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JASA FORUM

Offshore wind energy development: Research priorities for sound and vibration effects on fishes and aquatic invertebrates

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ABSTRACT:
There are substantial knowledge gaps regarding both the bioacoustics and the responses of animals to sounds associated with pre-construction, construction, and operations of offshore wind (OSW) energy development. A workgroup of the 2020 State of the Science Workshop on Wildlife and Offshore Wind Energy identified studies for the next five years to help stakeholders better understand potential cumulative biological impacts of sound and vibration to fishes and aquatic invertebrates as the OSW industry develops. The workgroup identified seven short-term priorities that include a mix of primary research and coordination efforts. Key research needs include the examination of animal displacement and other behavioral responses to sound, as well as hearing sensitivity studies related to particle motion, substrate vibration, and sound pressure. Other needs include: identification of priority taxa on which to focus research; standardization of methods; development of a long-term highly instrumented field site; and examination of sound mitigation options for fishes and aquatic invertebrates. Effective assessment of potential cumulative impacts of sound and vibration on fishes and aquatic invertebrates is currently precluded by these and other knowledge gaps. However, filling critical gaps in knowledge will improve our understanding of possible sound-related impacts of OSW energy development to populations and ecosystems.
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I. INTRODUCTION AND PURPOSE

Offshore wind (OSW) energy is a growing industry in the U.S. and around the world, and can play a key role in meeting decarbonization goals (Cranmer and Baker, 2020). The development and operation of OSW also has the potential for short- and long-term effects on the in-air and underwater environment that can be perceived as either positive or negative for taxa of interest. For example, sounds associated with pre-construction activities, construction, and operations of OSW energy development have the potential to adversely affect aquatic life in several ways. However, there are substantial gaps in knowledge regarding animals' bioacoustics and individual responses to OSW sound. Even less is known about the potential for sound-related population- or ecosystem-level impacts from cumulative OSW development activities. The purpose of this paper is to identify the most pressing data gaps and inform sound-related research as the OSW industry expands in the U.S.

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A. Origin of this paper

This paper arises from the 2020 State of the Science Workshop on Wildlife and Offshore Wind Energy, hosted by the New York State Energy Research and Development Authority (NYSERDA; 2020) from November 16–20, 2020. The aim of the workshop was to assess the state of the knowledge regarding potential cumulative impacts of offshore wind development on wildlife populations and ecosystems.

Subsequent to the workshop, attendees formed seven workgroups focusing on benthos, fishes and aquatic invertebrates, birds, bats, marine mammals, sea turtles, and environmental change. The goal for each workgroup was to identify a list of studies that could be implemented in the next five years to position the stakeholder community to better understand potential cumulative biological impacts as the OSW industry develops in the U.S. The current paper is based on the report (Popper *et al.*, 2021) from the workgroup focused on fishes and aquatic invertebrates, and specifically on issues related to the potential impacts of sound and vibration associated with OSW farms on fishes and aquatic invertebrates. Other types of potential OSW-related impacts to fishes and aquatic invertebrates were considered elsewhere (e.g., Twigg *et al.*, 2020; Degraer *et al.*, 2021).

B. Goals

The primary goal of this paper is to present the priorities identified by the Fishes and Aquatic Invertebrates Workgroup as recommendations for near-term research and coordination on sound and bioacoustics to inform the development of OSW farms (Popper *et al.*, 2021). The authors have preserved the findings and recommendations of that report as much as possible but have refined recommendations for purposes of clarity and precision. The intended audience for this paper encompasses a range of stakeholders including researchers, state and federal agencies, OSW energy developers, non-governmental organizations, regional science entities, and other potential funding entities that could target these priorities for future funding.

The priorities identified in this paper should not be interpreted as research that must occur prior to any development activity. Rather, these priorities are intended to further inform environmentally responsible development and minimize cumulative impacts, and many of these research needs are specifically directed at understanding and measuring impacts as the OSW industry progresses. Some data are available from OSW studies in Europe and around the world (e.g., Thomsen *et al.*, 2016; Gill *et al.*, 2018; Mooney *et al.*, 2020), but industrial-scale OSW development has yet to occur in the U.S., providing an opportunity for targeted research. *While this paper focuses to a degree on issues relating to the OSW industry in the eastern U.S., the approach and resulting recommendations are generally applicable to OSW development globally.* Indeed, the issues can be considered a focusing of an earlier gap analysis (Normandeau, 2012; Hawkins *et al.*, 2015) that dealt with all cases where there are long-term increases in anthropogenic sound.

