tests) support field observations that fish can exhibit avoidance and evasion behaviors under controlled conditions with relatively low flow ($<2.5\ \mathrm{ms}^{-1}$) (Castro-Santos and Haro, 2013; Amaral et al., 2015; Müller et al., 2023). However, the extent to which free-swimming fish can detect devices and exhibit avoidance and evasion in environments dominated by greater flow rates is generally unknown (Shen et al., 2016), but will be influenced by their size and swimming ability (Zhang et al., 2017) and the size and rotational speed of the device.

3.1.3. *Nature of scaling and caveats*

Considerable uncertainty remains about collision risk with single devices, and this limits what can be determined for arrays. Results to date suggest that collisions may manifest as additive, antagonistic, or synergistic effects (Table 2), but this may depend on the configuration and location of the array. Additive or perhaps synergistic effects may result if an array is configured to optimize energy extraction and is installed across an important migratory corridor (i.e., ‘in-parallel’; Wilson et al., 2006) with no alternative routes for animals to access important resources (e.g., foraging grounds, spawning habitats, etc.) (Fig. 3). Under this scenario, migratory animals would need to navigate through the array and may have an elevated risk of collision as they attempt to access resources. Additive effects could also arise under this scenario if the animals exhibit avoidance and/or evasion behaviors to prevent collisions. Antagonistic effects could manifest if the array is configured ‘in series’ (Wilson et al., 2006) so that much of the migratory corridor remains unobstructed and animals have ample space to navigate around the array (Fig. 3).

How effects of collisions manifest for arrays may be site specific and technology specific (e.g., floating vs. bottom-mounted devices) and dependent on a variety of additional factors, including the physical habitat characteristics of the environment and the species under consideration, including their capacity to exhibit evasion and avoidance.

3.1.4. *Research required to understand scaling effects*

A better understanding of collision risk for marine animals with single devices is required to advance our understanding of the potential effects of arrays. In the absence of arrays for in situ assessments, modeling approaches and simulation studies provide some insight into understanding how effects may scale up (Table 3). Species distribution

Table 3
Generalized concepts, associated hypotheses, and research required to understand how environmental effects scale up for key stressors.

Stressor-receptor interaction	Conceptualized environmental effect(s) of arrays	Associated hypotheses	Research required
Collision risk	Additive, antagonistic, or synergistic	• How effects manifest is largely dependent on array layout/configuration (i.e., 'in parallel' vs. 'in series'). • Relevant factors are MRE technology type, habitat characteristics of deployment location, and species' capacity for avoidance and evasion.	• Additional in situ observations of marine animal interactions with single turbines are needed to determine number and effect of potential collisions. • Numerical models and simulations using realistic array layouts and configurations are needed to determine encounter rate, collision risk, and effects on populations. • Future collision risk modeling and simulations should incorporate avoidance and evasion behavior.
Underwater noise	Additive	• The elevation in received levels will be low but will increase logarithmically and level off after an initially rapid increase.	• Robust in situ characterization of received levels for a variety of MRE technologies using standardized protocols with comparison to known levels of disturbance. • Characterization of pertinent environmental parameters for meaningful interpretation of received levels. • Development of new, or modification of existing, underwater acoustic propagation models to predict received levels for arrays.
Electromagnetic fields	Dominance, additive, or antagonistic	• Effects will increase linearly with additional electrical current but will be dependent on array cable layout.	• Development of robust sensors for in situ measurement. • Systematic measurement over a range of power outputs where devices connect to shore-based facilities. • Controlled laboratory- and field-based studies of behavioral responses for EMF sensitive species to validate model predictions.
Changes to habitat	Additive, antagonistic, or synergistic	• Effects will vary across spatial and temporal scales, and with array configuration/layout and habitat characteristics (e.g., sediment type).	• Consistent collection of high-quality baseline habitat data prior to device deployment. • Incorporation of empirical data and development of habitat suitability models and ecosystem-wide models for simulating effects of arrays.
Displacement	Additive or synergistic	• Effects will become manifest at a threshold number of devices that induces sufficient levels of underwater noise, EMF, habitat changes, etc. to cause avoidance, exclusion, or attraction relative to array. • No single threshold number of devices is applicable across species or device type.	• A commonly accepted definition of displacement is required. • Models that simulate animal movement and migration in the vicinity of array are needed to predict effects of displacement. • Model validation using empirical observations are needed to determine deviations from normal movement pathways and migratory routes.
Risk of entanglement	Additive or antagonistic	• Effect will increase with number of deployed floating devices and associated mooring lines and draped power cables.	• Models and simulations are required to understand how effect increases with array size. • Empirical observational data (e.g., acoustic telemetry, imaging sonars, underwater video) for susceptible species required to validate model predictions.
Changes to oceanographic systems	Additive, antagonistic, or synergistic	• Effects will become manifest at a threshold number of devices. • Magnitude of effects will depend on MRE technology type, hydrodynamic conditions, and array size/layout/configuration.	• Improvements to numerical and physical hydrodynamic models are required, with particular focus on accurate resource characterization, site-specific bathymetry and hydrodynamics, and using realistic energy extraction modules (devices and their operation). • Empirical data for standard oceanographic variables to validate model predictions, with focus towards quantifying variability and uncertainty once arrays are deployed.

models derived from acoustic telemetry studies that draw linkages between species presence and physical environmental variables (e.g., turbulence and flow characteristics, water temperature, etc.) provide a means to predict the likelihood of species distributions overlapping with proposed MRE installations (Bangley et al., 2022) and can help quantify encounter rate and collision risk (Sanderson et al., 2023a, 2023b, 2023c). Incorporating studies of avoidance behavior into this framework and expansion to collision risk models, perhaps using a numerical Agent-Based Model (Rossington and Benson, 2020), a Eulerian-Lagrangian-Agent Method (ELAM) (Grippo et al., 2017), or fault tree analysis used in probabilistic risk assessments (Hammar et al., 2015), may further elucidate how site-specific effects of collisions scale up with an increasing number of devices (Table 3).

