NOAA Technical Memorandum NMFS-NE-291

Fisheries and Offshore Wind Interactions: Synthesis of Science

US DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northeast Fisheries Science Center
Woods Hole, Massachusetts
March 2023

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Fisheries and Offshore Wind Interactions: Synthesis of Science

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Editorial Notes

Information Quality Act Compliance: In accordance with section 515 of Public Law 106-554, the Northeast Fisheries Science Center (NEFSC) completed both technical and policy reviews for this report. These pre-dissemination reviews are on file at the NEFSC Editorial Office.

Species Names: The NEFSC Editorial Office's policy on the use of species names in all technical communications is generally to follow the American Fisheries Society's lists of scientific and common names for fishes, mollusks, and decapod crustaceans and to follow the Society for Marine Mammalogy's guidance on scientific and common names for marine mammals. Exceptions to this policy occur when there are subsequent compelling revisions in the classifications of species, resulting in changes in the names of species.

Statistical Terms: The NEFSC Editorial Office's policy on the use of statistical terms in all technical communications is generally to follow the International Standards Organization's handbook of statistical methods.

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This document was coordinated by the Responsible Offshore Development Alliance (RODA) and prepared by authors led by Section Leads who also served on the Steering Committee. The Section Leads included representatives from RODA, the Bureau of Ocean Energy Management (BOEM), and National Marine Fisheries Service (NMFS) Northeast Fisheries Science Center (NEFSC). Additional authors contributed to each section and are listed under each section for clarity.

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LIST OF ACRONYMS IN REPORT

A = Current (Amps)
ABC = Acceptable Biological Catch
ABM = Agent-Based Model
AC = Alternating Current
ACPARS = The Atlantic Coast Port Access Route Study
ADCP = Acoustic Doppler Current Profiler
AIS = Automatic Identification System
AMO = Atlantic Multidecadal Oscillation
ARIMA = Auto-Regressive Integrated Moving Average
ASM = At-Sea Monitoring
ASMFC = Atlantic States Marine Fisheries Commission
ATON = Aids to Navigation
BACI = Before-After-Control-Impact
BAG = Before-After-Gradient
BIWF = Block Island Wind Farm
BMP = Best Management Practice
BOEM = Bureau of Ocean Energy Management
CBRA = Cable Burial Risk Assessment
CEA = Cumulative Effects Analysis
CFD = Computational Fluid Dynamics
CI = Control-Impact
CIA = Cumulative Impact Assessment
CPUE = Catch-Per-Unit-Effort
CRMC = Rhode Island Coastal Resources Management Council
CSVI = Community Social Vulnerability Indicator
CTD = Conductivity-Temperature-Depth
CV = Coefficient of Variation
CVOW = Coastal Virginia Offshore Wind
D = Pile Diameter
DAS = Days-at-Sea
dBBC = Double Big Bubble Curtains
DC = Direct Current
DEIS = Draft Environmental Impact Statement
DIDSON = Dual-Frequency Identification Sonar
DMIS = Data Matching and Imputation System
DOF = Declared out of Fishery
DOI = United State Department of the Interior
DOL = Depth of Lowering for Cable
DRIP = Data-Rich Information-Poor
EA = Environmental Assessment
EAFM = Ecosystem Approach to Fisheries Management
EBFM = Ecosystem-Based Fisheries Management
EBM = Ecosystem-Based Management

eDNA = environmental Deoxyribonucleic Acid
EFH = Essential Fish Habitat
EIA = Environmental Impact Assessment
EIS = Environmental Impact Statement
EMF = Electromagnetic Fields
ENA = Ecological Network Analysis
ESA = Endangered Species Act
EwE = Ecopath with Ecosim Modeling Suite
FAB = Fishermen's Advisory Board
FAD = Fish Aggregating Device
FAIR = Findability, Accessibility, Interoperability, and Reusability Data Standards
FDD = Fishery Dependent Data
FEIS = Final Environmental Impact Statement
FEK = Fishermen's Ecological Knowledge
FID = Fishery Independent Data
FKT = Fisheries Knowledge Trust
FL = Fisheries Liaison
FLOWW = Fishing Liaison with Offshore Wind and Wet Renewables Group
FMP = Fishery Management Plan
GARFO = Greater Atlantic Regional Fisheries Office
GDP = Gross Domestic Product
GIS = Geographical Information Systems
GMF = Geomagnetic Field
GRT = Gross Register Tonnage
HDM = Hydrodynamic Model
HIA = Human Impact Assessment
HMS = Highly Migratory Species
HV = High Voltage
HVAC = High Voltage Alternative Current
HVC = High Voltage Cable
HVDC = High Voltage Direct Current
ICES = International Council for the Exploration of the Sea
ICPC = International Cable Protection Committee
IEA = Integrated Ecosystem Assessment
IFS = Industry-Funded Scallop
IOOS = Integrated Ocean Observing System
IPF = Impact Producing Factor
LV = Low Voltage
MAB = Mid-Atlantic Bight
MAFMC = Mid-Atlantic Fishery Management Council
MARIPARS = The Areas Offshore of Massachusetts and Rhode Island Port Access Route Study
MBTG = Mobile Bottom Tending Gear
MF = Magnetic Field
MMO = Marine Management Organization
MOP = Massachusetts Ocean Partnership
MoU = Memorandum of Understanding

MPA = Marine Protected Area
MRIP = Marine Recreational Information Program
MSA = Magnuson-Stevens Fishery Conservation and Management Act
MSE = Management Strategy Evaluation
MSP = Marine Spatial Planning
MV = Medium Voltage
NAO = North Atlantic Oscillation
NARW = North Atlantic Right Whale
NASCA = North American Submarine Cable Association
NCEI = National Center for Environmental Information
NEAMAP = Northeast Area Monitoring and Assessment Program
NEFMC = New England Fishery Management Council
NEFOP = Northeast Observer Program
NEFSC = Northeast Fisheries Science Center
NEPA = National Environmental Policy Act
NES LME = Northeast Shelf Large Marine Ecosystem
NEUS = Northeast US Shelf Ecosystem
NM = Nautical Miles
NMFS = National Marine Fisheries Service
NOAA = National Oceanic and Atmospheric Administration
NRA = Navigational Risk Assessment
NREL = National Renewable Energy Laboratory
NYSDEC = New York State Department of Environmental Conservation
NYSERDA = New York State Energy Research and Development Authority
O&M = Operations and Maintenance
OCS = Outer Continental Shelf
OWE = Offshore Wind Energy
OSW = Offshore Wind Development
PAM = Passive Acoustic Monitoring
PAR = Photosynthetically Active Radiation
PDO = Pacific Decadal Oscillation
POC = Particulate Organic Carbon
R&D = Research and Development
RI DEM = Rhode Island Department of Environmental Management
RNVC = Revenues Net Variable Costs
RODA = Responsible Offshore Development Alliance
RODEO = Realtime Opportunity for Development of Environmental Observations
ROSA = Responsible Offshore Science Alliance
ROV = Remotely Operated Vehicles
RUM = Random Utility Model
SAMP = Special Area Management Plan
SAR = Search and Rescue
SCeMFiS = Science Center for Marine Fisheries
SEIS = Supplemental Environmental Impact Statement
SIA = Stable Isotope Analysis
SMAST = University of Massachusetts Dartmouth School for Marine Science and Technology

SML = Surface Mixed Layer
SMS = Safety Management System
SNE = Southern New England
SNECVTS = Cooperative Ventless Trap Survey
SOS = Synthesis of the Science
TSS = Traffic Separation Scheme
USCG = United States Coast Guard
V = Voltage in Volts
VMS = Vessel Monitoring System
VPR = Video Plankton Recorder
VTR = Vessel Trip Report
WEA = Wind Energy Area
WTRIM = Offshore Wind Turbine Radar Interference Mitigation Series

EXECUTIVE SUMMARY

Overview

Given the forecasted rapid pace and broad scope of offshore wind development (OSW) in the U.S. and globally, there is a need to synthesize current and past scientific research that has examined the interactions between OSW, fisheries, and the marine ecosystems. The research community has built and continues to build a scientific knowledge base around offshore wind topics. Compiling this information and identifying knowledge gaps will provide a comprehensive understanding of offshore wind science to date and illuminate the path forward for scientific research. From 2020-2022, NOAA Fisheries and the Bureau of Ocean Energy Management (BOEM) partnered with the Responsible Offshore Development Alliance (RODA) on the "Synthesis of the Science: Fisheries and Offshore Wind Energy," bringing together the agencies, states, fisheries representatives, and offshore wind developers to start this task. This effort is meant to support diverse parties in co-producing knowledge by identifying potential future research needs and priorities.

This Synthesis of the Science (SoS) focused on 5 topics collectively identified by the project partners as critical for consideration in relation to OSW: ecosystem effects, fisheries socioeconomics, fisheries management and data collection, methods and approaches, and regional science planning. The project consisted of 2 integrated components: a virtual workshop and this published report, which together have the overarching purpose of enhancing regional and national understanding of existing science and data gaps related to offshore wind interactions with fish and fisheries. The steering committee was composed of individuals from RODA, the National Oceanic and Atmospheric Administration (NOAA), BOEM, the Responsible Offshore Science Alliance (ROSA), and an offshore wind developer representative. The overall project goals include:

1. introducing fisheries science, management, and industry experts to the topic of offshore wind energy and fisheries interactions in order to inform their work, leverage existing knowledge, create networks among interested professionals, and develop effective approaches to short- and long-term cross-disciplinary challenges;
2. providing a model of best practices for successful engagement of the fishing industry in complex scientific processes and setting research and monitoring agendas;
3. integrating offshore wind energy development into existing science and research efforts in the field of fisheries science and management;
4. establishing a shared body of understanding and knowledge on offshore wind energy and fisheries interactions;
5. identifying data and knowledge gaps relevant to the study of marine fisheries biology and behavior, ecosystem function, and fisheries operations for use in future scientific and policy decisions;
6. providing fora for open discussion to set relevant research and monitoring priorities for impacts to fish and fisheries; and
7. promoting future collaborative work across disciplines and sectors.

Workshop

The SoS workshop was held October 14-16th and 30th, 2020. Over 550 participants from a wide range of backgrounds and disciplines participated through the Zoom platform. The workshop presented a high-level overview of key topics by section, initiated dialogue to frame issues and facilitate research networks, and identified important groups to work with the authors during the drafting process to ensure inclusive representation in the report drafting. Daily agendas, workshop summaries and videos of panel discussions are available on RODA's website.

Report

This report synthesizes available information compiled by subject matter experts regarding the interactions between offshore wind and fisheries. The primary focus was on fixed turbine technology; interactions with floating turbine technology were briefly addressed during the workshop and are currently being more fully evaluated in a separate project led by RODA. This report strives to synthesize the existing knowledge on ecosystem, socioeconomic, and fisheries management/data collection effects, and methods/approaches for research and monitoring in order to examine how fisheries and fisheries resources interact with offshore wind. These topics are strongly interrelated, and while this may give the perception that more emphasis is placed on some topics than others, it was our intention to focus on areas of study that are relevant to understanding offshore wind interactions. The report focuses on the U.S. but incorporates global expertise whenever possible. The authors attempted to identify gaps in knowledge and, when possible, make specific recommendations for future research needs to enhance our understanding of offshore wind interactions. The result was intended to be a shared body of knowledge for industry, regulators, and fisheries managers to draw from. The report is not an annotated bibliography of every research project conducted to date.

The Steering Committee assigned section leads from the Committee, who were knowledgeable in the subject matter, who then identified and coordinated a set of authors for each section. Authors endeavored to address a standardized set of topics in each report section: (1) introduction; (2) description of the state of knowledge and understanding on this topic with regard to OSW interactions; (3) major gaps in knowledge; (4) characterization of the perspectives of commercial and recreational fishing communities on this topic; and (5) recommendations for future directions or studies. Due to wide differences in the nature, quantity, and quality of available research, some sections depart from this strict outline. For each section, RODA identified fishing advisors (fishermen with specialized expertise relevant to the section) to support the report's development by serving as authors, reviewers, and sources of important input and feedback.

Peer review was conducted by the scientific community. This single-blind process was managed by ROSA with support from RODA. Peer review placed emphasis on scientific rigor and integrity and strove to mirror the peer review process of scientific journals. Once RODA determined that authors had sufficiently addressed reviewers' comments, the report was submitted into the NOAA internal technical review process where it underwent additional peer review. Authors further addressed comments made by reviewers at NOAA after which the report was published as a NOAA technical memorandum.

Section-by-Section Report Summary

The following topics form the body of the SoS report:

Ecosystem Effects – Benthic Habitat Modification

The addition of hard structures to the marine environment can interact with, and redistribute, natural seafloor sediments. These changes to the physical environment affect benthic communities of the natural seabed surrounding the turbines and provide novel hard substrate habitat for attached organisms. Because the local effects of benthic habitat modification are multiplied many times within and between OSW development areas, these installations can have population-level effects on regional spatial scales. Foundations are swiftly colonized by an attached community, attracting fish and their fouling communities after installation. Presence of turbine foundations also alters localized hydrodynamics, resulting in potential variable modification of benthic habitats through scour and deposition. Connectivity depends on a variety of physical oceanographic factors and population dynamics in addition to the distance from shore or other sources of flora and fauna.

A major challenge is understanding the spatial and temporal impacts of OSW projects on the regional availability of fisheries species, including those for harvest. These species rely on and their distributions are influenced by benthic habitats. A near-term priority should be to establish baseline benthic conditions prior to construction. The effects on the response variables should be monitored through the operational phase, as effects may not be well understood for several years.

Commercial and recreational fishermen are concerned about the uncertainty around these effects and about how benthic changes will affect their catches. Specific issues of concern for fishermen include concentrating fish and fishing pressure, introduction of invasive and nonindigenous species, contaminants introduced by construction materials, structures and debris preventing towing access, and reducing or eliminating the ability of vessels to operate within an array. There is also concern about the inability to accurately assess stocks due to the habitat complexity introduced by OSW structures.

Ecosystem Effects – Physical Habitat Modification

Physical changes associated with OSW developments will affect the marine environment—and, subsequently, the species that live there—to varying degrees. These include construction and operation noise and vibration, electromagnetic fields (EMF), and thermal radiation from cables, as well as secondary gear entanglement. In general, propagation or emission rates for these stressors decrease with distance from the source but are intrinsically dependent on the marine environmental conditions.

Underwater noise levels generated during pile driving depend on the pile material and size, characteristics of the substrate, penetration of the pile into the seabed, hammer energy used, and water depth. Throughout the life of the project, continuous low-level sounds may be generated by each turbine during normal operations, and continuous moderate-level vessel noise will be introduced. Several noise abatement measures are known to reduce underwater noise from pile driving and can help mitigate acoustic impacts on marine species. However, future research is recommended to understand the impact of operational noise with noise abatement systems in place because turbine size and the noise they produce are increasing as technology advances.

EMFs are emitted from subsea power cables transferring the energy from OSW turbines to transmission grids onshore and may disrupt natural electromagnetic cues that receptive animals rely on for ecologically important information. There are presently no thresholds indicating acceptable or unacceptable levels of EMF emissions in the marine environment. Thermal radiation occurs as an emission from subsea power cables and has the potential to increase the temperature of the surrounding environment, which may affect the local thermal habitat and, subsequently, the species present.

OSW turbine foundations and floating turbine moorings may present an entanglement risk for marine megafauna, such as sharks, sea turtles, and marine mammals.

Marine species of ecological and commercial importance may be sensitive to sound and vibrations, EMF, and thermal radiation in the marine environment to varying degrees. Cables are buried for their own protection, where possible, and that increases the distance from the EMF and heat source for many receptor species. Future work must employ in situ and standardized data collection to better understand spatiotemporal variability in different conditions, such as the substrate type for pile-driving foundations, EMF and thermal radiation along cable routes, and how these stressors will impact commercial and recreational fish stocks.

The fishing community is highly concerned that fish near the construction sites may be injured or killed by percussive injury or may continue to avoid the area for a time after construction is completed. Any impacts of EMF to the availability of species may result in negative socioeconomic impacts to the fishing industry if they cannot safely harvest species. The commercial fishing sector strongly encourages the use of efficient environmental protection measures to minimize impacts and to investigate this where understanding is lacking.

Ecosystem Effects – Interactions of Offshore Wind on Oceanographic Processes

Oceanographic processes can significantly influence the available nutrients and thermal habitat that may directly or indirectly impact important fishery species. Interactions between OSW and ocean processes generally fall into 3 categories: (1) wind extraction reducing surface wind stress and altering water column turbulence; (2) wind farm wake-driven divergence and convergence driving upwelling and downwelling; and (3) turbulence generated by turbine foundations.

Remote sensing and in situ observational studies have been carried out to investigate the extent of turbine wakes in the offshore environment; however, comprehensive long-duration observations of these features remain elusive. Reductions in wind speeds from wind extraction in the lee of turbine arrays may stabilize water columns, altering normal ocean conditions. Models also indicate that reduced wind stress at the sea surface can drive horizontal velocity shears, which generate upwelling and downwelling cells that, in turn, alter water column structure. Direct observations provide evidence that turbine foundations can increase turbulent mixing in the wake of the piling, and this can affect local hydrography and downstream stratification. Impacts on mixing and stratification depend heavily on local conditions.

Localized sediment transport and erosion following turbine installation can impact localized mixing and turbulence. Determining the level of scour protection required for foundation bases has been challenging. In general, an area is more likely to experience scour with larger structure diameters, shallower water depths, more uniform and sandier sediment conditions, and stronger oceanographic forces.

The impacts on fish species from changes in upwelling, habitat type, and ocean circulation are largely unknown, including cumulative effects. OSW facilities have the potential to affect flow and turbulence that may alter larval dispersal and ultimately settlement patterns. The uncertainties associated with how potential changes in ocean currents, alteration of predominant features, and unique regional processes will affect important fisheries resources in the region remain a barrier in predicting interactions between OSW facilities and the socio-ecological structure in the region.

Future work should focus on gathering empirical and observational data focused on downstream turbulence and mixing, and wind extraction effects on surface wind. Modeling studies should be paired with observations when possible (e.g., interactions between wind farms and local stratification events, such as the Mid-Atlantic Cold Pool).

Ecosystem Effects – Phytoplankton and Zooplankton

Phytoplankton and zooplankton can influence the distribution and abundance of upper trophic levels organisms, including fisheries resource species. The effects of OSW on the linkages between plankton, fish, and fisheries remain speculative, as the underlying processes are ecosystem-specific and influenced by fisheries regulations. The likely main effects of upscaling OSW on the pelagic realm are the more local impacts of underwater structures and the atmospheric effects of wind energy extraction. The local effects can be further divided into consequences of increased turbulence at and downstream of the wind turbine foundations and pile structures, as well as the creation of hard substrate as a vertically structured sublittoral zone.

OSW structures modify oceanic responses, which may have significant effects on fundamental ecosystem processes. Disruptions in connectivity may pose a risk to certain subpopulations with planktonic larvae, warranting future localized investigations. Installation of piles increases the biomass and distribution of filter feeders. It can also affect the local plankton community through the seasonally massive release of mero-planktonic larvae. High productivity of these filter feeders may lead to increased sedimentation rates of organic material.

There are no known empirical studies on potential effects of OSW on primary and secondary producers within the U.S., only a limited number analyzing effects on the pelagic ecosystem in Europe, and even fewer including field measurements. Efficient application of research within strategic assessments or project-specific OSW environmental analyses depends on the isolation of a collection of indicator impact vectors representative of key linkages between lower and upper trophic levels. Additional research is required to isolate these relationships, which should involve maintaining, and improving, integrated numerical models into OSW operational phases and linking pertinent results with targeted components of field experiment studies to verify observed structural changes and the corresponding impacts.

Ecosystem Effects – Demersal Finfish

The potential effects of OSW on demersal fish have been addressed through multiple studies in Europe and the U.S., and they remain a concern given the variety of mechanisms by which fisheries can be affected. European studies have primarily found higher abundances of structure-associated taxa closer to turbine foundations and that this high abundance attenuates with distance from the foundations. Fish dietary habits have been found to be affected by invertebrates that colonize the turbine foundations.

Responses by demersal fish to different types of noise disturbances vary with distance from the source. The effects of pile-driving noise have received much attention and can be severe, resulting in mortality or injury of hearing tissues. The continuous noise of OSW operation can shift in frequency depending on wind and rotation speed. Although operation noise levels are not associated with direct physical injury, long-term exposures may have negative effects on communication, foraging, and predator detection. Fish proximity to the turbines is a primary factor determining noise exposure that will increase with the cumulative contribution from many turbines. At present, studies assessing responses to particle motion and vibrational sounds from OSW activities to demersal species are lacking.

Demersal species which are electro- or magneto-receptive may derive ecologically important information from natural cues, such as EMF. Knowledge of species responses to EMFs is patchy and derived from a variety of methods. A better characterization of the EMFs would enable the design of more contextually relevant effect/impact studies for the species of interest.

Changes in hydrodynamics and wind wake effects may influence demersal species larval transport, connectivity, and recruitment. The direct influences of these changes are not well characterized but may be important, particularly if OSW overlaps with fish spawning habitat and the artificial reef effect concentrates fish during the spawning season.

It was particularly important to the fishing community that studies are conducted specific to U.S. commercial species. Habitat transition from soft to hard bottom habitats could be detrimental to important fisheries resources typically found in soft bottom habitats. The impacts of EMF masking natural cues on fish movements were also a concern as cables may become a barrier to migrating fish, changing migratory patterns and altering spawning timing and behavior.

Ecosystem Effects – Medium Pelagic, Large Pelagic, and Highly Migratory Finfish Species

OSW development is likely to affect the distribution, localized abundance, ecology, and behavior of highly migratory species (HMS), as well as other species they interact with as predators and prey. Localized OSW impacts have the potential to impact HMS throughout their natural range, particularly if they are constructed in essential fish habitat.

HMS covered in this section consist of species across the range of acoustic detection methods, including species with no swim bladder (elasmobranchs) to highly evolved structures (billfish). The majority of the limited research on sound perception to date involves the use of sound pressure signals to determine auditory ranges or threshold detection levels, even though most fishes primarily detect particle motion. Behavioral responses to introduced noise have been noted in some HMS. OSW operation noise levels are not generally associated with direct physical injury, but short-term behavioral modification has been noted in at least 1 HMS study.

No studies have directly examined the effects of OSW or operation on the distribution or movements of HMS off the Northeast U.S. However, trophic interactions associated with artificial structures have the potential to impact HMS over variable spatial scales and life stages, particularly for species that undergo extensive migrations between feeding and mating or spawning areas. Highly stratified hydrodynamics help to aggregate a variety of prey in dense patches and provide seasonal foraging habitat for several HMS. Increased upwelling events in these areas could decrease foraging opportunities by reducing stratification of the water column, thereby cooling the mixing layer and dispersing seasonal prey aggregations. Additionally, increased turbidity and modified flow could decrease prey detection for predators using visual or olfactory cues.

The effects of EMF emissions from high voltage OSW cables on electrically and magnetically sensitive marine fishes are largely unknown. EMF emissions have the potential to be attractive or aversive and could disrupt the foraging or migratory behavior of HMS. EMFs associated with OSW are likely detectable by many HMS over short distances and could interfere with local geomagnetic field orientation and foraging behavior. Despite observations of increased use or aggregation of HMS at anthropogenic structures, the full impacts of this behavior on species' populations at a local or stock-wide scale are poorly understood. Another important knowledge gap is how large-scale OSW will modify predator-prey interactions.

The greatest concerns of the fishing industry for these species groups include disruption of migration due to EMF, the displacement of species due to sonar or seismic impacts during exploration, acoustic impacts during construction and operation, and hydrodynamic impacts during operation. Some fishermen believe offshore wind structures will aggregate prey, which in turn will aggregate pelagic predators. While some posit this may have a positive effect on fishing success, others are concerned that species aggregation will alter prey availability, abundance, and predator-prey dynamics.

Ecosystem Effects – Small Pelagic Finfish

Small pelagic finfish are a functionally important species group; they provide an essential forage base for upper trophic levels and thus play a critical role in overall ecosystem function and dynamics. Because of their diverse living habitats throughout life history, small pelagic fish species may be sensitive to impact producing factors (IPFs) during each stage of OSW development, including EMFs, sound pressure and particle motion, substrate vibration, addition of new habitat, and changes to the hydrodynamic regime.

The sensitivities of small pelagic species to EMFs and the potential for them to disrupt migration patterns is not well understood. Impacts on migratory patterns could have long-term implications for species that develop migratory routes early in life and maintain those patterns even after the environmental stimulus no longer exists. Small pelagic species have demonstrated sensitivity to both sound pressure and particle motion. The limited research available indicates these species could be vulnerable to impacts to noise from all phases of OSW development, including operational noise.

Turbines and associated communities may act as fish aggregating devices (FADs) for small pelagic species. OSW projects have the potential to affect both vertical and horizontal migration patterns. Creation of feeding oases or predation refugia may cause migrating individuals or schools to change course or increase dwell times in OSW areas, potentially creating opportunities for energy acquisition or predation risk. Sediment resuspension by hydrodynamic action can increase turbidity, affecting prey and predator detection.

Several field studies are recommended, including those exploring the sensitivity to sound pressure, particle motion, and substrate vibration; the physical and behavioral impacts of sound; changes in movement, migration pattern, dwell or stopover time; behaviors during stopovers, diel vertical migrations, and distribution and usage of small pelagic fish species in OSW areas. Further suggested studies include impacts caused by localized and variable spatial scale predator-prey dynamics, and hydrodynamic patterns on the distribution and abundance of pelagic fish, as well as their larvae and food resources, and studies on the effect of sediment deposition from construction on benthic egg survival.

The fishing industry is highly concerned about OSW activities negatively impacting targeted species and reducing access to fish because of turbines. Because fish are known to be sensitive to sound, fishermen are concerned that they may be deterred from OSW development areas. Given the limited information regarding the impacts of long-term exposure of fish to persistent sound, there are concerns that this could result in major shifts in distribution.

Ecosystem Effects – Shellfish

OSW introduces new hard substrate, often in a previously soft or mixed sediment environment, which is important to some shellfish species. To date, no studies have taken place specifically addressing changes in abundance or distribution of clams or scallops relating to OSW. Limited studies have been conducted on ecosystem effects to squid; while none have evaluated artificial reef effects, there is evidence of decreases in squid abundance between baseline and operational phases of the Block Island project. Many studies report increased abundance of the blue mussel (*Mytilus edulis*) as a colonizing species of the hard substrate offered by OSW structures.

Sound plays a key role in conveying environmental information to marine organisms, and introduced sound during OSW activities can affect benthic fauna, such as shellfish. Recent advances have focused attention on the importance of particle motion and vibrational sound to marine invertebrates, with some demonstrating reduced mobility and burial, burrow flushing, and changes in the ability to feed. To date, there are no studies specifically assessing the effects of impact of OSW noise on clams or scallops, though laboratory studies have found that other bivalves respond to vibrational sound within the expected range of pile-driving activities. Such studies have also shown squid initially exhibited responses, such as body pattern changes, inking, and jetting, and were less likely to capture prey.

Magnetic fields (MFs) have been shown to induce responses or changes in distribution in crabs and lobsters. There are no published studies to date on U.S. commercial species of scallop or clams with regard to the effects of EMF. Hydrodynamics play an important role in the transport of larvae, connectivity between populations, and recruitment to habitats for many shellfish species. Impacts of changes in hydrodynamics and wind wake effects on the pelagic larval life stages of shellfish species have not been assessed in the context of commercial shellfish species. However, studies have indicated that anthropogenic structures enhance the ability of species such as blue mussel to survive offshore, and rare events combined with average migration patterns may increase connectivity between distant populations.

The fishing industry identified crustaceans, clams, scallops, and squid as understudied populations of particular concern in the context of OSW development. Specific topics of concern for fishermen included ecosystem-level impacts, predator-prey interactions, and the specific effects of noise, EMF, and heat on shellfish, as well as the influence of upwelling on the larval dispersion and plankton production and potential cascading consequences through the food web.

Ecosystem Effects – Community Interactions

An important component of ecosystem effects is community-level interactions, or interactions between 2 or more species. There have been limited studies on how most of the IPFs associated with offshore wind development (EMF, sound pressure, particle motion, altered hydrodynamic regimes) affect community interactions.

In many instances, the addition of new hard substrates associated with OSW development converts habitat from soft to hard bottom. Such conversion can create complex habitats for numerous species. However, soft bottom habitats are important for many fish species across life history stages and thus, the reduction of those habitats may have important population-level implications. Ultimately, a terminal climax community may become established once the community is stabilized and has reached an equilibrium with the surrounding ecosystem. New habitats introduced by OSW structures alter predator-prey interactions by aggregating prey and predator species, providing forage for predators, and providing refuge spaces for prey species. There is direct empirical evidence of predation and species-specific feeding relationships for OSW epibenthic communities. Limited direct evidence is available to characterize the trophic relationships at OSWs and their potential impacts on shaping fish and invertebrate communities. Many fouling species on OSW structures are suspension feeders that consume primary production and are an important component of food webs.

Deposition of organic materials from the structures alter sediment characteristics and benthic community composition, potentially leading to higher food web complexity, high trophic diversity, high resource partitioning, and low trophic redundancy. The addition of hard bottom habitat in areas that previously consisted of soft sediments could potentially facilitate the establishment of non-native species, which can alter community structure, modify food web dynamics, and reduce marine biodiversity. Feeding relationships—whether through predation, herbivory, or suspension feeding—underpin the structure and functioning of marine ecosystems. Ecosystem simulation models can be an effective tool for examining holistic ecosystem dynamics and exploring impacts associated with OSW development. In this context, there is a paucity of information on predation, herbivory, suspension feeding, and non-native species interactions regarding the effects of IPFs on successional patterns.

Fishing industry representatives specifically highlighted the potential for aggregation and artificial reef effects to alter predator-prey relationships or trophic dynamics as a key concern. Other IPFs of concern include potential drivers of change to predator-prey dynamics, including acoustic effects, hydrodynamic patterns, cold pool changes, EMF, heat, and benthic sediment changes. The establishment and range expansion of non-natives was also highlighted as a concern with particular emphasis on how non-natives would affect the survival of fisheries resources.

Socioeconomics – Fisheries Sociocultural Effects

The cultural implications of OSW development are recognized as a major gap in our collective knowledge. The fishing industry is an integral part of the social and cultural fabric of many coastal communities. Coastal fisheries consist of commercial, recreational, and subsistence activities. Many businesses within the fishing community are family businesses, with multiple—sometimes intergenerational—family members working within the business. The sustainability of fisheries has long been aligned with individual, familial, and community wellbeing, and thus demographics, job satisfaction, and welfare of individual fishermen must be considered in understanding the effects of OSW development. Any change to the fishing industry, whether it be management, environment, or coastal development, affects the vulnerability of coastal communities.

It is unclear whether the development of OSW will lead to lost or displaced jobs in fisheries. There are generally high levels of job satisfaction and occupation attachment within fisheries, but no known studies have evaluated fishermen’s willingness or ability to change or supplement their income from OSW. The effects of OSW to fishermen’s mental health, and its relation to compounding issues with spatial conflict and uncertainty, are similarly poorly understood.

Several additional key topics should be considered for developing knowledge regarding the sociocultural interactions of OSW and fisheries: (1) the impacts to or costs of food security; (2) how the OSW industry could affect the cultural importance and identity of fishing infrastructure within a fishing community; (3) the seafood industry as a resource for the tourism industry and resultant effects to tourism and community identity; (4) social effects of energy transitions and changing ocean uses; (5) social resilience, including the magnitude and duration of perturbation; and (6) adaptability.

There is no identified research on fishermen’s resilience and ability to adapt to changes with OSW development in the U.S. The ability of fishermen to adapt to changes will be dependent on a number of factors discussed throughout this paper, including policies, technologies, ecosystem effects, access to capital, and social and cultural demographics. The speed and scale of OSW development will also impact fishing community resilience. Commercial and recreational fishing are essential components contributing to the economic viability of many coastal communities that must be preserved and minimized in the development of every OSW project.

Fishermen’s attitudes toward and perceptions of OSW may be informed by cultural models and governance arrangements through which oceans are viewed as a commons subject to shared access and use vs. as a frontier to be developed and privatized. Attitudes and perceptions regarding fisheries and OSW also include consideration of fishermen’s role in decision-making processes, including as ocean users and stakeholders. Understanding and valuing fishing communities requires understanding and valuing fishermen and their knowledge of the sea. Fishermen’s expert knowledge of the fisheries and environment, and its utility via cooperative fisheries research, has been well documented and respected. Using local ecological knowledge held by fishermen, and other ocean users, could provide potential developers and policymakers alike with information that cannot be found in literature or data banks.

Fisheries Management and Data – Fishery Dependent Data Collections

Fishery dependent data (FDD) are those collected during fishing operations. They are used to evaluate changes to fishing patterns, describe socioeconomic trends and impacts, monitor fishery quotas, inform stock assessments, and support ecosystem-based science. FDD have a wide range of applications which to date have largely focused on fisheries science and management. They have been used to some extent in early or existing evaluations of proposed OSW projects to identify species caught, gear used, revenue exposure, area fished, transit direction, and communities affected. However, FDD were not originally designed at the spatial resolution necessary to most effectively inform OSW development decisions, with each FDD source having individual limitations that must be considered when evaluating fishery operations.

Opportunities for increased resolution and spatial accuracy of FDD may more effectively link fishing effort to economic impacts. Verification of area fished could help improve spatial accuracy, while increased area precision could improve spatial resolution. Efforts to improve these deficiencies could include alternative documentation of areas fished through automation and indirect reporting. An audit of the cost of data reporting and limits of existing technology would also be beneficial to understand the full extent of the financial impacts to the fishing industry. Finally, information on shoreside support services, including fish processors and equipment and repair suppliers, is needed to provide a more comprehensive evaluation of socioeconomic impacts to fishing communities.

Consideration of FDD suggests several recommendations for future research. Access to confidential FDD by non-federal scientists should be improved while maintaining confidentiality or with permission from data producers. Better spatial and temporal resolution of FDD could assist in understanding fisheries behavior and needs in relation to OSW development. If fishermen avoid OSW areas, impacts to FDD collection and dependent analyses must be addressed. Fisheries submit different scales and types of FDD, which should be better communicated to improve understanding of FDD utility and limitations. FDD can also inform alternative metrics of economic impacts beyond ex-vessel value. Finally, data related to fisheries shoreside support businesses should be further evaluated.

The fishing industry has been proactive in providing solutions to questions by participating in cooperative research. RODA’s Fishery Knowledge Trust (FKT) is a fishing industry-owned and -managed integrated knowledge and database infrastructure used to develop a consensus hypothesis of research needs supported by data. This includes the potential interactions of OSW development with the key socioecological and management dimensions of fisheries to identify early strategies for conflict reduction. The FKT is currently conducting a pilot project on the Atlantic herring (*Clupea harengus*), Atlantic mackerel (*Scomber scombrus*), Atlantic surfclam (*Spisula solidissima*), and ocean quahog (*Arctica islandica*) fisheries. The Science Center for

Marine Fisheries (SCeMFiS) is also supported by members of the fishing industry. It is a National Science Foundation Industry/University Cooperative Research Center that has conducted a number of research projects, including those focused on OSW impacts.

Fisheries Management and Data – Fishery Independent Data Collections

NOAA Fisheries and other researchers operate surveys to track the abundance and distribution of marine animals over time. These surveys use a statistical design to calculate estimates of abundance and biomass, and associated uncertainties, with the goal to sample over a broad geographic area to capture the spatial extent of target species and populations. The research enterprise consisting of federal, state, and cooperative surveys supplies a wealth of annual information on fisheries resources and the environment in which they exist. Removal or significant modification to scope and geographic scale of these established efforts will critically challenge our ability to assess and manage stocks.

OSW development impacts surveys through preclusion, habitat change, changes in statistical design, and reduced sampling productivity. In turn, preclusion can occur in at least 3 ways: (1) turbines spaced too closely or blades too close to the water's surface to allow NOAA vessels to work safely; (2) electrical cables between turbines and to shore preventing use of many types of survey gear; and (3) for aerial surveys, turbine heights or low cloud ceilings requiring adjustments to flying altitudes that could prevent operation or decrease detectability.

By disrupting survey programs and the assessments that depend upon them, OSW development will result in serious adverse impacts on U.S. fisheries stakeholders. These impacts will lead to greater uncertainty in abundance estimates, which will likely lead to lower fishery quotas and lost revenue to commercial and recreational fishermen. With the expected overlap between OSW development sites and fisheries resources that span numerous taxa, jurisdictions, and management authorities, the ultimate impact is expected to be both variable and uncertain. Given the novelty of OSW development in the United States, there is extremely limited existing research or literature that evaluates its impact on the ability to monitor, assess, and manage fish stocks.

Several efforts are under way to better understand the interactions between fisheries independent surveys and OSW development. In 2021, NOAA Fisheries and BOEM announced a research initiative to begin evaluating the impact of OSW development on the Northeast Fisheries Science Center's Bottom Trawl Survey. The International Council on the Exploration of the Sea's Working Group on Offshore Wind Development and Fisheries, established in 2020, is also focusing on this topic. Specific gaps in knowledge include: (1) best practices for adapting survey design and methodology within and around OSW areas; (2) approaches to account for differences in species distribution, abundance, and vital rates inside and outside OSW areas on stock assessments and fisheries management; (3) quantification of stock assessment impacts resulting from survey exclusion or alteration due to offshore wind energy development; and (4) quantification of changes in habitat as a result of OSW development and downstream effect on availability of species to surveys.

Commercial and recreational fishing representatives should be included in all aspects of planning of OSW development and management, including survey adaptation and execution. Cooperative solutions benefit from the participation of varied subject matter experts, including scientists and fishing industry members. A number of efforts have recognized the need for inclusivity in addressing issues. In addition to on-the-water collaboration for surveys, the fishing community holds knowledge of fishing gear and species availability, which is key for development and refinement of survey protocols in the face of OSW development.

Fisheries Management and Data – Impacts on Fisheries Management

Federal commercial and recreational fisheries are managed through complex systems governed by the Magnuson-Stevens Fishery Conservation and Management Act and other laws. Oversight is assigned to NOAA Fisheries, regional fishery management councils (Councils), states, and others to meet conservation and management objectives, such as preventing overfishing; protecting habitat; minimizing interactions with non-target species, marine mammals, and endangered and threatened species; reducing fishing mortality on spawning or juvenile fish; reducing gear conflicts; and minimizing catch of non-target species. To meet the multiple legal requirements, fisheries managers use many different types of regulatory measures. Given the unique challenges and uncertainties that OSW development presents to existing fishery management practices, it will likely take several years before management authorities understand how wind development affects both fishery resources and fishery operations. This may necessitate an iterative management approach to adapt to new conditions. When considering how fisheries management should adapt, it will be important to holistically evaluate fishery management programs as conditions change while considering complex future scenarios.

Fisheries managers use a variety of measures, including but not limited to closed areas, gear restricted areas, exempted fishery areas, rotational fishing areas, landings limits, possession limits, size limits, seasonal management, habitat and spawning closures, bycatch limits, and limited access systems. Changes in fishing effort can impact the effectiveness of these management measures. Impacts from OSW development and consequential changes to fishing effort will be essential to understand so fishery managers can re-evaluate these measures and determine whether adjustments are needed. In turn, it will be important to acknowledge existing spatial management measures when considering how the distribution of fishing effort might change in response to OSW development since existing measures restrict where displaced effort can go and may require augmented information or approaches.

Catch and landings limits for managed stocks are informed by peer-reviewed stock assessments when possible. Fisheries independent surveys are often the primary data set used in stock assessment models, though most stock assessments use multiple data sets, including FDD. When a peer-reviewed stock assessment is not available, surveys can be used as an index of relative abundance to inform catch limits. For especially data-poor stocks, FDD can also be used as the basis for setting catch limits. Impacts of OSW development on these data could therefore have important implications for the setting of catch limits for commercial and recreational fisheries. Changes in fishing effort resulting from OSW development will be important to quantify and account for in stock assessment models. Fishermen may adapt by changing gear types or target species; however, this is not expected to occur to a great extent, especially for commercial fishermen, due to restrictions on availability of permits, existing area-specific regulations, market demand, and costs associated with changing gear types.

While this report does not specifically examine interactions between OSW and protected species, such interactions can impact fisheries management. Measures such as gear restrictions are sometimes necessary to limit these interactions. Changes in commercial and recreational fishing patterns can alter interactions with protected species and the effectiveness of fishery management measures in their reduction. It will be important to evaluate both changes in fishing effort and changes in protected species distribution and behavior, and to distinguish potential changes due to OSW development to predict changes in interactions between fisheries and protected species.

Many fishery stakeholders are concerned about the potential for reduced future catch and landings limits in response to increased scientific uncertainty resulting from OSW development, including exclusion of regional fisheries independent surveys. They also believe it is essential to minimize negative impacts of OSW development on marine habitats.

Cumulative Impacts

The link between communities and environment is one of the major drivers of analyzing cumulative effects resulting from an action. Cumulative effects analysis (CEA) evaluates the combined impact of past, present, and near future projects to determine the overall effect on the environment and the dedicated footprint of these short-, medium-, and long-term effects. CEAs used in marine management and planning are mostly initiated in response to legal obligations to assess cumulative effects.

The importance of cumulative effects arises when individual projects have negligible to minor impacts, but moderate to major impacts occur after multiple individual projects are implemented. Similarly, narrowing the focus of an assessment to individual stressors may underestimate the scale of realized impacts on the environment. Research on cumulative impacts assessments consistently concludes that cumulative analysis should inform future planning and aim toward a regional perspective due to the transboundary nature of ocean resources. However, CEAs must make assumptions about interactions among IPFs and future plans, which imparts uncertainty due to the lack of data and unknowable eventualities. It is necessary to identify and generate a matrix of activities to disentangle the levels of project effects, the scales in which these developments will modify the environment, and the overall environmental changes over the life of the development.

The fishing industry in the U.S. is highly concerned with the quality of cumulative impacts assessments currently being conducted for OSW development. BOEM’s current approach is to analyze projects on an individual basis. The environmental and economic effects will not be isolated, and fishing communities have suggested the scale of analysis should match that of fisheries and ecosystem management practices.

Integrated Ecosystem Assessment

The prospects of integrating OSW development with fisheries is a daunting task that will require expanding current management strategies. Ecosystem management is a tool to facilitate such integration and examine the inherent trade-offs in considering multiple ecological and socioeconomic factors in concert. Fisheries management includes several forms of ecosystem assessments; of these, ecosystem-based management (EBM) expands beyond the fisheries sector to include other ecosystem uses and human sectors, and NOAA’s Integrated Ecosystem Assessment (IEA) Program was designed to help address this nexus. The IEA approach is a 6-step process that starts with scoping to identify ecosystem goals. Like all steps, this should be an iterative process that includes engagement with stakeholders and managers. An IEA can help fill a knowledge gap, such as the full extent of impacts from OSW development to fisheries, by relying on the fishing industry and other experts’ knowledge.

The NOAA IEA program and RODA are leveraging previous work in the region to conduct an IEA for OSW development and fisheries interactions. This will be the first IEA to study these interactions, although IEA efforts have been under way in the Northeast U.S. for some time. The NOAA IEA program is working with RODA and a steering committee to plan and execute a series of stakeholder workshops. Through participatory modeling, a conceptual model will be developed that will highlight various aspects of the system that warrant further investigation and elicit ecosystem goals. After scoping and indicator development is completed, a risk assessment will be conducted. The IEA could potentially feed into the existing framework of environmental impact statements (EIS) required by the National Environmental Policy Act (NEPA) or a structured decision-making analysis, such as scenario planning.

Innovative Monitoring Approaches and Technologies

Data and information needs should drive which technologies and methodologies are employed for the study of offshore wind development and fisheries interactions rather than the technology driving the questions. There are many sensors and platforms available to sample over many spatial and temporal scales, but the information needs should dictate which methods should be used. Advanced sampling technologies are known for collecting large amounts of data. Remote or autonomous sensors can collect data around the clock, amassing large amounts that need to be processed, analyzed, archived, accessible, and discoverable. A data management scheme needs to be developed prior to, or at the very latest in the early stages of, monitoring to enable efficient and effective use of the data.

There are a number of strategies to evaluate the impact of OSW on flora and fauna. From a sampling perspective, developing a hierarchical spatiotemporal context of the area may be useful, as each technology has its specific measurement scale. Using advanced technologies to sample in and around OSW facilities will require at least 2 sampling modalities: (1) deploying, retrieving, and collecting data from the instruments; and (2) addressing ways to validate the data by in situ sampling of the environment, weather, geology, and biology in the pelagic, demersal, and benthic zones.

The experimental design chosen for a given study should be based on the question being asked. Two designs often discussed for offshore wind studies are the Before-After-Control-Impact (BACI) and Before-After-Gradient (BAG) designs. There are inherent assumptions made by each of these designs that lend to the advantages and disadvantages in their application. Generally, BACI can be used to examine effects that are assumed to have a limited spatial and temporal extent whereas BAG designs are advisable when the spatial extent of effects is either unknown or hypothesized to be large in scale.

Regional Science Planning

Fishermen and federal regulators have identified the need for a coherent regional framework to collect and disseminate credible research on the relationships between fisheries and proposed development since OSW development planning took off exponentially in the last decade. In the U.S., offshore wind developers conduct project-specific monitoring and data collection. Multiple entities, including federal and state agencies, academic institutions, fishing industry associations, and others, perform additional research related to fisheries and offshore wind, and some offshore wind developers conduct supplemental data collection and monitoring efforts related to fish stocks. Individual project-specific monitoring data in itself is not necessarily informative to evaluation of regional or cumulative impacts of offshore wind to fisheries. It is also challenging to integrate with longstanding fisheries science activities, such as stock assessments and habitat management.

The development and implementation of a coordinated effort in the U.S. toward regional science planning have lagged behind many other aspects of offshore wind energy planning. However, the thoroughness of scientific research to understand interactions between OSW and fisheries, and the credibility of the information generated, is both a goal of, and prerequisite to, effective collaboration. The lack of coordination for regional science has resulted in a barrier to these planning efforts and a lost opportunity to improve these planning efforts. Expanding efforts for regional science coordination is considered a high priority that would be responsive to longstanding fishing industry requests. Better incorporation of their knowledge and participation, including affording full due weight to industry-proposed research topics, would facilitate the achievement of many shared goals for the natural and human environments.

In March 2019, RODA, National Marine Fisheries Service (NMFS), and BOEM announced a Memorandum of Understanding in which they agreed to explore collaboration on the development of a regional research and monitoring framework to ensure decisions are made on the best available science pursuant to a mutual interest in improving the accuracy, relevance, and usefulness of this information and research. There is broad interest in such a collaborative regional research and monitoring framework. There is also a substantial need for improved information sharing across all interested parties. However, individual sectors should also strive to improve dissemination, communication, and transparency of research and knowledge.

Fishing Industry Identification of Research Priorities

Involvement of fishing industry members in the co-design of methods and approaches to mitigate adverse impacts is integral to achieving a sustainable ocean economy. In considering regional science overall, it is important to note that hypotheses generated by the fishing industry regarding the environmental effects of OSW remain relatively unstudied and uncommunicated in comparison to those advanced through the OSW permitting process. Therefore, RODA conducted the first ever comprehensive effort to survey commercial fishermen, summarize their areas of key concern, and identify opportunities for cooperative research. The result is a list of research priorities to better understand the impacts OSW development will have on the marine ecosystem from the perspective of a group of individuals with significant local ecological knowledge, which is essential for predicting and evaluating socioeconomic and environmental impacts and interactions among fisheries, fish stocks, and OSW.

The research recommendations evidenced a clear perception that meaningful interaction has not occurred with the fishing industry during OSW siting processes. Survey respondents stressed that once necessary data sets are gathered, and the scale of potential environmental and socioeconomic impacts is identified and better understood, strategies to effectively reduce impacts must be designed in consultation with the fishing industry and OSW developers. The following broad categories were identified as research priorities:

- cumulative impacts;
- business, communities, and socioeconomics;
- environmental impacts;
- fishing regulations and management impacts;
- recommendations for project monitoring and review;
- safety;
- supply chain; and
- transmission.

The recommendations indicate an enormous amount of research is still needed in order to understand the impact of OSW on our environment and fisheries, but time is limited. A timely, productive regional science plan for offshore wind could have resulted in an enhanced ability to understand the environmental interactions resulting from the first large-scale OSW projects, especially on a cumulative scale.

1. ECOSYSTEM EFFECTS

1.1 Benthic Habitat Modification

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1.1.1 Introduction

The installation of offshore wind turbines and associated inter-array and export cables interacts with, and redistributes, natural seafloor sediments. These installations also introduce various types of sediments and hard substrata into the marine environment, specifically the turbine foundations themselves, scour protection placed around the turbine foundations, and armoring to protect cables that are installed on or near the surface of the seabed when they are unable to be deeply buried. One particular feature of wind turbine foundations is that they represent artificial substrata not only near the seabed where soft bottom or hard substrata naturally occur but in the water column extending into the intertidal zone, where such vertical surfaces do not naturally occur offshore.

These changes to the physical environment affect benthic communities of the natural seabed surrounding the turbines and provide novel hard substrate habitat for attached organisms (Degraer et al. 2020a). These epifauna, in turn, provide food and shelter for other inhabitants of the benthic and pelagic environment, referred to as an “artificial reef effect.” Provision or alteration of feeding habitats can affect the tight trophic link between the benthos and many fish species, including those important to commercial and recreational fisheries. Both the attached organisms and the species attracted to them modify the physico-chemical properties of the surrounding sediments through the deposition of organic material in the form of feces, pseudofeces, and shells.

Wind development may also affect sand bedforms. Various features (ridges, waves, megaripples, ripples) occur in combination with each other on different spatial scales, and these systems vary by location. These features, especially the troughs and depressions between the crests, serve as fish habitat, and the effects of turbine placement or cable trenching on the persistence and stability of these features are largely unknown.

Benthic habitat modification associated with offshore wind structures could have a direct effect on an area up to 250 m away from foundations, but these local (near-field) modifications may affect adjacent (mid- and far-field) environments (Lefaible et al. 2018). Three frameworks whereby benthic alterations affect the surrounding ecosystem are described in the literature: meta-connectivity, food web connectivity, and broader effects of carbon export. Meta-population connectivity between turbines and adjacent habitat occurs when introduced species spread beyond the physical effects of sediment modification. Changes in food web connectivity may propagate through the food web, beyond the immediate artificial reef effect. Finally, carbon can be exported from the offshore wind development (OSW) due to biomass production associated with the attached filter feeders such as mussels or barnacles. This represents a transfer of pelagic carbon (plankton) through the attached biofiltering organisms to the benthos. The local depletion in phytoplankton from the concentrations of sessile filter feeders could affect zooplankton and ichthyoplankton distribution and, in turn, the species that feed on them.

In addition to these trophic changes, marine species use habitat structures for sheltering, spawning, dispersal, and egg deposition, and changes in habitats can affect these uses. Hard substrata within soft sediment-dominated environments provide stepping stones for hard bottom species to disperse across local and regional areas (Adams et al. 2014; Coolen et al. 2020; De Mesel et al. 2015). Improved or diminished habitat suitability at these scales will affect individual fitness, which may influence population-level changes if enough individuals are affected. Net increases or decreases in availability and quality of habitats should therefore be considered at both local and regional scales in the context of a species' overall distribution and habitat use. Near- and far-field interactions may also be detectable at an individual turbine, an entire wind farm, or across multiple wind farms. Temporal scales are also important to consider, including both the lifetime of the wind farm from construction to decommissioning (0-25+ years) and the timeframe over which colonization of the structure occurs (Degraer et al. 2020). Species colonization of offshore wind structures occurs in stages. Broadly, Coolen et al. (2020) classified these periods as the pioneer stage (0-2 years), the intermediate stage (3-5 years), and the climax stage (6+ years).

In summary, habitat suitability and ecosystem connectivity can be considered at multiple scales: individual to population level, near-field to regional, and short- to long-term. Here, we explicitly define the scales considered in this assessment as:

- Species-scale
  - Individual
  - Population/stock
- Spatial-scale
  - Turbine or near-field (1 turbine, 10s of meters)
  - Wind farm or mid-field (Dozens of turbines, 10s of kilometers)
  - Regional or far-field (Hundreds of turbines/multiple wind farms, 100s of kilometers)
- Temporal-scale
  - Short- or near-term (0-5 years)
  - Intermediate-term (5-10 years)
  - Long-term (10-25+ years)

Overall, because the local effects of benthic habitat modification are multiplied many times within and between wind farms, these installations can have population-level effects on regional spatial scales. These regional changes can, in turn, affect fisheries and management efforts. The introduction of infrastructure in the coastal ocean is not occurring in a vacuum; these seafloor habitats have been influenced by human activities such as fishing, shipping, and coastal development for hundreds of years, and climate-related changes on seafloor temperature and acidification have direct effects on the benthos. This chapter focuses on the benthic effects of a single ocean use, OSW, while recognizing that these habitats will experience the cumulative impacts of multiple natural processes and anthropogenic activities.

1.1.2 State of Knowledge and Understanding on Benthic Ecosystem Interactions with Offshore Wind

1.1.2.1 Existing Studies

The original studies on benthic sediment modification focused on the community composition of organisms colonizing OSW foundations, including commercially important fish that are attracted to the artificial hard substrata (Schröder et al. 2006; Zettler et al. 2006). Studies have since expanded to include assessments of changes in sediment particle size, habitat structure (e.g., shell deposition), and benthic flora and fauna on the seafloor around foundations (Causon and Gill 2018; De Mesel et al. 2015). More recently, studies have addressed carbon flow from the pelagic environment via the artificial hard substrata communities to the surrounding natural seafloor (i.e., the biofilter effect; Ivanov et al. 2021). Changes in sediment nutrient cycling, especially nitrogen, as a consequence of organic enrichment and sediment fining are also being investigated (De Borger et al. 2021). Some studies target a differentiation between the effects of different types of foundations and scour protection materials (Coolen et al. 2019; Lengkeek et al. 2017). Studies on effects of construction and operation of wind farms on landforms that provide habitat (glacial moraine, sand ridges) have not been conducted.

While benthic habitat change associated with OSW foundations has been studied extensively, the connectivity to surrounding areas beyond these readily detectable physical changes has not been systematically studied. There are some data available from studies of artificial reefs in the Northwest Atlantic, although unlike wind turbines, these have no intertidal component. Offshore oil and gas platforms have also been studied, and these structures do have an intertidal component, but there are no oil and gas platforms in the Northwest Atlantic. Recent studies with stable isotopes and pulse-chase experiments in Belgium demonstrated how local food webs might change due to the introduction of artificial hard substrata (Mavraki et al. 2020a, b, 2021a). While these studies provide important clues to potential connectivity patterns, they did not examine mid- or far-field effects (> 65 m).

Models of dispersion suggest that larvae from intertidal species could, in some conditions, extend their range due to the presence of OSW (Adams et al. 2014). There is evidence of this "stepping stone effect" whereby non-indigenous attached species extended their range into a wind farm by taking advantage of introduced hard substrata (De Mesel et al. 2015); however, these species were not sampled outside of the wind farms. Tangible evidence for expansion of the range of attached species was seen at the Block Island Wind Farm (BIWF), where blue mussels appeared for the first time in trawl sampling control areas as far as 2 miles away after mussels settled on the foundation structures and were found in fish stomachs (Carey et al. 2020; HDR 2020; Wilber et al. 2022a, b).

An overarching question for ecosystems altered by offshore wind infrastructure is whether the altered habitat positively or negatively impacts habitat suitability for native species (i.e., the ability of that environment to provide forage, shelter, and feeding opportunities). Existing studies have primarily documented physical habitat alterations and increases or decreases in abundance of associated species to infer how habitat suitability has changed.

Arguably the most relevant study type assesses the habitat use patterns of individual species via direct observations of species in their habitats at various life history stages and survey seasons. However, such studies are less common than research that pairs habitat mapping with separate surveys of managed species. A useful way to investigate the relationships between species occurrence or abundance and environmental variables is habitat suitability modeling (e.g., Friedland et al. 2021). These models can combine data from multiple surveys, methods, and time periods. One drawback is that they are typically run at large spatial scales, and average habitat use patterns may not match exactly with how species use habitats within an individual OSW. The scale of the NOAA Fisheries Northeast Fisheries Science Center random stratified trawl design matches entire wind farm footprints but does not cover the smaller habitat alterations from individual turbines and scour protection installation. Pending compliance monitoring of the U.S. OSW includes Before-After-Control-Impact (BACI) designs with habitat and depth stratified sampling as well as Before-After-Gradient (BAG) designs designed to examine small scale habitat changes.

1.1.2.2 Relevant Studies (Key words)

- Connectivity (Bergström et al. 2013; Causon and Gill 2018)
- Habitat suitability, Meta-population connectivity, blue mussel, Block Island Wind Farm (BIWF), lobster, demersal fish (Carey et al. 2020)
- Meta-population connectivity, blue mussel, limpet, North Sea (Coolen et al. 2020; De Mesel et al. unpublished data; De Mesel et al. 2015)
- Knowledge gaps (Dannheim et al. 2020)
- Habitat suitability (Degraer et al. 2020a)
- Multi-year monitoring, North Sea (Degraer et al. 2020b)
- Multi-year monitoring, Northwest Atlantic (HDR 2020a; Hutchison et al. 2020c)
- Local benthic effects, total organic carbon flux (Ivanov et al. 2021)
- Local benthic effects, multi-year monitoring, North Sea, brown crab (Krone et al. 2017)
- Local benthic effects, North Sea (Reichart et al. 2017)
- Meta-population connectivity, Multi-year monitoring, North Sea (Reubens et al. 2014)
- Local benthic effects, multi-year monitoring, Northwest Atlantic (HDR 2020a)
- Local benthic effects, multi-year monitoring, North Sea (Schröder et al. 2006)
- Multi-year monitoring, Northwest Atlantic, Meta-connectivity, blue mussel, demersal fish (Wilber et al. 2020)
- Multi-year monitoring, Northwest Atlantic, Diet, blue mussel, demersal fish (Wilber et al. 2022a)
- Multi-year monitoring, Northwest Atlantic, Meta-connectivity, blue mussel, demersal fish (Wilber et al. 2022b)
- Multi-year monitoring, North Sea, Baltic Sea (Zettler and Pollehne 2006)

1.1.2.3 Key Findings

OSW foundations are swiftly colonized by an attached community that reaches a mature state dominated by mussels, amphipods, and anemones after about 10 years (Degraer et al. 2020b; Kerckhoff et al. 2019). Fish are attracted to the structures and their colonizing communities immediately after installation of the turbines (HDR 2020; Wilber et al. 2022b). Changes in the community structure of the surrounding natural seafloor, attributed primarily to organic enrichment and mussel shell deposition, are detected at near-field distances (~10s of meters) from the turbines within 1-3 years after installation (Hutchison et al. 2020c). Signs of organic enrichment and sediment fining at mid-field distances (~100s of meters) were detected only after approximately 10 years. The introduction of intertidal hard substrata can lead to colonization of the surrounding seafloor by mussels and other attached fauna (Carey et al. 2021; HDR 2020; Wilber et al. 2022b).

Attached filter feeding communities consume a portion of the pelagic primary production within a wind farm and locally deposit substantial amounts of organic matter (i.e., biofiltering; Reichart et al. 2017; Mavraki 2020b; Slavik et al. 2019). The locally enhanced food resources typically attract structure-loving and demersal fish (Bergstrom et al. 2013; Reubens et al. 2014; Wilber et al. 2020). The biological growth on the turbines and scour protection can provide a food resource, but dietary analysis of gadids and flounders at the BIWF saw little change in diets except for the addition of mussels and mysids to winter flounder (*Pseudopleuronectes americanus*) stomachs (Wilber et al. 2022a). Concerns have been raised by lobstermen that the increase in some predators could affect survival of juvenile lobsters. A study of stomach contents of black sea bass (*Centropristis striata*) for 1 year at the BIWF revealed relatively high numbers of crabs but no lobsters (Wilber et al. 2022a). Pelagic fish tend to be attracted for presently unknown reasons other than food (Mavraki 2020); this is similar to the principles of fish attraction devices (FADs). Nitrogen cycling and sediment oxygen consumption were shown to be lowered in surrounding sandy sediments because of sediment fining, affecting sediment permeability downstream of turbine foundations depending on the surrounding geology and current flow (Lefaible et al. 2019). Research on artificial reefs suggests that oxygen depletion from enrichment is unlikely except in cases where sediments are already oxygen stressed (Baltic Sea) or where algal macrodetritus may accumulate (Wilding 2014).

The presence of the turbine foundations also alters localized hydrodynamics resulting in potential modification of benthic habitats through scour and deposition (Dannheim et al. 2020). The modifications may not be evenly distributed around the foundations, but studies show that fining and enrichment is localized and may vary with foundation type (monopile, gravity base, jacket; Lefaible et al. 2018, 2019). The presence of numerous turbine foundations or even adjacent wind farms has led to the hypothesis of a “stepping stone” effect due to larval dispersal (De Mesel et al. 2015). This effect depends on a variety of physical oceanographic factors and population dynamics in addition to the distance from shore, hard bottom, or other sources of flora and fauna. Barbut et al. (2020) modeled a differential overlap between the spatial distribution of the spawning grounds of 6 southern North Sea flatfish species and the distribution of OSW. While it has not been verified, the work suggests a species-specific effect of OSW on the larval influx to the nursery grounds along the southern North Sea coasts. In some cases, no regional effect on production was detected for Atlantic cod (*Gadus morhua*) or pouting (*Trisopterus luscus*; Reubens et al. 2014). OSW were found to not, or only marginally, add to the meta-population connectivity of common species like blue mussels or limpets (Coolen et al. 2020; De Mesel et al. 2015, unpublished data). However, enhanced stepping stone effects have been demonstrated for oil and gas rigs (Henry et al. 2018).

1.1.2.4 Similarity of Study Outcomes

Overall, there is a high level of consistency in the general pattern of the impacts. However, results may vary based on wind farm specifics and site conditions. While the general pattern of colonization of turbines may apply, substantial differences may occur based on design, materials used, and location. For example, jacket foundations tend to host more mussels than monopiles because of the larger number of different surfaces they afford for attachment. On the other hand, the scour protection is absent or minimal in the case of jacket foundations compared to monopiles and particularly gravity-based foundations which provide fewer seafloor settlement sites (ICF 2021). Differences in the sediment grain size distribution of the surrounding seafloor and near bottom currents are expected to control the effect size of organic enrichment and sediment fining. This remains underexplored as most studies were executed in mobile, coarse-grained sediments. Furthermore, nearly all effects related to artificial reefs remain largely unexplored for natural hard substrata.

European studies, for the most part, include effects that result when fishing within wind farms is prohibited; thus, confounding the reef effect and provision of increased structure with reserve effect. For example, evidence that lobster abundance and size increases were observed during construction (Coates et al. 2016; Roach et al. 2018), but if these lobsters could be harvested within the windfarm, you might not observe this to the same extent (Carey et al. 2020).

Another example is the restoration of populations of conservation concern as a result of exclusion of bottom contact mobile gear in areas depleted by habitat disturbance in the North Sea (tubeworms and Atlantic cod, Degraer pers. comm.; Coates et al. 2016). These results are unlikely in the U.S. setting as bottom contact mobile gear will not be deliberately excluded from wind farm boundaries. Results to date are site-specific and likely to vary within the U.S. due to a wide range of benthic conditions. This represents a substantial data gap due to the inability to generalize results.

1.1.2.5 Current Effective Research Methods

Changes in community composition are usually explored using BACI or BAG in situ monitoring programs, targeting the attached fouling communities, mobile fish communities, and surrounding seafloor communities (Methratta 2020; Wilding et al. 2017). To allow comparative analysis and assess cumulative effects, standardized sampling techniques need to be applied. Across all methods, measurements should account for horizontal gradients (~distance from foundation) and vertical gradients (~zonation).

Fouling communities can be explored by scraping performed by scientific divers or using scientific diver- or remotely-operated vehicle (ROV) underwater imagery. Evaluation of settlement plates distributed in a BAG design can capture distribution of non-indigenous species related to the placement of foundations.

Changes in carbon flow are usually tackled either by in situ measurements or lab experiments. In situ measurements comprise (fish) stomach content, stable isotope, and sediment particulate organic carbon (POC) analyses. Lab experiments are targeting filtering and (pseudo) fecal pellet production rates of suspension feeders. Stable isotope studies can be used to assess the dietary composition of predators and link to the distribution of prey (Mavraki et al. 2021a). Pulse-chase studies can track assimilation of organic carbon by introducing carbon-13 (^{13}C)-labeled microalgae to colonizing fauna (Mavraki et al. 2020).

Changes in nutrient cycling are typically investigated by means of chemical fluxes in incubated, in situ-collected sediment samples and lab experiments with artificially enriched and/or fined sediments targeting measurements of permeability. There are proxies for soft sediment nutrient cycling and bioturbation but none for hard substrata. Incubation chambers for in situ measurements of chemical fluxes at hard substrata are being tested.

The most effective research methods currently being used to study mobile species are acoustic telemetry and video/photographic monitoring. Traditional fisheries survey approaches using trawl, gillnet, or trap gear are also used. Telemetry studies of highly mobile pelagic and demersal organisms linked with physical oceanographic modeling can generalize occupation of OSWs and surrounding areas over time. Digital aerial photography can be used to map distribution of forage fish aggregations and surface predators (birds and marine mammals). These distribution maps can also be linked to physical oceanography and species distribution models to evaluate connectivity beyond OSWs. Development and validation of habitat or species distribution models based on oceanographic data can be combined with existing regional trawl or water column sampling (plankton tows, mid-water trawls, environmental Deoxyribonucleic Acid [eDNA]). Refer to Section 4.3, Innovative Monitoring Approaches and Technologies, for additional sampling methodologies.

1.1.3 Major Knowledge Gaps

The following topics are considered major knowledge gaps. These all touch upon meaningful impacts on fishes, including commercially and recreationally important species, at spatial and temporal scales that matter. This information is binned into relevant themes and prioritized using the following criteria (Table 1):

- Primary criteria: focus on certain focal species of importance (i.e., receptors)
    - Commercial and recreational species and their associated Essential Fish Habitat (EFH)
    - Forage species
    - Federally protected species
- Secondary criterion: risk assessment
    - What is the likelihood of occurrence and effect size (i.e., magnitude of effect)?
- Tertiary criteria: information return on technological and financial investment
    - Technical complexity of studies
    - Scale in space and time
    - Factors evaluated (e.g., depth, position within array, habitat type)
    - Financial implications

The topics in Table 2 would benefit from additional or expanded research despite the studies that have been conducted due to conflicting results, limitations of scope, or lack of integration with other topics.

1.1.4 Recommendations for Future Research

The ultimate challenge regarding benthic effects of OSW is to know how these projects impact the regional availability of fisheries species for harvest, which influences food security now and in the future. As the basis of the food web, benthic organisms are key forage species for crustaceans and demersal fish. Initial insights as to how OSWs impact food webs—and hence, carbon flow through the ocean—are available but not to the extent that they allow assessment of impacts on commercial and recreational fish species at the population level.

Thus, future focus should be on (1) in situ and ex situ collection of data on carbon flow in the vicinity of wind turbines (e.g., suspension feeding rates, carbon deposition, and local food web dynamics) and (2) the integration of these data into carbon flow models accounting for the spatiotemporal dynamics of selected fish species. The latter should comprise both direct impacts (i.e., food web dynamics, including daily to seasonal dynamics and migrations) and indirect impacts (i.e., associated with impacts on plankton). These findings will inform the extent to which OSW structures enhance or degrade habitat suitability for managed species and why. Note that while disentangling whether an effect is “meaningful” necessitates a focus on spatial scales at which ecosystems function (e.g., relevance to stocks), substantial knowledge gaps and uncertainty remain at regional scales (Figure 1).

In terms of near-term priorities, “baseline” benthic conditions should be captured prior to construction, and the effects on the response variables should be monitored for a longer period of time (e.g., +10 years), as effects will not likely be detectable until after several years of presence of the wind turbines. Response variables should be selected based on their relevance to addressing the effects on food web dynamics, and hence, stock dynamics of selected commercial and recreational species.

The greatest barriers to addressing these recommendations are likely financial because addressing these questions will involve long-temporal and large-spatial scale monitoring alongside detailed targeted local (near- and mid-field) surveys and experiments. These financial barriers can most easily be breached by integrating monitoring and research programs over large geographic scales (e.g., U.S. New England and Mid-Atlantic coasts), centralizing the bulk of financial resources to be invested in region-wide prioritized research and monitoring.

In some cases, innovative methods (see Section 4.3) may be required to address knowledge gaps. For instance, there is a need for non-invasive measurement techniques that can scale across distances. For appropriate methodologies, see Barbut et al. 2020; Harrison and Rousseau 2020; Lindseth and Lobel 2018; Mavraki et al. 2020a; Mavraki et al. 2020b; Mavraki et al. 2021a; Raoux et al. 2017; Reubens et al. 2014; and Stoeckle et al. 2020.

1.1.5 Commercial and Recreational Fishing Communities Perspective

The construction of wind farms will add turbine structures, scour protection, and cable protection to the benthic environment, causing the physical and ecological effects described above. Commercial and recreational fishermen are concerned about how these benthic changes will affect their catches and about the uncertainty around these effects. Specific issues fishermen have expressed concerns about that may directly or indirectly affect harvest include concentrating fish and fishing pressure, introduction of invasive and nonindigenous species, contaminants introduced by construction materials, structure and debris making the bottom untowable, and reducing or eliminating the ability of vessels to operate within an array (ten Brink and Dalton 2018; Haggett et al. 2020; Smythe et al. 2021). Cables and their associated protection methods pose a serious risk to the fishing industry for fear of their mobile bottom-tending gear getting caught on them. This could result in lost gear and/or a higher risk for loss of life. There is also concern about the inability to accurately assess stocks due to the habitat complexity introduced by the wind farms (lack of calibrated sampling tools, sampling strategies, and the complexity of introduced gradients).

A major concern of fishermen is the vast scale at which wind farm construction is occurring in the Northeast U.S. There is no upper limit to the area that could be leased for development, there is no minimum distance between projects such that large contiguous areas are planned to be developed, the size of turbines is continually increasing, and the potential spatial arrangements of turbines and cables are almost limitless. This means the amount of habitat ultimately being shifted from one form to another is unknown. Recreational fishermen have expressed concern that creating these complex habitat “reefs” offshore may prevent target species from moving closer inshore, thus keeping them out of reach of shoreside and small boat private anglers. Other recreational fishermen see the increase in artificial reef habitats as an opportunity if fish aggregate around the turbines and enhance their ability to target species. As with any artificial reef, it is unclear whether turbine foundations will just aggregate fish or actually add to productivity by adding food sources and increasing the flow of carbon.

In the current fisheries management process, fishermen cannot go out and fish for anything available; they are restricted to species they can catch via limited entry permit systems, gear and vessel restrictions, and other means. This limits their flexibility to respond to change if their target species is displaced by another species they have no authorization to catch. Even if increases in productivity of specific species occurred, these changes do not benefit all fishermen. This shift in available catch is also occurring with range shifts due to ocean temperature increases (Nye et al. 2009).

Changes in sediment characteristics within and around wind farms can alter ecological factors that may, in turn, affect commercial fish populations and their dependent fisheries. For example, a shift toward increased hard substrate (introduced as scour protection materials, turbines) might lead to increased concentrations of black sea bass resulting in a fixed-gear pot fishery that displaces a mobile gear clam dredge fishery. The alteration of the surrounding seafloor can impact fisheries resources directly (e.g., secondary production because of altered food availability) and indirectly (e.g., through an altered habitat suitability for critical life history stages such as spawners, settling larvae, or juveniles; Gill et al. 2020; Mavraki et al. 2021a; Reubens et al. 2013; Stenberg et al. 2015; van Berkel et al. 2020). Some production will remain local to the turbine; other production may be exported by localized temporal predation and migration.

Epifauna on wind turbine foundations can potentially filter eggs and larvae out of the water column, causing mortality at these life stages. There are also concerns that benthic organisms such as larval sea scallops may settle onto vertical artificial reef structures, which will not provide suitable habitat as they grow. Hard structure may benefit some species which compete for space (e.g., lobster) or use hard structures as habitat (e.g., mussels) but may displace others that require sandy or soft bottom habitat, such as benthic shellfish like surfclams (*Spisula solidissima*) that bury into the bottom and spawning cod that prefer sandy open spaces free of acoustic disturbance (Dean et al. 2012). Introduction of hard structures and noise could go so far as to undermine cod spawning protection measures developed by the regional fishery management councils designed to minimize interruptions to spawning activities (NEFMC 2015, 2016).

In summation, it is easier to predict first-order changes in physical substrate than it is to predict second-order changes in the resulting biological populations that ultimately impact fishermen. Uncertainty can drive fear of change. One way to mitigate the impact is to start developing strategies for gear coexistence within and around wind farms, since these may require management actions which can take time to develop. Another approach is to develop new fisheries or fishing methods so fishermen have alternatives if the need arises. This could include developing new fisheries in other areas as wind farms displace or impact existing fisheries. Fisheries should consider targeting new stocks outside of the wind energy areas but funded by wind production. These changes will not be simple or straightforward to implement and may require changes to fishery management systems from both biological and harvest control perspectives. Many concerns of fishermen could be assuaged by ensuring that there is certainty of funding available to the fishing industry to pursue these potential mitigation measures.

1.1.6 Overall Summary of Findings

U.S. offshore wind energy facilities are poised to significantly increase within the coming decade, starting with the Northeast region. Observations and studies from other U.S. offshore structures (e.g., oil and gas platforms) and from other global OSW examples give evidence of the ensuing interactions with respect to benthic sediments, habitat suitability, and food web connectivity. These interactions have some predictable as well as lesser-known potential effects on commercially important fisheries species, habitat, and the way these resources are managed.

Replacement of soft benthic sediments on and around OSW foundations with hard structures provides habitat for a wide range of intertidal and subtidal flora and fauna. These artificial reefs have the potential to support fish that are attracted to these structures. However, trophic connectivity among important fish species and the organisms that colonize these artificial habitats is not well understood. Our ability to predict these interactions becomes less reliable when factoring in multiple species at the population level, across broad spatial scales, and over long-term temporal extents. The uncertainty associated with cumulative effects across large spatial and time scales and secondary effects are a deep concern for commercial and recreational fisheries. This chapter summarizes what we do know about OSW structure and benthic habitat interactions with fisheries but also identifies current knowledge gaps and direction for future studies.

1.2 Physical Habitat Modification

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1.2.1 Introduction

Physical habitat modifications occur in the marine environment as a result of offshore wind energy development. These include modifications arising from multiple phases of a development (pre-construction, construction, operation and maintenance, decommissioning). Physical habitat modifications under consideration here include the potential effects of (1) sound and vibration, (2) electromagnetic fields, (3) changes in the thermal habitat, and (4) secondary gear entanglement.

These physical habitat modifications are considered within the context of fisheries science and management as relevant to potential receptive fishery species. However, receptor species' vulnerability to these physical changes will be addressed in Section 1.4, "Ecosystem Synthesis" under the receptor subheadings (highly migratory species, pelagic species, small pelagic, demersal, and shellfish). Here, the focus is on the specifics of the physical changes to the habitat which may be ecologically important.

