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Marine energy converters: Potential acoustic effects on fishes and aquatic invertebrates^{a)}

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ABSTRACT:

The potential effects of underwater anthropogenic sound and substrate vibration from offshore renewable energy development on the behavior, fitness, and health of aquatic animals is a continuing concern with increased deployments and installation of these devices. Initial focus of related studies concerned offshore wind. However, over the past decade, marine energy devices, such as a tidal turbines and wave energy converters, have begun to emerge as additional, scalable renewable energy sources. Because marine energy converters (MECs) are not as well-known as other anthropogenic sources of potential disturbance, their general function and what is known about the sounds and substrate vibrations that they produce are introduced. While most previous studies focused on MECs and marine mammals, this paper considers the potential of MECs to cause acoustic disturbances affecting nearshore and tidal fishes and invertebrates. In particular, the focus is on particle motion and substrate vibration from MECs because these effects are the most likely to be detected by these animals. Finally, an analysis of major data gaps in understanding the acoustics of MECs and their potential impacts on fishes and aquatic invertebrates and recommendations for research needed over the next several years to improve understanding of these potential impacts are provided. <https://doi.org/10.1121/10.0020150>

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I. INTRODUCTION

There is growing concern about the potential effects of increased underwater anthropogenic (human-generated) sound on the behavior, fitness, and health of aquatic animals (e.g., Popper and Hawkins, 2016; Merchant *et al.*, 2022). Although the interest first focused on marine mammals, impacts on fishes and aquatic invertebrates are of increasing concern (e.g., Hawkins *et al.*, 2015; Di Franco *et al.*, 2020) because of their important contributions to biodiversity, food webs, and the health of aquatic ecosystems.

Initial considerations of anthropogenic sound and substrate vibration focused on classical industrial sources such as (but not limited to) seismic air guns, high-powered sonars, pile driving, and marine vessel traffic (Popper *et al.*, 2014). However, there is growing interest in the sounds

from devices that provide renewable energy alternatives to achieve reduced carbon emissions.

The interest in alternative energy sources initially focused on offshore wind (OSW) because of sounds produced during preconstruction, construction, operational, and decommission phases (e.g., Popper *et al.*, 2022). However, over the past decade, marine energy (ME) has begun to be explored as an additional renewable energy source. There are differences in many of the characteristics of the sounds emitted from OSW and ME devices. Furthermore, ME will be deployed in the inshore, near-coast, shallower water environments of tidal streams and nearshore waves, which are habitats different from those considered for OSW. Therefore, many (although not all) of the species potentially affected by sounds from marine energy converters (MECs) are likely to be different from those encountering OSW devices, and the impacts on those species may differ as well.

As ME devices are not nearly as well-known as other anthropogenic sources, such as OSW devices, this paper is a focused review and perspective of the general function of MECs and the sounds and substrate vibrations that they produce. In addition, while a majority of previous studies focused on sound pressure and marine mammal disturbance

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(e.g., Tougaard, 2015), we specifically consider the potential for MECs to cause acoustic and substrate disturbance for nearshore and tidal fishes and invertebrates. In particular, we consider particle motion from MECs in the water column and vibration in the seabed because the majority of hearing animals have ears (or other sensory organs) that have evolved to detect these stimuli. Finally, we provide an analysis of major data gaps in understanding the effects of vibroacoustics from MECs and their potential impacts on fishes and aquatic invertebrates and suggest areas of research that are most immediately needed to understand these potential impacts.

Note that this paper is not a comprehensive review that considers all research on any particular topic that we discuss. Rather, the paper provides an overview of the topic for use by a broad audience—from investigators to regulators to industry—such that they have a general understanding of the material. Thus, sections of this review may not be needed by all readers, but our goal is to provide sufficient background so that all readers will be able to understand the topic and relevant issues.

II. SOUNDS AND SUBSTRATE VIBRATIONS FROM MECs

MECs primarily include technologies used to harness and convert hydrokinetic energy from waves and currents into electrical energy (Clément *et al.*, 2002; Wolfram, 2006). They are, generally, of two types: current energy converters (CECs), which extract energy from tidal and riverine currents, and wave energy converters (WECs), which convert hydrokinetic energy from ocean waves into useful mechanical or electrical energy (Fig. 1). We will not consider extraction of energy from thermal gradients, referred to as ocean thermal energy conversion (OTEC), or other uses of deep seawater devices (Herrera *et al.*, 2021) because these technologies

involve significantly different infrastructure and mechanical operations than those of CECs and WECs and, therefore, will have different potential acoustic impacts on marine animals in very specific, limited areas where OTEC is viable.

CECs, often in the form of turbines, are typically deployed in areas that feature fast or constricted tidal exchanges or rivers with high-velocity currents. In contrast, WECs use a variety of technology approaches such as point absorbers and attenuators. Both types of MEC can produce unwanted sound that carries through the water column and which can also transfer to the seabed and direct vibrations into the substrate. This is because both technologies used to convert hydrokinetic energy to electrical energy are mechanical in nature and often involve moving parts that produce operational sounds and vibrations.

However, the frequencies and amplitudes of sounds generated by MECs are not well studied, mostly because of the lack of sufficient device deployments to acquire a body of data. In addition, and unlike the turbines used in the OSW industry, technology has not converged on an optimal WEC design for harnessing open water wave power in the ocean, hence, the range of device types is nearly unlimited. Further complicating the understanding of the expected sounds and substrate vibrations from WECs is that different types of devices operate in different water depths and environments, creating a large spectrum of technological approaches, each of which works best in particular environments. For instance, a shallow water surge WEC mounted on the seafloor just outside of the surf zone is likely to have a substantially different acoustic and substrate vibration footprint than an open water point absorber WEC system located on or near the surface in deeper water (≥ 30 m depth).

MEC-related underwater and vibrational noise occurs during construction, operation, and decommissioning of these systems. Most devices use gravity anchors that rest on