3.2. *Underwater noise*

3.2.1. *Description*

Animals use sound in the marine environment for a variety of biological functions, including communication, navigation, intraspecific and interspecific interactions, foraging and predation, and to avoid predation. Underwater noise generated during device installation may disrupt animal behavior, induce stress, and if sufficiently high in intensity (e.g., pile driving), may result in a range of physical injuries including a temporary or permanent reduction in hearing ability (Copping et al., 2013; Copping and Hemery, 2020; Hawkins and Popper, 2017; Southall et al., 2019), and in extreme cases barotrauma or death (Polagye and Bassett, 2020). Because of this, regulatory thresholds have been established in the United States for underwater noise effects on marine mammals (NMFS, 2018), and guidance has been provided for fish (Hawkins et al., 2020). While the simplicity of such thresholds is attractive, ongoing research (e.g., Southall et al., 2021) aims to improve the understanding of behavioral effects, which have more nuanced drivers than the onset of hearing loss. Operational noise identified to date has been primarily associated with the device power take-off system (e.g., generator, power electronics), cable strumming, moorings, and maintenance activities (e.g., vessel traffic).

3.2.2. *Existing knowledge*

Operational noise measurements from tidal turbines and wave energy converters in France, Portugal, Spain, the United Kingdom, and the United States have not been associated with effects on marine life (Copping et al., 2020). While evidence suggests that operational noise is unlikely to cause acoustic injury to marine animals, behavioral responses are possible (Polagye and Bassett, 2020), and it has been shown that harbour seals (*Phoca vitulina*) avoid sounds from operational devices (Hastie et al., 2018), and harbour porpoise (*Phocoena phocoena*) activity was significantly reduced compared to baseline levels (Tollit et al., 2019). Because operational noise is generally low intensity (Polagye and Bassett, 2020), establishing a causal link between MRE operational noise and consequences to marine animals is challenging. Indeed, extrapolation of noise levels to effects on animals can be difficult because the undisturbed behavioral ecology of many marine animals is poorly characterized (De Dominicis et al., 2017), and because effects may be confounded by variation in the probability and severity of behavioral responses across taxonomic groups, among individuals across situational contexts, and across the temporal and spatial scales