Note that changes in sedimentation and the addition of novel hard substrate are addressed in Section 1.1, "Benthic Habitat Modification" and physical oceanographic processes are considered in Section 1.3, "Interactions of Offshore Wind on Oceanographic Processes" and are not addressed here.

1.2.1.1 Environmental Acoustics

Development of OSW will introduce different types of sound into the marine environment depending on the phase. Prior to construction, high-resolution geophysical surveys (HRG) use sparkers, sub-bottom profilers, and other active acoustic sources to resolve features of the sea bottom. Several of these sources (e.g., multibeam echosounders, side-scan sonars, and some sub-bottom profilers; Crocker and Fratanonio 2016) use frequencies above the hearing range of most fish and invertebrates (~2 kHz; Popper and Hawkins 2018), so based on frequency alone, they are unlikely to result in significant impacts to most fish. Some of the lower-frequency sources (e.g., boomers, bubble guns, and sparkers) may be detectable by fish but would only be disturbing over very small distances. For example, if one assumes a 150 dB re: 1 μPa RMS threshold for behavioral disturbance of fishes, sounds with source levels of 190 dB re: 1 μPa would fall below this threshold at a distance of approximately 100 m from the source due to propagation loss (spherical spreading). This means that the most commonly-used, lowest-powered sparkers, boomers, and bubble guns would not result in behavioral disturbance beyond approximately 100 m (Crocker and Fratantonio 2016). In addition, it is important to consider the beamwidth and duty cycle of the source; most HRG sources are typically "on" for short periods with silence in between. This means that only a handful of "pings" emitted from a moving vessel towing an active acoustic source would reach a fish aggregation below or at received levels sufficient to elicit a behavioral response. On the other hand, a stationary source like pile driving can generate high sound levels with some acoustic energy propagating several kilometers away from the pile installation site. Throughout the life of the project and over certain transit routes, vessel noise will be introduced due to the transit of service vessels. Additionally, continuous low-level sounds may be generated by each turbine during normal operations.

When considering the way OSW development introduces sound and vibration into the marine environment, it is essential to first define the words "sound" and "vibration." A sound is created by the vibration of an object within its medium, such as a pile being driven into the substrate. This movement generates a propagating wave that is composed of both pressure and particle motion. As this wave moves through the medium (e.g., sediment, water, or air), the particles undergo tiny back-and-forth movements, or oscillation, in the axis of propagation, which is called "particle motion" (Popper and Hawkins 2018). The particles themselves do not travel with the wave, but their oscillation creates regions of high pressure (compression) and low pressure (rarefaction). Therefore, in a broad sense, "sound" is the mechanical wave produced by a vibrating object which contains both pressure and particle motion components. It is important to define these terms because some marine species are sensitive to acoustic pressure (e.g., mammals and some fishes), while others are only sensitive to particle motion (invertebrates and most fishes). Sound can propagate in the water column and in the substrate. Within the substrate, particle motion can be in the direction of propagation (as a compressional wave) and perpendicular to the propagation direction (as a shear wave). It is likely that some of the acoustic energy that initially travels through the substrate may re-enter the water column at some distance from the sound source.

1.2.1.2 Electromagnetic Interactions

Electromagnetic fields (EMFs) are emitted from subsea power cables transferring the energy from offshore wind turbines to transmission grids onshore and may disrupt natural electromagnetic cues that receptive animals rely on for ecologically important information (Gill et al. 2014). Potential impacts of EMF on biological species are reviewed in Section 1.4, "Ecosystem synthesis." Here, we first consider the position of the cables in the marine environment and then review the state of the knowledge regarding EMF emissions.

1.2.1.2.1 Cable Type and Spatial Configurations in the Marine Environment

Within OSW developments, inter-array cables occur between turbines, and higher capacity export cables transfer energy to shore. Cables may be low, medium, or high voltage (LV, MV, HV) and are either alternating current (AC, time altering state) or direct current (DC, static). In larger wind farms, inter-array cables are typically connected to a substation and then to a higher capacity export cable. Presently, high voltage alternative current (HVAC) cables are the most common type of cable in use by the OSW industry; however, high voltage direct current (HVDC) cables are in use and are expected to become more common as the industry progresses further offshore (Soares-Ramos et al. 2020). This is largely due to the higher capacity of HVDC cables and their ability to minimize losses over longer distances. Cables and associated EMF emissions extend beyond the OSW array, connecting the wind farm to the onshore power grid. The EMFs must be considered in the context of the horizontal and vertical spatial configurations of cables within the marine environment (Figure 2; Hutchison et al. 2020a).

1.2.1.2.2 Electromagnetic Fields – Components of Emissions

Regardless of the cable's position in the marine environment and the cable type (i.e., AC, DC), the transmission of energy through the cable generates an electric and magnetic field (Gill et al. 2014). When perfectly grounded, the cable sheathing contains the electric field; however, the magnetic field is emitted into the marine environment (Gill et al. 2012). In the AC scenario, the time altering state of the magnetic field induces an electric field within the marine environment (also considered a direct emission). Magnetic fields pass through the surrounding material unaltered (assuming non-magnetic materials); however, the propagation of the induced electric field is dependent on the conductivity of the environment (i.e., more saline water will propagate further; CMACS 2003; Gill et al. 2012). Furthermore, in both the AC and DC scenarios, a motionally induced electric field arises from a water body or animal moving through the magnetic field (Gill et al. 2014). Species that are magneto- and/or electro-receptive may be directly or indirectly responsive to the different components of the EMF (e.g., emitted magnetic field, induced electric field, motionally induced electric field; Formicki et al. 2019; Newton et al. 2019; Hutchison et al. 2020a).

1.2.1.3 Heat Production

Thermal radiation occurs as an emission from subsea power cables and has the potential to increase the temperature of the surrounding environment (Boehlert and Gill 2010; Taormina et al. 2018). Concerns have been raised that the heat produced may affect the local thermal habitat and, subsequently, the species present. Since the thermal radiation occurs from the cables, the heat is associated with the spatial configurations of the cables (Figure 2).

Thermal emissions from cables are associated with resistive losses, which are more prominent with AC cables than DC cables at similar transmission rates (Worzyk 2009). Thermal emissions are dependent on the cable properties and the power levels being transmitted, and therefore will be temporally variable (Meißner et al. 2006). Heat may also occur due to cable faults and overheating (Det Norske Veritas AS 2016).

1.2.1.4 Marine Entanglement Risk

Offshore wind turbine foundations and floating turbine moorings may present an entanglement risk (primary entanglement) for marine megafauna, such as sharks, sea turtles, and marine mammals. When moorings and turbine foundations become entangled with derelict fishing gear, that gear becomes a secondary entanglement risk to those species, as well as other fishes, invertebrates, and diving birds. Bycatch associated with secondary entanglement may result in direct impacts to fisheries through loss of individuals of a managed species. Indirect impacts could occur if a protected species becomes entangled. This secondary entanglement of protected species could result in loss of fishing opportunities in the area if management measures (e.g., area-based fishing prohibitions) are implemented to avoid additional gear loss, to minimize additional risk of entanglement for those species (Barnette 2017).

1.2.2 Description of the State of Our Knowledge and Understanding on this Topic with Regard to Interactions with Offshore Wind

1.2.2.1 Sound and Vibration

1.2.2.1.1 Pile Driving

Impact pile driving employs a hammer to strike the pile head and force the pile into the sediment. For OSW, the typical hammer strike rate is approximately 30 strikes/minute. Typically, force is applied over a period of less than 20 milliseconds, but the pile can generate sound for upwards of 0.5 seconds (s). Pile-driving noise is characterized as impulsive because of its high peak pressure, short duration, and rapid onset time. Underwater noise levels generated during pile driving depend on the pile material and size, characteristics of the substrate, penetration of the pile in the seabed, hammer energy used, and water depth. The propagation of pile-driving sounds depends on the sound speed in the water column (influenced by temperature, salinity, and depth), the bathymetry, and the composition of sediments in the seabed, and will therefore vary between sites. Due to variation in these features, sounds may not radiate symmetrically outward from a pile. In addition, if piles are driven at a slant angle, sound levels measured in different azimuthal directions are expected to vary.

The Bureau of Ocean Energy Managemet (BOEM) has invested in the Realtime Opportunity for Development of Environmental Observations (RODEO) efforts to measure sound installation and operation of BIWF and Coastal Virginia Offshore Wind (CVOW). Similar studies have been completed at multiple facilities in Europe. Measurements of sounds from impact driving the 7.8 m diameter piles at CVOW were conducted between 750 m and 30 km from the monopiles. Results showed that the maximum broadband peak sound pressure level at 750 m from the pile was 190 dB re 1 µPa, and the maximum single strike sound exposure level was 170 dB re 1 µPa^2·s. Most of the acoustic energy occurred between 30 and 300 Hz (HDR 2020). In addition to acoustic pressure, in-water particle motion was measured at 1.5 km from the source. The mean particle velocities (vertical and radial) from the geophone array were 0.16 mm/s (104 dB re 1 NM/s) and 0.48 mm/s (114 dB re 1 NM/s), respectively (HDR 2020b). The CVOW piles are smaller than the 10-15 m diameter piles planned to be installed in future projects, but there has never been driving of piles this large, so the CVOW pilot project is the best available data.

Various noise abatement technologies—such as bubble curtains, arrays of Helmholtz resonators, or segmented nets made of rubber or foam—may be employed to reduce noise from impact pile driving. Measurements from European wind farms have shown that a single noise abatement system can reduce broadband sound levels by 10-15 dB, while using 2 systems together can reduce sound levels up to 20 dB (Bellman et al. 2020). Based on measurements from CVOW, double Big Bubble Curtains (dBBC) are shown to be most effective for frequencies above 200 Hz. Approximate noise reduction is 3-5 dB below 200 Hz and 8-20 dB above 200 Hz, depending on the frequency and the characteristics of the bubble curtain (HDR 2020b).

Vibratory hammers may be used as an alternative to impact pile driving. The vibratory hammer continuously exerts vertical vibrations into the pile, which causes the sediment surrounding the pile to liquefy, allowing the pile to penetrate the substrate. Noise from vibratory pile driving is typically below 2 kHz, and measured sound levels 10 m from a 1.8 m diameter steel pile, for example, were 185 dB re 1 µPa RMS (Matuschek and Betke 2009). The turbine monopiles planned to be installed are 5-10 times larger than this, and vibratory pile driving would be louder than this example; even so, this type of driving is expected to be less energetic than impact pile driving, and because the sound is non-impulsive, it may be less detrimental to sealife.

1.2.2.1.2 Vessel Noise

Large vessels (>= 100 m) will be needed for construction and cable-laying, and smaller vessels (25-60 m) will be used to transport crew and other equipment. During transit, vessels emit continuous noise from propeller cavitation and machinery inside the hull. During construction, dynamic positioning systems may be used to keep machinery in place. Large vessels typically have source levels ranging from 175-185 dB re 1 µPa, with energy up to frequencies of 10 kHz but with dominant energy below 100 Hz (Jiminez-Arranz et al. 2020); when dynamic positioning systems are active, dominant energy is between 100-1000 Hz. Smaller boats are typically quieter (<165 dB re 1 µPa) and have more energy in the higher frequencies, potentially up to 150 kHz (Jiminez-Arranz et al. 2020; Hermannsen et al. 2019). Vessel noise is generally related to vessel speed (McKenna et al. 2013); a secondary benefit of vessel speed restrictions may be a reduction in radiated noise. While most studies of vessel noise have focused on acoustic pressure, it may not be necessary to quantify particle motion because it is unlikely that marine species will come within 10s of meters of a transiting vessel, where particle motion is the dominant cue.

1.2.2.1.3 Operational Noise

Field measurements during OSW operations indicate that sound levels are much lower than during construction; on average, broadband RMS levels measured 50 m from a BIWF turbine were 119 dB re 1 µPa, and tonal peaks were observed at 30, 60, 70, and 120 Hz (Elliott et al. 2019). The BIWF turbines are 6 megawatts (MWs), direct-drive, 4-legged jacket-pile structures. The maximum particle velocity during operations (as measured 100 m from the turbine, just above the seabed) in winter was 40 dB re 1 NM/sec, while in summer it was closer to 90 dB re 1 NM/sec (Elliott et al. 2019). Overall, results from this study indicate that there is a correlation between underwater sound levels and increasing wind speed, but this is not clearly influenced by turbine machinery; rather, it may be the natural effects that wind and sea state have on underwater sound (Elliott et al. 2019; Urick 1983).

A recent compilation of operational noise from several wind farms, with turbines up to 6.15 MW in size, showed that operational noise generally attenuates rapidly with distance from the turbines (falling below normal ocean ambient noise within ~1 km from the source), and the combined noise levels from multiple turbines is lower or comparable to that generated by a small cargo ship (Tougaard et al. 2020). Larger turbines do produce higher levels of operational noise, and the least squares fit of that data set would predict that a sound pressure level measured 100 m from a hypothetical 15 MW turbine in operation in 10 m/s (19 kt or 22 mph) wind would be 125 dB re 1 µPa. However, all the turbines in that data set except for BIWF were operated with gear boxes of various designs rather than the new use of direct drive technology. Stober and Thomsen (2021) noted that BIWF, using direct drive, was approximately 10 dB quieter than other equivalently sized jacket pile turbines. There is also reason to believe, based on the Tougaard et al. (2020) data set, that operational noise from jacket piles could be louder than from monopiles due to there being more surface area for the foundation to interact with the water, however the paper does point out that received level differences among different pile types could be confounded by differences in water depth and turbine size. In any case, additional data is needed to fully understand the effects of size, foundation type, and drive type on the amount of sound produced during turbine operation.

1.2.2.2 Electromagnetic Fields from Subsea Power Cables

Models are most frequently used to understand EMF emissions from cables and less frequently EMFs are measured in situ (CMACS 2003; Normandeau Exponent et al. 2011). Models use the cable properties (type, core configuration, layers of shielding, amperage, voltage [V]) and ideally should incorporate the 3-dimensional (3D) local geomagnetic field to determine expected emissions for the modeled scenario (i.e., specific burial depth, power level; Kavet et al. 2016; Hutchison et al. 2020b). However, models are often based on single point scenarios and omit the interaction with the local geomagnetic field. There are no regulatory requirements to model EMF; however, the Construction and Operations Plan must include an evaluation of activities that result in changes to ambient EMF, including testing, operations, and decommissioning (BOEM 2020). A report must include the type, duration, and intensity of EMF-producing activities and their potential impacts on biological resources.

Recent advances in technology have facilitated the measurement of EMFs in situ which now allows cable EMFs to be characterized in the marine environment (Table 3). This is particularly important since measurements of EMFs from cables in the marine environment help to validate and update models to be more representative. There are only a few examples of EMFs being measured in the marine environment, and the methods used are varied. Most recent studies which measured EMFs in situ have focused on domestic or regional/state transmission cables (Dhanak et al. 2015; Kavet et al. 2016; Sherwood et al. 2016; Hutchison et al. 2020b). However, EMF measurements have also been taken from OSW cables. These include a preliminary trial of a bespoke instrument—completed at Belgian OSW farms—and once the method was more established, the EMF from the sea2shore cable of BIWF was measured (Thomsen et al. 2015; Hutchison et al. 2018; Table 3).

Overall measurements have indicated good agreement of the modeled DC magnetic fields when variable parameters such as power level, burial depth (i.e., distance from source), twist of the cable, and 3D interaction with the geomagnetic field are taken into consideration (Kavet et al. 2016; Hutchison et al. 2020b). However, measurements of DC cable EMFs identified AC fields (magnetic and electric); these are not accounted for in present models, and AC fields occurred at broader spatial scales (Hutchison et al. 2020b; Table 3). Measurements also provide useful information about other natural or anthropogenic sources of EMFs that interact in the marine environment (Kavet et al. 2016; Hutchison et al. 2020b). Although some AC cables offer a degree of self-cancelation of the magnetic field, they still emit measurable EMFs (Hutchison et al. 2018).

There are presently no thresholds indicating acceptable or unacceptable levels of EMF emissions in the marine environment (Hutchison et al. 2020a). Cable protections which increase the distance from source, thereby providing a physical barrier and reducing the maximum intensity that animals are exposed to, are often promoted as a mitigative measure. However, burial does not eliminate the EMF, and the burial depth is a variable entity, even along a single cable route (Hutchison et al. 2021). It is possible that a lower intensity brings emissions into a more perceivable range to the receptive species (Hutchison et al. 2020a), and some cable protections provide habitats to species which may inadvertently increase exposure durations and reduce distances to the source (Taormina et al. 2020; Hutchison et al. 2021). While improving the present understanding of EMFs emitted from OSW subsea cables, it is important to take the vantage point of the receptive species (Figure 3; Hutchison et al. 2020a). This approach requires consideration of the species' sensory ecology, life stage, and, importantly, their movement ecology to fully understand the encounter with the cable EMF, as well as the characteristics that define the EMF in the marine environment.

1.2.2.3 Thermal Radiation

The maximal operating conductor temperature (i.e., cable core) for HV cables is 90 °C which can theoretically translate to cable surface temperatures of 70 °C (Hughes et al. 2015; Emeana et al. 2016). Thermal emissions from cables are strongest close to the cable and dissipate with distance; however, the rate of dissipation is dependent on the surrounding medium (e.g., permeability of sediment or velocity of seawater in the marine environment; Hughes et al. 2015; Emeana et al. 2016; Duraisamy et al. 2020; Zhang et al. 2020). Heat dissipation is preferential and a consideration in cable protection design (e.g., J-tubes and I-tubes are designed to allow heat dissipation) and is also a reason why cables are not buried more deeply (Det Norske Veritas AS 2016). Retaining heat in the external medium is not desired since it increases the cable core temperature, which has a negative influence on the cable operation (Zhang et al. 2020).

Models are typically used to understand heat emissions from cables, often from an engineering perspective (Hughes et al. 2015; Duraisamy et al. 2020; Zhang et al. 2020). Some thermal characterizations have also occurred in laboratory settings simulating heat emissions and the permeability of shelf sediments (Emeana et al. 2016). Models specifically reported for OSW cables are typically varied in their parameters and therefore are difficult to compare (see Meißner et al. 2006). Field measurements are rare; however, Meißner et al. (2006) report on efforts to measure the heat signature of low-capacity cables at the Nysted OSW (Denmark, Baltic Sea) which had 72 turbines (2.3 MW each, 9 turbines per inter-array cable). Dual titanium poles equipped with 16 thermosensors were placed close to the buried 33kV inter-array and 132kV export power cables. The poles were positioned vertically with the closest sensor 25 cm directly above the cable and the second pole 30 cm to the side; each pole had multiple sensors spaced at 10 cm intervals to obtain a range of distances from the cable. Over the course of the 6-month study, the temperature emitted was greatest for the higher capacity cable, and at closest range, the maximum difference between the cable and control site was reported as 2.5 K (2.5 °C) with a mean difference of 0.8 K (0.8 °C). For context, the maximal heat difference at 10 cm below the seabed was 0.3 K (0.3 °C) and at 20 cm was 1.4 K (1.4 °C). Overall, the cable temperature was more variable than the control site and was positively correlated with power production and water temperature.

There are no specific regulations for thermal emissions from cables in the U.K.; however, German regulations require that the increase in temperature should not exceed 2 K (2 °C; Det Norske Veritas AS 2016). Potential effects on the surrounding sediment habitat where heat emissions occur may include changes of physico-chemical conditions, such as the alteration of redox profiles (oxygen, sulfide), nutrient profiles, bacterial activity, and distribution of infauna (Meißner et al. 2006; Emeana et al. 2016; Taormina et al. 2018). However, these aspects cannot be considered without better characterization of heat signatures (intensity and spatial extent) around OSW cables based on the cable characteristics and surrounding medium (e.g., permeability of sediment type, water velocity).

1.2.2.4 Secondary Gear Entanglement

Little research has been conducted on impacts of secondary gear entanglement on marine resources. Harnois et al. (2015) notes the difficulty in detecting entanglements associated with offshore structures due to the typically remote locations of the occurrences. Modeling and observational studies have quantified loss of organisms to derelict gear (Good et al. 2010), drift patterns of derelict gear (Wilcox et al. 2013), and entanglements of protected species with fixed fishing gear (Howle et al. 2018). BOEM is currently funding a modeling study to examine impacts of derelict fishing gear associated with offshore floating wind turbine mooring systems on whales and leatherback sea turtles (*Dermochelys coriacea*; BOEM 2021c).

Benjamins et al. (2014) conducted a risk assessment for potential entanglement of marine megafauna associated with moorings of floating marine renewable energy projects and identified secondary gear entanglement as a risk to many marine species due to the potential for increased bycatch rates from entangled derelict gear.

1.2.3 Major Knowledge Gaps and Future Research

A summary of major knowledge gaps and future research can be found in Table 4.

1.2.4 Characterization of the Perspectives of Commercial and Recreational Fishing Communities

The commercial fishing industry is concerned about sound impacts on fishery stocks during wind farm construction and throughout operation. Impulsive sounds produced by pile driving during construction would be the most impactful to marine species and could result in their avoidance of the construction area. Fishermen are highly concerned that fish near the sites may be injured or killed from percussive injury or may continue to avoid the area for a time after construction is completed. Species with short life cycles (e.g., squid) that are also highly sensitive to noise-induced mortality, are considered high risk for long-term impacts on populations. A recent study on the interactions of pile-driving noise on longfin squid (*Doryteuthis pealeii*) detected slight effects on startle response and feeding but no appreciable effects on spawning or reproduction (Stanley et al. 2021). Atlantic cod use sound during spawning events (Rowe and Hutchings 2006), so if pile driving co-occurs with spawning (i.e., both occur at night, in the same location), it is possible that pile-driving noise could interfere with this behavior. Operational noise could also mask biologically-important cues, such as communication during spawning activities. Additional research regarding impact producing factors on other marine species are provided in Section 1d. Models estimating distance that operational noise of OSW turbines can travel suggest low overall noise levels, comparable to commercial ships, but the true level of noise is difficult to model given its dependence on local conditions, other noise sources, and turbine size (Tougaard et al. 2020). Each section of this technical memorandum discusses the current literature regarding the impacts of noise on various species. Potential mitigation strategies for noise impacts could include environmental protection measures, such as bubble curtains to attenuate noise, soft starts for pile driving to induce fish stocks to leave the area before injury could occur, and time of year restrictions on pile driving to avoid impacts to spawning stocks. However, these don’t address the impacts that cumulative operational noise of the turbines needed to meet OSW production goals could have on marine species if this scale of development is found to be louder than expected. Any mortality or change in distribution of fish will likely negatively impact the fishing industry, which depends on healthy fish stocks harvested sustainably.

Fishermen are especially concerned about the ability of NOAA Fisheries and state agencies to continue their long-term survey efforts because the majority of stock assessments use, or in some cases completely rely on, these data. If fish shift to the introduced habitat created by the turbines and associated scour protection, they may be harder to survey if traditional methods cannot be used because of an increased risk to vessel and crew safety. This complication is expected to increase uncertainty in assessments, which typically results in lower (i.e., more conservative) quotas to mitigate risk to populations. However, in this case, that uncertainty could result directly from an underestimation of fish species caused by the inability to effectively sample. This would have socioeconomic impacts on both commercial and recreational fisheries.

Any changes in fish behavior caused by EMF will impact the fishing industry. It is unclear what impact EMFs from subsea cables will have on fishery species at various life stages. The lack of knowledge on the intensities of EMF anticipated from OSW cables makes it difficult to draw conclusions based on the studies to date. Additionally, comparability of responses to AC and DC type EMFs are not clear. Species such as skates and rays, as well as sturgeon, appear to be most receptive to EMF and therefore have the greatest potential for impacts, but fishermen are also concerned about potential impacts on inshore/offshore migration of demersal species, such as summer flounder (*Paralichthys dentatus*), and behavioral and physiological effects on invertebrate species. It would be beneficial to provide increased clarity to the fishing industry on the EMF emissions and if population-level effects and impacts are likely. Any impacts of EMF to the availability of species may result in negative socioeconomic impacts to the fishing industry if they cannot safely harvest species attracted to turbines, cables, and the associated scour/mattress protection methods due to the risk posed by gear hanging up.

Little research has been conducted on impacts of export and inter-array cables to the thermal environment. Although thermal impacts would likely be minimized with buried cables or cables covered with concrete mattresses to potentially only a few feet, the cables extend for many miles. Fishermen have noted some attraction by invertebrates, such as lobsters, to cables, but it is unknown whether the attraction is due to EMF, warmth produced by the cables, combined effects, or other factors. If such an attraction exists, it could concentrate resources along a cable route, which could expose the population to increased harvest or natural predation.

Fishermen have been impacted by area closures for protection of North Atlantic Right Whales as any risk to endangered species under the Endangered Species Act (ESA) must be addressed in the biological opinion for fishing. The fishing industry is also highly concerned that the noise from turbines will negatively impact North Atlantic Right Whales, requiring mitigation measures directed at the fishing industry and not OSW projects as required by the Marine Mammal Protection Act and Atlantic Large Whale Take Reduction Plan.

The introduction of new hard habitat may give other species a competitive advantage, especially concerning species restricted in their range by the lack of preferred habitat that may no longer be limiting. In the Northeast region of the U.S., the waters have been warming, and some Mid-Atlantic (typically warmer waters) species are becoming more frequently found in New England (typically cooler) waters. U.S. fisheries management practices require fishermen to hold current permits to harvest regulated fish species, meaning fishermen are restricted in which species they can harvest. If more Mid-Atlantic species are able to expand their habitat into New England waters, New England fishermen can’t legally catch them. These Mid-Atlantic species may also outcompete native species, negatively affecting those existing species and the region’s diversity, especially concerning for any species in rebuilding plans.

1.2.5 Overall Summary of Findings

Construction and operational noise and vibration, EMF and thermal radiation from cables, and secondary gear entanglement associated with OSW development will affect the marine environment to varying degrees. In general, propagation or emission rates for these stressors decrease with distance from the source but are intrinsically dependent on the marine environmental conditions (such as temperature, salinity, and sediment/substrate type). The majority of studies to date have used modeling to investigate how these stressors will propagate around turbines and cables. Future work must employ additional in situ measurements to better understand spatiotemporal variability in different conditions, such as substrate type for pile-driving foundations or EMF and thermal radiation along cable routes.

Other stressors will be dependent on conditions around wind energy areas once they are constructed. These include sound from vessel traffic servicing offshore structures, which add noise to the marine soundscape, or secondary gear entanglement on various mooring and foundations, which may pose a threat to a number of marine species.

Several mitigation measures are known to minimize effects from stressors. For example, bubble (or double-bubble) curtains have shown a reduction in sound propagation from pile driving.

Mitigation for EMFs and thermal radiation from cables should be based on evidence that mitigation is needed. At present, cables are buried for their own protection, where possible, and that increases the distance from the EMF and heat source for many receptive species. The commercial fishing sector strongly encourages the use of efficient environmental protection measures to minimize impacts.

Biological species may be sensitive to sound and vibrations, EMF, and thermal radiation in the marine environment to varying degrees (see section 1d for how species may be impacted). Therefore, it is important to improve the collective understanding of stressors associated with OSW development. Improved in situ measurements, realistic modeling, and standardization of data collection and reporting are necessary first steps in understanding how these stressors will impact commercial and recreational fish stocks.

1.2.6 Acknowledgements

We would like to acknowledge Shane Guan and Samuel Denes from BOEM for their contributions to this section.

1.3 Interactions of Offshore Wind on Oceanographic Processes

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1.3.1 Introduction

Oceanographic processes (e.g., changes in temperature or salinity) can significantly impact ecological processes, as they influence the available nutrients and thermal habitat that may directly or indirectly impact important fishery species. Observational studies in Europe and numerical modeling studies indicate that impacts resulting from offshore wind turbines are expected to occur throughout the water column; however, the nature, magnitude, and extent of impacts in the Mid-Atlantic Bight are not well known. In this section, we provide a brief synopsis of the current literature with a focus on the potential interactions between offshore wind turbines and ocean mixing and scour, followed by identification of major (but not necessarily comprehensive) gaps in our knowledge, some recommendations for future research, and some perspectives from the fishing industry.

1.3.2 Synthesis of Existing Knowledge

A recent review article (Miles et al. 2021) has highlighted the growing body of research on the specific processes that describe the interaction between offshore wind turbines and underlying ocean conditions at scales ranging from individual turbines to entire wind farms. These studies generally fall into 3 categories, including (1) wind extraction reducing surface wind stress and altering water column turbulence, (2) wind farm wake-driven divergence and convergence driving upwelling and downwelling, and (3) turbulence generated by turbine foundations. All of these categories of impact could influence ocean mixing and, in turn, stratification that is a key characteristic of the U.S. Northeast Shelf (NES) and the Cold Pool, a core seasonal feature of the Mid-Atlantic subregion. The net impact of OSWs on ocean stratification is dependent on the relative contribution of these 3 processes and potentially other currently unknown processes in a particular wind farm facility. While not addressed within this synthesis, the potential interactions of offshore wind with the water column and ecosystems of the Mid-Atlantic and the NES should be placed in the context of climate change. For example, a recent estimate of long-term warming trends in the Cold Pool are 0.029 ºC year-1 (Friedland et al. 2022) with potentially accelerated warming in the overlying surface ocean over the past decade (Forsyth et al. 2015). Changes in stratification over the Mid-Atlantic and NES are less understood but ultimately dependent on the warming trajectory of both surface and bottom waters, as well as changes in surface freshwater inputs.

1.3.2.1 Wind Speed Deficits

Both remote sensing and in situ observational studies have been carried out to investigate the extent of wind wakes in the offshore environment. For example, Christiansen and Hasager (2005) used satellite observations with synthetic aperture radar to observe offshore wind wake effects from existing facilities that extended 2-20 km (1.2-12.4 miles) depending on ambient wind speed, direction, degree of atmospheric stability, and the number of turbines within a facility. A study using aircraft-based scanning lidar found that during stable atmospheric conditions, these offshore wakes can be longer than 70 km (43.5 miles; Platis et al. 2018). Studies such as these have provided snapshots of potential impacts; however, comprehensive long-duration observations of these features remain elusive. Modeling studies (Afsharian and Taylor 2019; Christiansen et al. 2022) have been informative on longer timescales, demonstrating reductions in wind speeds in the lee of farms leading to reductions in surface wind stress and upper ocean turbulence, resulting in more stable water columns at the simulated sites in Lake Erie and the North Sea, respectively.

1.3.2.2 Downstream Divergence and Convergence

A number of studies (Broström 2008; Ludwig 2015; Paskyabi and Fer 2012; Christiansen et al. 2022) have modeled the potential for upper ocean divergence (horizontal separation of surface water leading to upwelling of subsurface waters) and convergence (coming together of surface waters leading to downwelling) caused by wind speed reductions in the lee of large wind farms. Their model results indicate that reduced wind stress at the sea surface can drive horizontal velocity shears, which generate upwelling and downwelling cells that, in turn, alter water column structure. The earlier studies under a range of idealized conditions (Broströom 2008; Ludwig 2015; Paskyabi and Fer 2012) identified the effects of these convergence and divergence dipoles as leading to upwelling and downwelling of meters per day. The more recent modeling study by Christansen et al. (2022) using more realistic wind turbine parameterizations confirms the presence of these up- and downwelling dipoles; however, with variable winds, their impacts were less pronounced. While evidence of these features from modeling studies has been growing, they have not been directly observed, and thus require further investigation in field exercises.

Broadly, the effects of wind farm wakes on the upper ocean is highly dependent on atmospheric stability, wind speed, wind direction, and underlying oceanographic conditions. These characteristics are highly variable in time and space and add to additional uncertainties from specific wind farm layout and turbine size.

1.3.2.3 Horizontal Flow and Turbulence

Wind turbine foundations in a moving ocean can increase vertical mixing. These structures can force water downward on the upstream side of the monopile and return water upward on the downstream side (Cazenave et al. 2016). Tank and modeling tests, such as those conducted by Miles et al. (2017) and Cazenave et al. (2016), conclude that mean flows are reduced/disrupted immediately (within 10s of meters) downstream of a monopile foundation but return to background conditions within a distance proportional to the pile diameter. These results indicate disruptions for a horizontal distance anywhere between 3.5 to 50.0 pile diameters, depending on whether it is a current-only regime or a wave and current regime, with a width of 20 to 50 m (65.6 to 164.0 ft). These results from the North Sea study locations (Casenave et al. 2016) are sensitive to the speed and persistence of the background flow, with tidal velocities that regularly exceed 1 m/s (3.3 ft/s). It is important to note that mixing is proportional to the background flow speeds and daily tides in the North Sea region are fast (>1 m/s; >3.3 ft/s). In the U.S. Mid-Atlantic, tidal velocities are slow (<0.1 m/s; 0.33 ft/s) and tidal mixing is weak; however, tidal mixing is stronger on the Northeast U.S. Shelf, including Georges Bank, and into the Gulf of Maine (Garrett 1978). Additionally, both the Mid-Atlantic and NES can experience significant wind-driven currents from intermittent storm events in both the stratified summer (from tropical cyclones) and the fall (nor'easters). As a result, less mixing is expected on a day-to-day basis due to tide/turbine interactions in the U.S. Mid-Atlantic, but this region may experience enhanced mixing during storm events.

Several studies have estimated impacts of mixing by turbine foundations on local hydrography. Using models with realistic wind turbine layouts, Rennau et al. (2012) concluded that turbine-induced mixing was small (reducing bottom salinities locally at a maximum of 0.3 and altering exchange flow between the Arkona Sea and the broader Baltic Sea by 0.02 practical salinity unit An observational study by Floeter et al. (2017) identified a dome-shaped thermocline within a study area containing 80 turbines, as well as increased nutrient transport, uptake, and enhanced primary productivity. However, similar characteristics were identified in surveys prior to OSW, highlighting the challenge of disentangling natural variability and impacts from farm construction. Using parameterizations, Carpenter et al. (2016) investigated the impact of OSW on stratification in the North Sea. They concluded that the current level of buildout during the study period was not sufficient to impact stratification but would need to be re-examined if large-scale development was planned. Their study showed a large range in the persistence of stable stratification between 37 and 688 days depending on model parameters (e.g., stratification strength, drag coefficient estimates, pycnocline depth), with realistic stratification durations of 80 days, thus highlighting the need for more specific regionally focused studies and additional research on appropriate model parameterizations for particular sites. In contrast, using unstructured grid modeling, Cazenave et al. (2016) found broad areas up to 250 times the monopile diameter of disturbed stratification in the Irish Sea, with localized reductions in stratification strength of 5 to 15% in their modeling studies. These large uncertainties in regions of influence between and within studies suggest that more modeling and observational work is needed, particularly considering local Mid-Atlantic Bight and Northeast U.S. Shelf seasonal stratification and mixing processes.

1.3.2.4 Seasonal Stratification

Stratification can be essential for the survival of a species throughout its range by allowing for colder bottom temperatures to persist during summer months and thus maintaining thermal habitat for species (Miles et al. 2021). The research summarized in the Horizontal Flow, Mixing, and Turbulence subsection above indicates turbines can result in localized changes in vertical mixing, upwelling, and downwelling, depending on background hydrodynamics (Cazenave et al. 2016; Floeter et al. 2017). Carpenter et al. (2016) concluded that the overall impact on stratification is directly related to the scale of development. In their study, current wind farms (Bard and Global Tech) had limited impact on stratification in the North Sea; however, large-scale build out (nearly an order of magnitude larger than at the time of the study), where wind farms covered the majority of the stratified shelf, could have major impacts on stratification. Carpenter et al. (2016) highlights stratification residence times based on wind turbine mixing impacts. A few scenarios within the large build-out cases resulted in complete mixing at timescales less than the typical seasonal stratification duration for the region.

The Mid-Atlantic Cold Pool is a feature that develops each year from an annual stratification that maintains a layer of cold bottom water which forms over the mid- and outer-shelf from Georges Bank to near Cape Hatteras (Houghton et al. 1982). The stratification begins as temperatures warm in the spring and persists until the fall when mixing of the water column occurs. Success for a number of fisheries is dependent on this strong annual stratification (e.g., Atlantic surfclams, scallops, and ocean quahogs [*Arctica islandica*]). Existing studies have focused on the seasonally dependent physical mixing and stabilizing processes that lead to the formation, maintenance, and ultimate breakdown of the seasonal stratification and the Cold Pool (Chen and Curchitser 2020; Friedland et al. 2022). Additional research has identified key links between these physical oceanographic processes to ecology, from phytoplankton up through the food web to fish. There have also been numerous studies on the processes that drive ocean currents throughout the region, which is relevant to the transport of larvae for many important fisheries found in the region (Zhang et al. 2016). Large scale OSW has the potential to alter or interact with specific physical oceanographic processes and features in the Mid-Atlantic Bight and Gulf of Maine, including seasonally dependent stratification and the Cold Pool. The evolution of these features are critical habitat elements for the ecology of the region, as well as the commercial species that reside in or migrate through the region.

As summarized in a recent review (Miles et al. 2021), European offshore wind studies provide evidence that turbine foundations can increase turbulent mixing in the wake of the piling, and this can affect downstream stratification. These impacts on mixing and stratification depend heavily on local conditions (e.g., degree of stratification, mixed layer depth, and water depth). While these studies provide some initial guidance about susceptibility of ocean processes to turbine placement, they have rarely been specified to the unique processes of the Mid-Atlantic and Northeast U.S. Shelf. One major challenge in applying these studies to U.S. scenarios is that the seasonal stratification in the North Sea (Carpenter et al. 2016; Schultze et al. 2020) is much weaker than the seasonal stratification in the Mid-Atlantic (Lentz 2017).

1.3.3 Scour

Changes in localized mixing and turbulence that occur around turbine foundations have additional impacts on localized sediment transport and scour. Scour occurs when oceanographic forces are strong enough to mobilize the local sediments away from their current location without additional sediments being added to the system to replace the mobilized sediments. Increased sediment transport and scour around a turbine foundation occur due to increased turbulence and current speeds in the immediate vicinity as the flow moves around the structure. Current understanding recognizes strong associations between scour, structure diameter, water depth, and sediment conditions. In general, the larger the diameter of the structure, the shallower the water depths, the more uniform and sandier the sediment conditions, the stronger the oceanographic forces, and the more likely an area is to experience scour.

The most commonly referenced examples of scour at OSWs often include observations from North Sea sites such as Scroby Sands. Subsequent research has shown the ratio of the water depth to foundation diameter can be a significant indicator for the potential for severe scour. Data from these sites have been used to construct relationships between sediment types, water depth, and scour. For example, scour depths in uniform sand conditions can be predicted by the relationship scour(S)/diameter(D) = 1.8 (Harris and Whitehouse 2014). Non-uniform marine soils (a combination of gravel, sand, silt, and clay) respond differently than uniform sandy soils, and scour predictions are more complex. Additional features such as scour wakes, which occur along the scour axis and are not observed in the surrounding seabed, have been observed at Scroby Sands (Harris and Whitehouse 2014). Due to the similar geologic conditions between the North Sea and the Mid-Atlantic and Northeast U.S. Shelf, scour predictions and behavior are likely to be similar, and therefore much of the knowledge of scour at wind turbine foundations can be applied in the U.S.

In areas of expected high erosion, scour protection is necessary to protect cables and prevent the deterioration of structural integrity of turbine foundations (Hoffmans and Verheij 1997; Whitehouse 1998; Sumer and Fredsøe 2002). Scour protection is intended to prevent local scour at turbine foundations, but scour may still occur beyond the scour protection, called "edge scour" or "secondary scour" (Whitehouse et al. 2011; Peterson et al. 2015). The need for scour protection will alter seabed morphology and may introduce new habitat types within a wind farm, especially in areas where sand or mud dominate because they will add hard structure. This is likely to benefit species that prefer hard habitat/structure (Degraer et al. 2020). Additionally, this modification of the physical environment will affect fisheries and navigation (Whitehouse et al. 2011) and potentially modify local hydrodynamics.

1.3.4 The Major Gaps in our Knowledge

Most studies regarding the interactions of wind farms on ocean atmospheric conditions and hydrodynamics to date have focused on European wind facilities (van Berkel et al. 2020). Generally, European facilities are in shallower, sheltered areas with tight turbine spacing. In the U.S., water depths are deeper, stratification can be stronger, facilities are exposed to the open ocean, and turbines will likely be installed at a spacing nearly double what is currently found in Europe. There needs to be more studies tailored to the conditions and facility layouts of the U.S. outer continental shelf (OCS; Table 3).

1.3.5 Recommendations for Future Research

- A high priority should be placed on gathering empirical and observational data concerning the interactions of turbines and physical processes. These should include downstream turbulence and mixing, and wind extraction effects on surface wind. There exists a plethora of baseline observational data and models, and therefore it is recommended that these studies occur during wind farm construction and operations. Additionally, these studies should focus on region specific oceanographic conditions to inform more regionally relevant modeling studies within wind energy areas (WEAs). Long-term temporal studies are recommended to measure wind farm interactions outside of climate or other inter-annual environmental variability.
- Additional focused modeling studies should be paired with observations within the Mid-Atlantic and Northeast U.S. continental Shelf. Both simple model parameterizations, such as Carpenter et al. (2016), and full 3D studies, such as those by Christiansen et al. (2022) in the North Sea, are good examples of the types of activities that could be undertaken but with the consideration of local oceanographic and atmospheric processes, as well as planned turbine characteristics.

- Regional and multi-stakeholder coordination is needed to ensure the community is working together to address these research gaps.
- There has been little research done within the U.S. Mid-Atlantic Cold Pool feature with respect to the size and scale of turbines and cable arrays (Miles et al. 2021). Research examining the potential physical interactions of wind farms and local conditions on stratification are needed.
- With respect to fisheries resources, integrated modeling of the combined effects of wind field modification and in situ structure friction and fish responses to related hydrodynamic predictors relevant to their key habitats and lifecycle stages.
- A review of the "Partners in Science Workshop: Identifying Ecological Metrics and Sampling Strategies for Baseline Monitoring During Offshore Wind Development" (Brodie et al. 2021) final report is recommended for further recommendations to focus future research priorities to address the knowledge gaps identified in this report.

1.3.6 Perspectives of the Fishing Industry

The impacts on fish species from turbine-induced changes in upwelling, habitat type, and ocean circulation are largely unknown. Fisheries operate in a variable environment, but large-scale, permanent changes in access to sustainably managed stocks are rare. Offshore wind facilities have the potential to affect flow and turbulence that may alter larval dispersal and ultimately settlement patterns for species such as scallops. If scallop (or other bivalve species) recruitment were to be enhanced within wind arrays due to retention of larvae within turbulent eddies, over the decades of operation of the wind areas, fishery access to those parts of the stock may be limited or lost because of the dangers associated with fishing mobile bottom tending gear around scour protection and over buried transmission cables (displacement is discussed further in Section 2.1.3). Changes in flow and turbulence may likewise impact the transport of pelagic free-floating eggs and alter their ultimate survival. The uncertainties associated with how potential changes in ocean currents and alteration of predominant Mid-Atlantic features, such as stratification and the Cold Pool, will affect important fisheries resources in the region and remain a bottleneck to our ability to anticipate how wind facilities will interact with the socioecological structure.

1.3.7 Overall Summary of Findings

Offshore wind infrastructure is known to have localized effects on turbulence and flow in the near vicinity of the turbine; however, there are large uncertainties in their overall area of influence. Cumulative effects of large-scale buildout on turbulence, stratification, ocean atmosphere, and particularly on fisheries is unknown within U.S. waters. We can learn from European examples; however, studies are needed to understand the interactions of wind farms on specific ocean characteristics found in U.S. offshore waters. Knowledge gaps identified in this report as well as in other publications are well documented (van Berkel et al. 2020; Brodie et al. 2021). Expertise and methods exist to address these knowledge gaps; however, barriers including funding and the proprietary nature of commercial wind extraction technologies need to be addressed. Research and coordination barriers also exist and need to be overcome in order to address the uncertainties of wind energy development on atmospheric and oceanographic conditions. Alteration to these conditions has the potential to affect dispersal and recruitment of shellfish and finfish resources, which require further study.

1.4 Ecosystem Synthesis

1.4.1 Phytoplankton and Zooplankton

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1.4.1.1 Introduction

Phytoplankton and zooplankton can influence the distribution and abundance of upper trophic-level organisms, including fisheries resource species, a fact known from the study of global (e.g., upwelling ecosystems vs. ocean deserts) to regional scale systems (e.g., tidal fronts vs. surface mixed layers). This section will focus on the potential effects of offshore wind development on phytoplankton and zooplankton and deduce potential consequences for fish and fisheries. As planktonic processes are directly influenced by hydrodynamic processes, brief descriptions of physical-ecological cause-effect mechanisms are provided. This chapter begins by setting the scene with a description of the current Northeast Shelf lower trophic-level ecosystem understanding followed by a review of potential effects of offshore wind developments on primary and secondary producers. We separate modeling studies from field-derived empirical evidence and also try to isolate common understanding from information that may not be well understood, known data gaps, and areas where tools may be needed.

1.4.1.1.1 Primary Producers of the Northeast Shelf

The fisheries productivity of the U.S. Northeast continental Shelf ecosystem is mainly dependent upon the primary production of phytoplankton communities, which also play a major role in defining the extent of habitat of many key species (Friedland et al. 2021). Some fisheries production can be traced to allochthonous energy sources, such as terrestrial vegetation, but these are relatively minor contributions. The trophic pathways fed by phytoplankton tend to fall within 2 main paradigms. In the first, fisheries production is governed by the utilization of pelagic productivity directly through pelagic food webs, classically viewed as energy flow from phytoplankton to zooplankton to fish species. In the second, fisheries production is the result of the flux of particulate organic carbon from pelagic productivity to the benthos and then into demersal food webs (Friedland et al. 2012; Stock et al. 2017). Hence, the measurements associated with primary production will take on different meanings. The rate of primary production is associated with the rate of fixed carbon entering pelagic food webs; however, chlorophyll biomass, which is not always correlated with primary production, is a better indicator of the intensity of the benthic flux of organic carbon. Hence, in considering the phytoplankton communities of the shelf ecosystem, it is useful to consider the distribution of both primary production and chlorophyll concentration in time and space.

The U.S. Northeast continental Shelf ecosystem is part of the western boundary of the Atlantic basin having complex bathymetry with shelf areas of varying width, deep basins, and an elevated bank (Sherman et al. 1996). The structure of the ecosystem contributes to the phenology of phytoplankton bloom patterns where the northern (Gulf of Maine and Georges Bank) and southern (Mid-Atlantic Bight) parts of the ecosystem are continuous with trans-Atlantic patterns of a bimodal or a single autumn/winter annual bloom cycle, respectively (Taboada and Anadon 2014). The northern part of the ecosystem tends to have a spring and fall bloom (Figure 4). However, the maxima of chlorophyll concentrations do not correlate with the maximum of primary production. The spring bloom in the northern part is driven by nutrient inputs from deep, off-shelf waters that enter the ecosystem via the Northeast Channel in the Gulf of Maine (Townsend et al. 2010), which reflect variation in the source waters contributing to this flow (Townsend et al. 2006). The relative proportions of Labrador Current and shelf slope source waters set the nutrient content and salinity in the region (Townsend et al. 2010). During late winter, wind-driven mixing replenishes nutrients in surface waters forming the conditions for a spring bloom. One of the strongest single factors affecting spring bloom timing is an association with salinity, which in turn can be related to a changing pattern of Arctic inflow into the Gulf of Maine (Song et al. 2010). Despite a high degree of variability, there does not appear to be a directional trend in spring bloom timing or magnitude (Friedland et al. 2015a). The fall bloom tends to be more variable (Friedland et al. 2015b), and its initiation has been linked to water column stability (Song et al. 2011).

The annual production cycle of the southern part of the ecosystem is very different from the northern part. The pattern of season bloom events appears to be replaced by an extended period of elevated chlorophyll concentration during autumn/winter (Figure 5). As in the northern segment, primary production is not correlated with chlorophyll concentration. Unlike the northern segment, waters on the Mid-Atlantic shelf are often oligotrophic, and rainfall in the region plays an important role in the addition of nutrients via runoff (Sedwick et al. 2018). The nutrients associated with runoff also contribute to new production in the region. Though river discharge is important in the southern area, physical forcing, such as wind mixing, also plays an important role (Xu et al. 2020). An important feature of the Mid-Atlantic Bight is the Cold Pool, which provides a cold refuge for many species (Chen et al. 2018) and is associated with strong water column stratification. This feature is a barrier to water column mixing and nutrient replenishment, and therefore, much of the primary production of the Mid-Atlantic Bight is not new production.

1.4.1.1.2 Zooplankton of the Northeast Shelf

1.4.1.1.2.1 Factors Affecting Zooplankton

Because of their sensitivity to environmental change and their integrative role as a link between trophic levels, zooplankton are often used as ecosystem indicators of both trophic structure and physical ocean conditions (Peterson 2009). On a global scale, the amount of primary productivity channeled through mesozooplankton is more highly correlated with fishery yields than primary productivity itself (Friedland et al. 2012). It is clear that zooplankton are important indicators of environmental variability, and an assessment of variability in zooplankton assemblages and drivers of such changes is essential to understanding the ecology of Northeast Shelf Large Marine Ecosystem (NES LME).

Basin scale climatological patterns, such as the North Atlantic Oscillation (NAO), often drive prolonged physical changes within ecosystems and contribute greatly to seasonal, interannual, and even multi-decadal variability within systems (Hurell 1995). The relationship between the NAO and local physical and biological variables in the Gulf of Maine is non-stationary (Hare and Kane 2012); the relationship deteriorated in the 1990s when the NAO remained in its positive phase but Gulf of Maine salinity declined (Greene et al. 2013). It has been suggested that these changes were related to a great salinity anomaly event driven by changes in the Arctic climate system reflected in the Arctic Oscillation (Greene et al. 2013). Furthermore, the relationship between the NAO and water temperatures at surface and depth is of opposite sign in the Gulf of Maine (Xu et al. 2015).

Temperature has long been known to be a major factor in determining distributions and survivorship in marine organisms. The NES is experiencing a general warming trend, which is most prominent in the summer and fall months and resulting in a concomitant loss of core thermal habitat for NES organisms (Friedland et al. 2013). The Gulf of Maine has warmed faster than 99.9% of the global ocean from 2004 to 2013, and this warming is positively correlated with the Gulf Stream position (Joyce index), Pacific decadal oscillation (PDO), and the Atlantic multidecadal oscillation (AMO), explaining 70% of the variance in temperature, particularly summer temperatures (Pershing et al. 2015). The AMO, an integrated index of water temperature variability in the North Atlantic, clearly delineated pre- and post-regime shift years for zooplankton communities in the Mid-Atlantic Bight for both spring and fall, suggesting a role in driving these regime shifts. The switch from negative to positive phase AMO in late 1990s, coupled with a switch in the fall PDO at the same time.

1.4.1.1.2.2 Factors affecting zooplankton

As a result of their critical importance in the ecosystem, regime shifts in zooplankton community composition—defined as abrupt changes between contrasting states of a system that persist through time (deYoung et al. 2008)—can have a large ecological impact (Greene et al. 2013; Möllmann et al. 2015; Rocha et al. 2015). Decadal scale shifts in zooplankton abundance and community structure have been previously documented for segments of the Northeast Continental Shelf Large Marine Ecosystem (Kane 2007, 2009; Kane and Prezioso 2008; Pershing et al. 2005; Pershing et al. 2010). These shifts have been associated with size-specific responses of large-bodied zooplankton taxa such as *Calanus finmarchicus*, which declined in abundance from the early 1990s to the early 2000s, while smaller species such as *Oithona* spp. and *Centropages typicus* increased in abundance (Kane 2007; Pershing et al. 2005; Pershing et al. 2010).

Previous studies in this area have shown a shift occurring in the 1990s for yearly-integrated plankton abundance, as well as the shift in the early 2000s (Pershing et al. 2005). A majority of taxa in the spring community in the Gulf of Maine were affected by this early 1980s shift, and it is clear that no single taxa was responsible for driving this shift (Morse et al. 2017). Bi et al. (2014) demonstrated a shift in the timing of the peak abundance of *C. typicus* in the Mid-Atlantic Bight and in Southern New England occurring in the mid-1980s as peak abundance shifted from late fall to early spring beginning in 1985 in the Mid-Atlantic Bight.

Regime shifts identified in different ecoregions (NMFS 2021a) of the NES often exhibited very distinct characteristics, emphasizing more granular fluctuations in NES plankton communities relative to previous work (Morse et al. 2017). Shifts early in the time series generally reflected an increase in abundance levels. The response of zooplankton abundance within fall communities was more similar among ecoregions than for spring communities. The Gulf of Maine exhibited highly distinct patterns from other ecoregions. These results highlight the importance of the individual ecoregions as distinct units and demonstrate that while some patterns are coherent across the NES, these results indicate a more granular response with implications for managing fish stocks and resources in the face of climate change.

In the Gulf of Maine during all seasons from 2000-2010, *C. finmarchicus* had high levels of abundance, coinciding with a period of strong recovery for the critically endangered North Atlantic Right Whale population. That recovery plateaued after 2010 and has since been in decline. Adult *C. finmarchicus* levels reached time series maxima between 2000 and 2010 in the Gulf of Maine, and the abundance of stage-5 copepodites also reached time series maxima in both spring and fall during this period. Due to their size and life-history strategy, these later-stage copepodites along with adult *Calanus* are thought to be the primary prey for the North Atlantic Right Whale. Following 2010, the abundance of *Calanus* plummeted in the Gulf of Maine, and a regime shift to lower biomass was detected for both Gulf of Maine and Georges Bank (Sorochan et al. 2019). North Atlantic Right Whales abandoned their traditional feeding grounds in the Gulf of Maine and were increasingly present in Canadian waters in the Gulf of St. Lawrence during summer and fall beginning in 2010 and peaking in 2015 (Simard et al. 2019).

The physical drivers and zooplankton responses of these regime shifts were distinct, and the ecological consequences of these regime shifts were equally distinct. Following the early 1980s regime shift, there was a 5-fold increase in the relative biomass of small pelagic fish on the shelf, and that biomass level has remained at or near time series maximum levels since the 1977 National Oceanic and Atmospheric Administration (NOAA) Ecosystem Status Report (NEFSC 2015). However, following the early 2000s community shift, there was a synchronous collapse in the recruitment of many groundfish stocks (NEFSC 2015). The synchronicity among the majority of the 20 groundfish stocks examined suggests a system-wide change coincident with the observed regime shift in the zooplankton community (Morse et al. 2017; Perretti et al. 2017). Recent declines in winter-spawning cod on the Northeast continental shelf have been associated with a reduced abundance of the copepod *Pseudocalanus* spp. in spring, while the decrease in the copepod *Centropages typicus* in autumn has affected spring-spawning cod (Friedland et al. 2013).

1.4.1.1.3 Potential Effects of OSWs on Primary and Secondary Producers

The first comprehensive literature review on the influence of large offshore wind developments on marine ecosystems was conducted by Clark et al. (2014). The most recent and complete overview of the state of the knowledge about the impact of OSW-induced changes to hydrodynamics on fishes (van Berkel et al. 2020) has direct and indirect relevance for phyto- and zooplankton, as most of the underlying cause-effect mechanisms affect the entire pelagic ecosystem. It is anticipated that vertical and lateral flows will be modified to the extent that stratification processes may be affected; furthermore, stratification has a governing effect on phytoplankton bloom formation via the distribution of nutrients and light availability (Christiansen et al. 2022).

There is empirical evidence that lower trophic-level factors affect fish habitat (Friedland et al. 2021). However, any further statements on how OSWs may affect the linkages between plankton and fish and even fisheries would have to remain speculative as the underlying processes, as we have outlined below, are certainly ecosystem-specific, still largely elusive (even without considering OSW effects), and moreover depend on fisheries regulations inside OSWs as well as in the surrounding waters. Generally, model results indicate that large-scale upscaling of offshore wind energy extraction most likely has significant effects on fundamental ecosystem processes.

1.4.1.1.3.1 Theoretical Cause-and-Effect Relationships

There are principally 2 main effects of OSWs on the pelagic realm: the more local impacts of underwater structures and the atmospheric effects of wind energy extraction. The local effects can be further divided into consequences of increased turbulence at and downstream of the wind turbine foundations and pile structures, as well as the creation of hard substrate as a vertically structured sublittoral zone. For example, Grashorn and Stanev (2016) showed with numerical experiments that levels of turbulence in the wake of the piles are locally enhanced resulting in eddy fields similar to von Kármán vortex streets.

In one of the first studies on OSW impacts on upper ocean hydrography, Broström (2008) analytically showed that the extraction of energy from the wind creates an upwelling/downwelling dipole in the surface mixed layer through divergence in the Ekman transport. Depending on the correspondence of the size of the wind wake and the Internal Rossby radius of deformation, the vertical water velocities may be in the order of 1 m day^-1.

1.4.1.1.3.2 Evidence from Modeling Studies

1.4.1.1.3.2.1 Existing Information from the U.S.

There are 2 existing examples of specific US OSW modeling studies that analyze zooplankton impacts. One is a study by Chen et al. (2021) which focused on the effects of offshore wind development on sea scallop larval transport and dispersal. The study applied a high-resolution, coupled physical and individual-based model system (equivalent to agent-based modeling [ABM] and used hereafter for consistency) to examine how an offshore wind development in Southern New England waters would affect the distribution and abundance of sea scallop larvae in the region (Chen et al. 2016, 2020, 2021a, 2022 in prep). The other study was the BOEM commissioned project "Hydrodynamic Modeling and Particle Tracking in the U.S. Mid-Atlantic Bight (NSL 19-04)" (BOEM 2021). While this project employed a similar approach to Chen et al. (2021), its coupled hydrodynamic and ABMs were used to assess how cumulative offshore wind energy facilities development (i.e., from multiple developers) scenarios in the Mid-Atlantic Bight would affect local and regional oceanic responses (e.g., currents, temperature stratification) and, among other aspects, the corresponding effect on larval transport of the Atlantic sea scallop (*Placopecten magellanicus*), silver hake (*Merluccius bilinearis*), and summer flounder (BOEM 2021).

Chen et al. (2021) focused on determining how the Vineyard Wind offshore wind development (80-100 turbines) would affect the distribution and abundance of sea scallop larvae. For the physical component of the model, a subdomain grid specific to the Northeast Shelf (regions of the shelf off MA, RI, Block Island, Block Island Sound, and Long Island Sound) was con9d using the FVCOM model under the Northeast Coastal Ocean Forecast System (NECOFS) platform (Chen et al. 2016). A strength of the Northeast Shelf-FVCOM, a pre-existing model developed jointly by the University of Massachusetts-Dartmouth and WHOI, is that it can resolve wind turbines in the offshore wind development areas and quantify regional responses to offshore wind facility development. The physical model was coupled with an individual-based scallop model (scallop-ABM). Biological realism was built into the scallop ABM by incorporating 4 pelagic phases for scallop larvae with age/size-specific behaviors assigned to each stage and a benthic stage with feeding, predation, starvation, resuspension, and natural/fishing mortality. In previous work by Chen et al. (2021b), simulations of the transport and dispersal of scallop larvae in early life stages over 1978-2016 were carried out and demonstrated that biophysical interactions (i.e., interactions associated with scallop larval swimming behaviors in their early stages) drive significant inter-annual variability of larval dispersal (Chen et al. 2021b).

Impact simulations were conducted with Vineyard Wind lease area offshore wind turbine generators (WTGs) to examine changes to the dispersal and settlement of scallop larvae in the region. Two years with significant larval settlement in the Southern New England region were used as pilot years for the model (2010 and 2013), and initial simulation results found that enhancement of the mesoscale eddy circulation and turbulent mixing within and around the turbine area reduced horizontal larval dispersion and pushed the larvae offshore. Model results showed that although larval behaviors played a critical role in dispersal and settlement by altering the flow-induced advection experienced at different depths (Chen et al. 2016), WTGs changed vertical mixing and horizontal advection, as well as horizontal turbulent dispersion. Overall, the study conducted by Chen et al. (2021, 2022 in prep) found that the operational WTGs could alter scallop larvae dispersion in the Southern New England region and have a discernible effect on their abundance in the Nantucket Lightship Closed Area (NLCA) as a large number of larvae were advected there. The study further suggests that future cumulative build-out scenarios could result in significant cumulative impacts from wind development on scallop larval dispersal and transport in the region.

In the BOEM (2021) study, a hydrodynamic model (HDM)[1]—which included input from Computational Fluid Dynamics (CFD) modeling of water flow turbulence at turbine foundations and an embedded wake loss model of localized wind wake effects—was coupled with ABMs[2] of target species larval stages to analyze the influence of 4 OSW development scenarios (i.e., various combinations of cumulative OSW development possibilities) on larval transport and settlement. The HDM and ABMs were developed, calibrated, and verified against a range of observed oceanographic and survey data to demonstrate that related conditions prior to offshore wind construction were well represented by the integrated model.

Model results indicate that OSW structures do modify the oceanic responses in terms of current magnitude, temperature, and wave heights, namely reductions in current magnitude due to added flow resistance, influenced temperature stratification from additional mixing, and reductions in the current magnitude and wave heights from the extraction of energy from the wind by the OSW turbines. The HDM results predict changes in the order of +11% to -8% (75th percentile depth averaged currents), depending on the OSW scenario investigated. Discernable increases and decreases in larval settlement density across the 3 target species and 4 OSW build-out scenarios were also observed. Here, depending on mobility characteristics or release areas of the particular larvae, altered current directions and speeds either acted independently and/or collectively as the key variable in the observed shifts. The study suggests that disruptions in connectivity may pose an impact risk to certain subpopulations, warranting future localized investigations.

The authors of the BOEM (2021) study emphasize, however, that due to limited temporal coverage, its results are more reliable in terms of the relative change of both oceanic responses to OSW developments and the related impacts to larval transport and settlement. Further HDM and ABM of larval transport and settlement modeling are thus recommended to include additional years of hindcast modeling. This would allow analyses of year-to-year variability in the residual currents and ABM modeling of additional spawning seasons to reveal long-term structural shifts in larval settlement patterns and possible corresponding secondary impacts. Other suggested areas

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[1] A 3D regional model ranging from Cape Hatteras to offshore Cape Cod was established in MIKE 3 FM HD and MIKE 21 SW, with a finer model mesh embedded in the specific study area.

[2] ABM was executed via MIKE ABM Lab/MIKE ECO Lab, which provides an open and flexible coding environment for defining and customizing simple to advanced biological traits and processes using a series of user-defined arithmetic expressions and state variables, ultimately allowing simulated agents (e.g., larvae) to react and interact with a dynamically changing virtual environment.

for future analyses include adding additional species, OSW development scenarios and locations in the Mid-Atlantic Bight, and target species life cycle stages.

In terms of the linkage between various components of the HDM and the ABMs, the integrated nature of the generated OSW numerical modeling in the BOEM (2021) and Chen et al. (2021) studies can be considered as unique and advanced (van Berkel et al. 2020). These studies addressed similar questions at different spatial scales (i.e., one at a single OSW project level and the other at a cumulative OSW project level). It is evident, however, that variations in modeling specifications led to different conclusions regarding impact magnitude. Regardless, both studies do conclude that offshore wind developments have the potential to affect larval transport and settlement in fisheries species, thereby illustrating the general effectiveness of the modeling approach for assessing OSW-related zooplankton dispersion impacts. Additional testing and refinement of specifications for the integrated modeling approach should, over time, normalize and allow for a fuller understanding of the overall significance of apparent shifts in larvae transport and settling.

1.4.1.1.3.2.2 Existing Information from Outside the U.S.

The creation of new "OSW-pile-habitats" for epistructural benthic species specifically increases the biomass and distribution of filter feeders in the upper 3 m, especially blue mussel (; Joschko et al. 2008; Krone et al. 2013). With a turnover rate of more than 50% of the stock (ca. 40 kg m^-2) per year (Krone et al. 2013), the mussels are expected to significantly reduce the ambient concentration of phytoplankton and of micro- and mesozooplankton. However, it will also affect the local plankton community through the seasonally massive release of meroplanktonic larvae. At the same time, the mussels' high productivity may lead to increased sedimentation rates of organic material. By circulating some nutrients needed for pelagic primary production, they may act as a new link between the pelagic and benthic ecosystem (Krone et al. 2013). In the first study investigating the accumulated effects on primary productivity at the marine ecosystems scale, Slavik et al. (2019) assessed the sensitivity of pelagic primary productivity to changed abundance and distribution of the blue mussel. The authors compared a scenario of maximum OSW increase with historic (2003-2013) observations in the southern North Sea to assess the large-scale impact of offshore wind development structures on pelagic primary productivity. By using a coupled MOSSCO hydrodynamical-biogeochemical-ecological model, they concluded the decreasing impact of OSWs on annual primary productivity is predominantly local. Even though the decrease in primary productivity is relatively small, it extends over a large area and intensifies in close proximity to OSWs, reaching a maximum reduction in annual net primary productivity of 8%. However, at short time scales, there is a positive regional effect on biomass and productivity in areas that receive nutrient-enriched and phytoplankton-reduced water masses from OSW areas by currents that extend up to several 100s of km beyond the bounds of the OSW area. However, regional scale physical OSW effects on ocean currents and vertical mixing have not been considered, although OSW-generated turbulent wakes have been shown to impact the large-scale stratification in larger-scale development scenarios (Carpenter et al. 2016).

Very recently, potential end-to-end ecosystem effects of large upscaling of offshore wind in the southern North Sea have been analyzed with a state-of-the-art modeling suite, suggesting that a relaxation of stratification, changes in local wind patterns, wave generation, tidal amplitudes, stratification of the water column, dynamics of suspended particles, and bedload transport of sediment may have far-reaching consequences for the ecological functioning, such as changes to the total amount and the timing of primary production, food availability of filter feeders and higher trophic levels (Zijl et al. 2021).

Christiansen et al. (2022) forced a cross-scale hydrodynamic unstructured-grid model with a realistic, temporally changing wind field. The authors observed that individual upwelling/ downwelling dipoles shift their spatial positions, following the directional changes of their causative wind-wakes. Therefore in some cases, specific dipoles superimposed or mitigated each other. Consequently, on the monthly average time scale, Christiansen et al. (2022) obtained large-scale surface elevation dipoles with spatial dimensions of up to 100s of kilometers in the German Bight, strong enough to structurally change the seasonal course of stratification strength.

1.4.1.1.3.2.3 Gaps in Coverage/Data/Information

Generally, ground truthing of local model predictions may be accomplished by sea-going process studies; however, they have been rarely conducted. Larger-scale ground truthing has been done by satellites, airplanes, remotely operated towed vehilces (ROTVs), and gliders (see van Berkel et al. [2020] for a comprehensive overview). All are snapshots in time and are limited when it comes to rate measurements, like production, predation, turbulence, and vertical flux; however, without adequate rates, all modeling studies have to remain speculative.

Physical effects of a wind farm on atmospheric boundary layer circulation and ocean currents and vertical mixing (e.g. Carpenter et al. 2016) are just beginning to be considered by coupled models; the issue of scale must be addressed in physical modeling to bridge the wind pile (order of 10 m) to ecosystem (order of 100 km) scales. Recent developments in nested or unstructured models seem promising here (Slavik et al. 2019).

1.4.1.1.3.3 Evidence from Empirical Studies

1.4.1.1.3.3.1 Existing Information from the U.S.

The authors do not know of any empirical study on potential effects of OSWs on primary and secondary producers within the U.S.

1.4.1.1.3.3.2 Existing Information from Outside the U.S.

All OSWs that have been built in Europe are subject to national environmental monitoring programs, as required by the European Environmental Impact Assessment Directive 85/337/EEC. However, the German Environmental Impact Assessment (EIA) standard (StUK4; BSH 2013), like other national monitoring standards, are generally focused on the conservation of some species, and there is no holistic approach for analyzing the effects arising from OSW construction and operation. The investigation or monitoring of the potential effects of OSWs on the pelagic ecosystem is not mandatory. Thus, only a limited number of studies have analyzed OSW effects on the pelagic ecosystem, and even fewer include field measurements.

Additionally, a particular emphasis was placed on iconic or flagship species not only due to their endangered status but also their highly popular image among the public (Pezy et al. 2020a). Floeter et al. (2017) used a ROTV (TRIAXUS ROTV) through 2 non-operating OSWs in the summer stratified North Sea. They provided empirical indication that vertical mixing is increased within the OSWs, leading to a doming of the thermocline and a subsequent transport of nutrients into the surface mixed layer. Nutrients were taken up rapidly because underwater photosynthetically active radiation (PAR) enabled net primary production in the entire 40-m water column, especially within submesoscale chlorophyll-a pillars that were observed at regular intervals within the OSW regions. Video Plankton Recorder (VPR) images revealed distinct meroplankton distribution patterns in a copepod-dominated plankton community. The comparative analysis of a pre-OSW survey showed, however, that it is difficult to fully separate anthropogenic impacts from natural variability.

Wang et al. (2018) analyzed zooplankton net samples from before and after the construction of an OSW in 10-m water depth off the coast of China. They concluded that suspended sediment concentration seems to be a key factor by which wind farms affect zooplankton through hydrodynamic effects. The results indicated that the concentration of suspended solids had opposite effects on the macro- and microzooplankton communities, which might lead to miniaturization of zooplankton.

1.4.1.1.3.3.3 Gaps in Coverage/Data/Information

The main gaps in field derived empirical knowledge are at the interface between fundamental and applied research (i.e., open questions in basic ecosystem understanding become even more complex when it comes to the task of isolating anthropogenic effects from "corridors of natural variability," especially in dynamic areas like frontal regions). Some examples of these known unknowns are listed below:

Some long-standing questions address the "coupling-of-scales" domain: How do local OSW pile-generated wakes affect regional stratification over the course of the production cycle (Carpenter et al. 2016; Slavik et al. 2019)? At which water depth does increased turbidity due to turbulence-induced sediment resuspension induce light limitation on primary production, and how does this vary with season and water column stability (Floeter et al. 2017)? Is the dominant blue mussel a dead end for a classic trophic food web since their consumption by top predators is low in comparison to their biomass (Pezy et al. 2020a), eventually leading to oxygen minimum zones? Or does the tidal advection of nutrient-enriched and phytoplankton-reduced water masses from blue mussel hot-spots in OSWs enhance primary production peaks in summer stratified waters (Slavik et al. 2019)? Has an upwelling/downwelling dipole been observed as predicted by Broström (2008), or are these effects of wind-induced spatial Ekman-transport differences distorted by tidal currents? Atmospheric wind wake effects have been quantified (see van Berkel et al. 2020), and the length of the wind wake critically depends on the atmospheric stability (Platis et al. 2020). Maybe, due to their ephemeral nature, empirical evidence of the underlying specific OSW wind-wake induced upwelling/downwelling dipoles is still missing. Besides the necessary atmospheric and hydrodynamic conditions (i.e., stratification), contrasting quasi-synoptic water column surveys of the leeward area are required to fill this gap. Is the seasonal release of vast amounts of meroplanktonic larvae from OSW-enhanced epibenthic species detrimental for the survival of fish larvae because they compete with the miniaturized copepods? How tied is the spatiotemporal coupling between local OSW effects on phytoplankton productivity and regional secondary production, given the relatively long copepod generation times? Does the locally enhanced benthic production lead to aggregations of juvenile gadoids with better body conditions, or does enhanced predation by larger piscivorous fish, sea mammals, and birds lead to reduced foraging times which compensate better prey availability (Reubens et al. 2013a, b, c, 2014)?

1.4.1.1.3.4 Implications of Information Gaps and Options for Moving Forward

The above-mentioned OSW-related phytoplankton and zooplankton knowledge gaps present unique challenges for OSW associated with EIA decision-making processes. These often rely on conventional modeling or simple quantitative analysis approaches that include impact stressor modeling (e.g., water quality, underwater noise, oil spills) and static data regarding the presence of various environmental receptors (socioeconomic and ecological) of concern. Impacts are assessed in relation to well-documented stressor tolerances, and validation is often assumed due to the well-known characteristics of the impact. This approach is ultimately far removed from the complexity of implied analyses associated with the aforementioned gaps, situation further complicated by cited shortcomings of European OSW BACI studies to segregate from natural variability (Floeter et al. 2017; van Berkel et al. 2020) and therefore validate assessed OSW-related impacts.

The need to understand and manage potentially relevant impacts therefore begs the question of what pre- and post-OSW project analyses techniques are needed, available, and appropriate to inform decision-making processes regarding project-specific and cumulative OSW impacts (i.e., both primary and secondary) associated with phytoplankton and zooplankton. In terms of EIA/environmental impact statement (EIS) processes, the approaches applied in the earlier mentioned BOEM particle tracking ABM project—which include modeling of the combined effects of wind field modification and in situ structure friction and are coupled to ABMs of larval transport responses to OSW-influenced oceanic predictors and others like it (e.g., Cavalcantea et al. 2020)—point to promising possibilities for identifying impact magnitude. Several sources (Cowen et al. 2009; Sale et al. 2010; van Berkel et al. 2020) refer to the advantages of these types of biophysical responses for larvae transport studies as they, "… capture important physical (e.g., transport and dispersion by water masses and eddies) and biological processes (e.g., growth, mortality, swimming ability), and response to gradients" (Werner et al. 2007). Other spatially and temporary explicit integrated modeling studies illustrate further possibilities for analyzing the dynamics behind nutrient availability and primary/secondary production (e.g., Kock Rasmussen et al. 2009), intraspecific interactions (see subsequent citations), and various combinations of primary and secondary impact vectors (Ault et al. 2003; Humston et al. 2004; Heinänen et al. 2018; Sato et al. 2007).

While these studies indicate significant advances in capabilities to model complex phytoplankton and zooplankton systems, their efficient application within strategic assessments or project-specific OSW environmental analyses ultimately depends on the isolation of a collection of indicator impact vectors representative of key linkages between lower and upper trophic levels. Additional research is required to isolate these relationships, and it is postulated that this should involve maintaining, and improving (e.g., with onsite measurements), integrated numerical models into OSW operational phases, and linking pertinent results with targeted components of BACI or BAG studies to verify observed structural changes and the corresponding impacts, including biological responses (see Section 4.3 on Innovative Monitoring Methods and Technologies). Current state of scientific knowledge cannot state whether offshore wind effects on plankton will cascade into negative, positive, or negligible effects on fishing communities

1.4.2 Demersals

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1.4.2.1 Introduction

The potential effects of OSWs on demersal fish (Appendix) have been addressed through multiple studies in Europe and the U.S., and they remain a concern given the variety of mechanisms by which fisheries can be affected. This chapter briefly synthesizes current knowledge—including the methods used to make assessments, and recent and ongoing baseline data collection in the U.S.—and summarizes artificial reef effects, as well as demersal fish responses to noise, electromagnetic fields, and hydrodynamic wakes. Knowledge gaps are highlighted and recommendations for future research are made.