This paper, and the report from which it is derived, focuses on better understanding the potential for negative impacts from sound and vibrations related to OSW energy development. This is not intended to imply that sound is the only aspect of OSW development that will affect fishes and aquatic invertebrates, nor that all effects are negative. For a comprehensive examination of the potential effects of OSW development on fishes and fisheries, including attraction of fishes due to artificial reef effects, see a recent special issue of *Oceanography* on this topic (Twigg *et al.*, 2020).

Likewise, the focus of this paper is not intended to imply that OSW is causing greater impacts than other stressors. Indeed, OSW farms may provide resources, such as food or shelter for some species, particularly those that prefer high-structure environments (Degraer *et al.*, 2020). For commercially and recreationally fished species, the interactions between fisheries and OSW (for example, changes in fishing patterns and use of certain gear types in and around OSW turbines) may also be relevant to future analyses (Methratta *et al.*, 2020). Regardless, cumulative impact estimates specifically for OSW energy development will be useful in broader cumulative impact frameworks that include impacts from multiple types of anthropogenic activities.

II. BACKGROUND

A. Definitions and concepts

To ensure continuity of meaning for this paper and across the various workgroups, ***OSW energy development*** was defined to include activities related to pre-construction (such as seismic surveys), construction, and operations of OSW farms (Fig. 1). ***Cumulative impacts*** were defined for this subject matter as collective changes to populations or ecosystems across spatiotemporal scales that are caused by anthropogenic (human-made) activities relating to the development of multiple OSW energy facilities. The terms ***impact*** and ***effect*** were defined as per Hawkins *et al.* (2020), such that an effect is considered to be a change caused by an exposure to an anthropogenic activity that is a departure from a prior state, condition, or situation, which is called the "baseline" condition. Impact is defined as a biologically significant effect that reflects a change whose direction, magnitude, and/or duration is sufficient to have consequences for the fitness of individuals or populations.

In the context of this paper, all three of the above effect and impact terms are used specifically in relation to sound and vibrations. For ease of description, and unless otherwise indicated, the terms ***sound*** and ***acoustic*** incorporate sound pressure, particle motion, and substrate vibration (see Sec. II B). In this paper, ***fishes*** are inclusive of cartilaginous and bony fishes. ***Aquatic invertebrate*** refers to any invertebrate species in the marine environment or substrate that detects sound and/or vibration.

B. Underwater sound and hearing

There are several key concepts relating to underwater sound that are critical for appreciation of the ideas and recommendations in this paper. For a fuller understanding of underwater sound, readers are directed to several recent