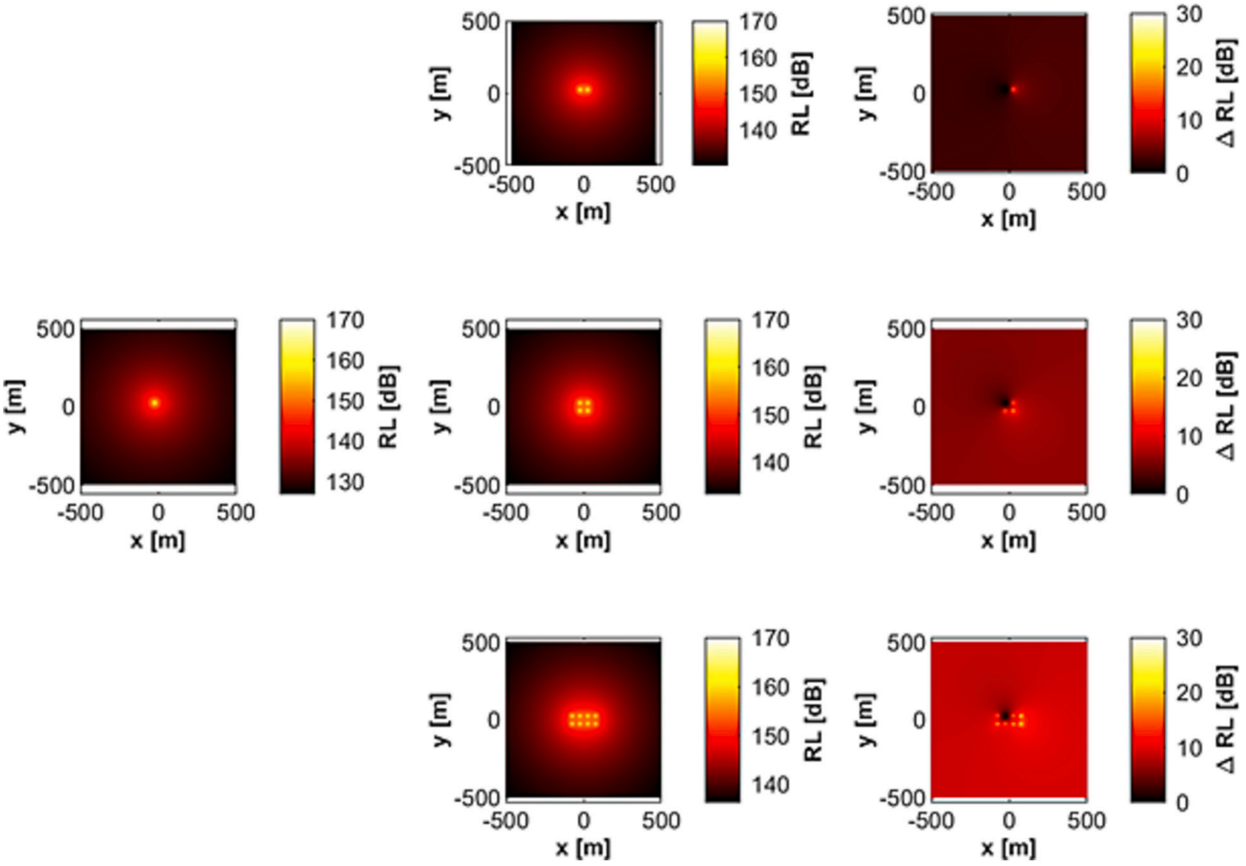

Fig. 4. Changes in far-field received levels (RL) as the number of MRE devices increases from two (top row) to four (middle row) to eight (bottom row), using as case study a source level of 170 dB, transmission loss coefficient of 15, 50 m spacing between devices, incoherent summation in pressure-squared space for the wave component of sound propagation. Left column is the spatial variation in RL for a single device (constant), the middle column is the map of RL for multiple devices, and the right column is the difference from the baseline case of a single marine renewable energy device. Note that the color bar range is different for the right column.

over which exposure can occur (Southall et al., 2021).

Sound propagates both as a pressure wave and as particle motion. There is greater scientific knowledge about the pressure wave portion of underwater noise, which affects marine mammals, than the particle motion component, which is more likely to affect fish and invertebrates (Nedelec et al., 2016; Popper and Hawkins, 2018; Copping et al., 2021). However, the distinction between wave and particle motion is only complicated at close range to a sound source (Popper and Hawkins, 2018); at greater range, a plane wave approximation is reasonable, and sound pressure (the propagating wave) and particle velocity are related by a simple algebraic expression.

3.2.3. *Nature of scaling and caveats*

The squared pressure for the wave portion of underwater noise is expected to scale in an additive manner with an increasing number of devices (Fig. 4; Table 2); however, the sound from adjacent devices will likely be incoherent due to variations in the tidal currents or wave fields. The area over which sound will be elevated from baseline levels is expected to scale with array size; although the maximum levels within the array are not expected to be significantly affected. Environmental conditions (e.g., bathymetry), array geometry, and technology type will influence how noise propagates within and around an array (e.g., Harding et al., 2023). While underwater noise from an array is expected to exceed baseline conditions at a greater range than for single devices, the elevation in received levels will be low; although greater at lower frequencies than at higher frequencies (Felis et al., 2021) (Fig. 4). As the number of devices increases, the elevation in received levels around an array is expected to increase logarithmically, leveling off after an initial rapid increase.

Several robust numerical acoustic propagation models exist (e.g., parabolic equation models) that can include the effects of environmental variables (e.g., bathymetry, seabed composition, sound speed profile). However, these attributes need to be thoroughly characterized in a MRE development area for the models to be meaningful (Madrid et al., 2021; Felis et al., 2021). Field data collected at MRE sites should adhere to the IEC 62600-40 technical specifications (International Electrotechnical Commission, 2019) to validate the models. Running these models will require intensive computational resources, and the requisite information about sound speed profiles and seabed composition can be difficult to collect, particularly at tidal energy sites where currents often result in a ‘cobble pavement’ that inhibits study of the seabed.

3.2.4. *Research required to understand scaling effects*

Gaps remain around acoustic characteristics of sound sources, the spatial and temporal resolution of acoustic data, incorporation of uncertainty in simulations, calibration of parameters and validation of results that need to be addressed (Madrid et al., 2021). To properly characterize the acoustic output of devices, we need in situ measurements of the underwater noise generated by multiple types of wave energy converter and tidal turbines in various environments using standardized protocols like the IEC 62600-40 technical specification (International Electrotechnical Commission, 2019) (Table 3). This protocol requires measurements at multiple ranges and operating conditions to build a more complete temporal-spatial knowledge base, as well as assess source directionality. To interpret these measurements through modeling, it would be beneficial to systematically collect additional environmental parameters such as bathymetry, seabed composition, and water column properties (e.g., temperature, salinity). However, we note that such data collection was explicitly excluded from the IEC 62600-40 specification to avoid imposing unreasonably high economic costs on early stage projects. That being said, with robust environmental data collected around single devices we could then develop or modify underwater acoustic propagation models to determine received levels within and around arrays (Harding et al., 2023). Even with significant uncertainty, the outputs from such models would be helpful in identifying relevant hydrophone deployment locations for in situ acoustic monitoring. In addition, through cooperation with MRE technology developers, it may be possible to systematically shut down turbines within an array during an acoustic survey, thereby isolating the effects of individual turbines from the array footprint and testing hypotheses about received sound levels.

