Workgroup Report on Sound and Vibration Effects on Fishes and Aquatic Invertebrates

State of the Science Workshop on Wildlife and Offshore Wind Energy 2020: Cumulative Impacts

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Additional Information

This report is one outcome from a broader effort to review the state of knowledge regarding offshore wind energy development's effects on wildlife and identify short-term research priorities to improve our understanding of cumulative biological impacts as the offshore wind industry develops in the eastern United States. This effort, titled *State of the Science Workshop on Wildlife and Offshore Wind Energy 2020: Cumulative Impacts*, included a week of plenary presentation sessions and contributed talks in November 2020, as well as the formation of six other workgroups similar to the fishes and aquatic invertebrates workgroup that met over the winter of 2020-2021. This report, and those from the six other workgroups, are available on the workshop website at https://www.nyetwg.com/2020-workgroups.

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Background

The 2020 State of the Science Workshop, hosted by the New York State Energy Research and Development Authority (NYSERDA), was held virtually from November 16-20, 2020. This workshop brought together over 430 stakeholders engaged with environmental and wildlife research relevant to offshore wind energy development. The aim of the workshop was to assess the state of the knowledge regarding offshore wind development's potential cumulative impacts on wildlife populations and ecosystems. **For this effort, cumulative impacts were defined as interacting or compounding effects across spatiotemporal scales, caused by anthropogenic activities relating to the development and operation of multiple offshore wind energy facilities, that collectively affect wildlife populations or ecosystems** (see call-out box for definitions of "effects" and "impacts").[1]

Workshop attendees included a wide range of stakeholders, including offshore wind developers, government agencies, non-profit organizations, the fishing industry, academia, and consultants. More information can be found at http://nyetwg.com/2020-workshop. Following the plenary sessions in November, workshop attendees formed seven workgroups focusing on benthos, fishes and mobile invertebrates, birds, bats, marine mammals, sea turtles, and environmental change. Workgroups, under the guidance of lead technical experts, met virtually in late 2020 and early 2021 to identify scientific research, monitoring, and coordination needs to improve our understanding of cumulative impacts from offshore wind energy development. **The goal for each group 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 offshore wind industry develops in the U.S.**

The intended audience for this report encompasses a range of stakeholders including researchers, state and federal agencies, offshore wind energy developers, regional science entities, and other potential funding entities that could potentially target these priorities for future funding. The priorities identified below 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 effects as the industry progresses.

Workgroup members represented a wide range of perspectives including (but not limited to) offshore wind developers, government agencies, non-profit organizations, the fishing industry, academia, and consultants, provided key input based on their respective specialties. Workgroup meetings included presentations as well as small and large group discussions to identify and prioritize key topics of interest. Workgroup members also provided input on the relative priority of different topics via live polls during meetings and/or online surveys between meetings. All workgroup documents were shared with workgroup members via a document collaboration platform (e.g., Google Drive, Microsoft Teams), and workgroup members

Defining Impacts vs. Effects (from Hawkins et al. 2020)

Effect: 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: 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.

[1] This effort was focused on better understanding effects specifically from offshore wind energy development. This was not intended to imply that offshore wind is causing greater impacts than other stressors. Cumulative impact estimates for offshore wind energy development will be useful in broader cumulative impact frameworks that include impacts from multiple types of anthropogenic activities.

had multiple opportunities over the course of several months to provide written input on earlier drafts of this report. The report indicates a general consensus among workgroup members, unless otherwise noted; where there was stated disagreement among workgroup members on a recommendation in this report, this disagreement is noted in the text. Despite the substantial input and influence of workgroup members on the workgroup reports, final report content was determined by the technical leads, in some cases with support from an additional small subgroup of experts within the group.

The fishes and aquatic invertebrates workgroup leaders were Arthur N. Popper (Professor Emeritus & Research Professor, University of Maryland, and Environmental BioAcoustics, LLC) and Lyndie Hice-Dunton (Executive Director, Responsible Offshore Science Alliance), with technical and logistical support from Kate Williams, Edward Jenkins, and Julia Gulka (Biodiversity Research Institute) and others (Cadmus Group). The workgroup consisted of 42 workshop attendees (Appendix A). More information about the workgroups can be found at https://www.nyetwg.com/workshop-workgroups.