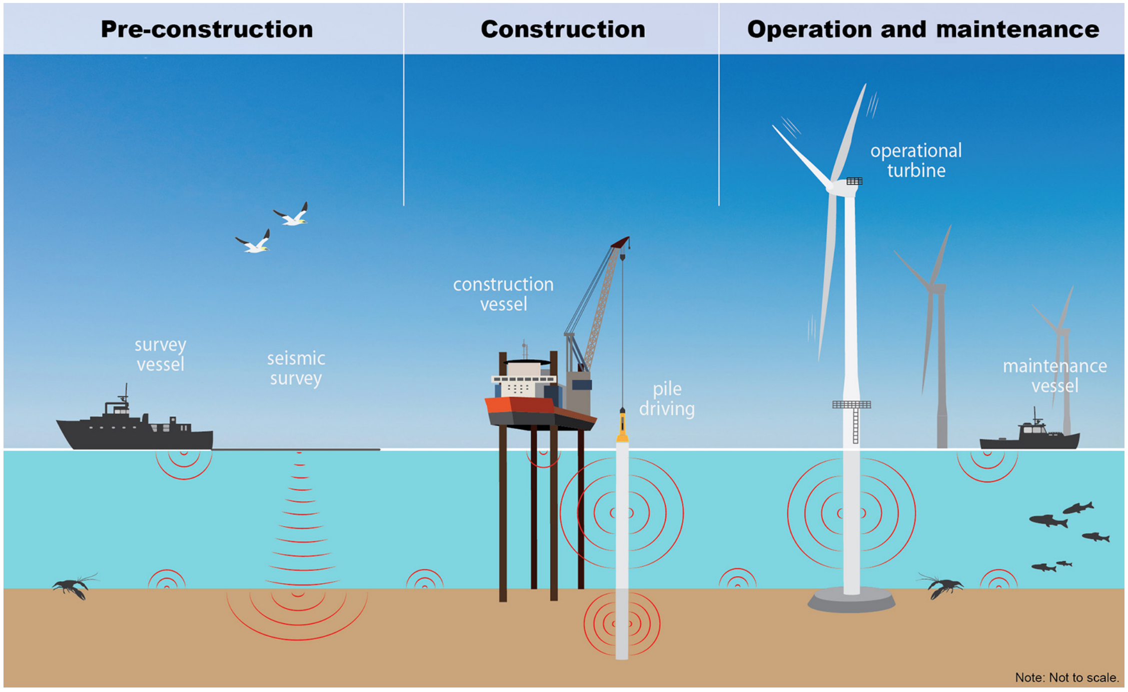

FIG. 1. (Color online) Major sources of sound and vibration from offshore wind farms during the pre-construction (left), construction (center), and operational (right) periods (not to scale). Sounds emitted from each source are indicated with red lines. Acoustic energy put into the substrate as a result of geophysical and geotechnical surveys and the pounding of piles during construction can emanate back into the water at considerable distances from the sources themselves (Popper and Hastings, 2009; Hawkins *et al.*, 2021) (Figure copyright 2021 Iain Stenhouse/Biodiversity Research Institute, all rights reserved).

papers (Hawkins and Popper, 2018; Popper and Hawkins, 2018; Hawkins *et al.*, 2021). In addition, a useful and very clear discussion of all aspects of underwater sound and animal bioacoustics can be found at Discovery of Sound in the Sea.

Importantly, the energy radiated from any underwater sound source—such as a driven pile, a boat, a fish making sounds, etc.—includes both sound pressure and particle motion. Sound pressure refers to the fluctuations in the density of the medium due to the presence of the sound, while particle motion refers to the movement of particles that make up the medium during that sound. Sound pressure is more familiar because it is the aspect of sound that most terrestrial animals can sense (including humans), and is measured using microphones and hydrophones.

However, it is now understood that all fishes, and probably all sound-detecting invertebrates, hear by the detection of particle motion, while only a subset of bony fishes are able to detect sound pressure (Nedelec *et al.*, 2016; Popper and Hawkins, 2018; Dinh and Radford, 2021). Thus, any consideration of the sounds that might affect fishes must not only include measurement of particle motion but also an understanding of how, and how well, fishes and invertebrates detect and respond to it.

In addition, it is increasingly apparent that fishes and aquatic invertebrates that live in, on, or close to the substrate (e.g., the seabed) are also potentially affected by vibrations (e.g., Roberts and Elliott, 2017; Hawkins *et al.*, 2021; Roberts and Howard, 2021). These vibrations are initiated by direct contact of a sound source with the substrate, such as during pile driving, and by sound energy entering the substrate through the water from intense sources, such as seismic air guns (e.g., Gisiner, 2016). Sound pressure and particle motion can also emanate from the substrate back into the water column as a result of such vibrations (Hawkins *et al.*, 2021).

The reason to understand underwater sound is that sounds and vibrations provide a great deal of important information to animals about their environment, potential mates, competitors, predators, and prey, just as sound in air is critical for the lives of all terrestrial animals (e.g., Fay and Popper, 2000; Slabbekoorn *et al.*, 2010; Hawkins and Popper, 2018; Slabbekoorn, 2018). Indeed, sound is an essential communication channel for aquatic vertebrates and many aquatic invertebrates (reviewed in Hawkins *et al.*, 2015; Popper and Hawkins, 2019). Thus, anything that interferes with the ability of animals to detect sounds has the potential to significantly impair survival of individuals and populations (see Slabbekoorn *et al.*, 2018). Some sounds produced by anthropogenic sources may also elicit behavioral responses and/or physiological effects that interfere with biological activities, such as feeding or spawning (Carroll *et al.*, 2017; Jones *et al.*, 2021; Puig-Pons *et al.*, 2021).

III. APPROACH USED TO DEVELOP PRIORITIES

The workgroup met virtually four times in the winter and spring of 2020–2021 to identify topics that seemed feasible to initiate on a short (<5 yr) timeframe. These were ranked by workgroup members in an online survey. The topics given here are, therefore, listed in order of priority according to these survey responses (i.e., by weighted average rank score), with the highest-priority topic listed first. However, it is recognized that several of these priorities could be pursued simultaneously to best inform OSW energy development as the industry progresses.