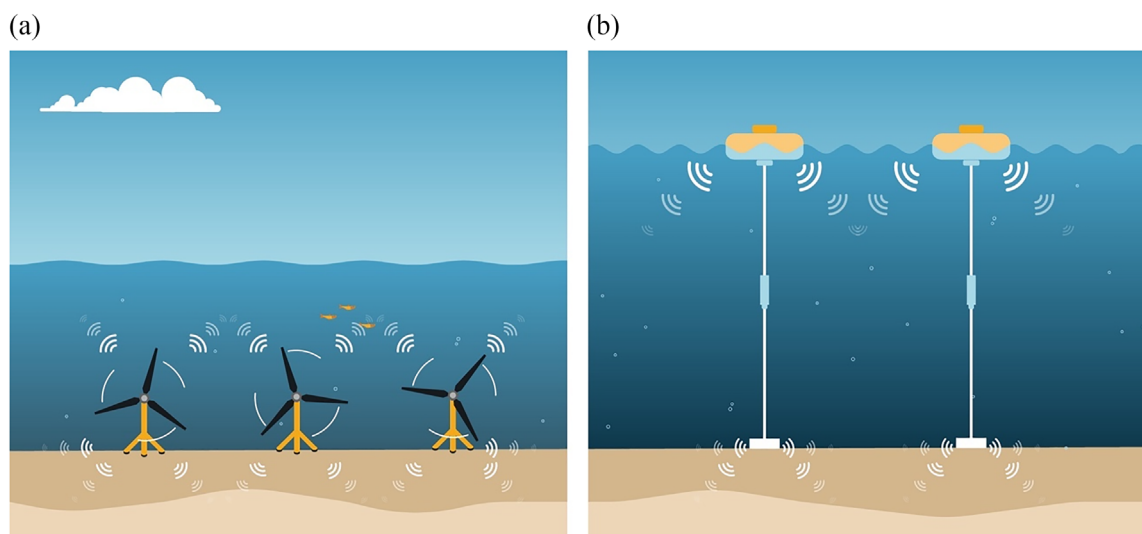


FIG. 1. (Color online) (a) An array of three seafloor-mounted CECs shows the acoustic emissions from the devices radiating into the water column and indirectly into the seabed plus substrate vibrations directly from the foundations. (b) Two WEC devices moored to the seafloor show possible pathways for sound emissions into the water column and indirectly into seafloor substrate and direct vibrations into the seafloor. [Copyright 2023, Pacific Northwest National Laboratory (PNNL).]

the seafloor to secure them to the bottom. Alternatively, devices are mounted to bridge pilings or floating platforms in the case of some riverine and tidal turbines. All contact points on the seafloor are likely to transmit vibrations to the bottom. Aside from this, construction noise during installations is expected to be mostly limited to vessel activity, except in the rare cases where strike or vibratory pile driving may be needed to support the device (Dahl *et al.*, 2015). Few studies have characterized the sounds produced by MECs and, thus, there are no known measurements of the substrate vibrations emitted by MECs. Still, it is clear that MEC sources differ from those of other energy sources in terms of bandwidth, amplitude, and duration (see Table I).

When striving to understand the potential effects of sounds on fishes and aquatic invertebrates, it is not always possible to extrapolate from experiments showing impacts of other sources to those of MECs. The effects of physical mechanisms (such as injury, hearing loss, and masking) are likely to be highly dependent on the precise characteristics of the sound, whereas the effects of perceptual mechanisms (those involving sensory experience such as stress and distraction) might be more likely to be similar across sound types, although these effects are more likely to be influenced by other contextual factors and the animal's internal state (Nedelec, 2023).

Low amplitude, discrete-frequency tonal sounds with harmonics have been most frequently observed with MECs, whereas significantly higher amplitude, short-duration, wideband sounds are more characteristic of seismic survey and pile driving activities (Table I). While the current state of ME focuses on testing single devices through a range of application scales (small-scale to power ocean observing up to utility grid-scale power), the sound emissions from multiple MECs deployed in arrays is unknown and likely to be more complex with higher amplitudes than what is reported in Table I.

Although there is uncertainty about the spectral characteristics of chronic noise from operational MECs, they are not expected to generate high-amplitude sounds (Robinson and Lepper, 2013) nor are they predicted to create a significant acoustic hazard for marine animals (Haikonen *et al.*, 2013; Tougaard, 2015; Haxel *et al.*, 2022). Operational MEC

noise may result from strumming mooring lines and the noise of chains used to secure the MEC. Power generators are the MEC's most likely chronic source of sound. These generators have a wide range of possible acoustic emissions, including from frequency-modulated tones and harmonics that oscillate with the wave period (Bassett *et al.*, 2011). Moreover, when these power electronics and generators are housed underwater, their sounds can propagate easily in the water and increase the acoustic footprint of the device, particularly as compared to those MECs which have generators above the water line (Tougaard, 2015; Haxel *et al.*, 2022). Other chronic noises from operational MECs might radiate directly through the base of the seafloor-mounted device, resulting in substrate vibration (e.g., bottom-mounted turbine). It is not possible to predict whether these effects present a significant hazard yet, although aquatic animals are able to detect substrate vibrations.

As the ME industry advances and designs begin to converge on technologies that optimize power generation in specific wave and current environments, sound radiated from operational MECs will become more predictable and easier to characterize, thereby lowering regulator concerns stemming from uncertainties. Also, as the industry progresses, more MECs will be installed, tested, and acoustically characterized, providing a data record for effective, informed decision-making by regulators. However, substrate vibration from these devices will still remain unpredictable because of vibrational propagation being highly dependent on substrate composition and type, to name a few factors (e.g., Hawkins *et al.*, 2021).

III. IMPORTANCE OF SOUND AND SUBSTRATE VIBRATION TO FISHES AND INVERTEBRATES

Hearing is a sense of great importance to fishes and many aquatic invertebrates because it, unlike other senses, provides animals with information about their environment and what is in it, not only from nearby but also from considerable distances (e.g., Myrberg, 1981; Popper and Hawkins, 2021b). Moreover, sounds give aquatic animals information that travels rapidly, is directional, and not affected by light levels, water currents, or objects in the environment. Thus, sound enables animals to learn about their environment and

TABLE I. Examples of acoustic signals generated by marine activities with characteristics that vary by frequency band, range from source to receiver, and other differences in recording parameters that do not facilitate direct comparisons of amplitude.

Marine activity	Examples of sound pressure signal characteristics
CECs	• Tonal sounds, concentrated in frequencies <1000 Hz, that scale in amplitude with turbine power generation state (Bevelhimer <i>et al.</i>, 2016)
WECs	• Periodic frequency-modulated or steady tonal sounds that oscillate with wave periods in frequencies ranging from 30 to 1000 Hz (Walsh <i>et al.</i>, 2017)
OSW turbine operation	• Tonal sounds, typically in frequencies <1000 Hz, that vary in amplitude with wind speed and turbine power generation state (Madsen <i>et al.</i>, 2006)
Seismic airgun surveys	• Low-frequency, short-duration (<0.75 s), high-amplitude pulse with energy concentrated in frequencies <100 Hz (Greene and Richardson, 1988)
Strike pile driving (OSW construction)	• Short-duration (0.200–0.600 ms), high-amplitude pulses with peak energy in frequencies from 100 Hz–10 000 Hz (Bailey <i>et al.</i>, 2010)

provides them with a “gestalt” of what is going on around them in three dimensions and at great distances (reviewed in [Hawkins and Popper, 2018a](#)). Mounting evidence suggests that substrate vibrations are also used in a similar way, as found extensively for animals on land ([Roberts and Elliott, 2017](#)). Acoustically, the myriad of sound is referred to as the “acoustic scene” or “soundscape” ([Bregman, 1994](#)) or as the “vibroscape” when referring to substrate vibrations (e.g., [Roberts and Elliott, 2017](#)).