1.4.2.2 Synthesis of Current Knowledge

1.4.2.2.1 Baseline for Future OSW Surveys

Baseline surveys provide important information that allow assessments of effects related to OSW developments and may direct future work. For instance, in monitoring studies that use a BACI design, a strong understanding of spatial and temporal variability in the species or community of interest prior to OSW development is needed (Wilding et al. 2017). Establishing the baseline variation in fish abundance/biomass and distribution patterns, as well as a target acceptable level of change (or effect size), is recommended (Wilding et al. 2017). In the U.S., baseline assessments of the seasonal migrations of Atlantic sturgeon through the WEAs in New York (Ingram et al. 2019) and Maryland (Rothermel et al. 2020; Secor et al. 2020) were assessed using acoustic telemetry. Striped bass (*Morone saxatilis*) were tracked within the Maryland WEA, as well. These studies were undertaken in advance of wind farm development to establish baseline data on the movement of fish through WEAs prior to OSW construction. Two studies are currently underway within the RI/MA WEA's using acoustic telemetry. One study is examining cod spawning activity in and around the WEAs, and a second study is gathering baseline information on the movements, presence, and persistence of highly migratory species (HMS) within the WEAs.

Other sampling methods used to characterize the baseline abundance and distribution patterns of demersal fish in northeastern U.S. wind lease areas include demersal (otter) trawls, beam trawls, gill nets, and fish pots. Bottom type in the lease area and mobility habits of the focal species are among the considerations in selecting a sampling method.

1.4.2.2.2 Artificial Reef Effect

The addition of OSW infrastructure creates new hard habitat in the marine environment that serves as an artificial reef affecting ecosystem structure and function (Degraer et al. 2020). A common research question concerning offshore wind development effects is whether the operation of the wind turbine generators affects the abundance or distribution of demersal fish. Studies addressing this question commonly use either a BACI or a Control-Impact (CI) design. A BACI design compares fish catches at a wind farm area between baseline and operation time periods relative to catches during these time periods at reference areas. A CI design compares fish catches contemporaneously between a reference and wind farm area. Additionally, targeted research is conducted to examine mechanisms of wind farm effects.

Fish communities have been compared between wind farm and reference areas at European offshore wind developments using a BACI design and a variety of sampling gears (e.g., beam trawl [Lindeboom et al. 2011; Vandendriessche et al. 2015; Degraer et al. 2018; De Backer et al. 2020], fyke nets [Bergstrom et al. 2013], and gill nets [Stenberg et al. 2015]). In the U.S., a demersal trawl was used to assess demersal fish and invertebrates at BIWF, approximately 5 km offshore of Rhode Island, U.S. (Carey et al. 2020; Wilber et al. 2018; Wilber et al. 2022a). Reference site locations are typically chosen that have similar physical characteristics to the impact area, such as bottom depth and type. The relative change in fish abundance, usually reported as catch-per-unit-effort (CPUE) is compared between before and after time periods within each area. Assessments of changes in fish abundances between baseline and operation time periods have been conducted by sampling fish in open areas between turbines, as well as within close proximity to the turbines. A common finding of the latter studies is an artificial reef effect (i.e., shelter-seeking fish are attracted to the structure offered by the wind turbine foundations and the colonizing fauna that, in turn, may attract other predatory fish; Degraer et al. 2020). Benthopelagic fish are commonly attracted to wind turbines at high densities in Europe (Andersson et al. 2009; Winter et al. 2010; Leonhard et al. 2011; van Deurs et al. 2012; Reubens et al. 2013a) and at BIWF (Carey et al. 2020; HDR 2020a; INSPIRE 2021). These species include Atlantic cod, pouting, black sea bass, and the gold sinny wrasse (*Ctenolabrus rupestris*; Bergstrom et al. 2013; Reubens et al. 2014a; INSPIRE 2021). The type of sampling method used may play an important role in detecting an artificial reef effect (i.e., demersal trawls, which typically are limited to sampling at a safe distance from turbine foundations, may be less likely to reliably intercept structure-oriented fish aggregations that can be quantified using scuba surveys, video monitoring, or fish pots).

An artificial reef effect is not necessarily restricted to the immediate vicinity of wind turbines. For instance, sampling between turbines at BIWF collected greater abundances of black sea bass during the operation time period (Carey et al. 2020; INSPIRE 2021; Wilber et al. 2022a) and recreational fishers reported higher catches of Atlantic cod in the general vicinity of BIWF (INSPIRE 2021; Smythe et al. 2021) following turbine installation, indicating higher abundances of shelter-seeking species may extend beyond the immediate turbine structure. Catches of other demersal fish species at BIWF did not vary between baseline and operation time periods differently from reference sites (INSPIRE 2021; Wilber et al. 2022a). Similarly, European studies found no large-scale effects of wind farm operation on fish diversity or abundance, but higher abundances of structure-associated taxa closer to turbine foundations (e.g., Bergstrom et al. 2013; Stenberg et al. 2015). A limitation of BACI study designs in OSW monitoring is that this approach is better suited for detecting impacts that create an acute or long-lasting change to the average of the biological metric and are less effective if the impact affects variability, which is a likely outcome for OSW monitoring (Wilding et al. 2017). Background variability can be reduced by conducting consistent sampling by season and time of day and by stratifying sample locations across physical parameters that affect fish distributions, such as depth and bottom type. A post-hoc examination of spatiotemporal variability in catch rates between 2 reference areas sampled during BIWF monitoring revealed minimum effect sizes ranged from 40% to 63% for the fish species examined, and thus smaller changes to catch rates would not be considered ecologically meaningful in this study (Wilber et al. 2022a). Ideally, ecologically meaningful effect sizes would first be determined based on public policy, and basic research and subsequent monitoring would be designed to characterize this level of change with sufficient statistical power. Currently, ecologically meaningful effect sizes have not yet been determined for demersal fishes in relation to OSW in the U.S.

Comparisons between wind farm and reference areas solely during operation time periods also provide valuable information on OSW effects. In Belgian OSW areas, catch rates of a target species, sole (*Solea solea*), in the vicinity of the operational OSWs remained comparable to catch rates in the wider International Council for the Exploration of the Sea (ICES) area, but catch rates and landings for plaice (*Pleuronectes platessa*) were even higher around some operational wind farms (De Backer et al. 2019). A decade of monitoring at the Belgian OSWs revealed no large changes in the demersal fish community after construction (De Backer et al. 2020). Fish densities of some common soft sediment-associated fish species, such as common dragonet (*Callionymus lyra*), solenette (*Buglossidium luteum*), lesser weever (*Echiichthys vipera*), and plaice, increased in 1 of the 2 studied wind farms. This effect was suggested to result from fisheries exclusion combined with increased food availability because of the artificial reef effect (De Backer et al. 2020). Acoustic telemetry was used to determine that juvenile cod exhibit a high degree of residency at individual European wind farms (Reubens et al. 2013b), with activity increasing during crepusular periods associated with foraging (Reubens et al. 2014b). Cod form large aggregations at the turbine foundations in the summer and fall and are not as common in OSWs in the winter. A Belgian OSW study is examining the attraction and movement of plaice within wind farms, investigating their residency, site fidelity, and fitness characteristics relative to reference locations (Jolien Buysse, ILVO, unpublished data).

The effects of OSWs on demersal fish are also addressed through studies that examine possible mechanisms of effect, such as potential changes to demersal fish feeding behavior and movement. Fish dietary habits are affected by the invertebrates that colonize the turbine foundations as determined in Europe through stomach content and stable isotope analyses (SIA) and at BIWF through stomach content analysis. In Europe, juvenile Atlantic cod, pouting, and sculpin (*M. scorpioides*) feed on epibenthic prey associated with wind turbines, such as amphipods and decapods (Reubens et al. 2011; Reubens et al. 2014b; Mavraki et al. 2021a). The combined stomach content analysis and SIA revealed that the benthic sculpin and the benthopelagic cod and pouting used the artificial reefs within OSWs as feeding grounds for a prolonged period of time (Mavraki et al. 2021a). For some pelagic species, however, these artificial reefs do not serve as feeding grounds. For instance, horse mackerel (*Trachurus trachurus*) only occasionally consumed species associated with hard substrata, feeding instead on zooplankton also in close proximity to the turbines (Mavraki et al. 2021a). At BIWF, the diets of flounders and hakes did not change substantially at the wind farm relative to 2 reference areas following wind farm construction, although some prey items associated with fouling communities (blue mussels and mysids) were more common in winter flounder and hake diets, respectively, during BIWF operation (Wilber et al. 2022b).

1.4.2.2.3 Demersal Fish Responses to Noise

Noise disturbances created by OSWs occur in 4 phases: (1) site surveys that include multibeam/side-scan sonar and sediment coring; (2) construction, which includes vessel operations, jet-plows, and pile driving; (3) operation with broadband and tonal turbine emissions; and (4) decommissioning, which includes vessel and construction noise (Mooney et al. 2020). As reviewed by Hawkins and Popper (2016), responses to the aforementioned types of sound vary with the distance from source and can be categorized as death, physical and physiological effects, impaired hearing (temporary/permanent threshold shifts), masking biologically important sounds (e.g., communications, predator/prey sounds, reproductive vocalizations), and behavioral responses. Recent evidence has promoted the importance of particle motion and vibrational sound for fish species in addition to sound pressure (see Section 1.4).

High-resolution geophysical surveys are used by wind energy developers to generate images of the seafloor that can be used to find suitable sites for installing wind farm turbines and cables. These surveys differ from those used for oil and gas exploration in methods used and the noise levels produced. Because information needed for siting wind turbines is limited to the uppermost portion of the seafloor (depths below the seafloor of 100 m or less), relatively low-intensity survey alternatives are recommended (BOEM 2007). Sub-bottom profiling systems recommended for wind farm siting surveys (BOEM 2015) include:

- a high-frequency CHIRP system, which uses wide-band, high-frequency modulation pulses, operates in the 2 to 16 kHz frequency range, and provides very-high resolution data within the uppermost 10 to 15 m of sediment (BOEM 2015);
- a medium penetration system in which a boomer generates a seismic signal electromagnetically, creating a high-energy, low-frequency transducer acoustic pulse in the water column in the range of 0.5 to 5 kHz (boomers can provide information on sedimentary structure at depths that exceed the capabilities of CHIRP systems; BOEM 2015); and
- sparkers, which have historically been used when deeper signal penetration depths are required than are achieved by boomers (Fugro 2017). Sparkers function similarly to a spark plug, generating a spark between positive and negative electrodes that create a pressure impulse in water.

Behavioral effects of ship noise on demersal fish may include masking communication signals as modeled in haddock (*Melanogrammus aeglefnus*) and cod (Stanley et al. 2017). Underwater sound pressure from vessel traffic was studied at Stellwagen Bank and compared to estimates of the communication ranges for haddock and Atlantic cod. Ambient sound and estimated vocalization ranges were naturally variable (e.g., lower range in winter, broader range in spring), but the estimated vocalization ranges were reduced in the presence of vessel noise inferring masking of important communications, particularly during spawning periods with potential consequences on reproductive success. In addition to masking courtship communications, ship noise playbacks in aquarium studies of demersal species have highlighted physiological responses in early life stages. For example, playback noise during cod spawning period reduced total egg production and reduced fertilization rates, which were negatively correlated with egg cortisol content (Sierra-Flores et al. 2015). Similar, regular playback approaches over 2 days indicated reduced growth and quicker use of egg sac reserves, and after 16 days, exposure resulted in smaller bodied fish, which were easier to catch by predators (Nedlec et al. 2015). Sound detection thresholds of black sea bass across 3 size classes were determined using auditory evoked potentials, revealing the largest individuals were least sensitive (Stanley et al. 2020). The black sea bass auditory detection bandwidth overlaps noises emitted by shipping and underwater construction.

The effects of pile-driving noise have received much attention given that the auditory bandwidth overlaps with detection sensitivities of many fish species, and the effects can be severe, resulting in mortality or injury of hearing tissues (Popper and Hastings 2009; Mooney et al. 2020). For example, using aquarium playbacks of pile-driving noise to several species, including hybrid striped bass, Casper et al. (2013c) demonstrated greater levels of barotraumas (e.g., swim bladder rupture, herniations, and hematomas) and hair cell damage with greater levels of sound exposure.

In Europe, similar aquarium-based and in situ playback studies have been completed. In situ playback studies of pile-driving noise have elicited contrasting physiological responses in species tested, with regard to oxygen consumption whereby increased rates are interpreted as stress. Increased oxygen consumption in black seabream (*Spondyliosoma cantharus*) was observed in contrast to no differences in oxygen consumption between pile-driving and ambient sounds in European plaice (Bruintijes et al. 2016). A decrease in oxygen uptake and whole-body lactate concentrations was demonstrated in in situ playback studies of juvenile European seabass indicative of acute stress, but 30 days after treatment, no changes in growth rate or condition were detected (Debusschere et al. 2016). Further work on European seabass demonstrated that increased ventilation rates resulting from pile-driving noise in aquarium playbacks was not exacerbated by elevated CO_2 levels (Poulton et al. 2017).

Playbacks of pile-driving noise to juvenile seabass have also demonstrated disrupted schooling behaviors indicating lower abilities to coordinate movement with one another which may suggest stress or distraction (Herbert-Read et al. 2017). Similar studies assessing behaviors of European seabass concluded that the temporal structure of sound is an important factor in the recovery of behaviors and that pile driving is expected to have a stronger impact than a constant sound of the same level (Neo et al. 2016).

Although no direct mortality of cod at short distance (75 m) from pile driving location was detected during an in situ experiment in Belgian waters, a steep increase in swim bladder barotrauma was detected with decreasing distance to the pile-driving location (with no effect at 1700 m from the pile driving location). All fish exposed to pile-driving noise at close distance to the pile driving location further showed multiple instances of internal bleeding and a high degree of abnormal swimming behavior, hinting toward a reduced survival rate on the longer term. However, these immediate detrimental effects seem to occur only locally, close to the high impulsive sound source, as swim bladder injuries rapidly decreased with increasing distance from the pile.

The continuous noise of a wind farm operation can shift in frequency depending on wind and rotation speed (Sigray and Andersson 2011). Although operation noise levels are not associated with direct physical injury, long-term (days) exposures may have negative effects on communication, foraging, and predator detection (Mooney et al. 2020). Cumulative noise levels may be elevated relative to background levels, up to a few kilometers from an OSW farm under very low ambient noise conditions, but be below ambient levels in areas with high ambient noise from shipping or high wind speeds (Tougaard et al. 2020). Fish proximity to the turbines, therefore, is a primary factor determining noise exposure that will increase with the cumulative contribution from many turbines.

Presently, most studies assessing the responses to noise are completed in aquarium conditions using playbacks of noise or in situ mesocosm exposures, while few studies have assessed responses to noise in situ accounting for the ability of species to move away from the sound source (Hawkins and Popper 2016). At present, studies assessing responses to particle motion and vibrational sounds that may be transferred from OSW activities to demersal species are lacking.

1.4.2.2.4 Demersal Fish Responses to EMF

EMFs associated with OSW are predominantly emitted from subsea cables, which include the inter-array cables and export cables transferring energy to the grid on shore. Demersal species that are electro- and/or magneto-receptive may derive ecologically important information from natural cues, such as the geomagnetic field or bioelectric fields. Such cues may be important in deriving locational information aiding navigation to important resources (e.g., natal homing, migration to feeding or spawning grounds) or in predator-prey interactions, communication, and finding mates (Formicki et al. 2019; Newton et al. 2019).

Early life stage responses to EMFs are not well defined and must be considered in conjunction with the likely encounter rate (Hutchison et al. 2020a). Formicki et al. (2019) summarize that finfish exposures to magnetic fields can influence gamete and embryonic development, motor function, and directional responses in embryos and larvae. Efforts to determine early life stage responses in Atlantic halibut (*Hippoglossus hippoglossus*) to DC magnetic fields were attempted in aquarium studies (Woodruff et al. 2012, 2013). The studies detected possible delayed development and reduced growth in larvae and distributional changes in 1-yr juveniles in response to DC fields, but in both cases, tank effects rendered the results inconclusive. In elasmobranchs, it has been demonstrated that the ability to detect predator-type bioelectric fields occurs early in development while still in egg cases (e.g., Ball et al. 2016), but it is not known if cable EMFs may mask this ability or evoke unnecessary responses.

Elasmobranchs are the better studied demersal group with regard to responses to EMFs, largely focusing on predator-prey interactions. Studies of benthic catsharks (*Scyliorhinus canuicula*) have indicated the ability to differentiate between AC and DC magnetic fields but not to differentiate between natural and artificial DC fields (Kimber et al. 2011), suggesting that cable EMF may mimic prey-type bioelectric fields. Field studies of catsharks, skates, and rays exposed to buried cable EMFs have supported this theory (Gill et al. 2009; Hutchison et al. 2020b). In situ mesocosm experiments exposed catsharks and thornback rays (*Raja clavata*) to AC fields. These studies reported that catsharks were found closer to the cables when the cables were powered and that rays that were exposed to powered cables reduced their activity (step-length) indicative of foraging (Gill et al. 2009). Later, a striking increase in foraging behavior was reported in little skates (*Leucoraja erinacea*) exposed to DC fields compared to control conditions (Hutchison et al. 2020b). Aquarium studies of the benthic catshark using food reward techniques in conjunction with electric field stimulation indicated that catsharks could learn if food was associated with an electric field or not, habituating to the non-rewarded stimulus (Kimber et al. 2014). However only a short-term memory (<3 weeks) of experiences was retained. Habituation to cable EMFs has not been assessed.

Diadromous species which undertake migrations from rivers to sea and vice versa may encounter subsea cables in coastal and offshore waters. Concerns have been raised that EMFs may result in barriers to movement for these species, impacting their abilities to reach spawning grounds. Westerberg and Lagenfelt (2008) reported that tagged European eels (*Anguilla anguilla*) that passed over an AC cable slowed down but continued their outward migration to sea. Laboratory studies of European eels reported no behavioral responses to simulated AC magnetic fields (Orpwood et al. 2015). American eels (*Anguilla rostrata*) are the focus of an ongoing study to establish the fine-scale behavioral response to a DC cable. Salmonids have also been the focus of recent research in this context. Wyman et al. (2018) assessed the migrations of tagged Chinook salmon (*Oncorhynchus tshawytscha*) smolts before and after a subsea DC cable was energized and found that the smolts still migrated but an increase in misdirection was evident which increased their journey to sea. In Europe, laboratory studies exposing captive Atlantic salmon (*Salmo salar*) to simulated AC magnetic fields did not reveal behavioral responses in adult salmon or smolts (Armstrong et al. 2015). Often the perception of a barrier to movement is that it prevents the animal from migrating; however, small changes in their migrations may cumulatively become important.

Knowledge of species responses to EMFs is patchy and derived from a variety of methods (e.g., aquariums, mesocosm, free-ranging telemetry) often using different exposure types in assessments, making it difficult to establish impacts in the context of OSW (reviewed by Hutchison et al. 2020a). A better characterization of the EMFs (see Chapter 1b) would enable more contextually relevant effect/impact studies to be designed for the species of interest. Species life stage and movement ecology must factor into assessments of effects, including the likelihood of encountering a cable EMF and/or multiple OSW cables and the potential for cumulative effects (Hutchison et al. 2020a).

1.4.2.2.5 Demersal Fish Responses to Hydrodynamic/Wind Wake Effects

Changes in hydrodynamics and wind wake effects may influence demersal species larval transport, connectivity, and recruitment. The direct influences of these changes are not well characterized but may be important, particularly if OSWs overlap with fish spawning habitat and the artificial reef effect concentrates fish during the spawning season. For instance, spawning habitat of flatfish in the North Sea overlaps with planned OSWs, which may affect 2% to 16% of settlers that originate from these areas, as predicted by a particle-tracking model coupled to a 3D hydrodynamic model (Barbut et al. 2020). Common dab (*Limanda limanda*) had the highest proportion of settlers originating from OSW areas, followed by European plaice and brill (*Scophtalmus rhombus*). Larval transport and flatfish recruitment in the North Sea are affected by hydrodynamics, and therefore, the influence of OSWs on hydrodynamics (Rivier et al. 2016) is of interest for future research. For instance, model simulations indicate that local reductions in surface wind stress can affect upwelling and downwelling (Brostrom 2008) and the duration of stratification (Carpenter et al. 2016); however, these effects have not been observed in the field (Miles et al. 2020). More research is needed to estimate the extent to which OSWs may influence the processes that establish the seasonal stratification that traps cold bottom waters on the Atlantic continental shelf (i.e., the Cold Pool), which sustains boreal fauna at lower-than-expected latitudes and supports important fisheries (see Section 1.3).

1.4.2.3 Commercial Fishing Perspectives

A questionnaire was provided to members of the fishing community in the northeastern U.S. to obtain feedback on their concerns regarding impacts to fisheries resources from offshore wind development. While participants had varying concerns, some issues were common among respondents (socioeconomic concerns regarding exclusion of vessels from these wind energy areas are discussed in Section 2.1.2). Noise and acoustic impacts from construction (e.g., pile driving, increased vessel traffic) and operations were a common concern given the relative lack of information on the effects of sound on demersal fish species. Conversion of habitat was also a major concern. The addition of turbine foundations and scour protection converts primarily soft bottom habitats (e.g., sand, mud) to hard bottom, leading to an artificial reef effect that could change the species assemblage and trophic dynamics of an area. This habitat transition could be detrimental to important fisheries resources typically found in these soft bottom habitats (e.g., flounders, monkfish). The impacts of EMFs masking natural cues on fish movements were also a concern should cables become a barrier to migrating fish (both predators and forage species), thereby changing migratory patterns and altering spawning timing and behavior. The applicability of using aquarium studies to address the effects of EMF in demersal species was questioned, with particular note of assessing potential effects in species which may be reliant on magneto-reception for cues facilitating natal homing. The concerns raised by the commercial and recreational fishing communities are in some cases the subject of extensive studies and in others an issue that warrants additional research effort. It was particularly important to the fishing community that U.S. species are studied and that there is not an over-reliance on European studies which lack U.S.-specific context.

1.4.2.4 Knowledge Gaps and Priorities

Artificial Reef Effects

- The spatial extent to which attraction to and foraging on wind turbines enhances fish production beyond local effects, and the degree of change in production
- Clarification on the balance of attraction/production/ecological trap
  - Upscaling of locally observed effects to the regional scale (i.e., demersal fish stock size)
- Impacts on spawning and nursery ground quality with regard to habitat change
- Trophic interactions
  - Quality of epifaunal organisms as food for fish and subsequent levels

Noise

- Seasonal noise effects on fish at appropriate life history stages
- Information on the ability of animals to evade noise
- Consideration of noise attenuation and distance from source in assessments of effects
- Effects of pile-driving noise and operational noise were identified as priority knowledge gaps although cumulative effects of other noise sources also require attention

EMF

- Sensitivity ranges for species of interest with regard to OSW EMF intensities and types
- Likely encounter rates for species of interest with EMFs from OSW cables, taking account of the most relevant life stages and their movement ecology; potential for cumulative effects
- Knowledge of migratory delays resulting from EMF encounters and any ecological consequences in the context of species/life stage-specific migration
- Knowledge of the ability of species to derive ecologically important cues in the presence of cable EMFs (and consideration of life stage)
- Determination and quantification of distorted predator-prey interactions and consequences for energy acquisition (for predators) or survival (for prey)
- Potential effects on sessile life stages (e.g., eggs which may be exposed to variable EMFs over longer periods)

Hydrodynamic/Wake Effects

- Consideration of stratification and altered hydrodynamics on species at appropriate scales, such as the influence on connectivity, larval transport, and recruitment

General

- Generational effect of energy emissions (noise and EMF)
- Early life stage effects of energy emissions on later life stages
- Consideration of multimodal stressors
- Consideration of cumulative effects rather than individual pressures
- Species-specific spillover rates

1.4.2.5 Recommendations for Future Studies

Although numerous studies have examined ecological effects of European OSW developments, with progress achieved on answering many questions, knowledge gaps remain. These efforts provide examples of approaches that can be applied to U.S. OSW studies to fill in knowledge gaps in an appropriate region-specific context.

1.4.2.5.1 Artificial Reef Effects

Long-term monitoring of fish movement and residence within and near wind farms using acoustic and satellite telemetry can reveal how local changes in commercial fish habitat use may affect population/stock productivity. This monitoring approach can be implemented at local and regional scales that span multiple OSW developments to better inform our understanding of the attraction/production functions of the artificial reef effect. Assessments of production will require that spatial distribution and abundance data are complemented with assessments of biomass, potentially incorporating existing long-term surveys (e.g., NOAA stock assessments) and fisheries landings data. Trophic interactions can be informed by targeted studies across the food web using diet analyses, stable isotopes, and condition indices. Assessments of habitat change effects on spawning require seasonally specific data collection and complementary modeling.

1.4.2.5.2 Noise

Studies of the effects of construction and operational noise on fish should target the life stages expected to be exposed. While detection and responses to noise can be assessed in aquaria and mesocosm studies, the ability to evade noise is important and is better examined in situ using free-swimming fish. Behavioral and physiological assessments are informative, especially when complemented with the soundscape, which will offer insights on potential masking of important audio cues (e.g., in situ recording of operation noise and biological communications). Knowledge of noise attenuation is a critical component of experimental design and effectively siting reference locations.

1.4.2.5.3 EMF

Improving our understanding of the effects of EMF in demersal species can be achieved by a combined complementary approach of controlled aquarium studies, in situ exposures (e.g., mesocosms, telemetry), and modeling. Determination of a likely encounter rate requires a strong knowledge of the movement ecology of species of interest and may include telemetry and modeling of species movements over various spatial and temporal scales (vertical and horizontal) and knowledge of cable routes with consideration of potential cumulative effects. Laboratory and/or field studies can be designed to assess effects in appropriate life stages (including mobile and sessile species/life stages) likely to encounter EMFs and may use behavioral and physiological metrics as appropriate. Aquariums studies may be used to assess effects in later life stages following early life stage exposures and dose-response relationships in various life stages. Dose-response relationships would also benefit in situ approaches to real cable EMFs. Derivation of natural EMF cues (predator, prey, locational) in the presence of cable EMFs can be assessed in aquarium and field studies. Effects can be assessed by before/after cable installation and telemetry/mesocosm studies and combined with models to assess potential energetic consequences. In general, AC and DC exposures should be considered, as should all components of the EMF (i.e., magnetic field, induced electric field, motion-induced electric field). Biological/ecological experiments can be better informed by improving our understanding of EMFs from OSW cables (Section 1.4).

1.4.2.5.4 Hydrodynamics and Wind Wake Effects

The effects on demersal fish of changes to hydrodynamic conditions and wind wakes can be best informed by a local/regional understanding of these effects in the U.S. (e.g., Cold Pool; Section 1.4). Predictive modeling on larval transport, connectivity, and recruitment can be included and model results later verified with in situ data collection. Baseline studies on species of concern can be developed based on present knowledge of larval transport, connectivity, and recruitment (modeling and data collection) and hydrodynamics.

1.4.2.5.5 General

Generational effects with regard to adaptation and evolution in offspring can be assessed in aquarium studies using model species with short life spans. Similarly, early life stage exposures resulting in later life stage consequences can be assessed in controlled settings using model species. Multimodal stessor experiments (e.g., vibrational noise and EMF, EMF and heat) can be designed for controlled environments using multifactorial experimental designs. Cumulative effects require that responses that may seem inconsequential at a local scale are given appropriate consideration when scaled to effects of larger wind farms (see Chapter 4.1). The potential for a spillover effect (i.e., increased fish abundances on wind farm margins) can be best demonstrated with strong baseline records of the abundance and distribution patterns of species of interest both within and outside of the wind farm. In the U.S., potential sources of baseline information include state and federal trawl surveys, as well as vessel monitoring system data, which documents the general locations of fishing vessel activity. A concern exists, however, related to the loss of information that will occur in federal trawl surveys when some long-term sampling stations are no longer accessible following turbine installation. Scaling up to regional effects will require the development of well-informed models, accounting for the influence of other changes in the environment that affect fish distributions (e.g., climate change).

1.4.2.6 Acknowledgements

We thank David Goethel for his careful reviews and feedback that improved this white paper.

1.4.3 Small Pelagics

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1.4.3.1 Introduction

Small pelagic finfish are a functionally important species group in the Northeast U.S. Shelf ecosystem; they provide an essential forage base for upper trophic levels and thus play a critical role in overall ecosystem function and dynamics (Link et al. 2008). Although composed of a diverse group of fish, small pelagics are unified by their utilization of pelagic habitats in the adult phase (Table 3). In the Northeast U.S., this group includes both marine and anadromous species. Spawning typically occurs in near shore habitats for marine species and in freshwater streams and rivers for anadromous species. Some species such as Atlantic herring (*Clupea harengus*) and mackerel can also spawn offshore. Eggs of some small pelagic species are sticky and adhere to benthic substrates (e.g., Atlantic herring; gizzard shad [*Dorosoma cepedianum*]) and eggs of other species occupy pelagic habitats (e.g., Atlantic mackerel [*Scomber scombrus*], Atlantic menhaden [*Brevoortia tyrannus*]). Larvae of these species are generally pelagic and frequently form large schools (Galego and Heath 1994). As adults, many are zooplankton feeders, but some consume invertebrates and other fish. Small pelagic species undergo both horizontal and vertical migrations (Sinclair and Iles 1985). Horizontal migrations may occur over long distances and are associated with seasonal temperature changes (Radlinski et al. 2013). Vertical migrations associated with food availability occur on a diel cycle with fish moving upward at dusk and downward at dawn (Studholme et al. 1999). Because of their diverse living habitats through life history, small pelagic fish species may be sensitive to impact producing factors (IPFs) during each stage of OSW development, including EMFs, sound pressure and particle motion, substrate vibration, addition of new habitat, and changes to the hydrodynamic regime. Squid species are addressed in Section 1.4.3 which considers shellfish and crustaceans; however, given their use of pelagic habitats, squid and pelagic fish species may have similar responses to some IPFs.

1.4.3.2 Synthesis of Existing Knowledge

1.4.3.2.1 Electromagnetic Fields

Buried cables associated with OSWs may alter the electromagnetic field. Potential impacts for fish include altered water column orientation, navigation, migration patterns, stopover rates, attraction to structure, dwell time, and ability to detect prey, predators, and mates (COWRIE 2004; Gauldie and Sharp 1996; Gill et al. 2004; Rothermel et al. 2020). Pelagic species are less likely to encounter buried cables compared to species occupying benthic habitats (Snyder et al. 2019); however, adults utilize benthic habitats for foraging or reproduction and thus could still experience EMF impacts (Chase 2002; Overholtz and Friedland 2002). EMFs have been shown to disrupt foraging and exploration for some benthic species (Hutchison et al. 2020b). Although pelagic species may experience impacts from offshore wind developments while using benthic habitats or during periods of vertical migrations, there is little information on these topics. Pelagic species may be particularly sensitive to induced electric fields during early life stages when they use shallow water nurseries.

For species that undertake long distance, time-limited migrations and utilize EMFs as migratory cues, impacts from EMF could be particularly challenging (Nyqvist et al. 2020). The sensitivities of small pelagic species to EMFs and the potential for cable EMFs to disrupt migration patterns is not well understood. Normandeau (2011) monitored the abundance of finfish species on the east and west sides of the sea-to-shore cable. Their finding—that the abundances of 4 species (Baltic herring [*Clupea harengus membras*], common eel, Atlantic cod, and European flounder [*Platichthys flesus*]) differed on the east vs. the west side of the cable—was attributed to a partial impairment of migration. Impacts on migratory patterns could have long-term implications. A review by Corten (2002) found that herring tend to develop migratory routes early in life history and maintain those patterns even after the environmental stimulus that triggered the change no longer exists. That is to say that after a recruiting year-class of herring changed their migration route, the new migration route was repeated each year. More study is needed to understand whether and how EMFs from OSWs could affect patterns of migration and the implications for reproduction.

1.4.3.2.2 Sound Pressure, Particle Motion, and Substrate Vibration

Small pelagic species such as Atlantic herring have demonstrated sensitivity to both sound pressure and particle motion (Popper and Hawkins 2019). In the context of offshore wind development, there is limited information available about the sensitivity or biological responses of finfish, including small pelagic species, at any life stage to sound pressure, particle motion, or substrate vibration (Mooney et al. 2020).

During the site exploration phase, sea floor mapping is conducted using multibeam and side-scan sonar surveys which ensonify the water column and bottom substrate. Current laboratory studies suggest that Clupeid species (e.g., herrings, shads, and menhaden) can detect mid-frequency active sonar (Mann et al. 1997) but show no behavioral responses (Doksæter et al. 2012). This limited evidence indicates that these species would not experience direct mortality, internal tissue damage, or population-level effects (Sivle et al. 2014).

During the construction phase, the striking of piles with impact or vibratory hammers during foundation installation creates sound pressure and particle motion in the water column and substrate vibration (Madsen et al. 2006; Anderson et al. 2017). Field measurements estimate these sounds at 220 dB re 1 μPa at a range of ~10 m and 200 dB re 1 μPa at a range of 300 m from 0.75 m and 5 m diameter piles, respectively (Reinhall and Dahl 2011). This overlaps the auditory range for many fish species, including small pelagics (Popper et al. 2019b; Popper and Hawkins 2019). In situ studies found that Atlantic herring demonstrated the best hearing in response to pure tone stimuli across a range of frequencies compared to Atlantic cod, common dab, and Atlantic salmon (Popper and Hawkins 2019). Field sound playback experiments in which behavioral responses were studied with sonar/echosounder methods provide some insight into how some small pelagic species respond to construction sounds (Hawkins et al. 2014). Schools of mackerel were found to change depth, and sprat (*Sprattus sprattus*) schools were reported to disperse in response to impulsive pile-driving sounds; these responses increased in likelihood as the sound intensity increased (Hawkins et al. 2014). For sprat, the sound pressure levels to which the fish schools responded on 50% of presentations were 163.2 and 163.3 dB re 1 μPa peak-to-peak, and for mackerel, the single strike sound exposure levels were 135.0 and 142.0 dB re 1 μPa(2) s, as estimated from dose response curves (Hawkins et al. 2014). Cluepids can also be sensitive to other anthropogenic sounds, such as acoustic alarms (with a frequency of 10 kHz and source level of 132 dB reference pressure 1 μPa, measured at 1 m) designed to reduce marine mammal entanglement (Kraus et al. 1997).

During the operational phase, sound and vibration produced in the nacelle of the rotating turbine propagates into the water column and potentially into sediment. Unlike other sound sources, operational sound will be stationary and continuous over the entire life span of the OSW, creating the potential for long term cumulative effects (English et al. 2017). The impacts of operational sound on finfish are relatively unstudied. Early reports indicated that sound produced during operation was limited (frequency <1kHz; Madsen et al. 2006). A recent literature review of operational sound produced by turbines ranging in size from 0.2-6.15 MW found that sound levels ranged from 81-137 dB and across a frequency range of 14-400 Hz, and were relatively low and similar to that of the sound produced by a large cargo ship at a similar distance (Tougaard et al. 2020). Distance from sound source, turbine size, and wind speed were important drivers of sound levels (Tougaard et al. 2020). In addition, rotating blades also produce low frequency vibrations (1-6 Hz) and particle motion within 10m of the turbines (Sigray and Andersson 2011).

Although sound attenuates with distance, cod and herring may detect operational turbine noise as far as 4-5 km from an operating turbine (Thomsen et al. 2006). Laboratory studies conducted by Mann et al. (2001) found that Clupeids responded to low-frequency noises similar to the constant low frequency noise emitted from an operational OSW but that only the subfamily Alosinae (e.g., American shad) were responsive to ultrasonic sound (Mann et al. 2001; Popper et al. 2004). The decommissioning phase could involve the removal of piles using methods similar to installation. This would also produce sound pressure and particle motion in the water column as well as substrate vibration, although little research has been done on this phase in the context of offshore wind.

As noted by Mooney et al. (2020), Popper et al. (2019a), and Hawkins et al. (2021), while there is some limited information available on some species of finfish (including small pelagic species), for the vast majority of species, there is a paucity of information on acoustic impacts for each phase of offshore wind development during each life stage of the species.

1.4.3.2.3 Artificial Structures

Turbine foundations and the complex epibenthic communities that live on them add new 3D habitat to the pelagic zone that previously did not exist (Boehlert and Gill 2010). Turbines and associated communities may act as FADs for small pelagic species (Wilhelmsson et al. 2006; Degraer et al. 2020a). Small pelagics such as horse mackerel and Atlantic mackerel have been collected near turbines in the Belgian North Sea using line fishing (Mavraki et al. 2020c, 2021a). However, van Hal (2017) reported no clear associations of mackerel or horse mackerel at an OSW using Dual-Frequency Identification Sonar (DIDSON) in the Dutch North Sea during periods of migration. Similarly, Floeter et al. (2017) found no spatial patterns of clupeid species in the German North Sea using towed hydroacoustic methods. At BIWF in the U.S., there have not yet been targeted studies of small pelagic finfish, although monitoring with demersal trawls has provided data on Clupeids and other pelagic species. These data show that in some years, herring, butterfish (*Peprilus triacanthus*), and other schooling species were abundant at BIWF, accounting for as much as 74% of the catch, but in other years, these species were less abundant (Wilber et al. 2020).

Some small pelagic fish species may utilize the complex biogenic habitats on turbine structures as hiding places or refugia from predators (Wilhelmsson et al. 2006). Other small pelagics may be attracted by foraging opportunities. Analyzing the carbon and nitrogen stable isotopes of fish associated with foundations, Mavraki et al. (2020c, 2021a) showed that horse mackerel fed on tube-building amphipods living on the foundations whereas Atlantic mackerel collected near foundations were primarily consuming zooplankton and suspended organic matter. Wang et al. (2018) demonstrated seasonal shifts in the zooplankton community after wind farm construction compared to before, and Floeter et al. (2017) found differences in the zooplankton community inside vs. outside of a wind farm. This suggests that food resources for zooplanktivores may be altered by operational turbines, as well.

OSWs have the potential to affect both vertical and horizontal migration patterns. Placing feeding oases or predation refugia in the flyway (sensu Secor 2020) of migrating fish species may cause individuals or schools to change course or increase dwell times in OSW areas, potentially creating opportunities for energy acquisition or increasing predation risk. These topics require further investigation.

Ecosystem models have been used to examine the impact of OSWs on marine ecosystems. Wang et al. (2019) developed Ecopath with Ecosim Modeling Suite (EwE) models using both pre-construction and post-construction data from the Jiangsu coastal ecosystem of China and found an increase in primary production and detritus, and thus an increase in the food supply for zooplankton, which subsequently provided forage for planktivorous species (particularly anchovies) that were consumed by benthic fish.

1.4.3.2.4 Hydrodynamics

Hydrodynamic patterns are altered at offshore wind developments (Clark et al. 2014). Changes in the hydrodynamic regime could alter the spatial distribution of thermal habitats for small pelagic fish and food resources for zooplanktivorous fish. Localized changes in the hydrodynamics at the scale of individual turbines and wind farms are possible as currents pass by structures and modify downstream turbulence, surface wave energy, and upwelling patterns (Bakhoday-Paskyabi et al. 2018; Clark et al. 2014; Brostrom 2008). Much larger scale effects (~80 km from structures) on hydrodynamics and vertical stratification are possible through the impact of wind wakes and coupling of the ocean and atmospheric systems (Schrum 2020; Schultze 2020; Carpenter et al. 2016.). Physical and biological oceanographic processes are directly linked through numerous mechanisms, including the vertical and horizontal transport of macro- and micronutrients to primary producers and the distribution of suspended particulates affecting the depth of the photic zone. Thus, altered hydrodynamic patterns have the potential to affect vertical stratification of the water column, as well as primary and secondary production and upper trophic levels.

These conceptual linkages have been demonstrated with empirical data in the southern North Sea, which revealed increased vertical mixing at an offshore wind development resulting in the transport of nutrients to the surface mixed layer and subsequent uptake by phytoplankton in the photic zone (Floeter et al. 2017). Wang et al. (2018) found a shift in the zooplankton community from larger to smaller cells after wind farm construction compared to pre-construction; these changes were linked to changes in water column properties (e.g., water temperature, dissolved oxygen, and suspended matter concentration). Floeter et al. (2017) sampled both the zooplankton community and the pelagic fish community by towing hydroacoustic instruments along transects that traversed both the inside and outside of a wind farm. Although they found no change in the pelagic fish community (primarily sprat and mackerel), Floeter et al. (2017) did find a shift in the zooplankton community with increased meroplankton densities in waters that had drifted through the wind farm that were believed to be from spawning echinoderms inside of the wind farm.

In the U.S., there has been some discussion regarding potential impacts of OSW development on the Mid-Atlantic Cold Pool, a persistent band of cool water (20-60m thick) near the seabed between Georges Bank and Cape Hatteras. The Cold Pool is surrounded by warmer waters and is separated from surface waters by the thermocline. For many northerly fish species, the Cold Pool serves as the southern limit of distribution. In their synthesis, Miles et al. (2020) highlight that previous analyses of OSWs on regional hydrodynamics have been conducted in European water bodies with stratification regimes that differ from those of the Mid-Atlantic coast of the U.S. To understand OSW effects on the U.S. Mid-Atlantic Cold Pool, oceanographic patterns specific to this region, as well as foundation size and type, hub height, and blade length would need to be considered (Miles et al. 2020).

Sediment resuspension by hydrodynamic action can increase turbidity, affecting prey and predator detection. Pelagic species such as herring and smelt have been shown to exit areas of elevated fine-grain sediment suspension. For example, herring exited at sediment concentrations of 10 mg/L and smelt exited at sediment concentrations of 20 mg/L (COWI/VKI 1992). Deposition of suspended materials may also affect egg survival for some pelagic species. For example, Hywind Park offshore wind development in Northeast Scotland is known to overlap with the spawning and nursery grounds of herring (Statoil 2015) whose demersal eggs adhere to bottom substrates, preferably gravel (Napier 1993). A laboratory study conducted by Westerberg et al. (1996) showed that for herring, suspended sediment reduced buoyancy and increased the rate of sinking of eggs and increased larval mortality at concentrations of 10 mg/L. Some reports suggest that herring egg survival and development can tolerate high concentrations of suspended sediments, yet smothering is possible (Birklund and Wijsam 2005), which could have detrimental effects on recruitment.

Modified patterns of thermal stratification and water currents also have the potential to affect larval transport, as well as vertical and horizontal patterns of migration, through impacts on water temperature and food availability. These topics are understudied in the context of OSWs.

1.4.3.3 Knowledge Gaps

- **Species- and life stage-specific sensitivity and behavioral responses to impact producing factors:** There is limited information available on how individual species of small pelagic fish or their life stages are affected by EMFs, sound pressure, particle motion, substrate vibration, artificial structures, and hydrodynamic changes in the context of offshore wind in the Northeast U.S.
- **Patterns of abundance and distribution at OSWs:** Targeted studies of small pelagic fish at offshore wind developments in Europe or in the U.S. are rare. In the absence of these data, it is difficult to assess how, when, and the degree to which small pelagic fish utilize OSW habitats.
- **Impacts on vertical and horizontal migration:** Migration is a key element in the life history of small pelagic fish species. All impact producing factors have the potential to alter patterns of vertical and horizontal migration.
- **Impacts on spawning habitats:** Utilization of benthic and pelagic spawning habitats has the potential to be affected by OSW impact producing factors.
- **Feeding dynamics of small pelagic fish at OSWs:** Small pelagic fish include many important forage fish that support upper trophic levels on the Northeast U.S. Shelf. Understanding their feeding dynamics at OSWs are key to understanding

how wind development is affecting food web dynamics locally and potentially regionally.

- **Effects on physical oceanographic processes and linkages to biological effects:** OSWs may affect water currents, upwelling, downwelling, vertical stratification, and other hydrodynamic patterns. These modifications may affect zooplankton distribution and thus resource availability for small pelagic fish.

1.4.3.4 Perspectives of the Fishing Industry

The fishing industry is highly concerned about OSW activities negatively impacting targeted species and reducing access to fish because of turbines. Because fish are known to be sensitive to sound (Krauss et al. 1997; Mann et al. 2001; Thomsen et al. 2006), fishermen are concerned that they may be deterred from OSW developments. Given the limited information regarding the impacts of long-term exposure of fish to persistent sound, the fishing industry is highly concerned that this could result in major shifts in distribution. As outlined in the Sound and Pressure and Particle Motion section above, the sensitivity of species like herring to sound makes them vulnerable to large-scale OSW development and may deter herring from these areas, potentially resulting in a shift in distribution and availability to the fishery.

1.4.3.5 Recommendations for Future Research

- **Sound pressure, particle motion, and substrate vibration:** Field and laboratory studies exploring the sensitivity to sound pressure, particle motion, and substrate vibration, as well as the physical, behavioral, impacts of sound, are needed. Impacts caused by pile driving and single turbine operation, as well as full build-out operation over time, could be explored. This topic has also been identified as a priority by the fishing industry.
- **Impacts on horizontal migration:** Long-distance horizontal migrations are a key element in the life history of small pelagic fish species. There is little known about how IPFs from OSW development may affect migration. Field studies that explore changes in movement, migration pattern, dwell or stopover time, and behaviors during stopovers would be informative.
- **Impacts on vertical migration:** Diel vertical migrations are an important component of foraging behavior for small pelagic fish species. Field studies that explore how OSW-associated IPFs affect this process are needed.
- **Distribution and abundance studies at OSWs**: Information about how small pelagic fish species are distributed at OSWs and how they utilize OSWs is needed. Such studies could include investigations of aggregations at turbines, as well as distributions occurring throughout the wind farm.
- **Foraging and diet studies:** Small pelagic fish provide the forage base for upper trophic levels. Understanding what species are consuming small pelagics and whether/how rates of predation differ at OSWs would be useful.
- **Impacts from changes in hydrodynamics:** How local and regional hydrodynamic patterns may be affected by OSW operation in the Northeast U.S. and how these changes may affect the distribution and abundance of pelagic fish species, as well as their larvae and food resources, requires investigation.

- **Impacts on spawning grounds:** For wind farms that overlap with spawning grounds of species that deposit benthic eggs, studies of the effect of sediment deposition from construction on egg survival and viability would be needed.

1.4.3.6 Acknowledgements

We thank N. David Bethoney (CFRF), David Goethel (commercial fishing industry representative), and 2 anonymous reviewers for their thoughtful review and comments which greatly improved this white paper. Perspectives of the commercial fishing industry was gained through questionnaire responses and direct conversations with members of industry.

1.4.4 Medium Pelagic, Large Pelagic, and Highly Migratory Finfish Species

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1.4.4.1 Introduction

Offshore wind energy installations are expanding along the U.S. Atlantic coast to help mitigate the growing impacts of climate change by increasing the use of renewable energy (Azzellino et al. 2013; Cronin et al. 2018; Methratta et al. 2020). However, these installations are not without their own impacts on marine resources and their associated fisheries (Azzellino et al. 2013; Haggett et al. 2020; Friedland et al. 2021). In recent years, progress has been made through research to assess the impacts of offshore wind development on various fishery resources, with an emphasis on protected species (e.g., marine mammals, sea birds) and commercially valuable benthic and demersal shellfish and finfish (Wilhelmsson et al. 2006; Tougaard et al. 2009; Bergström et al. 2013; Thompson et al. 2013; Hastie et al. 2015; Krone et al. 2017; Vallejo et al. 2017; Brandt et al. 2018; Hutchison et al. 2020c; Friedland et al. 2021). There has been less emphasis on studies concerning highly migratory finfish species (HMS). This is likely due to the perception that such species, with their high mobility, may be less susceptible to the direct effects of stressors associated with offshore wind construction and operation. While prolonged exposure to localized, acute stressors may be mitigated by these species' ability to avoid disturbed areas as compared to more sedentary species, there remains a number of mechanisms by which HMS may be affected.

For the purposes of this analysis, we consider medium- and large-bodied highly migratory finfish species ("HMS" collectively) to include those species managed by the NOAA Fisheries HMS Management Division (e.g., sharks, billfishes, tunas), as well as other migratory fishes including rays, mackerels, cobia (*Rachycentrum canadum*), striped bass, bluefish (*Pomatomus saltatrix*), and similar mobile predatory fishes (Table 4) that periodically populate and/or migrate through the proposed wind turbine areas on the Northeast U.S. continental shelf. This broad group of fishes includes some of the most commercially and recreationally important species in the western North Atlantic, including bluefin (*Thunnus thynnus*) and yellowfin tuna (*Thunnus albacares*), swordfish (*Xiphias gladius*), blacktip shark (*Carcharhinus limbatus*), and striped bass (Hutt and Silva 2019; NMFS 2020; NOAA 2021a). These HMS also include a number of overfished stocks that have a concerning conservation status, such as bigeye tuna (*Thunnus obesus*), bluefish, blue marlin (*Makaira nigricans*), white marlin (*Kajikia albida*), dusky shark (*Carcharhinus obscurus*), porbeagle (*Lamna nasus*), shortfin mako (*Isurus oxyrinchus*), and sandbar shark (*Carcharhinus plumbeus*), as well as Atlantic salmon, which has not been assessed for vulnerability since 1996 (NOAA 2020; IUCN 2020). Most HMS in this group are high-order marine consumers that play an important ecological role across their seasonal distributions (Cortes 1999; Trenkel et al. 2014; NOAA 2017). While their ranges are broad and migratory patterns dynamic, there is growing information that many HMS will overlap with offshore wind energy areas and be exposed to the stressors associated with development and operation of such areas (Bangley et al. 2020; Kneebone and Capizzano 2020; Rothermel et al. 2020; Shaw et al. 2021). Thus, offshore wind development is likely to affect the distribution, localized abundance, ecology, and behavior of HMS, as well as other species they interact with as predators and prey. Further, given the broad distribution of HMS essential fish habitat in the northwest Atlantic, localized effects of offshore wind may affect populations far beyond wind energy area boundaries.

The purpose of this section is to review and synthesize the available scientific literature on the potential effects of offshore wind development on HMS, identify critical gaps in knowledge, and provide recommendations for future research. This includes such effects as EMFs, acoustic stressors, changes in hydrodynamics, the influence of artificial structures on distribution, and potential disruptions to migration and feeding/foraging. The synthesis will help fisheries managers and relevant agencies assess the potential magnitude (large vs. small, short-term vs. long-term) and direction (positive vs. negative) of impacts on HMS and their associated fisheries in the U.S. Atlantic. It may also serve as a roadmap for marine scientists prioritizing data collection in this emerging area of research.

1.4.4.2 State of Knowledge

1.4.4.2.1 Electromagnetic Fields

The effect that EMF emissions from offshore wind high voltage cables (HVC) have on electrically and magnetically sensitive marine fishes is largely unknown. Mesocosm studies on small demersal species have shown that EMFs can be attractive stimuli (Gill et al. 2009; Hutchison et al. 2018), yet the challenges associated with the husbandry of large pelagic fishes will require field-based studies. Based on what is known in related species, EMF emissions have the potential to be attractive or aversive and could disrupt the foraging or migratory behavior of HMS.

EMF emissions are a function of the HVC composition (single or multi-core), purpose of the cable within the project (inter-array, back to shore), and the type (AC or DC) and power (voltage, amperage) of the electricity being transported (Figure 6; Albert et al. 2020; Hutchison et al. 2020a). As electric current is conducted through an HVC it radiates magnetic field artifacts of 0.05-150 µT (~ 3X of geomagnetic field [GMF]) up to 10 m from the cable, which then induce electric field artifacts of 1-700 µV/m up to 100 m into the surrounding seawater (Gill et al. 2020). The EMF emissions from offshore floating arrays are most likely to impact HMS; therefore, standardized protocols are required to characterize these attributes of EMF emissions (Klimley et al. 2021).

EMF sensitivities of HMS, with an emphasis on sharks and rays, have been previously reviewed (e.g., Montgomery and Walker 2001; Tricas 2001; Normandeau et al. 2011; Claisse et al. 2015; Newton et al. 2019). Sharks are known to bite subsea cables, such as the Trans-Atlantic cable (MacKenzie 1986) and the lightwave subsea cables in the Canary Islands (Marra 1989), presumably due to EMF emissions. A field survey of the fish community near an energized HVC in Southern California showed no significant difference in the presence or absence of EMF sensitive elasmobranchs (Love et al. 2016). Field-based mesocosm studies that acoustically tracked the thornback ray and small-spotted catshark have shown that they spend significantly more time near an energized HVC compared to an unenergized cable (Gill et al. 2009). Likewise, the little skate spends more time engaged in foraging behavior near an energized HVC vs. an unenergized HVC (Hutchison et al. 2018).

1.4.4.2.2 Electroreception

Chondrichthyan electroreceptors respond best to weak (~1 nV/cm) sinusoidal (AC) electric fields with a low frequency range (1-20 Hz) because they are tuned to detect the bioelectric fields produced by prey, predators, and conspecifics (Bedore and Kajiura 2013; reviewed in Newton et al. 2019). Consequently, electroreception primarily mediates foraging (Kajiura and Holland 2002), predator avoidance (Sisneros et al. 1998), mating (Tricas et al. 1995), and communication (Bratton and Ayers 1987) behaviors. White sharks (*Carcharodon carcharias*) prefer bait that emits pulsed but not static DC fields (Tricas and McCosker 1984), whereas blue (*Prionace glauca*; Heyer et al. 1981; Ryan 1981), bonnethead (*Sphyrna tiburo*; Kajiura 2003), scalloped hammerhead (*Sphyrna lewini*; Kajiura and Holland 2002; Kajiura and Fitzgerald 2009), sandbar (Kajiura and Holland 2002), bull (*Carcharhinus leucas*; Collin and Whitehead 2004), and small-spotted catsharks (Gill and Taylor 2001) that are aroused by olfactory stimuli will bite at electric dipoles that emit prey-simulating fields. Additionally, the yellow stingray (*Urobatis jamaicensis*) can distinguish between the positive and negative poles of an electric field (Siciliano et al. 2013), and the euryhaline Atlantic stingray (*Dasyatis sabina*) in freshwater experiences elevated detection thresholds and reduced detection distances to prey stimuli compared to seawater (McGowan and Kajiura 2009).

Electropositive metals shed electrons into seawater, and they have been tested as depredation deterrents in several sharks with mixed results (summarized in McCutcheon and Kajiura 2013). Some species were deterred to varying degrees, while others were not. Similarly, strong magnets have shown aversive responses in a number of sharks (reviewed in Newton et al. 2019). In general, the sensitivities and responses of HMS to EMF stimuli can be species-dependent due to variation in electrosensory and brain morphology, habitat use, and how much a species relies on electroreception for prey detection. Therefore, the few studies available on a small number of species should not be considered representative of the potential effects across the breadth of HMS taxa.

1.4.4.2.3 Magnetoreception

The electroreceptors of the common stingray (*Dasyatis pastinaca*) and thornback ray are known to respond to the onset of magnetic stimuli (Akoev et al. 1976; Brown and Ilyinsky 1978). Electroreceptors are hypothesized to allow chondrichthyans to use the GMF as a cue to orient and navigate (Kalmijn 1978; Molteno and Kennedy 2009). Acoustic tracking shows that scalloped hammerhead movements were highly correlated with localized gradients in magnetic topography (Klimley 1993). Behavioral conditioning has demonstrated sensitivity to GMF strength magnetic fields (25-100 µT) in scalloped hammerhead and sandbar sharks (Meyer et al. 2005), with a lower threshold of 0.03-2.9 µT in the sandbar shark (Anderson et al. 2017). The yellow stingray can use hidden magnets to find food rewards (Newton and Kajiura 2017), use GMF polarity (north-south poles) to navigate a maze (Newton and Kajiura 2020a), and distinguish between the strength and inclination angle of the GMF (Newton and Kajiura 2020b), which are cues used by bonnethead sharks to determine their current location and reorient toward their home range (Keller et al. 2021).

Pelagic teleosts do not have electroreceptors, but some species are known to respond to magnetic stimuli. Magnetoreception has been documented in yellowfin tuna that could detect 10-50 µT changes in the ambient GMF (Walker 1984), and biogenic magnetite, possibly from a magnetoreceptive cell, has been reported in the ethmoid region of yellowfin tuna (Walker et al. 1984) and sockeye salmon (*Oncorhynchus nerka*; Walker et al. 1988). Several salmonids have demonstrated magnetoreception, and these studies are excellent models to test if other species use the GMF to orient and navigate. Juvenile sockeye (Putman et al. 2013), Chinook (Putman et al. 2014), and pink (*Oncorhynchus gorbuscha*; Putman et al. 2020) salmon imprint on the GMF signature of their natal stream. As adults, they use this GMF information as a map to navigate their pelagic habitat and return to their natal stream to spawn. This GMF map sense is present in Atlantic salmon that are anadromous and non-migratory (Scanlon et al. 2018) and European eels (Naisbett-Jones et al. 2017), which suggests that GMF sensitivity is likely present in other teleosts, in particular HMS.

1.4.4.2.4 Sound Pressure and Particle Motion

The ocean is an excellent sound conductor and propagates sound through the water faster with increasing temperature, salinity, and pressure (depth; Urick 1975). All fish can detect sound through particle motion (acceleration, velocity, or displacement) using the inner ear through a direct connection or by way of the lateral line system, but not all fish can detect sound pressure (Radford et al. 2012; Collin et al. 2015). The presence of a swim bladder or similar structure allows species to detect sound pressure through displacement (Collin et al. 2015). HMS covered in this section consist of species across the range of acoustic detection methods, including species with no swim bladder or similar structure (elasmobranchs) to highly evolved structures (billfish). The majority of research on sound perception to date involved the use of sound pressure signals to determine auditory ranges or threshold detection levels, even though most fishes primarily detect particle motion (Popper and Hawkins 2019). For this reason, it is important to describe sound in terms of particle motion as well as sound pressure when studying the effects of sounds on fish (Radford et al. 2012; Nedelec et al. 2016; Popper and Hawkins 2019; Mooney et al. 2020).

The sources and impacts of sound on these species can vary depending on the phase of the offshore wind development project (e.g., pre-construction site surveys, construction, operation, and decommissioning; Mooney et al. 2020). The effects of the noise produced by these phases can result in physical injury or physiological changes producing stress and mask other biologically relevant sounds that elicit behavioral responses (Popper and Hawkins 2019). Mortality or injury to hearing tissues may occur from pile-driving noise (Popper and Hastings 2009), though fish anatomy may affect vulnerability. Laboratory studies on juvenile hybrid striped bass and Chinook salmon exposed to acoustic pressure levels similar to those of pile-driving showed the striped bass exhibited more extensive injuries than the salmon due to the salmon's more primitive swim bladder (Casper et al. 2013a, 2013b). Behavioral responses to introduced noise have been noted in some HMS. Chapuis et al. (2019) found fewer interactions with baited underwater video rigs from 3 shark species when subjected to artificial noise than during silent control periods. Commercial and recreational fishermen reported the absence of striped bass during pile driving at the BIWF, but they were found on the other side of the island where no construction occurred (ten Brink and Dalton 2018).

Operation noise levels are not generally associated with direct physical injury, but short-term behavioral modification has been noted in at least 1 HMS study. Bluefin tuna located in a fixed commercial fattening cage in the Mediterranean Sea were exposed to low-frequency noises created by a wind turbine, and their behavior changed during exposure with schools shrinking in diameter, moving up to the surface, and some individuals appearing to be disoriented (Pérez-Arjona et al. 2014). Long-term (days) exposures could have negative effects on communication, foraging, and predator detection in some species (Mooney et al. 2020). Additionally, cumulative noise levels may be elevated in close proximity to a wind farm under very low ambient noise conditions, which could lead to masking of biological sounds but be below ambient levels in areas with high ambient noise from shipping or high wind speeds (Tougaard et al. 2020). Species biology, behavior, and proximity to the turbines should all be considered primary factors when examining noise exposure to HMS from offshore wind turbines.

1.4.4.2.5 Artificial Structures

No studies have directly examined the effects of offshore wind development or operation on the distribution or movements of HMS off the Northeast U.S. However, inferences about these effects can be drawn from studies in other areas and on the behavior or response of species of similar size and demography to both natural and anthropogenic structures. Karama et al. (2021) reported that Japanese yellowtail (*Seriola quinqeradiata*) exhibited low affinity to a single offshore wind turbine off the coast of Japan over the course of 1 year but speculated that this may have been environmentally driven. In contrast, numerous studies have reported that HMS aggregate around anthropogenic structures, such as oil and gas platforms and FADs, with tunas and mackerels and jacks being the most commonly-observed species (Roundtree 1990; Edwards and Sulak 2002; Jablonski 2008; da Silva et al. 2015; Snodgrass et al. 2020; Todd et al. 2020). Medium and large migratory predators such as jacks, mackerels, and sharks (particularly sand tigers [*Carcharias Taurus*]) have also been documented to occur in higher densities on artificial reefs than on nearby natural reefs off the coast of North Carolina, potentially due to the increased complexity and vertical relief of the artificial reef structures (Paxton et al. 2020). This increased aggregation was speculated to occur due to increased feeding opportunities on smaller reef-associated species or the more frequent visitation of structures with high vertical relief (e.g., shipwrecks) that serve as waypoints along the migration corridor of a species. Thus, trophic-level interactions may be one of the factors driving the aggregation or use of artificial structures by HMS. For example, whale sharks (*Rhincodon typus*) have been observed in large aggregations around oil platforms in the Arabian Gulf in association with mackerel tuna (*Euthynnus affinis*) spawning events, the latter of which may be occurring due to the aggregation of tuna around the oil platform (Robinson et al. 2013). Although at least 20 porbeagles were observed in the surface waters of the North Sea circling an oil platform over several days during seismic surveys, no feeding events were witnessed (Haugen and Papastamatiou 2019).

Trophic interactions associated with artificial structures (such as wind turbines) have the potential to impact HMS over variable spatial scales and life stages, particularly for species that undergo extensive migrations between feeding and mating/spawning areas. For example, aggregation of prey species in offshore wind developments may lead to improved feeding opportunities for HMS, which in turn may increase fitness by enhancing juvenile growth rates, improving gamete quality, and improving animal condition during reproductive events (e.g., migration to spawning/mating areas, gestation). Conversely, displacement of HMS from traditional feeding grounds due to wind turbine construction or operation may reduce feeding opportunities and decrease fitness across all life stages due to several factors (e.g., increased competition in alternative feeding areas, feeding on less desirable prey). In any event, localized impacts of wind turbines have the potential to impact HMS throughout their natural range, particularly if they are constructed in essential fish habitat (e.g., nursery areas, feeding areas, mating or pupping areas).

1.4.4.2.6 Hydrodynamics

Studies have shown that the turbulent wake produced by offshore wind developments can generate upwelling events in local ecosystems (Broström 2008; Segtnan and Christakos 2015; Carpenter et al. 2016). This can occur when wind or tidal driven currents move past offshore wind structures. The turbulence promotes vertical mixing of the stratified water column when the size of the wake is the same size or larger than the internal radius of deformation, or internal Rossby radius (Broström 2008; Carpenter et al. 2016). Magnitude of the vertical mixing increases with wind farm size and is also affected by the design of the wind farm (Broström 2008; Segtnan and Christakos 2015). The resulting turbulent wake and vertical mixing caused by the presence of wind farms can also increase the turbidity and alter the flow conditions of the surrounding water, which can affect the visibility and modify transport of nutrients and odor plumes (Shields et al. 2011).

Northwest Atlantic shelf waters are highly stratified during the late spring through early fall with a strong thermocline and shallow mixing layer (Mann and Lazier 2006; Li et al. 2015). Such hydrodynamics help to aggregate a variety of prey in dense patches and provide seasonal foraging habitat for several HMS, including basking shark (*Cetorhinus maximus*), bluefin tuna, blue shark, ocean sunfish (*Mola mola*), and swordfish (Carey and Robinson 1981; Carey and Sharold 1990; Block et al. 2001; Stokesbury et al. 2004; Wilson et al. 2005; Skomal et al 2004; Skomal et al. 2009; Potter and Howell 2011). Increased upwelling events in these areas could decrease HMS foraging opportunities by reducing stratification of the water column, thereby cooling the mixing layer and dispersing seasonal prey aggregations. Additionally, increased turbidity and modified flow could decrease prey detection for predators using visual or olfactory cues.

1.4.4.3 Knowledge Gaps

Each of the topics discussed in the State of Knowledge section needs further research to better evaluate the impact of offshore wind development on HMS (Figure 7). A better understanding of the individual effects of these stressors is needed, but also the potential cumulative and synergistic effects of all of these stressors that are likely to operate concurrently in HMS habitats. EMFs associated with offshore wind are likely detectable by many HMS over short distances and could interfere with local GMF orientation and foraging behavior. While such EMF disruptions may be unlikely to have direct negative effects in terms of creating barriers to movement, the potential cumulative, long-term effects on distributions and migrations require more study (Klimley et al. 2021). Research on the direct effects of sound from offshore wind or similar sound production on HMS is very limited. The majority of research for HMS is in determining auditory frequency ranges and detection thresholds, which will aid in predictions with respect to offshore wind, but data are still limited for this species group. Laboratory studies were conducted on the sensory biology for a few of the medium-bodied HMS with respect to offshore wind EMF and noise, but results will be species-specific and should not be generalized across taxa. Additionally, given the size of most species in this group, field studies will likely be necessary.

Despite observations of increased use and/or aggregation of HMS at anthropogenic structures (artificial reefs), the true impacts (positive or negative) of this behavior on species' populations at a local or stock-wide scale are poorly understood. For example, while an increased feeding opportunity at an artificial structure may promote animal condition or production, increased fishing pressure at the aggregation site may lead to heightened fishing mortality (Bohnsack 1989; Snodgrass et al. 2020). It is also essential to understand the extent to which anthropogenic structures aggregate species or promote their productivity through increased spawning success (recruitment), increased growth, and decreased mortality. Decommissioning of oil and gas platforms may impact certain species due to their strong attachment and affinity to artificial reef communities created by the structures (Martin and Lowe 2010; van Elden et al. 2019).

Another important knowledge gap is how large-scale operational wind farms in the Northeast U.S. will modify predator-prey interactions. For example, changes in the benthic community structure due to turbines or scour protection may attract HMS in higher trophic levels (Degraer et al. 2020), which in turn could alter HMS migration patterns or residency times in wind farms. Additionally, disruption of stratification in the water column in or around wind farms may alter primary productivity (van Berkel et al. 2020), which is a major factor that influences the distribution and movements of many HMS. These impacts may be direct for ocean sunfish and basking sharks, who seasonally feed on zooplankton, primarily gelatinous and copepod species, respectively, in this region (Desjardin 2005; Skomal et al. 2004; Crowe et al. 2018) and indirectly influence other predatory HMS via potential disruptions to forage fish (e.g., clupeids) and invertebrate (e.g., squid) abundance or distribution in the wind energy areas.

1.4.4.4 Fishing Community Perspectives

Members of the commercial and recreational fishing communities have varying perspectives about the potential impacts of offshore wind development on HMS. In general, there is concern over impacts from all phases of offshore wind development. However, the greatest concerns for these species groups include disruption of migration due to EMF, the displacement of species due to sonar or seismic impacts during exploration, acoustic impacts during construction and operation, and hydrodynamic impacts during operation. Some fishermen believe offshore wind structures will function to aggregate prey, which in turn will aggregate pelagic predators. While this is viewed by some to have a potential positive effect on fishing success, others are concerned that the presence, abundance, and spatial distribution of forage fish will be altered, causing potential displacement of predatory HMS from traditional fishing locations and subsequent disruptions to fishing activities therein. Compared to other taxa, some fishermen believe that HMS will be less impacted by offshore wind construction than less mobile species, while others think these fishes will be impacted as much or even more than demersal fish species. Impacts to tunas (albacore [*Thunnus alalunga*], bluefin, yellowfin) were identified as being of greatest interest. Fishermen appear acutely aware of the broad lack of data on offshore wind impacts on HMS, and regional HMS fisheries, and generally support efforts to reduce such uncertainties. This shared awareness of data limitations is providing some new opportunities for cooperative research between fishermen and scientists.

1.4.4.5 Future Directions

It is clear that scientific research on the impacts of offshore wind development on HMS is an emerging field of study, particularly in U.S. waters. This group of fishes presents unique challenges as well as unique opportunities for experimental work to better characterize these impacts. Our synthesis suggests the following priorities moving forward:

- The most important tool for determining the effects of offshore wind energy is long-term monitoring in wind energy areas during exploration, surveying, construction, and operation. Continuous, well-developed monitoring frameworks for both oceanographic conditions and the biological community are essential for monitoring HMS due to their life histories, sensory capabilities, and diverse movement ecology.
- It is also important to continue long-term monitoring programs already in place in the area, such as conventional tagging programs like the Cooperative Shark Tagging Program (Kohler and Turner 2019) and Cooperative Tagging Center (NOAA 2022a). These programs have collected decades of baseline data on HMS presence and movements in proposed wind energy areas (e.g., Kohler and Turner 2019; Kneebone and Capizzano 2020), and therefore will play a key role in

monitoring for changes in HMS presence and movements due to offshore wind activity. Although there is no associated effort, tag and recapture events from these programs also provide data on fishery interactions within proposed wind energy areas (Kneebone and Capizzano 2020).

- Unlike with commercial fisheries, recreational effort data is generally lacking in proposed wind energy areas, which complicates efforts to assess potential impacts to large recreational fisheries operating in these areas. Surveys and reports of catch data from the Large Pelagics Survey (NOAA 2022b, Marine Recreational Information Program (NOAA 2022c), and Vessel Trip Reports (NOAA 2022d) provide critical spatial information on HMS interactions with fisheries and should be expanded to increase their capacity to assess the impacts of offshore wind development on fishing industries (Kneebone and Capizzano 2020). It would also be beneficial to set up a recreational reporting program that includes effort, through something as extensive as NOAA Fisheries Study Fleet (NOAA 2022e) or something less invasive like a mobile app.
- Standardized surveys designed and executed in collaboration with the recreational, for-hire and commercial fishers targeting the species of interest are also important, such as fishing gear surveys (e.g., fixed/anchored pelagic and bottom and longlines, vertical hook and line, rod and reel) and visual surveys (e.g., aerial, diver, video) for HMS. Biological sampling should occur as a part of each survey to monitor for changes in growth, maturity, energetics, health/condition, and diet over the duration of offshore wind projects.
- Laboratory studies on nearshore and demersal EMF-sensitive species are needed to create standardized dose-response protocols to assess the behavioral and physiological response of HMS to EMFs in the field. Laboratory measurements of energized HVCs are needed to generate spatiotemporal models of EMF emissions. Then variations in HVC current and EMF output can be used to quantify the sensitivity thresholds, habituation time, and potential disruption of foraging and navigation behaviors for several species.
- Field measurements of acoustic and EMF emissions and captive mesocosms can be used to assess short-term behavioral responses of demersal species, whereas long-term monitoring could be achieved through a combination of telemetry, biologging, video and sonar cameras, and machine learning technologies that identify and track or model HMS behavior near HVCs.
- Field-based telemetry studies are also essential to monitor the impacts of offshore wind development on HMS. Passive acoustic telemetry is an ideal method for long-term monitoring of HMS during all phases of offshore wind development and operation and can provide both large (e.g., residency, distribution, migrations, and timing) and fine scale (e.g., structure association, EMF and acoustic behavioral responses) movement data.
- Various forms of satellite telemetry and archival tagging may also be useful for larger species, providing data on movements and swimming behavior within and across wind energy areas and cable corridors before, during, and after construction.

There is much to be learned about offshore wind energy and HMS, but these methods will produce results and increase our understanding of how HMS will be impacted as the development of offshore wind energy expands.

1.4.4.6 Acknowledgements

We thank the participants who provided feedback on our talk at the Fisheries and Offshore Wind Energy Synthesis of Science Workshop and those who participated in the break-out sessions, including Dr. Dave Secor (University of Maryland), Mike Conroy (West Coast Fisheries Consultants, LLC), and Captain Dewey Hemilright (F/V Tarbaby). We especially thank Captain Mike Pierdinock (CPF Charters) and Willy Goldsmith (American Saltwater Guides Association) for continuing discussions throughout the year as we gathered information for this synthesis and for reviewing earlier drafts.

1.4.5 Shellfish and Crustaceans

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1.4.5.1 Introduction

This section focuses on the biological and ecological effects of OSW developments on shellfish resources of commercial interest. The taxa of interest are both crustaceans (e.g., lobster, crab) and mollusks (e.g., clams, scallops, squid); see Table 5 for a full species list. The available literature of known effects is synthesized in the sections below to exemplify the present knowledge base and identify priority knowledge gaps. Where species of interest on the northeastern U.S. coast have not been studied, comparable species from other countries or related species are mentioned to provide context and illustrate present understanding. In synthesizing this information, the methods used are highlighted, and where appropriate, agreement/disagreement between studies and possible reasons are reported. The effects of OSW are broadly categorized and therefore organized as the artificial reef effects, responses to noise, and electromagnetic fields. Note that no specific studies on the effects of heat from subsea cables have been undertaken on shellfish and so are not discussed here, but readers are directed to Section 1b for information regarding heat emissions from cables. Each species may encounter and interact with these factors throughout their life cycle and/or in unison. The potential interactions with OSW effects are demonstrated for the life cycle of lobsters (*Homarus americanus*) in Figure 8. These factors will need to be considered with regard to the potential cumulative effects for the species (see Section 4.1). Knowledge gaps and priorities are then reported with recommendations for future directions/studies.

At the time of writing, a baseline sampling was ongoing at the lease areas for the Vineyard Wind and Southfork Wind projects. Southfork efforts focused on beam trawl efforts for benthic fish species. There was also dedicated work with a Cooperative Ventless Trap Survey (SNECVTS), conducted from 2014-2015. SNECVTS was developed to provide a baseline assessment of the lobster and crab populations in the Rhode Island-Massachusetts WEA prior to offshore wind energy development in Southern New England. The survey was also designed to contribute to the assessment of the Southern New England lobster stock. The study was necessary to establish the pre-construction status of the lobster population (Collie and King 2016; Collie et al. 2019). At Vineyard Wind lease sites, the ventless trap survey with a tagging component targeted adult lobsters, and neuston plankton net trawls targeted the larval life stages of lobsters (Stokesbury et al. 2020). Also at Vineyard Wind, a drop-down camera approach was being used to determine the baseline benthic macrofauna (megafauna) communities within the lease sites (Bethoney et al. 2020 a, b, c). These studies are still ongoing and will build baseline data on the abundance and distribution of the targeted species and communities within these specific sites.

1.4.5.2 Synthesis of Current Knowledge

1.4.5.2.1 The Artificial Reef Effect on Shellfish

The introduction of OSW introduces new hard substrate, often in a previously soft or mixed sediment environment. The increase in hard substrate will result in the loss of the soft sediment environment, which may be important to some shellfish species. This change in habitat is considered in detail in Section 1a. During the operation phase, the OSW infrastructures, including the foundations, scour, and cable protections, will change the local characteristics by providing a surface for colonization and acting as an artificial reef (Boehlert and Gill 2010). Artificial reef effects include the change in structure and function and expand to include the colonization of the structures, as well as the cascading effects of the community (e.g., organic enrichments, secondary production; Birchenough and Degraer 2020; Dannheim et al. 2020; Degraer et al. 2020).