During the time in which this workgroup operated, there were several other research prioritization efforts around offshore wind energy development and fishes that had the potential to overlap with this group, including the State of the Science benthos workgroup (working concurrently with this fishes group; Degraer et al. 2021), as well as several groups involved in developing a white paper for the *Fisheries and Offshore Wind Energy: Synthesis of the Science* effort[2], which was discussed during Session 8 at the November State of the Science workshop[3]. Given these factors, and based on the results of the online survey indicating group members' areas of expertise, workgroup leads chose to focus this workgroup primarily on effects from sound and vibrations. Workgroup members that were primarily interested in topics such as electromagnetic fields (EMF) and benthic disturbance joined the benthos workgroup (Degraer et al. 2021).

Introduction

Sounds and vibrations provide a great deal of important information to animals, aquatic or terrestrial, about their environment, potential mates, competitors, predators, and prey. 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 of biological relevance to them has the potential to significantly impair survival of individuals and populations (Slabbekoorn et al. 2018). Importantly, 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.

Compared to marine mammals, there are substantial gaps in what is known about fish and invertebrate bioacoustics, including, but is not limited to, hearing capabilities and behavioral responses to sound (e.g., Normandeau 2012; Hawkins et al. 2015). Moreover, much of the existing data on underwater sound and fishes has been based on studies focusing on the pressure component of the sound field, but there is a growing understanding that other aspects of sound—e.g., particle motion and substrate vibration—are equally or more important for both fishes and invertebrates (e.g., Popper et al. 2019a, b;

[2] Fisheries and Offshore Wind Energy: Synthesis of the Science effort https://rodafisheries.org/portfolio/synthesis-of-the-science/
[3] 2020 State of the Science Workshop www.nyetwg.com/2020-workshop

Hawkins et al. 2021). In the remainder of this document, unless otherwise indicated, we use the term "sound" to incorporate all three aspects of sound pressure, particle motion, and substrate vibration.

For offshore wind energy development, the lack of understanding of bioacoustics, starting with sound detection and acoustic behaviors of bony fishes, cartilaginous fishes, and aquatic invertebrates, represent gaps that need to be addressed using several different approaches. Generally speaking, this workgroup recommends that the scientific and offshore wind energy communities do the following:

- **Identify priority taxa for research.** Since it is impossible to study the hundreds of species in the areas of interest, it will be important to focus research on a selection of species/taxa with a representative range of hearing capabilities and mechanisms, and which might be expected to co-occur in areas of OSW development in the eastern U.S. (e.g., Friedland et al. 2021). This will help maximize resources over the short term and build our understanding over time.
- **Assess the extent of existing data and prioritize remaining knowledge gaps.** A workshop on interface effects on benthic communities, for example, might be a useful first step to identify what is known and key gaps and research needs on this topic in relation to OSW. This could set a "baseline" for our understanding of vibration and its effects on key species.
- **Appropriately balance the need for small-scale lab studies, controlled field studies, and studies at OSW sites.** Different questions are most appropriate to address at different scales. However, the difficulties associated with recreating a real-world marine sound environment in a laboratory setting must not be underestimated. Thus, it is important to conduct field or field-relevant research on the behavior and responses of fishes and invertebrates to OSW sound sources whenever possible. Several workgroup members also emphasized the importance of focusing efforts on field research to fill knowledge gaps and inform decisions. Though it is recognized that lab studies may be the best way to initially ask a broad range of questions that might be very difficult to do in the field, such as questions around physiological response (e.g., stress levels, hormone physiology) to the sounds and vibrations associated with operational wind farms.
- **Focus on understanding the potential behavioral effects of particle motion, substrate vibration, and sound pressure at all life stages for species of concern.** All sound-related effects should be considered collectively; it should be standard practice to examine seabed vibration and particle motion alongside sound pressure in research studies where appropriate (e.g., substrate vibration is going to be important for species and life history stages that utilize the seabed). Substrate vibration, in particular, is poorly understood at present, especially in terms of the biological effects of vibration sensitivity pressure (Roberts and Elliot 2017; Hawkins et al. 2021); it will be important to develop a better understanding of potential substrate vibration-related sound impacts from OSW on aquatic animals in or near the seabed. This is particularly important given the potential long-term effects of substrate vibration produced by operational wind farms after the more acute and short-term effects of sound produced by wind farm construction have subsided.
- **Focus on animal behavioral responses as well as on their hearing.** To best inform our understanding of impacts, as well as potential mitigation measures, it is less important to understand whether fishes and invertebrates can detect a given sound source (which may not entail an effect) than to assess how they are affected by it.