For each topic (listed A to G), information is included on the study goal, potential methods, and related information with relevance to the proposed study (i.e., existing data, or other efforts with which a proposed study should be coordinated). Several priorities identified during workgroup discussions were determined to require longer timelines for completion or to be at least partially addressed through existing research projects. These are briefly noted in Sec. V following the list of short-term priorities.

IV. PRIORITIES FOR THE NEXT FIVE YEARS

For each topic (listed A to G), the workgroup identified goals for research and potential methodological approaches for studies to achieve those goals.

A. Identify key species/groups for studies of the effects of OSW sound exposure on fishes and invertebrates

There are more than 34 000 species of fishes (e.g., Fishbase) and far more species of aquatic invertebrates. While most species are not located in the vicinity of likely OSW development areas, either in the eastern U.S. or elsewhere, the number of species in those areas is still too numerous to study individually. Thus, it is necessary to prioritize species for study that have the most relevance for understanding the potential effects of sound from OSW in a particular region and are "representative" of other potential species of interest.

1. Goal

Concentrate OSW and sound-related research on a few key species that represent varied hearing capabilities, hearing mechanisms, life stages, and ecological niches, as suggested by Popper *et al.* (2014) and Hawkins *et al.* (2020). Identification of representative species will help focus research and improve our understanding of the potential for individual and population effects to those, and similar, species. This also allows some level of generalization of study results over the greatest number of fish and invertebrate species, which will help us to understand community responses over the longer term.

2. Potential methods

Selecting specific species for study is complex, especially given the substantial variation in hearing characteristics that can exist, even among closely related species. Initial development of fish groupings for selection of research species has been provided in the American National Standards Institute (ANSI) guidance document cited as Popper *et al.* (2014). Possible criteria for the selection of focal species include:

- Species known to occur within and near OSW areas (e.g., Friedland *et al.*, 2021).
- Species of fishes and aquatic invertebrates with a representative range of hearing capabilities and mechanisms (Popper *et al.*, 2014; Hawkins *et al.*, 2020), inasmuch as these data are available.
- Species that represent a range of ecological niches (different habitats, diets, etc.).
- Important species, defined as some combination of:
  - Species of commercial and recreational fishing importance that occur in OSW areas.
  - Species of ecosystem importance (e.g., key forage fish/prey species, sentinel, keystone, or umbrella species) in OSW areas.
  - Protected and at-risk species in OSW areas.
- Species with potential vulnerability to OSW, including:
  - Species that spawn in or near OSW areas, as well as species that transit OSW areas during reproductive migrations.
  - Structure-oriented species that may be common in (and may be attracted to) OSW areas (Degraer *et al.*, 2020).
  - Species that are expected or known to be sensitive to displacement from OSW construction or operations.
  - Species that may be vulnerable to substrate vibration at one or more life history stages (given the lack of data on this type of effect).

Species that can be classified in more than one of the above groups could be given higher priority for selection as study species.

B. Conduct behavioral response studies to examine non-displacement changes

While some research exists on the responses of fishes and aquatic invertebrates to a variety of different sounds, less is known about how sounds specifically emitted from OSW energy development could potentially alter behaviors (e.g., Wahlberg and Westerberg, 2005; Siddagangaiah *et al.*, 2021; Zhang *et al.*, 2021). However, the available data suggest that behavioral changes resulting from exposure to sounds from OSW energy development could be a concern for at least some species (e.g., Perrow *et al.*, 2011; Thomsen *et al.*, 2012; Hawkins *et al.*, 2014; Iafrate *et al.*, 2016; Methratta and Dardick, 2019; Kok *et al.*, 2021; Puig-Pons *et al.*, 2021). A range of behavioral changes with potential fitness consequences have been hypothesized, in part, based on observations or inference from responses to other anthropogenic or environmental noise sources. These include changes in movement patterns that increase predation risk or increase energetic requirements, reductions in foraging activity or predation success rates, changes in breeding or display behavior (including spawning aggregations), and reductions or changes in vocalization behavior that may affect reproductive success (e.g., Roberts *et al.*, 2015;

Bruintjes *et al.*, 2016; Herbert-Read *et al.*, 2017; Jones *et al.*, 2021).

1. Goal

Examine behavioral and physiological changes in relation to sound exposure that may have implications for fitness, including individual survival, predator–prey relationships, and/or breeding success (e.g., Weilgart, 2017).

