Benthos Workgroup Report

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 benthos 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 http://www.nyetwg.com/2020-workgroups.

Preferred citation

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Contents

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 (OSW) development. The aim of the workshop was to assess the state of the knowledge regarding potential cumulative impacts on wildlife populations and ecosystems from OSW development. **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] Attendees included a wide range of stakeholders from offshore industry, government agencies, non-profit organizations, and academia. 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 OSW 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 OSW industry develops in the U.S.**

The intended audience for this report encompasses a range of stakeholders including researchers, state and federal agencies, OSW developers, regional science entities, and other potential funding entities who 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 inform environmentally responsible OSW development and minimize cumulative impacts over the long term, and many of these research needs are specifically directed at understanding and measuring effects as the industry progresses.

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.

The benthos workgroup was led by Steven Degraer (Senior Scientist, Royal Belgian Institute of Natural Sciences) and Zoe Hutchison (Research Fellow, University of St. Andrews, and Honorary Fellow of the Scottish Association for Marine Science), with technical and logistical support from Carl LoBue (New York Ocean Programs Director, The Nature Conservancy), Kate Williams, Edward Jenkins, and Julia Gulka (Biodiversity Research Institute) and Ashley Arayas and others

[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.

(Cadmus Group). The workgroup consisted of 36 participants (Appendix A), who met virtually four times in the winter and spring of 2020-2021 to discuss research priorities to improve our understanding of cumulative impacts to benthos from OSW development on the east coast of the U.S. Workgroup members represented a wide range of perspectives, from OSW developers, the fishing industry, government agencies, non-profit organizations, and academia, and provided key input based on their respective specialties. All workgroup documents were shared with workgroup members via a document collaboration platform (e.g., Google Drive, Microsoft Teams), and workgroup members had multiple opportunities over the course of several months to provide written input on earlier working drafts of this report. The report indicates a general consensus among workgroup members, unless otherwise noted. Despite the substantial input and influence of workgroup members on the workgroup reports, final report contents were determined by the technical leads. More information about the workgroups can be found at www.nyetwg.com/2020-workgroups.

Introduction

The marine benthos, the organisms living in or in proximity to the ocean floor, have a strong influence on the functioning of marine ecosystems (Griffiths et al. 2017). Benthic effects of OSW developments and other marine industries have been examined for several decades, and a substantial body of literature has been developed regarding these effects. Several recent reviews (Dannheim et al. 2020, Degraer et al. 2020, Gill et al. 2020) have summarized the state of knowledge in relation to OSW development and identified areas of further research needs. The development of OSW presents a range of pressures and consequent changes to benthic ecosystems at various points in the development process (pre-construction, construction, operation, decommissioning). These changes include artificial reef effects, seafloor disturbance, and the introduction of energy emissions (e.g., noise, vibrations, electromagnetic fields, heat), and may affect benthic ecosystem structure and function in various ways. These effects may include both undesirable or "negative" effects, as well as those that are considered more desirable effects and may be complementary to societal goals in some way (i.e., benefit societally relevant ecological functions like nutrient cycling or commercial fish production). Consideration of both undesirable and desirable outcomes during scoping exercises may offer opportunities to mitigate the bad and promote the good (Degraer et al. 2020).

Considerable information on benthic effects of OSW development has been gained from studies at European OSW farms (Dannheim et al. 2020), other marine industries, and early studies of OSW facilities in the U.S. (e.g., HDR 2020, Hutchison et al. 2020a, b). Initial studies at the Block Island Wind Farm (BIWF) suggest similarities in observed effects as compared to OSW studies in Europe. Findings from Europe may be more transferable in some areas than others, however, as the prevailing soft-bottom habitats in the North Sea are generally more analogous to parts of the mid-Atlantic U.S. than to hard-bottom habitats in New England. Moreover, while considerable progress has been made in Europe in our understanding of benthic effects from OSW development, gaps in our understanding remain. Thus, it is important to build U.S. research programs around this foundational European work. The research and monitoring highlighted in this report would help inform and eventually predict the impacts of large-scale OSW development on the east coast of the U.S. Furthermore, this work will inform recommendations for decommissioning scenarios, such as determinations of whether and how much

OSW infrastructure (that has become benthic habitat during the operation phase) should be removed during decommissioning (Birchenough and Degraer 2020, Fortune and Paterson 2020, Fowler et al. 2020).

This workgroup focused on identifying key research priorities for which studies could be initiated in the next five years, and that would improve our knowledge of the potential for cumulative impacts across OSW development areas in the eastern U.S.

Materials and Methods

For the purpose of this report, benthos is defined to include the following:

- Infaunal and epibenthic invertebrates and fish of the seafloor;
- Invertebrates colonizing the artificial hard substrates of OSW farms, including foundations and scour protection layer;
- Bentho-pelagic fish living associated with the seafloor inside and close to an OSW farm and/or with the artificial hard substrates of OSW farms.

During the time in which this workgroup operated, there were other research prioritization efforts around OSW development and effects on marine ecosystems that had the potential to overlap with this group. This includes the partner NYSERDA State of the Science workgroup focused on fishes and aquatic invertebrates (Popper et al. 2021) as well as several groups involved in developing the Responsible Offshore Development Alliance (RODA) white paper for the Fisheries and Offshore Wind Energy: Synthesis of the Science effort.[2] The potential overlap among these efforts was discussed during Session Eight at the November State of the Science workshop[3], and the benthos workgroup leads and some workgroup members were involved in the RODA Synthesis of the Science effort. The two initiatives adopted different approaches, in that the RODA Synthesis of the Science effort was focused on synthesizing information and capturing fishing community perspectives, while this workgroup focused on the identification of priority research questions that could be taken forward in the next five years. To further reduce duplication among these efforts and best apply the expertise of the respective workgroup members, the State of the Science fishes and aquatic invertebrates workgroup, led by Dr. Arthur N. Popper and Dr. Lyndie Hice-Dunton, focused exclusively on the effects of vibration and sound (including both particle motion and sound pressure; Popper et al. 2021). For that reason, the effects of vibration and sound were not considered by the benthos workgroup.

To be able to categorize and start prioritizing knowledge gaps, the workgroup used a conceptual framework for designing research programs developed by Gill et al. (2020), in which broad societal concerns are linked to overarching scientific questions and then further defined as operational scientific questions that may be directly translated into research studies (Figure 1, Step 1). Over the course of four meetings, with additional intersessional submission of written comments and summarization by

[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

workgroup leads, the workgroup went through a multi-step process to identify research priorities (Figure 1).

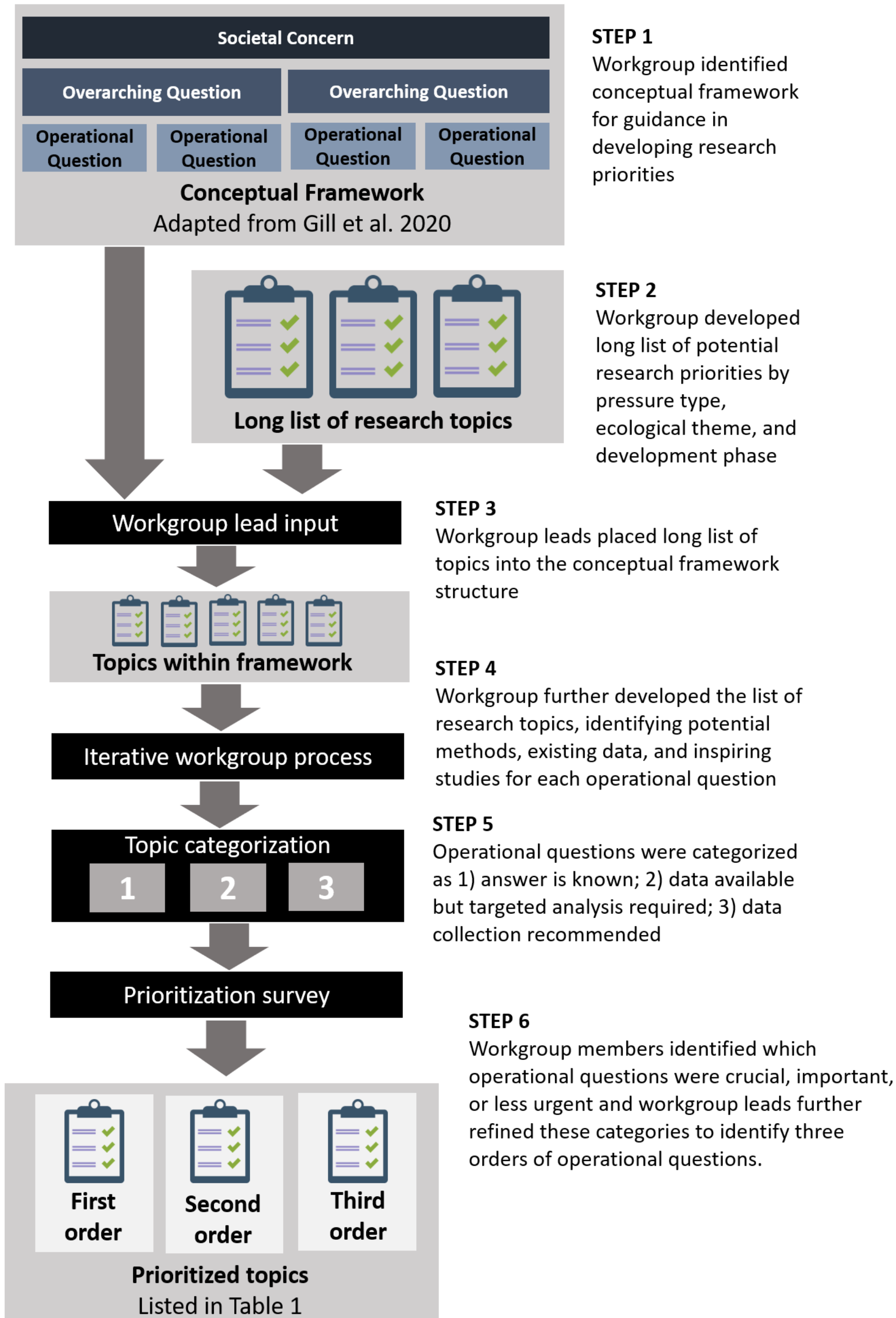

Figure 1. Benthos workgroup process for identifying short-term research priorities related to cumulative impacts from offshore wind development. Workgroup members identified a framework for developing research questions and an initial long list of research studies during meetings in early 2021. Research topics were refined and categorized based on the level of existing information. Through an online survey, workgroup members identified which of the research topics were crucial, important, or less urgent, and workgroup leads further refined these categories to identify high priority operational questions.