While the above, general considerations may be helpful for guiding research on this topic, we also suggest several specific short-term research priorities for improving our understanding of sound-related effects from OSW development to fishes and aquatic invertebrates in coastal and offshore waters of the eastern U.S. Addressing these specific knowledge gaps will be important to meet the longer-term goals of effectively predicting and understanding cumulative impacts of sound and vibrations on fishes and aquatic invertebrates.

Methods

The workgroup met virtually four times in the winter and spring of 2020-2021. Group members identified a range of possible priority topics for improving our understanding of OSW effects on physical and oceanographic conditions in the eastern U.S. A smaller subgroup of bioacoustics experts refined this list of topics and identified those topics that seemed feasible to initiate on a short (<5 year) timeframe. Following further development of these seven topic ideas by group leads and members, the workgroup participated in an online survey (n=27) to rank the topics in order from highest to lowest priority. The below topics are listed in order of priority according to these survey responses, with the highest-priority topic listed first. For each topic, information is included on the study goal, potential methods, and existing data and/or related information with relevance to the proposed study (i.e., other ongoing studies or coordination efforts with which a proposed study should be coordinated). Where there was disagreement among workgroup members on relative prioritization of topics, this is indicated in the text.

While priorities are generally presented in order as ranked by the workgroup, workgroup members agreed that several of these priorities could be pursued simultaneously to best inform offshore wind energy development as the industry progresses. Indeed, several studies listed below require similar methods, or could (and should) be conducted concurrently (e.g., behavioral response topics #2-3), and thus could be combined for efficiency. The identification of key species for Topic #1 will directly inform the choice of study species for behavioral studies (#2-3), as well as hearing studies (#5). Development of a long-term field site (#6) and a feasibility study on sound mitigation options (#7) can both be initiated independently of these other priorities (with the caveat that a field site, once it has been developed, represents an ideal place to carry out some of the hearing studies suggested in #5). Methods and metrics standardization (#4) could inform many of the other studies (#2-3, #5-6), though 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. The identification of key knowledge gaps and the standardization of data collection methods (e.g., as outlined in this list of short-term priorities) are the first steps towards understanding cumulative impacts of OSW-related sound and vibrations on fishes and aquatic invertebrates in the eastern U.S.

Short-term Priorities That Could Be Initiated in the Next Five Years

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

Background: There are more than 33,000 species of fishes (e.g., www.fishbase.org) and far more species of aquatic invertebrates. While most species are not located in the vicinity of OSW lease areas, the number of species in those areas are still too numerous to study individually. Thus, it is necessary to begin to prioritize the most important and critical species for study that have the most relevance for understanding the potential effects of sound from OSW in the eastern U.S. The species chosen for study should be “representative” of other potential species of interest.

Goal: (1) Identify important “groups” of fishes and aquatic invertebrates on which to focus initial research, and (2) concentrate OSW and sound-related research on a few key species that represent different 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 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.

Potential methods: Selecting specific species for study is complex, especially given the substantial variation in hearing characteristics that can occur, even among closely related species. Some variables for consideration in the selection of focal species are listed below; for example, we would suggest the identification of focal species that represent a diversity of hearing systems and capabilities in both fishes and aquatic invertebrates (Popper et al. 2014; Hawkins et al. 2020), inasmuch as these data are available. Possible criteria (in no particular order) include:

- Species with a representative range of hearing capabilities and mechanisms (Popper et al. 2014; Hawkins et al. 2020).
- Species that represent a range of ecological niches.
- Species that represent a range of diets (e.g., planktivore, piscivore, etc.).
- Species known to occur within and near wind energy areas in the eastern U.S. (Friedland et al. 2021).
- Species of commercial and recreational fishing importance in OSW areas.
- Non-commercial fishes with ecosystem importance (e.g., key forage fish/prey species, sentinel, keystone, or umbrella species).
- Protected and at-risk species.
- Species that spawn in or near OSW areas.
- Species that transit OSW areas during reproductive migrations, regardless of whether they spawn in these areas.
- Structure-oriented species that may be common in (and may be attracted to) OSW areas.
- Species that are expected or known to be sensitive to displacement from OSW construction or operations.
- Species for which we have at least some prior knowledge of their hearing capabilities, ecology, and behavior.
- Species that may be vulnerable to substrate vibration at one or more life history stages (given the particular lack of data on this type of effect).