Additionally, understanding how marine animals react to the frequency and sound level of underwater noise from devices is needed (ORJIP, 2022). While information about animal response to underwater noise could be generated through controlled laboratory studies, the most meaningful empirical data will be acquired around operational devices, and through relating noise levels to marine animal behavior at varying distances from a device. In addition, playback studies in representative environments (e.g., Hastie et al., 2018) can help to disentangle acoustic effects from other factors (e.g., prey aggregation). While some knowledge can be gained from single devices, greater uncertainty remains about how fish and marine mammals may respond to the noise emitted by arrays, which are likely to exceed ambient noise at greater ranges. For devices with novel components or larger size than those previously characterized, it will be important to examine the acoustic output to determine potential levels of harm and, if necessary, pursue mitigation measures.

3.3. *Electromagnetic fields*

3.3.1. *Description*

Electromagnetic fields (EMFs) are naturally present throughout the world’s oceans from the background magnetic field of the Earth and also from atmospheric and solar influences. All species live within these natural fields and some animals have evolved the ability to sense and respond to them. EMFs are also generated by subsea power cables (inter-array and power export cables) that are needed to transmit power from MRE devices to shore. These sources may modify natural EMFs and can influence animal behavior (Gill et al., 2014; Hutchison et al., 2020) or have effects on species physiology, development, and growth (Woodruff et al., 2012) and biochemical processes (Kuz’mina et al., 2015); reviewed by Gill and Desender (2020). Power export cables that transmit the combined energy from multiple devices in an array have higher EMF levels resulting in greater spatial extent of EMFs; thereby, increasing the likelihood of encounter with EMF that may affect animals. While subsea cables between bottom-mounted devices will be placed on the seafloor, subsea cables between floating devices may be suspended in the water column; the location and orientation of the cable may result in different organisms coming into contact with emitted EMFs.

3.3.2. *Existing knowledge*

EMF research has primarily focused on single species responses for power cables from surrogate industries (e.g., offshore wind), or has involved laboratory-based experiments (Gill and Desender, 2020). Marine animals known to be receptive to EMFs include elasmobranchs (e.g., sharks and rays) and several other fish species, mammals, sea turtles, and some invertebrates (e.g., several molluscs and crustaceans) (Taormina et al., 2018). There is consensus among MRE researchers, developers, and regulators that EMFs traveling through cables from single or small numbers of devices will have relatively low EMF intensities and therefore of very localized extent, resulting in low potential for encounter with animals, and therefore pose a low risk to sensitive marine species (Copping et al., 2020).

Modeling studies have deduced levels of EMFs from energized cables, but none shed light on the potential effects on marine animals, and are only speculative about effects on behavior (Hutchison et al., 2021). Numerical models show that EMFs decrease with distance from the cable core (known as ‘r’, with the decay being $1/r$ or $1/r^2$, or exponential depending on the cable characteristics and geometries (Hutchison et al., 2021; Chainho and Bald, 2021)) which represents depending on whether power is direct current (HVDC) or alternating current (HVAC) (Normandeau Associates et al., 2011; Hutchison et al., 2021. In situ measurements have shown that the EMFs can be present over several 10s of metres as the overall EMF environment is complex, and influenced by the power system, ambient magnetic fields (such as the geomagnetic field) and water movements (Hutchison et al., 2020, 2021). While burying cables under 1–2 m of sediment is often possible in areas with soft substrate and will reduce animal exposure to the strongest EMFs near the cable surface, the sediment layer does not alter the magnetic field (Taormina et al., 2018). Cable burial is not possible on hard bottom and, although cable protections (e.g., concrete mattresses or rock dumps) can provide some distance between a cable and most mobile EMF-receptive species, they also create new habitat for shelter-seeking animals like crustaceans, increasing their risk of EMF exposure (Albert et al., 2020).

3.3.3. Nature of scaling and caveats

The effects of EMFs for arrays are likely to be additive if cables are 10s of metres apart so that they do not interact (Fig. 2; Table 2). Basic physics shows that magnetic fields increase linearly as electrical current in a cable increases; this would occur with the additional power generation from multiple devices in an array, given a fixed transmission voltage. The layout of inter-array cables may also have additive effects, as each additional cable generates its own magnetic field. However, depending on the proximity and orientation of these cables relative to each other (e.g., 180°), the magnetic fields from separate cables could overlap, combine or cancel each other out (dominance or antagonistic effects).

Theoretical models of the intensity of EMF emitted from cables are available, but have rarely been verified or validated at scales that are relevant to the marine environment and EMF-sensitive animal (Madrid et al., 2021). Most EMF models have focused on deployments of bipole HVDC, or HVAC 3-conductor cables which are typically twisted around each other, which will lower emissions compared to the basic HVAC model (Grear et al., 2022).

It is possible that some magnetic field emissions are more biologically relevant than others. EMF-receptive species can respond to very low intensity changes (i.e., nT to μT for magnetic fields, nV/m to uV/m for electric fields) but the emission range at which these species may respond (such as attraction or avoidance) to artificial EMFs remains unknown and challenging to identify (Albert et al., 2020; Hutchison et al., 2020).