As such, the group developed a ‘long list’ of potential research topics or questions (Figure 1, Step 2). To think broadly about cumulative impacts, three dimensions were identified and considered throughout the long-listing exercise (Figure 2) including 1) pressure type (i.e., the artificial reef effect, mechanical seafloor disturbance, introduction of energy), 2) the ecological themes of ecosystem structure (i.e., changes in community structure and distribution patterns) and ecosystem function (i.e., food webs, productivity, biogeochemistry and connectivity), and 3) development phase (i.e., pre-construction, construction, operation, and decommissioning). In addition to these dimensions, workgroup members added some logistical and organizational concerns relating to data collection and standardization. Following initial brainstorming of the list, workgroup leads re-organized topics into societal concerns and overarching scientific questions to aid the iterative development of more defined operational questions in subsequent meetings and intersessional activities (Figure 1, Step 3). Four societal concerns could be discerned from the long-listing exercise, each with various overarching scientific questions within:

1. **How do offshore wind farms affect ecosystem services?**
    a. Does the artificial reef effect increase production or act as an attractant?
    b. Are ecosystem functions shifting because of OSW farms?
    c. How are bioenergetics, energy pathways, and trophic interactions altered by the presence of OSW farms?
    d. What is the net effect on available habitat and benthic communities when OSW development occurs in rocky hard habitats?
    e. Does OSW development affect how habitat is used during juvenile life history stages?
    f. How do OSW farms affect reproduction?
2. **Do we have enough good-quality regional-scale baseline data to inform siting and allow us to fully understand the potential ecological effects of offshore wind energy development?**
    g. What environmental aspects related to ecological effects are important to be considered when siting OSW farms?
    h. How will OSW development and climate change interact to cause changes to ecosystems?
3. **How will offshore wind farms affect surrounding (often soft-sedimented) habitat?**
    i. How does energy emitted by OSW farms affect communities and (re)production?
    j. Do we have sufficient information to assess attraction of non-indigenous (invasive) species?
    k. How do artificial reef effects (colonizing communities) influence benthic systems?
    l. How do OSW farms affect connectivity?
4. **How can we address organizational challenges posed by offshore wind energy development?**
    m. Will OSW farms compromise our ability to assess benthic and bentho-pelagic fish or shellfish stocks?
    n. How do we ensure data standardization and transparency?

The above societal concerns (1-4) and overarching questions (a-n) were then used in meetings as a basis to further identify more specific operational questions. For each operational question, topic descriptions were developed, and the group identified potential study methods, existing data, and previous studies that inspired or informed the identification of the question (Figure 1, Step 4). In general, multiple techniques can be used to address these knowledge gaps. Some potential methods are suggested below, though these should not be considered comprehensive. In many cases a combined approach, incorporating multiple techniques and both laboratory-based and field-based study components, may be beneficial or even required to answer the identified questions. The workgroup also preliminarily identified a current status of knowledge and data availability for each operational question (Figure 1, Step 5) including:

- **Category 1**: answer is known (no further research needed);
- **Category 2**: data are available but targeted analysis is required (e.g., additional analysis of existing data is needed);
- **Category 3**: new data collection is recommended.

Workgroup members then participated in an online survey (n=17) to indicate which societal concerns, overarching scientific questions, and operational questions they felt to be the most urgent immediate needs by categorizing each as “crucial”, “important” or “less urgent” (Figure 1, Step 6). Given the goals of this workgroup, members were asked to consider the following criteria when identifying priorities:

- *Urgency of the need for information.* Questions should be prioritized that will most likely effectively improve our understanding of cumulative impacts and inform decision making.
- Sequencing of objectives. If the results of Study #1 are needed to inform design of Study #2, the former should be designated higher priority in the short term.
- *Ability to inform cumulative impact models.*
- *Effectiveness at addressing one or more key societal concerns,* as identified through multi-stakeholder engagement processes (e.g., Gill et al. 2020).
- Following this prioritization process, workgroup leads examined the survey results and primarily used the weighted average rankings of operational questions to identify research priorities. Closely related operational questions were combined and their score was recalculated by averaging the weighted average of each combined question.

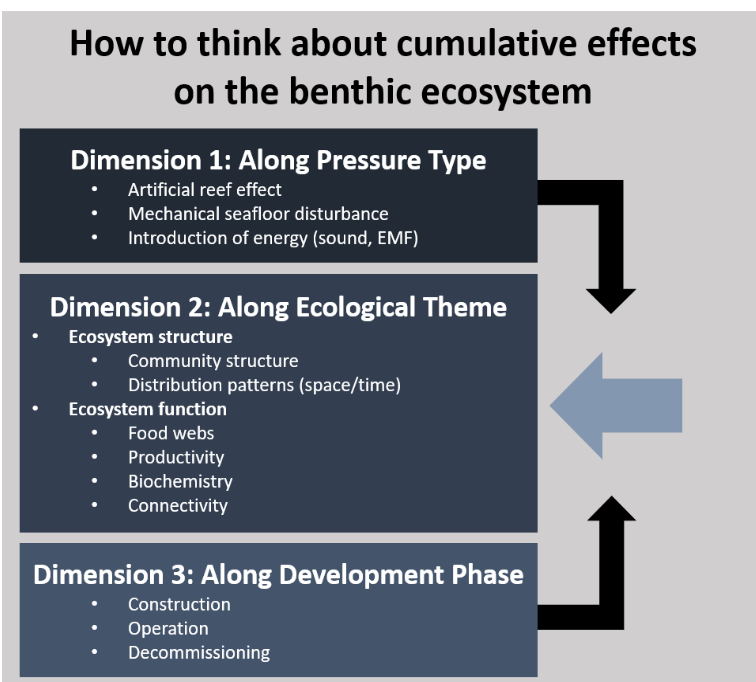

Figure 2. Three dimensions for thinking about cumulative impacts on benthic ecosystems. The workgroup used this framework to guide the development of a long list of research questions.

Research Priorities

The process undertaken by the workgroup resulted in a total of 32 operational questions (Tables 1-2), which were categorized into first, second, and third order priorities. After identifying the list of first, second and third order research priorities, the workgroup leads revisited the three dimensions (Figure 2) and summarized the questions by topic area. Dimension One appears horizontally and Dimension two appears vertically in Table 1. Dimension 3 was integral but not tabulated. It is immediately clear that many of the questions were focused on artificial reef effects. This may be due to familiarity with the topic area and also because some questions have already been addressed, which has led to a greater level of understanding. Artificial reef effects are also very broad, covering topics such as organic enrichment, habitat provisions, and others. Comparatively, seafloor disturbance is well-studied and understood from other marine activities. In contrast, there is less familiarity with the topic of energy emission and a higher level of uncertainty with regard to energy emissions (physical) and the effects on marine species (biological, ecological).[4]

While many of the questions are focused on the operational phase of development, understanding the operational effects on the benthic ecosystem will be useful with regard to decommissioning. This is true both in the context of decommissioning decisions (e.g., full or partial removal of structures; Fowler et al. 2018) as well as future ecological scenarios.

Table 1. An overview of the number of first (1°), second (2°) and third (3°) order priority questions according to the pressure type and ecological theme. Note the total sum of topics (n=40*) exceeds the total number of questions listed in Table 2 (n=32) as some questions address multiple ecological themes.

Ecological Theme:	**Pressure Type:**	**Artificial Reef Effect**			**Seafloor Disturbance**			**Energy Introduction****		
	Prioritization:	**1°**	**2°**	**3°**	**1°**	**2°**	**3°**	**1°**	**2°**	**3°**
Ecosystem Structure	Community Structure	1		2		1				1
	Distribution	2	2					1		1
Ecosystem Function	Food Webs	2						1		
	Productivity	3	1	2					1	1
	Biogeochemistry	1	1	1					1	1
	Connectivity	2	1	1						

*Priority questions that do not fit into the above themes include 5 first order and 4 second order questions.

** The effects of sound and vibration were not included in the context of introduced energy (see Popper et al. 2021 for a discussion of these topics).

[4] Note that this workgroup only considered heat and electromagnetic fields, and omitted sound and vibrations, which were covered in detail by the 'Fishes and mobile invertebrates' workgroup.

Table 2. Operational question priorities (1-3), with first order being the highest priority operational questions for the benthos workgroup. Relevant societal concerns and overarching scientific questions are indicated using the numbers/letters designated for each topic from the above list. Category represents the present knowledge and data availability for each operational question (1: knowledge sufficient, 2: data available and further analysis required, 3: data collection required). Ref No. indicates the number assigned to each operational question in the text below (this does not indicate relative priority).