Species that can be classified in more than one of the above groups may be given higher priority for selection as study species. As an example of how several species might be selected, Friedland et al. (2021) identified species of fishes and macroinvertebrates that demonstrate particular reliance on habitats found in wind energy lease areas and planning areas from Massachusetts to North Carolina. They called out several species in particular that were important fisheries species as well as being moderately to heavily reliant on these habitats, namely Atlantic menhaden (*Brevoortia tyrannus*), summer flounder (*Paralichthys dentatus*), and black seabass (*Centropristis striata*). These three species differ markedly in their hearing abilities, and also likely represent different hearing mechanisms. Menhaden would be most likely to detect changes in sound pressure, while seabass and flounder might detect particle motion, and flounder might detect substrate vibration. Thus, these species meet several of the criteria defined above for further study. However, it should be noted that this is presented purely as an example of application of several of the above criteria, rather than as a recommendation to study these species in particular.

Related information:

- This effort should inform the choice of focal species for other topics listed below, particularly for behavioral response studies at OSW areas (Topics #2-3).

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).

2. Conduct behavioral response studies to examine non-displacement changes in relation to sound exposure and substrate vibration

Background: Little is known about how fishes and aquatic invertebrates respond to sound, or how the addition of anthropogenic sound, such as that from OSW construction and operation, could potentially alter behaviors. However, the available data suggest that behavioral changes could be a concern for at least some species (e.g., Perrow et al. 2011; reviewed in Boyle and New 2018). A range of behavioral changes with potential fitness consequences have been hypothesized. These include changes in movement patterns that increase predation risk or increase energetic requirements, reductions in foraging activity, changes in reproductive dynamics and/or mating systems, and reductions or changes in vocalization behavior that may affect reproductive success.

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; Weilgart 2018). Behavioral changes might include, among other things, acoustic behavior (e.g., vocalizations), movement behavior, breeding and display behavior (including spawning aggregations), and predation success rates.

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. A focus on changes with survival or reproductive implications (e.g., changes in spawning behavior) will allow us to get at population-level effects. It can be difficult to measure fitness directly; while this should be the goal where possible, in some cases we may more easily be able to measure behavioral or physiological changes with fitness implications. Response variables of interest must be chosen carefully.
- Both mobile and non-mobile species and life stages require attention and will require different study designs. It may be effective to focus particularly 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 needs to be conducted in the field since it is likely that the behaviors exhibited by captive animals (e.g., in tanks or cages) would be very different than that of wild unrestrained animals, even in response to the same sounds. At the same time, there are some types of studies associated with sound that may only be easily done in the lab, such as physiological studies (e.g., examining the potential effects of sound on stress levels). However, lab studies must be carefully designed so that the sounds to which the animals are exposed are as representative as possible of sound pressure, particle motion, and substrate vibration to those in the field (Rogers et al. 2016). Moreover, there is a lack of consensus among workgroup members about the value of initial lab studies to inform the choice of field studies, particularly

with regard to whether the behavior and physiology of animals restrained in tanks or pens is anything like what they would exhibit in response to a stimulus when in the wild and unrestrained.
- Develop methods to examine behavioral effects of substrate vibration on invertebrates. Such studies might be appropriate in a lab environment, although design of such an environment with proper stimulus parameters needs to be developed.

Related information:

- Choice of species for study should be decided from the work done in Topic #1. If feasible, this research should ideally be conducted in conjunction with behavioral response studies of displacement (described below).
- Some existing lab studies could inform the choice of focal species and behaviors to examine in the field (e.g., Jones et al. 2020).
- For State of the Science workgroup discussions on potential sound-related behavioral effects to marine mammals and sea turtles, see Southall et al. (2021) and Gitschlag et al. (2021), respectively.

3. Conduct a multi-method behavioral response study to examine displacement from noise and vibration generated by wind farm construction and operation

Background: A critical question is whether the sounds associated with development and/or operations of OSW will result in short- or long-term changes in the ecosystem due to animals leaving the area, either temporarily or permanently (Thomsen et al. 2015). There are few data that currently address this issue.

Goal: Examine displacement due to behavioral response of one or more species identified in Topic #1 (or via other efforts). Determine the spatiotemporal scale of displacement for these species (e.g., are fishes displaced by construction and operation noise? If so, how far from the stressor are species displaced horizontally or vertically [including into the sediment]? Do they return to the area afterwards? If so, for how long are they displaced?)