3.3.4. Research required to understand scaling effects

Accurately measuring in situ EMF emissions has been challenging and the development of robust sensors are needed for additional data acquisition from the marine environment (Gill and Desender, 2020; Hutchison et al., 2020), and for understanding how the effects of EMFs for arrays scale up (Table 3). Indeed, systematic measurements of EMFs are required where devices are connected to shore, particularly at test sites with multiple berths and power export cables. In the absence of arrays, such measurements could be gathered from existing high-capacity subsea power cables used in surrogate industries (e.g., offshore wind). Further, controlled laboratory and field-based studies using underwater imagery combined with fine-scale acoustic telemetry for EMF-sensitive species could enable observations of behavioral changes in the presence of EMFs (Table 3). Other effects and determination of thresholds to responses could be assisted by specific controlled studies as well.

3.4. Changes to habitat

3.4.1. Description

MRE systems (i.e., the device and supporting infrastructure – foundations and anchors, mooring lines and cables) will interact with benthic and pelagic habitats (Hemery, 2020) and may alter where animals live and how common they are in particular locations. Changes to habitats can result from the installation, operation, and/or decommissioning of MRE systems. Installations may lead to alteration, loss or creation of benthic and pelagic habitats, can lead to the inadvertent introduction of non-native species, and may cause potential changes to animal behavior or ecosystem function (Copping et al., 2016; Hemery, 2020).

3.4.2. Existing knowledge

The effects of MRE on benthic and pelagic habitats are similar to those of infrastructure involved in other well-studied marine industries (e.g., offshore wind turbines, oil and gas rigs, navigation and observation buoys, platforms, docks, and piers). However, unlike most other marine industries, MRE devices rarely span the entire water column to provide a continuum between intertidal and subtidal habitats.

Several studies of individually deployed devices have shown rapid recovery of the seafloor from the disturbance caused by device (O'Carroll et al., 2017) and cable installations (Taormina et al., 2018). While arrays have yet to be deployed, 21 "ecological foundations" were installed off the coast of Sweden in 2007 to study the effects of wave energy converter gravity-based foundations on the benthic environment. Soon after installation, a greater abundance of fish and invertebrates was observed on and around the foundations than at control sites (Langhamer and Wilhelmsson, 2009). The greater abundance persisted throughout the 12 year study, although with inter-annual variation in all taxa and years; successional increases in abundance and species richness were observed over the course of the study (Bender et al., 2020). Similar results have been observed elsewhere (Muxika et al., 2020, 2022).

Modeling studies suggest that i) species with pelagic larval dispersal may benefit from the presence of arrays to cross dispersal barriers (Adams et al., 2014), ii) increases in biomass at lower trophic levels due to the greater artificial reef effect of arrays will contribute to increasing biomass for higher trophic levels (Alexander et al., 2016), iii) effects on habitat suitability will differ for different species and array designs (du Feu et al., 2019), and iv) changes in biogeochemistry and primary productivity are not expected from array operations (Van Der Molen et al., 2016). The knowledge gained from these studies, combined with existing information from analogous offshore industries, can be leveraged to understand how effects of habitat changes will scale up with arrays; particularly with respect to the relatively small footprint of MRE foundations, anchors, cables, and mooring lines.

3.4.3. Nature of scaling and caveats

Changes to habitat is a complex stressor-receptor interaction with differing effects at varying spatiotemporal scales and different expectations about how effects may scale with an increasing number of devices. For changes like alterations to sedimentation patterns due to seabed scour and/or cable installation, seafloor area loss due to installation of foundations or cables, or artificial reef effects and biofouling biomass increases associated with new habitat creation, the scaling of effects is expected to be additive, with each device or associated structure in an array producing relatively similar levels of effects. However, scaling of the seabed scouring effect may depend on array geometry (e.g., spacing of anchors or foundations) and sediment type, and may be antagonistic in some cases (Fig. 2; Table 2). Moreover, each device within an array may not result in the same level of effect for facilitating larval dispersal of non-native species, or contributing to the overall changes to the local food web or reserve effect, due to the location of the device within the array (i.e., antagonistic or synergistic effects). Uncertainties remain about the spatial scales of these ecosystem-wide effects and their potential cumulative impacts, and there is an absence of empirical data to implement models (especially for less-studied species and habitats) and a lack of standardized methods for data collection.

3.4.4. Research required to understand scaling effects

Additional research is needed to identify the habitat changes that are most likely at MRE sites. Collecting robust and consistent baseline data prior to device deployments will provide empirical data for modeling studies (e.g., habitat suitability models or ecosystem-wide models) that simulate the presence and operation of MRE arrays (Buenau et al., 2022) (Table 3). However, validation data will not be available until arrays are installed. Moreover, ecosystem-wide models need specific types of biological data (e.g., diet, growth rate, mortality rate) that are rarely (if ever) required by licensing authorities to be collected during baseline and monitoring surveys at MRE project sites. Comprehensive literature reviews will be needed to gather such data from foundational research studies; in the absence of such information, empirical data will need to be collected and included in models.

3.5. Displacement

3.5.1. Description

Displacement of aquatic animals due to the presence and/or operation of devices can be defined as the result of mechanisms (i.e., avoidance, exclusion, or attraction) that cause animals to depart from, or not enter into, their preferred or critical habitats, or to move into areas that are new to them (Hemery et al. *in review*). These mechanisms are triggered by a receptor's response to stressor(s), with a range of potential consequences from effects on individuals to populations.