An important concern regarding anthropogenic sounds, including those from MECs, is that they can interfere with the ability of animals to detect and use the sounds that are biologically important, not only those produced by members of the same species but also a myriad of sounds and substrate vibrations produced by other biological and geological sounds sources. Additionally, noise from MECs could cause stress and distraction. Consequently, the potential effects of MECs on normal physiology and behavior could include, but are not limited to, communication, reproduction, migration, feeding, and detection of potential mates and predators ([Myrberg, 1981](#); [Ladich, 2019](#)).

IV. SOUND PRESSURE, WATERBORNE PARTICLE MOTION, AND SUBSTRATE MOTION

A. Sound pressure and waterborne particle motion

In general, acoustic waves that propagate in a fluid medium (e.g., air or water) are called “sound.” The same waves that propagate in a solid medium (e.g., substrate) are called “vibration.” These acoustic waves are generated by the mechanical oscillatory movements of a sound source that disturbs the molecules of the surrounding media. When such distinction is warranted, this paper uses the term “acoustics” to refer to mechanical waves that propagate in a medium (air, water, or substrate). Otherwise, the term “sound” is used in a broader context to indicate acoustic waves emitted by a source and those that stimulate the receiver.

The molecular disturbance of the medium creates regions of a pressure field that oscillate above and below the ambient pressure (e.g., hydrostatic pressure in water), which rapidly radiates outward from the source. This is called the propagation of an acoustic wave, and the oscillating pressure is called acoustic pressure, something that can be measured with a hydrophone. Acoustic pressure is a scalar quantity, which means that it is fully described by its magnitude alone.

The molecular disturbance of the medium also generates an oscillatory acoustic particle motion (the term used throughout this review). As with all quantities of physical motion, particle motion can be measured and expressed in terms of particle velocity, particle acceleration, and particle displacement. Moreover, because particle motion is a vector, it is fully described by its magnitude and direction.

Greater detail about sound in water can be found in various acoustics texts (e.g., [Kinsler et al., 1999](#)). In addition, descriptions of underwater sound for a broad audience can be found online.¹

A critical issue related to understanding the underwater acoustics from any sound source, including MECs, is the need to determine not only sound pressure but also particle motion ([Nedelec et al., 2016a](#)). Under some circumstances, where the measures are made at a substantial distance from reflecting boundaries, such as the bottom, water surface, or other discontinuities (e.g., the walls of fish tanks), the magnitude of the particle motion can be derived from single point measures of sound pressure (e.g., [MacGillivray et al., 2004](#); [Nedelec et al., 2021](#)).

However, boundaries alter the sound field; they affect the magnitude and direction of the particle motion. When boundaries are within a few wavelengths of a sound source, particle motion is not predictable from pressure measures and, therefore, vector sensors are required to detect particle motion magnitude and the directional components of the vector in three dimensions ([Nedelec et al., 2021](#)). MECs are often sited in shallow, coastal areas where estimates of particle motion from sound pressure are not possible; thus, direct measurements are required. [Nedelec et al. \(2021\)](#) provide a best practice guide for measurement of particle motion.

B. Substrate vibration

In solids, such as bedrock, or semi-solid media, such as sandy or muddy bottoms, plus potentially other aquatic substrates, waves can travel not only along the direction of particle motion but also in a direction that is perpendicular to the direction of particle motion. Such a wave is called a transverse wave or shear wave (e.g., [Hawkins et al., 2021](#)).

A variety of surface waves also exists at the boundary of two media. For example, compressional and transverse waves that radiate downward can be refracted back to the seabed-water boundary to form an interface wave (also known as ground roll or Scholte wave; [Soloway et al., 2015](#)). These Scholte waves have an elliptical particle motion pattern such that their direction is perpendicular to the wave propagation direction. Moreover, Scholte waves can travel long distances along the boundary, decaying exponentially above the seafloor and beneath the sea bottom ([Jensen et al., 2011](#)).

Importantly, numerous animals reside in or at this boundary area and, over the past few years, aquatic investigators have come to realize that some of these animals, and particularly those that live on or close to the substrate, are able to detect these substrate vibrations ([Hawkins et al., 2021](#); [Roberts and Howard, 2022](#)). These observations parallel findings on land where interface waves are of great biological relevance to a wide range of animals that use these signals for vibrational communication and environmental sensing ([Hill and Wessel, 2016](#)).

Substrate vibrations may be caused by mechanical disturbance of a source that is placed on, in, or very near the seabed (e.g., tidal turbines and anchor systems) or intense waterborne acoustic waves that excite the seabed (e.g., substrate vibration caused by seismic air guns; e.g., [McCauley et al., 2021](#)). Because some MECs are installed directly on

the seabed, the coupling between the MEC and anchor system is substantial. Where movements generate substrate vibration, it is critical to understand the physics of such disturbances to accurately assess the biological impacts.

V. SOUND AND SUBSTRATE VIBRATION DETECTION BY FISHES AND AQUATIC INVERTEBRATES

Fundamental to understanding the potential effects of any anthropogenic source on animals is the mechanism of detection as well as which stimuli are detected. All fishes, and very likely those aquatic invertebrates that detect acoustic signals, detect the particle motion (water and perhaps substrate) inherent to the sound field. The sound detector of fishes is the inner ear, the basic structure of which is very similar to the inner ears of all vertebrates. The actual sound-detecting regions of the ear, the otolith organs, are accelerometers that directly detect particle motion (e.g., Popper and Hawkins, 2018).

A. Sound and substrate vibration detection by fishes

Most fishes studied to date detect sounds from below 50 Hz to up to 500–1000 Hz (Fig. 2; e.g., Ladich and Fay, 2013)—the range of sounds produced by many anthropogenic sources, including OSW devices and MECs (see Table I). In addition, a limited number of fish species with special adaptations in the auditory system can detect sound pressure to more than 3000 Hz (Ladich and Fay, 2013; Popper and Hawkins, 2021a).

A significant issue with regard to understanding what fishes hear is that most of the data in the literature are based on testing the reception of sound pressure (e.g., Fig. 2 left) without considering the potential for sensitivity to particle motion. Relatively few studies, for few species, have focused on particle motion (Fig. 2, right). Another issue regarding fish hearing is that the vast majority of studies have focused on determining the frequency range of hearing and the level of sensitivity, whereas other aspects of hearing

are far more important for fish fitness and survival. These aspects include signal discrimination, determining the direction of a sound source, and the ability to detect critical signals amid noise that masks them (also known as masking).