In Europe, mobile benthic crustaceans, including the European lobster (*Homarus gammarus*) and edible crab (*Cancer pagurus*), are often observed in high densities in the proximity of OSW structures (Coates et al. 2016; Griffin et al. 2016; Krone et al. 2017; Roach et al. 2018; Birchenough and Degraer 2020; Taormina et al. 2020b). Krone et al. (2017) highlighted that the abundance of edible crabs was much higher around turbine foundations than in surrounding areas, concluding that foundations acted as aggregation sites and nursery grounds. Differences in abundance of crabs were found between foundation types; specifically, monopiles with scour protection offered more habitat to crabs (average of 5000 individuals per footprint) than jacket or gravity-based structures. Taormina et al. (2020) studied the mobile fauna of cable protection mattresses (non-energized cables) and identified edible crab and European lobster as residents. It was further reported that the size and number of shelters available influenced the colonization potential for these species. An increased size of European lobster, as well as an increased abundance, was observed during the initial operation of an OSW after temporary fishing closure during the construction period (Coates et al. 2016; Roach et al. 2018).

Early studies of colonization at BIWF support that similar effects will be likely expected at future U.S. OSW developments. Juvenile crabs (*Cancer* spp.*)* were found associated with mussel aggregations under the jacket structures (HDR 2020; Hutchison et al. 2020c). Further work would be required to establish abundance levels per footprint to be comparable with Krone et al. (2017). Similarly, the American lobster was observed taking residence under BIWF concrete mattress cable protections (HDR 2020). Ventless trap surveys conducted before, during, and after construction in the BIWF area and a reference area 22 km distant from the wind farm collected approximately 40,000 lobsters over the first 6 years of a 7-year study (INSPIRE 2021). Results of the first 6 years showed that the abundances reflected regional fluctuations of lobster abundance rather than construction or operational effects of BIWF (Carey et al. 2020; Wilber et al. 2020). It was also reported that female reproductive status, shell disease, and claw loss (cull status) varied spatially and temporally, but trends did not indicate a detrimental effect from BIWF operations (Wilber et al. 2020). Catch rates of bycatch species such as Jonah crab and rock crab (*Cancer irroratus*) were approximately 85,000 and 40,000 total crabs, respectively, over the first 6 years of sampling (Wilber et al. 2020). Lobster catches in Southern New England have declined over recent decades, and Jonah crab, which is caught as bycatch in the lobster fishery (Truesdale et al. 2019), is now targeted, with landings increasing over 6-fold since the early 2000s (ASMFC 2015). Monitoring data from BIWF, therefore, provide valuable information on distribution patterns for this data-poor fishery.

Many studies report an increased abundance of the blue mussel as a colonizing species of the hard substrate offered by OSW structures (Degraer et al. 2020; Section 1.1). This was also observed at BIWF, both on the structures and as aggregations under the jacket foundations with presence in surrounding areas becoming more evident over time (HDR 2020; Hutchison et al. 2020a). Malerba et al. (2017) highlighted the importance of sizes across organisms. Different sizes could influence physiological and ecological responses, translating directly across the transfer of energy and overall ecological performance. In an OSW context, these are important considerations, particularly in areas with large belts of colonizing mussels.

To date, no studies have taken place specifically addressing changes in abundance or distribution of clams (e.g., *Mercenaria mercenaria*) or scallops (e.g., *Placopecten magellanicus*) around or near OSW in the U.S. or elsewhere. While scallops are a commercial species in the U.K. and E.U., the direct and cascading effects of OSW artificial reefs remain a knowledge gap for these species.

Similarly, squid have not been a focus for research regarding artificial reef effects of OSW in the U.K. or E.U. (the effects of noise has attracted more effort; next section). However, studies around BIWF assessed longfin squid (*Loligo pealei*) abundances and found decreases in abundance between baseline and operational phases, and the reduction was less than that observed in local reference areas (Carey et al. 2020). To date, there are no assessments on earlier life stages for squid.

Since the artificial reef effects have largely been addressed in the aforementioned studies by establishing abundances of shellfish, methods have adopted trap surveys (e.g., ventless traps, static creels), diver surveys, and image collection (photography, videography), and grab samples; in the case of squid, beam trawls were also employed. Although the methods are varied, reports of increased abundance of lobsters and crabs are consistent with each other.

1.4.5.2.2 Shellfish Responses to Noise

The introduced sound in the marine environment during construction activities and during operation of OSW can affect benthic fauna, such as shellfish. Sound plays a key role in conveying environmental information to marine organisms for communication, mate selection, and predator-prey interactions in marine species (Roberts and Elliott 2017). Recent advances have focused attention on the importance of particle motion and vibrational sound to marine invertebrates (Hawkins and Popper 2016; Roberts and Elliott 2017).

Generally, commercial species of crabs and lobsters have not been the focus of noise effect studies with regard to OSW. However, recent laboratory experiments of the Norway lobster (*Nephrops norvegicus*) demonstrated behavioral and physiological effects in response to sound mimicking effects of construction and shipping activities (Solan et al. 2016). Responses in this species were reduced mobility and burial, burrow flushing, and changes in their ability to feed; these responses were dependent on whether the sound was continuous or impulsive. Roberts et al. (2016) has demonstrated behavioral responses to vibrational noise simulating pile driving in the hermit crab (*Pagurus bernhardus*). Laboratory studies of a non-commercial species, European green crab (*Carcinus maenas*), with playbacks of pile-driving noise showed decreased mobility and feeding activity (Corbett 2018). While the responses were specific to hermit crabs (e.g., shell searching behaviors) or the studies of non-commercial species, these results support that behavioral responses to sound in commercially important crabs should be investigated.

Responses to particle motion in mollusks were initially demonstrated in laboratory settings, indicating full body vibrations indicative of statocyst stimulations (hearing hair cells) in scallops and squid (André et al. 2015). To date, there are no studies specifically assessing the effects of impact of OSW noise on clams or scallops. However, laboratory studies have highlighted that other bivalves, such as *M. edulis,* respond to vibrational sound within the expected range of pile-driving activities (Roberts et al. 2017). The responses were deemed to influence the overall fitness of individuals due to disruption of natural valve periodicity (Roberts and Elliott 2017). Additionally, *M. edulis* responds negatively to ship-noise playbacks, exhibiting physiological and behavioral changes (Wale et al. 2019). Such effects may be indicative of responses in clams and scallops, but specific assessments for those species would be required to establish the degree of the effect and subsequent ecological implications, particularly due to the different life history traits.

Studies of squid and cuttlefish provide insights on responses to noise. It has been experimentally demonstrated that longfin squid (*Loligo pealeii*) are sensitive to low-frequency particle motion rather than sound pressure (Mooney et al. 2010). These authors suggested that it is likely that squid detect sound from predators and prey and may use low-frequency sound from the local environment to aid navigation. Later experiments of another longfin squid species (*Doryteuthis pealeii*) defined the behavioral response ranges to be 80 to 1000 Hz with variation in response types dependent on the frequency and the sound level, indicating that sound level is an important consideration (Mooney et al. 2016), in assessing responses of squid to OSW noise. Similar aquarium exposures of cephalopods (European squid [*Loligo vulgaris*], common cuttlefish [*Sepia officinalis*], common octopus [*Octopus vulgaris*], and southern shortfin squid [*Illex coindetti*]) to low-frequency sound (50-400 Hz) for 12-96 hours were undertaken to explore physiological effects (André et al. 2011). All 4 species exhibited lesions which were more pronounced with increasing periods of exposure. Presently, there is no available knowledge of noise effects on earlier life stages of squid (e.g., vibrational sound may be important to egg mops).

Recent laboratory studies assessed the responses of longfin squid (*Doryteuthis pealeii*) to OSW pile-driving playbacks in an aquarium setting (Jones et al. 2020, 2021). During playbacks, squid initially exhibited a startle response, as well as body pattern changes, inking, and jetting, which are collectively considered alarm responses often used in defense (Jones et al. 2020). The responses were strongest in the initial period of exposure and then rapidly diminished, suggesting the squid habituated to the noise. Concerns were raised regarding their ability to detect predators during exposure. Later, it was established that they were less likely to capture prey (killifish [*Fundulus heteroclitus*]) during pile-driving playbacks, indicating that noise may impact feeding abilities during construction activities (Jones et al. 2021).

Although cuttlefish are not a commercially valuable species in the U.S., they are closely related and demonstrate similar responses to noise, including habituation (Samson et al. 2014). Therefore, studies of a European cuttlefish species provide useful information from field exposures to noise which may be more representative of noise in their natural habitat. Field studies of the common cuttlefish allowed assessments of statocyst trauma and the onset of lesions to be assessed following exposure to noise at different depths, and therefore distances, from source (Solé et al. 2017). The sound levels at the mesocosms were measured as particle motion and sound pressure. Measured amplitudes were greater at increased water depths due to being closer to the source. In control exposures, the statocysts were intact, but in the exposed squid, the statocyst were often damaged, extruded, or occasionally missing. Such damage was more pronounced 48 hours after exposure. The authors concluded that such changes to the statocysts would alter their ability to perceive sound, which in turn may compromise their behavioral responses to natural sound cues and may impede their capacity to function normally and survive (Solé et al. 2017).

To date, all studies investigating responses of crabs, lobsters, and bivalves have been completed in laboratory-controlled conditions, often using playbacks of pile driving to mimic the noise. There are acknowledged difficulties in playback studies in aquariums due to acoustic conditions (Hawkins and Popper 2016). Similarly, studies have predominantly focused on laboratory-controlled experiments for assessing squid responses to noise. Field studies have advanced our understanding of responses in their natural habitat, but such mesocosm studies do not allow specimens to leave the area therefore reducing their exposure to sound. There is a call for more contextually realistic assessments since, if species are able to leave the area, they may reduce their exposure levels and durations (Hawkins and Popper 2016). Additionally, while the aforementioned studies have focused on injury from acute noise, the potential auditory masking of natural sound cues that are ecologically important to invertebrate species has not been assessed in the context of noise from OSW (Mooney et al. 2020).

1.4.5.2.3 Shellfish Responses to EMF

The transmission of electricity through OSW inter-array and export cables results in the emission of electromagnetic fields into the marine environment that electro- and magneto-receptive species may respond to. There is a concern that these emissions may disrupt natural electromagnetic cues, from which receptive species may derive important ecological information. Examples of crustacea and mollusks responding to geomagnetic cues for the purposes of navigation, either through a magnetic map or magnetic compass sense, exist but are generally not well defined for these taxa (Normandeau Exponent et al. 2011). The best example to date of shellfish using the geomagnetic field to derive locational cues in the absence of other cues, facilitating true navigation, comes from studies of the Caribbean spiny lobster (*Panulirus argus*; Boles and Lohman 2003). The effects of cable EMFs on commercially important crustaceans and mollusks are not well defined; however, emerging studies on lobster and crabs and non-commercial bivalves provide initial insights into potential behavioral and physiological effects of OSW cables (Hutchison et al. 2020b).

Commercial crabs and lobster species have become a focus of studies assessing responses to EMF emissions from subsea power cables using semi-controlled field experiments and responses to magnetic fields in aquarium settings. Choice chambers assessing the position of rock crabs (*Metacarcinus anthonyu*, *Cancer productus*) in relation to exposed, AC-powered, or unpowered cables reported no differences in behaviors (Love et al. 2015). Later, studies of a similar nature reported no differences in the ability Dungeness crabs (*Metacarcinus magister*) and rock crabs (*C. productus*) to cross AC-powered or non-powered cables to obtain food, suggesting that crabs may still be caught in baited traps (Love et al. 2017). However, in aquarium studies, more frequent changes in activities were observed in *M. magister* exposed to DC magnetic fields, suggesting that the species is responsive to magnetic fields (Woodruff et al. 2012). Studies of European species further supported that crabs were responsive to magnetic fields. Aquarium studies of the edible crab revealed an attraction to shelters exposed to AC magnetic fields and disrupted cycles of metabolic markers in crabs exposed to much stronger magnetic field intensities (Scott et al. 2018, 2021).

American lobsters (*H. americanus*) were observed in mesocosms exposed to the EMF of a buried DC cable and compared to their activity in control mesocosms (Hutchison et al. 2020c). American lobsters were found to be closer to the seabed and displayed a change in their distribution in response to the EMF, which was interpreted as an increase in exploratory behavior. In contrast, juvenile European lobsters (*H. gammarus*) in an aquarium setting were not responsive to a gradient of AC and DC magnetic fields (Taormina et al. 2020a), which may be indicative of a species-specific or life stage-specific response.

There are no published studies to date on U.S. commercial species of scallop or clams with regard to the effects of EMF. Mollusks, in general, have received less attention; however, some indications of potential effects may be drawn from non-commercial species. Earlier aquarium studies of *M. edulis* reported no lethal effects when exposed to DC magnetic fields (Bochert and Zettler 2004). Later studies assessing physiological responses in *M. edulis* revealed immunological and stress protein responses to AC EMFs (Malagoli et al. 2003, 2004). Recent assessments of Baltic clam (*Limecola balthica*) indicated geneotoxic and cytotoxic responses to AC EMFs (Stankevičiūtė et al. 2019). To date, there are no published studies on the abilities of squid to respond to electric or magnetic fields of natural or anthropogenic origin.

Varied information on the effects of EMF on shellfish exists, largely due to the variety of methods and endpoints selected to study the species in different contexts. The knowledge base is comprised of information from aquarium-based studies using helmholtz coils to simulate magnetic fields (AC and/or DC; µT – mT range) and semi-controlled field studies exposing animals to subsea power cable EMFs (AC and DC, µT range). There is a need to improve the knowledge base from which to assess effects and impacts for the species and, specifically, the relevant life stages that are likely to be exposed to OSW cable EMFs; this must include consideration of the likely encounter rate and potential for cumulative effects of multiple cable encounters (Hutchison et al. 2020b).

1.4.5.2.4 Hydrodynamic/Wind Wake Effects

Changes in hydrodynamics, wind wake effects, stratification, and subsequent influences on nutrient mixing are detailed in Section 1c. Briefly, studies indicate that changes in wind speeds due to OSW may result in upwelling and downwelling influencing local ecosystems (Broström 2008; Stegtnan and Christakos 2015) and that turbulence of water moving past turbine foundations can alter stratification (Carpenter et al. 2016), influencing nutrient mixing (Floeter et al. 2017). For many shellfish species, hydrodynamics play an important role in the transport of larvae, connectivity between populations, and recruitment to habitats. Therefore, changes in hydrodynamics and wind wake effects may have an influence on the pelagic life stages of squid and pelagic larval life stages of other shellfish species. To date, this has not been assessed in the context of commercial shellfish species. However, studies assessing connectivity for colonizing species, such as *M. edulis*, have been undertaken in the North Sea, indicating that anthropogenic structures enhance their ability to survive offshore, and rare events combined with average migration patterns may increase connectivity between distant populations (Coolen et al. 2020). At the time of writing, ongoing work was assessing Atlantic sea scallop larval dispersal and juvenile transport between U.S. regions (Georges Bank/Great South Channel, the New England shelf and the Mid-Atlantic Bight) with a view to modeling how OSW may influence the population at a regional scale (Chen et al. 2020). Potential effects of changes in hydrodynamics, stratification, and nutrient mixing on shellfish species remains a topic of interest, as does the potential resultant implications for changes in thermal regimes (Narváez et al. 2015; Hofmann et al. 2018). Further advancements in the physical changes from large scale OSW development will be required to inform this topic.

1.4.5.3 Commercial Fishing Perspectives

In addition to synthesizing information from peer-reviewed and gray literature, questionnaires were used to engage further with the fishing community and obtain their perspectives. Populations of particular concern were identified as crustaceans (crabs, lobsters, shrimp), clams and scallops, and market squid due to the lack of attention to date for OSW studies. Specific species were typically not reported, although longfin squid was highlighted, as were horseshoe crabs, Atlantic surf clams, and ocean quahog. Some emphasis was placed on clams, squid, and squid spawning/eggs. Generally, for shellfish, larval life stages (including predation of) were highlighted in addition to adult life stages. Concerns were raised regarding the scale of the studies and translation to the scale of the OSW developments with an overarching concern of cumulative effects and how these would be addressed. All phases of OSW development were raised as having uncertain effects on shellfish populations (pre-construction, construction, operation, decommissioning) and, further, the differences between fixed and floating wind effects. Specific topics of concern which were biological or ecological in nature were ecosystem-level impacts; predator-prey interactions; the specific effects of noise, EMF, and heat on shellfish; as well as the influence of upwelling on larval dispersion and plankton production, and potential cascading consequences through the food web. EMF concerns were emphasized for AC and DC emissions from cables. Operational noise was emphasized with specific mention of vibrational noise. The change in habitat type was specifically mentioned with regard to the loss of soft sediment, which many shellfish species rely on, but was also focused on the potential cascading consequences for other species in the food web and resultant changes in productivity. Particular attention was drawn to the need for focused studies on U.S. species. Assessments of effects and impacts require U.S. context and therefore cannot solely rely on studies from other locations. The present state of shellfish stocks was further highlighted as an important consideration with regard to OSW effects and, again, the potential for cumulative effects.

1.4.5.4 Knowledge Gaps and Priorities

Artificial Reef Effects

- Artificial reef effects (including cascading effects) on clams and scallops (e.g., distribution and abundance relative to OSW) and the effects of organic enrichment, including quality of inputs
- Lobster/crab (specifically U.S. species) distributions relative to turbine foundations, cable mattressing, and scour protection, and potential options to enhance biomass and productivity with nature inclusive designs, if desired
- No known effects of OSW artificial reefs on squid, including early life stages (e.g., egg mops)
- Influence of predator-prey interactions on shellfish populations at specific life stages (i.e., benefits to shellfish where more prey are available and potentially negative influences due to increased prey populations)
- Potential influence of non-native species on shellfish
- Settlement of shellfish species around OSW, larval or juvenile, including consideration of filtration of larvae by colonizing fauna

Noise

- Responses to sound (particularly particle motion and vibrations) by all shellfish with an emphasis on their natural habitat and ability to evade the noise
- Consideration of noise for different life stages and potential masking of sound cues in addition to behavioral or physiological responses
- Quantification of effect of chronic and acute exposures to noise on shellfish at relevant spatiotemporal scales

EMF

- Expected and in-situ OSW EMF exposure intensities
- Determinations of whether the exposure intensities are within sensitivity ranges of commercial shellfish species at relevant life stages with consideration of likely encounter rate
- No information for U.S. commercial mollusk species
- Cumulative effects

Hydrodynamic and Wind Wakes

- Clarification of the potential effects on larval transport, connectivity, and recruitment with particular consideration of upwelling, stratification, and influence on nutrients and thermal regimes

General

- Generational effects of energy emissions
- Early life stage effects of energy emissions on later life stages
- Consideration of multimodal stressors
- Consideration of cumulative effects rather than individual pressures
- Translation of individual-based effects to population-level impacts
- Translation of local scale (e.g., turbine foundation/small wind farm) to large-scale developments and regional scale effects

1.4.5.5 Recommendations for Future Studies

This chapter has considered the current understanding of available evidence on shellfish resources. To help showcase the expected magnitude and footprint of effects, we have included studies that can help to inform hypotheses and modeling studies with potential scenarios. The final sections included a list of current gaps and our recommendations on how these gaps could be tackled with a combination of methodological approaches.

Artificial reef effects in shellfish will require the abundance and distribution of species to be determined around OSW developments at appropriate spatiotemporal scale, using equipment specific for the species of interest, and considering variable infrastructures that may be inhabited. Cascading effects, such as trophic interactions, can be addressed using stomach content analyses of predators accompanied by stable isotope and fatty acid analysis. Predator species, including non-natives, will require knowledge of those species' distributions and consideration of food web analyses. Biomass and condition indices will assist in assessments of changes in shellfish productivity. This can also be applied to the effects of changes in nutrients and plankton. Accompanying efforts to establish biogeochemical changes in the surrounding sediment will help establish the influence of organic enrichment on shellfish. Early life stages or spawning effects will require species-specific seasonal efforts.

Noise assessment can be made in aquarium settings with careful design considerations and are recommended for screening-level studies on species for which information is lacking. Species with demonstrable effects of noise (e.g., squid) are recommended to be studied further in situ, facilitating the possibility to evade the noise, thereby reducing exposure durations. Experimental designs can be informed by spatiotemporal attenuation of noise sources. Noise studies for shellfish species should focus on particle motion and vibrational noise, and consider potential acute and chronic exposures. Assessments of OSW noise and biological soundscapes may be helpful for shellfish, which rely on sound for important cues (e.g., settlement, communication).

The effects of both AC and DC EMF components can be studied in aquarium settings and in situ, accommodating exposure to real cable EMFs. Both are recommended for species likely to encounter EMFs and with particular attention to appropriate life-stages. Consideration of earlier life stage effects on later life stages can be addressed in controlled aquarium settings. A suite of dose-response experiments of behavioral and biological nature are recommended either in aquariums or in situ. Establishing likely encounter rates (i.e., how often will species encounter a cable EMF) is an important component of EMF assessments and can be facilitated by telemetry for mobile species, and may also be informed by modeling for some species. Some sessile species may still have the ability to move closer to or away from cable EMFs, and that should also be a consideration in experiments. The potential for increased exposure for some mobile species requires knowledge of the species movements as well as the spatiotemporal changes in EMF emissions (see Section1.2).

Assessment of the effects of changes in hydrodynamics, upwelling, stratification, nutrients, and thermal regimes are reliant on more information on these physical factors. Nekton trawls can inform larval distributions and modeling of present scenarios compared to OSW scenarios. Improving larval dispersion and recruitment knowledge will subsequently improve models that incorporate biological information. Biophysical models should be verified as far as possible where developments occur.

Generational effects of energy emissions (e.g., noise, EMF) can be addressed in aquarium studies using model species with short life spans. Similarly, early life stage effects influencing later life stages can be addressed with similar approaches. Multimodal stressors (e.g., the co-occurrence of noise, EMF, heat) may be able to be addressed with careful planning in situ and could also be addressed using multifactorial experimental designs. Cumulative effects are an important consideration and may be considered at the level of the species (e.g., through a life cycle) and/or at the scale of the OSW development (small-scale, large-scale). Translation of individual effects to population effects and local scale effects to regional scale effects will require carefully developed and well-informed models specific to the species and present stock.

Acknowledging that OSW effects will generate direct and/or indirect faunal responses, there will also be further expected effects, such as ocean acidification and temperature changes, already happening and influencing for example species' development, physiological responses, survival. These will continue to occur as ongoing pressures. Therefore, it will be relevant to study and assess the effects of OSW within the context of the aforementioned factors. Recording temperature, pH, oxygen, and seasonality during studies is recommended, as is the incorporation into forecasting models.

1.4.6 Community Interactions

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1.4.6.1 Introduction

Interactions between OSWs and fisheries resources occur across trophic levels and life stages during each phase of energy infrastructure development and through biotic and abiotic pathways (Dannheim et al. 2020). This section focuses on community-level interactions or interactions between 2 or more species. There has been limited study on how most of the impact producing factors (IPFs) associated with offshore wind development (e.g., EMFs, sound pressure, particle motion, altered hydrodynamic regimes) affect community interactions. Most studies of modified community interactions have focused on the IPF of infrastructure addition (including foundations, scour protection, and cabling in the case of fixed structures, and submerged platforms, cabling, and anchoring in the case of floating platforms) and creation of new hard bottom habitat, setting the stage for novel community-level interactions that would not otherwise have occurred. Often referred to as the “artificial reef effect,” these include changes in successional patterns of epibenthic invertebrates, competitive relationships, predator-prey relationships, food web dynamics, and potential secondary interactions through trophic transfer, effects on sediment composition via biodeposition, and facilitation of non-native species establishment. Empirical data have been collected at the wind farm scale, but altered community interactions have the potential to reach beyond the footprint of the OSW and affect the regional distribution and abundance of fisheries resource species.

1.4.6.2 Synthesis of Current Knowledge

Community interactions are complex and multifaceted. The introduction of man-made structures creates new habitat for species to utilize. This, in turn, can have regional effects on feeding relationships whether through predation, herbivory, or suspension feeding which underpin the structure and function of the marine ecosystems. Below, we synthesize the current knowledge about the impacts of OSWs on communities both in terms of habitat usage and altered feeding relationships, and explore common tools for studying the impacts of OSWs.

1.4.6.2.1 Succession

The addition of new hard bottom habitat into previously soft bottom areas re-initializes the foundation habitat on which benthic and epibenthic communities can become established. Ecological succession is the process by which new species arrive, settle, grow, reproduce, and die in a habitat over time, thereby altering the species composition, richness, and diversity of the habitat (Connell and Slayter 1977). Competition for resources such as space, food, and mates underlies successional patterns. Species composition may change in the same habitat over time as new migrants arrive and resource availability and competitive outcomes change. Ultimately, a terminal climax community may become established once the community is stabilized and has reached an equilibrium with the surrounding ecosystem. Studies of successional patterns for epibenthic communities at OSWs have revealed some key patterns (Wilhelmsson and

Malm 2008; Kerckhof et al. 2010; Lindeboom et al. 2011; Langhamer 2012; Krone et al. 2013). In the Belgian North Sea, the longest study of succession on OSW turbine foundations identified 3 stages of succession: pioneer (2 yrs), intermediate (2-10 yrs), and climax with clear dominants (Kerckhof et al. 2019). Colonization of installed structures was rapid and dependent upon the planktonic propagules that were available to settle the surface (Kerckhof et al. 2010). Early species were those capable of colonizing ephemeral habitats quickly, expanding rapidly, and producing numerous offspring (De Mesel et al. 2015). Richness and evenness increased over time (Kerckhof et al. 2010; Hutchinson et al. 2020). The potential for sound to affect settlement patterns has been demonstrated by laboratory playback studies in which sound levels associated with passing vessels induced settlement in blue mussels (Wilkens et al. 2012; Jolivet et al. 2016). Altered hydrodynamic regimes at OSWs may affect the delivery of larvae for benthic and epibenthic species (Christiansen et al. 2022; Chen et al. 2020; van Berkel et al. 2020).

Patterns of vertical zonation in the intertidal and subtidal portions of turbine foundations are reported in the North Sea (Degraer et al. 2020a; Figure 9), and these patterns are believed to be maintained by competition as well as predation and environmental tolerances (De Mesel et al. 2015). De Mesel et al. (2015) found clear vertical zonation patterns in communities on man-made structures: a splash zone dominated by a marine midge (*Telmatogeton japonicus*), an intertidal and shallow subtidal zone dominated by barnacles (*Semibalanus balanoides*) and blue mussels, and a deeper subtidal zone composed of a community that included several amphipods, polychaetes, crab species, and echinoderms during various successional stages. Other studies in the North Sea found similar patterns: the intertidal zone dominated by barnacles and mussels and the subtidal zone dominated by tubicolous amphipods, hydroids, and anemones (Andersson and Ohman 2010; Krone et al. 2013; van der Stap et al. 2016). At BIWF in the U.S., vertical zonation was not yet evident 4-years post-construction (Hutchison et al. 2020b) which would indicate that a climax community has yet to be established.

1.4.6.2.2 Artificial Reefs and Community Structure

The addition of artificial structures, scour protection, and rock dumps together with the subsequent 3D biogenic reefs that form on this artificial hard bottom create complex habitat for numerous species, a pattern reported across European OSWs and in the U.S. (Figure 9; Degraer et al. 2020a; Hutchison et al. 2020b; Andersson and Ohman 2010; Langhamer 2012). Interstices in between mussels and other sessile attached invertebrates on and around the turbines can provide habitat for small crustaceans, such as amphipods, and increase biodiversity of macroinvertebrates on the turbines which provide forage for predators (Ragnarsson and Raffaelli 1999; Norling and Kautsky 2007, 2008; Wilhelmsson and Malm 2008). The benthic and epibenthic communities attract a biodiverse community of mobile macrobenthos, including decapod crabs and sea stars, as well as reef-associated finfish and their predators (Langhamer et al. 2012; Degraer et al. 2020a; Hutchison et al. 2020b; Carey et al. 2020). Cables covered by rock armoring can also be colonized by epibenthos (Sheehan et al. 2020). The resulting “reef effect” gives rise to a biodiverse and complex ecosystem associated with turbine structures that could have energetic implications beyond the OSW depending upon the site fidelity, mobility, and migratory behavior of species that feed there and the scale of development (Reubens et al. 2011, 2013; Russell et al. 2016). In the Northeast U.S. Shelf ecosystem, the addition of new hard substrates associated with wind development will represent a conversion of habitat from soft bottom (e.g., fine and coarse sands) to hard bottom in many instances. Soft bottom habitats are important for many fish species across life history stages (Kritzer et al. 2016), and thus the reduction of those habitats may have important population-level implications (Barbut et al. 2020).

1.4.6.2.3 Predation

Predator-prey dynamics are an important determinant of community structure in marine ecosystems. New habitats introduced by OSW structures alter predator-prey interactions by aggregating prey and predator species at and around the turbines (Reubens et al. 2011), providing benthic and epibenthic forage for predators, and providing refuge spaces for prey species (Gill et al. 2020).

Predation risk is likely to be dependent on life stage and the IPFs during each stage of wind development. For example, Gill et al. (2020) illustrated these dependencies using *Homarus* species as an example: During construction, elevated turbidity could reduce visibility and thereby decrease capture efficiency of visual predators of lobster larvae. During the operational phase, juvenile lobsters utilize hard bottom habitats associated with the OSW as refuges from predators. Juveniles are unlikely to leave burrows but could be forced out by vibration or EMF associated with development, which could lead to increased predation risk (Gill et al. 2020). Limited evidence from laboratory studies supports that effects on predation risk may occur and that these effects may be life stage dependent. For example, Dungeness crab have demonstrated responsiveness to magnetic fields (Woodruff et al. 2012) and edible crab are attracted to shelters when exposed to an AC magnetic field (Scott et al. 2018) in laboratory settings, which could affect foraging by or predation on these species.

Direct empirical evidence of predation and species-specific feeding relationships at OSWs has been reported for the epibenthic community attached to the turbines, within the scour protection zone, and between turbines using diet studies and stable isotope analyses (Reubens et al. 2011, 2014a; Mavraki et al. 2020, 2021b; Wilber et al. 2022b; Raoux et al. 2020). Laboratory investigations have shown that sound produced by pile driving is associated with failed capture rates and higher failed predation in longfin squid (*Doryteuthis pealeii*; Jones et al. 2021). At BIWF, monthly diet composition data based on stomach content analysis has been described for key predators (Atlantic cod, red hake, silver hake, spotted hake, summer flounder, and winter flounder) over a 7-year time span, including pre-construction years (Wilber et al. 2022b). Ten times more winter flounder consumed blue mussels during operation compared to baseline, reflecting the increase in abundance of mussels due to the presence of structure (Carey et al. 2020; HDR 2020a; Wilber et al. 2020). Crabs were found in the stomachs of black sea bass at BIWF while lobster were not (Carey et al. 2020). Carey et al. (2020) recommend measuring the metrics of diet composition and stomach fullness for future OSW monitoring. Wilber et al. (2022b) found blue mussels, an epibenthic species that colonized the foundations at BIWF, to be more common in the stomachs of predators, including Atlantic cod, haddock, red hake, silver hake, and winter flounder, following construction.

In the Belgian North Sea, Mavraki et al. (2021b) used stomach content analysis and stable isotope data to determine feeding relationships: 2 benthopelagic species (pouting and cod) both consumed a tube-building amphipod (*Jassa herdmani)*; 1 benthic species (sculpin [*Myoxocephalus scorpioides*]) mainly consumed decapods; 1 pelagic species (horse mackerel) opportunistically fed on zooplankton at the OSW while another pelagic species (mackerel) did not feed at the OSW. This was consistent with the findings of stomach content data and diver observations reported by Reubens et al. (2011) that showed that pouting consumed *Jassa* and the porcelain crab (*Pisidia longicornis)*. Stable isotope analysis also demonstrated trophic generalism for 7 members of the benthic community (3 sessile, 1 hemi-sessile, and 3 mobile species) across vertical zones at turbine structures in the Belgian North Sea (Mavraki et al. 2020). Reubens et al. (2014a) combined acoustic telemetry with stomach content analysis to show that cod feeding aggregations at turbines occur at sunrise and sunset, and suggested that this natural semi-diurnal feeding strategy may minimize predation risk for cod.

Predation at and around turbine structures has been hypothesized for other wildlife species. Harbor seals (*Phoca vitulina*) outfitted with GPS tracking devices appeared to trace a grid pattern between turbine structures presumably to feed on aggregates of fish associated with the structures (Russell et al. 2016). Seabirds may also utilize turbines as foraging locations despite the collision risk and potential for mortality for these species (Hill et al. 2019; Peschko et al. 2020). Species such as lesser and great black-backed gull (*Larus fuscus* and *Larus marinus*) have been found to be attracted to OSW structures suggesting they may be foraging there, and photographic evidence has borne this out for great black-backed and herring (*Larus argentatus*) gulls (Vanerman et al. 2017). This pattern is in contrast to most other avian species studied to date which tend to avoid OSWs (Maclean et al. 2007; May 2015; Welcker and Nehls 2016). Limited direct evidence is available to characterize the wildlife trophic relationships at OSWs and their potential impacts on shaping fish and invertebrate communities.

1.4.6.2.4 Herbivory

Herbivores regularly appear in the surveys of species presence/absence or abundance at OSWs (HDR 2020a; De Mesel et al. 2015). Herbivorous groups, such as some species of gastropods and echinoderms, provide food for higher trophic levels. Herbivory can modify the surface conditions and maintain hard bottom habitat exposed to the water column for settling epibenthos. For example, sea urchin grazing fronts reportedly occur at foundations in the Belgian North Sea (De Mesel et al. 2015) where they have been observed “clearing the surface” of epibenthic organisms.

1.4.6.2.5 Suspension Feeding

Many fouling species on OSW structures are suspension feeders that consume primary and secondary producers. Suspension feeding organisms are consistently an important component of OSW food webs in the Belgian North Sea; the diets of 2 benthopelagic species (cod and pouting) as well as the pelagic horse mackerel were dominated by a tube-building amphipod (*Jassa herdmani*) that consumes mainly zooplankton (Mavraki et al. 2020, 2021b). One suspension feeding species in particular, the blue mussel, is reported to dominate OSW communities throughout the North Sea, as well as at BIWF, potentially having important implications for feeding dynamics in the system (Bouma and Lengkeek 2012; Krone et al. 2013; Hutchison et al. 2020b).

Mussels located higher in the water column on turbines may accumulate greater biomass than their counterparts located in the scour protection due to enhanced advective food supply, and these areas of high blue mussel biomass may become hot spots of biological activity via consumption, excretion, and egestion (Maar et al. 2008). Laboratory studies of substrate borne vibration at levels similar to those occurring during pile driving stimulated valve closure in the blue mussel, potentially reducing individual and overall mussel bed fitness (Roberts et al. 2015). Modeling by Slavik et al. (2019) suggested that all existing and future planned OSWs (those currently planned, consented, or under construction) in the southern North Sea could increase the abundance of blue mussels by more than 10%, though this estimate did not account for potential increased predation on mussels. Given this increase, it was projected that the levels of filtration could have strong effects on primary production at local scales. Modeling suggested this was especially the case within the surface layer within OSWs, where it was estimated that phytoplankton carbon could be reduced by as much as 10% (Slavik et al 2019). Mavraki et al. (2020) studied suspension feeding using a laboratory pulse-chase experiment that offered labeled

C-13 fragmented microalgae to blue mussels and *Jassa herdmani* that had colonized panels deployed at an OSW. Upscaled to the scale of the Belgian North Sea, their results suggest that suspension feeding by these 2 species could reduce primary producer standing stock by 1.3%.

1.4.6.2.6 Nutrient Turnover via Biodeposition and Organic Enrichment of the Sediment

Deposition of organic materials that fall from the structures alter sediment characteristics and benthic community composition (De Mesel et al. 2013). Sediment grain size has been shown to increase with distance from turbine structures while macrofaunal species abundance, density, and richness, as well as sediment organic content, decreases with distance (Coates et al. 2014; Wilhelmsson and Malm 2008; Griffin et al. 2016; Lu et al. 2020; Lefaible et al. 2019; Braeckman et al. 2020; Hutchison et al. 2020b; HDR 2020a). Organic enrichment of the surrounding natural seafloor is reported to affect at least a 50 m zone around turbines (Coates et al. 2014) and potentially extend to a 200+ m zone. Higher food web complexity, high trophic diversity, high resource partitioning, and low trophic redundancy have been reported for soft sediment and the scour protection layer based on stable isotope data collected at a gravity-based OSW foundation in the Belgian North Sea (Mavraki et al. 2021b).

1.4.6.2.7 Facilitation of Non-Native Species Establishment

The addition of hard bottom habitat in areas that previously consisted of soft sediments could potentially facilitate the establishment of non-native species. Non-native species can alter community structure, food web dynamics, and reduce marine biodiversity (Molnar et al. 2008). Ten non-native species were reported at one OSW in the Belgian North Sea during a 5-year time span (De Mesel et al. 2015). At BIWF, the invasive tunicate (*Didemnum vexillum*) has been reported (Hutchison et al. 2020b); this species could have adverse effects on settlement habitat and increase predation risk for scallops (Morris et al. 2009; Dijkstra and Nolan 2011).

If structures both receive propagules and act as a source of those propagules, species may use structures as stepping stones, allowing them to move into areas from which they would have otherwise been excluded (Adams et al. 2014). Stepping stone effects could occur during operation, decommissioning, and beyond if some portions of the structures are left in place (Fowler et al. 2020). In the North Sea, the stepping stone effect has facilitated a northward range expansion of the southern barnacle (*Balanus perforatus*; De Mesel et al. 2015). A coupled biological hydrodynamic model demonstrated species with pelagic larvae (e.g., the snail [*Phorcus lineatus*], the urchin [*Paracentrotus lividus*], or the macroalga [*Bifurcaria bifurcata*]) could potentially use turbine foundations to move from the coast of Northern Ireland northward to the western coast of Scotland where they do not yet occur (Adams et al. 2014). Coolen et al. (2020) found blue mussels attached to man-made structures, including turbines located more than 181 km from the nearest shoreline; this is far beyond the 85 km from shore that blue mussels would otherwise be expected to travel in the absence of turbines (Coolen et al. 2020).

1.4.6.2.8 Studying the Effects of OSWs on Communities with Modeling Tools

Ecosystem simulation models can be an effective tool for examining holistic ecosystem dynamics and exploring the impacts associated with anthropogenic interventions, such as offshore wind development. Results from ecosystem models can provide insights to the major properties of the system as well as highlight gaps in our knowledge within that system (Link 1999). One way to explore ecosystem dynamics is through the use of mass balance models. These models have been popularized by the Ecopath with Ecosim (EwE) modeling suite (Christensen and Pauly 1992; Walters et al. 1997; Christensen and Walters 2004). Ecopath is a static snapshot of the energy flow through the system. The term “mass balance” refers to the model ensuring that consumption and production are balanced. This static snapshot can then be converted to a time dynamic simulation model using Ecosim that simulates trophic dynamics in response to various scenarios. Ecospace is an additional module within the EwE software that can add a spatial component to the dynamic simulations. EwE combined with the calculation of emergent ecosystem properties using Ecological Network Analysis (ENA; Ulanowicz 1986) has been applied to the study of offshore wind effects on ecosystem dynamics.

EwE has been used to examine baseline conditions prior to construction as well as the ecosystem consequences of artificial reef development, fisheries exclusion, and spillover that wind development may create. Table 6 describes the research questions and hypotheses explored and general findings of these models. The majority of the OSW EwE models developed to date have been created for prospective or hypothetical OSWs; therefore, their outcomes have not yet been validated with empirical data. One exception is Wang et al. (2019) who developed EwE models using both pre-construction and post-construction data from the Jiangsu coastal ecosystem of China and found an increase in primary production and detritus, and thus an increase in the food supply for zooplankton, which subsequently provided forage for planktivorous species (particularly anchovies) that were consumed by benthic fish. The post-construction ecosystem tended to develop toward higher maturity with higher energy throughput, ecosystem activity, and recycling capability (Wang et al. 2019).

This approach has not been applied in the Northeast U.S. Shelfecosystem. However, there are multiple ecosystem models that have been developed for the region (Link et al. 2011). Existing models include but are not limited to multispecies surplus production models (Gamble and Link 2012), multispecies length-based models (Gaichas et al. 2017), and whole ecosystem models, such as Atlantis and Ecopath (Link et al. 2008, 2010). These existing models could be used to address questions about impacts from OSWs in the Northeast U.S. Shelf if appropriately downscaled to match the spatial resolution of ecological processes at OSWs.

1.4.6.3 Knowledge Gaps

Community interactions are relatively understudied at OSWs. Feeding relationships, whether through predation, herbivory, or suspension feeding, underpin the structure and functioning of marine ecosystems. To understand how OSW development affects the ecosystem, it is imperative to understand how OSWs affect these interactions. For succession, predation, herbivory, suspension feeding, and non-native species interactions, there is a paucity of information regarding the effects of EMF, sound pressure, particle motion, substrate vibration, or altered hydrodynamic patterns on successional patterns in the context of OSW development. Field data for these interactions as well as that for artificial reef formation and nutrient cycling at OSWs were primarily collected in European ecosystems which differ from the Northeast U.S. Shelf with regard to species composition, physical oceanography, and important drivers of fish distributions. Thus, while this information can inform hypotheses regarding OSW effects in the U.S., it cannot be assumed with certainty that outcomes of research at U.S. OSWs will match those from Europe.

1.4.6.3.1 Species/Functional Groups

There is some limited information on feeding relationships as established by diet and stable isotope studies for a small number of example benthic and benthopelagic species. Very little to no information exists to describe whether and how small, mid-sized, pelagic, or large pelagic/highly migratory species may prey on species living on or around OSWs.

1.4.6.3.2 Life Stage Specific Effects

Vulnerability to predation and prey preference can change throughout the life history of an organism. There is little information on how utilization of structures and artificial reefs as a refugia from predation or as foraging habitat changes with life history stage.

1.4.6.3.3 Modification of Community Interactions by OSW Impact Producing Factors

There is limited information available describing how OSW IPFs modify community interactions and what the implications are for energy transfer throughout the system. For example, does construction sound mask communication among individuals, and how does this affect foraging, movement, and spawning behaviors? Does sound, EMF, or the artificial reef effect attract or repel potential predators, and what are the consequences for predator-prey and energy dynamics? How would trophic relationships be affected by the introduction of a non-native species, and what would the implications be for fisheries resource species?

1.4.6.3.4 Scale

A better understanding of the temporal and spatial scale of OSW effects on community interactions is needed (Ryan et al. 2019; Figure 10). How do predator-prey relationships change seasonally or annually, and how does the magnitude of effect change with distance from the structures and from the OSW itself? Do stepping stone effects occur, and over what distance and time scales? While the artificial reef effect (≤50 turbines) is often discussed, little is known about interactions among species at the reef either at the bottom or in the water column. Even less is known about community interactions at distances beyond 50 m of turbines. In the Northeast U.S., it is possible that species may utilize OSWs as foraging habitat during cross-shelf or north-south migrations, so community-level interactions could have effects that reach much farther than the OSW boundary.

1.4.6.3.5 Ecosystem-Level Effects

There is limited knowledge about how the altered feeding relationships created by OSWs affect fishery species abundance and distribution. These questions could be examined using dynamic ecosystem modeling. Of the 10 papers describing dynamic ecosystem modeling of OSWs, 8 were based on prospective or hypothetical OSW scenarios. These modeling approaches provide an opportunity to explore holistic ecosystem impacts and, if spatially resolved, could also examine the spatial scale of effects (Figure 9). Ecosystems where wind farms have actually been constructed are underrepresented among these studies which has limited any ability to validate their findings.

1.4.6.4 Commercial and Recreational Fishing Community Perspectives

Fishing industry representatives have specifically highlighted as a key concern the potential for aggregation/artificial reef effects to alter predator-prey relationships or trophic dynamics. Other IPFs of concern include potential drivers of change to predator-prey dynamics, including acoustic effects, hydrodynamic patterns, cold pool changes, EMF/heat, and benthic sediment changes. Specific examples offered by the fishing industry include: the potential for altered predator-prey dynamics to negatively impact the biomass of Atlantic surfclam and ocean quahog through increased feeding on small clams; the potential for aggregation of black sea bass in an area previously utilized by squid for spawning; potential effects of sediment modification and sound on the abundance of sand lance, an important prey species. The possibility that OSWs could facilitate the establishment and range expansion of non-natives was also highlighted as a concern with particular emphasis on how non-natives would affect the survival of fisheries resources.

1.4.6.5 Recommendations for Future Research: Ecological Research on Community Interactions

- Regional Research and Monitoring: Establish an ecoregion-wide research and monitoring program that efficiently and effectively targets the spatiotemporal scales relevant for community interactions (Figure 10).
- Changes in Predator-Prey Dynamics: Empirical diet and stable isotope data for fisheries resource species are needed to better understand feeding relationships and the energetic consequences of OSW development. To understand the spatial and temporal dynamics for demersal as well as for more mobile species, such as large pelagics/highly migratory species and marine mammals, methods such as acoustic tagging and optical technologies could provide insight into the frequency and duration of foraging events.
- Facilitation of Non-Natives: Once a non-native species is detected at an OSW, this species should be tracked through regular monitoring. Molecular techniques could be used to study stepping stone effects (e.g., Coolen et al. 2020).
- Ecosystem Modeling: Need for understanding holistic ecosystem impacts and to consider potential long-term scenarios; need to investigate ecosystem effects at scales that are relevant for ecosystem processes like secondary production of commercial fish and not at scales dictated by the size of the individual OSW projects (Figure 10).

1.4.6.6 Acknowledgements

We thank Meghan Lapp (SeaFreeze Ltd.) for thoughtful comments on earlier drafts of this paper

2. FISHERIES SOCIOECONOMICS

2.1 Fishing Operation Effects

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2.1.1 Introduction

There is both offshore and onshore spatial overlap for offshore wind development and fisheries activities' footprints. These overlaps generate interactions that can impact human and non-human/marine faunal communities. Impacts to fishing operations include transit and fishing operations at sea, navigation, risk/safety, decision making, potential displacement for port operations, infrastructure and business ecosystem.. This section outlines offshore wind development's de jure (legal) and de facto (practical) implications for commercial and recreational fishery navigation and operations. These implications are based on fishery type (e.g., static or mobile gear), activity type (e.g., fishing, transiting), and OSW area configuration of turbines and cable placement and have temporal and spatial differences. Although OSW areas are expected to be open to commercial fishing in the U.S. during the operational phase (BOEM 2021a), there are many logistical challenges with vessels operating within an array. These include navigation, safety, gear loss, and possible insurance changes. Alexander et al. (2013) identified 3 key effects of offshore wind development on fishery operations: (1) a potential loss of fishing grounds which could ultimately affect income and catch, (2) gear conflicts with offshore wind infrastructure, and (3) safety implications for fisheries. Navigation and safety has been identified as a top concern by fishermen regarding offshore wind development (Gray et al. 2016; Mackinson et al. 2006; ten Brink and Dalton 2018). Similar concerns were found in connection with ocean wave energy development in the U.S. (Industrial Economics 2012; Pomeroy et al. 2015; Sullivan et al. 2015). This section provides a review of relevant literature on fisheries access concerns, navigational risks and safety, and displacement with offshore wind development, and highlights data gaps and research needs in understanding fisheries' operations and behavior in response to offshore wind development. The uncertainty with a new use of ocean space poses challenges in identifying data gaps and research needs. While the objective of this paper is not to define research priorities, a clear set of research needs and monitoring protocols for fisheries operations is needed as a next step to fully understand the effects before, during, and after construction of wind development in the region.

2.1.2 Fisheries Access and Safety

2.1.2.1 Fishing Access

Fisheries access to offshore wind areas will depend on the phase of development. In Europe, depending on OSW phase of development and national legislation, fishing operations are either allowed, not allowed, or partially allowed. This leads to a loss of fishing grounds, displacement, or co-location of fisheries and OSW. Access is not expected to be legally restricted within offshore wind developments in the U.S. unless it is for safety and navigation reasons (BOEM 2021a), although operational constraints on mobile gear are understood to restrict access for several fisheries. During the surveying phase, operational restrictions are in place to maintain a safe distance from survey vessels. Commercial and recreational fishing vessels will be excluded and lose access to any fishing grounds within safety zones during the construction phase of offshore wind developments (BOEM 2021a). In Europe, a 500-m safety zone excluding fishing activities and navigation can be implemented around construction zones, and a 50-m zone around the turbine bases during operation (FLOWSS 2014). Although fishing vessels will not be fishing or navigating within these construction areas and safety zones, navigational risks and safety related to increased vessel traffic still are of concern. With displacement of vessels during these phases, traffic on the water between fishing industry vessels, wind industry vessels, and other marine sector vessels, such as shipping, could create safety issues and increase conflict. Navigation and safety concerns with vessel traffic can be mitigated through open communication with fisheries liaisons (FLs) on wind developers plans for and timing of construction (FLOWSS 2014). The utility of communication for coordinating ocean space is common for other sectors outside of offshore wind, such as the West Coast Crabber-Towboat Agreement (Pomeroy et al. 2015) and the California Joint Oil/Fisheries Liaison Office (Dewees and Richards 1990; Knaster et al. 1998).

Access to fishing grounds during the operational phase will be dependent on navigational risk and operational needs of certain gear types and fisheries. Fishermen in Europe stated they would avoid offshore wind developments even if they were permitted to fish within them (Mackinson et al. 2006; Catherall and Kaiser 2014). In Europe, there are differences in fisheries access regulations within offshore wind depending on management jurisdictions (Gill et al., 2020; Schupp et al. 2020). OSW areas in the Netherlands excluded fishing vessels until 2015. Risk assessments were carried out by the Dutch government, OSW operators, and an independent third party. Arrangements were made between different stakeholders, and the Dutch government adapted regulations and mitigation measures with conditions for multi-use and transit of vessels. The regulations were designed to limit hazards while providing opportunities and include: (1) transit permitted by commercial fishermen with gear above the waterline and visible, (2) bottom-disturbing activities (anchoring or dragging fishing gear) are forbidden within wind farm safety zone, and (3) professional fishing is allowed only if the gear is permissible by the Dutch government (European MSP Platform 2019). During the process, the Netherlands Enterprise Agency found that designing OSW areas to allow for mobile fisheries operations would increase the cost of energy produced. In order to allow safe fishing operations, development would require creating wider corridors, resulting in larger OSW farms or fewer turbines. There would also be a probable increase in the cost of insurance policies for both the wind developers and fishing industries (Primo Marine 2019).

The U.K. allows the navigation of all fishing vessels and fixed-gear fishing (e.g., pots) within offshore wind developments. Passive gear (e.g., trawl, dredge) is still not allowed in English wind farms. However, in a study on changes in fishing practices in the North Irish Sea, a small number of demersal trawl gear fishermen reported they had operated between the turbines where cables ran parallel to the trawl tracks (Gray et al. 2016). However, most Northern Irish skippers in the study avoided the wind areas. Even with fixed-gear fishing permitted, it is still not common practice due to safety concerns and gear loss (Hooper et al. 2015), and representatives of fishing organizations in Scotland identified safety and navigation, lack of insurance coverage within wind farms, and limited cooperation and communication with wind developers as factors limiting fishermen's decisions to fish within wind areas (Gusatu et al. 2020). The decision of captains to not operate within a wind array will result in long term displacement from fishing grounds (Methratta et al. 2020). See Section 2.1.2 for a further discussion of displacement.

Fine scale access could be restricted in areas around the turbines for safety reasons. The U.K. has a 50-m exclusion zone established around each turbine (BERR 2007; Van Hoey 2021). Fishing vessels may be restricted due to safety concerns. BOEM has indicated that accessibility may be impacted due to operational constraints once turbines are installed (BOEM 2021a). Insights can be gained from a review of research on offshore oil and gas development/operations and fisheries (Glazier et al. 2006; Knaster 1998), although spacing constraints may be different between gas and oil facilities layout.

2.1.2.2 Navigational Risk and Vessel Traffic

Navigation risk varies among types of fishing operations based on vessels, gear, and equipment, as well as where, when, and how these are used (IEC 2012). Increase in vessel traffic can cause conflict between ocean users. For the fishing industry, an increase in vessel traffic can impact fisheries access and increase costs. With the increase of automatic identification system (AIS), tools and techniques for modeling traffic risk have been developed, including vessel activity and route analysis (Christensen et al. 2001; Mazaheri and Ylitalo 2010; Wawruch and Stupak 2011).

Navigational Risk Assessments (NRA) are completed during wind area planning and are intended to balance safety and efficiency for decisions over space use. Rawson and Rogers (2015) report that most research on navigational risk modeling is predictive and there is little understanding if navigational safety modeling accurately reflects the post-construction risks. In the U.K., the authors found that the impact of vessel traffic is specific to the location of each development, driven by traffic management measures and other local constraints (Rawson and Rogers 2015). NRAs should be valid for all phases of offshore wind development, including installation, operation, anddecommissioning (Mehdi et al. 2018). Additionally, a fishing vessel with gear in the water is a navigational status that must be considered and studied as such. The World Association for Waterborne Transport Infrastructure (PIANC) published a paper on the interaction between offshore wind developments and maritime navigation (PIANC MarCom Wg 161, 2018) that consists of a thorough analysis for transit navigation of large/cargo vessels, but the same must be done for fishing vessels.

The United States Coast Guard (USCG) has primary authority and responsibility for ensuring navigational safety in U.S. waters. The USCG requires the analysis of offshore renewable energy development impacts, including: potential changes to traffic density; shipping traffic, including rerouting, funneling, and obstructions to navigation; and whether changes to safe access routes for vessels are needed in connection with the installation of offshore wind developments, including modifications to fairways or Traffic Separation Schemes (TSSs; Copping et al. 2013). The Atlantic Coast Port Access Study (ACPARS) was completed to assess future port access and navigational needs for the U.S. Atlantic coast. The Areas Offshore of Massachusetts and Rhode Island Port Access Route Study (MARIPARS; USCG 2020) study was undertaken by the USCG to evaluate the proposed layout of offshore wind projects in the New England MA/RI WEA. The study concluded that turbine layouts should be developed along uniform grid patterns, preferably with a minimum of 3 lines of orientation (USCG 2020). The assumptions that guided the safe navigation analysis included: (1) no current laws or regulations prevent vessels from transiting through, fishing, or recreating in the WEA; (2) mariners are required to follow the International Regulations for Preventing Collisions at Sea 1972 (COLREGS)[3] or “rules of the road”; and (3) mariners will likely have to adjust their watch keeping requirements and level of vigilance when navigating within the WEA (USCG 2020).

The footprint of wind construction in the Northeast U.S. also poses issues with vessel traffic. Within the South Fork Final Environmental Impact Statement Cumulative Effects scenarios, a total of 20 projects over 32 phases from Southern New England to North Carolina between now and 2030 are outlined in a project construction schedule. According to their scenarios, 4 projects will be under construction in 2023 (i.e., within the same year) in the MA/RI WEA: Revolution Wind, Sunrise Wind, Mayflower Wind Phase 1, and Park City Wind (BOEM 2020, Table E-4). BOEM (2020) estimates that construction of each individual offshore wind project would generate an average of 25 with a maximum of 46 vessels in the area at any given time over the 2 years of projects proposed. Under the assumed construction schedule, in 2026, construction activities will be ongoing at 903 sites during the year. Increased traffic due to construction and decommissioning of future offshore wind can lead to congestion and delays at ports and increased traffic along vessel transit routes (BOEM 2020). According to the South Fork Draft Environmental Impact Statement (DEIS), even with staggered construction schedules and phases, cumulative impact to traffic routes could occur, as BOEM states that vessel activity would peak in 2025 with as many as 207 vessels involved in construction of reasonably foreseeable projects (BOEM 2020).

Increased vessel activity could cause collision with both other vessels and turbines. In a simulation analysis of ship strikes on turbines, Bela et al. (2017) found that under certain conditions, turbine structures can be at risk for ship allisions, when a vessel strikes a fixed obstacle. In a Risk Assessment for Marine Vessel Traffic and Wind Energy Development in the Atlantic, Copping et al. (2013) found a moderate increase in collisions (~12%) and a small increase in groundings (~0.4%) over a year of vessel traffic along the Atlantic coast. However, Copping et al. (2016) created a model to recreate present day commercial vessel movement and simulate future routing that may be required to avoid wind areas and found that more vessels were forced seaward by the wind farms, showing little increase in vessel collisions or allisions. Studies have also been done on allisions between wind maintenance vessels and wind turbines (Dai et al. 2013; Presencia and Shafiee 2017).

2.1.2.3 Operational Risks within a Wind Array

Wind array layouts impact fishing vessels differently, depending on gear type and whether the vessel is harvesting or transiting through the array. Different gear types must be assessed

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[3] *Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs)* Archived 14, from the IMO (The International Maritime Organisation). Retrieved 13 February 2021.

independently. The maneuverability of a fishing vessel with bottom gear within a wind farm is a risk (Verhulst and Smit 2019). As dredges or bottom trawl gear have contact with the bottom, these vessels are at risk of becoming entangled with obstructions on the seafloor and are operationally affected by turbine spacing of 1 NM or less (RODA 2020a). The base of turbine structures, cables, or scour protection poses hazards for these types of vessels. In a study of perceptions of fishermen and developers on the co-location of decapod fisheries in the U.K., Hooper et al. (2015) found that the lack of potting within offshore wind was due to safety concerns and gear loss. Developers also expressed concerns regarding deploying pot gear within a wind array, with the risk of snagging and damage to cables, interference with maintenance operations, and liability issues if pots become entangled with their operations. Fishermen and developers both agreed that pots should be deployed a distance from turbine infrastructure, with more than half of developers reporting a minimum distance of 100 m from the turbine infrastructure (range of 25 m to 500 m reported) and fishermen reporting a median distance of 100 m (1 m to 2000 m reported). These reported distances by fishermen were found to be more conservative than their normal fishing practices related to other structures due to collision risk and uncertainty in navigating the structures. Fishermen have also stated concerns that bad weather and strong tides would lead to nets and pots becoming entangled with turbines and result in unsafe retrievals (Ashley et al. 2014). Deployed nets are susceptible to currents and may not be able to be deployed during certain sea states. Net "wrapping" has been documented as a significant concern in the Salmon Drift Gillnet Fishery and oil development (Glazier et al. 2006). Schupp et al. (2020) note that having empirical studies on the compatibility of fisheries and offshore wind can drive insurance costs down, boost fishing industry confidence to return to fishing grounds (if communicated effectively), and have financial benefits to both parties.

The MARIPARS (USCG 2020) recommends a standard and uniform gridded layout and notes that determining an appropriate distance between structures, or the need for any vessel routing measure between structures is an "inexact science as there is no single international standard or common methodology for determining such widths." While there were cited guidance documents on determining widths in the MARIPARS study (MGN 543; MSP 2015), these do not include specific recommendations to commercial fishing vessels and their spatial needs to safely harvest fish and coexist with wind energy areas. To date, there are no studies in the U.S. that seek to identify the spatial operational needs of fishing vessels and identify the risks and costs of harvesting within a wind farm. Without understanding this issue, it is difficult to measure impacts appropriately to the fishing industry.

In the Netherlands, Primo Marine (2019) conducted a study to provide an inventory of the requirements in order for the future Dutch offshore wind to be accessible for sea-bed fishery. The authors report on the spatial needs of bottom fishing gear around the turbine and seek to quantify the distance a vessel can safely maneuver in the wind farm, including turning while towing around a monopile. The authors recommend that for water depths up to 30 m, the approximate safety distance should be 180 m, and for water depths up to 40 m, the distance should be 215 m. These recommendations were made under a number of assumptions, including that 12MW WTG, anti-scour extends 4-5 times the monopile and that vessels are "standard" trawler size (Primo Marine 2019).

Fishermen need to be able to safely and directly transit through a wind area when heading to fishing grounds or to and from ports. The fishing industry has raised considerable concerns for safe transit in wind energy areas (Equinor et al. 2019; BOEM 2020; RODA 2020a) as they may need to transit through a wind area during poor weather to maximize fishing time and/or reduce time to market with a quicker route through a WEA to maintain product quality by. Learning from the RI/MA WEA, New York State Energy Research and Development Authority (NYSERDA) and New York State Department of Environmental Conservation (NYSDEC) have worked with the Responsible Offshore Development Alliance (RODA) to jointly develop, convene, and complete a process for engaging fishermen and agencies to work together to identify transit routes in proposed NY Bight WEAs (National Renewable Energy Laboratory [NREL] forthcoming; NYSERDA 2020). Transit Routes create denser traffic in one area, which can displace fishing. If fishing is displaced from inside wind farms, transit routes may suffer increased volume and complications with fishing vessels attempting to fish within these transit lanes. Fishing vessels navigating while fishing must be included in models of transit lanes and not just transiting vessels. Because there are no studies on the spatial needs of fishing vessels as identified above, the burden of deciding what is safe falls on the individual fisher. The potential displacement then depends on an operator's competence in assessing risk and deciding what level of risk they are willing to accept. These social considerations and how fishermen make decisions under levels of risk uncertainty is needed to better understand displacement (further synthesis of displacement in Section 2.1.3).

Additionally, fog, wind, or exhaustion could cause issues with navigation and potentially lead to allision with turbines (ten Brink and Dalton 2018). Sea state conditions can have a significant impact on the ability of fishermen to safely operate or transit within a wind array. Research is also needed on how large-scale offshore wind development may affect atmospheric flow and ocean mixing that could alter localized weather conditions in the region. Christiansen et al. (2022) investigated potential impacts of offshore wind and changes in ocean dynamics and found through simulation modeling that induced changes in the vertical and lateral flow are sufficiently strong to influence the residual current. This could impact the ability of fisheries to operate within an array. In interviews with scallop fishermen in the Northeast U.S., NREL (forthcoming) identified the expected differences in operational practices from their normal fishing practices when/if they choose to operate within a wind area. They predict sea state conditions will be a major factor in their decision to fish within an array. Operating with other vessels within an array was also identified as a risk that would determine their decision to fish. The number of vessels fishing within the WEA, fixed-gear vessels operating, and the social relationships captains have with other vessels in the area were all determined to be important factors in determining whether to operate (NREL, forthcoming). Fishermen have expressed the need to mark individual turbines with AIS transmitters to cut down on the potential for radar interference becoming a problem within the arrays (e.g., BOEM RFI Fisheries Mitigation public comments).

While the operations between commercial and recreational fishing may induce different levels of risk within wind arrays, many of the safety concerns (e.g., fog, traffic, allisions) are risks for all operators. Studies specific to recreational fishing have been completed in the region and captured safety and navigation concerns. In focus groups with recreation and tourism sectors, Smythe et al. (2020, ERSS) found that the BIWF was acting as an attractant, drawing visitors to the site. This included attracting inexperienced boaters/anglers, which was viewed as a navigational risk from more experienced anglers (Smith et al. 2018). Additionally, Smythe et al. (2021) found that anglers reporting crowding of other fisheries and boats around offshore wind developments. Whereas interviewees reported this as diminishing their fishing experience, survey respondents viewed the BIWF as having a slightly negative effect on navigation and boat traffic. A possible explanation for this difference is the difference in boating experience among respondents. The Fisheries Advisory Board for South Fork Wind Farm indicated that charter and recreational fishermen anticipate losses due to the impracticality of drift fishing methods inside a wind turbine array (CRMC 2021). The turbines can also obscure visibility in smaller crafts, such as recreational fishing and maintenance vessels (Rawson and Rogers 2015).

2.1.2.4 Radar Interference

The functionality of vessel radar within offshore wind areas has been expressed as a major concern with the fishing industry. Vessel radar is used to track other vessels and gear and is required aboard vessels larger than 300 GT by the Safety of Life at Sea (SOLAS) convention. Fishermen need to be able to maneuver their vessels in all conditions and be able to navigate at low visibility, within dense fog, or at night, and radar is a vital navigation component for safety at sea (Dameron and Hansen 2020). Radar needs to discern all targets at all times ranging in size from turbines to fixed fishing gear buoys. The potential for interference of WTGs with marine radar is site-specific and depends on the following factors: turbine size, array layouts, number of turbines, construction material(s), and vessel types (USCG 2020).

The types of interference with radar include radar clutter, radar saturation, and radar shadowing (BWEA 2007; QINETIQ 2015). On the BIWF, QinetiQ (2015) modeled X-band and S-band radar. The Radar Clutter Assessment showed that radar clutter could be reduced by an operator’s use of gain control, but as the gain and sea clutter are adjusted to reduce interference, small targets will be lost or tuned out due to interference reduction (e.g., recreational boats, Highliners), which can affect navigation decision making and situational awareness (Marico Marine 2007; National Academies of Science, Engineering and Medicine 2022). A vessel may choose to navigate farther from a wind farm to avoid these radar effects, which would increase steaming time and fuel costs. QinetiQ (2015) note that this increased distance reduces the risk of collisions with vessels within the wind farm. However, if vessels are navigating to the wind array to harvest, there are other vessels that did not show on radar at further distances, and they discover later they cannot safely operate together, this could also result in increased fuel costs and steaming time. Within 0.5 NM, radar saturation is possible, but results of the study showed that S-band and X-band gain control adjustments can be adjusted by the operator. Shadowing effects may also result in smaller vessels situated behind the turbines not visible on radars of nearby transiting vessels, up to 328 ft wide behind the turbines (QinetiQ 2015).

MARICO Marine (2007) on behalf of the British Wind Energy Association assessed the effects of the Kentish Flats wind farm in the U.K. and had similar findings that trained mariners can identify the effects of wind farms on radar display and make necessary adjustments to mitigate their impacts. Experienced fishermen in a presentation for the Offshore Wind Turbine Radar Interference Mitigation Series (WTRIM) stated they are concerned with the overwhelming amount of information on a radar screen during the Kentish Flats study and stated that radar units on fishing vessels are often less advanced than in other sectors (Dameron and Hanson 2020). While the Kentish Flats study collected data on magnetron-based radar, recent research by the National Academies of Sciences, Engineering and Medicine (2022) studied the impacts of WTGs on both magnetron-based and Doppler-based solid-state marine radar systems and is the first published report to study Doppler-based solid-state radar. The Doppler-based solid-state radar is a newer technology, and the authors outline the improved features and advantages over existing vessel radars. The magnetron-based radar is still the majority of vessel radars in operation today due to the cost of replacement and long life cycle of existing marine vessel radars. Results of the study found that WTG returns can complicate navigational decision making by obscuring the picture for both types of marine radar, and interference includes strong stationary returns from WTGs, strong blade flash return, and Doppler spread clutter, which could obscure smaller watercraft, buoys, and so forth. (for a full list of impacts, see Box 4.5 Findings: Wind Turbine Generator Impacts on Marine Vessel Radar, in National Academies of Sciences, Engineering and Medicine 2022). WTGs can also affect other radar systems, such as surface high frequency (Trockel et al. 2018; Kirincich et al. 2019).

The AIS was developed for maritime safety and security purposes and is an important tool in safe navigation. The AIS system provides users with information on other vessels, including location and direction. Based on Very High Frequency (VHF), AIS allows vessels within radio range to be displayed on a vessel's radar. Studies have looked at using AIS to understand vessel activities; however, AIS was not designed for research or conservation, and challenges exist in using the data for these purposes (Robards et al. 2016; Emmens et al. 2021). Only vessels greater than 65 ft in length are required to have AIS installed (33 CFR 164.46). AIS is not an adequate source to describe fishing patterns because of these length requirements; strength of the VHF signal can vary with distance to shore, as well (Robards et al. 2016; RODA 2020b). Additionally, some fishermen will switch off AIS to hide their fishing spots from competitors (USCG 2021). Fishermen have expressed the need to mark individual turbines with AIS transmitters to cut down on the potential for radar interference becoming a problem within the arrays (e.g., BOEM RFI Fisheries Mitigation public comments).

2.1.2.5 Search and Rescue

The feasibility of search and rescue (SAR) operations within a wind energy area is another factor in a vessel operator's decision to harvest or transit through a wind energy area, especially during certain weather conditions and visibility. Safety and welfare is also critical to both the offshore wind industry and USCG SAR crew, and it is important to consider relative to the ability to conduct SAR missions. The MARIPARS study recommends a standard and uniform gridded layout and notes that a minimum of 1 NM spacing in an east to west orientation between turbines will provide more flexibility for SAR missions (USCG 2020). Between 2005 and 2018, there was an annual average of 9.5 incidents requiring SAR within or near the MA/RI WEAs. Due to the distance offshore, helicopters will be most relied upon for SAR within the WEA, and a minimum of 1 NM allows safe turning and operation at normal search speeds. If less than 1 NM, this "may require aircrews to deviate from normal flight procedures or to transit the entire length and conduct turns outside of the wind area" (USCG 2020, 29). In terms of altitude, normal search altitudes in optimal weather are between 200-300 ft above the water, but there may be times that flight crews will need to operate higher due to the height of the turbines being installed (USCG 2020). The average hub height for offshore wind turbines has increased 59% since 1998-1999 to about 90 m (295 ft) in 2020. In the U.S., the average hub height for offshore wind turbines is projected to grow to around 100 m (330 ft) in 2016 to about 150 m (500 ft) by 2035 (DoE 2021). Environmental conditions, such as icing, thunderstorms or turbulence, will also impact altitude and safe operation. The USCG notes that they will continue to examine this issue and evaluate SAR operations and mitigation strategies as WEAs are built in U.S. waters (USCG 2020).

2.1.2.6 Fisheries Operations and Offshore Wind Cables

Fishermen are familiar with operating with cables along the seafloor (i.e., telecommunication cables). However, the number of cables laid on the seabed is increasing and will continue to grow rapidly as more offshore renewable energy projects are constructed (NYSERDA/TetraTech 2021). Concerns with offshore wind cables include the high voltage, risk of being unburied, and proper markings of these cables on navigational charts (NREL, forthcoming). On a global scale, Drew and Hopper (2009) note that cables are broken by fishing or anchors about 100-150 times a year. Anchors and fishing gear have been estimated to cause one-third of accidental damage to all subsea cables in Europe (European MSP Platform 2019). Catching or snagging a cable in fishing gear can be extremely dangerous, affecting stability and possibly capsizing a vessel and endangering crew. This is especially a concern under certain sea state conditions. The International Cable Protection Committee (ICPC) cautions fishermen to keep at least 1 NM away from a cable laying vessel (ICPC 1996). The increase in maintenance activities with cable installation has the potential to increase the risk of collision with existing navigational users (NYSERDA/TetraTech 2021). During cable installation, repair, or removal, fishing vessels will be excluded from the area for safety purposes, which can result in reduced catch and increased steaming times to fishing grounds and increased fuel costs (Vize et al. 2008; NIRAS 2015). Fishermen will be displaced to adjacent fishing grounds, which could result in increased risks of gear conflict and reductions in catch as fishermen work in unfamiliar or less productive areas (Vize et al. 2008).

In a review of cable techniques and effects of offshore wind development, the most significant risk associated with fishing-cable interactions is to trawlers that may snag a cable, which poses significant danger to the vessel and its crew (Vize et al. 2008). Similar to operation around turbines, the effects of cables can differ between mobile gear and static gear. Otter trawls, beam trawls, scallop dredges, gill nets, and demersal longlines all involve weighted nets, chain bags, or lines that may snag on exposed cables or cable armor (NYSERDA/TetraTech 2021). Globally, the number one cause of submarine cable interactions in fishing is with mobile gear, although static (fixed) gear have also had interactions with cables (Vize et al. 2008). Fishing gear and any catch within the gear may be damaged or lost completely if it interacts with a cable. Oftentimes, it is not the fishing gear that causes problems but the grapnels fishermen use to recover lost gear (Drew and Hopper 2009). Hooper et al. (2015) found that fishermen identified a perceived risk in deploying gear that is too close (median of 100 m was identified) to turbine structures due to the risk of losing pots without being able to locate with grappling hooks for fear of snagging on cables. Fishermen are encouraged to contact the USCG regarding fouled gear rather than attempting to recover it themselves (NYSERDA/TetraTech 2021). Smaller vessels will be at greater risk than larger vessels if entangled with a cable. Drew and Hopper (2009) highlight that some small vessels carry high engine power compared to the hull size and can therefore be at more risk of capsizing without the righting forces from the ship weight to avoid capsizing. Wave height and length, tide, and current flow are all key elements in determining a vessel’s stability when entangled with a cable (Drew and Hopper 2009).

Cables are primarily buried under the seabed for protection. In the U.S., although there are no legal requirements for burial depth outside of shipping channels, there are a number of sources that guide cable burial recommendations (NYSERDA/TetraTech 2021). BOEM provides guidelines for cables through their Construction and Operations Plan (COP) Best Management Practices. The BOEM COP guidance states cables should be buried, where practical, to minimize impacts to the fishing industry. Where cables are buried, they should be inspected periodically during project operation to ensure there is adequate coverage to avoid interactions with fishing gear (BOEM 2020). The ICPC provides industry best practices that serves as a guide for burial planning (IPCC 2019) but does not provide a recommended depth. Local states may have minimum burial depth requirements (NYSERDA/TetraTech 2021). The Carbon Trust (2015) provides methodology for undertaking a Cable Burial Risk Assessment (CBRA). The CBRA uses a risk-based methodology to determine the minimum recommended depth of lowering (DOL) for cable. There is a vast list of information that goes into a comprehensive CBRA, as listed in

NYSERDA/TetraTech (2021). For fisheries considerations, the knowledge of fisheries that are undertaken around the cable area (which should be identified early in the cable planning process) and the types of fishing gear, together with the seabed composition, are used to determine the maximum likely penetration depth of the fishing gear(NYSERDA/TetraTech 2021). The outcome of the CBRA consists of a recommended minimum DOL at each point along the cable route. For proposed projects in the Northeast, burial depth has differed with South Fork Wind Farm proposed for 4 to 6 ft (Deepwater Wind 2020) and 5 to 8 ft for Vineyard Wind (BOEM 2021b).

Where cable burial is impractical, such as over bedrock, other cable protections can be used (Carter et al. 2009). Additionally, export cables from an offshore wind array will need protection (e.g., concrete mattresses or rock berms) where they cross other subsea assets between the offshore wind development and the shore landing. Fishermen are concerned that fishing gear may snag on seabed obstructions, such as concrete mattresses. Many mattresses are designed with tapered edges to minimize the risk, and mats should be laid flat(NYSERDA/TetraTech 2021). Other protection material includes natural boulders, gravel, concrete, polyurethane, or synthetic fronds to replicate a natural range of habitats (Glarou et al., 2020) and are introduced to the seafloor to protect the turbine and cable infrastructure against changing benthic conditions and accidental damage (NYSERDA/TetraTech 2000). All of the gear types in the Northeast mentioned above risk snagging on cable armor. Despite gear interactions with the seabed, approximately 90% of active crossings over exposed cables do not result in cable damage or gear damage, and fishermen may not even be aware of the occurrence (Wilson 2006).

Recreational fishing in the Northeast involves the use of hook and line (rod and reel) which are unlikely to have substantial interactions with subsea cables. The most significant effect on recreational fishing will be from activity exclusion and possibly fish stock displacement. However, large recreationally valuable species, such as black sea bass, summer flounder, and tautog (*Tautoga onitis*), may be attracted to cable protection measures due to higher densities of forage fish and crustaceans (Vize et al. 20008; Carter et al. 2009). Recreational and private charter boats have capitalized off reef-associated assemblages in the BIWF and associated cable protections (Prevost 2019). Anchoring party charter vessels within arrays could also present cable concerns.