3.5.2. Existing knowledge

Displacement of marine animals around single devices has not been thoroughly investigated and it is not expected to be observed at the current scale of the industry; it is likely to only become observable once arrays are installed (Buenau et al., 2022; Copping et al., 2021). Stressors likely to trigger displacement are the physical presence of devices, underwater noise, EMF, changes to habitat (including formation of artificial reefs), movement of devices, and hydrodynamic changes (Sparling et al., 2020b). Various marine animals are susceptible to displacement because of their lifestyle and biological attributes (e.g., maneuverability around devices): large whales, small cetaceans, pinnipeds, sirenians, sea turtles, seabirds, pelagic sharks and large fish, benthic sharks and rays, demersal fish, mobile invertebrates, and sessile invertebrates.

3.5.3. Nature of scaling and caveats

With little information available from single devices (e.g., Palmer et al., 2021), we anticipate that displacement will be observed at some threshold number of devices. This threshold may be device- and environment-specific, with no single threshold being broadly applicable across species or device types. Even though we may come to understand how some of the triggering stressors will scale up from single devices to arrays, there is nothing to indicate how the environmental effects of displacement will change with the number of MRE devices; they may be additive or synergistic (Fig. 2; Table 2). Although it seems intuitive that the effects of displacement will scale with the physical increase in area covered by an array, this hypothesis needs to be tested.

3.5.4. Research required to understand scaling effects

A commonly accepted definition of displacement is required to advance targeted research. With that definition established, and prior to the deployment of arrays, some information could be gleaned from agent-based models to demonstrate movement of animals in the vicinity of simulated arrays and the likely changes resulting from their presence (Table 3). These modeling exercises will need to consider the driving forces of attraction, avoidance, and exclusion. Both long distance migratory animals and those engaged in localized movements should be considered in models, including various life stages (e.g., pelagic larvae of benthic organisms) and animals with different maneuverability capacity around devices. Once arrays are installed, validation of model predictions using empirical data from field observations will be needed to ensure that the movements are as anticipated (Table 3). This could be conducted using acoustic and/or satellite telemetry, unmanned aerial vehicles (drones), passive acoustic monitoring, or other observational methods.

3.6. Risk of entanglement

3.6.1. Description

Floating and mid-water devices are attached to the seabed using anchors and mooring lines that allow them to maintain their position in the water column or on the sea surface. In an array, cables are often used to transport power from multiple devices to a single power export cable on the seabed. The potential for these lines and cables to become a hazard for marine animals that may become entangled or entrapped in them increases with the number of devices in an array.

3.6.2. Existing knowledge

Marine animals most at risk of entanglement are large cetaceans and sharks because of their size and behavior; however, smaller marine mammals, sea turtles, seabirds, and some large fish may also be at risk (Benjamins et al., 2014; Garavelli, 2020). The likelihood of entanglement in mooring lines and cables is a function of the line or cable configuration and scale, water depth at the MRE site, and animal size and behavior. The likely consequences of marine animal encounters with mooring lines and power cables (e.g., risk of injury or death) remains largely unknown, but parallels can be drawn from studies of entanglement with fishing gear (Garavelli, 2020). However, unlike lost or abandoned fishing gear, device mooring lines and cables do not have sufficient slack to form a loop, and there are no loose ends on lines or cables that pose such a risk. While the risk from single devices is perceived to be quite low, it may increase with the deployment of arrays.

3.6.3. Nature of scaling and caveats

While the presence of many mooring lines and intra-array cables in an array could create an increased risk of entanglement, this has not been shown for surrogate industries (e.g., nearshore or offshore aquaculture pens) (DeCew et al., 2012; Clement, 2013). We hypothesize that the effects will increase with the number and length of lines/cables in an additive or antagonistic manner (Fig. 2; Table 2). However, this will need to be tested using data collected from field observations and using numerical models. Currently, there is no empirical data about interactions of marine animals with MRE mooring lines and cables, and knowledge of animal usage, areas of occupancy, and behavior around MRE infrastructure is absent. Although simulation models of entanglement are being developed for large cetaceans with fishing gear (Howle et al., 2019), these would need to be adapted to the specific case of devices and deployment locations to be applicable.

3.6.4. Research required to understand scaling effects

There is an absence of empirical data for understanding the effects of entanglement, and it is not generally understood how much room species need to safely navigate through the series of mooring lines and cables required to support devices. This may be both species and site dependent. Prior to the deployment of arrays, baseline data about the spatial and temporal distribution of marine animals in the planned deployment area is needed to understand what species may be susceptible to entanglement. Thereafter, information from agent-based models and computer simulations that demonstrate animal movement in the vicinity of an array could be used to estimate the probability of an animal's path intersecting with mooring lines and cables (Table 3). This work should focus on species that are deemed to be at greatest risk from entanglement (e.g., large marine mammals, sea turtles). Once arrays are installed, validation of model predictions using empirical data from field observations will be needed to ensure that animal movements and probability of encounter estimates are accurate. This could be conducted using acoustic tags, imaging sonars mounted at various locations in the array, and underwater optical video.