2. Potential methods

- Examine changes in acoustic behavior, movement behavior, reproductive behavior, predation success rates, or other behaviors during the pre-construction, construction, and operational periods of OSW development. A focus on changes with survival or reproductive implications (e.g., changes in spawning behavior) will allow investigation of population-level effects. It can be difficult to measure fitness directly; while this should be the goal where possible, in some cases, it may be easier to measure behavioral or physiological changes with fitness implications. Response variables of interest must be chosen carefully.
- Choice of focal species should be informed by Priority A (Sec. IV A). Both mobile and non-mobile species and varied life stages require attention and will require different study designs. Some existing lab studies could inform the choice of focal species and behaviors to examine in the field (e.g., Jones *et al.*, 2021; but see next bullet). It may be effective to focus on species that are associated with the types of habitats frequently present at OSW facilities (e.g., Friedland *et al.*, 2021).
- Much of this work must be conducted in the field, since behaviors exhibited by captive animals (e.g., in tanks or cages) may be very different than those of wild unrestrained animals, even in response to the same sounds (Popper *et al.*, 2019). There are some types of studies associated with sound that may only be easily done in the lab, however, such as physiological studies (e.g., examining the potential effects of sound on stress levels). Lab studies must be carefully designed so that the sounds to which the animals are exposed are well quantified and as representative as possible of sound pressure, particle motion, and substrate vibration that animals might be exposed to in the field (Rogers *et al.*, 2016). There was a lack of consensus among workgroup members about the value of initial lab studies to inform the choice of field studies, and specifically, whether the behavior and physiology of animals restrained in tanks or pens is at all similar to what they would exhibit in response to a stimulus when in the wild and unrestrained. Comparisons between field and laboratory responses within a species would be a profitable avenue to explore this question (e.g., Pieniazek *et al.*, 2020).
- Develop methods to examine behavioral effects of substrate vibration on invertebrates (e.g., Roberts and Elliott, 2017; Roberts and Howard, 2021). Given the novelty of the research area, highly controlled small-scale studies in the lab appear to be an appropriate first step, although an understanding of such an environment in terms of the stimulus parameters needs to be further developed.
- If feasible, this research should ideally be conducted in conjunction with behavioral response studies of displacement (described in Sec. V C).

C. Conduct a multi-method behavioral response study to examine animal displacement

A critical question is whether the sounds associated with development and/or operation of OSW will result in short- or long-term changes in the ecosystem due to animals leaving the area, either temporarily or permanently (e.g., Thomsen *et al.*, 2016). There are few data that currently address this issue. OSW developers are generally required to monitor underwater sound pressure levels produced by activities, such as pile driving (reviewed in Thomsen and Verfuss, 2019), but studies of resulting displacement of fishes are limited, as are studies of whether animals return to the sites from which they are displaced after termination of pile driving (e.g., Perrow *et al.*, 2011; Iafrate *et al.*, 2016).

1. Goal

Examine displacement due to behavioral response of one or more species identified in Sec. IV A (or via other efforts), including questions such as: are fishes and aquatic invertebrates displaced by construction and/or operational noise? If so, how far from the stressor are species displaced horizontally or vertically (including into the sediment)? Do they return to the area afterward? If so, for how long are they displaced?

2. Potential methods

Studies should employ a multi-method approach (e.g., acoustic telemetry, passive acoustic monitoring, cameras, sonar, spatial modeling), with methods tailored to address the geographic scale of interest, focal species, and characteristics of the study location, such as turbidity and currents.

- The technology and methodologies exist to conduct many of these experiments and monitoring studies in the field. This is important, as the spatial range of effects may be too large to measure in the lab. Ecological/spatial models can help to identify parameters to be measured. In particular, power analysis should be conducted prior to initiating field work, such that each field study is appropriately designed to test the chosen hypothesis (see Heinänen *et al.*, 2018).
- A focus is suggested specifically on displacement during spawning or other aggregation periods, since: (1) spawning areas are discrete locations with suspected sensitivity to sound; and (2) a focus on spawning (or other biologically important life functions) facilitates an understanding of the fitness consequences of behavioral changes that are observed. A focus on known foraging/feeding areas could also be useful for similar reasons.