2.1.2.7 Safety and Navigation Mitigation

BOEM outlines safety as one of their 5 Best Management Practices for offshore wind and fisheries mitigation (BOEM 2014). They include recommendations regarding wind facility marking, radio, lighting, and safety equipment. BOEM regulations require a Safety Management System (SMS) that includes clear communication protocols and must include procedures for emergency events, such as: allision of a vessel with a turbine structure, gear entanglement or damage to cabling by fishing activity, or catastrophic failure of a turbine.

To ensure navigation safety, aids to navigation (ATON), such as lights, signals, buoys, and day beacons, should be used in wind energy areas. All structures within a wind array will have appropriate markings and lighting according to USCG and International Association of Marine Aids to Navigation and Lighthouse Authorities guidelines. NOAA would chart wind turbine locations through physical charts.. AIS has been proposed by South Fork Wind Farm (South Fork DEIS 2020) to mark the corners of the wind farm to assist in safe navigation. In 2019, RODA announced a Notice of Availability of Guidelines for Lighting and Marking of Structures Supporting Renewable Energy Projects for public comment. Working together with OSW developers and fishermen through RODA’s Joint Industry Task Force, recommendations for further aids to navigation were provided to BOEM and USCG.

Fishermen in Europe proposed recommendations for mitigation options that include: laying cables in such a way that would cause the least damage to the seabed, burying them into the ground, and laying cables with opposing currents alongside each other (Mackinson et al. 2006). In the U.S., there are 2 primary considerations outlined by NYSERDA/TetraTech (2021) from cable route engineers when considering fishing and cable interactions. The first is to identify heavily fished grounds during upfront planning and to avoid these areas whenever possible, and the second is to develop mitigation that is focused on types of fishing gear and seabed composition. The cable burial depth is informed by stakeholder engagement in the commercial fishery and an assessment of seabed conditions. The North American Submarine Cable Association (NASCA) has developed a set of electronic cable awareness charts that are compatible with navigation software used by most fishermen in the Northeast U.S.. In response to cable threats during the 1980's and 1990's, submarine cables since 2000 have been buried at a target depth of 5 to 6 ft where seabed conditions permit, which was an increase from 2 to 3 ft. Where hard, dense sea beds exist, shallower burial has been sufficient in protecting cables (see discussion of Crescent Beach in 2.3.2 below). The Association notes that since this change, subsea cable damage rates from fishing operations have been reduced to near 0 (NASCA 2019). NASCA cites research by Stevenson et al. (2004) on seabed penetration on mobile fishing gear (hydraulic dredge, scallop dredge and otter trawls) in determining these metrics. The hydraulic clam dredges have been shown to interact with cables 2 to 3 ft but little to no interactions at 5 to 6 ft (NASCA 2019). When selecting appropriate routes, fishing industries are consulted directly (Carter et al. 2009), but there is currently no mechanism for holding wind developers accountable to the recommendations of the fishing industry.

Drew and Hopper (2009) with the ICPC provide a report with the intention of helping fishermen avoid submarine cables. The authors provide details on specific cable concerns and potential interactions by gear type and guidance on what to do when interacting with a cable. The authors identify that the most effective way to avoid the dangers of catching cables is to keep fishing gear away from cables and avoid using anchors, grapnels, and any gear that penetrates the seabed near a cable (Drew and Hopper 2009).

The Oregon Fishermen's Cable Committee established in 1998 provides a cooperative approach to discuss, describe, and delineate with cable companies their shared use of the ocean. The Committee provides safety procedures developed jointly with trawl fishing industries and telecommunication companies. Those fishermen who sign agreements with companies that are maintaining cables in their fishing area and follow the procedures are protected from liability for ordinary negligence. The committee also states that, "participation and compliance also provides for defined compensation for trawl gear sacrificed to avoid damage to a submarine cable."

NYSERDA/TetraTech (2021) note that the risk of damage to either cable or fishing gear remains low. Modifications to bottom gear have been made previously in order to pass over natural and artificial seabed obstacles (e.g., rollers, cookies, rockhoppers), and these specific designs reduce the probability of gear damage or loss. Vineyard Wind (2021) in their EIS have stated they will engage with the fishing industry to determine what form of cable armoring would be least likely to create hangs for mobile gear.

Other identified mitigation strategies include communication of cable laying activities through Notices to Mariners, fishing news publications, project emails and bulletins, and navigational charters (Vize et al. 2008). Fisheries liaisons can also communicate cable laying activities. As recommended by BOEM COP guidance, cables are further monitored during the operational phase of the wind energy area to address potential risks to fisheries. Cable positions can be tracked through bathymetric surveys and specialized equipment and techniques (NYSERDA/TetraTech 2021).

It is critical that updated cable coordinates are easily accessible to fishermen. Many electronic chart plotters and navigation software that link to GPS are frequently used on fishing vessels. Having these link to Geographical Information Systems (GIS) could provide a warning if the operator is coming too close to the cable route (Drew and Hopper 2009).

The National Academies of Sciences, Engineering and Medicine (2022) report recommends that BOEM and other relevant federal agencies pursue any practicable option to mitigate wind turbine generator impacts on vessel radar. Some of these include: radar observer training and reference targets around wind areas to allow gain, as well as other radar settings to assist in smaller target detections. Fishermen have also expressed the need to mark individual turbines with AIS transmitters to cut down on the potential for radar interference becoming a problem within the arrays (e.g., BOEM RFI Fisheries Mitigation public comments).

2.1.2.8 Access, Navigation, and Safety Data Gaps and Research Recommendations

- Collision risk studies with commercial fishing vessels and turbines
- Empirical studies exploring the compatibility between offshore wind and commercial fisheries
- Studies that identify fishing vessels with gear in the water as a navigational status
- Spatial operation needs for operating around turbines and within wind arrays for commercial fisheries (all gear types)
- Fishing behavior studies and the perceived risk of operating within a wind area
- Technical risk assessment focused on wind
- Traffic route analysis that includes fishing vessels under all operational conditions (e.g., towing, trawling, transiting)
- “Fishable-spacing” is not always fishable—studies on feasibility of deploying gill net fisheries
- How large-scale wind development affects wind patterns and wind conditions within arrays and how this will affect the ability of fishermen to operate.
- Fishermen’s perceptions of risk and assessments of operators decisions under risk uncertainty through surveys

2.1.3 Fisheries Displacement and Resulting Space Conflicts

The expansion of offshore wind development in the Northeast is expected to result in changes in access to fishing grounds, space-use conflicts, fisheries displacement, and redistribution. The aforementioned topics are closely interrelated and impact each other. Furthermore, there is a vital need to understand changes in fishermen’s behavior and the resulting space and gear conflicts stemming from these exclusions and displacement. Behavior should be studied in a way that is mindful of differences in preferences and capabilities across Fishery Management Plans (FMPs). These factors are cumulative and will be fluid over time. Effort displacement and spatial competition could affect commercial and recreational fisheries with differing magnitudes. The variation in perceived risk reveals an essential need to make research distinctions in both sectors. This section reviews literature relevant to offshore wind and fisheries exclusion, displacement, space conflicts, identifies data gaps, and provides recommendations for future research.

2.1.3.1 Coexistence and Co-location/Space Use

Coexistence refers to the idea that 2 activities (e.g., fisheries and offshore wind) can exist at the same time and/or in the same place (Stelzenmüller et al. 2020). The concept of co-location is 2 activities that are actively managed together while sharing space at sea (Stelzenmüller et al. 2020). In Europe, research has explored the potential for co-location of offshore wind developments. For example, the coexistence of crab and lobster fishing and offshore wind developments may be considered feasible, but site-specific attitudes and issues need to be considered (Hooper et al. 2015; Haggett et al. 2020).

Aquaculture has been discussed as a possible co-location option with offshore wind (Benassai et al. 2014; Gimpel et al. 2015). The economic feasibility of co-location of offshore wind developments with aquaculture in the North Sea has been explored for mussels (van den Burg et al. 2017; Griffin et al. 2015) and seaweeds (van den Burg et. al. 2016).

Coexistence has been researched for recreational fisheries, including charter vessels (Hooper et al. 2017; ten Brink and Dalton 2018; Smythe et al. 2020; Smythe et al. 2021). In interviews with recreational fishers, ten Brink and Dalton (2018) found that both commercial fishermen and anglers reported increased vessel traffic around BIWF turbines. Many reported this as an impact to the fishing experience and appeal of this fishing “destination” (ten Brink and Dalton 2018; Smythe et al. 2020). This suggests a form of use conflict and could feasibly result in future recreational fishing effort displacement. In focus groups with charter/party boat operators and recreational anglers, Smythe et al. (2020) found that anglers reported increased vessel traffic around the BIWF. Although it’s far offshore, boat tours could be an option (Lilley et al. 2010; ten Brink and Dalton 2018; Haggett et al. 2020). Potential loss of fishing access to the BIWF or other future wind farms is a major concern identified by both party/charter boat operators and anglers (Smythe et al. 2020) and in a follow-on study of recreational anglers (Smythe et al. 2021).

Results indicate that there were perceived impacts of the BIWF on the local ecosystem and the behavior of the marine resource users. For some recreational fishers, the wind farm functioned as a destination or target and served as an artificial reef for spearfishing. For some commercial fishers, the increase in recreational fishing due to the establishment of the BIWF crowded out commercial fishers in these areas. As the offshore wind development industry expands within U.S. waters, findings from this study and others like it can provide valuable insights on the potential impacts of these wind farms on marine resource users (ten Brink and Dalton 2018).

Clarifying this issue can illuminate whether the ecosystem will be able to support more fishermen. For example, a gear ban in offshore wind development areas can provide refugia for target stocks but increase fishing pressure on surrounding areas (Campbell et al. 2014). If fishermen avoid turbines due to potential gear loss or safety concerns, they may not be able to take advantage of the increased biomass, except through spillover, and will then concentrate on the edges of the de facto marine protected area (MPA; Slijkerman and Tamis 2015; Murawski et al. 2005). Modeling that includes the habitat around the wind farms could show whether there is predicted to be an increase in biomass and if the fisheries can redistribute to those areas.

As new uses are introduced into an area, if they cannot coexist, one of the uses will be displaced. Henceforth, there will need to be effort displacement for fisheries that cannot exist in the same spatial-temporal situation. Similarly, wind turbine construction would temporarily displace fishing effort. Different fisheries have learned to coexist (e.g., fixed and mobile gear), and the ocean space in the region has established footprints for all different gear types that have been established over decades. Offshore wind is a new static use that may disrupt these footprints and increase conflict between fisheries.

2.1.3.2 Effort Displacement

Some of the most significant OSW impacts on commercial and recreational fisheries identified in the literature involve issues of displacement (Bergström et al. 2014; Murawski et al. 2005; De Backer et al. 2019). There are 2 types of displacement with offshore wind development: short-term and long-term (Stelzenmüller 2020). In the short term, fishing vessels will be excluded from accessing fishing grounds within offshore wind areas during the construction phase. During the operational phase, access to fishing grounds will be dependent on navigational risk and operational needs of certain gear types, or de facto closures. The decision of captains to not operate within a wind array will result in long-term displacement of fishing grounds (Methratta et al. 2020). The cumulative effects of offshore wind development could also result in more significant long-term or permanent displacement.

Appropriate assessment methods for fishing effort displacement are needed. Site-choice models are one way of predicting location choice and displacement in both recreational and commercial fishing sectors. They have been used to evaluate fishing effort displacement in MPAs. Still, they have not been widely used with more current integrated data sets or applied to the emerging and unique needs associated with offshore energy development in the Greater Atlantic region. Additional studies on site-choice models can support finding proper consultation protocols. Site-choice models and the spatial database, if properly developed in collaboration with other users, can produce mechanisms to maximize the utility and create analytical summaries that fishery management council staff can use to evaluate fishery management actions in and around wind energy sites. Site-choice models are primarily developed using a choice set that utilizes “fully closed” location scenarios that mimic MPAs. The impact on fishermen from the displacement of fishing effort from offshore wind is very similar to that of MPAs since fishers have to use less familiar fishing grounds, incorporating greater fuel costs and less predictable catches (Mangi 2013). One stark difference between most MPA displacement studies and those related to offshore wind is that “fully closed” scenarios do not imply that the scenario is desired or even legally feasible since no federal agency has regulatory authority to restrict access to wind energy facilities. Subsequently there is an incentive to structure future studies in a way better suited to offshore wind areas which may still be accessed for some fishing sectors. As mentioned above, mobile gear types will be operationally prevented from working in these areas as they have in the past. Fishermen go where the fish are known to be, and not all areas are equal in terms of availability of each species.

Better understanding current fishing activity in terms of tow patterns, gear configurations, and areas important for fishing is needed in order to determine displacement and associate location choices. Understanding the potential expansion of species, especially with climate change, into other areas can also help. Additionally, newer technologies, such as bigger turbines, need to be evaluated in terms of how they impact vessel traffic. For many projects in the United States, the approach is unprecedented, and there is limited data from Europe or Asia. This work is therefore very relevant to fisheries, fisheries science, and fisheries management.

Changes to fisheries that result from offshore wind development may be considered positive or negative depending on various stakeholders’ perspectives (ten Brink and Dalton 2018). Offshore wind structures can act as artificial reefs that may benefit secondary fish production, but such effects may also have ecological consequences (e.g., Wilhelmsson and Malm 2008; Lindeboom et al. 2011; Bergström et al. 2014). The fisheries exclusion effect that turns some offshore wind into no-go areas, hence effectively no-take zones, could provide resource enhancements or redistribution and attract fishermen to an area. The spillover effect of avoiding fisheries in a particular area can lead to the process of “fishing the line,” where fishing intensity is increased on the boundaries of a closed area. Spatial displacement of effort into another area can increase pressure on fisheries and lead to increased competition among fishers. This is especially the case in static gear fisheries where individual fishers can have a strong fidelity to specific sites (Roach et al. 2018). In addition, changes in the sensory environment related to sound and electromagnetic fields and physical alterations of current and wind wakes may also have as yet unknown impacts on fisheries resources (Gill et al. 2020). Due to the large array of potential factors, studies driven toward creating a clear baseline are essential before predicting possible changes (e.g., fisheries abundance, habitat, fishing locations, seafood supply chain employment).

Effort redistribution is another gap in understanding. The outcomes of alternative scenarios for spatial effort displacement are exemplified by evaluating the fishers' abilities to adapt to spatial plans under various constraints. Interlinked spatial, technical, and biological dynamics of vessels and stocks in the scenarios result in stable profits, which compensate for the additional costs from effort displacement and release pressure on the fish stocks (Bastardie et al. 2014). Furthermore, spatial competition and displacement/redistribution can provide essential insight into days-at-sea (DAS) effects, changes in CPUE, product quality, and transit times (see Section 2.2 Economic Effects for further discussion of these topics).

Studies have shown that fishermen can adapt their areas to other regions if evaluated in advance to allow for stable profits that compensate for the costs of effort displacement and release pressure of fish stocks (Bastardie et al. 2014). Therefore, assessment methods for fishing effort displacement are necessary (de Groot et al. 2014). However, not all fishermen are necessarily flexible to redistribution. An analysis of fisheries impacts to displacement around closed areas of benthic invertebrates has been conducted by Van Oostenbrugge et al. (2015) and Slijkerman and Tamis (2015). Slijkerman and Tamis (2015) found that more experienced and generalized fishermen will be less affected by displacement than species-specific and less experienced fishermen. As Livermore's (2017) work demonstrated, they may also be constrained by distance from their home port.

The major concerns with changes to ocean space use include increased conflict, total or partial loss of access and exclusion, safety, and gear interactions. Due to space limitations, conflicts may arise between commercial fishers and lead to higher competition of fishing grounds, which could lead to gear conflicts between fisheries (Gray et al. 2016; Methratta et al. 2020). Fishermen operating around BIWF have reported in various collected interviews that displacement can redistribute the fishing effort into alternative spaces that may conflict with existing fishing (ten Brink and Dalton 2018). These conflicts, or direct conflicts with the wind turbines, can also result in gear loss (ten Brink and Dalton 2018). Considering BIWF is 5 turbines in a single plane, displacement is likely to be magnified when commercial scale turbines are developed in the future.

These concerns are most prominent in commercial fisheries, though some have been identified regarding recreational fisheries (ten Brink and Dalton 2018; Smythe et al. 2021). For example, Smythe, Bidwell and Tyler (2021) found that recreational fishers reported "crowding" of anglers at the BIWF, which raised concerns of use conflicts, safety, and potential enjoyment as a fishing destination. Perceptions of risk around the offshore wind development are important considerations for commercial and recreational fishermen, as they will impact where the fishermen feel comfortable transiting or fishing (ten Brink and Dalton 2018). These risk perceptions are affected and vary in conjunction with many factors, including but not limited to insurance rates/policies (see further discussions in Section 2b Economic Effects), perceived competition, weather, vessel characteristics, gear type, and other safety-related elements (see further discussions in Section 2.1.2 Fisheries Access and Safety). For example, mobile gear users might be particularly cautious when determining how close fishing is performed from structures due to the associated fishing method which requires them to be untethered from the seafloor, introducing additional collision risks. Some types of fixed-gear use introduce other constraints for fear of equipment entanglement.

Achieving optimum yield is challenging given the dynamic nature of fisheries operations due to markets and regulations, environmental/climate variability, and emerging competing uses for offshore fishing grounds. To help specify and achieve optimum yield in fisheries, we need to accurately and comprehensively identify where and when fishing occurs and evaluate economic tradeoffs of fishery operations promptly (see Section 2.2 Economic Effects for further discussion). Vessel Monitoring System (VMS) data can demonstrate how fisheries are displaced by offshore wind turbines. Vandendriessche et al. (2011) explored potential changes in fisheries methods as a result of OSW development, specifically to increase passive fishing methods around an offshore wind development. They found that the closure of the wind farm area to fisheries did not result in a major disruption of fisheries activities (Vandendriessche et al. 2011).

In the U.S., Livermore (2017) developed a baseline of commercial fishing activity location and value of landings for vessels with VMS onboard for the U.S. Southern New England wind energy lease areas. It was found that fishing off of one state may be conducted by fishermen from elsewhere and result in landings in other states (Livermore 2017). However, inaccuracy/incomplete reporting of fishing locations during commercial and recreational trips are barriers to wholly understanding spatial competition. While VMS does provide high-resolution data on cruise tracks, speed rules need to be applied to distinguish between steaming and fishing where adjustments are required depending on gear (Muench et al. 2018). Approximately 30% of fisheries in the Northeast region do not require VMS, so fishing locations require use of data from self-reported Vessel Trip Reports (VTRs) that report a single position for the entire trip. To overcome this problem, DePiper (2014) uses tow-by-tow position data from observers to estimate statistical models that have been used to infer the spatial extent or footprint for unobserved trips. While this approach improves the spatial capability to identify fishing locations, uncertainties over inaccuracies noted in previous ocean use mapping initiatives remain (Battista et al. 2013). The Northeast data portals[4] provide publicly accessible VMS data as baseline data. Commercial fishermen engaged in the development of updated maps and provided a final report with feedback from the industry and recommendations on how best to use/interpret the data (RODA 2020b). Developing methods for collecting proprietary fine-scale spatial data would allow for a better understanding of activities (e.g., through Fisheries Knowledge Trust)[5].

There are also unknowns in terms of understanding when biological impacts will happen. Current fishery management relies on biomass estimates from the Northeast Fisheries Science Center (NEFSC) Trawl Survey; however, the NEFSC Trawl Survey may not be able to continue within proposed arrays, which will introduce uncertainty into the stock assessment process (Lipsky and Gabriel 2019; Haggett et al. 2020). This uncertainty hinders fishermen from preparing for the future with a clear prediction of next year's potential catch. See further discussions in Section 3.2 Fisheries Independent Survey Effects.

In order to improve resilience of our fishing communities, managers will need to prepare fisheries for these changes by working with the fishermen to have clear timelines with areas of impact to decrease disruption of vessel traffic and gear loss (ten Brink and Dalton 2018; ten Brink et al. 2021). Gear loss can be due to fishermen whose gear types conflict when trying to fish the

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[4] https://www.northeastoceandata.org/, https://portal.midatlanticocean.org/

[5] https://rodafisheries.org/portfolio/fisheries-knowledge-trust/

same area (ten Brink and Dalton 2018). Fishermen operating around BIWF have reported in various interviews that displacement can redistribute the fishing effort into alternative spaces that may conflict with existing fishing (ten Brink and Dalton 2018). Therefore, acceptable consultation protocols between the sectors is necessary (de Groot et al. 2014; ten Brink et al. 2021). Also, having a clear vision for fisheries changes can reduce frustration by fishermen (Van Oostenbrugge et al. 2015). These types of options for working with fishermen provide increased support for offshore wind from fishermen (Reilly et al. 2015).

Cables can also result in gear loss and have been shown to impact fishing distribution as it can result in gear loss for fishermen (ten Brink and Dalton 2018). In an example of spatial conflict with offshore oil pipelines, which are covered by riprap and fishing, Rouse et al. (2020) found via a risk model that the risk of an incident along a pipeline could increase due to the intensity and angle of fishing. Rouse et al. (2020) also calls for more study of the potential losses in fisheries impact assessments due to the installation and decommissioning of oil and gas facilities.

2.1.3.3 Data Gaps and Research Recommendations

- Site-choice models to help predict location choice and displacement (including biological, economic, regulatory, and social considerations)
- Fine-scale operational data analyses
- Space-use conflicts between fisheries and impacts to established fishing footprints/fishing grounds (fixed vs. mobile gear)

2.1.4 Ports and Infrastructure

Ports and working waterfronts represent critical access nodes linking land-based and ocean economies. They are complex and dynamic, comprised of water-dependent, water-enhanced, and water-independent businesses and uses. Often these businesses are related and have developed collaborative, synergistic relationships with other businesses, creating economic efficiencies. These arrangements have been called “business ecosystems.” Productive business ecosystems need “access to capital, workforce, or contract opportunities to flourish,” while forest ecosystems need “rich soil, sunlight, an ideal climate and a steady water supply” (Ferguson and Zeuli undated).

Sometimes these relationships have become formally coordinated as in areas where industrial symbioses have developed and businesses share inputs and outputs of their production processes, examined by the field of industrial ecology (Chertow 2000). Business clusters represent another form of coordinated business environment. Maritime clusters encompass some port-based business ecosystems and describe a suite of related and interconnected businesses, often geographically concentrated and including suppliers and service providers which compete and collaborate, creating an environment in which innovation and performance are enhanced (Doloreux 2017). In other cases, more tenuous business ecosystems have developed. Business ecosystems can change over time as a result of internal or external events and interventions. Some businesses may thrive, others may migrate, and others may be forced out of business.

Working waterfronts generally share a suite of physical characteristics that make them more or less suited to various economic activities. Traditionally, this included deep and sheltered waters with close proximity to multimodal transport options, including access to rail, highway, and air transport. Offshore wind energy projects require shoreside areas for staging, storage, fabrication of the turbines, including assembly of parts, and ongoing maintenance and deployment.

Desirable characteristics for offshore wind ports include water depths of at least 24 ft at low tide, a minimum of multiple berths of at least 450 ft, a minimum horizontal channel clearance of 130 ft, and navigation to open waters unobstructed by bridges and other overhead infrastructure (Urban Harbors Institute 2013). In general, staging areas need at least 10 acres or more of laydown space for delivery, storage, and assembly of turbines as well as heavy-lift cranes and other shoreside infrastructure to facilitate assembly and to transport turbines and other materials on and off of rail and ships on their routes to offshore deployment areas.

The shoreside needs of offshore wind operations change through the life of the project; the largest amount of shoreside space is needed during the assembly stage of turbine installation, and therefore, this phase has the greatest potential to spawn allocation conflicts over the use of port space. After the initial turbine assembly and deployment has been completed over a period of a few years, offshore wind shoreside space requirements usually decline, allowing more waterfront dependent businesses to use the facilities. Offshore wind related enhancements may result in improved port infrastructure that may be used by other port industries, including fisheries, processing, and distribution operations after offshore wind development phases are completed or possibly simultaneously. Improvements may provide fisheries with valuable shoreside staging, storage, boat repair, and maintenance areas and improved transportation connectivity, including rail and highway access, may facilitate fisheries, processing, and distribution operations.

Fishing ports constitute a subset of working waterfronts, connecting the harvest of fish to their ultimate consumption, providing safe harborage and services to the fishermen who utilize the port. For commercial and recreational fisheries, ports or harbor characteristics desired or required by recreational and commercial fishing fleets may differ significantly from those of the offshore wind industry. Although the basic needs of offshore wind and fishing vessels are similar (e.g., protected waters and access to fuel, supplies and maintenance),other attributes, such as maximum water depth at mean low tide and channel and overhead clearance distances may diverge for the two uses. Support services that constitute a fisheries or offshore wind business ecosystem may also differ. Overall, fishing ports need to be commensurate with the type of fleet and the nature and volume of resources being targeted. Additionally, fishing quota and access to the resource where it has traditionally been found is the foundation of the capital available to our food-producing businesses.

Given the diversity of recreational and commercial fisheries, it is difficult to generalize infrastructure requirements. However, using the Food and Agriculture Association typology of fisheries with categories including artisanal, coastal, offshore and distant water fleets, the Northeastern U.S. fleet could be characterized as artisanal (many recreational fishing vessels), coastal (smaller day-trip or overnight boats), or offshore (participating in week-long trips). The Northeast generally lacks large deepwater fishing vessels which spend up to a year at sea and range from large trawlers (500-1,000 tons Gross Register Tonnage (GRT) to factory vessels (5,000 tons GRT; Sciortino, 2013). Fishery management regulations restrict vessel sizes in fisheries such as the Northeast Multispecies fishery (vessel upgrades or replacements cannot exceed 20% or 10%of baseline horsepower or length, respectively (50 CFR 648.4(a)(1)(i)(E))) or the Atlantic herring and mackerel fisheries where vessels cannot exceed 165 ft in length overall (50 CFR 648.4(a)(10)(iii)). A 2010 FAO report includes basic fishing port requirements, noting they consist of “a safe mooring area (the cheapest form is beaching, the most expensive a deepwater port); provision for utilities and boat servicing (water, fuel, workshops); fish handling infrastructure (ice, cold storage, sorting areas, processing facilities); and marketing infrastructure (local market, road to nearest city market or connection to a motorway or airport)” (Sciortino 2010).

2.1.4.1 Offshore Wind and Fisheries: Port and Coastal Infrastructure Interactions

Fisheries and offshore wind development will need to coexist not only offshore but onshore, specifically within ports, sharing or competing for coastal space, and infrastructure. The business ecosystem that has developed in New England fishing ports includes a suite of businesses that support commercial and recreational fisheries. Many of these are water-dependent or water-enhanced businesses that are being displaced given current high demand and concurrent high monetary values for waterfront or near waterfront properties. Increased competition for these properties from the OSW industry may impact the already tenuous ability of the support businesses and services that constitute the business ecosystem of fisheries to retain their critical presence in these areas. These indirect effects will also impact the viability of fishing businesses in these ports, especially small fishing ports and businesses and owner operator fishing operations.

Parkison and Kempton (2022) outline the types of offshore wind-related port and the requirements for each type, including: (1) small oceanic ports for survey vessels, (2) manufacturing ports, (3) marshaling ports, and (4) Operations and Maintenance (O&M) ports. Others identify storage ports as a fifth wind-related port type (Connecticut Offshore Wind Strategic Study 2021). Marshaling ports have the most challenging spatial requirements of all port types (Parkison and Kempton 2022). Port needs are outlined on a project-by-project basis within BOEM's EIS. For example, Table 7 outlines U.S. East Coast ports, communities, counties, and states that could be directly or indirectly affected by the recently approved South Fork Wind Farm and South Fork Cable Export Project (BOEM 2021). It documents ports that have commercial or for-hire recreational fishing activity and ports where wind operations could be located based on port attributes. Deepwater Wind South Fork LLC, awarded Commercial Lease OCS-A 0486 for waters off the coast of Rhode Island, noted that 12 of the 20 regional ports examined could be used as wind staging areas (including fabrication, assembly, storage, or deployment of materials and crew during development, construction, and decommissioning), but only 4 of these host commercial fishing operations: New London, New Bedford, Montauk, and Point Judith. Of these ports, Montauk and Point Judith are identified as potential sites for "crew transfer, logistics, and storage," not for "fabrication, assembly, and deployment," activities that necessitate a much larger dedicated area. Two ports within North Kingstown (Port of Davisville and Quonset Point) are identified as potential areas for fabrication, assembly, or deployment but host recreational rather than commercial fishing operations. Finally, the remainder of identified ports—Shinnecock and Greenport harbors on Long Island, and Old and New Harbors on Block Island—are identified for crew transfer, logistics, and storage and host for-hire recreational fisheries. It should be noted, however, that there are some problems with Table 7 as it indicates that some ports lack a commercial fisheries presence (e.g., Shinnecock Fish Dock, Greenport Harbor) because the vessels homeported in these areas do not fish within the designated offshore wind energy areas. Developers should characterize port usage based upon the existence of commercial or recreational fishing activities and not on where the fishers operate offshore.

Given the range of New England ports, some stakeholders believe there are opportunities for these disparate fleets to coexist and share port facilities without displacing fishing fleets (Synthesis of the Science (SOS) Workshop Breakout Session October 16, 2020 1 PM). Multi-use ports that integrate one or more activities, such as recreational and commercial fishing, eco-tourism (whale watching, dive boats), marine transport, aquaculture production, or offshore wind, may provide fisherman with alternative livelihoods during off seasons, closures, or resource declines, as well as provide new uses for fishing vessels. In New London, CT, a new company, Sea Services North America, just began operations and a collaboration with offshore wind joint venture Orsted-

Eversource. They now include other wind companies in their portfolio, such as Avangrid, the company building Park City Wind and based in Bridgeport, CT. According to their website, the company provides marine services "for offshore asset management, powered by a collective of experienced and knowledgeable fishermen with a deep understanding of our shared marine environment" and seeks to take advantage of new opportunities created by offshore wind, allowing fishermen to diversify and keep working during closures. Orsted claims, "This is the first time an offshore wind developer and a commercial fishing consortium have signed a substantial commercial contract in the history of U.S. offshore wind" (Smith 2021b: B1). The company, formed by an attorney and the owner of a Seafood Distribution company, has hired a local fisherman as their manager of operations. To date, the company has provided scouting and monitoring services for the preconstruction phase of Revolution Wind and Park City Wind.

However, some U.S. fishing ports have experienced problems associated with offshore wind development. The Rhode Island Coastal Resources Management Council pointed to port disruption as one of many "potential unavoidable impacts" of offshore wind project construction to commercial fisheries and for-hire recreational fishing interests, as well as "disruption to access or temporary restriction in port access" during the assembly, construction, and installation phase as possible concerns (RI Coastal Resources Management Council 2021). They also reported that temporary displacement of commercial fishing activity occurred during the construction and installation phase of the BIWF in 2015 and 2016, although it is not clear if that temporary displacement occurred in port space or at the ocean wind farm site (Ibid, p. 4). Acute internal competition between recreational and commercial fleets has been evidenced on the West Coast in California where conflicts over dockage and wharf access have occurred, and it is generally perceived that the recreational boating/tourist sector prevailed (SOS Workshop Breakout Session October 16, 2020 1 PM). Additional dredging in harbors where offshore wind assembly is planned or occurring may be required in order to accommodate the large size of vessels used for wind turbine parts and especially fully assembled wind turbines. Noise pollution may increase both above and below the surface from port activity due to the size of the vessels involved with turbine assembly.

Dredging activities associated with efforts to deepen ports for transit by larger OSW vessels may improve navigation for fishing boats; however, sedimentation and remobilization of toxic compounds in the sediment associated with these operations may impact marine species, especially benthic biota and filter feeders, and may negatively impact nearby aquaculture operations.

The case of Connecticut's New London State Pier provides a revealing example of conflicts over waterfront use and space. Conflict has emerged between existing port users and the Connecticut Port Authority as the use of the entire port area has apparently been given to offshore wind developer Orsted-Eversource, displacing all existing users of the facilities, with no opportunities for public deliberation or input on the project prior to the submission of permits (Ebbin and Trumbull 2021). Seven acres of water between 2 existing arms of the State Pier is slated to be filled in order to create additional space for wind turbine assembly. Concern on the part of Cross Sound Ferry about navigation of its ferries around the newly configured pier led to design changes reported to have added an additional $50-60 million to project costs. Two commercial fishing companies, Montville-based Donna May Fisheries and Waterford-based Out of Our Shell Enterprises, who utilize the State Pier, were told to leave the State Pier area; however, their eviction has been stayed at least temporarily, and they have relocated to another part of the State Pier (Smith 2021a).

High voltage submarine cables transfer energy produced by offshore turbines to the electrical grid where it is distributed and ultimately used by communities. Cable placement can be fraught with problems as their installation can disrupt benthic communities and the existence of cables may displace certain fishing activities, especially benthic trawl gear and possibly some types of aquaculture operations. Cables must be deeply buried to avoid creating a hazard, snagging or destroying fishing gear, or becoming unburied and exposed. An illustrative example of problematic cable deployment occurred with the 2016 installation of the electrical transmission cables which connect the BIWF turbines with the new National Grid Substation on Block Island making landfall at Fred Benson Town Beach. High voltage cables leave Block Island for the Narragansett mainland at Crescent Beach. Within months of deployment, the nearshore cables at Crescent Beach became exposed, creating a hazard for recreational swimmers, boaters, and fishers, as well as commercial fishing activities. The RI Coastal Resources Management Council (CRMC) permitted the cables to be installed at 4-ft depth rather than the 8 to 10 ft recommended by staff and allowed a less costly “jet-plow” installation technique to be used (Faulkner 2020). The cable reconstruction efforts estimated to cost $30 million were put on pause in May of 2021 as the Block Island tourist season commenced (EcoRI 2021). Repair was to begin in the fall of 2021 but was further suspended through the winter with National Grid stating they hope to continue in early spring 2022 (Meyer 2021). Developers have proposed using horizontal directional drilling techniques in order to place cables deeper as they make landfall (Bragg 2019). In a case in Falmouth, MA, residents criticized the possibility of cables interfering with a very popular beach and waterfront use (Hill 2020). In response, Mayflower Wind has pledged to bury cable using horizontal directional drilling techniques and at a depth of 50 ft where the cable makes landfall.

In addition to physical impacts, cables generate electromagnetic fields which may impact target species such as lobster and Jonah crab, thereby impacting commercial fisheries harvests (Petruny-Parker et al. 2015). See Section 1.2.1.2 for further discussion on electromagnetic field effects. The potential health danger of electromagnetic fields from the cables has been cited by some members of the public as a possible health danger of cables passing through their neighborhoods (Hill 2020). Burial of those cables will likely help to address those concerns. However, some of the cable burial designs which utilize concrete pads above and below are also sources of concern for some commercial fishing operations. Some fishers have noted that delays associated with the installation of cables have extended the amount of lost fishing time experienced and for which fishers were not compensated (ten Brink and Dalton 2018).

The siting of land-based and coastal substations from wind projects has also emerged as a potential source of conflict over coastal resources. Offshore wind development has addressed many of the objections to coastal siting of substations by moving substations further inland and placing cables to those substations underground as they enter and exit the shore. One of the potential benefits of high coastal population densities is that a great deal of electrical cable infrastructure already exists, so power lines and large portions of the electrical grid may be able to utilize existing infrastructure or utilize established cable routing.

While offshore wind’s demands on ports and coastal infrastructure will inevitably compete to some degree with pre-existing water-dependent uses, especially in offshore areas, it appears the wind industry is not seeking to displace traditional fishing ports for staging areas; these port characteristics simply do not meet offshore wind needs.

Given the artisanal, coastal, and offshore nature of the fishing industry in New England, some level of shoreside coexistence of offshore wind and fishing industry operations may even be possible. In the best scenarios, shoreside coexistence could potentially be complementary, especially in areas where different operations are spatially separated, as in New Bedford. During those times of the year when fishing fleets are not fully operational, offshore wind may be able to provide demand for labor and other shoreside businesses. One of the longer-term unknowns is the extent to which specific U.S. ports emerge with a specialization in one or another of the activities required for offshore wind deployment, operation, and maintenance. Without specialization and some level of cooperation among New England's relatively limited number of ports suitable to support offshore wind development, offshore wind requirements for landside support during offshore wind assembly and deployment may outstrip existing port space and infrastructure.

Marshaling ports have the most challenging spatial and load-bearing requirements of all OSW-related port types, and wind industry planners have expressed that no suitable ports exist in the U.S. (Parkison and Kempton 2022). Port managers from Hull, United Kingdom, stated that there are no advantages from starting with an existing port to starting with bare land adjacent to the water as it had been more costly to tear out old fishing piers and inadequate ground reinforcements (Parkison and Kempton 2022). In an analysis of infrastructure needs to offshore wind targets, Parkison and Kempton (2022) attribute the lack of marshaling area supply to developers having built ports to support early, smaller projects and choosing location based on incentives with state power contracts. Studies have shown that a cumulative, long-term coordinated effort in port development is necessary to ensure infrastructure needs of OSW are met (NYSERDA 2022; Parkison and Kempton 2022). Regional, long-term planning will also limit space-use conflicts in traditional fishing ports.

New Bedford entered the era of offshore wind development in New England with an advantage in terms of availability and preparedness of space. New Bedford Marine Commerce Terminal, managed by the Massachusetts Clean Energy Center, had been planned in New Bedford as a 26-acre facility specifically for offshore wind development and was largely completed in January 2015. The terminal was developed specifically for offshore wind and on a former brownsite. Conflicts with other port users could be entirely avoided there. Elsewhere in New Bedford, there is competition for space. Nordic Fisheries, which co-owns Eastern Fisheries, a scallop fishing company located on Hervey Tichon Avenue, sued the City of New Bedford for allegedly breaching a 99-year lease contract and misleading the companies regarding the North Terminal expansion project. The future bulkhead of the project will increase dockage capacity, expand direct access to the port's offloading and seafood processing facilities, and provide additional capacity for offshore wind opportunities (Lennon Feb. 15, 2021). There have been positive economic port-related developments at the same time. The future Bristol Community College National Offshore Wind Institute will be constructed at the previous Packaging Products Corporation on Herman Melville Boulevard in New Bedford (Lennon, July 8, 2021). One underlying constraint for New Bedford is that some offshore wind-related infrastructure is proving to be too large to pass into New Bedford Harbor through the port's hurricane barrier entrance, including the first Jones Act compliant vessel that will be completed in the U.S. (Chesto, June 1, 2021).

2.1.4.2 Ports and Infrastructure Research Gaps

- Which ports will benefit from new infrastructure?
- What fishing ports may face potential space-use conflicts with onshore wind staging needs?
- Will business ecosystems associated with wind displace the existing business ecosystem? Will new jobs be filled by existing workers or are skill sets different?

- Once wind farms are decommissioned, what will happen to ports? Are there other uses of these ports by fishing industry? Will space remain available for the fishing industry?
- How useful might reconstructed port/pier space from OSW industry be for use by the fishing industry in future?
- How will small fishing ports and owner-operator businesses be impacted by offshore wind?

2.1.4.3 Ports and Infrastructure Research Recommendations

A methodical survey of shoreside fleet and individual boat needs and requirements in ports could provide a baseline of current port uses. As some fishing industry activity moves north (for example, New Bedford continues to increase the number of its scallop fishery boats due to greater use by boats registered in southern states), study of shoreside businesses and perceptions of port space is critical information. Seasonal variation in terms of which ports are needed during which months of the year is also highly relevant. Gathering local knowledge about shoreside components of existing supply chains would be relevant to both offshore wind and the fishing industry in terms of identifying opportunities for shoreside businesses which could serve both industries.

Spatial planning, including a GIS analysis of port real estate and related port space, could be mutually beneficial to both the fishing and offshore wind industries. Data collection of any changes to port space, including new space and allocation (for example, New Bedford is developing a new North Terminal space), could help to provide a more detailed inventory and understanding of available spaces. Study of trends and growth and any contraction of expected future space needs could also be conducted.

2.1.5 Perspectives of Fishing Communities

Fishing community perspectives for each topic were discussed throughout this section. Overall, fishermen have expressed significant concern with the interaction of offshore wind development and fisheries. Fishermen have worked with the industry to understand operational needs (e.g., scallop and clam industry and cable burial depths); however, fishermen, especially from mobile gear fisheries, have expressed through public meetings, research interviews, and collaborative work that they will not be able to safely operate within a wind area. This is especially true within varying sea state conditions. Maintaining the viability of fishing businesses and the support infrastructure, especially small owner-operator fishing operations, is a significant concern of the industry. All of the research needs outlined in this section would greatly benefit from collaborating with fishermen and maximizing their knowledge in filling data gaps.

2.1.6 Conclusions

This section reviewed relevant literature on fisheries access concerns, navigational risks and safety, and displacement with offshore wind development, and highlights data gaps and research needs in understanding fisheries' operations and behavior in response to offshore wind development. Understanding access and safety/navigation concerns will help understand fishing behavior, including where and how they fish, which in turn could have social (conflict), biological (e.g., species abundance/distribution) and management (e.g., increased quota restrictions due to changes in effort and impacts on stock advice) effects. Fishing behavior will also affect ports with potential changes in homeport, landing port, infrastructure availability, and port traffic. A clear set of research needs and monitoring protocols for fisheries operations is needed as a next step to fully understand the effects before, during, and after construction of wind development in the region.

2.2 Fisheries Economic Impacts

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2.2.1 Introduction

The intersection of U.S. offshore wind and fishing activities is expected to result in economic implications given the contributions both industries play in the national economy. In 2018, the American Blue Economy, including goods and services, contributed about $373 billion to the nation’s gross domestic product (GDP), supporting 2.3 million jobs and growing faster than the nation’s economy in its entirety (NOAA 2021b). Marine-related GDP grew 5.8% from 2017 to 2018, faster than the 5.4% growth of the total U.S. GDP as measured in current dollars. The economic activity from America’s seaports alone grew from 2014 to 2018 by 17% to $5.4 trillion, comprising nearly 26% of the nation’s $20.5 trillion GDP. If American coastal counties were an individual country, they would rank third in the world in GDP, surpassed only by the United States and China (NOAA 2021b). In terms of fisheries economics, commercial landings (edible and industrial) by U.S. fishermen in ports across the 50 states were 9.3 billion pounds or 4.2 million metric tons valued at $5.5 billion in 2019; of these, the Atlantic region[6] made up 13% of total U.S. commercial landings and 39% of ex-vessel value (Fisheries of the United States, 2019 Infographics, 2021). Shoreside fisheries-dependent communities are major drivers of this sector of GDP where fishing support businesses play major roles in stimulating local economies. The economic importance of recreational and commercial fishing in the U.S. is well documented (NMFS 2021b; Lovell et al. 2020). Still, the construction and operation of offshore wind developments have introduced many unknowns which may impact these fishing communities and the overall contribution to the nation's economy. OSW development offers a low-carbon source of electricity for the nation, but understanding social and economic externalities stemming from OSW remains essential to ensure that both the benefits and costs and how they are distributed are considered in mitigating negative impacts. Implementing strategic policies and plans from research findings can ensure minimization of direct and indirect costs and maximization of both monetary and non-monetary benefits. Each community has a unique set of identifiers that make planning essential to realize equitable impacts. Policies and incentives for mitigation should be modeled around these differences and applied using methods that support diverse stakeholder engagement and internal decision making to consider aggregate and cumulative economic effects. Studying the

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[6] Data from the east coast of Florida are included in the Atlantic while Florida west coast data are included in the Gulf Coast. Puerto Rico data is not available for 2019.

areas where OSW is expected to economically impact recreational and commercial fisheries allows for more complete descriptions of implicit as well as explicit costs and benefits imposed.

In this section, we focus on summarizing the findings from the literature related to direct economic impacts of OSW on the recreational and commercial fishing sector. Research methods and findings from existing literature are summarized for the various economic indicators and factors which have been consistently identified as possible areas of concern. To keep the review tractable, research from the Greater Atlantic Region is the primary focus of the economic synthesis, followed by a global perspective where research findings from the U.S. are lacking. In most cases, recreational fishery impacts are less common given the lack of species-specific recreational demand models and the uncertainty of displacement and existing spatial angler data. As such, references should be noted as commercial unless stated otherwise. Each section/subsection is concluded with a section focused on data and knowledge gaps to offer pathways forward in improving each area of study. The fisheries economic effects are interrelated to social and cultural effects, and it's often difficult to separate these connections. For the purpose of this report, this section focuses on economic effects and social and cultural effects are discussed in Section 2.3.

2.2.2 Changes in CPUE/Transit Time/Time to Market

2.2.2.1 DAS Effects/Time to Market

The impacts of OSW on a fisherman's DAS and the time it takes for fishermen to sell catch at their destination port have been indirectly addressed in multiple studies and reports (Samoteskul et al. 2014; Kirkpatrick et al. 2017; Moura et al. 2015). Wind farm maintenance work was cited as causing disruption to fishing operations within and around wind farms. Conflict with OSW maintenance vessels, excessive area closures for maintenance work, and poor communication between fishermen and OSW maintenance vessel operators was reported by fishermen in the U.K. Fishermen reported increased steaming distance and time to fishing grounds beyond the OSWs (Gray et al. 2016). The freshness of a catch impacts the quality and price of the product, and therefore, the OSW navigational issues expressed by commercial fishermen are of economic concern.

2.2.2.1.1 DAS Effects/Time to Market Data and Knowledge Gaps

In some environmental impact statements, negative effects are hypothesized to be mitigated by compensation plans. Vineyard Wind, for example, agreed to provide fisheries mitigations as required by Rhode Island enforceable policies 11.10.5(C), (G), and (H), which includes a $4.2 million fund for direct compensation to Rhode Island fishermen for loss of equipment or claims of direct impact (U.S. Department of the Interior (DOI) / Bureau of Ocean Energy Management (BOEM) 2020). Deepwater Wind South Fork, LLC has also developed a financial compensation policy for use when interactions between the fishing industries and project activities or infrastructure cause undue interference with gear (Bureau of Ocean Energy Management and Office of Renewable Energy Programs 2021). Compensation plans are typically state-specific, and not enough data has been collected in the United States to definitively assess their effectiveness. Even in the European Union, where more information may be available, many fishermen claimed compensation arrangements were inequitable, alleging that some fishermen eligible for compensation did not receive any while others received too little as fisheries were undervalued and compensation was not based on vessel size and allocated fishing time (DAS; Gray et al. 2016). These plans may capture increased DAS costs due to OSW; however, these additional costs have not been adequately quantified and would need to consider increases in all related business costs. It was not possible to confirm these allegations as compensation details were not requested or provided (Gray et al. 2016).

2.2.2.2 Bycatch Composition Shifts and Changes in CPUE

CPUE often measures a harvester's or vessel's landings over a certain time period. This metric lends insight into the efficiency of the commercial fishing trip and can be used as a metric to measure performance for commercial fishing businesses. For recreation, CPUE may result in changes in satisfaction and can relate to how many trips an angler is willing to take. CPUE can be impacted by fishing location and fishing tactics employed by the angler as well as external factors, such as resource availability. Bycatch is another component that can detract from CPUE. Bycatch composition shifts can be especially difficult to predict and measure when discerning effects directly imposed by OSW due to the large number of externalities that also contribute to driving shifts in species compositions. Other factors that impact bycatch composition include weather, vessel traffic, water temperature changes, and many more. Bycatch composition and CPUE are both dependent on changes in resource conditions (see sections 1.4.2, 1.4.3, 1.4.4, and 2.1).

Similarly, a study on co-locating offshore wind developments and MPAs found that during the operation phase of the wind farm, net primary production reached almost the same annual sum as before construction. It would therefore seem reasonable to assume that ecosystems do not flip into another state due to OSWs but some ecosystem structures and processes are altered, which could have a considerable effect on the ability of ecosystems to withstand additional environmental stresses in the future, although this is unquantifiable (Mangi 2013).

2.2.2.2.1 Bycatch Composition Shifts and Changes in CPUE Data and Knowledge Gaps

Improving knowledge on how OSW developments may affect fishery resources requires research examining fishes' life histories and determining how the effects may act at the cellular, organismal, population, and/or ecosystem levels of organization (Gill and Wilhelmsson 2019). Regardless of how and at what life stage the species is affected, what is significant to the fishery stock is whether effects are seen in catches, landings, and in the quality of the species. The links between the biological, ecological, and socioeconomic outcomes of OSW effects and how they change stocks require further investigation. Changes in the sensory environment caused by the emission of energy from OSWs (e.g., EMFs) and by underwater sound along with changes to the physical environment caused by the alteration of water currents and wind wakes may be significant to the fishery if they affect fish (re)production, migration, and/or distribution. Similar to artificial reefs and often fisheries exclusion zones, OSW areas are contributors to locally increased attraction, concentration, and food provision for some fish species, with possible effects on fish stocks (see Section 1.4 for further synthesis of these ecosystem effects). No OSW-related evidence currently exists regarding whether there are changes to fish production (Gill and Wilhelmsson, 2019). In the offshore oil and gas sector, increased fish production studies have focused on investigating trophic pathways that lead from artificial reef effects to increased fish production (Daigle et al. 2013; Dance et al. 2018; Reeves et al. 2019), and fish numbers and biomass have been shown to be greater than in nearby natural hard substrate areas (Claisse et al. 2014). Because OSW footprints are different from those of oil and gas installations, there remains uncertainty about how local ecological changes at the wind turbine scale translate to the wider ecosystem and about any consequence to resource species stock dynamics.

2.2.3 Fisheries Direct Cost Effects – Crew/Labor, Moorage, Fuel Costs, Insurance

2.2.3.1 Crew/Labor and Fuel Costs

There is a large body of European literature investigating the optimal parameters for O&M of offshore wind developments. These studies often consider the minimization of travel costs (fuel) and service crew-related costs from the wind developer's perspective (Irawan et al. 2017; Dalgic et al. 2015; Van Bussel and Zaaijer 2001; Rademakers et. al. 2003; Besnard 2009; Snyder and Kaiser 2009; Scheu et al. 2012). Results of these studies are contingent on the areas under consideration for development and the model specifications; however, findings are often related to those of Snyder and Kaiser (2009), identifying that capital costs are likely to be positively correlated with the wind area's distance from shore. There are few studies investigating how the crew and fuel costs incurred by commercial and recreational fishing operations may be impacted by offshore wind development.

2.2.3.2 Crew/Labor Costs

There is a lack of information describing if and how commercial and recreational fishing crew/labor costs or payments may be impacted by offshore wind development. Studies have, however, investigated the perceived impacts of offshore wind developments on fishing income (See section on Changes in Revenues, Income and Livelihoods) which can translate into impacts on crew earnings, specifically to the commercial sector. There is more ambiguity around the recreational sector given the lack of understanding on numbers of recreational crew and how wind will impact recreational demand and therefore recreational crew opportunities. In the Northeast U.S., commercial vessel crew costs or payments to crew are generally based on share systems where revenue is split by a specific percentage between the owner, crew, and captain. Operating costs, such as supplies, food, fuel, bait, and ice, vary on each trip but also vary in terms of how they are deducted from trip-level earnings. In some cases, these trip expenses are deducted prior to dividing up the payment and other times after (i.e., off the top or after the split). The types of trip expenses deducted from the crew's earnings (i.e., ice, fuel, bait, groceries) and when (i.e., before or after the split) are not consistent across vessels. Currently, there is no literature identified investigating how these crew payment systems might change as a result of offshore wind development. However, if revenues decrease as expected by many fishers, crew and captain earnings would be directly (negatively) impacted under the current payment systems. See the section: 2.2.4.1 Changes in Revenues, Income and Livelihoods.

2.2.3.2.1 Crew/Labor Data and Knowledge Gaps

Investigating perceived and realized changes in commercial and recreation fishery crew payment systems and fishery labor costs as a result of offshore wind development would require an extensive investigation to fill the existing knowledge gaps. Primarily, there is a lack of information on how fishers perceive crew payment systems/labor costs changing in the wake of offshore wind development. Secondly, to quantitatively assess how changes in fishing revenue might impact crew labor costs/payments, a more thorough understanding of regional crew payment systems is required. Trends in crew remunerations have been captured in the NEFSC Social Sciences Brach Crew Survey and could serve as a baseline for crew compensation prior to extensive wind development (Silva et al. 2021). Efforts to collect more detailed information on crew payment systems and earnings has been conducted through the NEFSC Social Sciences Branch Business Cost Survey (Ardini et al. 2022). This voluntary survey has experienced decreasing participation over the various implementation phases, making it difficult to draw conclusions about crew payment systems and crew earnings using survey results. Fishing industry participation in this and other survey efforts is crucial to investigating individual cost categories, such as crew/labor payments, and how they may shift over time. Initial scoping and engagement sessions with regional fishermen are necessary to understand if labor or crew payment systems are expected to be impacted by offshore wind development. Once the issue has been properly scoped, mandatory survey efforts investigating crew payment systems, earnings, and fishing revenues can help fill in the remaining knowledge gaps on this topic. Mandatory data collection on crew payments are found in other regional survey efforts such as in the Alaska Economic Data Report (Thunberg et al. 2015). Survey data can be used to track changes in the crew payment systems over time as well as be used to estimate the extent to which offshore wind may impact crew payments.

2.2.3.3 Fuel Costs

There is a lack of information on how and to what extent commercial and recreational commercial fuel expenditures are expected to be impacted by offshore wind (Hattam et al. 2015; Berkenhagen et al. 2010). As previously mentioned, the largely qualitative study by Gray et al. (2016) found that U.K. fishers incurred increased steam times and increased distances to fishing areas due to established OSWs, which relates to increases in fuel consumption. Further, the majority of North West of England fishermen agreed that the cost of fuel impacted their fishing effort. The report goes on to suggest the development of the fuel depots as a method to offset increased fuel expenditures. Fuel cost mitigation measures have not been mandated in the Greater Atlantic region as of 2021. In theory, an increase in the population consuming fuel is a demand curve shifter and would increase fuel prices if all else were held constant. NOAA and the National Marine Fisheries Service (NMFS) conducted a study investigating wind development on the Atlantic OCS which uses a location choice model to identify the probability of commercial fishers operating in particular ocean patches (Kirkpatrick et al. 2017). From this model, the relative difference in trip-level revenues—net variable costs where variable costs include fuel, ice, bait, and an average measure of gear damage or loss—are estimated. However, differences in fuel usage is not summarized, specifically, in this report. The work by Kirkpatrick et al. (2017) is discussed further in 2.2.4 of this paper. An analysis by Samoteskul et al. (2014) uses cost effectiveness analyses and Coastal and Marine Spatial Planning modeling frameworks to identify optimal locations for wind development in relation to Mid-Atlantic U.S. transport vessels routes. The report models 1,500 commercial shipping vessel transports, calculating direct and indirect costs pertaining to each trip. The direct costs include fuel expenditures, operational costs, and capital costs, and the indirect costs pertain to the external cost of greenhouse gas emissions. For the calculation of direct costs, fuel usage is estimated for each trip based on the vessel's main and auxiliary engine. The price of fuel is assumed to be $1000/mt based on Marine Diesel Oil or Marine Gas Oil global prices (2012 U.S. dollars). The study found that, on average, nearshore wind development causes an additional 18.5 km per transit which relates to a 54% increase in annual fuel expenditures (i.e., an additional $5.29 million dollars to the total fleet's fuel expenditures). Projected increases in commercial and recreational fishing fuel expenditures due to wind farms have not been analyzed to the degree in which Samoteskul et al. (2014) investigates large deep-draft ships; however, similar methods could be employed to model costs incurred by fishing industry participants under various wind area closure scenarios. There have been multiple methods proposed to minimize or avoid increases in fuel expenditures that are directly impacted by offshore wind areas. Fuel subsidies provided by the government are a suggested best practice in a 2015 review of offshore wind development tools and best practices by Moura, Lipsky, and Morse. The review, however, does not offer best practices or methods on how to accurately estimate the level of subsidization required to offset possible increases in fuel expenditures due to offshore wind sites. Designated transit lanes have also been suggested as another tool to increase vessel safety as well as decrease fuel expenditures (Responsible Offshore Development Alliance RODA 2019). More information on transit lanes can be found in section 2.1.2.2. RODA utilized commercial fishermen survey data to map vessel transit through the proposed New York Bight Wind Energy Areas. The USCG initiated the Areas Offshore of Massachusetts and Rhode Island Port Access Route Study in March 2019 to investigate various components of vessel transit lanes off the coast of Massachusetts and Rhode Island (USCG 2020). The ongoing study relies on extensive stakeholder engagement as well as AIS density data to study transit patterns near OSW areas to explore vessel routing measures. These studies, however, have not yet reported on the cost savings resulting from fuel expended in transit lanes relative to navigating around wind areas.

2.2.3.4 Fuel Cost Data, Knowledge Gaps, and Suggested Studies

In the Northeast and Mid-Atlantic U.S., trip-related costs (including fuel expenditures) are collected on a subset of commercial fishing vessels (about 4% of trips, annually) by the Northeast Observer Program (NEFOP). The trips are sampled based on a stratified sampling design created to satisfy biological data needs rather than economic, which can lead to bias in econometric models that rely on these data. Trip costs have been modeled using methods to correct for selection bias in order to predict trip costs for the entire fleet; however, verifying the accuracy of these model predictions is difficult due to the nature of selection bias and the lack of trip-level data collected solely for economic analyses (Werner et al. 2020). These models are also currently designed to predict total trip costs rather than each cost component individually such that obtaining fuel costs for each trip would require additional research and modeling. A comprehensive, mandatory, economic cost data collection effort would aid in creating a foundation for estimating how changes imposed by wind areas could impact fuel and other trip-related expenses. Mandatory trip-level data collection efforts exist in Southeast fisheries and for Atlantic HMS (Thunberg et al. 2015). One major data gap in understanding the impacts of offshore wind on fuel expenditures is the quantification of possible costs to the fishing industry. Using estimates or industry provided cost data, methods similar to those of Samoteskul et al. (2014) can be employed to estimate increases in fuel expenditures driven by offshore wind development. Lastly, similar to Kirkpatrick et al. (2017), modeling changes in fuel usage in the recreational and commercial fishery requires modeling the fisher's choice of fishing location which would be necessary when examining how offshore wind will play a role in altering vessel owners' fuel expenses.

2.2.3.5 Cost of Insurance

The cost of insurance has been discussed in a handful of offshore wind development stakeholder engagement sessions and best practices reports where insurance rates are speculated to increase due to the navigational hazards posed by turbines (See safety section for more). A 2015 report summarizing themes from stakeholder meetings focusing on floating turbines off the coast of Maine identifies insurance costs as a concern of local fishermen. The fishermen specifically highlight that insurance rates may change due to development of the turbines and expressed ambiguity as to whether or not insurance companies would create their own exclusionary distances from the turbines (Hall and Lazarus 2015). Hooper et al. (2015) found that one-third of the 67 U.K. crab and lobster fishermen interviewed for their study were concerned about the validity of their insurance while fishing in wind areas. Interview participants from a review of offshore wind development best practices note that increases in insurance premiums may financially bar commercial fishermen from operating in wind areas, even if the area is open to fishing. The review suggests that insurance support be provided by government and wind developers as a best practice strategy to offset potential increases in insurance premiums (Moura et al. 2015). The review, however, does not provide guidance on how to estimate the increases in insurance premiums of those operating in offshore wind areas. Lastly, there are concerns around the liability of fishermen if underwater cables are damaged—an issue which has surfaced in other, non-wind related projects.

2.2.3.6 Cost of Insurance Data and Knowledge Gaps

To better understand how insurance rates might be impacted by offshore wind development, time series data is necessary to fill the existing knowledge gaps. Although obtaining insurance cost data from insurance companies would be useful, each company uses proprietary formulas to determine rates and, therefore, a strong incentive for companies to not share responses to inquiries. Furthermore, the overall lack of transparency in how claims processes may affect rates and policies makes determining long-term costs very difficult. The NEFSC's Social Sciences Branch Business Cost Survey has aimed to collect annual vessel and business-level costs from commercial fishermen in the Northeast and Mid-Atlantic, including insurance premiums (Ardini et al. 2022). Given that this survey effort is voluntary, response rates have suffered, and insurance data analyses, such as annual increases or econometric models of insurance premiums, have not been generated. Mandatory collection of insurance cost data would enhance the opportunity to assess the impacts of wind areas on insurance rates and fill the data gaps related to this topic. With fishing industry insurance cost data, econometric models can be generated to identify the variables which influence rates and predict how wind areas may alter these costs. Lastly, there has been little to no research or discussions which explore possible liability agreements established between wind companies and local fishermen groups.

2.2.3.7 Cost of Moorage

Space for moorage in ports and harbors is limited. The space demands for OSW activities for support vessels as well as assembly and maintenance of equipment will compete for limited harbor space and may result in higher moorage costs to existing commercial and recreation users. The extent to which this may occur is uncertain as mooring costs have generally only been examined from the perspective of the wind developer (Devin 2019; Zhao and Gong 2013; Chung 2012; Musial and Butterfield 2004). The Department of the Interior (DOI)/BOEM released a report which mainly focuses on environmental and ecological impacts; however, the report considers moorage in relation to wind related structures but not the impact of wind development on commercial or recreational fishers' moorage (Petruny-Parker et al. 2015). Unlike other costs, there are no studies identified documenting fishing industry members' perspectives on how or if offshore wind is expected to impact the cost of moorage. To fill data gaps, scoping around this topic is required to understand if the fishing industry identifies moorage costs being impacted by offshore wind and, if so, to what extent. Commercial fishing moorage costs are collected in the NEFSC's Social Sciences Branch Business Cost Survey, which could be used to track changes in moorage costs over time, however, industry participation in this survey effort will need to increase and stay consistent for the data to be useful in such an analysis.

2.2.4 Fishing Revenue/Income/Livelihoods

2.2.4.1 Changes in Revenues, Income and Livelihoods

During the preliminary planning stages of offshore wind development, it is not uncommon for initial scoping sessions and community engagement meetings to take place. During these meetings or interviews, potential/perceived stakeholder concerns are documented. A common concern expressed by the fishing community is negative impacts of offshore wind development on revenues, earnings, income, and/or livelihoods. A report by Mackinson et al. (2006) uses questionnaire data to summarize U.K. fishing industry perceptions of the socioeconomic impacts of the construction and operation of offshore wind developments. All but 1 respondent suggested that wind development would have negative impacts on fishing income due to the exclusion of access to high-value fishing areas, navigation around wind areas, and the crowding of alternative fishing areas as a result of displacement. It should be noted that this study received an 8% response rate (n=23), and responses may not be representative of the fishing industry as a whole. Fishermen were unable to quantify the predicted change in expected revenues resulting from the development of the wind areas. The report also summarizes the percentages of fishers' total revenues earned within the various proposed wind areas, which gives insight as to which vessels would remain profitable if wind areas were completely closed to fishing. In another U.K. study, stakeholder questionnaires and workshop results were thematically coded to decipher key challenges related to renewable energy developments. Results suggest that socioeconomic data are the third leading area of challenge behind ecological data and environmental monitoring. The study suggests that more research is needed on topics such as capturing the economic contributions of each fishing location, understanding the realized or estimated economic impacts due to displacement of fishers, estimating the potential loss of employment, and generation of supply chain analyses (de Groot et al. 2014). Loss of commercial fishing livelihood was also identified as one of the top 3 main concerns identified in a study examining potential impacts to Scottish west coast fisheries (Alexander et al. 2013). Gray et al. (2005) also conducted a study on wind development perceptions in the U.K. through interviews with wind developers, regulators, and key industry members. The study reports that the average annual income for the 12,000 commercial fishermen in the U.K. is about £15K (about 18,000 USD), creating a baseline for potential impacts on earnings. Both regulators and wind developers identify wind development as a possible source of major negative impacts to fishers' incomes and identify compensation to the industry as a method to counter lack of access to fishing grounds. Wind developer and fishing industry perceptions of offshore co-located U.K. wind farms was investigated by Hooper et al. (2015), who find that the majority of fishermen interviewed expect to lose fishing grounds if the proposed OSWs are built; however, whether or not this loss of fishing area would impact the fishers' livelihoods was not investigated. Loss of fishing grounds and crowding concerns were also expressed by a handful of fishermen in a Block Island study (ten Brink and Dalton 2018).

2.2.4.2 Changes in Revenues, Income, and Livelihoods: Quantitative Analyses

Despite the level of concern surrounding fishing revenue and livelihoods, there are limited analyses in the Greater Atlantic U.S. that aim to quantify the changes in commercial and recreational income and revenues stemming from offshore wind development. In this section, we focus on the U.S. East Coast for assessment of revenues; however, it should be noted that the use of identifying changes in landings based on VMS and vessel logbook information is also a technique used in Europe (Stelzenmüller et al. 2016). Kirkpatrick et al. (2017) estimate revenues resulting from catch landed in Northeast and Mid-Atlantic U.S. WEAs using data from 3 main sources: VMS, NEFOP, and vessel logbooks. A novel statistical method described by DePiper (2014) is used to obtain more precise location estimates from self-reported catch landing data. Revenues are estimated using a multi-way fixed effects model, and results are summarized by exposure measures. The exposure measures, rather than reporting economic impact or losses, suggest the extent of potential impacts stemming from wind development and are estimated using data from 2007 to 2012. This analysis accounts for 82.5% of all exposed wind area revenues, where the other ~17.5% of revenues exposed in wind areas are not accounted for due to data reporting limitations. Results suggest that the 8 proposed WEAs generate an average of $14 million in commercial revenue annually (i.e., 1.5% percent of the total commercial fishing revenue generated in the New England and Mid-Atlantic Region). Total exposure, based on absolute revenues, is further summarized by port, vessel size-class/gear type, and commercial species. The ports with the highest exposure to potential impacts from offshore wind are New Bedford, MA; Atlantic City, NJ; Cape May, NJ; and Narragansett, RI. The types of vessels and gear types most exposed vary by port: In New York and New Jersey, large scallop/clam dredges have the highest potential exposure, but in Rhode Island and southern Massachusetts, small pot and gillnet vessels have the highest potential impacts resulting from wind development. Lastly, sea scallops are the species with the highest exposure, with an annual average of $4.3 million in revenue generated from WEAs. The relative exposure of recreational for-hire vessels and private and for-hire trips to WEAs was also investigated by Kirkpatrick et al. (2017) where exposure is calculated using recreational expenditure data rather than revenues. About 6.3% of average annual for-hire gross revenues ($23.9 million) and 3.8% percent of for-hire and private-boat fisher trips are exposed to the WEAs. Lastly, cumulative impacts are estimated to describe the degree to which exposed vessels are expected to be impacted by wind areas. For this analysis, a fishing location discrete choice model is used to identify the likelihood that fishing will occur in each WEA. A random utility model (RUM) estimates the utility of fishing in a particular zone given expected revenue, costs, revenues net variable costs (RNVC), wind speed, ex-vessel prices of key species, season, and vessel characteristics. From this model, the changes in RNVC are assessed and reported in 2012 U.S. dollars. To keep the analysis tractable, permits are grouped into various clusters based on fishing area and gear types. Assuming all WEAs are closed, the cumulative commercial fishery impact summary reports changes in RNVC ranging from -$6,588 to -$516,984 across the permit clusters. Smaller vessels, grouped in Cluster 1, show higher changes in RNVC and are more heavily impacted by loss of fishing grounds.

An analysis by BOEM (2018) uses similar methods and approaches to Kirkpatrick et al. (2017), assessing the exposure of various ports, species, and, in addition, vessel-level exposure in terms of revenue and earnings acquired from proposed NY Bight wind areas. The methods include the use of VMS effort data along with the methods and data sources used by DePiper (2014) to estimate exposures based on ex-vessel revenues from 2012 to 2017. The study suggests that total revenues from all the proposed wind areas range from $5 million to just under $20 million from 2012 to 2017, with large annual fluctuations in total revenue earned in these areas. The finding suggests that scallop, surfclam, and ocean quahog are the species most exposed. The exposure of various vessels ranges, with some permits earning up to 40% of annual revenues from a single wind area. The study also suggests that smaller ports may be more exposed when considering the secondary wind areas.

The Rhode Island Department of Environmental Management Division of Marine Fisheries also uses VMS, VTR (logbook) and dealer, logbook, and dealer reports to identify the various gear types, species, and FMPs which account for the highest landings in revenues earned in wind areas the following wind areas in the Greater North Atlantic from 2011 and 2017 (RI DEM 2017). Results suggest that the 3 highest FMPs impacted are sea scallop ($23.1 million); squid, mackerel, and butterfish ($5.7 million); and monkfish ($3 million) when assessed over the 6-year time period. It is not clear how the coverage of exposed fisheries captured in this study compares to that captured in Kirkpatrick et al. (2017). Rhode Island Department of Environmental Management (RI DEM) also used similar methods for the New York Bight Call areas and reports the sea scallop;

monkfish; squid, mackerel, butterfish; and summer flounder, scup, black sea bass FMPs to be the most impacted (2018). RI DEM also created a report using a combination of methods to estimate exposure over a 30-year time series for the Vineyard Wind areas given certain wind area buffers (RI DEM 2019). The RI DEM Vineyard Wind study uses an Auto-Regressive Integrated Moving Average (ARIMA) to project exposures for the 30-year time series. The model parameters, model performance, and peer review status of the model and methods were not disclosed in the report.

The Socioeconomic Impacts of Atlantic Offshore Wind Development reports by NOAA/ NMFS rely on commercial fisheries landings data, VTRs, and additional logbook data to highlight how various gear types, FMPs, species, ports, and percentage of vessels are most likely to be impacted by offshore wind areas. These analysis reports include summaries for commercial fisheries as well as limited information from recreational party and charter trips. The wind areas and vessel locations were generated, again, using techniques outlined in DePiper (2014) as well as Benjamin et al. (2018). The analysis summarizes those most impacted based on the landings and revenues earned within wind areas from 2008 to 2019. When summarizing the data by FMP across all years and proposed wind areas ranging from Maine to North Carolina, the FMPs most exposed by landings are surfclam and ocean quahog (44.5 million lbs.); skate (17.1 million lbs.); mackerel, squid, and butterfish (15.4 million lbs.); and Atlantic herring (14.1 million lbs.).[7] In terms of revenues, the FMPs most impacted are sea scallops; surfclam and ocean quahog; and mackerel, squid, and butterfish with cumulative revenues of $42.5 million, $31.6 million, and $14.2 million and for each FMP, respectively, across all years and proposed wind areas.

The differences in exposure results across the various studies most likely result from differences in which wind areas are considered, the timing of when the analysis was conducted, differences in fishing location data sources (i.e., the usage of VMS and/or logbook information), as well as the time series analyzed. All of the variables listed need to be considered when these analyses and tools are being utilized in understanding how wind areas impact commercial fishing revenues.

A suite of NOAA wind area maps and web tools have been generated by the NEFSC and the Greater Atlantic Regional Fisheries Office (GARFO) which are often informed by methods used in DePiper's (2014) seminal paper. Additional mapping initiatives include The Island Institute's Mapping Working Waters project, which generated maps of heavily fished areas off the coast of Maine informed by fishermen interviews (Island Institute 2009; Klain 2017). Similar mapping efforts and engagement strategies were implemented by University of Rhode Island Coastal Resources Center/Rhode Island Sea Grant College in The Rhode Island Ocean Special Area Management Plan and the RODA partnership Ocean Data Portals project mapping the Northeastern cost of the U.S. (McCann et al. 2013; RODA 2020b). In terms of additional studies aiming to quantify changes in fishing industry revenues due to offshore wind, the Fishing Liaison with Offshore Wind and Wet Renewables Group (FLOWW) offers a best practices guide for offshore wind development in the U.K. which includes methods for identifying and calculating revenues from impacted areas, tactics for remuneration in the event of lost or damaged fishing equipment, and other plans related to capturing the economic impacts of offshore wind development on commercial fishers.

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[7] Data provided in Appendix A by Social Sciences Branch (SSB) Data Analysts (May 2021) through the use of the internal SSB "wind tool," which generates automated wind reports. The data differs from those displayed in the "Wind Data Download Website" as data and wind areas are continuously being modified. Located here: https://www.greateratlantic.fisheries.noaa.gov/ro/fso/reports/WIND/ALL_WEA_BY_AREA_DATA.html

2.2.4.3 Changes in Revenues, Income, and Livelihoods: Qualitative Analyses

Qualitative methods are more common when summarizing expected and realized impacts of offshore wind development on commercial and recreational fishing revenues. One example of this methodology is the BOEM' Draft EIS of the Vineyard Wind projects. Using NEPA guidance, non-monetary methods were used to quantify various impacts stemming from the project proposal, defining impacts as negligible, minor, moderate, and major. Cumulative impacts of the proposed alternatives on the commercial fisheries and for-hire recreational fishing are expected to be "major," according to the report. Specifically related to commercial and recreational revenues, short-term losses are expected as a result of the proposed cable placement/maintenance and the noise related to construction (U.S. DOI/BOEM 2020a). Concerns about fishing income and revenue are cited as the main concern in a BOEM environmental study update on the North and Mid-Atlantic OCS wind planning areas (U.S. DOI/BOEM 2020b). The concerns voiced in this study are the underlying motivation for an additional project assessment which will include additional economic analyses on the surfclam/ocean quahog commercial fishery.[8] A U.K. study published by the Crown Estate uses qualitative questionnaire data paired with secondary landings and vessel movement data to identify impacts on commercial fishing before and after the implementation of Eastern Irish Sea offshore wind developments (Gray et al. 2016). Fishermen questionnaire results suggest that wind farms have caused negative/very negative impacts on income, though no qualitative analysis of revenues was conducted to further support these results or quantify losses attributed to the wind farms. Structured interviews with 67 fishers and 11 wind developer industry members were conducted in a 2015 U.K. study investigating wind area challenges (Hooper et al. 2015). From the industry interviews, participants were asked if they expect to be impacted by future wind projects as well as if they had been affected by offshore wind development in the past. Results suggest that 70% of participants had been impacted by previous wind projects and 77% expect to be impacted in the future. However, the degree to which these participants were affected and how they expect to be impacted in the future was not captured quantitatively.

2.2.4.3.1 Changes in Revenues, Income, and Livelihoods: Data and Knowledge Gaps

More is known about federal commercial fishing revenues than other economic data components in the Greater Atlantic U.S. overall due to federal seafood dealer reporting requirements which make analyses by Kirkpatrick et al. (2017) possible. Despite these reporting requirements, there are still many data gaps that exist in determining how and to what extent wind development impacts fishery revenue, income, and earnings. Understanding recreational demand in response to expected landings is another data gap that requires further research to better understand how wind areas may impact this sector. The indirect impacts of WEAs on revenues, such as the impact of crowding due to fishing displacement, is another area of uncertainty. In addition, calculating the profitability of commercial fishing businesses requires detailed information of total variable, fixed, and quasi-fixed costs incurred. A large portion of these costs are collected in the NEFSC Social Sciences Branch Business Cost Survey; however, low response rates have caused complications in summarizing and modeling the data collected (Ardini et al. 2022). Industry member participation in this survey is crucial for obtaining core data needed for basic economic analyses and summaries. After initial data limitations are remedied, methods

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[8] The final report is expected in September 2021. The BOEM project update references a lawsuit brought about by 9 commercial fishing organizations and businesses (i.e., the Fisheries Survival Fund) against BOEM (Fisheries Survival Fund [FSF] et al. v Jewell, 2016) as well as a letter of concern from Thomas Nies, the Executive Director of the New England Fishery Management Council (NEFMC 2016) to highlight concerns pertaining to fishing livelihoods.

similar to those used in Kirkpatrick et al. (2017) can be implemented to better understand the impact of wind development on fishing revenues, earnings, and income at various scales. Lastly, additional research must be conducted to link the primary impacts on fishing revenues and earnings to secondary impacts on support businesses, which is further explored in a later section (see Support Businesses).