Priority Order	Operational Question	Societal Concern	Overarching Question	Category	Ref No.
1	Can we create an integrated survey design that allows for trawl surveys and stock assessment practices both inside and outside of wind farms, and allows for comparison of biases and limitations of different survey methods?	4	m	N/A	1
1	How do we define the link between monitoring by developers with cause-and-effect studies and regional monitoring?	4	n	N/A	2
1	What QA/QC should be standard practice for new data collection? Where should benthos data be housed and how should they be made accessible to data analysis across projects?	4	n	N/A	3
1	Does the use of habitat by juveniles (fishes/crustaceans) change in offshore wind farms, and are nursery function and spawning grounds affected?	1	e, f	3	4
1	Do offshore wind areas provide spawning habitat and for what species?	1	f	3	5
1	How do we disentangle changes due to offshore wind farms from those due to climate change? E.g., how do we deal with shifting baselines?	2	h	3	6
1	How much organic enrichment and increased productivity occurs and how far do these effects stretch?	1	a	2, 3	7
1	How do natural and artificial substrata compare in their structural and functional ecology (e.g., spectrum of trophic interactions) and why?	1,3	c, d, k	2, 3	8
1	What is the influence of changes in recruitment, connectivity, and settlement around the offshore wind farm area (pelagic-benthic transition phases and other life stages, including less mobile species)?	1	e, l	3	9
1	How are bio-energetics and trophic interactions altered by the installation of OSW? What new feeding opportunities do offshore wind farms offer for fish, and how much better are fish feeding in offshore wind farms doing compared to those outside offshore wind farms?	1	c	2	10
1	Do electromagnetic fields (EMFs) emitted by offshore wind farm components affect energy acquisition (predator) or survival (prey) due to changes in predator-prey interactions?	3	i	3	11
1	How do offshore wind farms affect the distribution/connectivity of mobile species?	3	l	3	12
1	What species should be considered when siting offshore wind projects and examining potential effects?	2	g	2	13
1	Do EMFs emitted by offshore wind farm components affect the ability of species to derive locational cues, potentially affecting homing or migration of species trying to move to reproductive or feeding grounds?	3	i	3	14

Priority Order	Operational Question	Societal Concern	Overarching Question	Category	Ref No.
2	Do OSW areas provide additional settlement habitat, thereby increasing production of substrate limited populations?	1	a, e	3	15
2	How long does recovery of the surrounding seafloor take after disturbance during construction?	3	j	2	16
2	How does distance between turbines and surrounding habitat type affect connectivity between artificial reefs (e.g., on turbine foundations)?	3	k	3	17
2	Where are areas of high benthic productivity?	2	g	3	18
2	What are the effects of increased epifauna grazing on broad-scale primary productivity?	1	b	2	19
2	What are the main environmental drivers for the distribution of organisms of concern, i.e., ecological niche?	1	a	2	20
2	How much does the presence of offshore wind turbines affect nutrient cycling?	1	b	2	21
2	What non-native species take advantage of OSW habitat, and how does OSW affect the risk of invasions in new colonization areas previously unreachable?	3	j	3	22
2	Do we know enough about habitat and species distributions in time and space (particularly winter/summer)?	2	g	3	23
2	Will the potential de-stratification effect of OSW development strengthen the climate change effect, that is, higher temperatures in the originally stratified areas?	2	h	2	24
2	Do EMF from OSW farms have effects on sessile/low activity life stages and early-life stage consequences (e.g., developmental consequences in sessile embryos)?	3	i	3	25
3	Which novel communities (including historical species, native shifters, non-native invasives) and associated functions will develop post-decommissioning?	1	b	2	26
3	How long does the colonization of turbines take to reach a climax community and what is the climax community?	3	k	2 ,3	27
3	How does habitat complexity (e.g., eco-friendly scour protection layers) link to diversity?	3	k	3	28
3	Do changes in community structure alter competition?	1	c	2, 3	29
3	Does the capacity of the sediment to store carbon (i.e., carbon sequestration) change in relation to offshore wind farm development?	1	b	3	30
3	Is there a net gain/loss of hard substrate habitat resulting from OSW infrastructure?	1	d	2	31
3	Does heat emitted by offshore wind farm cables affect benthic communities?	3	i	3	32

First Order Research Priorities

1. Can we create an integrated survey design that allows for trawl surveys and stock assessment practices both inside and outside of wind farms, and allows for comparison of biases and limitations of different survey methods?

Long-term stock assessment surveys will need to continue after the installation of OSW farms. The limited access to long-term survey stations inside OSW farms may, however, pose logistical challenges to the continuation of these surveys, and surveys will need to account for the likely increased patchiness in fish distribution because of the OSW developments. Proper consideration of how to best reshape the surveys is urgently needed in order to minimize impacts on the long-term data series and to maximize the assessment of OSW farm effects on benthic and bentho-pelagic fish and shellfish populations.

Potential methods: Analysis of spatial overlap between OSW areas and long-term monitoring stations; analysis of accessibility of OSW areas for survey methods that best target benthic populations.

Existing data: The National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) and Bureau of Ocean Energy Management (BOEM) are currently considering how best to design surveys within OSW farms and integrate those into existing, long-term trawl survey datasets such that our ability to conduct stock assessments remains uncompromised.[5]

Inspiring studies: None provided.

2. How do we define the link between monitoring by developers with cause-and-effect studies and regional monitoring?

Linking monitoring by developers, cause-and-effect studies, and regional monitoring is an efficient and cost-effective manner of collating the knowledge needed not only to understand the effects of OSW farms but also to effectively mitigate undesired effects and eventually promote desired effects (i.e., nature-inclusive designs; NIDs). Such an approach is beneficial for society, authorities, environmental non-governmental organizations (eNGOs), and developers because it contributes to optimal monitoring and research designs and minimizes permitting risk.

Potential methods: Organize a workshop or working group to frame priority knowledge gaps by scale/type of monitoring (e.g., by developers, cause-and-effect studies, and regional monitoring needs) and coordinate research and monitoring at different scales.

Existing data: The Responsible Offshore Science Alliance (ROSA)'s interim Offshore Wind Project Monitoring Framework and Guidance could be used as a framework for guiding these conversations and

[5] Development of a Strategy to Evaluate NMFS Northeast Fisheries Science Center (NEFSC) Fishery Resource Surveys Affected by Offshore Wind Development www.boem.gov/sites/default/files/documents/environment/environmental-studies/AT%2020-x07.pdf

considering the types of questions that can be answered at project versus regional scales.[6] The Environmental Technical Working Group is also beginning to consider (as of 2021) similar questions for wildlife and OSW development regarding the types of priority research topics that are appropriate to address at different spatial scales.

Inspiring studies: None provided.

3. What Quality Assurance and Quality Control (QA/QC) should be standard practice for new data collection? Where should benthos data be housed and how should they be made accessible to data analysis across projects?

Monitoring data on benthos at OSW farms will inevitably be collected by several parties. Combining such data will maximize efficiency and effectiveness of the data collection. To ensure the compatibility of all data collected in the framework of OSW farm monitoring, a proper QA/QC has to be set up and applied to all data collection. Accessibility of data is also essential, preferably via use of a single centralized database across projects (including studies by academics, OSW developers, others). Proper data storage and access across OSW projects are indispensable to tackle the many open questions on OSW impacts stretching beyond the spatial scale of a single OSW farm. This is particularly important with regard to future high-quality data exchange; centralizing data and making it as accessible as possible prevents duplication of effort and allows for more collaboration and joint publication.

Potential methods: Develop standardized data collection, QA/QC, and reporting standards to ensure compatibility of methods and comparability of data.

Existing data:

- Data collection: A forthcoming report from the International Council for the Exploration of the Sea Working Group on Marine Benthal and Renewable Energy Developments (ICES-WGMBRED)[7] will provide some guidance on data collection needs.
- Data storage: There is a need to identify a database for housing these data, or if no suitable database currently exists, to explore options for creation of a centralized database for these data in the U.S. There are Coastal and Marine Ecological Classification Standard (CMECS)[8] standards in place for benthic substrate and biological components, but logical next steps for data standardization could be to better define those standards for OSW-related research and monitoring, and build off of them to develop the database requirements. A data stakeholder workshop may be a helpful approach.

Inspiring studies: A need for methodological and data standardization and transparency was also noted in other State of the Science workgroups, including those focused on marine mammals (Southall et al.

[6] Responsible Offshore Science Alliance interim Offshore Wind Project Monitoring Framework and Guidance https://e9f0eb5f-7fec-4e41-9395-960128956e6f.filesusr.com/ugd/99421e_b8932042e6e140ee84c5f8531c2530ab.pdf
[7] ICES Working Group on Marine Benthal and Renewable Energy Developments https://www.ices.dk/community/groups/Pages/WGMBRED.aspx
[8] CMECS https://iocm.noaa.gov/standards/cmecs-home.html

2021), birds (Cook et al. 2021), bats (Hein et al. 2021), acoustic effects on fishes and aquatic invertebrates (Popper et al. 2021), and environmental stratification (Carpenter et al. 2021).

CritterBase is an example of a centralized database (created by a consortium of scientists led by the Alfred Wegener Institute in Germany; a paper about this is in preparation) that is mostly focused on benthos; there are also several examples of such databases in the UK, including a benthic data portal. Databases commonly used to store data collected in relation to OSW development in the U.S. include Ocean Biodiversity Information System,[9] and (for derived data products such as distribution models) the Northeast[10] and Mid-Atlantic[11] Ocean Data Portals. Databases for abiotic environmental data include the Integrated Ocean Observing System (IOOS).[12] However, benthic data in these databases are somewhat limited, if they are included at all. The only U.S.-based database that focuses explicitly on benthos that workgroup members are aware of is the National Deep-Sea Corals and Sponges Database.[13]

4. Does the use of habitat by juveniles (fishes/crustaceans) change in offshore wind farms, and are nursery function and spawning grounds affected? – Category 3

Offshore wind farms may overlap with natural spawning grounds and introduce habitat that often considerably differs from the surrounding seafloor. This introduction can cause changes of the habitat, including nursery habitat and spawning grounds. Such changes may be advantageous or disadvantageous depending on how the respective species are affected by the presence of the OSW farm. This may ultimately result in shifts in spatial distribution of spawning grounds, as well as changes in how juvenile fish and crustaceans make use of novel habitat. We have information on important spawning and nursery habitats (to some extent), but lack knowledge on the effects of OSW on their distribution.

Potential methods: Fish telemetry will provide insights into what fish species are attracted to or avoid OSW farms and presence during spawning seasons; acoustic surveys may identify schooling of individual fish which may indicate spawning activity, while spawning activity itself can also be acoustically detected; the routine uptake of condition and gravidity indices in Before-After-Impact-Control (BACI) or Before-After-Gradient (BAG) monitoring programs may also hint towards spawning activity; reverse dispersal modelling to back track spawning grounds based on the presence of juveniles; otolith chemistry of juvenile fish may indicate origin; scientific diving and video monitoring in search for eggs will provide the ultimate proof of spawning. Data collection for identifying nursery function should be based on a combination of techniques suitable for the detection of often small juvenile organisms inhabiting a complex habitat, e.g., drop cameras, video, scientific diving; tagging of juveniles of larger species may provide insight into smaller-scale behavior, while diet analysis based on stomach content and stable isotope analysis could inform eventual use of food resources from OSW farms.