D. Promote standardized collection of high-quality data

Sound is not the only OSW-related stressor that may affect marine ecosystems. To get a comprehensive picture of the biological effects and resulting impacts of OSW, a variety of biological and non-biological data must be collected, and this must done in a standardized fashion so that monitoring results are comparable between locations (see Thomsen *et al.*, 2021). In relation to the effects of OSW sound and vibration on fishes and aquatic invertebrates, it is essential that studies use comparable methods to record, analyze, and present data. Standardization will not only allow for much more effective and useful comparisons between studies but also for a more comprehensive assessment of cumulative impacts. To date, guidance for acoustic research standardization of methodologies and data have primarily focused on marine mammals, rather than on fishes and invertebrates.

1. Goal

Develop improved monitoring and data collection plans that promote standardization and collection of high-quality acoustic data for fishes and aquatic invertebrates. Plans should include recommended acoustic terminology and metrics (e.g., ISO18405, 2017; Ainslie *et al.*, 2021), methods to answer different types of questions (e.g., appropriate sound sources to use for playback experiments), and approaches for standardizing technologies to measure and record sounds (e.g., instrumentation to deploy on buoys and/or turbines) such that data can be aggregated for larger-scale analyses (e.g., ISO18406, 2017).

2. Potential methods

- Develop standard methods of measurement for sound pressure, particle motion, and substrate vibration, or identify appropriate existing standards where possible. Methods and metrics standardization could inform many of the other priority studies identified herein. Still, workgroup members noted that sufficient methods information is already available such that important field studies should not be delayed until more comprehensive standardized methods and metrics can be finalized. Recommendations and guidance might, in part, build from:
    - Atlantic Deepwater Ecosystem Observatory Network (ADEON), Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS), and other specifications for acoustic measurements of soundscapes (Ainslie, 2011; Dekeling *et al.*, 2014a; Dekeling *et al.*, 2014b; ISO18405, 2017; Ainslie *et al.*, 2018). There is a need to determine what is missing specifically for fishes and invertebrates, as well as for particle motion and substrate vibration.
    - Standards for underwater sound assessment and measurement of particle motion that are currently in development by the Exploration and Production Sound and Marine Life Joint Industry Programme (Nedelec *et al.*, 2021).
    - Lessons learned from the U.S. Bureau of Ocean Energy Management (BOEM) Realtime Opportunity for Development of Environmental Observations (RODEO) project (e.g., Amaral *et al.*, 2020), as well as from research on oil and gas and other industries, as relevant.
- Develop consensus for the metrics of description for sound pressure, particle motion, and substrate vibration. For particle motion, for example, are data presented in terms of velocity, acceleration, or other criteria? Similarly, for sound pressure, when is it best to use root-mean-square (RMS), peak, or sound exposure level (SEL)? Moreover, what would these metrics mean in understanding animal responses, how are they calculated, and how do fishes respond?
- Consider whether kurtosis (Qiu *et al.*, 2020) should be used as a metric for sound exposure, as it has been adopted for sound exposure studies for humans.
- Recommend standardized measurement approaches to obtain the most useful recordings of sound pressure, particle motion, and substrate vibration (e.g., Hawkins *et al.*, 2020).
- Include standards for experimentation-controlled exposures.
- Include a focus on experimental design and collection of control data in a Before-After Control-Impact (BACI), Before-After Gradient (BAG), or other design as appropriate (Methratta, 2021).
- Equipment and experimental approaches might best be developed in a controlled environment (e.g., Duncan *et al.*, 2016; Gray *et al.*, 2016a; Gray *et al.*, 2016b; Jones *et al.*, 2019; Popper and Hawkins, 2021). Lab methods and metrics for studies of responses to substrate vibration are especially needed. However, tank acoustics are very different than the acoustics in open water, and so it is not possible to easily, or accurately, extrapolate acoustics from tank studies to the natural environment (e.g., Rogers *et al.*, 2016). In fact, in terms of behavioral questions, field investigations (where possible) often generate more useful results than lab-based research, and the two methods should be paired to compare results where appropriate.
- Metrics and methods recommendations should be written in such a way as to be generally understandable to a non-expert audience, recognizing that a range of OSW developers, consultants, regulators, and other stakeholders may reference them. Where possible, specific instrumentation should be recommended that is affordable and easy to use by non-experts.
- Have an open data policy for all findings and make data publicly available on as short a timescale as is feasible, so that results can be used by others dealing with similar issues. It should be noted that in some cases, appropriate databases may need to be developed or modified to publicly house these data (NYSERDA, 2021).