3.7. Changes to oceanographic systems

3.7.1. Description

Tides, waves, currents, and water circulation comprise the oceanographic processes that control the marine environment by determining the concentrations of dissolved gases and nutrients, transporting sediment, and supporting habitats and water quality that maintain marine organism health and ecosystem function. The presence of devices and the extraction of energy from tidal currents and waves may alter these processes at varying spatial scales, reducing the amount of energy available in marine systems, potentially affecting water circulation (Hasegawa et al., 2011) and wave heights, and may impact marine chemical and biological processes with ecosystem-level effects. Depending on the location, scale of energy extraction, and local hydrodynamic processes, changes to water column and hydrography may be felt over large geographic areas (Frid et al., 2012).

3.7.2. Existing knowledge

Marine energy extraction may impact hydrodynamic features that are important for marine animal distribution (Jones et al., 2014; Mcilvenny et al., 2021; Bangley et al., 2022), predator-prey interactions (Lieber et al., 2021; Couto et al., 2022), and may influence sedimentation patterns and coastal erosion processes (Neill et al., 2012). However, the effects of energy extraction by single devices on circulation patterns and wave height are too small to be measured against the natural variability inherent in dynamic marine environments. While numerical models predict physical changes to current speed and wave amplitude from MRE extraction, these changes are only likely to become observable with the installation of arrays (e.g., de Santiago et al., 2020; Santiago et al., 2023). These changes and their subsequent effects on chemical and biological processes are likely to be site specific, but trends may be identified that apply across marine environments, differing MRE technology types, and specific groups of organisms (Whiting and Chang, 2020).

3.7.3. Nature of scaling and caveats

With no information available on the effects of single MRE devices on water circulation and wave height, we must rely on hydrodynamic models that use realistic simulations of devices for identifying the potential effects of arrays. Changes to oceanographic systems will become observable at some threshold number of devices, but this is highly dependent on the MRE technology, the number of devices in the array and their spatial arrangement, and site-specific hydrodynamic conditions. We anticipate that the effects of an array may be additive (Fairley et al., 2015), increasing with the physical area occupied by the array, or perhaps antagonistic or synergistic (Fig. 2; Table 2).

3.7.4. Research required to understand scaling effects

To understand the effects of arrays on oceanographic systems, numerical and physical models of systems must continue to be improved. Particular focus should be paid to accurate resource characterization, site-specific bathymetry and hydrodynamics, and the use of simulations that incorporate realistic devices and their operation (Table 3). Once arrays are installed, these models need to be validated using standard oceanographic measurements (i.e., temperature, salinity, conductivity, current measurements, wave height and period) with a focus on quantifying variability and uncertainty (Madrid et al., 2021).

4. Discussion and future directions

The generalized concepts established herein provide a basis for developing testable hypotheses so that a robust scientific approach can be used to increase our understanding of effects of arrays; thereby, improving our ability to delineate between unknown and realized risks of MRE development, identify critical knowledge gaps, and facilitate expansion of the MRE sector. A variety of factors (e.g., environmental heterogeneity, physical habitat characteristics, biological constituents of the environment, spatial arrangement of an array, etc.) will influence how effects of various interactions scale with an increasing number of devices. Beyond the potential for non-linear effects, it is important to consider that neither ecosystem components nor stressors exist in isolation, and associations between stressor-receptor interactions may result in magnified effects at larger spatiotemporal scales as the MRE sector expands (Raoux et al., 2021).

We have identified the need for simulation and modeling studies for several stressor-receptor interactions to help advance our understanding of environmental effects around large-scale commercial MRE arrays (Table 3). It is equally important to gather empirical data using standardized (where applicable) and appropriate methods to validate (or refute) model predictions and improve our capacity to understand how environmental effects of devices scale up. Future modeling exercises should consider realistic array configurations that will be limited by the physical constraints of the environment (e.g., geography, water depth, hydrodynamic complexities, channel width, bathymetric constraints, etc.) rather than the hypothetical configurations that have previously been used for understanding wake characteristics to maximize efficient energy extraction (Bryden et al., 2007; Myers and Bahaj, 2005; Turnock et al., 2011) (Appendix).

In this paper, we have defined large-scale commercial arrays based on the number of individual devices that independently contribute to increasing the magnitude of environmental effects for a given stressor-receptor interaction. Thus, MRE technologies with multiple converters/rotors can be considered as arrays (albeit, typically small) and have inherent value for in situ testing of some of the hypotheses developed herein and for collection of required empirical data; advancing our understanding about how environmental effects ‘scale up’ and informing decisions about commercial scale development of the MRE sector.

While the generalities of the effects for some stressors (e.g., underwater noise, EMF) may be transferable across some MRE sites, the specifics about how the magnitude of these effects scale up may not be, and could manifest as dominance, additive, antagonistic, or synergistic effects depending on the location. It is therefore important to recognize that the effects observed for an array in one location are not necessarily indicative of the effects of an array in a different area, and will need to be investigated using standardized methodologies.

As larger arrays are deployed in the ocean, there will be a need to assess the effects in the context of other anthropogenic activities. Using methods from the advancing field of cumulative effects assessment (Stelzenmüller et al., 2020), the pressures of devices and arrays on marine environments can be placed in context. At the same time, it will be important to assess the cumulative effects of the stressor-receptor interactions described in this paper. The framework proposed here, derived from cumulative environmental effects literature, may hold clues for determining the overall effect of a device or array on a group of animals or area of the ocean, from the sum of the stressors applied.