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[9] Ocean Biodiversity Information System https://obis.org/
[10] Northeast Ocean Data Portal https://www.northeastoceandata.org/
[11] Mid-Atlantic Ocean Data Portal https://portal.midatlanticocean.org/
[12] Integrated Ocean Observing System https://ioos.noaa.gov/
[13] NOAA Deep-Sea Coral Data Portal https://deepseacoraldata.noaa.gov/

Existing data: Data from a range of fish acoustic telemetry studies are available through the Ocean Tracking Network[14] and Atlantic Cooperative Telemetry Network.[15] Some data are available on how habitat is used by juveniles of various species, but little of these data are OSW farm-specific. For example, data are available on variations in juvenile fish assemblages in relation to characteristics of structured habitat (Cheminée et al. 2017), including for juvenile Atlantic cod (*Gadus morhua*; e.g., Cote et al. 2004). In relation to OSW development, telemetry and acoustic surveys are in place for new studies, and some information on condition indices is available.

Inspiring studies: Stocking of edible crab (*Cancer pagurus*) and lobster (Krone et al. 2013, 2017); juvenile cod tagging (Reubens et al. 2014); spatial overlap of North Sea flatfish spawning grounds and OSW farms (Barbut et al. 2020). Juvenile American lobster (*Homarus americanus*) are strongly linked to benthic habitat complexity, presumably for shelter from predators (Wahle and Steneck 1991). In the mid-Atlantic, studies have likewise examined the relationship between habitat complexity and juvenile survival (Scharf et al. 2006) and between fish abundance and benthic community structure (Schweitzer and Stevens, 2019). There has also been some characterization of reef habitats and their importance for various species in the Mid-Atlantic Bight (Steimle and Zetlin, 2000). Data on the presence of adult and juvenile mussels around BIWF structures with indications of juvenile crab presence is also recently available (Hutchison et al. 2020a).

5. Do offshore wind areas provide spawning habitat and for what species? – Category 3

The introduced hard substrata of OSW turbines may offer spawning habitat for several species groups, including benthic fish or squid, that use hard substrata for egg attachment. However, it remains unknown whether and which species may benefit from such increased spawning habitat.

Potential methods: Fish telemetry and video monitoring could provide insights into what fish species are attracted to the hard substrata; the routine uptake of condition and gravidity indices in BACI/BAG monitoring programs for OSW developments may also provide information on spawning activity; scientific diving and video monitoring in search for eggs will provide the ultimate proof of spawning. A first step may be a synthesis of candidate species (data are available but need to be evaluated), which may include squid and Atlantic cod.

Existing data: Synthesis can be derived from environmental baseline surveys (e.g., BIWF monitoring data) combined with species-specific trait information from FishBase.[16]

Inspiring studies: Cod and pouting (*Trisopterus luscus*) attraction to foundation identified using telemetry (Reubens et al. 2013a).

[14] Ocean Tracking Network https://oceantrackingnetwork.org/
[15] The Atlantic Cooperative Telemetry Network https://www.theactnetwork.com/home
[16] FishBase https://www.fishbase.se/home.htm

6. How do we disentangle changes due to offshore wind farms from those due to climate change? E.g., how do we deal with shifting baselines? – Category 3

Changes to the benthos in OSW farms cannot always be attributed solely to the presence of the development. Regional or even global pressures, like climate change, will also affect the benthos. Differentiation of OSW-driven effects from regionally- and globally-driven effects will assist in an appropriate assessment of the effects of OSW farms.

Potential methods: Laboratory studies in which climate change-related and OSW-related pressures are combined with the aim of disentangling both. Regional Ocean Monitoring Systems (ROMS) model projections may inform how the area is expected to change (e.g., temperature, salinity, currents). Careful monitoring of abiotic parameters during monitoring/research initiatives.

Existing data: Ongoing research by the Northeast Fisheries Science Center (NEFSC) on vulnerability of species to temperature increase and ocean acidification (focusing on commercial species), ROMS models.

Inspiring studies: PERSUADE project investigating the combined effects of OSW farms, climate change and aquaculture.[17]

7. How much organic enrichment and increased productivity occur and how far do these effects stretch? – Category 2/3

When filter feeders such as mussels attach themselves to OSW substrates, their (pseudo)fecal pellets are deposited on the ocean floor close to these structures and enrich local sediments (Maar et al. 2009). Such organic enrichment may lead to changes in the benthic community structure and productivity to form a "halo" of community changes in a broader area around structures. It is beneficial to understand at what distance this effect extends from each foundation and hence, whether these halos potentially overlap to form a "meta-reef effect".

Potential methods: Assess level of organic enrichment, quantification and qualification of (pseudo)feces production and deposition; examination of distribution, biomass, and abundance of deposit-feeding benthic organisms along a gradient away from the turbine; food web modeling. For consideration of attraction, fish telemetry to assess habitat use; examination of change in infaunal and epibenthic biomass with distance from turbine; examination of spatial patterns of fisheries activity or apex predator activity to assess spillover effects (e.g., use fishing activity or seabird/marine mammal habitat use or foraging activity as proxies for productivity); trawl surveys (assuming similar surveys can be conducted within and outside wind farms). Predators may also be attracted to or displaced by fishing activity. Predators may also be attracted to OSW due to non-trophic factors (e.g., provision of shelter or meeting points) having no direct effect on the production of fish. Study would need to be carefully designed to tease apart antagonistic and protagonistic influences.

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[17] PERSUADE Project https://www.researchgate.net/project/PERSUADE-ExPERimental-approaches-towards-Future-Sustainable-Use-of-North-Sea-Artificial-HarD-SubstratEs

Existing data:

- Local seafloor enrichment does occur, on the scale of tens to hundreds of meters around turbine foundations (Belgian FaCE-It project[18] results). Enrichment can be significant for monopile turbine foundations in the North Sea, but higher enrichment has been observed for structures other than steel monopiles (e.g., lattice foundations, Degraer et al. 2020).
- The FaCE-It project is currently using a combination of field work, lab experiments, and modeling to examine the effects of "hardening" marine ecosystems in the North Sea on food web structure and biogeochemical cycling.
- Current project OUTFLOW[19] is assessing the effects of epifauna on OSW turbine foundations on the distribution of organic matter at local and regional scales.
- Some individual grey (*Halichoerus grypus*) and harbor seals (Phoca *vitulina*) have been observed using offshore wind turbine foundations and pipelines as foraging areas (Russell et al. 2014). There may be different scales for productivity spread for benthos vs. motile species coming off of structures vs. upper trophic level predators. Some studies on coral reefs might be useful analogues.

Inspiring studies: University of Rhode Island/RODEO projects (HDR 2020); studies of offshore oil and gas platforms; Belgian FaCE-It and OUTFLOW projects with recent publications regarding organic carbon flux and remineralizations around OSW structures (De Borger et al. 2021, Ivanov et al. 2021); Raoux et al. (2018) about food web modeling studies at future French wind farms.

8. How do natural and artificial substrata compare in their structural and functional ecology (e.g., spectrum of trophic interactions) and why? – Category 2/3 (Category 2 for structural aspects; Category 3 for functional aspects)

Turbine foundations and associated scour protection layers (SPL), possibly including NIDs, offer artificial habitat to species. The structural and functional ecology of artificial hard substrata is known to significantly differ from that of natural hard substrata in other contexts, possibly attributed to differences in habitat heterogeneity and spatial extent. Natural hard substrate ecosystems are structured bottom-up (e.g., via food availability) as well as top-down (e.g., via predation). Because of their small spatial extent, OSW hard substrate ecosystems may lack the top-down control spearheaded by keystone species and lead to impoverished communities. To date, this question has not been addressed in relation to OSW development with the introduction of vertical hard structures.

Potential methods:

- Sample communities, biomass, diversity, habitat, function use comparatively at multiple sites (natural and artificial);

[18] FaCE-It Project www.researchgate.net/project/FaCE-It-Functional-biodiversity-in-a-Changing-sedimentary-Environment-Implications-for-biogeochemistry-and-food-webs-in-a-managerial-setting
[19] OUTFLOW Project www.researchgate.net/project/OUTFLOW

- Biodiversity surveys could be picture-based or sample-based;
- BACI study design targeting both artificial and natural hard substrate;
- To examine trophic interactions, stable isotope analysis, trophic interaction matrices, and ECOSIM modeling[20] based on existing data.
- Meta-analysis on how structural (e.g., species richness and type of species) and functional (e.g., food web ecology, essential fish habitat [EFH] considerations) ecology differ between natural and artificial hard substrate types;
- Methods to assess habitat heterogeneity of substrates will be applicable. Habitat should be characterized using CMECS, which BOEM and NMFS are requiring for benthic characterization surveys conducted by developers/consultants for identification of EFH, but a more detailed characterization of habitat heterogeneity may be needed.

Existing data: NOAA has conducted a historical characterization of natural and artificial reef habitats in the mid-Atlantic Bight (Steimle and Zetlin 2000). Existing data from the BIWF RODEO initiative (HDR 2020, Hutchison et al. 2020a)[21] and European OSW could be used and built upon, including the FaCE-It project; a comparison at BIWF is planned for BOEM's RODEO 2 program. Data on Northwest Atlantic and Scottish natural hard substrate ecology both mainly comprise species richness and community composition, yet functional derivatives like habitat modification are deductible. Additional data may be available from offshore oil rig platforms.

Inspiring research: Coolen et al. 2020a; Schulze et al. 2020; Rouse et al. 2020; Klunder et al. 2020; Dannheim et al. 2014; Steger et al. 2019; extrapolate from extensive work with red snapper (*Lutjanus campechanus*) and other species in the Gulf of Mexico; ecological studies in the North Sea; modelling by Couce et al. (2020); Critterbase and ongoing work by ICES WGMBRED; Structure and function offered by OSW reefs (Degraer et al. 2020).

9. What is the influence of changes in recruitment, connectivity, and settlement around the offshore wind farm area (pelagic-benthic transition phases and other life stages, including less mobile species)? – Category 3

OSW structures not only add habitat, but also affect local hydrodynamics, which in turn affect the settlement conditions in and around OSW farms. Recruitment and connectivity may hence also be influenced within OSW farms. Hard substrate can act as seed habitat for certain species, assuming connectivity with natural reef habitat. While this effect has often been raised, it is not well studied to date.