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

- The technology and methodologies exist to conduct experiments and monitoring in the field. This is important as effect ranges are too large to measure in the lab. Ecological/spatial models can help to identify parameters to measure and power analysis should be conducted prior to initiating field work, such that field studies are appropriately designed to test the chosen hypothesis (see Heinänen et al. 2018).
- A suggested focus is on displacement specifically 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, especially for species that do not spawn in the area.

Related information: OSW developers are required to monitor underwater sound levels produced by activities such as pile driving, which could be a source of supplemental information for studies of sound-related displacement. The Bureau of Ocean Energy Management (BOEM) has also funded or is currently funding several acoustic telemetry studies of black sea bass, Atlantic sturgeon (*Acipenser oxyrhynchus oxyrhynchus*), winter skate (*Leucoraja ocellata*), striped bass (*Morone saxatilis*), and other species[4]; results of these studies could provide pre-construction baseline information on the movement of these species for comparison with results of telemetry studies conducted during the construction and operation of wind farms.

4. Methods standardization: develop recommendations to promote standardized collection of high-quality data to understand offshore wind sound-related effects on fishes and invertebrates

Background: It is essential that studies use comparable methods to record, analyze, and present data on the effects of OSW sounds and vibrations on fishes and aquatic invertebrates. Standardization will allow for much more effective and useful comparisons between studies and assessment of cumulative impacts. Workgroup members recommended that this need for standardization should not preclude the initiation of other field studies, with metrics and methods developed in part through initial field studies at OSW sites.

Goal: Develop improved monitoring and data collection plans that promote standardization and collection of high-quality acoustic data. These should include recommended acoustic metrics, 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.

Potential methods:

- Develop standard methods of measurement for sound pressure, particle motion, and substrate vibration, or identify appropriate existing standards where possible (see related information, below). Where possible, recommend specific instrumentation that is affordable and easy to use by non-experts.
- 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 should be used as a metric for sound exposure, as it has been adopted for sound exposure studies for humans (Qiu et al. 2020).
- Recommend specific approaches to be used for measurement of sound (e.g., how instruments should be placed to get the most useful recordings of sound pressure).
- Include standards for experimentation-controlled exposure, etc.
- 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).

[4] BOEM Environmental Studies Program. https://www.boem.gov/environmental-studies

- Equipment and experimental approaches might best be developed in a controlled environment; lab methods and metrics for doing studies of responses to substrate vibration are particularly 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). For behavioral studies, in particular, field studies (where possible) will 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.

Related information: The Responsible Offshore Science Alliance (ROSA)[5], has developed an OSW project monitoring framework and guidelines for fisheries research and monitoring[6] (not focused on sound specifically). These guidelines could be used as a starting point to build in the next level of detail, focusing specifically on sound and vibrations. Recommendations and guidance should also build from:

- Lessons learned from the BOEM Realtime Opportunity for Development of Environmental Observations (RODEO) project[7].
- Lessons learned from research on oil and gas and other industries, as relevant.
- Atlantic Deepwater Ecosystem Observatory Network (ADEON)[8], Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS)[9], and other specifications for acoustic measurements of soundscapes. 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[10].

A need for methodological and data standardization and transparency was also noted in other State of the Science workgroups, including those focused on the benthos (Degraer et al. 2021), marine mammals (Southall et al. 2021), birds (Cook et al. 2021), bats (Hein et al. 2021), and environmental stratification (Carpenter et al. 2021).

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

Background: Very little is known about sound detection capacities of fishes, and far less is known about hearing in aquatic invertebrates. While many of the studies that would accompany Priorities #2 and #3 (above) can be done without knowing hearing capabilities directly, data on hearing will be imperative if we are to extrapolate results from studies at one site or on one species to other sites, species, or research questions. In effect, by knowing the sound levels and other sound parameters that might affect one species (e.g., sound detection in the presence of anthropogenic sounds that might interfere [mask] biologically important sounds), it may be possible, just by knowing how well a second species hears the

[5] ROSA https://www.rosascience.org/
[6] ROSA offshore wind project monitoring framework and guidelines https://4d715fff-7bce-4957-b10b-aead478f74f6.filesusr.com/ugd/99421e_b8932042e6e140ee84c5f8531c2530ab.pdf
[7] BOEM Realtime Opportunity for Development of Environmental Observations project www.boem.gov/rodeo
[8] Atlantic Deepwater Ecosystem Observatory Network https://adeon.unh.edu/standards
[9] Joint Monitoring Programme for Ambient Noise North Sea https://northsearegion.eu/jomopans
[10] Exploration and Production Sound and Marine Life Joint Industry Programme https://www.soundandmarinelife.org/

same sound, to make some tentative predictions as to whether the second species is likely to hear the sound, and at what distances from the source it might show behavioral responses. In addition, almost nothing is known about vibration detection by fishes or aquatic invertebrates (Roberts and Elliott 2017).