In addition to waterborne particle motion, some fishes may be sensitive to substrate vibrations and also produce vibrational signals for communication. This has been demonstrated for some fishes, for example, those performing “head nods” when directly hitting the substrate. Other fishes have been shown to localize vibrational stimuli associated with prey by contacting the mandible to the sediment (reviewed in Lema and Kelly, 2002).

B. Sound and substrate vibration detection by aquatic invertebrates

While there is one basic organization of the inner ears of all vertebrates, there is far more variability in the organization of potential sound- and vibration-detecting organs in the aquatic invertebrates that detect and respond to sound, and far less is known about these systems than those in the vertebrates (e.g., Budelmann, 1992; Popper *et al.*, 2001; Solé *et al.*, 2023). There appear to be three basic types of sensory organs, all of which are thought to detect particle motion (perhaps substrate vibration as well; Budelmann, 1992), but there is little or no evidence that aquatic invertebrates are likely to detect sound pressure (e.g., Breithaupt, 2002; Popper and Hawkins, 2018).

One sensory organ, found among diverse species, is the statocyst. Statocysts contain sensory cells that are analogous, but not homologous, to those in the vertebrate ear and vary by taxa (Cate and Royce, 1997). Other systems have hairs on various body parts that are associated with sensory cells—movement of the hairs stimulates the cells. Receptors also include chordotonal organs in leg joints that may respond to low-frequency sound (reviewed in Popper *et al.*, 2001), while some crabs appear to detect substrate vibration through the exoskeleton (Salmon *et al.*, 1977).

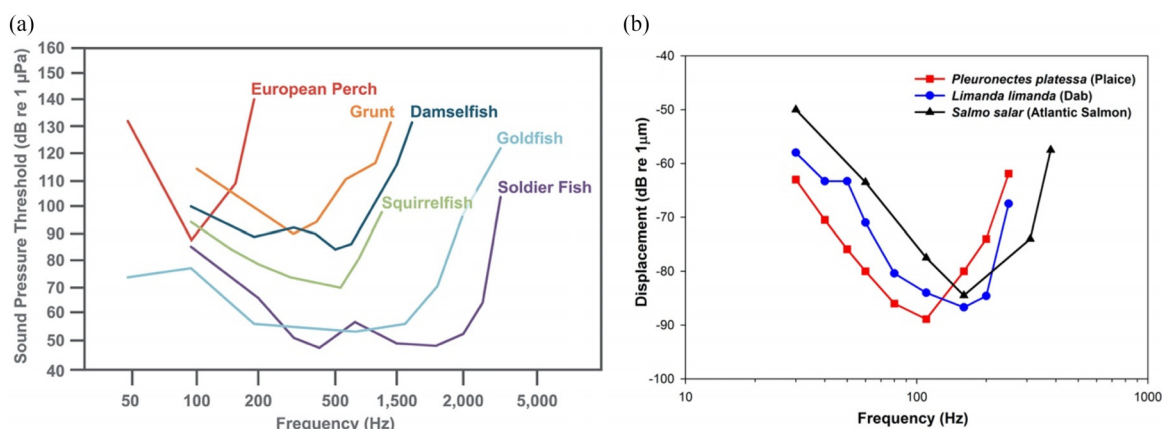


FIG. 2. (Color online) Hearing thresholds determined using behavioral methods. (a) Lowest sound level (threshold; Y axis) for different frequencies (X axis) was determined using pressure measures. Only goldfish and soldierfish have specializations for hearing that enable them to detect sound pressure at higher frequencies. The other species likely only detect particle motion. Species, European perch (*Perca fluviatilis*; Wolff, 1967); blue-striped grunt (*Haemulon sciurus*; Tavalga and Wodinsky, 1965); damselfish (*Eupomacentrus partitus*; Myrberg and Spires, 1980); squirrelfish (*Adioryx xantherythrus*) and soldierfish (*Myripritis kuntee*; Coombs and Popper, 1979); goldfish (*Carassius auratus*; Jacobs and Tavalga, 1967). (b) Hearing range and sensitivity of three of the few species that were measured in terms of particle motion, European plaice and common dab (Chapman and Sand, 1974) and Atlantic salmon (Hawkins and Johnstone, 1978). (Adapted from Hawkins and Popper, 2018b.)

Invertebrates detect particle motion in a range similar to that of fishes, from below 50 Hz (the lowest frequencies tested to date) up to around 1000 Hz, with sensitivity likely best in the low hundred hertz as found in crustaceans (e.g., Roberts and Breithaupt, 2016; Charifi *et al.*, 2017; Jézéquel *et al.*, 2021) and mollusks (Roberts *et al.*, 2015; Charifi *et al.*, 2017). Several species of cephalopod can detect sounds to up to 1500 Hz (Hu *et al.*, 2009).

Additionally, many invertebrates also interact with the seafloor, hence, vibrational sensitivity needs to be examined in addition to particle motion. Vibrational sensitivity thresholds have been experimentally defined for approximately ten species (crustaceans and bivalve mollusks), and the greatest (best) sensitivity is below 500 Hz (Roberts and Elliott, 2017). However, as for fish hearing studies, experimental methodologies differ in some cases, making comparisons difficult. Finally, nothing is known about whether any invertebrate can discriminate between sounds and substrate vibrations, determine the direction of a source, or detect signals in the presence of masking.

C. Conclusion: The importance of understanding particle motion and substrate vibration

All fishes (including cartilaginous fishes) and many aquatic invertebrates detect and use particle motion, particularly at frequencies below several hundred Hz (Nedelec *et al.*, 2016a; Popper and Hawkins, 2018), whereas a substantially smaller number of fish species also hear using sound pressure (e.g., Popper and Hawkins, 2021a). The same particle motion receptors are likely to be used for substrate vibration. Thus, it is imperative that all bioacoustics studies of fishes and aquatic invertebrate include particle motion and substrate vibration (where relevant to the animal lifestyle) as their focus, both from the perspective of measuring sound and in the responses of animals to underwater acoustics.

Particle motion should be presented in units of acceleration to facilitate comparison between studies and reflect the functionality of many auditory structures (Nedelec *et al.*, 2021). To date, however, most studies have focused on measuring sound pressure and few have been able to effectively and accurately measure particle motion, and almost none have focused on substrate vibration (Miller *et al.*, 2016). This omission occurred because researchers did not fully appreciate the importance of particle motion and substrate vibration to fishes and invertebrates, as well as the aforementioned difficulty of obtaining instrumentation to measure these signals (Lumsdon *et al.*, 2018; Nedelec *et al.*, 2021).