2.2.5 Support Businesses

As explained by stakeholders in a survey aimed to provide fine-resolution socioeconomic data by scientists in the U.K., "the value of commercial fishing to the nation is not limited to food provisioning" (Richardson et al. 2006). Study participants in this survey noted that the business of commercial fishing has strong multiplier effects on shoreside businesses and the communities as a whole. Such comments given by the aforementioned participants demonstrated an awareness that evaluation of "best uses" (e.g., the value of fish landings in some cases), while often used as markers for the value of the whole industry, fail to consider the way that the income from fishing reverberates through the community and beyond. One study on Economic Impacts Associated with the Commercial Fishery for longfin squid in the Northeast U.S. found the total amount of economic activity between 2013 and 2017 in all U.S. longfin squid landings corresponds to an output multiplier of 7.64 (i.e., every dollar in landings leads to $7.64 in total economic output; Scheld 2018). Another study which analyzed the scope and extent of economic impacts evaluated at each level along the market chain of distribution from the fishermen in the harvest sector through final sale to consumers (generally by retail markets and restaurants) found an increase from $81,135,000 to $1,308,331,000 combined value to the U.S. in 2014 (Murray 2016). Shoreside businesses that are either necessary to the fishing industry or reliant on the industry are often understudied. Each fall, NOAA Fisheries produces Fisheries Economics of the United States which is a report that describes how U.S. commercial and recreational fishing affects the economy in terms of employment, sales, and value-added impacts (NOAA 2022i). However, the reports are designed to capture economic impacts at the state, regional, and national level, whereas impacts on shoreside support industries of OSW are more likely to be felt at a smaller spatial scale. Despite the importance of shoreside businesses, there are few studies investigating how OSW impacts this sector.

The limited studies available on shoreside business often aim at capturing the economic effects of OSW on tourism and job creation. Using stated preference data from 949 Delaware households, the economic value associated with the visual disamenity from 500 440-ft turbines located 0.9, 3.6, 6.0, and 9.0 miles offshore was estimated. The authors' results call into question the conventional wisdom that wind farms should be located outside the viewshed. Savings associated with siting a facility nearer to shore were roughly comparable to the calculated disamenity costs (Bush and Hoagland 2016). However, studies conducted by stakeholders in the Cape Wind debate reported both economic losses in terms of tourism and property value (Haughton et al. 2003; Giuffre et al. 2004) and gains in terms of jobs and new industries (Global Insight 2003; Charles River Associates 2010) would result from wind turbines being located out of the viewshed. The intersection between both results requires a holistic view of all costs and benefits, including shoreside businesses.

2.2.5.1 Gaps in Knowledge

Job creation both directly and indirectly related to offshore wind is widely recognized as a beneficial result of OSWs and, in turn, can stimulate shoreside economies, although the magnitude varies (Bureau of Ocean Energy Management and Office of Renewable Energy Programs 2021;

U.S. Department of the Interior Bureau of Ocean Energy Management 2020; BVG Associates Limited 2018). In some circumstances, job creation may only provide short-term economic stimulus, so it is imperative to collect additional information on factors such as sourcing and contract length in order to determine long-term impacts.

Despite the benefits of OSW job creation, supply chain secondary and tertiary effects are underexamined in both commercial and recreational fisheries. The Jobs and Economic Development Impact (JEDI) offshore wind model allows a user to estimate economic development impacts from wind power generation projects, such as outputs on jobs, earnings, and other elements during the construction period, but does not include all major support business market sectors (The National Renewable Energy Laboratory 2018). The distinct market sectors for commercial fisheries are outlined below (Murray 2016):

- Harvesting sector – fishermen
- Primary wholesaling and processing – the initial phase of distribution typically unloading vessels and/or purchasing directly from the harvesters
- Import-export operations – receiving and/or preparing product for shipment and brokering
- Secondary wholesaling or distributing sector – all distribution, storage, packing, or repacking that takes place between the wholesale market or processor
- Final retail point of sale, food service – all activities resulting in the sale of prepared foods to the end consumer, such as restaurants
- Retail markets – establishments selling seafood for at-home consumption including supermarkets, independent grocers, and specialty seafood markets

Recreational fisheries also support a wide array of market sectors by providing products and services to anglers. When anglers participate in fishing activities, they support sales and employment in recreational fishing and other types of businesses. Anglers buy fishing equipment from bait and tackle shops, rent or buy boats, or pay to have others take them on charter boats to fish. They may also pay for food and drink at local restaurants, purchase gas for their boats, and stay in hotels for overnight fishing trips (NMFS 2021b). Vertically integrated fisheries are especially prone to being impacted due to interrelation and should be researched, as well.

Commercial fishery product landings undergo product development, processing, and distribution changes that create additional economic value and impacts beyond the initial landed value. The lack of data on secondary and tertiary effects of the supply chain in relation to OSW leaves a gap in the scope and extent of potential and realized economic impacts. Impacts should be evaluated at each level along the entire market chain of distribution from the fishermen in the harvest sector, through final sale to consumers generally by retail markets and restaurants. Impacts can be researched using new methods or improving existing processes to align more closely with offshore wind. Research on methods of how to make necessary adaptations to improve input-output models for use in regulatory analyses of fisheries management actions in the Northeast U.S has already been performed for use in IMPLAN Pro (Steinback and Thunberg 2006), though adaptations for uses related to offshore wind specifically have yet to be developed.

2.2.6 Product Quality Effects

The quality of a good plays a large role in its capacity to satisfy a given need, which affects demand and, in turn, product prices. Although supply plays a significant role in market prices, there are price premiums that have been shown to be associated with attributes such as fish size, gear used, and freshness (Lee 2014; Ardini and Lee 2018; Asche and Guillen 2012). Additionally, product prices have been shown to be influenced by the geographic location where fish supplies are provided (Pettersen and Asche 2020) and even at the firm or plant level (Asche et al. 2015). This finding, coupled with an increased demand for locally produced seafood, suggests that there may be localized price effects that may be masked by focusing only on aggregate seafood market supply and demand.

The potential impact of OSW on the fine scale product attributes affecting seafood prices noted above has not been examined in general or for the Greater Atlantic Region, in particular. Nevertheless, the available information for species landed in the region (Lee 2014; Ardini and Lee 2018) suggests freshness is an important product attribute that may be compromised with longer steaming times to deliver seafood; marketing windows may also be missed, resulting in lower prices received. The geographic and localized impacts described for Norwegian fisheries (Asche et al. 2015) have not been studied, although daily prices received by port and dealer are collected by NOAA Fisheries, so an analysis similar to that done in Norway may be feasible.

Studies of product quality attributes have focused on the prices received for harvested fish and shellfish. However, development of OSW may influence the presence and composition of species or the product price attributes, of which size is of particular importance, within wind energy sites. This means that monitoring programs for construction and operation of OSW should include not only the presence and numbers of fish but the size distribution, as well. For example, studies over 7 years were conducted in the Block Island Wind lease area as a requirement of the lease agreement between the State of Rhode Island and the developer, Deepwater Wind Block Island. The objectives of the studies were to separate the effects of construction and operation and changes in conditions. Study elements included: early engagement with stakeholders (fishermen and boaters), adaptive monitoring based on data and stakeholder feedback, cooperative research with commercial fishermen, use of methods consistent with regional surveys, stratified random sampling within a BACI design, power analysis (when possible) to determine sample size, and multiple metrics to evaluate fish and fisheries resources. The study did not find a statistically significant impact on catch rates for loligo squid or black sea bass but did find that annual lobster catches were higher on average near the wind farm in Phase I, Phase II, and in the post-construction periods (Wilber et al. 2020). Notably, size premiums are paid for each of these species, so monitoring of the size distributions would have provided additional information on the economic implications of the Block Island site. Fishermen reported reduced quantity and quality of lobsters and lower quantities of commercial demersal fish within and in close proximity to OSWs. In some areas in the U.K., interviewed fishermen reported that the quantity and quality of prawns caught close to the wind farms have declined. There is additional concern about the vibrations from OSW, which could cause potential changes to fishing behavior and practices. Changes in the quality of fish landed may also be due to fishermen avoiding fishing within the OSW areas for fear of snagging gear on cables and risks associated with a vessel breakdown (Gray et al. 2016). As a part of a series of questionnaires, fishermen were asked what the main negative impact of the OSW on the fishing industry was to which the majority of respondents reported it was loss of fishing grounds (Figure 11). This is especially important to quality effects because it includes predicted increases in steaming to fishing grounds beyond the OSW and potential impact on future fishing activity (Gray et al. 2016).

2.2.6.1 Product Quality Data and Knowledge Gaps

Data required to value food provision, such as catch and value of landings and the number of people employed in the fishing industry, are readily available as they are routinely collected by the Marine Management Organization (MMO). However, these data lack the spatial resolution required to evaluate the service within OSWs with high confidence. These landings data also do not indicate where the landed fish were actually caught. Valuation of changes in food provision data due to OSWs will need to address these data limitations if the data are to inform the economic impacts of OSW on the fishing industry and community (Mangi 2013). Since offshore wind is fairly new to the United States, the already limited information that can be collected from around the world is further minimized due to the unique demographics of the area in question. Scientists should develop studies focused on all stages of the OSW process to determine how fishing product quality changes with dynamic disruptions induced by planning, construction, operation, and decommissioning. Product quality may be heavily impacted by effort displacement and can play a significant role in a fishermen’s location choice. The quality of fisheries products can also drive decisions related to, but not limited to, transit time, perceived safety, closures, and environmental influences (e.g., weather, water quality, movement patterns of ocean). Overall, many components of OSW can induce longer steam times and changes in preferred fishing locations, which can translate into lower product quality.

2.2.7 Conclusion

The vast majority of North American studies focus on hypothetical or proposed wind facilities rather than existing facilities across only a handful of locations, such that results cannot be generalized to the wider population living near wind turbines (e.g. Baxter et al. 2013; Bidwell 2013; Firestone and Kempton 2007; Firestone et al. 2012b; Groothuis et al. 2008; Groth and Vogt 2014; Olson-Hazboun et al. 2016; Pasqualetti and Butler 1987; Petrova 2014; Slattery et al. 2012; Thayer and Freeman 1987). Some studies have used convenience samples rather than robust random samples, further limiting their external validity (e.g., Landry et al. 2012; Mulvaney et al. 2013; Walker et al. 2014). Fast and Mabee (2015) suggest that this qualitative, case-study nature of wind acceptance research “does not translate well to conventional policymaking.”

There are considerable challenges and costs to developing and deploying research that is broadly representative across large regions like North America, making such studies out of reach for most researchers, which is indicative of past shortcomings. Future research should attempt to standardize some survey items and protocols in order to enable the comparison of data across multiple case studies. Overall, the need for additional economically focused studies are required to fill existing knowledge gaps on how OSW will impact the commercial and recreational fishing industry along with surrounding communities. Additional research can offer support in highlighting areas where benefits and costs are imposed by offshore wind and can be used in offsetting potential negative impacts to the fishing industry.

2.3 Fisheries Sociocultural Effects

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2.3.1 Introduction

This section synthesizes social and cultural research on fishing communities as relevant to the potential effects from offshore wind development. To understand the implications of offshore wind development on fishing communities, the definition of a fishing community is described here, as well as the importance of fishing to individual fishermen, their families, and communities. This section also discusses social science research on attitudes and perceptions of fishermen, resilience and adaptation of fishing communities as well as a review of fisheries mitigation strategies to offshore wind development to date. The cultural implications of offshore wind is recognized as a major gap. This section’s purpose is to provide a brief overview of social and cultural topics that have been researched in fisheries and are important to consider in the context of offshore wind development.

2.3.2 Fishing Communities

2.3.2.1 What is a fishing community?

The fishing industry is an integral part of the social and cultural fabric of many coastal communities. Coastal fisheries are comprised of commercial, recreational, subsistence, and even ceremonial fishing activities. Commercial fishing is the harvesting of fish that enters the market for profit. For-hire fishing consists of renting out recreational fishing time on a vessel to a group (charter) or a set of individuals (party charter fishing; Seara et al. 2016; Magnuson-Stevens Act 16 U.S.C. §§1801-1891d). Recreational fishing also includes private angler fishing (shore-based or offshore). Subsistence fishing, present in many coastal communities, has been defined in various ways, its meaning varying by location and the local cultural and legal context (Schumann and Macinko 2007; Ebbin 2017). It is generally considered to be “local, non-commercial fisheries, oriented not primarily for recreation but for the procurement of fish for consumption of the fishers, their families, and community" (Berkes 1988). The commercial seafood industry includes harvesters, processors, distributors, and consumers as well as fuel companies, gear shops/manufacturing, shipyards, ice plants, and local grocery stores. Businesses that support recreational fishing include, but are not limited to, bait and tackle shops, marinas, hotels, and boat manufacturers. Within these communities, the fishing industry provides business to local coffee shops, gas stations, and restaurants, and in turn, they depend on the fishing industry's patronage. Fishing communities can be discussed as "place-based," which is tied to a specific location as defined in Magnuson-Stevens Fishery Conservation and Management Act (MSA) National Standard 8 (MSA sec. 301(a)(8)) and discussed later in this section (2.3.3). However, researchers have defined fishing communities beyond a specific geographic location as members of a "community" that share a sense of "togetherness," but identification can also be widely geographically dispersed (Brookfield et al. 2005). Therefore, the fishing community is also a community of interest or practice (i.e., gear type, target species) that is made up of individuals who operate based on their own values and perceptions while being part of the larger fishing industry and the communities where they live and work (Gilden and Conway 1999; Conway et al. 2002; Hall-Arber et al. 2001; Clay and Olson 2008). With increasing prevalence of off-the-boat sales, community-supported fisheries, and dockside markets, it could be argued that the consumer is increasingly becoming an indispensable part of the broader definition of fishing community. Fishing communities can also be defined by historical perspective. The significance of fishing to a place may persist due to its historical, cultural, psychological, and even spiritual (Ebbin 1998) importance, even if fishing has declined in economic importance (ICES 2021a).

2.3.2.2 Members of the Commercial Fishing Industry: Demographics and Family Involvement

To understand the changes in fishing behavior that lead to changes in fishing patterns, social considerations need to be examined, and the individual fishermen need to be considered as the operating entity. Many businesses within the fishing community are family businesses where multiple members of the family work within the family business and are often intergenerational. Fishing family youth often start out as crew (deckhands) and work their way into leadership roles (skipper, vessel owner). These familial linkages are not limited to work on fishing vessels but extend to shoreside support services, such as seafood dealers, gear manufacturers, ice houses, fuel docks, or accounting and bookkeeping. Women play various and highly significant roles within the fishing family business and industry, which can contribute to industry resilience (Nadel-Klein and Davis 1988; Conway et al. 2002; Conway and Cramer 2018; Calhoun et al. 2016; Schadeberg et al. 2021). In the U.S, there is no national-level collection of basic demographic data for commercial fishing crew involved in commercial or recreational fisheries. To fill this gap, the NEFSC began collecting data on crew and hired captains in 2012, with the expectation of data collection occurring every 5 years. In the most recent crew data collection in the Northeast (Maine to North Carolina), 60% of crew reported having at least 1 family member involved in the commercial fishing industry, and 42% had 3 or more generations of their family involved in the industry. Despite a high number of reported family members in the Northeast, researchers elsewhere have found a weakening of the tradition of family succession into the fishing family business (Russell et al. 2014; Messick 2015) and a loss of a stable and traditional family structure that supported local seafood and helped the identity of the local community (Jacob and Witman 2006). Owner-operator businesses (often family businesses) and fishing companies can have differences in how and who makes the tactical decisions (how fishermen make decisions at sea during a fishing trip) and strategic decisions (e.g., hiring of crew, purchase or sale of quota, investments in gear, selection of fishing grounds; Schadeberg et al. 2021).

In recent years, commercial fishing crew in the Northeast region reported an increase in difficulty finding employment and more movement from vessel to vessel in search of more consistent employment (Silva et al. 2021). Although job and economic development studies have been completed to understand the potential job growth in the U.S. from offshore wind development (see Tegen et al. 2015), research is needed on how offshore wind development could affect the fishing industry job market. In a study of multiplier effects of offshore wind development in the MA/RI wind energy area, Hoagland et al. (2015) found that every job loss in the commercial fishing industry leads to 1.32 jobs lost in the regional economy.

The phenomenon of an aging commercial fishing fleet, or "graying of the fleet," has been documented across the U.S. (Haugen et al. 2021; Cramer et al. 2018; Cullenberg et al. 2017; Donkersloot and Carothers 2016; Himes-Cornell and Hoelting 2015; Johnson and Mazur 2018). More studies are needed to understand how OSW development could intensify the aging trend. Not being able to attract the next generation of fishermen necessary to ensure the profession's sustainability remains a major threat to the fishing industry (AK CSHCR 18 2012; PFMC 2013; Russell et al. 2014). Graying of the fleet is the result of a number of stressors, including a shift in interest of fishery-related jobs (Stimpfle 2012; Pascoe et al. 2015). Additionally, a number of economic and regulatory challenges have impacted the ability of fishermen to own one's own fishing business, resulting in an ongoing decline in the number of small-scale fishing operations (Andreatta and Parlier 2010), which have served as a point of entry for new fishermen. Higher entry costs due to limited entry and catch share approaches to fishery management require increased financial capital for new entrants (Rosvold 2007). The majority of crew in the Northeast U.S. have family involved in commercial fishing, making it the key point of entry into the industry (Silva et al. 2021; Cutler et al. 2021). There has been a decline in training opportunities in the region (e.g., vocational/technical fishing industry training programs). Limited available financial instruments have made it difficult for fishermen to invest in fishing businesses and overcome these financial hurdles. The cost of permits and quota have become a financial hurdle for new members of the industry (Cramer et al. 2018). Fishing has increasingly become a risky investment proposition with high business uncertainties and risk due to regulatory changes, ecosystem shifts, endangered species, and market changes. Offshore wind has increased uncertainty in the region for fishing businesses and maintaining viability with the determination by BOEM of major adverse impacts to the commercial fishing industry due to cumulative offshore wind development (BOEM 2021). More research is needed on the impact offshore wind development will have on the attractiveness, business risk, and investment opportunities in commercial fishing business. The risk that offshore wind development will increase older generation owner-operators selling out of the industry due to uncertainty and fear of decreased value in business (e.g., quota value) needs further exploration. This would impact the transfer of knowledge as generational fishermen leave the industry, which is exacerbated by the limited available training programs. Given the rising average age of fishermen, the age of those who would be job retraining should be considered in analyses for the ability of fishermen to switch careers or take on jobs in the offshore wind industry.

NOAA's Fishing Community Profiles and Snapshots (NOAA 2019b) provide detailed information about the demographics of fishing communities of interest embedded within communities of place in the U.S. In a 2015 study that used data from the American Community Survey to estimate the contributions of immigrants in the fishing and seafood processing industries, it was clear that while not making up a large share of the commercial fishing industry (which has a primarily white workforce), almost 63% of fish processing workers (including butchers and others who use hand tools to cut seafood) were born outside of the U.S. (Ferreira 2015). NOAA's Voices Oral History Archives (NOAA 2021) also provide insight into the demographics in Northeast fisheries, including the New Bedford Process Workers and Oral Histories from the New England Fisheries collections. There could be disproportionate impacts to traditionally disadvantaged communities from offshore wind, and no studies were identified that seek to understand these impacts.

2.3.2.3 Fishermen's Identify, Occupational Attachment, Job Satisfaction and Well-being

When considering the effects of offshore wind development on fishermen and the ability to adapt and coexist, demographics (age, education, vessel ownership, and years fishing) and job satisfaction and well-being (Pollnac et al. 2019) of individual fishermen should be considered. The sustainability of fisheries has long been aligned with individual, familial, and community well-being (Pollnac et al. 2008; Smith and Clay 2010; Coulthard 2012; Carothers 2015). Changes in governance may assist in fishermen's well-being (Pollnac et al. 2019). Well-being has several dimensions and characteristics, such as job stability and satisfaction, identity, and attachment to place (Altman 1993; Pollnac et al. 2008; Hausmann et al. 2016; García Quijano 2015). Data on commercial fisheries job satisfaction has been collected for decades in the Northeast (Pollnac and Poggie 1980; Pollnac et al. 2015; Silva 2016; Seara et al. 2017). This data has been used in human impact assessments (HIA) to help show that changes in ocean governance have impacts on the human communities who use fisheries resources (Pollnac et al. 2008; Pollnac et al. 2019). Well-being research can assist in understanding how fishermen's lives can be improved on the individual, household, and community level as it captures material, relational, and subjective dimensions of their lives (Weeratunge et al. 2013). Resource access and self-determination were found to be important attributes of fishermen's well-being. Management decisions or other changes in the fishery that are perceived to create or exacerbate social inequity in the community may compromise the well-being of fishermen (Pollnac et al. 2019). Hattam et al. (2015) identify a lack of subjective well-being research on the impacts of offshore wind development. There is a suite of literature on measuring subjective and objective well-being in fisheries and many efforts to identify variables and indices for ecosystem-based management (Breslow et al. 2017; Smith and Clay 2010; Leong et al. 2019). Research on offshore wind developments through the well-being lens could provide integrated understandings about offshore wind development effects.

Of all of the ocean users studied in the U.S., it's clear that commercial fishermen view their work as not just an income earning opportunity but also a way of life. In a socioeconomic assessment of hired captains and crew in the Northeast U.S. from Maine to North Carolina, Silva et al. (2021) found that 70% of crew found fishing to be more than just a job. Being a fisherman (and a fishing family/community member) is a core part of their identity. In a study in the U.K. on the perceptions of the fishing industry regarding the potential socioeconomic impacts of offshore wind, Mackinson et al. (2006) noted that "undermining the traditional way of life" was one of the top concerns from the fishing industry. Researchers have associated fishery participation behavior and higher non-monetary job satisfaction, social capital, and identity to a willingness to forgo higher income to be a fisherman (Holland, Abbott and Norman 2020). The U.S. commercial fishing heritage and social identity is very strong, as demonstrated by the oral histories on NOAA's Voices from the Fisheries (NOAA 2020). Rich written literature also describes commercial fishing heritage and social identity (Hall-Arber et al. 2009; Cramer et al. 2018).

It is not clear whether the development of offshore wind will lead to lost or displaced jobs in fisheries (Hattam et al. 2015). Many studies link fisheries to high levels of job satisfaction and occupation attachment (Acheson 1980; Pollnac and Poggie 1988; Binkley 1995; Marshall et al. 2007; Pollnac et al. 2015; Seara et al. 2017). This occupational attachment, together with the consideration of fishing having an occupational culture (Poggie et al. 1995; Reed et al. 2013), can lead to high reluctance to leave fishing, even in the face of declining income and economic hardship (Pomeroy et al. 2001; Crosson 2014; Pascoe et al. 2015; Sweke et al. 2016; Conway and Cramer 2018; Conway and Shaw 2008). Facing uncertainty, many fishermen have adapted their fishing businesses to increasing pressures and economic disruptions, such as declining fish stocks, increase in fuel prices, management regimes, and climate change impacts (Seara et al. 2016; Cramer et al. 2018; Haugen et al. 2021) in order to maintain their way of life. More information on resilience and adaptation can be found in Section 2.3.6. Research on fisheries occupational attachment should be considered when determining the ability and willingness of fishermen to find work elsewhere or supplement their income with wind industry jobs or other non-fishing jobs. While there are studies that document fishermen's reluctance to change careers due to other major changes (i.e., fishery management changes, climate change), to date, there are no studies determining U.S. fishermen's willingness or ability to change fishing practices or take jobs outside of fishing to supplement their income due to offshore wind development.

2.3.2.4 Mental Health in the Fishing Industry

Another important component of well-being is mental health, and a data gap exists in understanding how offshore wind could affect fishermen's mental health. Mackinson et al. (2006) in their report on perceptions from the U.K. fishing industry noted that offshore wind development was causing anxiety, familial stress, and less enjoyment in their job. In a review of literature on health in fishing communities, Woodhead et al. (2018) found a lack of attention to mental health issues in fisheries. There isn't a lot of direct data on mental health within fishing communities. In the U.S., fishermen are grouped with workers in agriculture, forestry, and hunting industries but show suicide rates double the national average and workplace fatalities 29 times higher than average (Couch 2021). A study by Smith et al. (2003) collected data from a group of commercial fishing families before and after the Florida net ban to assess mental health impacts. The authors' findings indicate that both husbands and wives experience mental health impacts of changes in the industry. King et al. (2021) in a national Australian survey quantitatively demonstrated the state of mental health among Australian fishermen and found that psychological distress is experienced at higher levels than the comparable Australian population. The researchers found that changes to factors associated with modern uncertainty stressors (management, media representation, and political support) could significantly improve mental health in commercial fishing (King et al. 2021). More research is needed on mental health impacts of offshore wind development as fishermen could spend more time away from home, face issues with spatial conflict (other gear types and/or recreational fishing) as well as the stress from uncertainty in adapting to new fishing grounds and uncertain incomes. Information on the mental health impacts of offshore wind is sparse and could benefit from a structured program of primary data collection and analysis (Hattam et al. 2015).

2.3.2.5 Fishermen's Knowledge of the Sea

Understanding and valuing fishing communities requires understanding and valuing fishermen and their knowledge of the sea (Jentoft 2000; Yochum et al. 2011; Conway and Pomeroy 2006). Fishermen's knowledge can paint a more holistic and detailed picture than science alone can do, which can lead to better decisions and outcomes (García-Quijano 2007; Walsh et al. 2013).

Fishermen’s knowledge of the fisheries and its helpfulness via cooperative fisheries research has been well documented and respected (Hartley and Robinson 2006; Conway and Pomeroy 2011; NRC 2004). This knowledge, however, goes beyond just the fish as it includes spatially-relevant knowledge, such as physical and biological aspects of habitat. It also includes atmospheric and oceanographic aspects, such as tides, temperatures, wind, and currents, as well as seasonal, weather, and long-term climatic changes (Kuonen et al. 2019; Conway and Cramer 2018; Haugen et al. 2021).

The experiential and ecological knowledge of fishermen is often underestimated and underappreciated (Sjostrom et al. 2021; Farr et al. 2018). Local ecological knowledge (LEK) refers to a form of experiential information about the natural environment that is accumulated by interacting with it on a regular basis (Berkes et al. 2000; Murray et al. 2006; Farr et al. 2018). Researchers have outlined and clarified the utility and limitations of LEK in scientific assessments (Gagnon and Berteaux 2009; Wohling 2009; Casagrande 2004), and Northeast regional case studies document the successful integration of LEK into management (Hanna 1998; Acheson 2003) and the drawbacks of not incorporating LEK into management approaches (Ames 2004). Studies of LEK should be developed for offshore wind and data collection instruments and interpretation of results carefully thought out. LEK offers the opportunity of coproduction of knowledge and two-way learning (Farr et al. 2018).

Fishermen’s knowledge, however, is helpful beyond the integration of it into a scientific research framework because this knowledge exists independent of encounters with scientists. LEK is often culturally transmitted from one generation to the next or horizontally through socialization (Ruddle 1994). It can, and should, be helpful in its own right—not just via cooperative research. This is important because offshore wind facilities will be a privatized and permanent closure of ocean space, and this will alter historical patterns of LEK development in much the same way that their existence will alter scientific data collection.

Fishermen’s knowledge is also woven through their world view of the ocean as public or common space, a place with space that one must coexist in. Fishermen have learned to coexist within groups by building relationships and communication strategies between people and/or vessels. This creates a social network that exists while fishing (on the water; between vessels at sea) and extends to time on shore (Conway 2006). This is true within the group (fishermen to fishermen) but also between fishermen and others. This is likely because most of the uses have temporary overlaps, such as shipping, scientific research vessels, and recreational boating. Marine users coexist primarily by negotiating temporal and spatial boundaries and following the International Regulations for Prevention of Collisions at Sea Navigation Rules, regulations which aid mariners in safe navigation when interacting with other mobile mariners, just as driving laws aid vehicles in safe driving. However, offshore wind development poses challenges with navigation (Sullivan et al. 2015; Pomeroy et al. 2015; Kerr et al. 2017) through its fixed nature offshore. More discussion on navigation and safety in Section 2.1.2.

The “communities at sea” approach (St. Martin and Olson 2017) has been used as a tool to define spaces where the presence of communities as it relates to fisheries exist. These included spaces with shared ecological knowledge, history, and culture; common fishing grounds and practices; and co-produced adaptations and innovations (St. Martin and Olson 2017). St. Martin and Hall-Arber (2007) created maps using NMFS Federal VTR to plot trip locations as well as to measure labor, or “fishermen days,” as an indicator of community presence. These maps were designed with fishermen in a participatory research approach. These methods and fishermen’s knowledge should be utilized for understanding fine-scale area usage in offshore wind development.

2.3.2.6 Fishing Industry Job Satisfaction and Occupational Attachment, Knowledge of the Sea, and Well-being Data Gaps

- How will offshore wind development affect fishing community well-being (individual fishermen-, industry- and community-level satisfaction, occupational attachment, and well-being)?
- How will offshore wind development impact fishing business risk?
- How will offshore wind development impact the attractiveness of fishing as a career path for young/new entrants?
- How will offshore wind development impede the transfer and sharing of ecological and experiential knowledge, independently and in conjunction with scientific knowledge?

2.3.2.7 Fishing Industry Job Satisfaction and Occupational Attachment, Knowledge of the Sea, and Well-being Research Recommendations

- Baseline, during, post-construction, and 3-year monitoring of fishing business structure (e.g., changes in the number of active vessels, owner-operator vs. corporate businesses, trends by fishing location relative to offshore wind development).
- Expand primary data collections to monitor changes in age structure, job satisfaction, well-being, and occupational attachment from OSW.
- Condcut studies on social networking and knowledge sharing with the development of OSW
- LEK methodology development and case studies of integration of LEK into offshore wind development processes.

2.3.3 Fishing Dependence and Cultural Importance in Coastal Communities

The contribution of fisheries to the sociocultural well-being of coastal communities is often overlooked. This section provides a description of the "place-based" fishing community and the social, cultural, and economic value fishing has within Northeast coastal communities.

2.3.3.1 Place-Based Fishing Community

A fishing community is defined in Magnuson Stevens Act National Standard 8 (MSA sec. 301(a)(8)) as being tied to a geographic location: "a community which is substantially dependent on or substantially engaged in the harvest or processing of fishery resources to meet social and economic needs, and includes fishing vessel owners, operators, and crew and United States fish processors that are based in such community." The development of offshore wind and the effects on the commercial and recreational fishing industry could have social and cultural effects to the "place-based" fishing community and broader community. Any change to the fishing industry, whether it be management, environmental, or coastal development, affects the vulnerability of coastal communities (Cramer et al. 2018; Colburn et al. 2016). Established fishing communities are forced to adapt to new social, economic, and environmental conditions, and as a result, many fishing communities in the Northeast have been supplemented with technology-based industries and tourism and are heavily impacted by coastal development, gentrification, and the emergence of retirement communities (Claesson et al. 2006). Offshore wind and the potential impacts to the fishing industry poses another change that could impact the vulnerability of fishing and coastal communities.

NOAA Fisheries developed social indicators to characterize community well-being for coastal communities that are engaged in fishing communities: the Community Social Vulnerability Indicators (CSVIs). A community's dependence on fishing is measured using 2 indicators: fishing engagement and fishing reliance (Colburn and Jepson 2013[9]; Holland et al 2021). These 2 measures of fishing engagement and reliance are available nationally for commercial and recreational fisheries and have been used in SIAs on management measures and Integrated Ecosystem Assessments (IEAs) for New England and the Mid-Atlantic region (see Section 4.2 for a further discussion of IEAs). The CSVIs also provide measures of Economic Vulnerability and Gentrification Pressure Vulnerability, which represent social factors that can affect the ability of communities to adapt to these changes (Jepson et al. 2013).

Based on one methodology for developing SIAs, Clay and Colburn (2021) outline baseline questions that should be asked when determining potential effects and vulnerabilities to communities. These questions could also be applied to offshore wind and fisheries interactions when understanding the social impacts. These include:

- Which communities could benefit from offshore wind development?
- Which of those communities are currently socially vulnerable or are experiencing gentrification pressure?

These questions should be answered based on both the species landed (value and pounds) from within a wind energy area to fishing ports and communities, as well as the number of fishing vessels (commercial and recreational) and shoreside support businesses. The port and infrastructure needs of the wind industry within a fishing community should also be considered. Additionally, the questions should be answered not only for individual wind project areas but the effects from cumulative wind development, as well.

2.3.3.2 Equity and Environmental Justice

Equity and environmental justice are critical concerns with the rapid expansion of offshore wind development in the Northeast. Executive Order 12898 and Executive Order 14008 mandate federal agencies to address the disproportionately high and adverse human health, environmental, and other cumulative impacts on disadvantaged communities and allow minority and low-income communities access to public information and public participation (Exec. Order no. 12898, 1994; Exec. Order No. 14008, 2021). Additionally, Executive Order 13985, "Advancing Racial Equity and Support for Underserved Communities Through the Federal Government," directs the federal government to account for racial inequities in their implementations (Exec. Order 13985). Environmental justice is often distinguished between procedural justice and substantive (distributive) justice. Procedural justice considers that people have a fair "say" in environmental decisions and the opportunity to have meaningful involvement in decision making. Distributive

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[9] Social Indicators for Coastal Communities: https://www.fisheries.noaa.gov/national/socioeconomics/social-indicators-coastal-communities
CSVI mapping tool: https://www.st.nmfs.noaa.gov/data-and-tools/social-indicators/

justice ensures environmental benefits and burdens (e.g., the costs of mitigating climate change) are fairly distributed. Ensuring a just procedure will make it more difficult for substantive (distributive) environmental injustice to occur (Global Justice and the Environment 2007).

According to NOAA Fisheries CSVI website, communities dependent upon commercial fishing are more likely to have higher poverty rates, have a larger percentage of minority and tribal populations, and/or have residents with less "personal capacity" to respond to change (e.g., higher unemployment rates or lower educational attainment; NOAA 2020). The CSVIs indicators can also be used to analyze the environmental justice concerns within fishing communities (Figure 12). There is no identified research in environmental justice and offshore wind effects to fishing communities. Procedural environmental justice involves including the opportunity for "all people regardless of race, ethnicity, income, national origin or education level to have meaningful involvement in environmental decision-making."

2.3.3.3 Seafood Supply and Food Security

The impacts on seafood supply and food security should also be considered in response to wind development and expanding energy goals in the U.S. A reduction in affordability of seafood can result in lower food security (Smith et al. 2010). Seafood sectors are more likely to react differently than other sectors to external shocks as they are more sensitive to movements in the prices of production units, and fishing is relatively capital-intensive (Qu et al. 2021). In an energy-food nexus macroeconomic analysis on seafood production in Scotland, researchers found some negative impacts on seafood production because labor and capital are bid away by expanding offshore wind development. Macroeconomic linkages found that the lower supply of seafood leads to higher seafood prices and therefore reduces household affordability. In the model, seafood exports were also shown to decrease in response to a fall in foreign price, and reduced export demand makes domestic seafood production decrease. Fisheries displacement was further explored by the researchers in one scenario which identified that a decrease in fishing productivity would have significant negative impacts in the 3 seafood sectors: fishing, aquaculture, and processing (Qu et al. 2021). Similar energy-nexus research is needed in the U.S. as well as understanding how offshore wind development may increase our reliance on seafood imports, something the U.S. is trying to reduce. Although information on carbon footprint reduction with offshore wind development is limited, the cost-benefit of food security and energy goals should be considered, and no studies were identified in this area. When considering carbon footprints of our food sources, wild seafood are amongst the lowest in greenhouse gas emissions. Research has shown that wild fisheries have 6 times lower carbon emissions than beef, 5 times lower than that of mutton, and 2 times lower than that of cheese, and it is also lower than pork and poultry emissions (Gephart et al. 2021).

2.3.3.4 Fishing Heritage, Tourism and Cultural Identity on the Waterfront

Fishing history, heritage, and culture are part of maritime landscapes and traditional working waterfronts throughout the Northeast (Davis 2001; Claesson et al. 2005; Hall-Arber et al. 2001). A number of stressors including increases in some stocks and declines in others, changes in regulations and management, and climate change challenge the resilience of fishing communities and, as a result, provide a threat to cultural heritage. Researchers suggest that maritime cultural heritage is a public good that should be preserved in order to slow down or prevent the loss of value and well-being associated with fishing (Duran et al. 2015; Brown 2004; Khakzad and Griffith 2016). Khakzad and Griffith (2016), through field work and rapid assessment of buildings and sites, created an inventory of existing traditional fishing communities in Brunswick County, NC, and assessed the level of significance of fishing culture. The authors found that fishing material culture (e.g., fish houses, boats, docks) are significant for "fishermen and their communities in sense that they represent their authentic activities, and they feel these items and places are repositories of history and memory, representing their individual and community's identity and sense of place." More research is needed on how the wind industry could affect the cultural importance and identity of fishing infrastructure within a fishing community. All effort should be made to avoid losses as this kind of loss is often irreversible, and compensatory mitigation is ineffective and repugnant.

Research has shown that the seafood industry can be an important resource for the tourism industry (Brookfield et al. 2005; Claesson et al. 2005). Heritage tourism has sustained some fishing communities threatened by a number of natural and anthropogenic factors. Brookfield et al. (2005) suggest that the imagery and symbolism of the fishing industry often has economic value that surpasses the value of the actual fishing industry. Fishing culture is directly marketed and sold to many tourists (Jacobs and Witman 2006) and the aesthetics of the fishing industry have served as a branding mechanism that allows both tourists and niche markets to purchase fish products (Brookfield et al. 2005). In the Northeast, many communities attract tourists by engaging the public in the appreciation of fishing cultural heritage through festivals (e.g., Working Waterfront Festival in New Bedford, MA, Blessing of the Fleet in Point Judith, RI, and Fisherman's Day in Stonington/Deer Isle, ME; Claesson et al. 2006). In Rockland, ME, a major shift from groundfish dependence to herring and lobster (Hall-Arber et al. 2001) has occurred, and the Rockland Lobster Festival has been a major factor in increasing a tourism economy. Although diversification in income to tourism can provide added economic benefits to communities, the shift can result in negative social impacts from gentrification, conflict between fishermen, tourists, retirees, and retail businesses, and competition for waterfront space (Claesson et al. 2006). It's possible that the wind industry could also increase tourism in communities. Ferguson et al. (2021), in a study on coastal recreation impacts and attitudes of offshore wind development in New Hampshire, found that OSW will have little impact on coastal recreational visitation and may even amplify visitation. Smythe et al. (2020) reached similar findings regarding the effects of the BIWF on tourism and recreation. There may also be benefits of offshore wind to species that are important to recreational fishing (i.e, hard substrate, reef-effect; see section 1.4.2.1 for demersals, section 1.4.2.3 for large pelagics, and section 1.4.3 for shellfish). This would provide benefits to coastal communities with an increase in recreational fishing and increase in shore-support businesses and revenue (e.g., bait and tackle shops) as well as businesses outside of fishing (e.g., restaurants, hotels). An increase in tourism and recreational fishing could potentially increase gentrification pressure. Gentrification provides both positive and negative effects to fishing communities (Thompson et al. 2016). Gentrification pressure and an increase in coastal development can have impacts to the commercial fishing industry with loss of infrastructure space within ports (Colburn and Jepson 2012; Thompson et al. 2016; Coperthwaite 2006). In a study on vulnerability of fishing communities undergoing gentrification in Maine (Thompson et al. 2016), authors found that migrants have the capacity to add new opportunities (i.e., employment in the service sector) and sources of revenue to rural communities. With the migration, however, communities in Maine face identity crises as gentrification alters the demographics of a community and changes social networks, culture, and people's relationship to the landscape (Thompson et al. 2016). The authors highlight that although the importance of fishing has diminished in their study communities, it is still prominent, and as long as the communities identify as fishing communities, they will be dependent on the fishing industry. More research is needed on the effect offshore wind development will have on tourism, including the impacts, benefits, and how to balance this potential new economic sector with existing uses within ports and fishing community identity.

Coastal communities in the Northeast have built fishing piers that allow access to the coast and fish resources. These piers are not only used by tourists and recreational sport fishermen but also provide access to an important food source for the economically disadvantaged and those that “fish for food,” or subsistence fishermen. In a study on values and benefits associated with coastal infrastructure in North Carolina, researchers found that fishermen who “fish for food” value and benefit these sites for access to recreation, nutrition, a social community, and mental health (Nieman et al. 2021). Port allocation plans associated with offshore wind development should consider the social and cultural value of these sites when allocating space, especially when considering cumulative wind development needs in the Northeast. Ethnographic and primary data collection through interviews in local communities can provide valuable insight on values and benefits associated with coastal infrastructure.

2.3.3.5 Fishing Community Data Gaps

- More information is needed on the social factors that could affect fishing behavior in response to offshore wind development.
- More information is needed on the effects of offshore wind on disadvantaged fishing communities.
- How will offshore wind development affect fishing community well-being (individual fishermen-, industry-, and community-level well-being)?
- How will offshore wind development affect the cultural value of fisheries within communities (e.g. tourism, identity)?
- How will offshore wind development affect the seafood supply chain, including seafood prices, supply, and effects to domestic seafood availability (decrease in exports and increase in imports) in the U.S.?
- What are the effects of offshore wind development on equity and environmental justice concerns within the fishing industry?

2.3.3.6 Fishing Community Research Recommendations

- Collecting primary data through interviews for those fishermen and businesses affected by offshore wind development could provide insight into fishing behavior/choices with offshore wind development.
- SIA of offshore wind and fisheries
- Energy-food nexus analysis in the Northeast
- Baseline studies exist on cultural importance in the region. Similar research/methods (e.g., interviews, focus groups, ethnographic field work) will be needed to track changes in perceptions/importance of fishing with the presence of a new industry and infrastructure
- For environmental justice research, analyses using census data in fishing communities and primary data collection/interviews with representatives in communities, such as community leaders and businesses.
- Develop research strategies that consider the needs of minority and underrepresented groups to participate in research and decision making (e.g.,

outreach materials, communication needs) in order to fill gaps in understanding these groups.

- Participatory mapping with fishermen to understand fine-scale use of space at sea, similar to Communities-at Sea (St. Martin and Olson 2017).

2.3.4 Attitudes and Perception Research for Fisheries and Offshore Wind Development

Energy transitions and changing ocean uses have many social effects. Social scientists try to better understand these in part to inform resource managers and decision makers so that decision-making processes can be improved. A primary area of social science research on energy transitions is the public's attitudes toward and perceptions of the new form of energy. Research on fishermen's attitudes and perceptions could help managers better understand concerns and help managers mitigate impacts on fishermen. This section synthesizes social science research to date on fishermen's perceptions of offshore wind and identifies research needs in this regard.

2.3.4.1 Use of Ocean Space/Ocean Grabbing

Fishermen's attitudes toward and perceptions of OSW may be informed by their views of ocean and coastal space. These views may be informed by cultural models and governance arrangements through which oceans are viewed as a commons, subject to shared access and use, versus as a frontier to be developed and privatized. These opposing paradigms of the ocean are reflective of the shift, over millennia, from open access and freedom of the seas to "enclosure," and the increased application of neoliberal, property rights-based approaches to natural resources management (Mansfield 2004; Schlager and Ostrom 1992). These constructs are particularly relevant to offshore wind (Bidwell 2017) and to the discussion of interactions between offshore wind and fisheries (Pomeroy et al. 2015).

Recent studies of the reallocation of ocean space explore the concept of ocean or coastal grabbing as a way to understand the tension between these views of ocean space (Bennett et al. 2015; Bavinck et al. 2017). Bennett et al. (2015) define ocean grabbing as the "dispossession or appropriation of use, control or access to ocean space or resources from prior resource users, rights holders or inhabitants. Ocean grabbing occurs through inappropriate governance processes and might employ acts that undermine human security or livelihoods or produce impacts that impair social-ecological well-being. Ocean grabbing can be perpetrated by public institutions or private interests." The authors identify the leasing of ocean space that leads to "exclusion of previous users or stakeholder groups" and the undermining of "historical access to areas of the sea" for "small-scale fishers" as examples of ocean grabbing. The authors have identified no research on marine renewable energy (MRE) as a form of ocean grabbing or on fishermen's perceptions in this regard to date. However, Bennett et al. (2015) identify research needs and outline criteria for evaluating initiatives as potential cases of ocean grabbing.

2.3.4.2 Place, Symbolic Value, and Landscape Fit

Fishers' attitudes and perceptions of MRE may also be shaped more broadly by their sense of place regarding the ocean and the areas they fish (Haggett et al. 2020). In the social sciences, place is not limited to a physical location or even to the economic activities associated with that location but includes a place imbued with meaning (Cresswell 2014). Pasqualetti (2011) identifies place as a core issue explaining opposition to wind energy landscapes, noting that wind energy is viewed as disrupting place identity and place attachment. Similarly, in a discussion of place and renewable energy, Devine-Wright (2009) examines the related concepts of place attachment, place identity, and place disruption. “Place disruption” refers to something disrupting or interrupting a place, whether through physical change or changes to associated social networks, and can bring about local opposition to renewable energy (Devine-Wright 2009). Although commentators often frame place-based wind farm opposition as a “NIMBY” reaction of local residents and stakeholders, scholars (Wolsink 2000; Devine-Wright 2009; Devine-Wright and Howes 2010; Wiersma and Devine-Wright 2014) critique this concept as it fails to explain these attitudes and behaviors and is dismissive of public concerns.

Attitudes and perceptions regarding place and related spatial considerations have been identified as key factors shaping public perceptions regarding offshore wind energy (Haggett 2008, 2011) and MRE in general (Wiersma and Devine-Wright 2014), as well as renewable energy more broadly (Boudet 2019). In their study of offshore wind development support and opposition, Kempton et al. (2005) found “the ocean as a special place” as a primary factor explaining opposition toward the proposed Cape Wind project. A study of multiple U.S. offshore wind demonstration projects found that the nature of place attachment may vary by community and the ocean-related activities most prevalent there (Bates and Firestone 2015). In a study of the BIWF, Russell et al. (2020) used place meaning to explain differences in perceptions between mainland and island residents, though a second BIWF study found that place-related measures had little explanatory value regarding wind farm support (Firestone et al. 2018).

Fishermen’s attitudes and perceptions regarding offshore wind energy may also be related to the symbolic value they associate with these projects or their views on landscape fit. Bidwell (2017) found that ocean beliefs and underlying values are associated with expectations and support for offshore wind projects. Stakeholder and resident attitudes and perceptions, as well as wind farm support and opposition, may also be explained through views related to landscape fit (Devine-Wright and Howes 2010; Devine-Wright 2009; Hoen et al. 2019).

Importantly, few studies to date have examined the ways in which place, symbolic value, or landscape fit inform fishermen’s attitudes and perceptions regarding MRE; this is an area of future research need. Place is addressed in Haggett et al. (2020) as an important consideration in managing offshore wind/fisheries conflict, though this paper does not include empirical research. Place was a dominant theme in research by Pomeroy et al. (2015), who found that fishermen value knowledge of and access to particular places in ways that are not usually considered by managers. A study of coastal zone users found that anglers and other boaters opposed offshore wind developments due to place attachment (Brownlee et al. 2015). Other studies of recreational anglers have found concerns about visual impacts of offshore wind developments (Ladenburg and Dubgaard 2009; Hooper et al. 2017); arguably, visual impact concerns could be related to place disruption.

Attitudes and perceptions of offshore wind may also be informed by views of the public process itself and individuals’ trust in government, developers, or other decision makers (Goedkoop and Devine-Wright 2016; Dwyer and Bidwell 2019; Haggett 2011, 2008; Haggett et al. 2020; Firestone et al. 2012b; Firestone et al. 2020). These attitudes and perceptions may be related to fishermen’s perceptions of risk more broadly and the extent to which decision makers can be trusted (Kuonen et al. 2019). There is also concern over power imbalances and trust in developers, many of which are large oil companies (or former oil companies) with significantly more wealth and power than fishing industry. Fishermen have voiced through public comments (e.g., BOEM Fisheries Mitigation public comment period) the need for decision makers to empower the fishing industry to participate in the development process as they don’t have the capacity and capital to engage in the offshore wind development process in similar ways that developers do. This research is not specific to fishermen and offshore wind and thus points to another area of future research need.

Attitudes and perceptions regarding fisheries and offshore wind also include consideration of fishermen’s role in decision-making processes, including perceptions of them as ocean users and stakeholders. In a study of stakeholders for a Maine tidal energy project, Johnson et al. (2015) found that fishermen were viewed as stakeholders with legitimacy, power, and urgency in the process and argued that public engagement strategies should reflect the salience of this group. Bennett et al. (2015) note that small-scale fishermen may be disenfranchised, disempowered, and marginalized in the process of reallocating ocean space to new uses. Kerr et al. (2014) note that fishermen’s knowledge networks are necessary for MRE but that fishermen interviewees reported feeling that their knowledge and expertise was undervalued and ignored in MRE planning.

Importantly, fishermen’s attitudes and perceptions of offshore wind energy may be more tangible, directly related to operational concerns, though few studies of these issues have specifically focused on fishermen themselves. This is another area ripe for future research. In a study of U.K. fishermen’s perceptions, Hooper et al. (2015) reported concerns surrounding access to fishing grounds, safety and liability, and gear loss. Acheson (2012) reported survey data including large percentages of fishermen who believed offshore wind would reduce fish catches, conflict with fishing gear, and pose a navigational safety hazard. See section 2.1 for further discussion regarding the impact of OSW on fishing operations. Insights from the broader literature may also be useful. In regional surveys of residents near proposed offshore wind projects, Firestone et al. (2012a) found that those who switched from wind farm support to opposition were most concerned about fishing and boating impacts. In an earlier survey regarding the Cape Wind project, Firestone and Kempton (2007) found that respondents also had concerns about fisheries impacts and boating safety, though these were second to broader concerns about environmental impacts and aesthetics.

Last, it is important to note that there is a broader literature examining offshore wind support/opposition (e.g., Firestone and Kempton 2007) and public perceptions/public acceptance of offshore wind energy (Teisl et al. 2015; Kerr et al. 2014). These materials provide useful context for a discussion of attitudes and perceptions that are specific to fishermen. However, we urge caution. From a fisheries perspective, a focus on support/opposition or acceptance might suggest a bias in favor of renewable energy that may be of limited use in building a nuanced understanding of fishermen’s attitudes and perceptions of offshore wind.

2.3.4.3 Attitudes and Perceptions Research Gaps

- Perceptions of offshore wind energy as a form of ocean grabbing
- How place, symbolic value, or landscape fit inform fishermen’s attitudes and perceptions regarding MRE; this is an area of future research need
- Perceptions of risk with operating within or being excluded from (as the case is on the West Coast) a wind energy area
- Perceptions of power imbalances and trust in process

2.3.4.4 Attitudes and Perceptions Research Recommendations

- Gathering of information from public hearings and public comments (qualitative text analysis of attitudes and perceptions)
- Stakeholder data collection on perceptions of place and identity

- Primary data collection on level of risk/perceptions of operating within a wind area/decisions

2.3.5 Stakeholder Engagement

2.3.5.1 General Definitions, Goals, and Benefits

Stakeholders are individuals, groups, or organizations with a current or future concern, interest, or investment in a particular issue or resource. These are people who must be taken into account by leaders, managers, or other decision makers (Bryson 2004). Stakeholders can be divided into those who will be involved in developing the system and those who will use the system directly or indirectly (Newman and Lamming 1995). While these divisions may offer a useful starting point, they cannot help identify specific stakeholders for a particular system or relevant to a particular project. It's important to not assume that stakeholders are obvious or create broad categories that are too generic to be of practical use (Sharp et al. 1999). Finally, in many ways, stakeholders are a subset of "the public." Thus, the literature regarding public participation in decision making about development in the coastal zone or nearshore marine environments may be informative, but meaningful stakeholder participation should be distinguished from broader public participation. Stakeholder involvement in its simplest form is the communication between the proponent of a given development project or policy and the people who will be affected (Colton et al. 2017).

Stakeholder participation is often used interchangeably with stakeholder consultation or engagement. Regardless of framing what it's called (consultation, participation, engagement), stakeholder involvement can be viewed or considered as having several stages or levels of depth. These variations are often described in terms of the flow of information: one-way flows from convener to stakeholders or from stakeholders to convener vs. two-way communications between them (Rowe and Frewer 2004). Stakeholder participation is performed by stakeholders (from the bottom) while consultation and engagement are typically performed by whoever is leading a decision-making process (from the top). At a minimum, stakeholder involvement processes that inform should provide the opportunity for participants to gain a better understanding of the issue (the facts, experiences, knowledge, ideas, hopes, preferences, fears, opinions, and values). By contrast, involvement processes that engage stakeholders take this further.

Stakeholder engagement processes facilitate the willingness and ability of stakeholders to take an active role in decisions that affect them (Reed 2008; Colton et al. 2017). Meaningful stakeholder engagement should provide the opportunity for participants to provide input and feel listened to. They should feel confident that their input will be considered or used in decision making and/or collective action. True engagement is two-way and is shaped by both sides' expectations. Without effective two-way engagement, stakeholders can feel left out of the process and decisions and thus are more likely to oppose the process outcome (Zoellner et al. 2008).

Engagement is guided by a variety of goals. A key goals framework by Fiorino (1990; see also Stirling 2008) distinguishes between instrumental, substantive, and normative goals. Instrumental goals are based on the role participation plays in the achievement of outcomes. In this light, engagement is a means to manage conflict and opposition, maintain budgets and timelines, and successfully implement a decision; instrumental engagement is often focused on meeting legal requirements for participation. Substantive goals are focused on the quality of projects by better incorporating information, whether about physical conditions or social values, into the decision-making process. Normative goals focus on ethical principles, such as democratic ideals that stakeholders should have a voice in decisions that affect them. More nuanced approaches to participation goals (Bidwell and Schweizer 2020; Renn and Schweizer 2009) have further identified emancipatory goals for engagement, which seek to level the playing field by giving less powerful social interests a voice in decisions. Incongruity of goals between conveners of engagement and stakeholders can be a source of conflict and diminish trust (Dietz and Stern 2008; Wesselink et al. 2011).

Structuring effective stakeholder engagement requires a better understanding of the perspectives, concerns, and information needs of the different stakeholder groups that may affect or be affected by the decision-making process. Choices of who to include how, when, and why are related to the questions of effectiveness and to the value of that particular stakeholder's involvement, and are relevant to planning for stakeholder participation (Mitchell et al. 1997; Bryson and Crosby 1992; Bardach 1998; Bryson 2004; Johnson et al. 2015; Colton et al. 2017).

While there is no one perfect recipe for stakeholder engagement, any process should have features such as effective communication, broad-based inclusion, prioritization strategies, early and mutual learning, and alternatives analysis. Stakeholder engagement requires adequate capacity, resources, and time (Colton et al. 2017). In practice, integrating input from numerous and diverse stakeholders into ongoing decision-making processes can be a significant challenge, and it may not be meeting the intended goals. Effective stakeholder engagement requires an improved understanding of how to engage relevant stakeholders at the most appropriate time and in a manner that will enable them to fairly and effectively shape decisions (Glicken 2000; Reed 2008; Colton et al. 2017; Pomeroy et al. 2015; Conway et al. 2010).

Stakeholder engagement processes can be designed to provide mutual education, a venue for gathering information, technical expertise, creative solutions, and social data about groups impacted by this process or decision. It can increase communication and compliance (buy-in). It may yield a change in awareness or perspective, and possibly a change in behavior. Paying attention to stakeholder input can help to assess and enhance political feasibility (Meltsner 1972; Eden and Ackermann 1998; van Horn et al. 2001), understand public attitudes (Portman 2009; Reddy and Painuly 2004; West et al. 2010; Devine-Wright 2005; Firestone and Kempton 2007; Firestone et al. 2009; Kempton et al. 2005), and design more effective stakeholder processes (Hindmarsh and Mathews 2008; Conway et al. 2010). Benefits associated with two-way stakeholder engagement include the opportunity to build or improve relationships and trust; addres power issues, such as equity, voice, level of vulnerability, marginalization, access to political power, and legitimization; improve transparency, accountability, and understanding; enhance the quality and durability of decisions; promote social learning; increase the likelihood that local needs and priorities are successfully met in the decision-making process; serve to broaden the number of dimensions considered for problem solving; and, in particular, potentially allow for nontechnical information provided by nonscientists to enter the decision-making process (Glicken 2000; Breukers and Wolsink 2007; Reed 2008; Richards et al. 2004; Holmes and Scoones 2000; Zoellner et al. 2008; Agterbosch et al. 2009; Colton et al 2018; Johnson et al. 2015; Conway et al 2010; Blackstock et al. 2007).

2.3.5.2 Beyond Economics; social license to operate

Social license to operate is a term that originated a few decades ago, especially related to mining. Here, industry consultants emphasized the importance of addressing community needs that go beyond just economic impacts—credibility, legitimacy, and trust—factors critically important to advance a contract between the community and the industry (and/or government). Social license can feel intangible, but it's associated with acceptance and consent, expectations and demands, and ultimately consent and approval (Colton et al. 2017). Similar in some ways but different in others, social acceptance is a more familiar term when it comes to renewable energy development, especially in Europe (Colton et al. 2017). The variables associated with social acceptance (attitudes, behavior, age, socioeconomic status, place attachment, and political views) are a bit easier to measure. Regardless of what it is called, a fundamental issue of both social license and social acceptance is trust. Development projects informed by processes that support the development of trust are more likely to be accepted by stakeholders, the local community, and the public.

2.3.5.3 Offshore Wind Related Stakeholders and Stakeholder Engagement

Researchers and practitioners have long advocated for stakeholder engagement and public participation as critical components of renewable energy planning and development (Bidwell 2016; Devine-Wright 2011; Stirling 2014), including offshore wind energy development (Haggett 2011). Regardless of the specific MREtechnology, after deciding to commit to engagement, the first step in designing effective stakeholder engagement processes is identifying and characterizing the stakeholders for this situation (Reed et al. 2009; Glicken 2000; Firestone et al. 2018; Johnson et al. 2015; Conway et al. 2010). Offshore wind stakeholders can include coastal states, agencies, fishermen (commercial and recreational), the larger fishing community, recreational boaters, commercial shipping, waterfront landowners, environmental groups, advocacy groups, utilities, and wind developers.

As key stakeholders, fishermen could/should be involved in various formal and informal ways throughout the offshore wind development process. This ocean-based community and industry are socially, culturally, and economically important to the place, region, state, nation, and globe.

Local fishermen’s involvement can help to improve understanding and decisions through the knowledge that they have of the local marine environment. Taking time and effort to include fishermen in meaningful engagement through incorporating local knowledge in the decision-making processes can be a rich and valuable resource. Fishermen can provide knowledge about marine space and place, the features associated with the ocean’s bottom in these places, and the movement of currents, wind, and marine inhabitants (e.g., fish, marine mammals). In this regard, they could be viewed as important partners in understanding design and placement of energy generation devices.

Utilizing local ecological knowledge of fishermen and other ocean users (researchers and even cooperative efforts such as RODA’s FKT, see RODA [2021]) could provide potential developers and policymakers alike with information that cannot be found in the literature or data banks. Local ecological knowledge goes beyond physical or other forms of environmental data. It also includes the values and beliefs associated with ocean place and space (Bidwell 2013; Haggett et al. 2020; Colton et al. 2017; deGroot et al. 2017; Pomeroy et al. 2015; Johnson et al. 2015; Conway et al. 2010). The value associated with cooperation or collaboration in marine-related studies has been widely documented (Roach et al. 2018; ten Brink et al. 2021; Haggett et al. 2020; Smythe and McCann 2018, 2019). The possibility, ability, and interest to provide this local knowledge has been documented across the globe (Colton et al. 2017; de Groot et al. 2017; Pomeroy et al. 2015; Johnson et al. 2015; Conway et al. 2010).

That said, there are challenges. Previous negative experiences with offshore wind planning left fishermen in Europe (and other places, as well) feeling left out of the process (Mackinson et al. 2006; Colton et al. 2017; de Groot et al. 2017; Goedkoop and Devine-Wright 2016). Fishermen expressed a lack of trust with offshore wind developers, government, and other authorities (Alexander et al. 2013) and felt there was little meaningful discussion between fishing and energy representatives (Gray et al. 2016). In order to establish meaningful engagement where fishing communities feel heard, early consultation with fishermen and fishing associations is critical and more likely to result in their active participation (BERR 2008; Reilly et al. 2016; others). Port visits should be made at the earliest opportunity by developers to engage with fishermen (FLOWW 2014). Consideration should be given to fishermen's unpredictable schedules, the time commitment of active engagement, and their availability to engage. Additionally, de Groot et al. (2014) report that technical report outputs should be easily available and understandable, and rather than long reports, short single page leaflets with clear and straightforward messages are preferred in communicating information.

Gray et al. (2005) note that face-to-face meetings and personal interactions are preferred, and engagement should be maintained throughout the EIA process (FLOWW 2014). Studies of engagement of the public for the BIWFfound that informal interactions were a welcome aspect of project planning (Dwyer and Bidwell 2019; Firestone et al. 2020). In fact, the formal processes mandated under NEPA and other federal and state policies are often viewed as inadequate and even problematic to meaningful engagement (Innes and Booher 2004).

Using fisheries liaisons can be key in effective engagement and help identify potential impacts and coexistence opportunities (FLOWW 2014). Fishing Liaison with Offshore Wind and Wet Renewables Group (FLOWW) was established by U.K. fishing groups to improve engagement between developers and fishermen. Including fisheries liaisons in the process has been adopted in the U.S. (Moura et al. 2015) and included in the BIWF process (McCann et al. 2013). BOEM's best practices guidance recommends that lessees plan and implement a project-specific fisheries communication plan which identifies at least 2 people responsible for communications between the lessee and the fishing community: (1) a fisheries liaison who would serve as the lessee's primary point of contact employed directly by the lessee and (2) a fisheries representative who would serve as the fishing community's primary point of contact for communicating its concerns to the lessee (BOEM 2020). The overwhelming amount of engagement demands and complications in understanding who to engage with and at what time has frequently been communicated by the fishing industry as developers and decision makers try to engage simultaneously for each wind development project (RODA 2021, personal communication). With over 25 projects proposed in the Northeast by 2030, this demand can be all consuming, especially as fishermen have variable schedules and are away for long periods of time. Engagement opportunities take away from their jobs and time with family. In the research community, this is often called research subject fatigue or survey fatigue, and similar burdens are seen in offshore wind development processes.

Importantly, no research has been published to date that specifically addresses fisheries stakeholder engagement in the U.S. offshore wind leasing and permitting process. This is a significant area of research need and may be used to develop policy recommendations.

2.3.5.4 Energy Planning and Spatial Planning

Discussions of fisheries and offshore energy are often in the context of Marine Spatial Planning (MSP) both in Europe (Stelzenmueller et al. 2006) and the U.S. (Nutters and DaSilva 2012; Sullivan et al. 2015; Pomeroy et al. 2015; Smythe and McCann 2018, 2019). MSP, alternately called marine or ocean planning, describes an approach through which managers and stakeholders analyze the natural resources and human uses of an area in order to achieve a range of planning objectives; importantly, stakeholder engagement is a defining principle of MSP (Ehler and Douvere 2009; Douvere, 2008). One example of this is through the Rhode Island Ocean Special Area Management Plan (SAMP) in which the location of the BIWF was selected through a 2-year planning process, including an intensive stakeholder process, and culminating in a plan codified as a state policy series of workshops. The CRMC, the state's coastal zone management agency, led plan development; once the plan was codified, the state permitting process for the BIWF began. The RI Ocean SAMP was developed through a process designed to honor existing activities and reduce conflicts, with policies that reflect science and stakeholder involvement (McCann et al. 2013). A major goal of the RI Ocean SAMP was to constructively engage major stakeholders, including fishermen, alternative energy proponents, environmentalists, scientists, federal and state agencies, the Narragansett Indian tribe, and concerned citizens, and to provide stakeholders with both access to and influence over decisions. To engage commercial and recreational fishermen in future offshore wind energy decision-making processes, the RI Ocean SAMP created in state law a role for fishermen in decision-making implementation of fisheries-related policies through a 9-member Fishermen's Advisory Board (FAB) which was tasked with advising the CRMC on proper siting of new developments and mitigation of any ensuing impacts.

Although MSP can be a successful tool in reducing conflict, much of the data used in MSP processes is quantitative economic data, such as ex-vessel value of fishery landings. While this data provides a quick method of quantifying the economic impacts to fishermen, it fails to show the true economic value (including downstream impacts), and it fails to capture social characteristics and values to space and can render small-scale fisheries and their associated communities invisible (Pomeroy et al. 2015). Participatory mapping can be a valuable tool in including representative fisheries stakeholders, incorporating knowledge in the process, and understanding fishermen's relationships with the ocean. Participatory mapping is often done in MSP efforts (Scholz Steinback and Mertens 2006; McCann et al. 2013). In Europe, mapping work was used to inform MSP in Scotland (Kafas et al. 2017). As part of the SAMP process, fishermen were also involved in a qualitative and quantitative mapping process (Chapter 5, RI SAMP). The Island Institute (2009) worked collaboratively with fishermen to document and map fishing areas and demonstrate the complexity of fisheries interactions (i.e., between fixed and mobile-gear), links port and harbors to fishing areas, and show seasonal variations and gear movement.

2.3.5.5 Formal Requirements, Policies, and Negotiated Agreements

The Energy Policy Act of 2005 designated BOEM as the lead authority for issuance of offshore renewable leases and management of offshore wind in federal waters. The National Environmental Policy Act of 1969 requires federal agencies to consider the environmental consequences of major actions through the formal assessment of impacts. Data collected by BOEM and consulting agencies, such as NOAA, are used to assess a project's environmental and socioeconomic effects and impacts through NEPA documents—EISs and Environmental Assessments (EAs). These require both project specific and cumulative assessments (BOEM 2020). A number of federal agencies have authority to comment on the regulatory process as cooperating agencies, such as NOAA Fisheries, the lead agency in managing fisheries. The NEPA EIS process has opportunities for public input (CEQ 2007), and BOEM provides information on stakeholder engagement and partnerships to help commercial fisheries learn more about opportunities for participating in their rule-making process (BOEM 2021), including an Atlantic Fishing Industry Communication and Engagement page.

Recommendations could be developed that encourage offshore wind companies to engage (up to sharing ownership of projects) with stakeholders and local communities. However, power sharing or shared ownership presumes that the company and community have common goals and are committed to building trust. Are these policies built or agreements negotiated that consider the sharing of power (relational, not energy)? How much legitimacy (the legal, moral, or presumed claim) do these stakeholders have associated with this ocean space and place? And how much immediate attention (urgency) from the decision makers are they willing to give to the stakeholders? All of these attributes are variable and socially constructed but quite important in finding lasting agreement (Johnson et al. 2015; Wright et al. 2016; Colton et al. 2017; Klain 2017; Haggett et al. 2020).

Even when a community trusts the intention of the developer of the project, they may not entirely approve of or feel ownership of the proposed project (Colton et al. 2017; Johnson et al. 2015). Effective partnerships must be thoughtfully formed and fair outcomes must be cultivated. There is limited but growing research on the process of shared ownership. While there might initially be excitement for shared ownership in principle, there are significant challenges in practice, such as skepticism regarding the capacities and representativeness of community partners and these partners viewing developers as solely motivated by profit and as entities use communities to gain planning consent. Partnerships should be identified and facilitated at an early stage, which can help to build trust and a more stable and supportive policy context (Goedkoop and Devine-Wright 2016; Portman 2009).

2.3.5.6 Stakeholder Engagement Research Gaps

- Are fishing communities actively engaged/provided the resources to be involved in offshore wind activities?
- What is the demand on commercial and recreational fishing communities to participate in offshore wind stakeholder activities?
- Methods for including stakeholders effectively in decision making.

2.3.5.7 Stakeholder Engagement Research Recommendations

- Analysis of stakeholder engagement demand (activities, timeline, formal, informal, and so on)
- Interviews with stakeholders to assess preferred methods of engagement in offshore wind development
- Qualitative text analysis of public comments by fishermen regarding offshore wind decisions

2.3.6 Resilience and Adaptation

This section synthesizes social science research to date on fishermen’s resilience and adaptation as relevant to offshore wind development and identifies research needs in this regard.

Resilience is a concept originating in ecology that refers to the ability of social-ecological systems to cope with and adapt to change while retaining their structure and function (Folke et al. 2002). However, Adger (2000), cautions against transferring the concept of ecological resilience directly to social systems, defining social resilience as simply “the ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change.” Social resilience, therefore, requires attention to multiple scales of fisheries systems (i.e., individuals, communities, and the larger social-ecological system [e.g., Cinner et al. 2019; Himes-Cornell and Hoelting 2015; Berkes and Ross 2016]). Similarly, the term “adaptive capacity” refers to the ability to endure or recover change and can also include responses in anticipation of changes (Johnson et al. 2014). For the purposes of this short review, we use these terms interchangeably.

Marshall and Marshall (2007), assessing social resilience to policy change in northern Australian fishing communities, identified 4 qualitative components of resilience: (1) perception of risk in approaching change; (2) ability to plan, learn, and organize; (3) perception of the ability to cope with change; and (4) level of interest in adapting to change. Maclean et al. (2013) identified 6 attributes of social resilience through an analysis of 6 community case studies: (1) knowledge, skills and learning; (2) community networks; (3) people-place connections; (4) community infrastructure; (5) diverse and innovative economy; and (6) engaged governance. Johnson et al. (2014), found that fishing community members in Maine defined resilience as (1) fishermens' survival in the industry; (2) self-identification as a fisher/fishing community; (3) diversification within and/or outside of fishing; (4) resources and strategies for coping with short-term changes; and (5) optimism about the future needed for investment rather than outmigration from fishing or the community. Cinner et al. (2019) recently summarized 6 social factors providing resilience in social-ecological systems: (1) assets, (2) flexibility, (3) social organization, (4) learning, (5) socio-cognitive constructs, and (6) agency.

Scholars identify various kinds of assets or capital as sources for resilience. For example, technical capital would include expertise regarding how to make, use, and maintain gear and local knowledge of how and where to fish. Social capital captures the importance of the network of individuals with established kinship and community relationships that allow them to work together to respond to changes. Cultural capital includes the values, ideas, aspirations, stories, and heritage passed from generation to generation and through the social network. Community capital refers to the degree to which the community can collectively develop and engage resources to improve well-being (Magis 2010).

When thinking about resilience and adaptation, it is important to consider the kind of stressors or threat, or perturbation, including their magnitude and duration. On one hand, small, fast stressors, such as random and cyclical changes in fisheries, extreme weather events, and unpredictable prices paid to fishermen for their catch, are going to result in different kinds of responses compared to large, slow changes, like climate change, cultural and economic globalization, and the regulatory environment. Offshore wind development is likely to create both small/fast and large/slow stressors to which communities must respond. Different kinds or levels of response are to be expected depending on the stressor and the capacity of the individual or community or broader social-ecological system. Himes-Cornell and Hoelting (2015), in their study of Alaskan fishing communities, distinguish between persistability, adaptability, and transformability. Persistability, like "coping" (McCay et al. 2011), can be considered responses that maintain system structure and function. Examples illustrating persistability include short-term behavioral change like reducing costs by using less bait and fuel, or putting off maintenance and repair. Johnson and Henry (2015) found Maine lobster fishermen responded to reduced prices mainly through coping strategies that reduced their costs or simply by fishing harder to increase their volume, rather than making any long-term changes to their operations.

Adaptability refers to being able to make more substantive changes in anticipation of or in response to stressors. Diversification within and outside of fishing is a common strategy that allows for adaptability. This includes being able to rely on non-fishing employment to supplement income from fishing. Fishermen in the Mid-Atlantic region are shifting fishing locations in response to changing species distributions (e.g., Young et al. 2018). However some fishermen are unable to switch fisheries or locations due to institutional (e.g., privatization of fisheries) and technological restrictions (e.g., gear restrictions or vessel mobility or closed geographic areas). Privatization of fisheries and limited access programs can lead to graying of the fleet, which can further limit resilience in fishing communities (e.g., Donkersloot and Carothers 2016; Ringer et al. 2018, Cramer et al. 2018, Johnson and Mazur et al. 2018).

Transformability involves actions that create a fundamentally new system because the stressors have left the existing system unworkable. This would involve, for example, outmigration from fishing (to other economic sectors) or the community (e.g., Himes-Cornell and Hoelting 2015).

2.3.6.1 Offshore Wind Energy Resilience and Adaptation

There is no identified research on fishermen's resilience and ability to adapt to changes with offshore wind development in the U.S., as offshore wind development is in its infancy. The ability of fishermen to adapt to changes from offshore wind will be dependent on a number of factors that are discussed throughout this paper, including policies, technologies, access to capital, and social and cultural demographics. The speed and scale of offshore wind development will also impact fishing community resilience. The level of displacement and costs associated with redistribution will be one determining factor to the ability of fishermen to adapt to change as well as compensation for any losses. Conducting studies on fishermen's perceived adaptive capacity to offshore wind development (for example, methodologies used in Seara et al. 2016; Marshall and Marshall 2007) may help close this social gap and identify methods of adaptation.

In the Synthesis of the Science Workshop, participants identified a number of challenges to adaptation with offshore wind development, including: lack of time and resources for engagement, lack of trust, lack of transparency and lack of inclusion within the regulatory processes. As discussed in the stakeholder engagement section, meaningful engagement will aid in adaptation to offshore wind development. Additionally, some opportunities for adaptation were discussed, including revitalized port facilities and giving fishermen first right for service vessels or research opportunities. Fisheries could also benefit from upgrades to the aging infrastructure that has affected fishing community vulnerability and resilience for decades.

A clear and collaborative process of developing mitigation strategies is necessary to aid in adaptation and resilience of fishing communities.

2.3.6.2 Resilience and Adaptation Data Gaps

- How will fishing communities adapt to offshore wind development?
- Adaptive capacity of fishing communities
- Businesses strategies to aid in adaptation of offshore wind development
- The opportunities (e.g., new target species) and limitations (e.g., regulatory restrictions) of adaptation

2.3.6.3 Resilience and Adaptation Research Recommendations

- Measure subjective resilience in fishermen to offshore wind development (e.g., Marshall and Marshall 2007).
- Analysis of diversity of fishing communities and adaptation strategies to past
- "Communities at Sea" approach and methods to understand adaptation to offshore wind development

- Cumulative impacts analysis to understand the adaptive capacity of fishing communities

2.3.7 Mitigation

Several factors are critical in mitigating any impacts on commercial and recreational fishing activities resulting from wind farm developments. Transparency, dependability, and uniformity are vital to successful mitigation approaches; however, the dynamic nature of the current state of offshore wind in the Northeastern United States has made achieving these objectives difficult. This section provides a brief summary of recommended fisheries mitigation strategies, some of which have been outlined in more detail throughout this section (e.g., Safety and Navigation mitigation within Section 2.1.2.7). This section also provides a summary of existing compensatory mitigation programs in Europe and in the U.S.