Goal: Investigate detection of sound pressure, particle motion, and vibration, including both bandwidth of detection and minimal level of signal detectable at each frequency (threshold, or sensitivity). These studies will inform models predicting spatial scales of effects, among other purposes. Since the most important roles of hearing involve more than just sensitivity and bandwidth, data must also be obtained on other aspects of hearing such as masking, discrimination, and determination of sound source direction.

Potential methods:

- 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).
- While electrophysiological response may be useful to approximate thresholds, data must be obtained using methods that involve behavioral responses when and where possible since they, unlike electrophysiological methods, provide detailed information on sound perception. They also allow for examining very important aspects of hearing such as masking, discrimination, and localization.
- Studies should focus on particle motion and vibration and not just sound pressure (this may require use of a research test site with instrumentation). Studies must also include invertebrates (including species living in and on top of 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 (1) "sensitivity" (including consideration of background noise as well as an appropriate metric), (2) significant change, and (3) biologically significant change (this is important in a regulatory context). Using multiple behavioral indices may help to assess biologically significant responses.

Related information: This could build off of other priority topics (Topics #1 and #6).

6. Develop a long-term, highly instrumented field site for research on the response of animals to sound and vibration that allows for some control of the soundscape/vibroscape while also allowing for research on relevant substrates and species.

Background: It is critical that the acoustic environment for studies of sound in fishes and invertebrates be carefully designed so that the investigators know 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. Therefore, there is great value in developing one or more acoustically-defined sites (e.g., where investigators can understand and calibrate the pre-existing sound environment) that can be used by multiple investigators and for different studies.

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.

Potential methods: While an oceanic loch or fjord might provide this combination of desired characteristics (e.g., Hawkins and Chapman 2020), there are other issues to consider (e.g., authentic substrate, ambient soundscape, etc.) which may suggest a test site more representative of offshore wind development locations in the area of interest. Using a site with actual turbines, and where realistic pile-driving noise and vibrations could be generated, could also be helpful, as this could also allow the study of other important aspects such as displacement, at one site. However, working at an actual OSW site would also have substantial limitations in terms of allowing for long-term instrumentation and control of the soundscape. Selection of an appropriate test site would require careful consideration and should be driven by the specific questions that are targeted for research.

Related information: The proposed test site could be thought of as a Long-Term Ecological Research (LTER) site for sound and acoustic equipment testing[11]. Hawkins and Chapman (2020) discussed the establishment and operation of an analogous field site at Loch Torridon, Scotland. The U.S. Navy also has a test site at Seneca Lake, New York (described in Popper et al. 2007), though not an appropriate ecosystem for learning about marine OSW. It would be important at such a site to carefully consider inclusivity and accessibility for a wide range of researchers.

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

Background: OSW noise mitigation has focused heavily on marine mammals. However, the frequencies of sounds important to marine mammals – and specifically to the smaller odontocetes that were the target of most early mitigation approaches in Europe – are, for the most part, well above the frequencies of importance to (and detectable by) fishes and aquatic invertebrates. 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. However, 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 #5; Popper et al. 2020).

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.

Potential methods:

- There is currently no research on this topic in relation to offshore wind energy development. Existing sound mitigation methods such as bubble curtains that were designed for marine mammals may be ineffective for fishes and invertebrates, including benthic specialists, due to the frequencies at which existing abatement methods are most effective and 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 that arises from the portions of the pile in the substrate (Hawkins et al. 2021). This energy may come out of the substate into the water well beyond any mitigation method (Popper and Hastings 2009). There are no known devices that will mitigate energy in the substrate. Other methods such as gradually "ramping up" loud sound sources to allow mobile animals to move away from the

[11] Long-Term Ecological Research Network https://lternet.edu/

sound source (Thomsen and Verfuss 2019) are not likely to be useful since most fishes and invertebrates are too slow to move far enough away from a source during ramp up. Furthermore, there are no data to support ramp up as being effective for fishes.