VI. ANTHROPOGENIC SOUND

Increased levels of anthropogenic sound in aquatic environments lead to concern about their potential impacts on fishes and invertebrates (e.g., Popper *et al.*, 2014; Hawkins *et al.*, 2015; Merchant *et al.*, 2022). Sounds from devices used in aquatic environments range from high-intensity impulsive signals produced by pile driving and seismic air guns to low-intensity, but continuous, signals from increased

boating in harbors or operation of OSW turbines and likely MECs. Sounds from the offshore energy devices may continue for many years. Such long-term sounds may have the most impact on fishes and aquatic invertebrates because they raise the overall level of sound in the environment, just as might happen in a terrestrial area where a large new highway increases the sound levels for nearby homes.

A. Overview of the potential effects of anthropogenic sources of sound

Although anthropogenic sound has the potential to affect animals (Table II), not all sounds will result in effects. Indeed, fishes and invertebrates have certainly evolved to deal with changes in sound levels within their normal soundscape. Some species may be able to increase their tolerance to some raised level of background sound resulting from anthropogenic sources, such as increased shipping or a renewable energy device (Nedelec *et al.*, 2016b) while others exposed to similar sound levels are not capable of increasing their tolerance (Nedelec *et al.*, 2017b; Harding *et al.*, 2018). Over time, this may lead to shifts in community compositions where more tolerant individuals and species exist in disturbed areas while sensitive individuals and species may only thrive in undisturbed areas.

The potential effects of anthropogenic sound range from death because of animals' exposure to loud impulsive sounds to eliciting very minor and transient behavioral responses (see Table II) to no effect at all. Indeed, few properly controlled research studies have found that exposure to sound results in a fish being mortally injured (e.g., California Department of Transportation, 2001; Popper and Hastings, 2009a; Dahl *et al.*, 2020). Moreover, in the cases of fish mortality, the sound was always impulsive, and the animals were close to the source (e.g., Casper *et al.*, 2017; Jenkins *et al.*, 2022).

Of the effects listed in Table II, death and physical injury can occur without the animal being able to hear the sound. In effect, loud sounds in the hearing range of the animal or outside of its hearing range can result in damage to body tissues such as the swim bladder. In contrast, other effects result from the animal hearing (or in the case of masking, not hearing) the sound.

B. Potential effects of sounds from MECs—Physical

Considering the potential sound levels from the variety of MECs, mortal injuries and physical damage are not likely (e.g., Casper *et al.*, 2012; Jenkins *et al.*, 2022). Moreover, the likelihood of temporary hearing loss [temporary threshold shift (TTS)] is very low because it is known only to occur in fishes that have been exposed to high sound levels for extended periods of time (reviewed in Smith and Monroe, 2016; Smith and Popper, 2023). TTS has yet to be examined in invertebrates.

C. Potential effects of MECs—Perceptual

It is likely that the major impacts of MECs on fishes and aquatic invertebrates will be perceptual, where the

TABLE II. Potential effects of anthropogenic sound on animals (adapted and modified from Popper and Hawkins, (2019). Only a few representative citations are included.

Effect	Description
Death	Instantaneous or delayed mortality (Popper and Hastings, 2009a).
Physical injury	Physical injury, externally or internally, such as a ruptured swim bladder or internal bleeding, that produces immediate or delayed death (Halvorsen et al., 2012).
Physiological changes	Physiological changes, such as in hormone levels, may result in increased stress or other effects, leading to reduced fitness (Filiciotto et al., 2017; Hudson et al., 2022). Note: Physiological effects may also come from long-term exposure to low-level sounds as well as high-level signals.
Hearing threshold shift	Temporary decreased hearing sensitivity leading to decreased detection of biologically relevant sounds such as those from oncoming predators or potential mates (Smith and Monroe, 2016).
Masking	Added sound reduces the detectability of biologically relevant sounds such as those from potential mates or other conspecifics, predators, and prey (Pyć et al., 2021; Rogers et al., 2021).
Behavioral responses	Changes in normal behaviors that could be anything from a short movement (e.g., minor startle response) to movement away from feeding or breeding sites to changes in migration routes (Engås et al., 1996). Behavioral responses to sound may vary by species, time of day, motivation (e.g., if the animal is feeding), etc. Some behavioral responses may be transient and have minimal or no consequences for an individual or population.
No obvious behavioral responses	Even if an animal detects a sound, it may show no response. This may occur in the presence of a low-level sound. Alternatively, animals may show habituation to repeated sounds. It is recognized that even when there is no overt response, the sound may cause physiological changes such as in stress levels.

animal senses the MEC and responds in some way. This may be evident in changes in behavior or physiology and may occur due to stress or impacts on cognition such as distraction (Nedelec, 2023).

The area around a source, where an animal is capable of detecting the sound emitted and may be affected by it, has been called the “zone of influence” (Richardson et al., 1995). The actual size of the zone of influence will depend on many factors such as the source level of the signal, propagation characteristics in the source area, sensitivity of the animal in detecting a signal, etc. Once an animal has detected a source, it may show a stress response or be distracted from its usual activity. Stress responses may manifest as changes in physiology such as hormone levels (primary stress response), heart rate, ventilation rate (secondary stress response), and/or behavior (tertiary stress response). Distraction may manifest as interruptions of normal activity. Stress and distraction have the potential to lead to impacts on fitness, and it is not always possible to know whether an impact on behavior, physiology, reproduction, or survival is the result of stress or distraction (Nedelec, 2023).

1. Effects on fishes

Several recent reviews consider the potential effects of anthropogenic noise on fishes (e.g., Di Franco et al., 2020; Chahouri et al., 2022). Thus, this section will only provide a very brief overview to give a sense of the types of effects that may be related to the presence of anthropogenic sound, with particular focus on potential responses to sounds that may be similar to those produced by MECs. The far broader literature on responses to other sound sources, such as pile driving, seismic air guns, and the like, is not considered here (e.g., Hawkins et al., 2015; Roberts and Laidre, 2019; Pine et al., 2020).

Some issues concern fishes that are migrating or recruiting and may be disorientated by noise from MECs (Holles

et al., 2013). This could result in fewer fish settling to benthic habitat or being drawn away from their migratory path (Simpson et al., 2015). Moreover, primary stress responses, such as increases in plasma cortisol or androgens (Mills et al., 2020), may lead to secondary stress responses, such as increased heart rate (e.g., Fakan and McCormick, 2019), gill ventilation rate (Nedelec et al., 2016b), and/or changes in social behavior (Nedelec et al., 2017a; Mills et al., 2020), feeding behavior (Gendron et al., 2020), hiding behavior (Nedelec et al., 2016b; Mills et al., 2020), parental care behavior (Nedelec et al., 2017b; Nedelec et al., 2022), and predator response behavior (Nedelec et al., 2015; Simpson et al., 2016b).