In the U.S., 2 publications outline recommendations to mitigate potential conflict and impacts between offshore wind energy and fisheries (Industrial Economics 2012; Ecology and Environment, Inc 2014). These documents are used by developers in creating required mitigation plans by some states (e.g., New York) on condition of their lease. BOEM sought additional information on potential conflicts and mitigation strategies between existing uses of the ocean environment and offshore wind development (Industrial Economics 2012). The recommended potential mitigation measures from the report are outlined in Table 8. In 2014, BOEM sought input from commercial and recreational fishing industries, as well as fisheries management agencies and scientists, through 8 stakeholder workshops to develop reasonable best management practices and mitigation measures (Ecology and Environment, Inc 2014). BOEM noted that publication of these BMPs does not indicate adoption of them, but that the agency will continue to refine and require implementation as appropriate as part of its NEPA review process to minimize impacts to commercial fisheries. The final 5 best management practices are: (1) Fisheries Communication and Outreach; (2) Project Siting, Design, Navigation, and Access; (3) Safety; (4) Environmental Monitoring; and (5) Financial Compensation.

2.3.7.1 Compensatory Mitigation

This section outlines what is presently known while synthesizing the most comprehensive compensatory mitigation strategies currently available. It is important to note that methods may vary for the same project depending on who reports findings and when. Literature included will be the most current and reputable information available at the time of writing.

The efficacy of compensation and mitigation plans has been linked to early consultation between developers and fishermen during the planning process, and its role in stakeholder engagement is critical. A U.K. report found that if fishermen are consulted late in the planning phase, there would inevitably be little opportunity to modify plans for wind farms or incorporate features that could mitigate any impacts (Blyth-Skyrme 2010). Therefore, an effective consultation process is needed for each development, and fishermen and fishermen’s associations must contribute to discussions.

In Europe, most countries do not have compensatory mitigation programs. In the U.K., compensation programs are not required by legislation and are considered as a last resort. Compensation plans that exist have consisted of negotiations between the developer and local community. In Denmark, compensatory mitigation is mandated by the Danish Fisheries Act, and developers are not granted a license until an agreement has been made with all affected fishermen. The Danish Fisheries Act foresees a consultancy process where developers present and discuss their development plan directly to the fishing industry. These negotiations include financial disruption or displacement compensation due to offshore wind areas and export cables. The Danish Fisheries Association carries out negotiations and are verified by an independent consultant. Compensation can be provided for suspension of fishing activities at all phases (survey, construction, operation) as well as longer distances traveled to new fishing areas (Dupont et al. 2020). A short summary of compensatory mitigation plans for Europe and the U.S. to date are presented in Table 9. The table presented here does not represent all compensatory mitigation plans that exist, but outlines information that should be collected in a separate, expanded effort to expand our knowledge in the U.S on possible methodologies.

In the U.S., federal, state, and local governments are responsible for ensuring that all appropriate involved parties are adequately informed, notified, and involved in any mitigation and compensation plans. The capability to properly include other stakeholders suggests that all levels of government are involved and aware of each project in its entirety. Recently, The Biden administration was considering ways to ensure the U.S. commercial fishing industry is paid for any losses it incurs from the planned expansion of offshore wind power in the Atlantic Ocean, according to state and federal officials involved in the matter (Groom 2021). At the state level, governors of Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Rhode Island, and Virginia (and the non-Alliance governor of New Hampshire) cosigned a letter pledging to work collaboratively to meet each state's respective clean energy targets, while offering strategies to build upon the key areas outlined by the Administration to advance further offshore wind in the United States (NYSERDA 2021).

In considering mitigation rather than compensation as a means to address fisheries impacts, it is noted in Blyth-Skyrme (2010) that a variety of external funding sources exist to promote the sustainability and viability of fisheries. These may be targeted to increase the level of funding available for mitigation projects. In contrast, it was thought unlikely that external funding for compensation would be made available. A significant issue with any mitigation project is ensuring that the impacted fishermen can benefit from the mitigation. In comparison, compensation is expected to be relatively simple to distribute and can be targeted directly at specific individuals. An issue identified for U.K. fisheries as a whole and for coastal fisheries, particularly, is that data showing where fishermen work and the value of different areas to different fisheries sectors are available only at a broad scale. In the absence of reliable data on fishing activity, developers may be understandably cautious in providing funding for mitigation or compensation options (Blyth-Skyrme 2010).

The Massachusetts Ocean Partnership (MOP) report concluded that monetary compensation should be provided to fishermen for lost use of ocean resources during the construction phase, but determining how to provide long-term compensation for unanticipated impacts may be more challenging (Industrial Economics Incorporated and The Massachusetts Ocean Partnership 2009). While fishing interests generally prefer a long-term insurance policy or lifetime payments rather than a single, upfront payment, it is in the developer's best interest to determine a finalized upfront mitigation cost to determine if the project is financially desirable. As a result, there is a great need for communication and trust-building between the developers and the fishing industry to work through the process of negotiating mitigation and compensation packages (Industrial Economics Incorporated and The Massachusetts Ocean Partnership 2009).

2.3.7.2 Vineyard Wind Compensatory Mitigation

The distinction between potential project impacts on fish resources and fishing activity is vital for identifying sources and types of potential economic impacts, determining how to reduce or avoid them, and developing mitigation compensation programs to offset them. (Epsilon Associates, Inc. 2019, 2-1). Vineyard Wind fisheries communication plan tries to do this by outlining, developing, and implementing procedures for handling compensation to fishermen for potential gear loss and the loss or reduction of income to fishermen. It is stated that they recognize that adequate plans require detailed discussions between the impacted fishing community and Vineyard Wind (Bank et al. 2020). To spearhead discussions and gauge the possible economic loss to the fishing fleet, Vineyard Wind hired an economist to look at different data sets of fisheries landing values and produce an economic exposure report.[10] Vineyard Wind is also planning to establish a mitigation program that will compensate commercial fishermen for any economic losses associated with lost or damaged gear (Epsilon Associates, Inc. 2019).

Vineyard Wind's offshore wind energy project also voluntarily committed to measures to avoid, reduce, mitigate, or monitor impacts on the resources discussed in the Final Environmental Impact Statement (FEIS). The FEIS Vineyard Wind LLC states that 2 measures will be implemented for commercial fisheries and for-hire recreational fishing (BOEM 2021). The package is structured in 2 funds: (1) an escrow fund for financial compensation for direct Rhode Island fisheries impact claims and (2) a Rhode Island Fishermen's Future Viability Trust that will disperse funds in accordance with the purpose of the Trust and the goals of the Ocean SAMP (Vineyard Wind LLC 2019). The Rhode Island direct compensation fund will be held in the amount of $4.2 million in escrow to compensate for any claims of direct impacts on Rhode Island vessels or Rhode Island fisheries interests in its project area. The Viability Trust will be in the amount of $25.4 million and is calculated as follows: Rhode Island economic exposure was valued at $6,190,281 over 30 years using a 2.5% annual escalator to the initial 1-year exposure value. When the Rhode Island Fisheries Advisory Board asked to front-load the initial payment, nominal dollars were reduced to $4.2 million (but the value in real terms is still $6.1 million). For Massachusetts, the economic exposure plus upstream and downstream multipliers is $19,185,016. The Rhode Island $6,190,281 plus the Massachusetts $19,185,016 equals $25,375,297. The $25.4 million compensation funds are calculated from Fishing VTRs, dealer reports, and VMS data (King and Associates 2019). Vineyard Wind and the Massachusetts Executive Office of Energy and Environmental Affairs can also be referenced for detailed methodology. Fishing interests are broadly defined to include owners and operators of vessels, vessel crews, shoreside processors, vessel supplier and support services, and other entities that can demonstrate losses directly related to the Vineyard Wind Project (BOEM 2021).

The Vineyard Wind fisheries communication plan also states that a process for filing fishery compensation claims will also be created. A third-party fiduciary agent will handle claims, and a review board consisting of members from the fishing industry will assist with the claims process. Until this process is developed, fishermen should make any such request through the fisheries liaisons. The Vineyard Wind FLs are employed by Vineyard Wind and report directly to the Vineyard Wind Chief Development Officer. The FLs are responsible for overall implementation of the communications plan, particularly communicating project plans and activities that might impact the fishing industry pre-, during, and post-construction activities of the offshore wind development and reporting interactions or concerns from the industry to the Chief Development Officer.

If fishermen are displaced during construction, fishermen will be required to submit evidence of income and fishing location(s) to Vineyard Wind to be compensated (Bank et al. 2020). However, it is not possible at this time to assess the exact likelihoods or potential magnitude

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[10] These reports can be found on Vineyard Wind's website: www.vineyardwind.com.

of gear damage or lost fishing time associated with bottom gear snags along the offshore export cable corridor after construction. There are contradicting views on whether funds like those mentioned above will be enough. Epsilon Associates, for example, stated that it is reasonable to expect that claims will be rare and to assume that fishermen will be fully compensated for any related economic losses as part of a fishermen's compensation program. The paper also states it is reasonable to assume that fishermen will be compensated for lost fishing income that could result from disruptions in the scheduling of OECC construction and/or shifts in the distribution or concentration of fish in the vicinity of the OECC that result in unexpected losses in fishing revenues (Epsilon Associates, Inc. 2019).

On the contrary, groups such as the Rhode Island Commercial Fishermen's Association state the impacts will be significant and the values and considerations associated with Vineyard Wind's COP are grossly lacking. They also argue that council members, in addition to the general public, were left out of meaningful mitigation measure discussions that directly impact their livelihood (Senate Fisheries 2019). Another source of contention is reported by RI DEM. They estimated the ex-vessel value of fishing in the Vineyard Wind COP area with an assumed 2 NM buffer along the north and south boundaries to be $35,611,702.85 for 30 years (including lease and construction time). The values in this analysis do not account for future increases in fish populations, increases in value, or inflation. It is reported that the ex-vessel values in the cited study should therefore not be considered an analysis of any economic value beyond the ex-vessel value of fishing in the COP area. In addition, the values reported do not include any shoreside impacts (including crew, fuel, gear, ice, processing, or packaging costs). Furthermore, the value of seafood served at local restaurants has not been accounted for; restaurants are expected to be affected by changes in seafood availability. Additionally, ecological impacts to marine resources and impacts that habitat alteration in this area may impose upon the productivity of various marine populations are not considered, which could also affect landings from the area as well as surrounding regions through time (Rhode Island Department of Environmental Management 2019).

2.3.7.3 South Fork Wind Farm Compensatory Mitigation

Deepwater Wind South Fork, LLC has also implemented fisheries compensation plans. The South Fork Wind Farm and South Fork Export Cable Project DEIS outlines a Rhode Island Fisheries Direct Compensation Program and Coastal Community Fund. This will be a $4.25 million direct compensation fund held in escrow to compensate for any claims of direct losses or impacts on Rhode Island commercial and for-hire charter fishing operations caused by the construction, operation, and decommissioning of the project. A $950,000 Coastal Community Fund will also be held in escrow to support Rhode Island companies that support Rhode Island fishing interests. An implementation agreement was executed between the Rhode Island CRMC and South Fork Wind, LLC on June 30, 2021. South Fork Wind has also committed to provide $2.6 million in compensatory mitigation as part of its overall project modifications and mitigations to achieve consistency with the enforceable policies of the Massachusetts Coastal Program. The total will be comprised of an upfront payment of $2.1 million for direct compensation for potential economic loss to Massachusetts commercial and for-hire (charter) fishermen through a claims process; an upfront payment of $200,000 to establish a Coastal Community Fund to support the coexistence of the fishing and offshore wind sectors through a grant program; and up to $300,000 (the "Navigational Enhancement and Training Funding") to fund claims when made through the Navigational Enhancement and Training Program (BOEM 2021). Furthermore, various news sources have reported efforts to spearhead a $12 million fisheries compensation package, consistent with the state's Ocean SAMP (Walsh 2021). Another presented option is for developers to make a one-time upfront payment of $5.2 million to the fishermen (Kuffner 2021). Others urge discontent fishermen not to accept the compensation package and to press on for more mitigation to reflect displacement from centuries-old fishing grounds (Allen 2021).

Although more recent wind farms in the Northeast have presented compensation plans and programs for the region's first wind farm, BIWF did not offer any compensation option for fishermen in the FEIS. However, the FEIS included an unpublished study sponsored by the Massachusetts Fishermen's Partnership to examine the potential economic impacts of the construction and operation of WTGs on the squid and fluke fisheries in Nantucket Sound. The author estimated a net present value over 25 years (using a discount rate of 10%) of $6 million for mean fishing income in the area of Horseshoe Shoal, and willingness to accept compensation for exclusion of $13 million or inconvenience of $8 million (U.S. Department of the Interior Minerals Management Service 2009). It is important to note that this does not encompass all fisheries, and the methodology is not widely used in the literature of this nature.

2.3.7.4 Science to Support Compensatory Mitigation Research Gaps and Recommendations

- Commercial and recreational fishing are essential components contributing to the economic viability of many coastal communities that must be preserved in the development of every OSW project. Impacts to such users (including supporting businesses; Section 2.2.5) should be minimized to ensure coexistence between fishing and offshore wind development and prevent interference with existing reasonable uses of the lease area. Analysis of impacts resulting from these projects should be based on the best scientific information available for all marine trust resources. Data should also include an acceptable range of years to reflect natural variability in resource and current conditions.
- Current data methods have limitations in estimating fishing compensation due to limited spatial resolution and fisheries coverage. New data methods that are at a finer scale should be explored in order to effectively inform compensation programs (see Section 3.1 Fisheries Dependent Data).
- Compensation plans are typically state-specific and not enough data has been collected in the United States to definitively assess their effectiveness. Many fishermen claimed compensation arrangements were inequitable, alleging that some fishermen eligible for compensation did not receive any, while others received too little, as fisheries were undervalued and compensation was not based on vessel size and allocated fishing time (DAS; Gray et al. 2016). These plans may capture increased DAS costs due to OSW; however, these additional costs have not been adequately quantified and would need to consider increases in all related business costs. Another object of focus is that once funds are depleted, there is no information available on fishermen being compensated for losses due to construction, operation, and decommission.
- Compensation and other mitigation measures should also be transparent and accessible to those affected in all respects. Furthermore, it is critical that the details of compensation plans describing qualifying factors, time constraints, allowed claim frequency, and so forth should be included when possible. Both economic impacts to primary harvesters as well as impacts to secondary and shoreside

businesses should be considered into compensation packages. To the extent that any conclusions are based on mitigation measures, those measures should be clearly defined to indicate whether the measure is considered part of the proposed action. It is important to ensure compensation and mitigation details are made available in a way conducive to the use of fisheries and supporting businesses.

3. FISHERIES MANAGEMENT AND DATA COLLECTION

3.1 Fishery Dependent Data Collections

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3.1.1 Introduction

Fishery dependent data (FDD) are collected as part of routine fishing operations based on the requirements established in each fishery. FDD are used to describe and evaluate changes in fishing patterns and associated socioeconomic trends and impacts, monitor fishery quotas, and inform stock assessments (Fox and Starr 1996; Bell et al. 2017; Turner et al. 2017; Cadrin et al. 2020; Essington et al. 2021; ICES 2019; McHenry et al. 2019). This utility means FDD are an essential component of fisheries science and management. In the Northeast U.S., FDD comes from many sources, including catch reports (such as VTRs), dealer landings reports, regulatory positioning data (such as VMS), and AIS data, as well as other catch and discard information from observer and at-sea monitors, portside samplers, and study and research fleets. In addition to these commercial sources, recreational FDD comes from the Marine Recreational Information Program (MRIP, or recreational angler survey). Fishermen may also provide information derived from local ecological knowledge (e.g., industry-based surveys and Fisheries Knowledge Trust [FKT; RODA 2022]) and socioeconomic data (e.g., market price, operational costs, crew numbers) through independent research surveys. The standard components of FDD include entity (vessel, dealer, operator); dates/times; species; catch amount (weight, number, size), disposition (kept, discarded), and value (price); fishing location; landing port and dealer location; gear type, amount, and use (duration of fishing effort); FMP and exemption program; and vessel costs.

All FDD submitted to regulatory entities (e.g., state and federal agencies) are confidential by law unless the submitter authorizes the sharing of such information. Confidentiality protection requirements could limit FDD availability for analysis at fine spatial or temporal scales. When sharing FDD with the public, care must be taken to protect the privacy of data submitted by individual vessels and businesses. Individual fishermen or vertically-integrated fishing companies, however, are able to grant access to their confidential data as they see fit (e.g., FKT [RODA 2022]). Typically, FDD are grouped to ensure a minimum of 3 vessels, dealers, or harvesters are included in the data sets made available for public use. This results in the loss of some spatial or temporal resolution in order to maintain confidentiality. Some sources of FDD (e.g., VTRs, dealer reports) were originally developed for broad-scale fishery management purposes and are not well suited to examine fishery dynamics at a finer scale, which limits the spatial resolution of such FDD sources. For example, catch limits are set across a stock area with regulators focused less on the precise location of catch and more on restricting catch of that species within any one stock area. As a result, reporting by commercial fishermen is only required at the statistical area level. Further, because the MRIP only asks whether fishing occurred inshore or offshore, very little spatial information exists for private angler fishing activity.

3.1.1.1 Types of FDD

The strengths and limitations of FDD in the Northeast U.S. vary with the source (Table 10). For fisheries that operate in federal waters (greater than 3 miles from shore), a VTR is required for each fishing trip. However, only the statistical area (each representing 300-10,000+ mi^2) and 1 geographic position per trip must be reported on each VTR; a new VTR must be completed whenever the vessel changes the statistical area where they are fishing or changes gear type, mesh or ring size on the trip. This limits the sub-trip resolution. Dealer data are the only source for revenue information for commercial fishing trips. Dealer reports also contain descriptions of landings, associated price, and resulting revenue but do not collect operational information, such as gear used, area fished, and effort. As a result, several FDD sources are needed to describe the full operations of a particular commercial fishing trip.

VMS is a satellite surveillance system used to monitor the location and movement of commercial fishing vessels in U.S. waters. VMS reports vessel locations every 30 to 60 minutes, depending on the fishery, and speed/direction of the vessel can be calculated by comparing positions, providing more precise information on where fishing is occurring. However, it can be difficult to distinguish between fishing and transit activity using VMS position data without making assumptions based on vessel speed and course (Muench et al. 2018; Palmer and Wigley 2009; see Table 10 for strengths and limitations). Based on information from the fishing industry, the speed of an actively fishing vessel is assumed to be approximately 5 knots or less. However, it is highly likely that other activities occurring at low speeds (e.g., processing catch, idling, gear repair) are attributed to active fishing because they're occurring below a set speed threshold. There are limitations to accurately estimating fishing time or location because assumptions regarding speed and direction are affected by factors such as weather, sea state, mechanical issues (Watson and Haynie 2016). Some fishing vessels may also use gear sensors that can provide greater detail on fishing activity, but this information is not readily available to researchers or managers. Some fisheries are not required to use VMS, resulting in variable VMS coverage of landings for fisheries in the New England and Mid-Atlantic regions (Table 11). However, because vessels may have VMS on board as a requirement of other fisheries for which they are permitted, overall coverage is increasing over time.

Vessels using VMS are required to make a declaration of trip intent (targeted fishery, management area, gear type to be used), allowing for an evaluation of fishing operations in various fisheries, areas, and gear types. However, trips by vessels participating in a fishery without VMS requirements (summer flounder/fluke, scup, black sea bass, bluefish, American lobster, spiny dogfish, skate, whiting, and tilefish) are difficult to differentiate. This is because such trips must declare out of a fishery (DOF) managed by DAS (e.g., Northeast multispecies, scallops, and monkfish) and are grouped together under the general "DOF" trip category. Despite the declaration of intent, there can be a disconnect between a vessel's intended and realized activities, with vessels declaring into one fishery but landing more of a different species. VMS represents a shorter time series, compared to VTR and dealer data, having gradually been implemented in several fisheries over time (NMFS Information Needs [NMFS 2021c]). Although VMS is mostly used for positional data, limited catch data exists for some target and bycatch species. Unlike the NEFSC Study Fleet data, there is no tow- or haul-level data, although daily catch amounts are reported in some fisheries.

Observer data provide more detailed information on fishing effort, including precise fishing area (start and end of an observed tow) information, species caught (e.g., identification, size, sex, weight, number), and disposition of the catch (amount kept or discarded). Table 10 highlights the strengths and limitations of this data source relative to wind energy research. Observer data is supplied by multiple programs, including NEFOP, at-sea monitoring (ASM), Industry-Funded Scallop (IFS); dockside monitoring (DSM), and electronic monitoring (EM) programs involving fixed cameras on vessels. The NEFOP program focuses on vessels operating from Maine to North Carolina that target all federally managed species, while certain programs focus on different fisheries. For example, ASM focuses on monitoring groundfish catch, while IFS focuses solely on scallop trips. Further, EM of vessel operations and DSM of vessel offloads are available for the groundfish and herring fisheries. NEFOP coverage, and observer coverage in general, is variable and can be low, as determined by management needs and budget (Wigley et al. 2007; Ardini et al. 2020). NEFOP coverage is driven by the Standardized Bycatch Reporting Methodology, which is set annually based on bycatch rates (NMFS 2022). For example, the surfclam/ocean quahog fishery has minimal coverage in most years because of their low level of bycatch. The presence of an observer or ASM may change the behavior of the vessel operator and bias data in some fisheries (Ardini et al. 2020). An example of an observer or ASM affecting a trip would be if a small vessel, selected for observer coverage, shortens a trip because of a lack of beds on the vessel. Fishermen operating in mixed fisheries may also alter their fishing plans in order to drastically minimize the risk of interaction with quota-limiting stocks when an observer or ASM is onboard or if the vessel is subject to EM with full catch retention or DSM (NEFMC 2019). EM uses cameras to collect FDD on landings and discards. FDD collected via EM can be used for quota monitoring and to support stock assessments. Fishermen are concerned with reduced privacy on vessels with the potential for cameras to record all activities. NOAA Fisheries is establishing EM policies and national guidance on issues such as cost allocation and data retention requirements, which can impact the cost of EM (NOAA 2022h.

Cooperative research programs, such as study fleets (e.g. Northeast Fisheries Science Center's Study Fleet [NOAA 2022f]) and research fleets, provide the finest-scale FDD available, including precise fishing area (tow tracks) and catch data (retained and discarded species and quantities) for individual fishing efforts. Data collected through these programs are self-reported by collaborating fishermen and have been demonstrated as reliable and accurate (Roman et al. 2011; Nedreaas et al. 2006; Bastille 2019; Mion et al. 2015; Bell et al. 2017; Steins et al. 2020). Sampling frames of these programs differ from observer data in that observers sample trips based on a planned pattern whereas the study and research fleets provide a longitudinal sample (i.e., sampling the same vessel[s] at different points in time) of a vessel's fishing pattern (Jones et al. 2022; Mercer et al. 2018). Similar to observer data, however, study fleet and research fleet data have variable coverage within different fisheries. The shortfin squid, longfin squid, haddock, and summer flounder fisheries have high NMFS Study Fleet data coverage, whereas the American lobster and scallop fisheries have little to no coverage (Jones et al. 2022). Fleets with low coverage in study fleet, however, frequently participate in other industry-based environmental monitoring programs (e.g., eMOLT; Manning and Pelletier 2009; Van Vranken et al. 2020) and other cooperative research projects (e.g., University of Massachusetts Dartmouth School for Marine Science and Technology (SMAST) yellowtail flounder and river herring bycatch avoidance programs; Turner et al. 2017; Roundtree et al. 2004). The Commercial Fisheries Research Foundation supports several research fleets, which focus on the American lobster, Jonah crab, black sea bass, and scallop fisheries (Mercer et al. 2018).

Traditional ecological knowledge can be very difficult to access as it is labor intensive. One approach to analyze fisheries issues is to use RODA's FKT. The FKT is the first industry-owned platform where fishermen can aggregate, secure, and share the knowledge they collect about our oceans into a standardized, accessible repository (Responsible Offshore Development Alliance 2021). The FKT will enable regulators, fishermen, and consumers for the first time to access the real-time, first-hand knowledge they need to adapt to our rapidly changing world. Regulatory efforts have struggled to describe fishing practices with the detail required to evaluate potential tradeoffs and mitigate competing ecosystem uses related to offshore energy development. By using individual data queries and spatial data sets, this project can produce maps and reports to show fishing spatial needs and generate data products to better communicate the science and understanding of the ecosystem. The key to the FKT is the access of fishermen's knowledge of ecological and social ecosystems to fully understand the data. The FKT is currently conducting a pilot project on the herring and surfclam/ocean quahog fisheries, which will be used to stand up the FKT.

The AIS is a "shipboard broadcast system that acts like a transponder, operating in the VHF maritime band, that is capable of handling well over 4,500 reports per minute and updates as often as every two seconds (USCG 2022)." The AIS database doesn't cover the entire commercial fishing fleet because it is not required to be installed on vessels less than 65 ft in length. For larger vessels with AIS installed, the VHF signal (dependent on line of sight) may be variable depending on the conditions. Vessels are allowed to deactivate their AIS transponders when farther than 12 miles offshore, potentially limiting its geographic coverage. AIS requirements began on March 1, 2016, limiting the time series available. AIS only includes vessel identity and geographic position, so it does not fully describe key trip attributes. Figure 13 depicts the data points available to each FDD source compared to the actual track taken by the fishing vessel.

3.1.1.2 Current Usage of FDD

FDD has a wide range of applications, which to date has largely focused on fisheries science and management. The components of FDD make it an essential source of fisheries data for quota monitoring, stock assessments, ecosystem-based science, and fishery action analysis. FDD is also currently used for protected species interaction monitoring and for data requests (Congressional, NOAA, and public). FDD and fishery independent data (FID; see Section 3.2) have been used in Europe to assist in the identification of essential habitat for 3 elasmobranch species and were determined to provide similar spatial patterns (Pennino et al. 2016). The authors noted FID was better at identifying the location of species; however, FDD was better at predicting when species would be present or absent. In the U.S., both FID and FDD are frequently used together to assess fish availability and abundance and help inform fisheries management decisions and habitat designations. Recently, FDD are also being used to evaluate potential impacts from OSW, as detailed below.

FDD has been used in early/existing evaluations of proposed wind development projects to identify species caught, gear used, revenue exposure, area fished, transit direction, and communities affected. NOAA Fisheries developed a tool examining the socioeconomic impacts of Atlantic offshore wind development (NOAA 2022g). The tool provides summary reports for fishing activity within the Atlantic lease areas. The data used come from commercial and party/charter fishery VTRs, surfclam/ocean quahog logbooks, and dealer reports (see Section 2.2 for additional information). The methodology developed for the summaries is based on the fishing footprint approach (DePiper 2014; Benjamin et al. 2018) to estimate landings and revenues within a particular lease area.

VTR data, in combination with dealer revenue data, has been used to estimate revenues previously generated in WEAs (for an example see South Fork Wind Farm DEIS; NOAA 2021c; Kirkpatrick et al. 2017). Notwithstanding the limitations discussed above, this can help form the basis of impacts analyses investigating potential lost revenues if fishing is excluded or displaced from the WEA by fishery (Table 12). These data can be broken down by gear type and port, providing insight into community-level impacts if fishing grounds were lost. Such data can also identify which communities will be affected and should be consulted to minimize impacts of these projects.

Polar histograms of VMS data have been used to describe the directionality of VMS-enabled vessels operating in all wind energy lease and project areas (e.g., South Fork Wind Farm DEIS in Figure 14). The trends in the direction of fishing and transiting activity based on VMS data along with the number of trips or vessels operating in each direction can help inform decisions on turbine orientation and spacing.

3.1.2 Description of the state of our knowledge on this topic with regard to interactions with offshore wind

3.1.2.1 Limitations of FDD

Availability of FDD is contingent on the ability of fishing to occur. The strength of FDD to inform scientific, management, and permitting questions is derived in part from the large volume of data being generated. If fishing activities are hindered by the presence of OSWs (or altered by changes to local ecology resulting from offshore wind) or management restriction, less FDD are available, and the sufficiency of information needed to inform scientific, management, and permitting decisions is impaired. More specifically, fishing location area resolution, reporting frequency, gear deployment, and effort metrics (time fishing vs. transit time) may all be affected by OSW. Analysis is further limited because of data system designs, which are not well integrated. This has resulted in challenges to answer specific research questions, such as overlaps with OSWs.

FDD are susceptible to biases resulting in fishing vessels avoiding areas with obstructions, (e.g., natural structures or fixed gear). A number of fisheries are executed using mobile bottom tending gear (MBTG; e.g. fish trawls and scallop or clam dredges), which are at risk of hanging up on structure while towing. The presence of scour or cable protection, in the form of large rocks or concrete mattresses, may discourage vessels from operating on or near (within 0.25-0.5 miles) of these protection methods. This will contribute to vessels changing their behavior at sea if, for example, they shorten tow length or change fishing location to avoid cables or turbines. These changes will exacerbate the biases caused by vessels avoiding structures, which may affect usage (Maunder and Punt 2004).

As noted above, the accuracy and precision of area fished as reported in FDD data can be variable. There are concerns that there may be underreporting of statistical areas fished on a trip when a vessel fishes in multiple statistical areas (Palmer and Wigley 2009). Palmer and Wigley (2009) developed a VMS algorithm to estimate locations of fishing activity. Their comparison of VMS- and VTR-based methods for allocating stock area provided similar results; however, the minor discrepancies were considered to have larger impacts on less abundant stocks.

There may not be 100% coverage in every fishery for VTRs, affecting its representativeness. For example, the federal Atlantic lobster fishery has variable coverage of landings based on VTRs submitted by state (Table 14). This may underestimate the lobster fishing activity, and any summary statistics based on this FDD source, for any state with low VTR coverage. Another gap in FDD is the lack of information regarding private anglers. A number of research projects are currently focused on FDD and OSW (Table 13).

3.1.3 The major gaps in our knowledge

There are some concerns over the accuracy, completeness, and precision of fishing location data. VTRs are also self-reported, which may raise concern over their accuracy, particularly regarding fishing location. VTR data are limited to statistical area, which is a large area (each representing 300-10,000+ mi^2), with only 1 position reported per trip and catch reported on a trip and sub-trip level. Reporting catch at the tow or haul level would provide a higher resolution of fishing location linked with resulting catch, but such reporting is burdensome to operators. DePiper (2014) analyzed the precision of self-reported VTR fishing locations using VTR and observer data at the trip level, concluding that gear type and length of the fishing trip could impact the spatial precision of VTRs; the longer the trip, the less likely a 10-minute square centered on the location reported on the VTR adequately represents the footprint of the trip. Benjamin et al. (2018) provide information on improving the spatial representation of VTR fishing locations. Their collective work helped create a data set that described the spatial data statistically as opposed to as point locations. This work has been integrated into recent efforts to "model" fishing locations from VTRs, which are then linked to dealer data to describe fishing effort and resulting revenue at smaller scales, such as within a wind project.

A number of research questions are still outstanding for FDD including ensuring catch or fishing effort can be more effectively linked to economic impacts. As discussed above, verification of area fished could help improve spatial accuracy, while increased area precision could improve spatial resolution. Efforts to improve these deficiencies could include alternative documentation of area fished through automation and indirect reporting (collecting from non-fishing entities, such as VMS providers, AIS, cellular services, and other vessel/position tracking technology). An audit of the cost of data reporting and limits of existing technology would also be beneficial. Finally, information on shoreside support services, including fish processors, shippers, equipment suppliers and maintenance services, is needed to provide a more comprehensive evaluation of socioeconomic impacts to fishing communities (see Section 2.2.5 for discussion of support businesses).

3.1.4 Characterization of the perspectives of commercial and recreational fishing communities

The fishing industry has been proactive in providing answers to questions by participating in cooperative research. The Northeast and Mid-Atlantic Ocean Data Portals recently partnered with RODA to update their fisheries products. The final report summarizes the data that are housed on the Portals, the process for engaging the commercial fishing industry, and the feedback from the industry on potential improvements and updates (RODA 2020b). RODA's FKT is a fishing industry-owned and managed integrated knowledge and database infrastructure that could be used to identify research needs and develop and analyze hypotheses. The FKT could also be used to evaluate potential interactions of offshore wind energy development with the key socio-ecological and management dimensions of fisheries to identify early strategies for conflict reduction.

The Science Center for Marine Fisheries (SCeMFiS) is a National Science Foundation Industry/University Cooperative Research Center that "utilizes academic, recreational and commercial fishery resources to address presently urgent and emerging scientific problems that could limit sustainable fisheries." SCeMFiS has conducted a number of research projects including those focused on OSW impacts, e.g., impacts to the Mid-Atlantic Cold Pool (Miles et al. 2020) and a review of the Vineyard Wind Supplement to the DEIS (Powell et al. 2020).

The fishing industry is concerned about the changes to the ecosystem resulting from the installation of turbines (Section 1), loss of access to offshore wind areas and other socioeconomic impacts (Section 2), and especially the impacts to fisheries management and supporting processes, such as fishery independent surveys and stock assessments (Section 3). Cumulatively, these changes have the potential to impact the status quo of fisheries in the Northeast United States, as well as other regions or countries, particularly in Europe where fishing has been excluded from offshore wind areas (except in the U.K.) and, therefore, the generation of FDD. Ultimately, the fishing industry is concerned about whether they will continue to fish, and how impacts to fishing effort will affect FDD data generation and its use for understanding our marine ecosystems.

3.1.5 Recommendations for future directions/studies

The following recommendations were based on input received during the October 2020 Synthesis of the Science Workshop and subsequent consultations with authors and reviewers of this report. Further discussions on research needs are ongoing in a number of fora, including those coordinated by ROSA and state/federal agencies.

- Improving access to confidential FDD by non-federal scientists. Possible solutions: FKT, Ocean Data Portals, Marine Cadastre/Ocean Reports.
- Improving the spatial and temporal resolution of FDD, including VTR, VMS, or other sources, to better understand fisheries behavior (where and when fishing occurs) and needs, in relation to OSW and other offshore development.
- Discuss and address impacts on FDD collection, and subsequent analyses, resulting from changes in fishing patterns and overall activity if fishing patterns change because of avoidance of OSW areas by mobile bottom tending gear (MBTG) or attraction to these areas by recreational or fixed gear fisheries. Response to changes is expected to vary by gear type, with MBTG more vulnerable to negative interactions compared to fixed gear.
- Examine the different scales and types of FDD submitted by various fisheries (e.g., lobster FDD has been very limited to date, but recent regulatory changes will increase data available) and fishery/gear type (e.g., VMS and AIS data are submitted by larger vessels fishing in more established VMS fisheries, like scallops).
- Explore alternative metrics of economic impacts beyond ex-vessel value (e.g., “multiplier” study from SCEMFIS [Scheld 2020], IMPLAN model [Kirkley 2009]) .
- Expand investigations into data related to support businesses for fisheries. Fishery impacts are more than just exclusion of F/Vs from fishing areas due to wind project development to include processors, markets, gear makers, welders, electronics, and mechanics, and maintainence of shoreside support and port access.
- Centralized database of ongoing research projects, including details of scope and timelines, to reduce redundancies and increase collaboration among researchers.

3.2 Interactions of Offshore Wind on Federal Fisheries Independent Surveys

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3.2.1 Introduction

NOAA Fisheries uses FID surveys to support the nation's living marine resources and specifically to meet responsibilities authorized by the Marine Mammal Protection Act, the ESA, the MSA, and several other laws and polices. These surveys provide data on the abundance, distribution, and vital rates of marine animals and marine habitat information over time. In the Northeast region, these surveys include multi-species bottom trawl surveys, Atlantic scallop surveys, ocean quahog and Atlantic surf clam surveys, ecosystem monitoring surveys, marine mammal and sea turtle ship-based and aerial surveys, apex predator surveys, Gulf of Maine Northern Shrimp and cooperative bottom long-line surveys, and North Atlantic right whale aerial surveys. These surveys conducted out of the Northeast region span from Maine to Florida. These surveys use a statistical design to calculate estimates of abundance and biomass as well as associated uncertainties (margin of error). The goal of these surveys is to sample over a broad geographic area so as to capture the spatial and temporal extent of target species and populations.

Data from these surveys form time series that can be used to evaluate the trends in abundance of marine animals over years and decades. The surveys in the Northeast U.S. are some of the longest marine time series in the world, and the region is recognized by the global scientific community as one of the best understood marine ecosystems (NOAA 2021c). Additionally, data collected through these surveys provide the foundation for critical stock assessments for fisheries, marine mammals, and other NOAA living trust resources.

Offshore wind energy development impacts surveys in 4 ways (BOEM 2021):

(1) **Preclusion** – The developments preclude safe operations of survey vessels and aircraft because of the presence of wind turbines and connecting electrical cables.
(2) **Habitat changes** – The wind turbines and electrical cables alter habitat, which may affect the distribution, abundance, and vital rates of marine animals. If these changes are significant and are not observed through scientifically robust monitoring, resulting survey indices could become biased and impact fisheries managers' ability to accurately monitor stock status.

(3) **Changes in statistical design** – Many NOAA surveys are based on a stratified random statistical design that will be disrupted by wind development; fixed station and transect designs may also be impacted.
(4) **Reduced sampling productivity** – Navigation impacts of wind infrastructure can decrease the ability to collect data that are already limited by annual sea day allocations by increasing vessel transit times between stations and reducing the amount of area that can be sampled.

3.2.1.1 Preclusion

Preclusion occurs in at least 3 ways:

(1) The turbines are spaced too closely and the blades too close to the water's surface to allow NOAA vessels to work safely in wind energy developments.
(2) The electrical cables between turbines and to shore preclude use of many types of survey gear (e.g., bottom trawls, bottom dredges).
(3) The height of the turbines affect the safe working distance of aircraft surveys, meaning surveys will need to fly at higher altitudes, thereby decreasing the detectability of the animals being surveyed. Moreover, low cloud ceilings could completely exclude aerial surveys in the vicinity of turbines, as the ability to safely operate below cloud ceilings can be restricted by turbine heights.

3.2.1.2 Habitat Changes

Federal surveys need to be adapted to address habitat changes that will stem from offshore wind energy development. Turbines and their foundations may create artificial reefs, which could attract some species and displace others (Degraer et al. 2020a). Other habitat alteration effects—including ocean noise from engineering surveys, construction and operation; EMFs from submarine cables, and changes in oceanographic conditions—also have the potential to change the distribution, abundance, and vital rates of some NOAA trust species (Methratta et al. 2020). Changes in habitat structure and distribution will impact availability of different species to federal surveys, thereby reducing accuracy and reliability of population estimates, and thus increasing uncertainty in management advice and legal risk associated therewith. Finally, several federal surveys are stratified by habitat type. The changes in habitat that will stem from offshore wind energy development will require surveys to be re-stratified, which impacts continuity and interpretability of survey time series. Wind energy developments affect areas broader than the developments themselves. In the North Sea, impacts have been described to occur at distances beyond 20 km of the wind development area (Slavik et al. 2019).

3.2.1.3 Changes in Statistical Design

Many NOAA surveys are based on a stratified random statistical design that will be disrupted by the presence of wind turbines. Even if NOAA ships could safely operate and deploy survey gear within wind development arrays, modifications to the statistical design of the surveys would be required. If these changes are not made, it would violate random sampling assumptions and thus the integrity of data collected with downstream consequences for fisheries stock assessments, catch advice, and population assessments of other NOAA trust resources, such as marine mammals, sea turtles, and other species.

3.2.1.4 Reduced Survey Efficiencies

The cumulative effects of wind developments can also reduce sampling efficiency of existing survey operations. Large fields of wind turbines, as currently planned, are likely to increase transit times of NOAA ships and other survey vessels, as they will be unable to transit through turbine areas to sample areas adjacent to wind arrays. These lost efficiencies would be compounded by adverse weather conditions. In addition, the presence of many offshore wind projects may cause displacement and changes in fishing operations, such as an increase in either fixed fishing gear or recreational fishing effort adjacent to these areas (Gill et al. 2020a). These changes would further decrease the ability to operate and sample adjacent to wind developments. Any increases in transit time between sampling stations or reductions in sampling efficiency due to increased interactions with fishing gear will further reduce the amount of data gathered by these surveys for use in species and ecosystem assessments, further increasing uncertainty in scientific advice.

3.2.1.5 Consequences of Federal Survey Impacts

By disrupting NOAA Fisheries survey programs and the advice that depends upon them, regional wind development will result in major adverse impacts on U.S. fisheries stakeholders, including fishermen and fishing communities, and the American public who consume American seafood and who also expect the recovery and conservation of endangered species and marine mammals. The impacts on survey programs will lead to greater uncertainty in estimates of abundance, which, through the application of the precautionary approach, will likely lead to lower fishery quotas, ultimately resulting in lost revenue to commercial and recreational fishermen (BOEM 2021).

In the Northeast region, if scientific survey mitigation is not prioritized, significant impacts are likely on commercial and recreational fisheries, which provide $17.5 billion and $2.6 billion, respectively, values added to the region’s economy (NMFS 2021b). Impacts on survey programs will also likely lead to greater uncertainty in protected species assessments, which will lead to impacts on a number of ocean use sectors, including shipping, energy exploration and development, and fishermen. Federal agencies engaged in ESA or marine mammal consultations on projects will be harmed, as managers would likely need to include more precautionary mitigation measures in the Incidental Take Statements of ESA Biological Opinions. Private industry and other applicants for Marine Mammal Protection Act Incidental Take Authorizations for any in-water activity that has the potential to take marine mammals could also be impacted, as managers would need to impose more stringent permitting limits. Moreover, owing to the long time series of these surveys in the U.S. (60+ years), the data are fundamental to understanding and mitigating the effects of climate change on marine resources. Disruption of these surveys decreases the ability to understand and mitigate the effects of climate change, which could impact the American public.

In summary, exclusion of fisheries and ecosystem surveys from wind energy areas and unmeasured effects of habitat alterations will lead to greater uncertainty in a survey’s measure of abundance. Fisheries management uses a precautionary approach, whereby in the face of uncertainty precaution is taken on behalf of the harvested animals. This approach supports the U.S. goal of building and maintaining sustainable fisheries. Based on the precautionary approach, regional Fishery Management Councils have processes and risk policies that would likely translate greater survey uncertainty into lower fisheries quotas, thereby decreasing fishing revenue and negatively impacting fishing communities and the coastal economy (e.g., MAFMC 2020; NEFMC 2021). Reduced domestic landings due to increased scientific uncertainty may affect our ability to minimize adverse economic impacts and provide for the sustained participation of fishing communities in our region’s important fisheries, as required by the MSA. There are more than 170 fishing communities from Maine to North Carolina, and the impacts would be broad but varied across fisheries and communities (Colburn et al. 2010). Further, reductions in domestic supply could increase demand for foreign sources where fisheries management is not as robust and fisheries are not as sustainable.

Finally, data from long-standing surveys are critical to ensure management is informed of and can respond to changes in resource abundance, distribution, and condition. For example, survey data are used to inform the development of Essential Fish Habitat designations for federally managed species, which form the basis for U.S. MSA consultation authority. The loss of valuable survey data may result in a reduction of the best scientific information available to support U.S. MSA management responsibilities (BOEM 2021).

3.2.2 State of our Knowledge

Offshore wind energy development, which is a subset of a broad approach to spatially partition marine space and subsequently allow specific uses, is relatively new across the continental shelf and adjacent waters of the United States (Stelzenmüller et al. 2013). With the expected overlap between offshore wind energy development sites and fisheries resources that span numerous taxa, jurisdictions, and management authorities, the ultimate impact is expected to be both variable and uncertain. Given the novel nature of OSW in the United States, there is very little existing research or literature that speaks to the impact of offshore wind energy development on our ability to monitor, assess, and manage fish stocks. Initial explorations of spatial overlap between fisheries surveys and offshore wind energy development in the Northeast region are provided in Figure 15 and also reported in Methratta et al. (2020). Further detail regarding the federal surveys that will be impacted by offshore wind energy development in the northeastern United States is provided in Table 15.

In 2021, the NEFSC, in partnership with BOEM, began a research initiative to evaluate the impact of offshore wind energy development on the NEFSC’s Bottom Trawl Survey. This project includes the development of a spatial observation simulation model for the Northeast Bottom Trawl Survey that is capable of evaluating the efficacy and statistical properties of changes to survey design and also assess the performance of alternative methods for monitoring species distribution, abundance, and trends. The simulator is expected to form the basis of an eventual Management Strategy Evaluation for a key set of Northeast U.S. fish stocks to evaluate expected changes in fishery performance that result from spatial reductions in scientific survey coverage due to proposed wind energy installations along the U.S. East Coast and to assess the efficacy of supplemental monitoring efforts.

In summary, the research enterprise consisting of federal, state, and cooperative (in conjunction with the fishing industry) surveys supplies a wealth of annual information on fisheries resources and the environment in which they exist (Table 15). Removal or significant modification to the scope and geographic scale of these established efforts will represent a critical challenge to our ability to assess and manage marine species. For some specific surveys, the impact is potentially great with significant downstream impacts to fisheries and protected resources management.

3.2.3 Major Gaps in our Knowledge

The body of knowledge and literature surrounding the impact of offshore wind energy development on fisheries surveys is extremely limited. Methratta et al. (2020) and BOEM (2021b) are 2 of the few publications that exist to cover this topic specifically. The recently established (2020) International Council on the Exploration of the Sea's Working Group on Offshore Wind Development and Fisheries also focuses on the science of data collection effects from OSW. Based on this group's terms of reference, upcoming methods publications on this topic by ICES are anticipated in 2022/2023. Thus, nearly every facet of this topic represents a gap in our knowledge. Specific gaps in knowledge include: (1) best practices for adapting survey design and methodology within and around areas developed for offshore wind energy production (e.g., gear designs, vessel requirements, re-stratification); (2) approaches for accounting for differences in species distribution, abundance, and vital rates inside and outside wind energy areas on stock assessments, in fisheries management, and in the conservation and recovery of protected species; (3) quantification of stock assessment impacts (e.g., increased uncertainty, decreased ability to detect spatio-temporal trends) resulting from survey exclusion or alteration due to offshore wind energy development; and (4) quantification of changes in habitat as a result of offshore wind energy development and downstream effect on availability of species to surveys.

3.2.4 Characterization of the perspectives of commercial and recreational fishing communities on fisheries independent surveys and offshore wind

Commercial and recreational fishing representatives should be included in all aspects of planning of offshore development and management, including survey adaptation and execution. Cooperative solutions benefit from the participation of all subject matter experts, i.e., scientists, managers, and fishing industry members. A number of efforts have recognized the need for inclusivity in addressing issues.

RODA was established in order to represent the fishing industry as ocean usage expands with commercial development, i.e., aquaculture and OSW. RODA is a coalition of fishery-dependent companies, associations, and community members committed to improving the compatibility of new offshore development with their businesses. RODA also works towards a science-based approach to offshore development.

ROSA focuses on improving the knowledge and understanding of the interactions of OSW and fisheries to improve compatibility of these 2 industries. ROSA is a cooperative effort among offshore wind developers, fisheries managers, fishery scientists, and fishermen. Its main objectives include: identifying regional research and monitoring needs, coordinating existing research and monitoring, advancing understanding through collaboration, partnerships, and cooperative research, administering research, improving access to scientific data, and sharing learnings.

The Northeast Area Monitoring and Assessment Program (NEAMAP) is a cooperative effort to provide FID primarily for fisheries management and stock assessments. This is achieved by a cooperative research program, focused on spring and fall surveys covering the area from Cape Cod, MA, to Cape Hatteras, NC (sampling at 150 stations). This is achieved through three coordinated efforts: the Massachusetts Division of Marine Fisheries Bottom Trawl Survey, the Maine/New Hampshire Inshore Trawl Survey, and the NEAMAP Southern New England/Mid-Atlantic Nearshore Trawl Survey. The nearshore survey is run by the Virginia Institute of Marine Science and is conducted with a commercial fishing vessel using gear that ensures compatibility with the NEFSC trawl survey.

The Northeast Trawl Advisory Panel (NTAP) is a joint advisory panel of the New England (NEFMC) and Mid-Atlantic Fishery Management Councils (MAFMC). Its members come from the commercial fishing industry, fisheries science, fishing gear engineering, and fishery management fields. The Panel's cooperative work on regional research survey performance and data outputs may contribute to the development of survey approaches in offshore wind energy areas and mitigation measures for minimizing the impact of offshore wind on existing surveys. NTAP's most recent research recommendation calls for an experimental evaluation of a standardized bottom trawl survey gear package using a restrictor rope. Initial research will focus on evaluating the impact of a restrictor rope on bottom trawl survey catch rate and composition. The results of this experiment can be used to inform the development of a standardized bottom trawl survey gear configuration for the purposes of sampling within wind energy areas and to inform future trawl survey calibrations. The NTAP is currently revising its charter (MAFMC 2021).

The NEFSC has a long running cooperative research program that relies on the fishing industry to conduct science and support fisheries management. The cooperative research program conducts fishery independent (e.g., Gulf of Maine cooperative bottom longline survey) and fishery dependent (e.g., study fleets) research. The fishery independent work is used to supplement the more extensive NEFSC Bottom Trawl Survey, especially for species that are known to not be well sampled by that survey. The GOM cooperative bottom longline survey can sample species that prefer rocky bottom, providing essential information for stock assessments of such species.

In addition to on-the-water collaboration for surveys, the fishing community holds critically important knowledge of fishing gear, which is key for development and refinement of survey protocols in the face of offshore wind energy development. Furthermore, members of the fishing industry can provide insight on changes in availability of species to surveys as a result of offshore wind, as they may continue fishing operations within wind energy areas that are not accessible to surveys. Overall, a key to adapting and mitigating the impact of offshore wind energy development on survey operation is engagement with and reliance on partners in the fishing industry.

3.2.5 Recommendations for future directions/studies

In order to address the major impacts and disruptions caused by OSW on scientific surveys and to avoid or minimize major impacts on fisheries and protected species management responsibilities, a comprehensive survey mitigation program should be established that would enable the United States to design and implement effective survey adaptations. Preliminary analyses of such a mitigation program are described in the Vineyard Wind 1 FEIS (BOEM 2021) and the 2022 Draft NOAA Fisheries and BOEM Federal Survey Mitigation Implementation Strategy-Northeast U.S. Region (Hare et al. 2022). A federal survey mitigation program that would be led by NOAA in partnership and collaboration through the participatory fisheries management and science process, as described, would include the following specific elements to address the adverse impacts caused by wind energy development on core recurring scientific surveys in the Northeast region:

(1) **Evaluate survey designs**: Evaluate and quantify effects and impacts of proposed project-related wind development activities on scientific survey operations and on provision of scientific advice to management.

    - (a) Advance modeling frameworks, such as Observation System Simulation Experiments and Management Strategy Evaluation.
    - (b) Analyses and evaluation of performance of new combinations of survey designs and methodologies on assessments and management advice.
    - (c) Engage members of the fishing community in review of alternative survey designs and expected/simulated impacts of offshore wind energy development on survey indices.

(2) **Identify and develop new survey approaches**: Evaluate or develop appropriate statistical designs, sampling protocols, and methods while determining if scientific data quality standards for the provision of management advice are maintained.

    - (a) Design new survey sampling approaches (e.g., platforms and gears) and survey methods for fish, shellfish, and protected species that can be applied outside, inside, or both inside/outside wind energy areas. New survey approaches would seek to quantify regional-wide species abundance and distribution, provide insight into the cumulative impact of offshore wind energy development, and account for potential offshore wind habitat effects on species composition, abundance, and biological rates.
    - (b) Within the context of developing and implementing a northeast federal survey mitigation program as identified in Hare et al. (2022) and based on existing technologies and operational experience, the following survey methods should be prioritized for evaluation and, if warranted, for immediate implementation in the Northeast region as survey adaptation solutions need to be established in advance of imminent wind energy development:

        - i. Integrated shellfish surveys for Atlantic scallop, ocean quahog, and surfclams. These efforts should assess use of industry vessels and modified sampling gear capable of sampling within wind development arrays, including modified clam dredge gear, autonomous underwater vehicle with integrated habcam, and associated instrumentation.
        - ii. Development of standardized bottom trawl survey package for use among multiple industry vessels (based upon NEAMAP gear package); evaluate effect of restrictor cables, doors, and vessel horsepower on gear performance and efficiency.
        - iii. Development of recreational hook survey and fixed-gear fish trap surveys, including remote sensing video imagery in order to address needed monitoring of new reef-like habitats associated with wind turbine structures. These surveys should be designed to be consistent with protocols and methods previously established for the Southern California Shelf Rockfish Hook and Line Survey and the Southeast Ecosystem Assessment and Monitoring Program’s Reef fish trap survey. Evaluation should include power analyses of sample size and identification of necessary calibration experiments among hook

survey, Southeast Fish Trap Survey, and Maine Center for Coastal Fisheries Jig Survey. Design and evaluate a chevron fish trap and video survey, including power analysis of sample size and calibration experiments among hook survey, ventless trap surveys, and southeast Fish Trap Survey.

iv. Development of an industry-based ecosystem monitoring survey to continue to perform shelf-wide oceanographic surveys on vessels capable of sampling within wind development areas and to include the design, evaluation, and development of eDNA sampling relative to ongoing trawl surveys.

v. Evaluation of modifications to and applications of adaptation strategies for HMS core surveys anticipated to be impacted by OSW, including enhancing the use of telemetry and tagging studies.

vi. Evaluation of modifications to and application of adaptation strategies for expanding the Gulf of Maine Cooperative Bottom Longline survey for deployment in future research lease areas and BOEM wind energy planning areas to be established.

vii. Evaluation of modifications to and application of adaptation strategies for addressing impacts to the Northern Shrimp Survey, including the additional development of industry-based survey calibrated to the NEFSC Northern Shrimp Survey, for deployment in future wind energy planning areas to be established.

(c) Advance survey adaptation plans that address time series integration and methods for calibrating new approaches with traditional survey methods. New survey methods should also assess the needed sampling frequency, duration, and sample sizes necessary to address the anticipated impacts of OSW on existing surveys.

(d) Engage the fishing community and other fisheries partners in development of new survey designs and approaches, including through the establishment of external steering groups to advise and provide independent peer review for each of these design and methods activities.

(3) **Calibrate new survey approaches**: Design and carry out necessary calibrations and required monitoring standardization to ensure continuity, interoperability, precision, and accuracy of data collections.

(a) Implement survey adaptation plan requirements, such as the design and execution of necessary calibration experiments to allow observations from new sampling methodologies to inform fisheries management. The calibration experiments allow comparability of abundance indices generated from existing trawl surveys and new methodologies within wind lease areas to be combined for a synthetic time series of information about how the stock and its composition change over time. This is critical for accurate perceptions of the effects of commercial harvest on the stock and generating catch advice that ensures future harvest is sustainable.

(4) **Develop interim provisional survey indices:** Develop interim indices from existing data sets to partially bridge the gap in data quality and availability between pre-construction and operational periods while new approaches are being identified, tested, or calibrated.

   (a) Advance improvements in using FDD collections, such as improving CPUE indices from commercial fishing data, including enhancements in research study fleet data collections.
   (b) Integrating state and federal survey data in swept-area biomass estimates and geostatistical models.
   (c) Develop additional abundance indices with ichthyoplankton data.

(5) **Wind energy monitoring to fill regional scientific survey data needs**: Apply new statistical designs and carryout sampling methods to effectively mitigate survey impacts due to offshore wind activities for the 30+ year operational life span of offshore wind energy projects.

   (a) Based on survey adaptation plan requirements and standards, implement recurring new annual survey operations to sustain the accuracy and precision of scientific advice for assessments and management of trust species.
   (b) Engage members of the fishing industry in execution of new regional scientific surveys, including as platforms for surveys, as advisors on approaches, and as experts in the regular review of the performance of new surveys.

(6) **Develop and communicate new regional data systems:** New data collections will require new data management infrastructure, analysis, management, dissemination, and reporting systems. Changes to surveys and new approaches will require substantial collaboration with fishery management, fishing industry, scientific institutions, and other partners.

   (a) Coordinate and support enhancements to fisheries and protected species data management partnerships.
   (b) Make data from surveys readily available to researchers and the public in a timely and transparent manner. All data collected should follow Findability, Accessibility, Interoperability, and Reusability (FAIR) data standards (Wilkinson et al. 2016) and ensure all data is machine readable, documented, and publicly accessible following Public Access to Research Results (PARR) data principles.

3.3 Impacts of Offshore Wind Energy Development on Fisheries Management

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3.3.1 Introduction

This section addresses the potential impacts of offshore wind energy development on fisheries management. Examples are drawn from commercial and recreational fisheries which operate in federal waters in the Mid-Atlantic and New England; however, this section is meant to broadly apply to fisheries management throughout the United States in federal and state waters.

Most commercial and recreational fisheries that operate in federal waters are subject to the requirements of the MSA and must comply with multiple other applicable laws, including but not limited to the ESA, the Marine Mammal Protection Act, and the NEPA.[11]

The MSA was first passed in 1976 and established eight Regional Fishery Management Councils which are charged with preparing Fishery Management Plans for fisheries within their jurisdiction. It also specifies circumstances in which the National Marine Fisheries Service (NMFS) shall develop Fishery Management Plans, including for certain highly migratory species. Between the Councils and NMFS, over 461 fish stocks and stock complexes are managed under the requirements of the Magnuson Act (NOAA 2020).[12]

The MSA defines 10 National Standards for fishery conservation and management. All fisheries managed by a Regional Fishery Management Council or NMFS must comply with these national standards. As shown in Table 16, the National Standards lay out potentially competing priorities, such as preventing overfishing, minimizing bycatch, minimizing interactions with marine mammals and endangered and threatened species, as well as minimizing adverse economic impacts on fishing communities. To meet the multiple requirements of the MSA and other applicable laws, the Councils and NMFS use many different types of fishery management

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[11] Most commercially and recreationally important fisheries in federal waters are managed by the Regional Fisheries Management Councils or NMFS and are bound by the requirements of the MSA. Other important federal waters fisheries are managed by other entities, such as the Atlantic States Marine Fisheries Commission (e.g., American lobster and Jonah crab). Atlantic States Marine Fisheries Commission management operates under the Atlantic Coastal Fisheries Cooperative Management Act and Atlantic Striped Bass Conservation Act. Several species are jointly managed by the Atlantic States Marine Fisheries Commission and a Regional Fishery Management Council. Those jointly managed fisheries are subject to the requirements of both the MSAand the Atlantic Coastal Fisheries Cooperative Management Act.

[12] Many additional stocks beyond the 461 noted above are managed under the discretionary provisions of the MSA with management measures such as possession limits but not with the full suite of management measures required for stocks that fall under the required provisions of the Magnuson Act as “stocks in need of conservation and management.”

measures, such as catch limits, landings limits, possession limits, gear restrictions, fish size limits, open/closed seasons, gear restricted areas, closed areas, spawning time and/or area restrictions, bycatch limits, permit requirements, limited access programs, and allocation systems (e.g., allocations among commercial and recreational fisheries, among states, among individual participants in a commercial fishery, and/or among different spatial areas). Many or all of these measures are often used as a suite of measures to meet multiple management objectives for a single fish stock. Overall, federal fishery management plans must achieve optimum yield, a catch level that takes these multiple objectives into account. Optimum yield is defined as an amount of fish that will provide the greatest overall benefit to the nation, including food production, recreational opportunities, and protection of marine ecosystems. A group of measures are carefully monitored and adjusted over time to ensure that management objectives are being achieved on a continuing basis.

If fishing effort or behavior changes in response to offshore wind energy development, the effectiveness of the current fishery management programs in continuing to meet their many objectives should be evaluated. It will be important to understand how offshore wind energy development impacts who fishes where, when, with what gear, and for what species. These impacts will vary depending on the type of fishing activity (e.g., commercial vs. recreational; hook and line vs. mobile bottom tending gear vs. pot/trap gear), as well as the characteristics of each offshore wind energy project (e.g., location, foundation type, number of turbines, turbine array layout). These impacts could also vary based on species-specific considerations of how offshore wind energy development will impact the availability and behavior of target species. Changes in any of these factors could impact the effectiveness of fisheries management measures in meeting objectives such as preventing overfishing, achieving optimum yield, protecting habitat, and minimizing interactions with non-target species, marine mammals, and endangered and threatened species.

It will be challenging to both predict and evaluate how fishing effort or behavior will change in response to offshore wind energy development. Fishermen choose where to fish based on a number of factors, including but not limited to fishery management measures, availability of target species and species which should be avoided, distance to the intended port of landing, markets, and weather. If fishing effort is partially or fully displaced, either temporarily or over the longer term, fishermen may shift their effort into new areas or may adapt their fishing practices in other ways. These changes will not be straightforward to predict and may take years to observe and interpret. Available data on current fishing locations are limited in coverage and precision, and the degree of these limitations vary by type of fishery (e.g., commercial or recreational), gear type, and target species (Section 3.1). Therefore, predictions of the future spatial and temporal distribution of fishing effort will require assumptions about the current distribution.

3.3.2 Stock Assessments and Catch Limit Advice

The Councils have legal mandates to base their fishery management measures on the best scientific information available. Catch and landings limits for managed stocks are informed by peer reviewed stock assessments when possible. Fisheries-independent trawl surveys are often the primary data set used in stock assessment models, though most stock assessments use multiple data sets, including FDD. When a peer reviewed stock assessment is not available (e.g., due to data limitations or life history characteristics that are challenging to model), fisheries-independent surveys can be used as an index of relative abundance to inform catch limits. For especially data poor stocks, FDD can also be used as the basis for setting catch limits. For these reasons, any impacts of offshore wind energy development on FDD (Section 3.1) and FID (Section 3.2) could have important implications for the setting of catch limits for commercial and recreational fisheries. For example, if fisheries-independent surveys can no longer maintain the same level of sampling throughout their historical range, or if modifications to survey design and subsequent calibrations are required, then appropriate catch limits derived from these data may be more uncertain. As described below, when uncertainty increases, catch limits are generally reduced, which can have negative economic consequences for fishery participants and communities.

Changes in fishing effort resulting from offshore wind energy development, such as changes in the proportion of total catch from different gear types, or from commercial vs. recreational fisheries, will be important to quantify and account for in stock assessment models. For example, different gear types and fishing practices can have important differences in the size and age of fish caught (i.e., selectivity) and discard mortality rates. Stock assessments must accurately characterize these catch patterns in order to estimate biomass trends and provide robust catch limit advice.

Catch limits adopted by Regional Fishery Management Councils must be based on the best available science, and they cannot exceed the acceptable biological catch (ABC) recommendations of each council’s Scientific and Statistical Committee. The ABCs are set less than or equal to the overfishing limit to prevent overfishing while accounting for scientific uncertainty. The overfishing limit is the level of catch above which overfishing is occurring and is derived from a peer reviewed stock assessment when possible. Each council has adopted an ABC control rule and risk policy to guide their Scientific and Statistical Committee in accounting for scientific uncertainty when recommending ABCs. In general, the ABC control rules and risk policies specify that the buffer between the overfishing limit and the ABC should increase as stock biomass decreases below the target level and should also increase with increased uncertainty in the estimate of the overfishing limit.

For example, under the MAFMC’s ABC control rule, the Scientific and Statistical Committee typically applies a 60%, 100%, or 150% coefficient of variation (CV) to the point estimate of the overfishing limit, as derived from a stock assessment, to account for uncertainty in that estimate. A higher CV accounts for higher uncertainty and results in a greater buffer between the overfishing limit and the ABC (MAFMC 2020). The differences between these 3 CVs are not inconsequential for the resulting catch limits. For example, when biomass is at the target level, the ABC is set at 93% of the overfishing limit under a 60% CV, 90% of the overfishing limit with a 100% CV, and 87% of the overfishing limit with a 150% CV. Under an example overfishing limit of 1,000 mt, this can mean a difference of 30-130 mt of total allowable catch in a given year. The differences in the ABC under the 3 potential CVs are even greater when biomass is below the target level. In this way, scientific uncertainty can have meaningful consequences for stocks that are at or below their target biomass levels.[13] The ABC control rules and risk policies for other Councils differ in their details; however, they all include mechanisms to reduce the ABC under higher levels of scientific uncertainty.

The ABC applies to catch from all sources, including commercial and recreational fisheries, and targeted as well as incidental catch or bycatch of the stock. Thus, potential ABC reductions due to increased scientific uncertainty can impact all components of the fisheries. Lower catch limits can result in reduced commercial revenues, reduced revenues from party and charter recreational fishing trips, reduced angler satisfaction, reduced revenues for businesses that

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[13] The CVs have minimal impacts for stocks that are at least 150% above their target biomass levels because the MAFMC has accepted a higher level of risk of overfishing for very abundant stocks.

provide fishery support services (e.g., commercial fish dealers and processors, fish markets, fuel and ice suppliers, bait and tackle shops, marinas), and less domestic seafood production.

Efforts can be made to reduce scientific uncertainty in catch limit advice through sustained investments in monitoring, iterative improvements in the use of existing data, investments in new research to improve data collection, and stock assessment models. However, these improvements can be challenged by non-stationarity in fisheries production due to changing ecosystems, natural fluctuations in recruitment, food web dynamics, sudden increases or decreases in population size, and periodic interruptions in FID and FDD streams due to storms, mechanical issues with vessels, global pandemics, OSW, and other factors (Secor 2020).

Estimation of recruitment (i.e., the number of fish born within a set time period that survive to the juvenile life stage) is an important component of a stock assessment. OSW has the potential to impact spawning areas or seasons that may have long-term implications on recruitment success and overall stock health and, therefore, achievement of fishery management objectives. Spawning activities are vulnerable to disruption by noise and physical disturbances created by human activities, such as fishing practices and offshore wind construction.

3.3.3 Spatial Fishery Management Measures

The Councils and states use a variety of spatial management measures such as closed areas, gear restricted areas, exempted fishery areas, and rotational fishing areas to achieve various objectives, including protecting marine habitats, reducing fishing mortality on spawning or juvenile fish, reducing gear conflicts, and minimizing catch of non-target species. For example, as shown in Figure 16, the entire Exclusive Economic Zone off New England and the Mid-Atlantic is covered by spatial management measures adopted by the New England and Mid-Atlantic Fishery Management Councils. These spatial management measures do not prohibit all fishing; most are tailored to specific gear types, certain times of year, and/or catch of certain species. For example, commercial fishing vessels using small mesh bottom otter trawl gear are restricted by many of the spatial management measures shown in Figure 16; however, recreational anglers using hook and line gear are restricted in few, if any, of these areas.

Spatial management measures are revised over time to address changing management priorities and environmental and stock conditions. These measures are intended to balance conservation with fishery access and are therefore designed with existing fishing opportunities in mind. Thus, it will be important to take these existing spatial management measures into account when considering how the distribution of fishing effort might change in response to offshore wind energy development. Fishing effort will be temporarily displaced during the construction phase of offshore wind energy projects, and some fishing effort may be displaced over the longer term during the operational phase. Existing spatial fishery management measures will restrict where this displaced effort can go. Therefore, it may be prudent to review and potentially adjust existing spatial management measures to fully consider the effects of OSW on the ability to achieve optimum yield on a continuing basis.

Changes in the distribution of fishing effort, changes in fishing behavior, and changes in the distribution and behavior of target species resulting from offshore wind energy development may necessitate re-evaluation of the continued effectiveness of existing spatial fishery management measures in meeting their objectives, as well as consideration of the need for new or revised spatial management measures. For example, a spatial closure may no longer achieve the desired effect of minimizing fishing mortality if fishing effort shifts into other areas, resulting in an increase in total fishing mortality or concentration of fishing effort in an area of concern (e.g., a spawning area). Alternatively, if total fishing mortality decreases or if a gear type of concern is effectively excluded from an important area due to concerns about safe vessel operations within a turbine array, then some existing spatial fishery management measures may no longer be needed to constrain fishing mortality to acceptable levels or within certain areas. In addition, consideration of new spatial management measures to address gear conflicts may be needed if, for example, high recreational fishing effort near turbine foundations leads to conflicts between recreational and commercial gear types.

Revision of and implementation of new spatial fishery management measures is a complex and resource-intensive process. These types of measures can be controversial and often take multiple years to develop and evaluate. Furthermore, predicting the effects of these measures is also challenging and will become more difficult with potential changing fishery conditions and data streams described above.

3.3.4 Other Types of Fishery Regulations

The Councils and states use many other types of fishery management measures, including but not limited to gear restrictions, restrictions on the size of harvested fish, possession limits, allocations, and limited access programs to achieve various objectives, such as minimizing catch of juvenile fish, constraining total potential fishing effort, spreading fishing mortality throughout the year, and ensuring fair and equitable access to different fishery participants. Changes in fishing effort can impact the effectiveness of these management measures. As with the spatial fishery management measures discussed above, it will be essential to understand how fishing effort is impacted by offshore wind energy development so fishery managers can re-evaluate these measures and determine whether adjustments are needed.

For example, in some fisheries, the total allowable catch or landings is allocated between the commercial and recreational fishing sectors based on fixed allocation percentages. These allocation percentages are usually based on historical trends in the fisheries. Offshore wind energy development may have different impacts on commercial fishing effort compared to recreational fishing effort. If availability of target species remains similar or increases and recreational fishing effort increases but commercial fishing effort decreases near turbine foundations, this could impact the proportion of total catch or landings from the commercial sector compared to the recreational sector. Similarly, some commercial quotas are allocated among states, and offshore wind energy development may have different impacts on fisheries which land their catch in different states. If future proportions of catch or landings by sector or state differ from the existing allocation percentages, this may pose challenges for constraining each sector or state to their respective catch or landings limits, constraining total fishing effort to acceptable levels, and ensuring that fishery management measures remain fair and equitable to all types of fishery participants. As with spatial management, allocation of fishing privileges is often very controversial and often takes many years to develop and implement.

3.3.5 Protected Species

Protected species are those afforded protections under the Marine Mammal Protection Act and/or the ESA. The Councils, states, and NMFS must consider the impacts of the fisheries they manage on protected species. In some cases, fishery management measures, such as gear restrictions, are necessary to limit interactions between fisheries and protected species. Depending on the fishery, these measures are generally developed by NMFS through the Take Reduction Plan process. This can add a layer of management complexity when the agency developing the measures (i.e., NMFS) is not the agency responsible for the FMP for the fishery as a whole (e.g., the Regional Fishery Management Councils or Atlantic States Marine Fisheries Commission). Changes in commercial and recreational fishing patterns (in space, time, and gear type) can change the impacts of those fisheries on protected species and may change the effectiveness of existing fishery management measures in reducing interactions between fisheries and protected species. It will be essential to understand any shifts in fishing effort that may occur due to offshore wind energy development in order to evaluate how this may, in turn, impact fishery interactions with protected species. Potential changes in bycatch in commercial fisheries can be assessed by continuing fishery observer programs and the collection of fishing effort data. However, assessing effort and bycatch in recreational fisheries, which are not monitored through fisheries surveys, is challenging. It will also be important to measure shifts in gear types. Currently, this may be difficult as not all gear types are well monitored by observer coverage (e.g., pot or trap gear), and thus it may be challenging to assess any resulting changes in bycatch. Proactive efforts should be taken to determine changes in gear types and effort changes/shifts in commercial and recreational fisheries.

It will also be essential to evaluate how the abundance, behavior, and distribution of protected species themselves may change in response to offshore wind energy development. For example, the distribution, movement, or migration of marine mammals may be impacted by noise associated with installation of turbine foundations or changes in prey availability (Section 1.2). To predict how interactions between fisheries and protected species may change, it will be important to evaluate both changes in fishing effort and changes in protected species abundance, distribution, and behavior. It may be challenging to distinguish potential changes due to the development of wind projects compared to other climate or regulatory changes. Continued survey efforts at both broad and fine scales, especially in WEAs, are necessary.

3.3.6 Perspectives of Commercial and Recreational Fishery Participants

Commercial and recreational fishery participants hold diverse perspectives on offshore wind energy development. Many commercial fishermen are concerned about their ability to continue to safely operate in areas where they have traditionally fished and transited once wind turbine arrays are constructed and cables are laid. Many recreational fishery participants, including party and charter boat captains and anglers who fish on private boats, are cautiously optimistic about fishing opportunities near wind turbine foundations, which might serve as new structured habitat and may attract some recreational target species (e.g., black sea bass; Section 1.1). Recreational fishermen who fish from shore will not experience these potential benefits.

Offshore wind energy development could have multiple types of impacts on the fisheries and on fisheries management. Many commercial and recreational fishermen are concerned about uncertainty in these impacts as this is a new use of the marine environment in U.S. waters, especially at the scale currently planned for. Furthermore, this uncertainty is coupled with other uncertain impacts to fisheries, such as climate change (e.g. stock distributions changes). It may be feasible for some fisheries to adjust to one or two offshore wind projects. However, the more projects developed in an area, the more challenging it will be for fisheries to remain safe and profitable. Potential impacts must be considered cumulatively for multiple projects and not just for each project individually. Furthermore, fishery participants vary, and some businesses may be able to adapt more effectively than others. For example, vessels and communities reliant upon fishing in particular areas in close proximity to several wind projects (e.g., Cox Ledge) may be more severely impacted if they are not able to adapt their operations due to projects in adjacent waters and/or limitations due to vessel size. These and other types of cumulative effects can be challenging to estimate and vary across multiple users.

Many fishery stakeholders, including commercial and recreational fishermen, managers, and scientists, are concerned that offshore wind energy development could increase scientific uncertainty (e.g., if long-term regional fisheries-independent surveys can no longer operate throughout their historical range; Section 3.2), and this could, in turn, result in more conservative catch and landings limits. Fishery stakeholders also broadly believe it is essential to minimize negative impacts of offshore wind energy development on marine habitats, especially habitats that are essential for managed species in the region.

Fishermen may adapt to offshore wind energy development by changing gear types, target species, areas fished, or areas for transiting. However, this adaptability is limited by restrictions on availability of permits to harvest many species,[14] existing area-specific regulations, and restrictions on the ability of permit holders to increase the horsepower or length of their vessels beyond a certain "baseline" level. Commercial and recreational fishermen are also constrained by non-management factors, such as availability of target species, market demand, existing shoreside infrastructure (e.g., processing facilities, marinas), costs associated with switching gear types or longer transit times, and local practices regarding where to place gear to avoid conflict with other fishermen.

Some fishery stakeholders have called for a more proactive approach to mitigating the effects of offshore wind energy development on the fisheries. For example, some stakeholders have recommended the creation of funding mechanisms that could be used for a variety of mitigation efforts, such as additional seafood marketing or assisting fishermen in changing gear types or exploring new fisheries (to the extent possible given existing regulations). Additional funding could also increase the resources available to fisheries scientists and managers when considering how FID and FDD collection and fisheries management measures might need to adapt to changing conditions. Some fisheries stakeholders have suggested that offshore wind energy developers should fund these mitigation efforts.