- This study may require more data than we currently have in some cases on how animals detect and are affected by noise. A gap analysis would be helpful and could allow for a focus on questions related to what animals can detect and respond to, rather than just developing mitigation without knowing the signals that potentially affect animals (see Normandeau 2012; Hawkins et al. 2015).
- Development of criteria/thresholds for particle motion (as already exist for sound pressure – Popper et al. 2014) could be a possible mitigation approach. OSW projects may be a good opportunity to collect the particle motion data needed to propose interim thresholds.

Related information: While this topic was ranked lowest (via weighted average) among the seven short-term topics in the workgroup prioritization survey, there was disagreement among workgroup members on the final ranking of this topic. Many participants suggested this study is very 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.

Long-term Priorities

The topics below were identified as priorities during workgroup discussions but were determined to require longer timelines for completion (e.g., the recommended studies likely could not be initiated within the next 5 years) or to be at least partially addressed through existing research projects currently underway.

Ecological community alteration on and around offshore wind farms

This is a longer-term effect and may require longer-term studies (possibly greater than 5 years), though changes in communities can be seen in as little as 2-3 years. This topic also potentially includes other types of effects besides sound (e.g., reef effects; Degraer et al. 2021), as it may be difficult to differentiate the primary drivers of displacement if it occurs.

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. 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.

Development/adaptation of a cumulative impact framework

Population Consequences of Disturbance (PCoD) or similar frameworks are suitable approaches for analyzing long-term effects of offshore wind farm noise exposure to fishes (see Mortensen et al. 2021).

However, we need far more data on effects (e.g., displacement) before we can apply these models, so this was judged to be a longer-term goal (outside the 5-year window).

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

The BOEM RODEO project at Block Island produced reports on pile driving sound, operational sound, and particle motion, and a second RODEO project is planned for 2020-2022, 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; as such, a longer-term intensive monitoring effort at one or more sites may still be of some utility.

Conclusions

There are substantial gaps in our understanding of the potential effects of sound (including sound pressure and particle motion) and substrate vibration on fishes and aquatic invertebrates. These gaps currently preclude assessment of potential cumulative impacts from offshore wind energy development. In particular, there is a dearth of data from field studies conducted under real-world conditions that examine behavioral and/or other effects with possible fitness consequences. We suggest focusing OSW-related research over the next 3 to 5 years on filling some of the most critical gaps in knowledge. Rather than studying a random selection of species, it will be important to carefully select a group of species for study that represent the range of hearing capabilities and mechanisms of the fishes present in OSW areas. 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 impacts to populations and ecosystems.

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Appendix A. Workgroup Participants

Table A1. Workgroup members who attended one or more workgroup meetings and/or provided written comments on research priorities (listed in alphabetical order by first name).

Participant	Affiliation
Aaron Baltich-Schecter	Equinor Wind US
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Carl Lobue	The Nature Conservancy
Carliane Johnson	SeaJay Environmental
Chris McGuire	The Nature Conservancy
Crista Bank	Vineyard Wind
David Zeddies	JASCO Applied Sciences
Dennis Higgs	University of Windsor
Doug Christel	National Marine Fisheries Service
Ed Jenkins	Biodiversity Research Institute
Elizabeth Methratta	National Oceanic and Atmospheric Administration NMFS
Frank Thomsen	DHI A/S
Greg DeCelles	Ørsted
Hadley Clark	Woods Hole Oceanographic Institution
Ian Jones	Woods Hole Oceanographic Institution
Jake LaBelle	Wildlife Conservation Society
Jeff Herter	New York Department of State
Joel Southall	Mayflower Wind LLC
Joost Bergsma	Bureau Waardenberg
June Mire	Tetra Tech
Justin Krebs	AKRF, Inc.
Kate McClellan Press	New York State Energy Research and Development Authority
Kate Wilke	The Nature Conservancy
Kate Williams	Biodiversity Research Institute
Kathleen Reardon	Maine Department of Marine Resources
Kathy Vigness-Raposa	INSPIRE Environmental
Katie Almeida	The Town Dock
Khatija Alliji	MarineSpace Ltd
Kim McKown	New York State Department of Environmental Conservation
Louise Roberts	University of Cornell
Lyndie Hice-Dunton	Responsible Offshore Science Alliance
Merry Camhi	Wildlife Conservation Society
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