Distraction or stress resulting from the sounds emanating from MECs could lead to failure to respond to predatory attacks (e.g., Simpson et al., 2016b), failed predatory attacks, and/or mishandling of food items (Purser and Radford, 2011). Impacts on development (Nedelec et al., 2015; Fakan and McCormick, 2019), reproduction (Nedelec et al., 2022), and/or survival (Simpson et al., 2016b) can occur as a result of the above impacts. Moreover, primary stress responses, such as increases in plasma cortisol or androgens (Mills et al., 2020), may lead to secondary stress responses, such as increased heart rate and gill ventilation rate (Nedelec et al., 2016b), and/or changes in social or other behaviors (e.g., Nedelec et al., 2017b; Mills et al., 2020; Nedelec et al., 2022).

Note that while the immediate concern for such species is when they are in the zone of influence, the effects may linger beyond that period such as if migrating animals go “off course” in trying to avoid a sound. Thus, the zone of influence should not be considered as the limit of potential impacts.

2. Effects on invertebrates

A number of reviews considered the potential effects of sound on invertebrates (e.g., Edmonds et al., 2016).

However, most of them tested responses to sound pressure in laboratory tanks rather than measuring particle motion, which is the much more relevant stimulus. For animals residing near, on, and in sediments (which may vary with life stage), substrate vibration is relevant.

Most of the literature considering invertebrates and anthropogenic sound focuses on impulsive sources such as pile driving and air guns. They generally do not consider low-frequency continuous sources, which are relevant for long-term sources such as MECs, OSW devices, and increased background sounds, such as those associated with sea-going vessels. However, there is some evidence that exposure to simulated sound from continuous sea-going vessels may have a physiological stress effect on at least some invertebrates (e.g., [Hudson et al., 2022](#)).

Behavioral studies have reported changes in locomotion and feeding behavior in response to impulsive sounds or bursts of low-frequency vibrations (e.g., [Spiga et al., 2016](#); [Aimon et al., 2021](#)). There is also some evidence that similar responses may occur after exposure to more continuous sources such as boat sounds ([Wale et al., 2019](#)). Studies that investigate the potential effects of continuous sound sources in field conditions have found that sound (measured in terms of pressure) affected foraging and antipredator behavior (e.g., [Hubert et al., 2018](#); [Doyle et al., 2020](#)). Habituation may occur in response to continuous sound sources, but evidence regarding habituation and invertebrates is rather ambiguous (e.g., [Hubert et al., 2021](#); [Jézéquel et al., 2021](#)).

Similarly, studies measuring substrate vibrations have focused on impulsive sources or pure tones. Behavioral responses depicted in a field scenario include changes in spatial and chemical information use, feeding, and antipredator behavior (reviewed in [Roberts and Howard, 2022](#)). Responses to more continuous sources have not been tested, but there is some indication of differing responses between vibratory and impact pile driving ([Jézéquel et al., 2022b](#)).

D. Caveats related to the interpretation of studies investigating the effects of sound

When considering research on the behavior of fishes and aquatic invertebrates, there are several caveats related to understanding and interpreting the data, even if not discussed by the investigators. First, care must be taken when extrapolating behavioral responses observed in tanks and larger enclosures to how animals might respond in the wild ([Hawkins and Popper, 2017](#); [Popper and Hawkins, 2018](#)) because captive animals very often do not show the same behaviors as wild animals, even to the same stimulus (e.g., [Oldfield, 2011](#)).

Nevertheless, it must be recognized that conducting studies in the field is very difficult, and they often yield far fewer data than laboratory studies. The difficulties arise because fishes and aquatic invertebrates in the field are very hard to observe, especially when studying the responses of species, such as Atlantic cod or sturgeon, that may cover large areas and are likely to move in and out of the zone of influence of MECs.

A second caveat is that the acoustics of sound in tanks is very different than what animals will encounter in the wild, including in terms of the relationship between sound pressure and particle motion (e.g., [Rogers et al., 2016](#); [Jézéquel et al., 2022a](#)). Thus, even if a fish responds in some way in the laboratory, it will not necessarily be exposed to the same pressure and particle motion in the wild, hence, the responses are likely to be different.

One additional problem in using much of the current data about the effects of anthropogenic sound on the behavior of fishes is that there have been relatively few studies of fish responses to sounds from anthropogenic sources and even fewer studies of invertebrate responses. Moreover, many of the fish studies have been performed in the laboratory using freshwater species that would never be exposed to most anthropogenic sources (e.g., zebrafish, goldfish, and catfish). In addition, many of these species are hearing specialists ([Popper et al., 2021](#)), therefore, their hearing is very different than most species that will be exposed to MECs or other anthropogenic sources. Thus, in addition to exercising caution in extrapolating from laboratory to field, there is also the problem of extrapolation between very different species.

Still, the difficulties of doing many studies in the field leave a clear place for laboratory investigations if the caveats related to the interpretation of results are considered. Moreover, studies that involve physiological measures are far easier and more effective to perform in the laboratory as are studies that might involve measures of behavioral responses such as hearing capabilities. However, in all cases, it is imperative that the sound field be well defined and controlled.

VII. CURRENT CRITERIA AND MEC SOURCES OF SOUND

Regulatory criteria that can be used to help protect fishes and invertebrates from the potential effects of anthropogenic sounds from all sources are needed. However, developing such criteria is harder for these species than for marine mammals (e.g., [Finneran, 2016](#)) because there are far fewer relevant data for fishes on which to base the criteria and even fewer data for invertebrates. Moreover, the very large number of species of fishes (>34 000) and even greater number of invertebrates and their very substantial differences in morphology, physiology, ecology (including habitats), and behavior make it impossible to develop a single set of criteria applicable to even a small portion of the potentially affected species.

The current interim criteria for fishes ([Popper et al., 2014](#)) were developed by focusing on sound sources ranging from impulsive signals, such as pile driving, to sounds that are of lower intensity but continue for long periods of time, such as those that might be produced by increased vessel noise in any area. However, when developing these interim criteria, the sounds and substrate vibrations from MECs were not considered because they were not widely known. Thus, while some of the assumptions about potential impacts from MECs might be extrapolated from the earlier interim criteria,

it is imperative to have a far better understanding of MEC sounds before earlier criteria can be applied.

A. Criteria for fishes

The initial attempt to develop criteria for fishes in the U.S. focused on pile driving (e.g., [Stadler and Woodbury, 2009](#); [Caltrans, 2015](#)), but they have been applied to other sound sources as well. A very significant shortcoming of these criteria is that a single exposure level for the onset of effects is used for all species, as well as the assumption that fishes do not leave the area of exposure ([Popper and Hastings, 2009a,b](#); [Popper et al., 2014](#)).