Potential methods: Modelling and *in situ* measurement of altered hydrodynamics (eddies, currents etc.) in the vicinity of the turbines (but also at further distance within and beyond the OSW farm) to assess possible effects on settlement, recruitment and connectivity; local ichthyoplankton sampling associated with local benthos sampling to ground truth alterations in actual settlement; metabarcoding of eDNA may be applied as a non-invasive means to sample genetic material for multiple species in OSW areas; genetic analyses of multiple populations over various scales would be required to determine

[20] EcoPath ECOSIM model https://ecopath.org/about/
[21] BOEM Block Island Wind Farm RODEO Project https://www.boem.gov/rodeo

connectivity between populations; hydrodynamic model predictions may help guide fine-resolution sampling. Alternatively, one may consider deployment of settling plates or the use of settlement experiments. Note that local sampling may require remotely operated sampling techniques such as autonomous reef monitoring structures (ARMS; deployed by scuba divers), as boat-based sampling may be difficult.

Existing data: Regional Ecosystem Monitoring Program (EcoMon) large-scale data on pelagic eggs, larvae and ichthyoplankton (to frame broader scale context).

Inspiring studies: INSITE-SHADOW project; connectivity assessments via particle tracking and genetics (Coolen et al. 2020a); ongoing BOEM studies looking at local hydrodynamic modelling[22]; nursery function for edible crab (Krone et al. 2017); Larval dispersal studies from Europe (Henry et al. 2018, van der Molen 2018); connectivity of coral species between oil and gas platforms (Sammarco et al. 2012) and succession of invertebrate species (Bram et al. 2005); various studies from oil and gas platforms as fish habitats, distribution and connectivity may also be helpful (Claisse et al. 2014; Gallaway et al. 2009; Linquist et al. 2005).

10. How are bio-energetics and trophic interactions altered by the installation of OSW? What new feeding opportunities do offshore wind farms offer for fish, and how much better are fish feeding in offshore wind farms doing compared to those outside offshore wind farms? – Category 3

The newly introduced habitat not only attracts species but also organically enriches the local surroundings (Degraer et al. 2020). This triggers changes to the local natural food webs, altering bio-energetics. Feeding opportunities have been demonstrated for multiple fish species, particularly benthic and demersal species (Mavraki et al. 2021). Several fish species have been found to have similar or better body condition inside OSW facilities than outside them (Reubens et al. 2013b). Changes in trophic interactions around OSW and associated change in bioenergetics are not well defined.

Potential methods: BACI or BAG design using stable isotope analysis and laboratory experiments to investigate species-specific interactions; modelling approaches using the data collected; surveys and eDNA to examine communities and distributions; fish stomach content analysis to get insights into short-term feeding activities; stable isotope analysis of fish muscular tissue to get more information on diet and prey choice at short and longer time scales; fatty acid analysis to assess quality of prey resources; fish condition indices; stable isotope analysis to assess Carbon:Nitrogen ratios. This question should be examined by guild, as the answer may vary. It may be effective to target resident species first, as this effect will be harder to detect for migratory species. Careful consideration of study design will be required, including identifying an appropriate control site for comparison and identifying a necessary sample size (and assessing the local effect of removing this sample size from the population, in the case of lethal sampling approaches).

[22] BOEM Environmental Studies http://www.boem.gov/sites/default/files/documents/environment/environmental-studies/NSL-19-04.pdf

Existing data: Some data from Belgian FaCE-IT studies available; data from Mavraki and Reubens PhD studies (both from Ghent University, Belgium).

Inspiring studies: Belgian FaCE-It project; Mavraki et al. (2020a, 2021). Studies of ecological effects of aquaculture installations may also be relevant (e.g., Cranford et al. 2007, Reubens et al. 2013b, Drouin et al. 2015, Callier et al. 2017, Cabre et al. 2021). This topic was also recently identified as a research need for sea turtles (Gitschlag et al. 2021).

11. Do EMFs emitted by offshore wind farm components affect energy acquisition (predator) or survival (prey) due to changes in predator-prey interactions? – Category 3

Some marine species are capable of detecting bioelectric fields enabling them to detect predators and/or prey. Cable EMFs may mimic or mask prey or predator bioelectric fields and influence predator-prey interactions, leading to changes in energy acquisition and survival. Similarly, a change in the activity of a species due to cable EMFs (e.g., change in sheltering or exploratory behavior) may influence their predator-prey interactions. More information is required on the potential consequences of cable EMPs on both predators and prey. Potential for noise and EMF interacting as multi-modal stressors masking cues has not been addressed.

Potential methods: Enclosure experiments exposing adult predators to EMF and prey while monitoring predator-prey interactions; similarly, experiments focusing on prey in the presence of predators and cable EMFs (e.g., prey may include earlier life stages such as egg embryos); laboratory experiments determining potential for predator and prey bioelectric fields to be mimicked or masked by cable EMFs; individual energy budget assessments (e.g., predator foraging for no return); tagging experiments in OSW areas to determine activity changes in context; multi-modal stressor experimental approaches; build on species specific knowledge.

Existing data: Draw on modelling and measurements of EMFs to inform laboratory studies, specific cable characteristics.

Inspiring studies: Ray embryo freeze response to predator-type bioelectric fields (Ball et al. 2016); increased exploratory/foraging responses to cable EMFs in skates and rays (Hutchison et al. 2020c, Gill et al. 2009); changes in activity in crustaceans (Woodruff et al. 2012, Scott et al. 2018, Hutchison et al. 2020b); consideration of multi-modal stressors exemplified through lobster life-cycle by Gill et al. (2020).

12. How do offshore wind farms affect the distribution/connectivity of mobile species? – Category 3

Data from the marine oil and gas industry suggest localized increases in commercial fishing around pipelines in some areas, and thus presumably local increases in biomass of demersal fish species of commercial interest (Rouse et al. 2018). OSW farms also attract mobile species for various reasons, including increased food resources, shelter, and meeting points. Attraction inevitably leads to a spatial redistribution of individuals, which may also affect population connectivity.

Potential methods: Larval and adult dispersal models; molecular analysis; eDNA; telemetry of mobile species; multi-site acoustic arrays and multi-species tagging over a broad region; surveys (plankton, benthic).

Existing data: Data from a range of fish acoustic telemetry studies are available through the Ocean Tracking Network and Atlantic Cooperative Telemetry Network.

Inspiring research: Modelling studies of connectivity (Adams et al. 2014, Henry et al. 2018, Bray et al. 2017, van der Molen et al. 2018, Coolen et al. 2020a); understanding fish movements around OSW (Reubens et al. 2014); lobster distribution within OSW (Roach et al. 2018).

13. What species should be considered when siting offshore wind projects and examining potential effects (e.g., commercially targeted vs. other species)? – Category 2

The benthos comprises a very high number of species. To include all species in siting decisions and investigations of effects of OSW farms would require spending an unprecedented amount of financial resources. A focus on species of particular interest, including those of commercial and conservation value, hence is needed.

Potential methods: Organize stakeholder (e.g., fisheries and eNGOs) and scientific workshops with the aim of identifying species of commercial and/or ecological importance. These should – as a starting point – comprise species of conservation concern, protected species, and unmanaged forage fish. The permitting process (e.g., Environmental Impact Assessments [EISs]) will also shed light onto focal species.

Existing data: Friedland et al. (2021).

Inspiring research: The improvement of forage fish maps in the North Sea has been undertaken (Langton et al. 2021; ICES 2020). Criteria for the identification of priority study species were also discussed by the State of the Science fishes and aquatic invertebrates workgroup that focused on potential OSW effects relating to sound and vibration (Popper et al. 2021).

14. Do EMFs emitted by offshore wind farm components affect the ability of species to derive locational cues, potentially affecting homing or migration of species trying to move to reproductive or feeding grounds? – Category 3

Animals that have a magnetic map sense or magnetic compass sense derive locational cues from the geomagnetic field (e.g., change in total intensity, angle of inclination) for homing and/or short- and long-distance migrations to important feeding or reproductive grounds. Cable EMFs interact with the local geomagnetic field and may affect the cues that animals rely on, and subsequently their movements towards important resources. Potential barrier effects may include delayed migrations or misdirection and potential for cumulative effects due to multiple encounters. Information on different life stages for relevant species is required.

Potential methods: Free-ranging telemetry for single or multiple species/cables; examine movements in close proximity to cables using free-ranging telemetry and/or mesocosm approaches to define behavioral responses; lab studies for assessing the detection of natural locational cues over cable EMFs; before/after cable installation and operation studies; experiments combined with modelling to assessing cumulative importance of delays or misdirection.

Existing data: Draw on modelling and measurements of EMFs to inform laboratory studies; draw on local geomagnetic field data and specific cable characteristics for local characterizations; build on species specific knowledge.

Inspiring studies: Salmon migration over the Trans Bay Cable (Wyman et al. 2018); eel migration over cables (Westerberg et al. 2008, ongoing BOEM study); elasmobranch detection of changes in the geomagnetic angle of inclination in lab studies (Newton et al. 2020); modelled and measured EMFs and mesocosm studies on crustaceans and elasmobranchs (Hutchison et al. 2020c); recent review on the topic (Hutchison et al. 2020b). This topic was also recently identified as a research need for sea turtles (Gitschlag et al. 2021).

Second Order Research Priorities

15. Do OSW areas provide additional settlement habitat, thereby increasing production of substrate-limited populations? – Category 3

Hard substrates at new OSW facilities can provide an opportunity for substrate-dependent populations and life history stages, including both native and non-native species. The importance of new hard substrate introduction to an area depends, in part, on pre-existing habitat; in rocky habitats, total hard substrate may not increase substantially and the overall effect may be low, while in softer sediments, local changes from infaunal to more epifaunal systems may be expected. Juvenile queen scallops (*Aequipecten opercularis),* for example, have been observed on Belgian turbine foundations. To what extent that happens and what species may be promoted along the U.S. east coast, however, remains unexplored.