E. Conduct hearing sensitivity studies for selected species, including detection of particle motion, vibration, and sound pressure

Little is known about sound detection capacities of fishes (Ladich and Fay, 2013; Popper and Hawkins, 2021), and even less is currently known about hearing in aquatic invertebrates (Hawkins *et al.*, 2015). While many of the studies that would accompany Priorities B and C (Secs. IV B and IV C) can be done without knowing hearing capabilities directly, data on hearing will be imperative to extrapolate results to other sites, species, or research questions. In particular, almost nothing is known about vibration detection by fishes or aquatic invertebrates (Roberts and Elliott, 2017).

1. Goal

Investigate detection of sound pressure, particle motion, and vibration, including bandwidth of detection, minimal level of signal detectable at each frequency (threshold, or sensitivity), and behavioral responses. These studies will inform models predicting spatial scales of effects, among other purposes.

2. Potential methods

- While electrophysiological response may be useful to broadly approximate thresholds, data must be obtained using methods that involve behavioral responses since such an approach is the only one that provides detailed information on sound perception (see Popper and Hawkins, 2021). This also allows for examination of important aspects of hearing such as masking, discrimination, and determination of sound source direction (e.g., localization).
- Studies should preferably be conducted at locations where the sound and vibration field being tested can be carefully and fully controlled (or at least fully characterized).
- Studies should focus on particle motion and vibration and not just sound pressure (this may require use of a research test site with instrumentation; Priority F, Sec. IV F). Studies should also include invertebrates, including species living in and on the sediment.
- Data should be collected on different developmental stages, life history stages, and sexes (when sexing is possible), since there may be different responses among groups.
- Methodologies should include an agreement on what constitutes sensitivity (including consideration of background noise as well as an appropriate metric) and biologically significant change (which is important in a regulatory context). Using multiple behavioral indices may help to assess biologically significant responses.

F. Develop a long-term, highly instrumented field site

It is critical that the acoustic environment for studies of sound in fishes and aquatic invertebrates be carefully designed and/or measured so that the investigators understand the precise sounds to which the animals respond. Developing such an environment is complex, expensive, and difficult, and cannot easily be done by a single investigator or group. Therefore, there is great value in developing one or more acoustically defined sites (e.g., where investigators can understand and calibrate the preexisting sound environment) that can be used by multiple investigators and for different studies.

1. Goal

Develop a long-term, highly instrumented field research site that can be worked at year-round, has well-defined acoustics, and ideally allows: (1) control of the sounds being added to the ambient soundscape; (2) tests on various authentic substrates, focal species, etc.; (3) examination of particle motion and substrate vibration (not just sound pressure); and (4) behavioral and physiological response studies.

2. Potential methods

The proposed test site could be thought of as a Long-Term Ecological Research (LTER) site for sound and acoustic equipment testing (Kratz *et al.*, 2003). Hawkins and Chapman (2020) discussed the establishment and operation of an analogous field site at Loch Torridon, Scotland. It would be important at such a site to carefully consider inclusivity and accessibility for a wide range of researchers.

While an oceanic loch or fjord might provide the combination of desired characteristics (e.g., Hawkins and Chapman, 2020), a test site more representative of offshore wind development locations would be desirable for purposes of OSW-focused research. Using a site with actual turbines, and where realistic pile-driving noise and vibrations could be generated, could also be helpful, as this could allow the study of other topics such as displacement at one site.

However, working at an actual OSW site could also create substantial limitations in terms of allowing for long-term instrumentation and control of the soundscape, and would likely require considerable coordination with the OSW developer in question during the project design process to ensure adequate access to electrical power and other needs for research equipment. Selection of an appropriate test site would require careful consideration and should be driven by the specific questions that are targeted for research.

G. Feasibility study to examine sound mitigation options for fishes and invertebrates

OSW noise mitigation has focused heavily on marine mammals (e.g., Verfuss *et al.*, 2016; Verfuss *et al.*, 2018; Verfuss *et al.*, 2019). It will, therefore, be important to examine current mitigation strategies to determine if they are protective of fishes and invertebrates, and then develop mitigation that would be most effective. There is currently no research on this topic that is known to us in relation to fishes or invertebrates and OSW. Existing sound mitigation methods designed for marine mammals (e.g., Duncan *et al.*, 2017; Bohne *et al.*, 2019) may be ineffective for fishes and invertebrates due to the frequencies at which these abatement methods are most effective, the speed at which most fishes and invertebrates move, and/or where in the environment such efforts are directed (Thomsen and Verfuss, 2019). Moreover, since many fishes and invertebrates live close to the bottom, they may be affected by energy emanating from the substrate back into the water well beyond the reach of any mitigation method (Popper and Hastings, 2009).