Later, interim criteria were developed ([Popper et al., 2014](#)), which recognized that (a) criteria could not use a single value for all species, (b) the likelihood of effects will be different for different sources, and (c) different criteria levels are likely needed for various types of effects (e.g., tissue damage, TTS, and various behaviors). Recognizing that they could not propose individual criteria for all species, all sources, or all possible effects, the authors developed a set of criteria based on grouping fishes according to how well they detect sound, several representative sound sources that had different acoustic characteristics, and several major effects. These interim criteria have become part of the regulatory environment in Europe and elsewhere (e.g., [Andersson et al., 2017](#); [EU Commission, 2021](#); [Thomsen et al., 2021](#)). [Popper et al. \(2014\)](#) pointed out that they could only propose criteria values for physical effects but that there were far too few data to allow for proposing values for effects associated with the perception of sound such as for physiological and behavioral changes. Additionally, the interim criteria were only developed in terms of sound pressure because there were very few data available for the detection of particle motion by fishes and none for substrate vibration.

Whereas exposure to intense sounds, such as pile driving or seismic air guns, may cause physical effects, these would likely only take place relatively close to a source. Much more likely is the animals hearing the sounds and then showing behavioral and/or physiological effects. Currently, the only value proposed for the onset of behavioral effects is 150 dB re 1 μ Pa ([Stadler and Woodbury, 2009](#); [Caltrans, 2015](#)). However, there appears to be no scientific basis for this value, and its origin is unclear ([Hastings, 2008](#)). Moreover, it is not clear whether the 150 dB is root-mean-square (rms) or peak (e.g., [Hawkins et al., 2015](#)).

Since the 2014 criteria, several researchers have demonstrated impacts on survival due to impacts on behavior at lower sound pressure levels (SPLs) and included reports of particle acceleration levels (PALs). For example, [Simpson et al. \(2016a\)](#) showed higher mortality in fish due to predation, and impacts on reproductive success in fish have been seen at SPL (re 1 μ Pa; in the frequency band 108–2046 Hz) of 123 dB or sound PAL (re 1 μ m/s², in the same frequency band) of 93 dB ([Nedelec et al., 2017b](#)). The onset of behavioral responses is likely lower than these sound levels, and

because fishes have different hearing sensitivities, the values for behavioral onsets cannot be the same for every species. A systematic review of more recent studies would inform updated criteria. At the same, the 150 dB for pressure and its application to every species is irrelevant for species that only, or primarily, detect particle motion or substrate vibration.

B. Criteria for aquatic invertebrates

There are no proposed criteria for aquatic invertebrates and, to date, there have been no attempts to develop such criteria. Developing such criteria would require a substantially larger body of data focused on specific species. Moreover, such data would likely need to focus on particle motion and substrate vibration—two areas that are also lacking for fishes. At the same time, perhaps some preliminary guidance could come from recent papers (e.g., [Day et al., 2022](#); [Stenton et al., 2022](#)).

VIII. DATA GAPS MOST RELEVANT TO THE EFFECTS OF MEC SOUND ON FISHES AND INVERTEBRATES

A. Data gaps identified on review of earlier studies

A substantial number of data gaps has been identified in understanding the bioacoustics of fishes and invertebrates and the potential impacts of anthropogenic sound ([Hawkins et al., 2015](#)). A more recent analysis of overall data about fishes suggests that the same overall knowledge gaps still exist ([Popper et al., 2019](#)). Furthermore, a recent analysis of data gaps with regard to OSW farms, a source that has a number of similarities to MECs in terms of frequency range, being primarily continuous, and production of particle motion, gives some guidance about potential issues with fishes and invertebrates ([Popper et al., 2022](#)).

At the same time, comparatively little is known about potential impacts of any anthropogenic sound on invertebrates (e.g., [Day et al., 2021](#); [Day et al., 2022](#)). While there is a rapidly growing literature base, it is not at the point where it can provide any real guidance, particularly because in many cases, particle motion and substrate vibration are not measured in any form yet that is likely of most relevance.

B. Most important data gaps

1. Behavior

As discussed in Sec. VI A, the likelihood of sound from MECs resulting in mortal and physical injuries and temporary hearing loss is very low because sound levels are not likely to be sufficiently loud to evoke such damage. Thus, the greatest impacts on fishes and invertebrates are likely to be a result of hearing the sound, resulting in changes in behavior or physiology that may extend to some distance from the source.

Some of the major behavioral questions are listed below. In each case, caveats about the understanding of the sound field and limitations of tank experiments must be

considered, as discussed in Sec. IX. Unless indicated otherwise, the questions pertain to fishes and aquatic invertebrates.

- Does an anthropogenic source mask the detection of biologically important sounds and substrate vibrations, including those used in mate finding, detection of predators, etc.?
- will long-duration anthropogenic sources, such as MECs, create an area of avoidance that alters the migration routes of fishes or changes their location for finding food, mating, etc.?
- will the presence of an anthropogenic source alter the behaviors of animals that normally live in a particular region? Will such sources result in animals moving from their home territories, thereby subjecting themselves to potential predation and/or not being able to find a new territory, thereby decreasing their fitness?
- how do animals react at the onset of an anthropogenic source and will they, over time, habituate to the source so it no longer affects their behavior such that the animals continue their normal activities in the presence of the stimulus?; and
- does the presence of a continuous anthropogenic source affect development of eggs and larvae in the area, and are there effects on their development, growth, and reaching maturity?

2. Physiology

In comparison with behavioral effects, even less is known about the physiological effects of anthropogenic sounds on fishes and aquatic invertebrates because such effects are difficult to observe due to the lack of visible responses. Still, there are data showing that fishes (e.g., Filiciotto *et al.*, 2017) and invertebrates (e.g., Filiciotto *et al.*, 2014) exhibited stress responses to anthropogenic sound, and this could affect their fitness and reproduction.

Major research questions concerning the physiological effects from MEC sound exposure on fishes and invertebrates include the following:

- Do anthropogenic disturbances cause changes in physiological status, such as vital rates and hormone levels, in fishes and aquatic invertebrates?
- at what amplitude levels from MEC sources do disturbances cause physiological effects in fishes and aquatic invertebrates?
- what forms of disturbances by MEC sources have the most physiological effects on fishes and aquatic invertebrates?; and
- what physiological effects of MEC noise exposure on fishes and aquatic invertebrates have a biologically significant impact on these species?

3. Hearing

As is true for behavioral responses, very little is known about hearing in most species of fishes, and even less is

known for sound detection by invertebrates. An understanding of hearing is intimately related to potential behavioral impacts because there will be no behavioral effect if the animal does not detect the signal. Indeed, if an anthropogenic source is not detectable by the species of interest, then the behavioral questions, including those above, are irrelevant (Popper *et al.*, 2020).

Critically, the questions that need to be asked about what an animal hears are not just related to the response of the ear to a sound as in physiological studies (e.g., Popper and Hawkins, 2021a). This is because even if an animal's ear responds to sound, it does not meet the definitions of hearing (e.g., Pumphrey, 1950; Dijkgraaf, 1960). Instead, hearing includes the processing of sound by the brain and the potential for a behavioral response, even if the response is not observable, such as a response that includes an increased stress level or a "decision" to ignore the sound. Indeed, such potential for response is fundamental to definitions of hearing (e.g., Ladich and Fay, 2013; Popper and Hawkins, 2021a).