Potential methods: Visual census and sampling of hard substrata organisms colonizing the foundations and scour protection layers; metabarcoding of sampled organisms, although this may be less suitable for the detection of newly arriving species whose molecular footprint may not be in the molecular baseline databases. Develop specific programs for collecting juvenile scallops from turbine foundations; use of ARMS; modeling approaches.

Existing data: Information on species settlement is available from studies at BIWF (HDR 2020, Hutchison et al. 2020a) and from European OSW farms as compared to shipwrecks and oil and gas platforms (Coolen et al. 2020a,b).

Inspiring existing research: Sabellaria reef development within OSW farms (Pearce et al. 2014); studies underway at Coastal Virginia Offshore Wind project[23] including plate settling data (van Hal et al. 2017); species settlement at European OSW farms (Krone et al. 2017).

16. How long does recovery of the surrounding seafloor take after disturbance during construction? – Category 2

Recovery of the seafloor varies by site due to seabed properties and local hydrodynamics, as well as specifics of the type of disturbance. While there is much literature available from other types of anthropogenic activities (e.g., dredging) the type of disturbance and localities are very different and therefore may not be directly transferable.

Potential methods: Site-specific data including that collected by developers; fine scale monitoring of the surrounding seafloor using BAG study design; grabs and/or imagery; regional comparison would be useful.

Existing data: Data collected by developers (as required by regulation) will be useful in this context, including sediment transport modeling and benthic habitat monitoring.

Inspiring research: Much literature exists but all is site-specific, e.g., Gulf of Mexico (Brooks et al. 2015), Bass Strait study (Kraus and Carter 2018), much relevant literature in Vineyard Wind Construction and Operations Plans (COPs).[24] Study of seafloor disturbance and subsequent recovery at BIWF (HDR 2020). Benthic community thresholds (Couce et al. 2020).

17. How does distance between turbines and surrounding habitat type affect connectivity between artificial reefs (e.g., on turbine foundations)? – Category 3

The ecology of OSW farms may be influenced by the distance between turbine foundations. The turbine foundations can be considered isolated reef hotspots but will have a degree of connectivity between them, which may vary depending on habitat type. If they are in soft-sediment habitats, turbine foundations ecology is more distinct to surrounding sediment, while in boulder fields, natural hard habitat exists. While pelagic larval dispersal may not be hampered by the distance between the turbine foundations within an OSW farm, it may affect the connectivity between turbines of mobile species like fishes.

Potential methods: Telemetry; consider local sessile and more mobile species.

Existing data: BIWF data may be useful or could build on the gradient benthic sampling approach.

Inspiring research: Belgian Federal Science Policy Office (BelSPO) OSW and marine protected area (MPA) research (Zupan et al. ongoing), benthic and epifaunal study at BIWF (HDR 2020).

[23] Coastal Virginia Offshore Wind project https://coastalvawind.com/
[24] Vineyard Wind Construction and Operations Plans https://www.boem.gov/vineyard-wind

18. Where are the areas of high benthic productivity? – Category 3

Areas and habitats of high ecological importance should be approached with high caution when siting OSW facilities. Areas of high benthic productivity are considered ecologically important. We know that high productivity in benthos cascades up to higher trophic levels and also links to ecosystem services. The current distribution of these areas, however, remains unknown.

Potential methods: Identification of features of benthic productivity (i.e., indicators) such as species-specific biomass data (P/B ratios as an indicator of productivity) and the availability of organic input. When sufficient baseline data are available, EcoSim modeling may help predict consequences to productivity when siting. If results are to be used to inform siting of OSW farms, a definition of "high productivity" and possible regulatory thresholds for siting may need to be developed.

Existing data: Data on benthic productivity of commercial species available from stock assessments, but much less on infaunal biomass; traditional ecological knowledge may point towards areas of high productivity as these often also attract commercial and recreational fish.

Inspiring research: EcoSim modelling of OSW effects on marine food webs (Raoux et al. 2017)

19. What are the effects of increased epifauna grazing on broad-scale primary productivity? – Category 2

There are potentially competing pressures of increased epifauna populations on primary productivity and nutrient cycling in local ecosystems (Degraer et al. 2020). Data from the Baltic Sea suggest mussels decrease primary productivity (e.g., via filter-feeding), but it is a relatively localized effect. Mussels also increase nutrient cycling and can positively affect primary productivity, so assessment of effects depends on the scale being examined. Questions of scale are very important for assessing effects to understand the degree to which changes detectable at a broad scale.

Potential methods:

- Pulse chase experiments and clearance rate experiments combined with hydrodynamic and ecosystem models informed by observations of epifaunal density, primary productivity, and other oceanographic parameters.
    - In pulse chase experiments, organisms are provided with a specific amount of food that contains labelled carbon. The labeled carbon is then reflected in the tissues of the organisms fed by it. By conducting stable isotope analysis on both the organisms feeding on the labelled carbon and organisms that were not feeding on it (for comparison), an estimate of how much carbon can be assimilated in the tissues of different species can be measured.
    - Clearance rate experiments measure the rate at which filter-feeders remove suspended particles from water, as an indicator of feeding activity; increased clearance rates are linked to increases in metabolic demand (example: Spiga et al. 2016).
- Important to use BAG designs (and also to have non-affected areas for controls outside the area of expected effect).

Existing data: None provided.

Inspiring studies: Slavik et al. 2019; Mavraki et al. 2020a; INSITE SHADOW project[25]; literature on the effects of shellfish aquaculture (e.g., Inglis and Gust 2003); these data are mostly in estuaries, however.

20. What are the main environmental drivers for the distribution of organisms of concern, i.e., ecological niche? – Category 2

Links between physical and biological environments are critical. Several drivers of distributions are noted above, including surrounding habitat types and degree of connectivity (including proximity of nearby reefs, shipwrecks, and other hard substrates). MPAs and benthic connectivity research suggest that oceanographic physical drivers are important for recruitment, larval supply, etc. (Di Franco et al. 2012, Coolen et al. 2016, Paxton et al. 2020). For example, previous research has shown that locations closer to established wrecks and within recruitment range for various species, have enhanced colonization (Meyer et al. 2017). Location in the water column also has a strong influence (Coolen et al. 2020b), with intertidal areas generally being covered in mussels.

Potential methods: A diversity of field and modeling approaches is needed (e.g., ecological niche, habitat suitability, species distribution modeling) combining occurrence or abundance numbers of species of interest and the distribution of a suite of environmental parameters (e.g., bottom temperature and salinity, sediment type, seafloor rugosity, current speed and direction, habitat complexity). It should be recognized that there may be daily, seasonal, and/or long-term changes occurring in the distribution of organisms of interest.

Existing data: The NOAA Wrecks and Obstructions Database,[26] IOOS data and other data on oceanographic drivers, species distribution data from NOAA and state trawl surveys and other sources. However, not all of these data are likely to be available at the necessary scales.

Inspiring studies: Schläppy et al. 2014, Coolen et al. 2016, Hemery et al. 2016, Mavraki et al. 2020b,c.

21. How much does the presence of offshore wind turbines affect nutrient cycling? – Category 2

Nutrient cycling is an important ecosystem service in the marine systems and is driven by bacterial activity. However, the macrobenthos alters the habitat for bacteria (e.g., bioturbation, bio-irrigation, biofilms, tube builder turf), and therefore plays an important role in nutrient cycling. Furthermore, the deposition of fine (organic and inorganic) materials will change the grain size distribution of the surrounding sediment and hence also the habitat for bacteria. Finally, water column destratification may affect bentho-pelagic coupling and hence also nutrient cycling. Changes in nutrient cycling may therefore be expected as a consequence of the presence of OSW farms.

Potential methods: Examine fluxes of nutrients and nutrient profiles in the sediment, and use these data in a modeling exercise; examine sediment characteristics including organic matter and fine sediment

[25] INSITE SHADOW project www.insitenorthsea.org/
[26] Wrecks and Obstructions Database https://nauticalcharts.noaa.gov/data/wrecks-and-obstructions.html

particles; assess nutrient cycling in hard substrata communities (including biofilms and tube builder "turf").

Existing data: This question is being considered by the NYSERDA State of the Science environmental change work group (Carpenter et al. 2021), and through Rutgers University's recent workshops on the Mid-Atlantic Cold Pool. There is also an ongoing modeling study in the Netherlands on destratification effects from OSW, Project PERSUADE, which is using a combination of experiments at different scales, genomic tools, and ecosystem modeling.

Inspiring studies: Belgian FaCE-It and PERSUADE projects.

22. What non-native species take advantage of OSW habitat, and how does OSW affect the risk of invasions in new colonization areas previously unreachable? – Category 3

OSW infrastructure offers new hard habitat to be colonized. This offers both intertidal and subtidal habitat to non-native species. Specifically, which species may colonize structures will partially depend on local populations as well as newly introduced non-native invasive species transported from local ports and harbors to OSW areas. OSW habitats may act as 'stepping-stones' to non-native invasive species facilitating their spread to new areas not previously available to them. This question addresses the presence and potential effects of non-native invasive species in OSW areas as well as the contribution to wider population expansion. There is a lack of studies comparing non-native invasive species in OSW areas and control areas (i.e., are OSW areas different from any other disturbed areas/artificial structures?).

Possible methods:

- This research will require data collection on the presence of non-native species once OSW infrastructure is in place, but in the interim can be informed by existing data and literature. This could include literature searches as well as local or regional surveys of non-native invasive species pools available on (inter-tidal and subtidal) artificial hard substrates (cf. risk assessment for invasions).
- Demersal as well as infaunal species will need to be considered. The Northeast Marine Introduced Species site (NEMIS)[27] provides a useful starting point.
- Study recent reefs/fish aggregating devices (FADs) as a comparison (however, OSW farms tend to be further offshore while reefs/FADs are inshore, and therefore may lack aspects of comparable hard structure).
- Studies to determine if boats carry species from ports to OSW sites (e.g., sample ballast water). Time series of settling plates after OSW structures are in place to quantify settlement and/or a gradient study.
- Quantification of non-native invasive species populations via eDNA, video sampling, specimen sampling of novel intertidal habitat and subtidal species in an offshore environment.