The greatest impediment to resolving the effects of MRE development on marine animals, habitats, and ecosystems remains the lack of empirical data collected around single devices and arrays after installation. The absence of available and consistent data will become more acute as the industry deploys arrays, particularly at scales that will provide substantial electricity to national grids. A system is needed to ensure that data are collected every time a demonstration, pilot, or commercial MRE project is deployed. While project and device developers are responsible for collecting data to satisfy regulatory requirements, much of the data needed to ensure that the design and operation of MRE systems cause minimal damage and change to the marine environment must be the purview of a wider public interest. Governments and stakeholders supporting the deployment of MRE projects must facilitate funding for independent data collection using consistent and comparable methods to decrease the uncertainty inherent in the interactions described in this paper. This could be achieved by following the research actions advocated herein to validate the generalized concepts and test the associated hypotheses for each stressor-receptor interaction (Table 3). Devices are deployed at dedicated test sites to assess their survivability, power production potential, and pathway to commercialization. These are ideal locations for creating robust coordinated environmental monitoring programs, and can provide important empirical data for assessing some of the generalized concepts developed herein, but they require a stable source and suitable level of funding to conduct the required work. Consistent data collection over time will yield the data required to confidently put aside low risk aspects of MRE development, identify the functional limits of data collection to avoid expensive studies that are unlikely to yield actionable information, and to focus on those interactions that may cause elevated risks to the marine environment and its constituents.

CRediT authorship contribution statement

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Elizabeth A. Fulton: Writing - Original draft preparation, Writing - Reviewing and editing

Jennifer Fox: Methodology

Andrew B. Gill: Writing - Reviewing and editing

Brian Polagye: Writing - Reviewing and editing

Declaration of competing interest

The authors declare no conflict of interest. The project funders had no role in the design of the study, in the synthesis of the available information, in the writing of the manuscript, or in the decision to publish the study.

Data availability

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

Acknowledgements

We sincerely thank C. Long (European Marine Energy Centre), A.M. O'Hagan (University College Cork), I. Machado (WavEC Offshore Renewables), A. Vishwanath (India National Institute of Ocean Technology), S. Narasimalu (Nanyang Technological University), C. Bassett (University of Washington), I. Hutchison (Aquatera Ltd.), L.P. McGarry (Fundy Ocean Research Center for Energy), and C. Briggs, D. Overhus, M. Grear, M. Freeman and M. Richlen (Pacific Northwest National Laboratory) for their contributions to various portions of this manuscript during its development. We similarly thank two anonymous reviewers whose constructive comments and suggested edits greatly improved the quality of this work. This work was supported with funding from Ocean Energy Systems (OES) and the U.S. Department of Energy Water Power Technologies Office to Pacific Northwest National Laboratory, operated by Battelle, under contract DE-AC05-76RL01830.

Appendix A

A.1. *MRE technologies*

Understanding environmental effects for MRE arrays requires knowledge of the technologies that may form the basis of large-scale commercial developments. While >40 ocean current and tidal stream turbine technologies were developed between 2006 and 2013, a convergence towards horizontal-axis turbines has been observed (Kempener and Neumann, 2014b; IRENA, 2020). Like the dominant wind turbine design, horizontal-axis turbines typically have 2–3 blades that are radially attached to a horizontal shaft that is connected to a powertrain system. Wave energy development has not witnessed a similar convergence on specific technologies, and over 50 different designs have been developed for generating electricity (Lewis et al., 2011). The most likely technologies for commercialization include i) point absorbers consisting of floating or submerged buoys that use the relative movement of the buoy to generate electricity, ii) oscillating water columns that use passing waves to compress air in a semi-submerged structure and drive an air turbine, and iii) oscillating water surge converters that use the surge motion of waves to capture energy via an oscillating flap (Kempener and Neumann, 2014a; IRENA, 2020).

A.2. *Prior considerations with MRE arrays*

Although consideration has been given to the effects of MRE arrays on seawater circulation patterns (Ahmadian et al., 2012; Bryden et al., 2007; De Dominicis et al., 2017; Zhang et al., 2022) and sediment dynamics (Neill et al., 2012; Robins et al., 2014; Fairley et al., 2015; Martin-Short et al., 2015; Auguste et al., 2022), the primary focus has been on optimizing device spacing to reduce detrimental wake interactions and maximize energy extraction and device efficiency (Stallard et al., 2013; Funke et al., 2016). This has been explored through laboratory experiments (Myers and Bahaj, 2012) and computer simulations (Wang and Müller, 2012; Malki et al., 2014; Karsten et al., 2013; Zhang et al., 2022) that typically use hypothetical rectilinear and staggered grid array configurations (Turnock et al., 2011). However, actual device deployments are limited by a variety of factors (e.g., geography, water depth, hydrodynamics, channel width, bathymetry) that directly influence array layout design (Bryden et al., 2007; Myers and Bahaj, 2005; Turnock et al., 2011). Consequently, large-scale commercial arrays will manifest as highly optimized geometric configurations (Malki et al., 2014; Myers and Bahaj, 2012) composed of clusters of devices vs. the generic/hypothetical layouts used in simulations. This reality of array configuration is important to consider for understanding how environmental effects for different stressors may scale up.

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