Moreover, a fundamental issue in asking about hearing is the need to be certain of the stimulus to which an animal responds—particle motion, substrate vibration, and/or pressure, which are produced in water and associated with the substrate. Thus, investigations must be in the field (Hawkins and Chapman, 2020) or in a laboratory environment in which the acoustic conditions are highly defined and understood (e.g., Rogers *et al.*, 2016; Jézéquel *et al.*, 2022a).

- What is the frequency range of hearing and sensitivity to particle motion and substrate vibration?
- what level of masking is associated with various anthropogenic sources?
- does masking occur and how do maskers affect sensitivity?
- how well do animals discriminate between signals and localize the source direction?; and
- do aquatic invertebrates demonstrate signal discrimination and sound source localization, and can they detect signals in the presence of maskers?

a. Other issues related to behavior. The potential behavioral effects from MECs are varied, but considering the sound levels, the zone of influence of sounds from these devices is not likely as great as that from louder sources or at shipping lanes or in harbors. At the same time, it is impossible to predict the zone of influence without conducting direct studies of each site and without inclusion of measures of particle motion and substrate vibration.

Of critical importance about the potential effects of anthropogenic sound are the dose-response relationships between behavioral and/or physiological responses and the level and duration of the anthropogenic source. Indeed, this is a fundamentally important question because the answers will determine whether mitigation is needed and the levels, if any, of criteria to potentially be developed by regulators. At the same time, it must be recognized that, at least for

potential effects that involve hearing the signal, responses may not scale with level. In other words, depending on many factors such as other behaviors in which fish are engaged, they may or may not respond even if they hear a stimulus.

To date, there have been few dose-response studies of fishes (e.g., McCauley *et al.*, 2003; Popper *et al.*, 2005; Popper *et al.*, 2007; Popper *et al.*, 2016; Dahl *et al.*, 2020) and even fewer studies of invertebrates (e.g., Day *et al.*, 2019; Day *et al.*, 2021; Day *et al.*, 2022). None of these studies, however, have provided a clear relationship between dose and response to sound signals. Moreover, all of the studies have focused on physical effects rather than behaviors.

An additional critical issue is how the potential effects of anthropogenic sound might change in animals of different ages and sizes, as well as in animals in different physiological states, such as in breeding season compared to other times of the year. There are virtually no data to help resolve these questions for any fish or invertebrate, but the questions are critical because one level of mitigation or one expectation of how an animal will respond to a signal behaviorally could change seasonally or as it ages.

IX. RESEARCH RECOMMENDATIONS

As noted earlier, it is likely that the sounds from operating MECs will be within the same frequency and intensity ranges as those sounds produced by operational OSW devices. At the same time, there are likely to be substantial differences in the potential effects of the sounds associated with OSW devices because MECs will generally be found in substantially shallower water and estuaries and rivers, as in the East River in New York City (Bevelhimer *et al.*, 2016).

The critical issue in understanding the potential MEC effects on fishes and invertebrates is the need to focus on particle motion and substrate vibration because they are the signals that most fishes and all invertebrates are likely to detect and potentially respond to. Thus, all of the studies must include measurements and analysis of such signals. Furthermore, it is critical that, whenever possible, studies must be performed in the field and use long-term low-frequency sounds, such as those produced by the devices. Additional relevant studies are those that focus on sounds and vibrations within, and emanating from, the substrate. Thus, based on such assumptions and to gain the greatest additional immediate understanding of the issues, it is concluded that the focus of research over the next several years should include the following areas:

- Sounds and substrate vibration measurements from MECs: Very little is known about the sounds produced by these devices and the potential variability related to specific devices and the nature of their sounds in different water depths, on different substrates, etc. Studies must include pressure, particle motion, and substrate vibration measures at different distances from the source;

- selection of representative species for study: As made clear by Popper *et al.* (2014) and repeated for OSW devices (Popper *et al.*, 2022), it is impossible to study all or even a small portion of fish and invertebrate species. Thus, representative species likely to live in the vicinity of MECs, and particularly species that are threatened or endangered and/or of economic value, must be selected to have data from diverse but relevant species. Conversely, studies of goldfish, zebrafish, and other common laboratory species are not acceptable substitutes;
- detection capabilities: Little is known about particle motion and substrate vibration detection by fishes and even less by invertebrates. Studies of sensory capabilities are needed, including those related to particle motion and substrate vibration, to determine the frequency and sensitivity range of hearing (lowest sound levels detectable). Of particular importance are issues related to masking. Experiments need to be performed under conditions where sound pressure, substrate vibration (where relevant), and particle motion can be carefully controlled and monitored (e.g., Chapman and Hawkins, 1973; Hawkins and Chapman, 2020) to understand the nature of the stimuli to which animals are responding;
- behavioral responses: Questions need to be asked about how fishes and invertebrates respond behaviorally to MECs. Work needs to be performed in the field where actual behaviors are observed. Questions of relevance include (but are not limited to) those about the behavioral responses (including behavioral changes) to sources; whether animals stay in the area of sources, and if they move away, do they return; whether animals' habituate; whether the presence of sources affects movement and migration in the vicinity of the devices; and what the effects of masking are;
- physiological responses: Not all effects are likely to be observable, but there may be changes in stress levels and other physiological effects that could affect fitness, survival, and development of eggs and larvae. In particular, studies of different life stages' responses to sound pressure, particle motion, and substrate vibration are needed. Such studies, assuming a controlled acoustic environment, may be easier to perform in a laboratory environment than in the field.

X. DEVELOPMENT OF CRITERIA

An important goal related to protecting fishes and aquatic invertebrates from the effects of anthropogenic sound is to develop criteria. However, as pointed out in Sec. VII, there are few current criteria for fishes and none for aquatic invertebrates, and those for fishes are based on very limited data.

The authors of this review have, thus, considered whether developing criteria for MECs and improving those for other anthropogenic sources should be one of the research priorities for the next several years. However, the conclusion is that even with the range of studies proposed in

this review, there will not be sufficient data to develop informed and science-based criteria for fishes, and it will take an even greater amount of work before criteria could be considered for invertebrates.

At the same time, there is a pressing need for a green energy transition to reduce carbon emissions, and we recognize that having even a limited set of interim criteria for MECs will potentially protect fishes even before the data needed are available for developing a full set of criteria. Moreover, considering that there have yet to be any attempts to start to develop criteria for invertebrates, it would be of real value to start considering how such criteria would be developed and what they might be. If nothing else, such a process might help guide research questions that would be most useful for development of such criteria.

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¹See www.dosits.org (Last viewed 5 July 2023).

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