[27] Northeast Marine Introduced Species https://nemis.mit.edu/

Existing data: existing data on species pool on existing OSW farms along the U.S. east coast (e.g., *Didemnum vexillum* presence at BIWF [HDR 2020]). Local data on non-native invasive species populations, NEMIS, and published literature. Ongoing pilot project examining biodiversity in intertidal areas in Boston Harbor,[28] which also includes a risk assessment.

Inspiring research: European studies of non-native invasive species at OSW farms such as de Mesel et al. (2015); literature on the spread of European green crab (*Carcinus maenas*) in northeastern America; INSITE research (e.g., UNDINE project - ongoing); larval dispersal modelling related to tidal energy (Adams et al. 2014) and ocean sprawl (Henry et al. 2018); broader larval dispersal studies such as Bray et al. (2017), van der Molen et al. (2018), and Coolen et al. (2020a).

23. Do we know enough about habitat and species distributions in time and space (particularly winter/summer)? – Category 3

Coastal benthic ecosystems are characterized by a high diversity in habitats and community structure. Each habitat and community will have a different sensitivity to pressures derived from OSW construction and operation. Improved knowledge about where, when and what species and habitats prevail is needed during the siting process for OSW facilities. Regional maps are available but the necessary fine-scale detail to properly site OSW farms is lacking for U.S. east coast waters. Furthermore, knowledge that would allow making use of benthic quality indicators (as in Europe) is lacking.

Potential methods:

- Fine-scale pre-siting habitat surveys using grabs (in sandy sediments), video transects, side-scan sonar, and scientific diving (e.g., may be required in boulder fields).
- Consider adopting Ecologically or Biologically Significant Areas criteria[29] for the delineation of important benthic habitat. Habitat suitability/species distribution models can help highlight areas that may be more suitable for a species of interest, which could trigger "ground-truthing" surveys in those areas rather than truly regional scale surveys.

Existing data: Regional-scale data acquisition/synthesis programs include The Northeast Ocean Plan,[30] Massachusetts Ocean Management Plan,[31] Rhode Island Ocean Special Area Management Plan (OSAMP),[32] Block Island Wind Farm (BIWF) monitoring data (RODEO program), EcoMon for regional pelagic egg, larval and ichthyoplankton surveys, NOAA bottom trawl surveys (winter and summer not sampled as frequently as spring and fall with a lot of species move offshore in the winter), national climate adaptation science center database BioShifts,[33] which includes mined literature about species range shifts and changes in abundance.

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[28] Boston harbor pilot project https://www.sciencebase.gov/catalog/item/5f34504d82cee144fb32e39f
[29] Ecologically or Biologically Significant Areas criteria https://portals.iucn.org/library/sites/library/files/documents/2011-055.pdf
[30] The Northeast Ocean Plan https://neoceanplanning.org/plan/
[31] Massachusetts Ocean Management Plan https://www.mass.gov/service-details/massachusetts-ocean-management-plan
[32] Rhode Island Ocean Special Area Management Plan https://seagrant.gso.uri.edu/oceansamp/
[33] BioShifts database https://www.usgs.gov/ecosystems/climate-adaptation-science-centers/national-casc?qt-science_support_page_related_con=0#qt-science_support_page_related_con

Inspiring existing research: OSAMP habitat characterization for Block Island Sound and Rhode Island Sound prior to BIWF siting; project funded by Massachusetts Clean Energy Center, BOEM, and Rhode Island Department of Environmental Management, "Developing Standard Approaches to Synthesizing, Visualizing, and Disseminating High-resolution Geophysical and Imagery Data to Advance Benthic Habitat Mapping for Offshore Wind in the Northeast"[34] which is being conducted by INSPIRE Environmental and the Northeast Regional Ocean Council.

24. Will the potential de-stratification effect of OSW development strengthen the climate change effect, that is, higher temperatures in the originally stratified areas? – Category 2

Seasonal stratification of the water column is an essential aspect of the ecology of the U.S. east coast, with the Cold Pool being a unique feature of the area. OSW developments create localized turbulent wakes and may hence affect regional stratification as suggested by modelling of large-scale OSW developments and effects in the German Bight. It is as yet unknown whether OSW development along the U.S. east coast will impact stratification.

Potential methods: Modeling (including biological and oceanographic coupling) will shed light on this effect, yet with high levels of uncertainty.

Existing data: Cold Pool hydrodynamics (Rutgers University)

Inspiring research: Combining modeling and *in situ* measurements to assess the possible effect of OSW farms on stratification as done in Europe (Carpenter et al. 2016); special issue from Elementa on potential climate change impacts to fish.[35] This topic was also discussed by the State of the Science workgroup focused on identifying research needs relating to environmental stratification and environmental change (Carpenter et al. 2021).

25. Do EMF from OSW farms have effects on sessile/low activity life stages and early-life stage consequences (e.g., developmental consequences in sessile embryos)? – Category 3

Sessile/low activity organisms or life-stages of mobile species may experience increased exposure to EMFs if they inhabit the seabed where a cable is buried or inhabit cable protections such as concrete mattressing or rock armor. The developmental effects for embryos and early-life stages exposed to cable EMFs are not known, nor are the consequences in later life stages (i.e., adults) or potential generational effects. Many studies have focused on adult life-stages of species of interest and have not considered earlier life stages that may encounter cable EMFs.

[34] Benthic habitat mapping project https://neoceanplanning.org/issues/seafloor-habitat-data/
[35] Elementa Special Issue https://collections.elementascience.org/climate-change-impacts

Potential methods: Dose-response laboratory experiments exposing younger life stages and eggs to cable EMF and monitoring development and behavior; early and adult sessile life stages collection from OSW areas; spatiotemporal considerations will be important in study design and species selection.

Existing data: Draw on modelling and measurements of EMFs to inform laboratory studies; use of specific OSW cable characteristics.

Inspiring studies: Review of magnetic field effects on early life stages (Formicki et al. 2019, 2021); fish larva orientation to reefs using geomagnetic field cues (O'Connor et al. 2017); genotoxic and cytotoxic effects on sessile species (Stankevičiūtė et al. 2019); behavioral changes in polychaetes exposed to magnetic fields (Jakubowska et al. 2019); lobster life-stages and likely EMF encounters (Gill et al. 2020, Taormina et al. 2020), and review by Hutchison et al. (2020b); ongoing larval research at the St Abbs Marine Research Station, Scotland.

Third Order Research Priorities

26. Which novel communities (including historical species, native shifters, non-native invasives) and associated functions will develop post-decommissioning? – Category 2

Future community composition and function (e.g., post-decommissioning, or post-repowering) will be established based on the operational communities present amidst shifting baselines. There are two questions that need to be integrated: what is technically feasible, and what is desirable? We must understand the scale of the effects on the benthic ecosystem first and the potential consequences of changing the seabed after stabilization over several decades of operation.

Potential methods: Through scenario-based thinking or ecological modelling of scenarios, identify the type of decommissioning that would maximize positive ecological outcomes.

Existing data: Examine oil and gas data, such as the rigs to reefs program in the Gulf of Mexico; the U.S. Geological Survey's National Climate Adaptation Science Centers database[36] may have some data on shifting species distributions, though it is currently focused on terrestrial and coastal environments.

Inspiring studies: Ongoing scoping initiative based on literature in ICES-WGMBRED; Birchenough and Degraer 2020; Fortune and Paterson 2020; Fowler et al. 2020.

27. How long does the colonization of turbines take to reach a climax community and what is the climax community? – Category 2/3

The climax community is deemed as the stable benthic community which forms and is sustained at OSW sites. It is understood that this climax community may be removed if decommissioning practices remove

[36] U.S. Geological Survey's National Climate Adaptation Science Centers database www.usgs.gov/ecosystems/climate-adaptation-science-centers

all OSW structures and associated infrastructure. However, the climax community which forms during the time of OSW presence will be the community that informs the ecological context both during long-term operation and after decommissioning. After decommissioning, the community composition will be unlikely to return to the prior state (i.e., pre-construction) and the climax community will influence the subsequent recolonization or new decommissioned climax community (historical species, native shifters, non-native invasives). Understanding the climax community can aid in identifying possible effects of climax community over the longer term. Here, we refer to the time period required for a stable colonizing community to form at an OSW site. While it is possible to draw on other artificial structures, OSW have unique properties which may not be fully comparable, and the community is likely to be site specific or at least region specific, therefore a combination approach of using existing data and collecting new data was deemed appropriate. This type of study was deemed to be too long-term (10+ years) within the scope of this initiative, yet will be important for informing recommendations concerning decommissioning.

Potential methods: Long-term monitoring of community composition through successive development stages; video transects; scrape samples (less likely to be approved) to determine percentage cover, community composition, functional attributes of species present; ARMS; likely to be site/region specific and requires a long-term approach (10+ years).

Existing data: Wrecks in similar regions may provide insight on likely subtidal climax communities; WinMon.BE (Kerckhof et al. 2019); may be able to draw synergies with oil and gas platforms (Love 2019)[37] but locations are likely to have limited similarities with OSW locations and structure types.

Inspiring research: WinMon.BE (Kerckhof et al. 2019); Gulf of Mexico and California studies provide examples; old and new platform colonizing community comparisons by Coolen et al. (2020a).

28. How does engineered habitat complexity (e.g., eco-friendly scour protection layers) link to diversity? – Category 3

Turbine foundations and SPL could be intentionally designed to be more diverse and complex (i.e., nature-inclusive designs) by providing different spacing, hiding places, feeding places, types of stone, characteristics of concrete, and other characteristics. Topographical habitat complexity drives biodiversity (Liversage et al. 2017, Loke et al. 2017) can be added to surfaces (e.g., addition of large boulders to a regular scour protection layer), which may be desirable as natural hard substrates are often more diverse than artificial ones.

Potential methods: Definitions of habitat complexity (e.g., microhabitats and surface area) could be better defined; a comparison of types of SPL (e.g., rugosity) would be useful to inform options for nature-inclusive design of SPL; species diversity metrics could be used to characterize different types of habitat offered by OSW infrastructure (e.g., different foundation structures, SPL options in use and under development).