1. Goal

(1) Characterize existing noise abatement and mitigation methods and explore which may potentially be effective for fish and invertebrates, and (2) use these data to identify mitigation options in case substantial impacts are detected. Such a feasibility study could also help identify specific gaps in knowledge that would need to be filled to develop effective mitigation measures, including mitigation for substrate vibration.

2. Potential methods

- In order to develop the most effective mitigation for fishes (and likely invertebrates), more data are needed about hearing and acoustic behavior of these animals (Priority E, Sec. IV E; Popper *et al.*, 2020). A gap analysis would be helpful to focus research on signals that potentially affect animals, and for which mitigation may be most effective (see Normandeau, 2012; Hawkins *et al.*, 2015).
- Development of criteria/thresholds for the onset of effects from particle motion, similar to those for sound pressure (Popper *et al.*, 2014), could provide a basis for establishment of possible mitigation approaches. OSW projects may be a good opportunity to collect the particle motion data needed to propose interim thresholds.
- While this topic was ranked lowest among the seven short-term topics in the workgroup prioritization survey, there was disagreement among workgroup members on its final ranking. Many participants suggested this study is important to begin now and to build from as more information is available. It was also suggested that this would be relatively simple to accomplish concurrently with other listed priorities.

V. LONG-TERM PRIORITIES

The topics in this section were identified as priorities during workgroup discussions but were determined not to be immediate needs, due to either (1) requiring longer timelines for completion (e.g., the recommended studies likely could not be initiated within the next five years), or (2) being at least partially addressed through existing research projects under way. Topics are not listed in any particular order.

A. Ecological community alteration on and around offshore wind farms

This may require longer-term studies, though changes in communities can be seen in as little as two to three years (e.g., Lindeboom *et al.*, 2011; Dannheim *et al.*, 2019). This topic also potentially includes other types of effects besides sound (e.g., reef effects; Degraer *et al.*, 2020), as it may be difficult to differentiate the primary drivers of animal displacement/attraction if it occurs.

B. Prediction of cumulative impacts of operational offshore wind facilities

It is important to try to understand the cumulative impacts of many operational wind farms over a long period of time, and how those effects might scale (e.g., are they additive? Multiplicative?). However, this is a long-term consideration that requires a range of additional research to be conducted before it can be examined; it is not a specific research question that is addressable with our current knowledge base or in the short term. The identification of key knowledge gaps and the standardization of data collection methods (e.g., as outlined in the list of short-term priorities identified above) are the first steps towards addressing this need.

C. Development/adaptation of a cumulative impact framework

Population Consequences of Disturbance (PCoD) or similar frameworks may be suitable approaches for analyzing long-term effects of OSW farm noise exposure to fishes (see Pirotta *et al.*, 2018; Slabbekoorn *et al.*, 2019; Mortensen *et al.*, 2021). However, far more data on effects are needed before such models can be applied, so this was judged to be a longer-term goal (outside the five-year window).

D. Long-term intensive monitoring of sound at an offshore wind development site

The BOEM RODEO project at the Block Island Wind Farm (Rhode Island, U.S.) produced reports on pile driving sound, operational sound, and particle motion (BOEM RODEO), and a second RODEO project is planned, so this was not identified as an unmet need. However, workgroup members noted that long-term intensive monitoring sites in Europe have greatly added to the knowledge base of OSW effects on wildlife and have been an important supplement to site-specific studies at individual wind farms (Beiersdorf and Wollny-Goerke, 2014). As such, a longer-term intensive monitoring effort at one or more sites outside of Europe may still be of some utility.

VI. CONCLUSIONS

There are substantial gaps in our understanding of the potential effects of sound (including sound pressure, particle motion, and substrate vibration) on fishes and aquatic invertebrates. These gaps currently preclude assessment of potential cumulative impacts of sound from OSW energy development. There is also a dearth of data from field studies conducted under real-world conditions that examine behavioral, physiological, and ecosystem effects of sound that may have possible fitness consequences. It is suggested that OSW-related sound research over the next five years focus on filling some of the most critical gaps in knowledge, as discussed in Sec. IV. This approach will most efficiently improve our broad understanding of potential effects. In the long term, the aim of such research should be to inform cumulative impact models, thereby substantially enhancing our understanding of possible sound-related impacts of OSW energy development to populations and ecosystems.

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