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[37] Several articles from this *Bulletin of Marine Science* special issue, "Fishes and invertebrates of oil and gas platforms off California," are relevant to this and other operational questions. The full list of articles is available at http://www.ingentaconnect.com/content/umrsmas/bullmar/2019/00000095/00000004

Existing data: Existing non-OSW infrastructure data are relevant for understanding this, e.g., artificial reef design data. According to Glarou et al. (2020), no empirical studies have examined the variation in ecological effects of specific scour and cable protection types or materials to date. Lengkeek et al. (2017) defined four ecological principles to enhance the value of the artificial reef effect of cable/scour protection. While the use of natural rocks and boulders has been suggested as preferable to man-made materials for scour protection, there is no empirical data yet available to suggest one specific material type that is preferable from an ecological perspective.

Inspiring research: BelSPO-OSW/MPA research (Zupan et al. ongoing, Belgium); Rouse et al. 2020; ongoing work at the Scottish Association for Marine Science (Redford et al. PhD in progress, Causon PhD thesis); research from the oil and gas industry on artificial reef effects including studies referenced in Love (2019); species associated with different shapes of space provided by cable protections (Taormina et al. 2020); using artificial-reef knowledge to enhance the ecological function of offshore wind turbine foundations (Glarou et al., 2020); Nature-inclusive Design Catalogue (Hermans et al. 2020).

29. Do changes in community structure alter competition? – Category 2/3

The attraction of species to newly introduced structures alters the local species composition. Subsequent effects on species interactions, such as competition for food, may be expected. For example, the addition of black sea bass (*Centropristis striata*) to areas around OSW structures could change trophic interactions, as they are voracious predators and therefore the prey population can change very quickly.

Potential methods: Ecopath modeling, stable isotope analysis, energy profiling.

Existing data: None specified, but examples from Europe exist (see inspiring studies)

Inspiring studies: Mavraki et al. 2020a, b, c, 2021; Reubens et al. 2013b.

30. Does the capacity of the sediment to store carbon (i.e., carbon sequestration) change in relation to offshore wind farm development? – Category 3

Because of the exclusion of bottom trawling in (part of) OSW farms and the locally increased levels of organic matter deposition, the seafloor may turn back to its original function of carbon storage. Whether and the degree to which this may be restored remains unknown.

Potential methods: Examine carbon profiles in sediment, in combination with sediment deposition rates and detailed characterization of the organic matter; coupling of hydrodynamic (including tides and waves) and sediment transport models with a description of the organic carbon and mineral particle dynamics in the water column and sediments (see FaCE-It project; Ivanov et al. 2021).

Existing data: None identified.

Inspiring studies: Belgian OUTFLOW project, Ivanov et al. 2021.

31. Is there a net gain/loss of hard substrate habitat resulting from OSW infrastructure? – Category 2

Offshore wind farms introduce artificial hard substrata, often in areas where there is little natural hard substrata. While these artificial hard substrates offer new habitat to species, there may be a subsequent loss of natural hard substrate habitat. Natural and artificial hard substrates may not host the same communities, with artificial hard substrates generally being impoverished. Answering this question requires a quantitative estimation of change of the surface area of (natural and artificial) hard substrata in full lease areas. Data to answer this question are available from data collected by developers during the permitting process.

Potential methods: Calculate quantitative gain and loss of hard substrate surface for each (planned) OSW farm based on 1) the actual footprint of the structures, 2) the disturbance 'envelope', and 3) the fine-scale distribution of natural hard substrata as identified during the permitting process.

Existing data: COPs and EISs for OSW farms along the U.S. east coast.

Inspiring studies: Foundation type-specific calculations of artificial hard substratum availability (Rumes et al. 2013); how to differentiate between habitat loss and disturbance (ICES 2019, Figure 5.5).

32. Does heat emitted by offshore wind farm cables affect benthic communities? – Category 3

The transfer of energy through cables generates heat, which may influence the benthic community surrounding the cable. The position of the cable (e.g., buried, exposed, protected with concrete mattressing/rock armor) will influence the rate of heat dissipation. Heat generation and dissipation is not well defined and requires data collection prior to assessing the effects on benthic communities and biogeochemistry. Note that heat generation and dissipation will be specific to the cable characteristics and the environment (e.g., ambient temperature, porosity of seabed/protection) and that heat and EMF may be a potential multi-modal stressor.

Potential methods: Defining the thermal change and its spatiotemporal scale; laboratory experiments assessing changes in survival, production, behavior; field studies assessing changes in infaunal community composition around cables; assessment in the field to understand scale and gradient of change with consideration of buried, exposed and protected cables; better definition of heat required before biological studies are designed.

Existing data: No existing data to draw on, but once the heat generated is properly defined, may be able to draw on existing literature.

Inspiring research: Taormina et al. (2018) review the potential heat emissions for subsea power cables; Meißner et al. (2006) report on measurements of heat around a buried cable; a modelling study of heat around a buried high-voltage cable by Emeana et al. (2016).

Conclusions and Further Considerations

Understanding the potential cumulative impacts of OSW development on the benthos is a wide-ranging subject, as the benthic ecosystem is home to a wide variety of organisms, each responding in a different way to the variety of pressures from OSW farm construction, operation and decommissioning (i.e., artificial reef effect, fisheries exclusion effect, effects of the introduction of energy). As such, the research priorities identified by this workgroup span a diversity of topics in many realms of benthic ecology (e.g., diversity, productivity, functional ecology, connectivity, settlement), as well as disentangling the effects of OSW development from other stressors such as climate change, and the need for effective data collection and standardization. The majority of identified knowledge gaps, however, relate to the artificial reef effect on ecosystem structure and functioning, followed by effect related to the introduction of energy. Knowledge gaps related to the effects of seafloor disturbance were far less prevalent. Some important considerations for the implementation of these research priorities include:

- **Consider shifting baselines.** Consideration of the effects of OSW will need to be placed in the context of changing ocean acidification and temperatures.
- **Build from existing knowledge.** A substantial body of literature has been developed regarding the effects of OSW on benthic ecosystems. Several recent reviews (Dannheim et al. 2020, Degraer et al. 2020, Gill et al. 2020) have summarized this state of knowledge in relation to OSW development and identified areas of needed further research. Rather than building new monitoring and research programs from scratch in the U.S., it will be important to target outstanding knowledge gaps. It is also important to consider where comparisons between studies from different regions are appropriate. For example, in the North Sea elasmobranch populations have been decimated due to intensive fisheries, while the U.S. east coast region still hosts healthy populations for many species; targeted monitoring and research on elasmobranchs in relation to OSW development may be more useful, and effective, in the latter scenario.
- **Carefully consider appropriate study methods.** This includes:
    - **Standardization of data collection and data sharing** across projects and lease areas, where appropriate. There are standards for benthic habitat characterization (CMECS), but these may require additional development specifically for OSW-related research and monitoring. Currently, there is a lack of a clear, standardized structure for the collection of some other types of data on the benthos, which can compromise the ability to make comparisons between sites. Additionally, developers currently do not share their data publicly.
    - **Identification of the appropriate methodological approach(es)** to address each question. Careful consideration should go into whether questions are best suited to lab experiments, field studies, and/or modelling. Each has advantages and disadvantages and often complementary approaches are necessary to fully answer a question.
- **Pursue integrated research approaches**, both for the sake of efficiency and to help detect cumulative effects caused by multiple factors. Early European studies at OSW farms tended to be conducted individually, and thus did not maximize resources (e.g., different methodologies across sites made data integration difficult). Where possible, it would be better to integrate multiple approaches in a single study to maximize resources and knowledge gain. It will be important to

consider the codependency of some of the research questions identified in this report, as well as the ability to design studies to answer multiple questions simultaneously.

- **Consider research priorities within a broader framework.** High productivity in benthos cascades up to higher trophic levels, and also links to ecosystem services. As such, characteristics of the benthos, and how the benthos are affected by OSW development, can strongly influence OSW's effects on other aspects of marine ecosystems. Additionally, many studies of the benthos during operation of OSW farms could help inform optimal decommissioning approaches (including the degree to which underwater structures are removed vs. left in place).

While the identification of research priorities happened largely independently within each of the seven State of the Science workgroups (e.g., Carpenter et al. 2021, Cook et al. 2021, Gitschlag et al. 2021, Hein et al. 2021, Popper et al. 2021, Southall et al. 2021), these priorities will need to be considered in an integrated framework across taxa and ecosystem components to 1) appropriately prioritize future research and monitoring, and 2) identify interconnections between studies and protocols proposed by different groups. Several large-scale research projects that integrate monitoring conducted by developers with targeted new research, and can sample multiple OSW areas, may be more efficient than small, piecemeal projects.

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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**
Alicia Morandi	RPS Group
Andrew Rella	ECOncrete Inc
Bob Erickson	CSA Ocean Sciences
Caela Howard	Vineyard Wind
Carl LoBue	The Nature Conservancy
Chris McGuire	The Nature Conservancy
Drew Carey	INSPIRE Environmental
Ed Jenkins	Biodiversity Research Institute
Emily Rochon	Vineyard Wind
Emily Shumchenia	Northeast Regional Ocean Council
Erin DiPersio	Vineyard Wind
Eugene Revelas	Integral Consulting
Ian Reach	MarineSpace Ltd
Jan Vanaverbeke	Royal Belgian Institute for Natural Sciences
Jeff Herter	New York Department of State
June Mire	Tetra Tech
Kate McClellan Press	New York State Energy Research and Development Authority
Kate Wilke	The Nature Conservancy
Kate Williams	Biodiversity Research Institute
Keith Hanson	National Marine Fisheries Service
Lenaig Hemery	Pacific Northwest National Laboratory
Marja Aberson	MarineSpace Ltd
Matt Robertson	Vineyard Wind
Merry Camhi	Wildlife Conservation Society
Michelle Staudinger	United States Geological Survey
Miriam Schutter	Bureau Waardenburg
Morgan Brunbauer	New York State Energy Research and Development Authority
Noah Chesnin	Wildlife Conservation Society
Scott Lundin	Equinor
Stephanie Wilson	Ørsted
Steven Degraer	Royal Belgian Institute for Natural Sciences
Todd Callaghan	Massachusetts Office of Coastal Zone Management
Tom van der Have	Bureau Waardenburg
Tony DiLernia	New York State Fisheries Liaison
Ursula Howson	Bureau of Ocean Energy Management
Zoe Hutchison	University of St. Andrews, Scottish Association for Marine Science