3.3.7 Conclusion

The considerations described in the previous sections on socioeconomics (Section 2), FDD collection (Section 3.1), and FID (Section 3.2) are also very relevant to fisheries management. Addressing the data gaps described in those sections will improve our ability to evaluate how fishing effort may change in response to offshore wind energy development. This will, in turn, improve our ability to evaluate the continued effectiveness of fishery management measures in meeting objectives, such as constraining fishing mortality to sustainable levels, minimizing bycatch, protecting marine habitats, minimizing interactions between fisheries and protected species, supporting safety at sea, and ensuring that fishery regulations are fair and equitable to different types of fishery participants and support fishing communities and recreational opportunities.

Multiple emerging and ongoing system-level changes are forcing consideration of how fisheries management may need to adapt to ensure the continued sustainability of U.S. fisheries and marine ecosystems. These changes include offshore wind energy development, as well as climate change and other marine uses (e.g., offshore aquaculture). Given the unique challenges and uncertainties that offshore wind energy development presents to existing fishery management

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[14] Many commercial fisheries have limitations on the number of permits (i.e., limited access), and several requirements must be met to obtain a permit. Usually, a new permit must replace an existing permit. This has led to the creation of non-governmental marketplaces where permits or bundles of permits are bought and sold, sometimes for tens or hundreds of thousands of dollars, depending on the target species, and even for millions of dollars in the case of some very high value species. Bundles of limited access permits for multiple different species issued to a single vessel must be transferred from one vessel to another as a group due to federal restrictions on permit splitting.

practices, it will likely take several years before management authorities understand how wind development affects both fishery resources and fishery operations. Adapting to new conditions may necessitate an iterative management approach that holistically evaluates programs against changing conditions while planning for complex future scenarios.

4. METHODS AND APPROACHES

4.1 Cumulative Impacts

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4.1.1 Introduction

Offshore wind development in the U.S. is subject to compliance with the National Environmental Policy Act of 1969 (NEPA). NEPA was established through political action arising from popular concern over environmental degradation caused by rapid industrial and agricultural progress in the 20th century, including the socioeconomic effects of those developments to the human environment. NEPA recognizes the link between the environment and human communities. The purposes of NEPA are, inter alia, "[...] To declare a national policy which will encourage productive and enjoyable harmony between man and his environment; to promote efforts which will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of man; [and] to enrich the understanding of the ecological systems and natural resources important to the Nation."

An essential component to NEPA, and environmental analysis in general, is the assessment of the incremental effects resulting from multiple actions called "cumulative effects assessments" and/or "cumulative effects impacts." The link between communities and environment is one of the major drivers of analyzing cumulative effects resulting from an action (i.e., how it will impact human communities). To date, a greater consideration has been given to the footprint over which effects occur, as the single or combined level of disturbance could have detrimental environmental effects. Cumulative impact analysis (CIA), also sometimes referred to as cumulative effects analysis (CEA), evaluates the combined impact of past, present, and near future projects to determine the overall effect on the environment and the dedicated footprint of these short-, medium- and long-term effects, but CIAs used in marine management and planning are mostly initiated in response to legal obligations to assess cumulative effects (Judd et al. 2015). Its importance arises from how individual projects could have negligible to minor impacts, but moderate to major impacts could occur after several individual projects are implemented.

Identifying and assessing cumulative effects has been noted as one of the great challenges of understanding interactions between offshore wind development and ocean ecosystems in the U.S. (Methratta et al. 2020) and worldwide. Multiple wind developments are proposed along the Atlantic and Pacific coasts of the U.S. in the relatively near term (~3-5 years), and understanding the cumulative effects of full build-out in combination with other past, present, and reasonably foreseeable stressors operating over several decades will be difficult. The high levels of analytical complexity and uncertainty associated with offshore wind interactions with marine ecosystems make these assessments very challenging. However, there are already several attempts to develop strategies and case studies to illustrate the different types of pressures and ecological receptors (Piet et al. 2021). Current best practice documents (Willsteed et al. 2018) have also been proposed to enable practitioners and regulators to consider the most pressing pressures and potential impacts. Similarly, new approaches considering risk identification, risk analysis, and risk evaluation are providing a robust level of science-to-policy interface, with considerations for "real-world management" processes (sensu Stelzenmüller et al. 2018). These tools will be extremely valuable to support ongoing efforts to progress and continue to develop refined methodologies for cumulative effect assessments.

Willsteed et al. (2017) reviewed approaches to CIAs in Europe and concluded that they were insufficient and largely lacking. Furthermore, Willsteed et al. (2017) also suggested the need to review and, where pertinent, improve current practices to ensure legal obligations to assess cumulative effects and to support marine management and planning commitments are met. Cumulative impacts analysis of offshore wind in U.S. waters has been limited to date, as only 2 projects have completed NEPA review where cumulative analysis takes place. BOEM published a Supplemental Environmental Impact Statement (SEIS) for the Vineyard Wind I project that evaluated cumulative impacts of "reasonably foreseeable" future offshore wind projects (BOEM 2020). BOEM's approach was to go activity by activity, each with their own sources, to look at what else was occurring in the Atlantic besides potentially offshore wind. The SEIS projected build-out with existing offshore wind energy technology and existing leased area necessary to meet the states' announced procurement goals. Each development parameter's associated IPFs were then defined and scaled to that level of build-out. Then, for each resource (including finfish, benthic, commercial fishing), all of the IPFs from these activities and the build-out projection were cross-walked as creating potential impacts. BOEM took a different approach for the subsequent South Fork project with a more condensed CIA, evaluating the proposed project against a full build-out scenario rather than comparing the latter to status quo (i.e., no offshore wind projects; BOEM 2021a). The critical goal of any cumulative impacts analysis of offshore wind is to understand the impact of the development of multiple wind energy projects. A systematic approach to this analysis has been rare to date (Bergström et al. 2014). Bergström et al. (2014) reviewed offshore wind impacts analyses available in Europe from the Skagerrak in the North Sea to the inner Baltic Sea. They found general consistency in conclusions across assessments for various impact categories, but they also found the same gaps (e.g., lack of physiological impacts on marine species resulting from the operational phase). The ability to conduct an adequate analysis is limited as the pace of offshore wind development is outpacing research and understanding of consequences of said development (MMO 2013).

Willsteed et al. (2017) identified temporal accumulation, spatial accumulation, endogenic and exogenic sources of pressure, ecological connectivity, placing receptors at the center of assessments, and purpose and context as key components of cumulative impacts.

Temporal accumulation "refers to change brought about by disturbances or perturbations accumulating as the period between perturbations is shorter than the period of ecological recovery" (Willsteed et al. 2017). OSW projects will result in short- and long-term perturbations to the local habitat and species occurring in the lease areas. They are also at risk of "shifting baselines," and it is becoming increasingly difficult to define what the "original" state of the lease areas is. The geological and geophysical (G & G) surveys, site cleaning, and other preliminary activities that occur prior to construction are already modifying the environment. The data collection systems and requirements have lagged behind these activities, hindering the ability to conduct cumulative assessments. Also relevant to temporal accumulation is the long duration of these structures, of which the effects will impact many year classes of most marine species.

Spatial accumulation is essential for consideration for OSW development in U.S. waters, especially in the Massachusetts/Rhode Island lease areas, which are large and contiguous. The lack of space between the lease areas means that impacts will be difficult to attribute to any individual wind project. The scale of analyses of these wind projects needs to be carefully considered. Analyzing them independently may be inappropriate if their effects do not, or cannot, dissipate with space but rather become integrated with those of a neighboring wind development.

Endogenic and exogenic sources of pressure represent impacts both created by the projects being assessed (e.g., offshore wind) and those beyond the control of the system (e.g., climate change). Although not expected to have a noticeable effect on warming ocean waters in situ, OSW developments may mitigate future greenhouse gas emissions if they replace generating facilities with higher climate impacts (BOEM 2021a). Disentangling endogenic and exogenic pressures represents a clear challenge for assessing the cumulative effects of OSW projects and ecosystem-level effects not only immediately in and around the turbines but also for more widely distributed species (e.g., migrating elasmobranchs and marine mammals). These larger-scale effects, which may be less intuitive because of the indirect linkages, characterize ecological connectivity and the need to understand the full scale of the ecosystem potentially impacted. For example, any changes in the availability of prey species, or seasonal temperatures (e.g., survival of Atlantic salmon post-smolts [Friedland 1998], Mid-Atlantic Cold Pool changes, upwelling in the California Current), may directly impact the success of migratory predators or the success of a year class. IEA efforts to inform fisheries management and other activities, including that of the MAFMC, may provide some initial guidance on the components of the ecosystem from forage species to predators.

Placing receptors at the center of assessments may be more difficult than focusing on the stressor; however, these types of approaches will improve the quality of the analysis. Receptors are vulnerable to multiple stressors. The combination of multiple stressors may result in different impacts on a receptor than if only 1 stressor was imposed on the system. Narrowing the focus to individual stressors may underestimate the scale of realized impacts on the environment.

Purpose and context of the cumulative effect assessments is also critical as it helps inform the approach. A programmatic EIS, including cumulative assessment, for all the wind projects proposed along the east or west coast in the U.S. is one possible method to frame the analysis for the entire region, focused on the primary Valued Ecosystem Components. This approach may provide the most effective scale for the cumulative assessment of OSW in U.S. waters because it would remove the focus from any 1 individual project, allowing for broader discussion of large-scale impacts.

Durning and Broderick (2019) developed Guiding Principles for cumulative impacts analysis in the U.K. based on rapid offshore wind development there. The Guiding Principles cover general, scoping, data, and assessment principles but focus on a project-level assessment. The authors called for the mitigation and monitoring to be informed by the CIA; however, this is not possible in the U.S. given the absence of a suitable framework. A number of studies recommend project-level cumulative assessments be conducted to support regional planning (e.g., Willsteed et al. 2018a).

4.1.2 Description of the state of our knowledge and understanding on this topic with regard to interactions with offshore wind

Robust cumulative assessment of OSW requires focus on the IPFs which can have multiple contributing activities in addition to offshore wind. Uncertainties should be addressed in a cumulative effects analysis and, where practicable, quantified. For example, the SEIS for the Vineyard Wind I project provided a cumulative assessment of OSW including WEAs leased by the end of 2020, but the challenges associated with rapidly developing technology, changing project parameters, rapid additional leasing, and research and knowledge gaps remain.

Research on cumulative impacts assessments consistently concludes that cumulative analysis should inform future planning and aim toward a regional perspective due to the transboundary nature of ocean resources. Much of the research in this area involves integrating information from many sources and finding synergies. Piet et al. (2021) also highlighted the need to consider the best types of information available to support a quantitative CIA. This stepwise approach describes the need to adequately select and apply data sets to accurately capture activities, pressures, and effects. This proposed approach systematically classifies risks as exposure and effects. These exposures and effects can then be quantified to ecological levels (e.g., pressure-state relationships and/or population dynamics models) with dedicated parameters, used to assess direct effects and can be easily communicated to stakeholders. This consistent approach provides the opportunity to identify different activities, pressures, and ecosystem receptors, with the relevant data sets and adequate spatial and temporal scales, which builds on previous frameworks (Willsteed et al. 2017, 2018b; Figure 17).

Reducing the uncertainty in CIAs requires supporting model assumptions with empirical data. In Europe, where commercial scale wind farms are already in place, studies are making strides toward reducing uncertainties in our understanding of the effects of fixed structures and fisheries exclusion. The provision of an artificial reef effect has been studied as the effects of the de facto closure for fisheries within a 500 m radius of the construction (UNCLOS Art. 60, paragraph 5), given that all European OSWs, except for Scotland's, are closed for trawl fisheries. This type of regulation brings the opportunity of the surrounding seafloor to recover from the introduced structure disturbance, a concept known as the "fisheries exclusion effect." The current literature documenting the effects arising from fisheries exclusion on benthic ecosystems in windfarm areas is currently in its infancy (Van Hoey et al. 2020). However, there are some studies that have considered these potential effects (Jak and Glorius 2017). The evidence suggests that there are minimal changes for the benthic community parameters (e.g., diversity, density, biomass) for a limited number of species. Also, some demersal fish species seem to profit from the more sheltered area, especially around the foundations. In the Belgian OSW monitoring program, more and larger individuals of European plaice within the windfarm area have been observed compared to surrounding areas (De Backer et al. 2019). To date, it remains difficult to demonstrate that fishery exclusion zones influence the seafloor communities in OSWs. The major compromising issue here is the short time frames of the different monitoring studies and the slow recovery time of certain types of species (e.g., K-strategists; Bergman et al. 2015). Additionally, the wind farm concession areas are probably not yet large enough to demonstrate (positive) effects of fisheries exclusion beyond the immediate vicinity of the wind turbines. Nevertheless, the example of the European lobster (Roach et al. 2018), and in some studies the occurrence of larger bivalve species (*Spisula*, *Tellina*; Jak and Glorius 2017) and fish, may indicate a size effect, potentially related to fishery exclusion. Although the potential of wind farms as shelter area, contributing to the health status of commercial fish stocks, still needs to be demonstrated, current marine management strategies consider it a potential benefit of having these structures in the sea to combine both protection and sustainable exploitation with artificial reefs (Claudet and Pelletier 2004).

4.1.3 The major gaps in our knowledge

CIAs must make assumptions about IPF interactions, which imparts uncertainty due to the lack of data to support these assumptions. Some of these are inherent to future plans and unknowable eventualities, such as vessel fleet selection for construction or development not associated with any specific procurement or plan at this time. A better understanding of OSW technology and project planning—such as where development may connect to the grid now and in the future (cable amounts and routes), planning implications regarding potential interactions with telecommunications cables, construction vessel availability, job creation, port changes, and the spatial and temporal interactions during simultaneous and consecutive construction activity and over the course of one and/or several structures placed along a dedicated area—will result in a different level of footprint and potential effects. It is necessary to list and generate a matrix of activities and disentangle the levels of project effects, the scales in which these developments will modify the environment, and the overall environmental changes over the life of the development. These knowledge gaps, which contribute to current limitations of cumulative impact assessments, are more fully described elsewhere in this report.

Bergström et al. (2014) conducted a generalized impact assessment of offshore wind development and fisheries in Swedish waters to analyze CIAs to date. This approach provides a methodology that can be refined and updated as more data become available. However, the quantity of research on the impacts of OSW on fisheries has remained limited (Methratta and Dardick 2019). Recent efforts have continued to synthesize the current opportunities and threats for co-existence and the potential for multiple uses of space for fisheries and aquaculture under current and future OSWs (Van Hoey et al. 2021). These types of overall assessments have been based on the current knowledge available across disciplines (e.g., ecology, fisheries, legislation, management, socioeconomics, and governance), helping to assess direct gaps and future linkages across sectors in the North and Baltic Seas. The need for integrated assessments, consideration of scales, and integrated planning with stakeholders and regulators are still areas which will need further integration and careful assessments over future planning stages of OSWs (Van Hoey et al. 2021).

4.1.4 Characterization of the perspectives of commercial and recreational fishing

The fishing industry in the U.S. is highly concerned with the quantity and quality of CIAs currently being conducted for U.S. OSW development. BOEM’s current approach is to analyze projects on an individual basis; however, along the East Coast a number of the leases are adjacent to each other (see lease areas off Southern New England), and many fishery stock areas are affected by multiple projects. The environmental and economic effects will therefore not be isolated, and fishing communities have suggested the scale of analysis should match that of fisheries and ecosystem management practices. Broadening the scope of the cumulative effects analysis through, for example, a programmatic EIS that incorporates the full anticipated build out over the entire continental shelf, would enhance the utility of the analysis.

Another concern stated by the fishing industry is that the values and public perceptions surrounding fishing and renewable energy can introduce bias in research. Analyses of offshore wind impacts on marine resources are frequently based on an assumption that construction and long-term presence of turbines will have positive impacts on the marine environment because the artificial reef effect is typically presented as a desirable outcome (BOEM 2021b; Section 1.4.4). In contrast, many offshore wind-related analyses portray commercial fishing practices as inherently unsustainable and negatively impacting fish populations. For example, in their impact assessment model, Bergström et al. (2014) analyzed fish species that were in an overfished condition and made the underlying assumption that a reduction in fishing pressure caused by exclusion from an OSW would benefit those populations; in contrast, the presence of turbines was assumed to have more positive than negative effects because of habitat gain. Such model assumptions, which the authors concede are fraught with uncertainty due to the lack of empirical data, can bias model outcomes and mislead the public. These biases must be overcome to conduct cumulative (and project-specific) impact assessments that are credible to the fishing industry.

4.1.5 Recommendations for future directions/studies

The current evidence available on CIA (i.e., CEA) has advanced a great deal since the first theoretical approaches were published. The current need to continue to extract greater economic returns from the oceans and degradation of some of these marine ecosystems make even more pressing our need to make progress on CIAs (Willsteed et al. 2018b). There are key aspects that should be taken into consideration going forward. These are as follows:

- synthesis of available lessons learned from other cumulative impact assessments;
- incorporation of more representative spatial and temporal scales;
- consideration of new advancements in wind technology;
- dedicated assessments of site-specific pressures and potential impacts across ecological receptors;
- further understanding of the footprint of spatial and temporal scales;
- research into the long-term (i.e., 30-year OWD lifespan) effects of offshore wind development;
- dedicated pressures resulting from climate driven impacts (e.g., temperature, oxygen, and pH) changes across commercial species and areas of main activities;
- programmatic CIA conducted on appropriate scale for development in U.S. waters;
- inclusion of greenhouse gas analyses within the CIA to improve the public’s understanding of full-scale impacts; and
- outreach and dissemination of key areas and activities that will need to be restricted (e.g., pile-driving noise over fish spawning areas and or/ nursery areas)

4.2 Integrated Ecosystem Assessment

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4.2.1 Introduction – What are Integrated Ecosystem Assessments

The prospects of integrating offshore wind energy development or other ocean uses with fisheries is a daunting task, one that will require expanding current management strategies. Luckily, there are tools at our disposal that can facilitate such integration and examine the inherent trade-offs associated with such a venture (Link and Browman 2014; Link 2010; Patrick and Link 2015). Efficient consideration of multiple ecological and socioeconomic factors in concert with one another rather than in isolation will require ecosystem management (Arkema et al. 2006; Levin et al. 2009; Link 2010).

From a fisheries perspective, ecosystem management can come in several different forms: ecosystem approach to fisheries management (EAFM), ecosystem-based fisheries management (EBFM), and ecosystem-based management (EBM; Figure 18; Arkema et al. 2006; Patrick and Link 2015; Dolan et al. 2016). EAFM, while still focused on single species/stock management, does incorporate relevant ecosystem factors to improve management decisions (Pitcher et al. 2009; Link and Browman 2014). EBFM goes a step further within the fisheries sector of synthesizing physical, biological, and socioeconomic trade-offs (Link and Browman 2014; Link 2010). This is typically approached from a place-based perspective rather than a species-based one (Fogarty 2014). EBM expands past just the fisheries sector to include other ecosystem uses/human sectors, such as offshore wind energy (Link and Browman 2014; Aburto et al. 2012; Curtin and Prellezo 2010). It is this nexus of multiple human uses that NOAA's IEA program was designed to help address (Monaco et al. 2021).

NOAA's IEA program was started in 2010 to provide the science to support EBM (Monaco et al. 2021). It is a NOAA-wide program incorporating 5 NOAA line offices: National Environmental Satellite, Data, and Information Service; NMFS; National Ocean Service; National Weather Service; and Office of Oceanic and Atmospheric Research. The program is run out of the Office of Science and Technology of the NMFS, although the program itself has a regional focus with active regions across the country. Through this regional approach, the NOAA IEA program has successfully developed various aspects of the IEA approach and improved the capacity of NOAA to provide ecosystem-level advice to assist with management of marine resources (Monaco et al. 2021).

The initial vision for IEA was to assess the cumulative impact of human activities while providing a tool for resource managers to achieve multiple ecosystem objectives (Levin et al.

2009). The structure of an IEA is similar to other formal decision analysis (Keeney and Raiffa 1993) with a marine ecosystem context in order to "guide the process of synthesizing and analyzing relevant scientific information supporting an ecosystem approach in any system" (Levin et al. 2009). The seminal paper by Levin et al. (2009) would further define IEAs as an incremental approach working collaboratively with stakeholders and managers in order to attain the goals of EBM. IEAs as a tool are meant to complement single-species and single-sector approaches (Levin et al. 2009).

The IEA approach itself is a 6-step process that starts with scoping to identify ecosystem goals (Figure 19; Levin et al. 2009, 2014; DePiper et al. 2017). Like all steps, this should be an iterative process that includes engagement with stakeholders and managers (deReynier et al. 2010; Levin et al. 2014). A useful tool during the scoping process is to develop a conceptual model that can identify key linkages and aspects of the system (Rosellon-Druker et al. 2019). Once goals have been identified, then a suite of indicators will be selected or potentially developed that can measure changes in the system relative to those goals (Brown et al. 2019). These indicators are then used to assess the system, usually in the form of an ecosystem status report (ESR; Slater et al. 2017). The next step is to analyze the uncertainty or risk inherent in the system based on the previous assessment. Using a risk assessment can help prioritize management action that can meet the ecosystem goals (Gaichas et al. 2018; Samhouri et al. 2019).

Once management actions have been prioritized, a structured decision-making process can be undertaken. Within the IEA literature, management strategy evaluations (MSEs) are the tool of choice (Levin et al. 2009; Muffley et al. 2020), but in reality, any type of structured decision-making process can be used (e.g., scenario planning). The reason for using structured decision making is to identify a management action that can be implemented to achieve the desired ecosystem goal. After the action has been initiated, the system should be monitored and assessed to see if the desired outcome is being achieved. This "final" step should be viewed as adaptive management whereas the actions or goals can be modified as needed (Levin et al. 2009; Monaco et al. 2021).

It is important to note that the 6 steps outlined above represent a complete IEA cycle, yet successful implementation of an IEA does not require that all steps be completed. Each step on its own enhances our understanding of the system and can aid managers in making informed, ecosystem-based decisions. The strength of the IEA process is that it is scalable, collaborative, and adaptable (Levin et al. 2009; Monaco et al. 2021; Samhouri et al. 2014).

The NOAA IEA program and RODA are leveraging previous work in the region in order to conduct an IEA for offshore wind energy development and fisheries interactions. This will be the first IEA to study these interactions, although IEA efforts have been underway in the Northeast U.S. for some time. Below, we outline some of those previous efforts as well as initial thoughts of what would be involved during this IEA.

4.2.2 Example application of the IEA process

NOAA's IEA program has been operating in the Northeast since its inception in 2010. Within the region the primary clients of IEA products have been the 2 federal fisheries management councils: MAFMC and New England Fishery Management Council (NEFMC). The broadest and most complete example of an IEA has been developed through several years of iteration with the MAFMC (Muffley et al. 2020). The work to date goes through the IEA loop from scoping to MSE.

The process began in 2011 with the MAFMC's Visioning Process, which they developed in order to engage stakeholders and receive their input on how to manage marine fisheries moving forward (MAFMC 2012). One of the themes that was identified was the need to incorporate more ecosystem considerations in management decisions. The feedback received during the Visioning Process was incorporated into the Council's 2014-2018 Strategic Plan (MAFMC 2013). Within that plan was a specific objective to advance an EAFM in the Mid-Atlantic through the development of an EAFM Guidance Document (Muffley et al. 2020).

Over the next several years the council engaged with their stakeholders on a number of workshops to discuss 4 priority topics identified during the Visioning Project. The priority topics were forage/lower-trophic level species considerations, fisheries habitat, climate change and variability, and ecosystem-level interactions (Muffley et al. 2020). They became the pillars of the EAFM Guidance Document, which outlines the Council's goals with respect to incorporating broader ecosystem context within their management approach (MAFMC 2016). This broader scoping has allowed the Council to work with the NOAA IEA program to make significant strides on the Council's priority area 4 (ecosystem-level interactions; Muffley et al. 2020; Gaichas et al. 2016).

The MAFMC developed their own modified version of the IEA loop that started with assessing risk (Figure 20; Gaichas et al. 2016). However, in order to accomplish this, they would need indicators to assess. Therefore, working within the IEA process, the NOAA IEA program identified a set of indicators to address broad-scale ecosystem goals (DePiper et al. 2017). These indicators are routinely assessed for status and trend within the NEFSC's State of the Ecosystem reports (e.g., NEFSC 2020). The purpose of the State of the Ecosystem report is to provide a relatively short, non-technical document to the management council that focuses on synthesis across indicators for a broader ecosystem perspective than that which the council is typically presented. These annual reports are presented to both the MAFMC and NEFMC and provide clear linkages from ecosystem indicators to management objectives. The Mid-Atlantic report forms the basis for the MAFMC's ecosystem risk assessment (Muffley et al. 2020; Gaichas et al. 2018).

The risk assessment identified a series of risk elements derived from existing legislation as well as engagement with stakeholders and managers (Gaichas et al. 2018). Prior to the analysis, a set of risk criteria were developed that provided a transparent and structured process for the assessment. Indicators were aligned with risk elements and evaluated based on the risk criteria. The outcome from the assessment has helped focus and prioritize the highest risk issues for the Council (Table 17). The ecosystem risk assessment is updated annually and presented to the MAFMC along with the State of the Ecosystem report (Muffley et al. 2020). This allows for an iterative process, which in turn allows for continuous improvements and responsiveness to the Council's needs.

The next step on the MAFMC's process was to develop a conceptual model based off the results of their risk assessment (Figure 20). As mentioned above, this is usually part of the scoping process. Here, the conceptual model was used to ensure that the key components of the system were accounted for before undergoing a more rigorous quantitative assessment. It also served as a good communication tool for both stakeholders and managers (Muffley et al. 2020). The MAFMC identified summer flounder as a high-risk fishery that warranted further evaluation. They developed example management questions that could be answered using the conceptual model and available data. Once again this was an iterative process that engaged stakeholders and managers (Muffley et al. 2020; DePiper et al. 2021).

The Council selected a management question focused on summer flounder discards to be evaluated using an MSE process (Muffley et al. 2020). They felt this issue would provide tangible benefits for the Council and would have broader applications to other recreational species.

Planning and execution of the MSE is currently underway. It is anticipated that the Council will consider potential management actions from the MSE sometime in 2022.

Using the IEA process has helped determine management priorities for the MAFMC by identifying indicator and risk criteria, evaluating potential risk to the system, and organizing ecosystem information within a conceptual model. Each step has been a collaborative and iterative process between stakeholders, managers, and scientists (Muffley et al. 2020). The success of this IEA has been the clear set of expectations and goals developed during the scoping process as well as the ability to be flexible and adaptive throughout the cycle. It is important to note that this process takes time; however, that time ensures that stakeholders are engaged and trust the science as well as allows the Council to see the benefits to the management process (Muffley et al. 2020).

4.2.3 Commercial and recreational fishing communities perspectives

The fishing industry will be directly impacted by OSW development; however, the full extent of that impact is currently unknown. An IEA can help fill in that knowledge gap by relying on the fishing industry's expertise. OSW can impact fisheries in multiple ways, direct impacts on individual species (e.g., noise-induced mortality of squid, changes in ocean circulation impacting larvae distribution), shifts in fishing location if vessels can't operate within a WEA, and increased uncertainty in stock assessments stemming from disruption of long-term federal surveys, which typically decreases quotas. Commercial and recreational fishing may have different impacts between and within each sector. For example, there may be differences between commercial and recreational fisheries but also within the commercial sector (e.g., fixed vs. mobile gear) and within the recreational sector (private anglers vs. for-hire). Impacts don't stop at the vessel level. Entire communities are dependent on fishing, including families of vessel owners or operators and support businesses (e.g., processors, shipping companies, ice houses, gear manufacturers, and mechanics).

The fishing industry is wary of new management strategies that are difficult to apply to traditional fisheries management (e.g., EBM) and consider the adjustment process to be disruptive. However, IEAs are not designed to directly implement management measures. Rather, they provide additional information to managers that would ideally reduce uncertainty and help identify potential disruptions.

4.2.4 Potential structure of an offshore wind energy IEA

As outlined above and demonstrated with the MAFMC example, the IEA process is a flexible framework for supporting EBM efforts. It will be important to employ this methodology when examining the interactions between commercial and recreational fisheries and offshore wind development. The MAFMC example highlights how IEA can be applied working with one management entity on a fairly large area (i.e., the Mid-Atlantic). There are other examples of IEAs conducted with multiple partners and at smaller scales (i.e. Rosellon-Druker et al. 2019; Maynard et al. 2019; Williams et al. 2021). Activities directly and indirectly associated with offshore wind fall under the jurisdictions of multiple government agencies. As such, applying the IEA process will require communication and coordination amongst multiple government agencies.

The first step in the IEA is conducting a thorough scoping exercise. The NOAA IEA program has partnered with RODA to set up a steering committee to carry out the scoping phase. The steering committee has broad representation from NMFS, BOEM, non-governmental organizations, and private industry. The goal of the initial phase of the IEA will be to compile existing data and assessments as well as develop a conceptual model. The conceptual model will be developed through a participatory process and highlight various aspects of the system that warrant further investigation. This will highlight where we already have data to inform management as well as identify high priority data gaps for assessing offshore wind impacts on the environment and fisheries. We will elicit ecosystem goals while working iteratively with the various management bodies.

There are several key questions that will need to be addressed during the scoping phase. One critical question will be determining the right scale to conduct the IEA: Should the IEA target individual lease locations or the broader network of potential lease areas within the Northeast? Many of the existing indicators in the region are at the ecosystem or sub-ecosystem scale but have been downscaled for other applications (Pittman 2019). Depending on the scale selected, there may be the need to develop new indicators or refine existing ones. One source that is currently underutilized in northeast IEA products is LEK. A secondary goal of building the conceptual model through a stakeholder driven workshop is to better utilize this knowledge.

After scoping and indicator development is completed, a risk assessment will be conducted. We will most likely follow the model of Gaichas et al. (2018), although other alternatives to this approach exist. It is worth noting that the IEA could potentially feed into the existing framework of EISs required by the NEPA. While that could be the logical conclusion for an IEA in this arena, it is also possible to continue with the IEA process and develop a structured decision-making analysis. One potential avenue would be scenario planning where robust management actions are developed with respect to divergent plausible future states (Frens and Morrison 2020).

As noted in Muffley et al. (2020), the IEA process takes time. However, the offshore wind energy development IEA should be able to take advantage of the infrastructure that has already been built in the region. The NOAA IEA program uses open science principles for most of their products (Bastille et al. 2021). Open science principles rely on open-source data and documentation that allows for greater transparency and reproducibility. This helps reduce the amount of time required to pivot from existing products as was done with the MAFMC ecosystem risk assessment, which used many indicators directly from the Mid-Atlantic State of the Ecosystem report (Gaichas et al. 2018). The rapid expanse of offshore wind energy will require this flexible and adaptable process which will implicitly address trade-offs between the energy and fishery sectors.

4.3 Innovative Monitoring Approaches and Technologies

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4.3.1 Sampling Technologies

We focus on technologies and approaches that can be applied to studies of offshore wind sites, with priority to well-established acoustical and optical monitoring and sampling technologies and platforms that can be deployed with little to no research and development (R&D) and return results in an appropriate time frame. We also suggest emerging technologies, methods, and platforms, such as environmental eDNA (Stoeckel et al. 2021), that have promise to provide useful information but still require R&D.

As a general rule, data and information needs should drive which technologies and methodologies are employed, rather than the technology driving the questions. There are many sensors and platforms available to sample over many spatial and temporal scales, but the information needs should dictate which methods are useful. For example, comparing spatial distributions of organisms within and outside of wind farms should be done using technologies and platforms that can survey large areas efficiently, albeit with lower spatial and temporal resolution; whereas investigating the effect of a turbine or cable on animal distribution will require technologies with high resolution and platforms that can get in close proximity to or be attached to the structures and are mostly autonomous (i.e., self powered unless power can be obtained from the turbine and can record data, or a data link on the turbine). Whether the data will be used for an ecosystem approach or a single-species stock assessment will also dictate the types of data collected. For example, if a stock assessment is primarily based on bottom trawl data, then the immediate need is to develop a sampling strategy to deploy bottom trawls in wind farms (highly unlikely) or to develop a suitable alternative to trawling, such as gillnets or traps. Then, if needed, longer-term strategies can be developed to utilize data collected with advanced technologies. Ecosystem-based approaches require data on multiple trophic levels, which will require multiple types of sensors and platforms for adequate sampling. In this case, spatiotemporal synchronization of these data will be required.

Advanced sampling technologies are notorious for collecting large amounts of data. Remote and/or autonomous sensors can collect data 24/7, 365 days a year, amassing large amounts of data that need to be processed, analyzed, archived, accessible, and discoverable. A data management scheme needs to be developed prior to, or at the very latest in the early stages of, monitoring to enable efficient and effective use of the data. Data management often gets overlooked when developing sampling strategies, but oversight will lead to delays in getting results and potentially irretrievable data. Existing examples of data portals for biological and technological data, such as the Integrated Ocean Observing System (IOOS 2022), the ICES data portals (ICES 2022), and NOAA's National Center for Environmental Information (NCEI 2022), could be used as models for developing a management scheme or as archival facilities for the data.

There are a number of strategies to evaluate the impact of a wind farm on the flora and fauna in and around the farm. From a sampling perspective, developing a hierarchical spatiotemporal context of the wind farms and surrounding area may be useful, as each technology has its specific measurement scale (i.e., resolution and extent; Figure 21).

Given the rapid pace of development and introduction of sensors and platforms, an exhaustive list of all potential technologies is not feasible or practical. Sampling technology is a combination of hardware (i.e., the sensor[s]), acquisition software, and processing/analysis software, and all 3 of these may or may not be in synchrony with respect to the ease of use or ability to efficiently transform the data into useful information. A sensor may be well developed, but the software to record the data in a user-friendly format may not be available, or the software to process the data may be in custom-built programs using proprietary software. Table 18 provides a categorical list of active sampling technologies as well as a subjective evaluation of the operational readiness of that technology. Table 19 provides a categorical list of passive sampling technologies. Table 21 provides a categorical list of stationary and mobile platforms that are used to position/locate active and passive sensors in situ (ex situ in the case of satellites). The order is based on measurement scale, from high resolution/short extent to low resolution/long extent.

All remote sensing technologies ultimately record a digitized signal that is an indirect measure of some aspect of the environment that we want to monitor. For example, a conductivity-temperature-depth (CTD) is a common technology that is used to measure temperature and salinity at depth. However, none of these variables are measured directly. All 3 variables are derived from measurements made by electrical sensors. We take these measurements for granted, but the CTD electronics must be routinely calibrated and compared to direct measures from water samples to ensure high-quality data. The same is true for all remote sensing technologies. They must be routinely calibrated and measured compared to in-situ samples collected using capture gear (for biological measurements; Table 20) or other independent measurements. For example, an acoustic signal by itself cannot at this time be used to identify the echoes to taxonomic species, so trawls and nets are often used to capture the animals responsible for the acoustic scatter. These specimens can be used to verify species identification and, additionally, provide biological information, such as age, sex, maturity, and diet. In fact, all remote sensing technologies require some level of validation before the data can be used to generate useful metrics and/or indicators. Some technologies, such as sea surface temperature from satellites or visual feature identification from cameras, require minimal validation, but others, such as automated species classification from acoustic and optical data or length measurements from optical data, require supplementary sampling.

Using advanced technologies to sample in and around offshore wind developments will require at least 2 sampling modalities: (1) deploying, retrieving, and collecting data from the instruments and (2) addressing ways to validate the data by in-situ sampling of the environment, weather, geology, and biology in the pelagic, demersal, and benthic zones.

Several studies have either been completed or are ongoing in the U.S. WEAs (Table 22). Table 22 provides an overview of the sampling technologies that have been employed and the spatial and temporal scales of research studies they have been applied to in the U.S. WEAs, the target species or species groups, and the general questions addressed.

4.3.1.1 Considerations for Choosing a Sampling Technology

The research question to be addressed should be the primary driver of the sampling technology to be employed. Once the research question is defined, considerations in choosing a sampling technology include:

- Spatial extent of the study
- Spatial resolution of the study
- Temporal extent of the study
- Temporal resolution of the study
- Biological indices to be measured—presence/absence, abundance, biomass, density, size, stage
- Biology of the species:
    - habitat use by adults, spawning adults, larvae, juveniles
    - association with benthic, mid-water, pelagic habitats
    - propensity to be attracted to structures
    - migratory behavior
    - high vs. low mobility
    - feeding habits
- Other covariables to be measured
    - Light (e.g., PAR, in-situ illumination)
    - Primary production
    - Temperature
    - Salinity
    - Current velocity
    - Turbidity
    - Meteorological conditions (e.g., wind speed and direction, atmospheric pressure)
    - Soundscape
    - Turbine activity (e.g., blades spinning, power transmission, volt/amp levels through cables)

4.3.2 Experimental Design

Robust experimental designs are needed to assess the effects that offshore wind development have on marine ecosystems. This section provides an overview of the advantages and disadvantages to the experimental designs most commonly applied or discussed for evaluating OSW effects: BACI and BAG. For both BACI and BAG designs, measuring covariables that potentially affect the response variables of interest can help to reduce unexplained variance in statistical models.

4.3.2.1 Before-After-Control-Impact and Control-Impact

The BACI and CI designs (Green 1979) are the most frequent approaches used to study the effects on fisheries resources at offshore wind developments (Methratta 2020, 2021). The majority of field experiments conducted to examine the effect of offshore wind developments on finfish have generally sought to examine how a single wind farm affects finfish metrics, such as abundance, biomass, diversity, size, distribution, or community composition. BACI can be a useful design in answering research questions about effects that are expected to occur over a limited spatial and temporal extent. For example, sessile and reef associated biota have been observed directly attached to and in the immediate vicinity of turbines (≤20 m; Collie and King 2016; Wilhelmsson et al. 2006). Although these artificial reefs could have indirect effects that reach much further afield, the direct effect of reef fish utilizing habitat associated with turbines occurs at or very near the structures. Similarly, BACI could be useful in short-term targeted studies of relatively slow moving or sedentary species. The assumptions inherent to the BACI design have presented challenges in its application to offshore wind research: (1) that suitable controls can be found (Stewart-Oaten et al. 1986); (2) that the area within the OSW is homogenous and all fish species respond the same way to the OSW regardless of where inside the wind farm they are sampled; and (3) spatial scale of the effect is known and does not extend beyond the boundary of the OSW (Methratta 2020).

4.3.2.2 Before-After-Gradient (BAG)

The BAG design is an experimental design in which samples are collected at relative distances from offshore wind structures both before and after the intervention (Ellis and Schneider 1997). Distance-based sampling is relevant because nearly every study that has considered proximity to the turbines in its sampling design and data analysis, even in some limited capacity (i.e., post-construction sampling of 2-3 distance categories), has found that effects depend on how close to the structures samples were collected (Methratta 2020, 2021). The increments along the gradient to be sampled and the spatial arrangement of sampling points are guided by the research question(s) of interest and determined through an exploration of existing baseline data from the location of study. BAG does not require a control, building into its design the capability to explore patterns of spatial variation in the target variables of interest, and collects data in a manner that allows for the evaluation of the scale of effect (Methratta 2020).

A common reasoning for not selecting a before-after distance-based sampling design such as BAG is the difficulty in collecting data along a distance-from-turbine gradient prior to the construction of the turbines. This difficulty arises because often the specific location of turbine structures and associated scour protection zones are not precisely known >2 years in advance of construction when baseline studies would occur. One solution is to resolve these conflicts and make a final selection about the turbine design and layout well in advance of the start of construction. Alternatively or perhaps additionally, data collection throughout the development area during 2+ years of baseline studies could be used to develop spatially-explicit models that generate a predicted surface of the abundance and distribution of target species which could provide the “before” data in impact assessment models (Petersen et al. 2011, 2014).

4.3.2.3 Experimental Designs in the U.S. Wind Energy Areas

Studies of finfish and benthic invertebrates at BIWF have utilized a BACI design (e.g., Wilber et al. 2020a, 2020b; Table 22). BACI comparisons are also planned for studies of lobster, lobster larvae, and black sea bass distribution in the Rhode Island-Massachusetts although turbines have not yet been installed there (Stokesbury et a. 2020). Pre-construction gradient (Secor et al. 2020) and post-construction gradient (HDR 2018) have also been used. A number of other studies were one-time projects with time-limited funding or reported baseline data without a characterization of the planned experimental design.

Case Study: Pre- and Post-Construction assessments of fisheries in the Vineyard Wind offshore wind lease area

The School for Marine Science and Technology (SMAST) collaborated with the fishing industry, regulatory agencies, and Vineyard Wind to develop a pre- and post-construction assessment of fisheries, associated ecological conditions, and socioeconomic aspects of fisheries, in and around the Vineyard Wind offshore wind lease area, as designated by the US Bureau of Ocean Energy Management, on the US Outer Continental Shelf.

In 2018/2019, Dr. S. Cadrin in SMAST's Department of Fisheries Oceanography, organized and hosted a series of workshops, with fishermen and regulators to present a relatively expansive set of monitoring component options and to identify which elements are most important to local fisheries and which are most important to regulators. The outreach mechanism included email, phone calls, networking at other meetings (e.g., New England Fishery Management Council process) and port visits (e.g., New Bedford, Pt Judith, Martha's Vineyard). Outreach included commercial and recreational fishermen and fishing organizations involved in fisheries that are active in the development area (e.g., squid-mackerel-butterfish, scup-sea bass-fluke, southern New England groundfish, scallop, monkfish-skate, lobster-crab). Monitoring components considered included fishery assessments, fishery resources surveys, tagging, oceanographic monitoring and modeling, socioeconomic analysis, and geostatistical integration of monitoring components. Optional design features such as important indicator species and seasonality of monitoring were presented and discussed. Results from these workshops were compiled into "Recommendations for planning pre- and post-construction assessments of fisheries in the Vineyard Wind offshore lese area" dated 24 March 2019 (Vineyard Wind 2023; MAFMC 2023) and https://www.mafmc.org/northeast-offshore-wind).

This plan first reviewed and considered the background scientific literature on windfarm/environmental impacts, state and federal guidance and scientific best practices. The status of currently available monitoring data was also examined including oceanographic, benthic, fish and invertebrate trawl, avian, marine mammal, and sea turtle surveys. This information coupled with data from a preliminary benthic trawl survey conducted by SMAST in 2018 and benthic drop camera surveys of the Massachusetts's windfarm lease area collected by SMAST in 2012 and 2013 were used to begin the discussions with fishermen and regulators. From these discussions a series of recommendations to best utilize the present knowledge emerged with the development of an environmental impact study. Seasonal fishery resource surveys were proposed examining the substrate and benthic macroinvertebrate, groundfish and planktonic communities. Supplemental studies were also suggested including juvenile and adult life stages movement patterns using tagging technology, egg and larval dispersal models, optical transect surveys extending from individual turbines, analysis of fisheries monitoring data to detect impacts on highly migratory species, cable monitoring and monitoring of acoustic impacts.

The experimental design for the seasonal surveys followed the Before-After-Control-Impact (BACI) design originally proposed by Green (1989), using his principals on environmental sampling as guidance (Underwood 1994; Christie et al 2020). The experimental design was also set up to coordinate with ongoing large-scale surveys conducted by SMAST and other institutes such as VIMS, NOAA fisheries and state fisheries agencies. This structure would enable the development of large scale Before-After-Gradient (BAG) experimental frames works as well. Following the BACI design a control area was designated close to the development area with the goal of comparing catch rates, population structure, community composition, abundance, size distributions, vital biological statistics (sex ratio, condition factor, etc) and environmental parameters (temperature, salinity, Dissolved Oxygen, substrate). Using a stratified random design, the sampling regime was developed to determine a 25% or less change in the abundance of the four most common species over time, based on preliminary data for the area. Surveys began in 2019.

Two benthic macro-invertebrate surveys are underway (led by K. Stokesbury and K. Cassidy), a drop camera optical survey and a ventless trap lobster/crab/black sea bass survey. The drop camera system is a quadrat sampling technique structure on classic ecological sampling; it uses the SMAST sampling pyramid that deploys three cameras (digital still and video) and estimates the substrate as well as 50 different invertebrate and fish species that associate with the sea floor (Bethoney and Stokesbury 2018a,b). Commercial scallop fishing vessels and crew conduct this sampling with SMAST scientists. This survey is used in the NOAA stock assessment of the sea scallop resource, the habitat omnibus developed by the New England Fisheries Management Council) and in an environmental impact assessment of the scallop fishery (Stokesbury and Harris 2006). The data set for Vineyard Wind therefore ties into a 20-year survey that covers the continental shelf from Virginia to Banquereau bank, Canada (Stokesbury and Bethoney 2020).

The Ventless trap survey is a baited sampling design that focuses on the American lobster, Jonah and rock crabs but also collects several other species (Courchene and Stokesbury 2011; Cassidy 2018). This work is conducted in partnership with the Massachusetts Lobstermen's Association. At 30 randomly selected stations in the impact and control areas (15 each) a string of 6 traps (3 vented and 3 ventless) are set the first and third weeks of each month from May to October. Three days later the traps are hauled, and the catch is speciated, measured and sexed (for lobsters and Jonah crabs). A seventh unbaited black sea bass pot is set to sample the black sea bass population. This survey follows the same sampling design as the Massachusetts, Maine, and Rhode Island state ventless trap surveys allowing broader scale comparisons (Zygmunt 2021). At each sampling location temperature is recorded as well as other environmental data (pH, Salinity, and Dissolved Oxygen) at select locations evenly distributed by each 10m depth contour. On survey days when the traps are baited and set for their soaking period a 10-minute plankton tow is also conducted at each location; larval lobster and associated ichthyofauna are collected and later identified at SMAST. The sampling net was designed by Robert Miller (DFO Canada, retired) and has been used in a series of Masters' theses examining distribution and abundance of lobster larvae in Buzzards Bay (Milligan 2010; Casey 2020). This research has been expanded to the larger Massachusetts-Rhode Island wind energy lease area through funding by the MACEC in 2020 and is being coordinated with larval sampling efforts in Rhode Island, Maine, Georges Bank, and the NOAA Narragansett laboratory.

A seasonal demersal trawl survey (led by Dr. P. He and C. Rillahan) monitors the species abundance, population characteristics and community structure of marine fish and invertebrate communities including commercially important species such as squid, groundfish, summer flounder, whiting and black sea bass. The survey samples the control and impact areas using a systematic random sampling design. Survey equipment and protocols were adapted from VIMS Northeast Area Monitoring and Assessment Program (NEAMAP), which in turn is linked to the NEFSC groundfish survey. Three commercial fishing vessels have been used to conduct this research, F/V Heather Lynn, F/V Guardian and F/V Endurance. Sixty 20-minute tows at 3.0 knots during daylight hours are made per season. Environmental (sea state, wind speed, wind direction, bottom temperature) biological (aggregated catch weight per species, individual weights, and lengths) and net measurements are recorded for each tow. As with the other surveys the impact analysis is comparable with the larger NEAMAP survey that extends along the Atlantic coast and is used in NEFSC stock assessments (VIMS 2023).

Successful field seasons have been completed for all these surveys in 2019 and 2020, despite the difficulted associated with the Covid-19 pandemic. The 2019 reports, after submission to Vineyard Wind, have been reviewed by representatives of the fishing industry and three independent scientists. All the documents are available to the public (Vineyard Wind 2023), and a data-sharing agreement is in place. These surveys are planned to continue until construction, sample during construction when possible, and ideally then sample for three years post-construction, with the possibility of additions years throughout the life of the windfarm.

4.3.3 Acknowledgements

We thank Ron Smolowitz (commercial fishing industry representative) and 2 anonymous reviewers for their thoughtful comments and suggestions that improved this paper.

5. REGIONAL SCIENCE PLANNING

5.1 Regional Science Planning

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5.1.1 Introduction

The scale and pace of planned offshore wind activity has been exponentially increasing in U.S. waters since the early 2010's. Fishermen and federal regulators have identified the need for a coherent regional framework to collect and disseminate credible research on the relationships between fisheries and proposed wind development ever since the large geographic span of this new industry became apparent (Dalton 2019). Innovative uses of existing tools such as monitoring technology, experimental design, LEK, and cooperative research must form the cornerstones of any approach to identify conflicts and solutions between these 2 industries (Methratta et al. 2020). The various involved sectors working individually or collectively have initiated efforts to improve research coordination, communication, and data sharing, but more progress is needed particularly to integrate these with traditional fisheries science.

Accurate and up-to-date information is crucial for sound offshore wind energy planning. The best available science is necessary to support and improve the quality of evidence-based agency decision making (FLOWW 2014). A robust scientific record is also a prerequisite to effective engagement and to support dialogue amongst affected parties (Reilly et al. 2016). The absence of such information, or pervasive scientific uncertainty, creates barriers to meaningful engagement (Haggett et al. 2020).

In the U.S., offshore wind energy developers are encouraged or required to conduct project-specific monitoring and data collection. Multiple entities, including federal and state agencies, academic institutions, fishing industry associations, and others, perform additional research related to fisheries and offshore wind, and some developers conduct supplemental data collection and monitoring efforts related to fish stocks. The lack of coordination among these monitoring efforts has led to individual developers collecting data without harmonized goals, which may hinder future analysis of long-term effects of OSW. All regions have lacked early cross-sectoral efforts to communicate and coordinate, which would expand the utility of existing efforts and minimize redundancy. The inclusion of the fishing industry, and other stakeholders, in designing, executing, and disseminating results from these efforts would improve research products and buy in across sectors.

5.1.2 Identifying the Need

Wilding et al. (2017) described the state of knowledge regarding the impacts of offshore wind to marine ecosystems as "data-rich, information-poor" (DRIP). They assert that benthic research to date is pervasive but lacking in clarity and rigor, formulaic, and unrelated to justified temporal or spatial scales, which has resulted in a failure to enhance understanding of offshore renewable energy interactions at relevant ecosystem scales.

Individual project-specific monitoring data in itself is not necessarily informative to evaluation of regional or cumulative impacts of offshore wind to fisheries. It is also challenging to integrate with longstanding fisheries science activities, such as stock assessments and habitat management (Methratta et al. 2020). The NEFSC has run its Northeast Bottom Trawl Survey since 1963. Any changes to the survey must be calibrated and integrated into the stock assessment process, which can require multiple years of data, at-sea trials, and analysis before full integration. In order to produce informative results, additional offshore wind scientific efforts must focus more on hypothesis-driven functional research at the relevant spatial and temporal scales, which will require coordination of data collections and exchange as well as joint research agendas (ICES 2021b).

5.1.2.1 Evolution of Approaches

The development and implementation of a coordinated effort in the U.S. toward regional science planning have lagged behind many other aspects of offshore wind energy planning. Many fisheries experts, particularly in the Northeast Region, began discussing the need for coordination soon after the first leases were announced. The Massachusetts Division of Marine Fisheries coordinated and published the first regional-scale studies recommendations with input from multiple groups including the fishing industry (MA DMF 2018). Various states, researchers, fishing industry members, and others engaged in less formal processes to expand upon this effort, developing ad hoc lists of research priorities, including a series of discussions between Rutgers University scientists and New Jersey fishing industry members specific to the Mid-Atlantic region. Later in 2019, 2 grant programs by the State of New York and a joint effort by Massachusetts, Rhode Island, and BOEM funded regional studies and region-wide scientific research in order to move in the important direction of improving the utility of offshore wind data and research related to fisheries (Mass.gov 2020; NYSERDA 2019). Each entity chose priorities for its own research funds based on input from its state fisheries and offshore wind working groups and informal coordination with regional experts.

5.1.2.2 Formation and Implementation of ROSA

As these regional discussions developed, the fishing industry in particular advocated for the formation of an organization focused on coordinating research about fishing and offshore wind interactions. In March 2019, RODA, NMFS, and BOEM announced a Memorandum of Understanding (MoU), in which they agreed to explore collaboration on the development of a regional research and monitoring framework to ensure decisions are made on the best available science, pursuant to a "mutual interest in improving the accuracy, relevance, and usefulness of this information and research."

Following execution of the MoU, RODA led an effort with the co-signatories to further develop the framework model and invited state agencies, regional fishery management councils, and offshore wind energy developers to join. The Consensus Building Institute provided significant facilitation support for this effort. Participants examined multiple models for collaborative scientific coordination, including the North Pacific Research Board, Gulf of Mexico Alliance, Collaborative Offshore Wind Research into the Environment (U.K.), Offshore Renewable Joint Industry Project (U.K.), and others. This resulted in RODA incorporating ROSA as a standalone entity focused solely on research, with a collaborative framework model completed in September 2019 (ROSA 2019). ROSA hired its first executive director in March 2020 and research director in July 2021.

ROSA is working to establish itself in the science community and determine its organizational priorities going forward. In an early successful project, ROSA partnered with staff at GARFO to coordinate a multisectoral team tasked with developing monitoring guidelines for offshore wind developers. The Offshore Wind Project Monitoring Framework and Guidelines provide a monitoring framework and principles for fisheries biological monitoring studies designed and conducted by offshore wind developers for each lease area for some fishery stocks; benthic habitat/EFH and socioeconomic monitoring studies are still to be addressed (ROSA 2021).

5.1.2.3 Further Regional Efforts

As described above, there is broad mutual interest in a collaborative regional research and monitoring framework to ensure decisions are based on the best available science. There is also a substantial need for improved information sharing across all interested parties. However, individual sectors (such as government, academia, fishing industry, developer, and conservation communities) should also strive to improve dissemination, communication, and transparency of research and knowledge.

More recently, multiple organized communication networks have supported regional coordination, although many are of short- or medium-term duration. Some of these include:

- ICES Working Group on Offshore Wind Development and Fisheries and ICES Annual Science Conferences;
- Oceanography journal special issue: Understanding the Effects of Offshore Wind Development on Fisheries (Twigg et al. 2020);
- American Fisheries Society Annual Conferences;
- This “Synthesis of the Science” project;
- State fisheries working group meetings; and
- Consortium for Ocean Leadership conference.

Each of these efforts bridges disciplines and sectors but has included strong participation from fisheries experts, thus enhancing their value to fisheries science. Findings and recommendations from these efforts are integrated throughout this Synthesis of the Science report and should be fully considered and implemented to continue to improve research coordination.

In considering regional science overall, it is important to note that hypotheses generated by the fishing industry regarding the environmental effects of offshore wind energy remain relatively unstudied and uncommunicated in comparison to those advanced through the permitting process or by offshore wind developers. Therefore, as a companion effort to existing regional research coordination, RODA organized the fishing industry to develop a list of research priorities considered essential from their perspective (Section 5.2 Fishing Industry Identification of Research Priorities) These priorities have been disseminated to decision makers, various sectors involved in fisheries and offshore wind energy efforts, academics, and the public to improve consideration of fishermen’s priorities and improve the use of FEK in regional priority setting.

5.1.3 The major gaps in our knowledge

The research recommendations outlined in the previous chapters indicate an enormous amount of research is still needed in order to understand the impact of offshore wind on the environment and fisheries, but time is limited. Fishing industry members have consistently identified research into the impacts of OSW as a priority prior to construction since their very first meetings with developers. A timely, productive regional science plan for offshore wind could have resulted in an enhanced ability to understand the environmental interactions resulting from the first large-scale projects, especially on a cumulative scale.

In early 2021, BOEM approved the Record of Decision for the first federal waters OSW project (Vineyard Wind I), with construction scheduled to begin in 2022, and announced plans to expedite timelines for multiple subsequent projects. Despite these permitting milestones, there are no standard requirements related to regional science planning. Fisheries experts continue to request rapidly improved coordination on this topic in light of planning to achieve 30 gigawatts of energy from this particular source in less than a decade.

The need for enhanced regional coordination applies to most or all areas of fisheries and offshore wind energy science, including the examples below.

5.1.3.1 Stock Assessment Surveys

BOEM and NOAA Fisheries announced in May 2021 that the 2 agencies were developing a program to "address impacts from offshore wind development on NOAA Fisheries' surveys…" (NMFS 2021d). Section 3.2 outlines the impact OSW will have on NOAA Fisheries' ability to assess fish stocks via its ecological survey, as it has done since 1963. NOAA Fisheries has advised that the offshore wind projects' current environmental monitoring work (frequently referred to as surveys) cannot be integrated with, or substituted for, the federal surveys for fishery management purposes. Rather, they use different methodologies, and no calibration work has been conducted. Integration of data collected by offshore wind developers through biological and habitat monitoring efforts with traditional fisheries data requires increased coordination between projects and sectors and a regional approach.

5.1.3.2 Fishermen's Ecological Knowledge

Fishermen's Ecological Knowledge (FEK) remains unstudied and underused despite being a major information resource regarding long-term trends in the marine environment, which may prove crucial to understanding the effects of climate change and OSW. A handful of studies in progress seek to incorporate FEK into offshore wind energy research through semi-structured interviews and other methods, but most are led by academic or industry groups, and there is no clear mechanism for broad information sharing. FEK studies, in general, are particularly time-consuming and lag far behind the pace of offshore wind decision making. Effective coordination could ultimately improve efficiency and applicability of these efforts to broader than single inquiries. It could also provide additional opportunities for fishermen to participate in development of hypotheses and move out of a "reactionary" role in the scientific process, in line with best practices in cooperative research (Stephenson et al. 2016).

5.1.3.3 Habitat Data

Detailed synoptic habitat data of lease areas would aid in understanding the status of habitats utilized by finfish and shellfish. Offshore wind energy developers generate large amounts of habitat data in the course of their survey activities. Currently, there is little to no integration of these data streams with fisheries science and management activities. Fisheries professionals have expressed interest in using this data for this purpose if it can be collected in usable formats and shared with interested researchers. Only data collected specifically for the EFH consultation is directly submitted to NOAA Fisheries, but the agency has found the existing BOEM benthic survey guidelines to be "inadequate" and "inconsistently applied" to achieve their intended purpose and therefore recently updated its Recommendations for Mapping Fish Habitat (GARFO 2021). The new guidance is intended to help to ensure developers "collect baseline habitat data and information that is both adequate for EFH consultation and consistent across all projects in our region (GARFO 2021)."

5.1.4 Recommendations/Conclusions

The thoroughness of scientific research to understand interactions between OSW and fisheries, and the credibility of the information generated, is both a goal of, and prerequisite to, effective collaboration. Developers and governing agencies approaching new large-scale development have expressed desire to maintain the trust from existing local communities in order to achieve coexistence, and fishing industry members have dutifully provided substantial input since the earliest days of OSW planning. However, the lack of coordination for regional science has resulted in a barrier (and lost opportunity) to these planning efforts.

Fishing industry members have reported great frustration over the lack of attention to their hypotheses regarding the effects of OSW development on fisheries and the environment. While the pace of OSW development continues to increase, research to inform the mitigation of its impacts is much less advanced and often project-specific or proprietary to a leaseholder. The timeliness of scientific efforts is a critical component of whether their discoveries can lead to real-world implementation, and open communication of their methods and results determines whether they are perceived as credible. Expanding efforts for regional science coordination is considered a high priority that would be responsive to these fishing industry criticisms. Better incorporation of fishing expert knowledge and participation, including by affording full due weight to industry-proposed research topics, would facilitate the achievement of many shared goals for the natural and human environments.

5.2 Fishing Industry Identification of Research Priorities

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5.2.1 Introduction

Members of the fishing industry have numerous concerns associated with offshore wind, and their involvement in the co-design of methods and approaches to mitigate adverse impacts is integral to achieving a sustainable ocean economy (Methratta et al. 2020). There has been no comprehensive attempt, to date, to summarize those concerns and identify opportunities for cooperative research. Thus, RODA compiled a list of research priorities identified by the fishing industry to assist in the efforts discussed in Section 5.1. Improving the state of information (and communication of such information) regarding these priorities will clarify the impacts OSW development will have on the marine ecosystem and the existing industries reliant on it.

Fishermen have long been considered trusted research partners in fisheries management activities, and enormous advances in scientific knowledge have been achieved through their valuable roles in hypothesis development and testing (Johnson and van Densen 2007). Research activities in OSW planning have lagged behind those of established marine ecosystem science with regard to the inclusion of fishermen’s knowledge. Therefore, a comprehensive list of research priorities developed by the fishing industry is essential for predicting and evaluating socioeconomic and environmental impacts and interactions among fisheries, fish stocks, and OSW.

5.2.2 Methods

RODA staff developed a survey for the fishing industry to identify perceived gaps in knowledge related to OSW and fisheries. The survey was not restricted in scope; answers could focus on any topic related to OSW and the marine environment/fisheries. RODA circulated the survey to its members, published it on the RODA website, provided it to regional fishery management councils for distribution, and requested participants in the fishing industry to circulate the survey throughout their networks to maximize the number and diversity of responses. A total of 88 survey responses were received from fishing industry participants from across the United States, representing thousands of employees and association members.

The responses were compiled and synthesized into draft summary tables. In situations where answers were unclear, the survey respondent was contacted to ensure correct interpretation. Response tables were then circulated to fishing industry reviewers to verify completeness and accuracy. The research priorities were not ranked for 2 reasons: (1) survey results indicated variability in priorities depending on fishery, region, and other factors that would lead to the omission of important concerns and potential impact factors if prioritized too broadly; and (2) this study did not evaluate the representativeness of the survey results received across the entire U.S. fishing industry; however, the highest number of responses were received from individuals heavily engaged in OSW development-related issues.

5.2.3 Survey Responses Generally

In addition to the specific research topics listed herein, a number of respondents suggested general considerations relevant to the role of research in OSW planning. The research recommendations evidenced a clear perception that meaningful interaction has not occurred with the fishing industry during OSW siting processes. The fishing industry has appealed to regulatory authorities to create regional environmental monitoring plans to address a large number of outstanding questions but observe that research approaches remain piecemeal. Monitoring alone is also considered insufficient to constitute a mitigation practice. Once necessary data sets are gathered, and the scale of potential environmental and socioeconomic impacts identified and better understood, adequate strategies must be identified, established, and implemented that would effectively reduce impacts. These mitigation actions should be designed in consultation with the fishing industry and OSW developers to maximize their chances of adoption and success. The fishing industry suggested enhancing opportunities to learn from established OSW projects abroad and recommended analyzing fisheries data from operational projects. Lessons can be learned on a large scale of topics, including sedimentation and scour. Respondents recommended that alternative siting strategies be developed that avoid key fishing grounds while benefiting OSW programs, reflecting the general preference to reduce significant negative impacts to both industries. There were also several suggestions to develop and clarify science-based decommissioning strategies from the earliest OSW planning stages.

5.2.4 Research Priorities

The following research priorities were identified from survey responses.

5.2.4.1 Cumulative Impacts

The fishing industry expressed clear concern over the lack of CIA identifying fishery- and ecosystem-level impacts from compounding impact factors and across multiple projects. The introduction of human-made structures to the ocean will affect every aspect of the ecosystem, as seen in the numerous research priorities identified below. At present, limited or no cumulative impact analyses exist at regional levels. A detailed analysis should address all scales as well the effects of project distance to the cumulative impact intensity.

The following list describes specific research recommendations gathered from the surveys, categorized by broad topic area.

5.2.4.1.1 Business, Communities, and Socioeconomics

- Economics
    - Compensation for lost fishing grounds
    - Direct and cumulative impacts to seafood supply, cost, and markets
    - Net economic impacts from loss of fishing-related revenues compared to OSW
    - Economic analysis of impacts of OSW accounting for regulatory restrictions on switching to other target fisheries or locations
    - Economic viability of legally harvesting an “alternative” stock by season if a vessel loses access to its primary species
    - Cost to fleet and public of losing access to more fishing grounds to closures or other factors, such as interarray cable connections for floating OSW turbines limiting access to those areas to surface gear types
    - Financial impact on future generations of family-owned fishing businesses, from OSW and in combination with other challenges to fishing communities

  - Expected economic losses to each potentially impacted coastal community, statewide and regionally

- Business Impacts

  - Seafood industry shoreside infrastructure losses
  - Increased OSW vessel maintenance activities crowding or usurping existing harbor infrastructure, and thus impacting fisheries operations, transit, and offloading activities
  - Higher fuel costs and resulting effects to fishermen, gear suppliers, fish markets, dock workers, and ice suppliers
  - Changes in fishing industry's fuel consumption and vessel maintenance due to transit and fishing impacts
  - Changes in insurance costs, including resulting shoreside economic and market effects

- Seafood Production

  - Direct and cumulative impacts to domestic seafood production and supply
  - Importance of seafood in sustaining domestic food security through climate-related anticipated disruptions, such as water shortages and drought, in other food production sectors
  - Increased reliance on imported seafood
  - Societal costs of OSW and displacement of protein provision in light of recent food security experiences associated with the COVID-19 pandemic
  - Changes in greenhouse gas emissions and net carbon footprint resulting from increased imported seafood and increased transit times compared with domestic production

- Displacement Effects

  - Impacts of loss of access and higher levels of localized overfishing
  - Impacts of increased competition from loss of fishing grounds
  - Creation of additional fishing closures
  - Impacts of exclusion in cases where an individual fishing permit only allows access to an area slated for development
  - Economic and societal impacts of relocating fishing effort due to closure of historic fishing grounds by OSW siting and no-fishing zones established around the lease sites
  - Ecological and socioeconomic impacts of shifting fishing effort due to increased fishing pressure on alternative/remaining fishing grounds
  - Socioeconomic impacts resulting from stock assessment survey modifications
  - Specific examples raised on this topic include the Atlantic surfclam fishery out of Atlantic City, NJ, and the Northwest pink shrimp fishery

- Culture and Heritage
    - Analysis of equity and the effects of displacing fishermen from public fishing grounds for private entities
    - Impacts to traditions and fishermen's displacement from historic grounds they have fished for over a century
    - Role of fishing in coastal tourism economy
    - Diversity and environmental justice in fishing communities
    - Environmental and social justice for the vast majority of Americans whose only access to the living marine resources off the U.S. coast is through the products the fishing industry provides.

- Employment
    - Potential benefits to traditional fishermen, including alternative occupations for fishermen approaching retirement or new entrants to the industry
    - Loss of experienced crew to OSW operations
    - Net job losses to the seafood industry and dependent businesses, by community, state, and in total

5.2.4.1.2 Environmental Impacts

- Biological Resources: Protected Resources
    - Impacts of strikes, sound, and EMF on protected resource migration patterns and mortality or serious injury
    - Impacts of cables tethering floating wind turbines on protected resource migration patterns and mortality or serious injury
    - Interactions between seabird life, offshore wind, and fisheries
    - Effects of climate/ecosystem change to species that constrain fisheries
    - Effect of mooring lines to whale migration, feeding, behavior, and entanglement
    - Impacts to migratory patterns of protected resources such that those species may be more likely to co-occur with other gear types
    - Socioeconomic impacts from potential mitigation measures, directed at the fishing industry, to reduce further mortality or serious injury due to immobility of turbines
    - Specific examples raised on this topic include salmon in the whiting fishery, whale entanglements in sablefish and Dungeness crab pot fisheries, Pacific flyway, species protection of short tailed albatross, humpback whales, blue whales, and grey whales

- Biological Resources: Fish Stocks and Ecosystems
    - Presence of structures on local environment, especially where overlapping with EFH and Habitat Areas of Particular Concern

  - Impacts to plankton, krill, and lower trophic level marine life
  - Effects to bait fish
  - Effect of turbine size on magnitude or extent of impacts sizes
  - Recolonization timelines after benthic disturbance
  - Impacts to benthic feeding, other fish behaviors, and full life history cycles
  - Ability to assess stocks using impacted state and federal surveys
  - Specific examples raised on this topic include scallops, whelk, squid, squid larvae, eggs, clams, lobster, spawning fish, salmon, crab, whiting, and black sea bass

- Spawning and Migration

  - Interactions with fish that use benthos for various life stages
  - Effects of climate change/changing ocean ecosystems to movements of target stocks
  - Mortality due to turbine installation, armoring, and operations
  - Impacts from turbines and installation and maintenance vessels to marine life and seafood
  - Impacts on fishing ground composition and productivity
  - Effects on shellfish and fish recruitment and population
  - Predator/prey relationship changes (including from hardening of sea floor and introduction of armoring or scour) and increase in prey species
  - Specific examples raised on this topic include crabs, sole, groundfish, sea stars, octopus, scallops, whelk, squid, squid larvae, eggs, clams, lobster, spawning fish, salmon, and whiting

- Physical Oceanography

  - Effect on vertical motion of the ocean (upwelling/downwelling) and water column stratification
  - Impacts to sea surface and water column temperatures
  - Atmospheric impacts associated with energy removal
  - Impacts to currents due to energy removal
  - Turbine-induced microclimatic effects, including localized warming or cooling
  - Interactions with hypoxic areas and/or ocean acidification
  - Specific examples raised on this topic include the Mid-Atlantic Cold Pool, West Coast upwelling, wind speeds, coastal and inland weather patterns, extent and impacts of wake disturbances, and reduction in surface winds off Northwest coast

- Habitat

  - Changes and conversion of bottom type due to flow and current changes and introduction of structure in the form of foundations and cable routes
  - Effects of bottom attachments and foundations

  - Loss of benthic habitat of sand shoaling species, associated effects to species distribution, and resultant impacts to commercial landings in different states based on fishing grounds and top landed catch
  - Siting considerations based on effects to specific habitats from structure in the water
  - Effects of anchors (may attract species that constrain fisheries or displace target species at various life stages)
  - Identification and avoidance of hard substrates and other sensitive habitats
  - Impacts when co-located in protected areas
  - Impacts of the use of cooling stations on local water temperatures, larval populations, and local food webs
  - Specific examples raised on this topic include eelgrass, Shuster sanctuary for horseshoe crabs, anchoring, rock piles, mattressing, black sea bass

- Studies by Impact Factor

  - EMF

    - Fish and shellfish behavior, spawning, and migratory patterns
    - Effects at individual, population, and ecosystem levels
    - Specific examples raised on this topic include Pacific coast salmon, finfish, shellfish, squid, whelk, HMS stocks, and crabs

  - Light

    - Impacts to photosensitive demersal and infaunal species, including those that bury to varying depth in soft substrate
    - Impacts to photosensitive pelagic species, including water column movement
    - Specific examples raised on this topic include whelk and squid

  - Noise, vibration, pressure

    - Impacts of pile driving on marine species
    - Pressure on shellfish
    - Effects of operational sound on marine species
    - Noise and other impacts impacts derived from geophysical and technical surveys on invertebrates, fish, and marine mammals
    - Effect of the operational noise from OSW facilities on marine species
    - Impacts of above water and sub-surface noise from turbine operations on fish stocks, behaviorally and otherwise
    - Specific examples raised on this topic include squid, scallops, whelk, fish, lobsters, and marine mammals

    - Effect on harmful algal blooms that result in domoic acid and other health toxins

    - Sedimentation and scour

        - Sediment plume and settlement effects on mollusc, invertebrate, and finfish populations, including filter feeding and recruitment
        - Impacts of silt migration from structures on the seafloor
        - Effects on scouring on sediment around turbines
        - Specific examples raised on this topic include clams and scallops

    - Role of OSW structure as FADs resulting in the potential to inhibit access to fishery stocks and effect migration patterns, stop-over points, and so forth, for fished species
    - Effect of mussel buildup on structures and cleaning strategies

5.2.4.1.3 Fishing Regulations/Management Impacts

- Ability to achieve optimum yield

    - Catch allocation among fisheries, including commercial, recreational, and state-by-state.
    - Inshore and offshore commercial and recreational regulations and allocations
    - Availability of commercial and recreational fish in harvestable areas
    - Magnitude of unnecessary (from a fisheries management perspective) reduction of fishing grounds

- Cumulative impacts of changing fisheries regulations and OSW to fisheries, both retrospectively and projections of future states estimate landings and revenue projections, using historical data as baseline
- External changes to fisheries management processes to accelerate wind leasing, such as NMFS or Councils changing fishing regulations to reduce fishing in potential lease areas
- Impacts to, and resulting from, regulations relevant to fisheries and marine mammal interactions
- Impacts to existing longstanding federal and state fishery surveys informing stock assessments
- Impacts to quotas resulting from inability to conduct existing surveys increasing uncertainty in stock assessments
- Impacts to rebuilding programs
- Explore mechanisms to lease ocean grounds to fishermen equitably with OSW
- Fisheries management actions to protect fishermen and fishing communities from OSW impacts

- Specific examples raised on this topic include the West Coast, northeast multispecies, and international stock assessments which include U.S. harvest as a model input, and coastal pelagic species

5.2.4.1.4 Monitoring and Review Recommendations

- Siting-Related Analyses:
    - Highest available resolution effort, catch, landings, and geographical data from all fisheries operating in areas under consideration for OSW development before siting occurs
    - Highest available resolution abundance and distribution data of all marine species in areas under consideration for OSW development before siting occurs

- Pre-Construction Monitoring to Establish Baseline:
    - Conduct comprehensive surveys in lease areas prior to construction covering:
        - State and federally managed commercial and recreational fish species
        - Habitat characterization of project sites, including cable routes
        - Acoustic characterization and acoustic modeling to anticipate construction noise levels and determine appropriate mitigation measures
        - Presence of protected species, with maps of seasonal abundance, migration routes, and known breeding and feeding areas
        - Baseline study of ocean circulation patterns/current speed, along with hydrodynamic modeling to predict how circulation and currents may change
        - Water quality conditions
        - Monitoring programs designed to adequately sample all species with appropriate gear and timing to detect spawning or migrating activities
        - Development and initiation of monitoring programs utilizing the recreational fishing industry to evaluate baseline conditions

- Before-and-After Analyses
    - Detect any changes in presence/absence of adult, juveniles, and eggs after construction
    - Detect any changes in species composition after construction
    - Evaluate CPUE pre/post construction
    - Specific examples raised on this topic include the ventless lobster/Jonah crab trap abundance survey and squid

- Construction

  - Detect any changes to pelagic and demersal species migration and/or behavior during cable deployment and turbine construction using acoustic tagging
  - Determine any acoustic impacts, marine mammal noise response, oceanographic processes, entanglement, invasive species, bird and bat collisions, and fish and fishery impacts occurring during construction phase

- Operational

  - Determine any acoustic impacts, marine mammal noise response, oceanographic processes, entanglement, invasive species, bird and bat collisions, and fish and fishery impacts occurring during operational phase
  - Monitor larvae and juvenile abundances and distribution
  - Analyze recreational CPUE data within and around lease areas to identify emerging issues

- Decommissioning

  - Impacts associated with decommissioning activities
  - Long-term impacts of abandoned infrastructure on fishing grounds and fish populations

5.2.4.1.5 Safety

- Radar

  - Aspects of radar that cannot be replaced by AIS
  - Clutter or interference, particularly in poor weather
  - False targets
  - Impacts to HF Codar OOS radar used for SAR in case of person overboard
  - Impacts to NEXRAD and weather condition forecasting
  - Impacts of noise, above water and sub-surface, on radar, sonar, fathometers or other electronics integral to fishing safety

- Physical loss or abandonment of turbines or other materials
- Spatial operational needs of mobile and fixed gear fisheries

  - Extent to which planned turbine configurations will limit mobile gear fisheries in normal operating conditions

- Radio

  - Interference of current safe channels entering and leaving port

    - USCG ability to communicate on radio channels

- SAR

    - Ability of fishing vessels to assist each other in times of difficulty
    - USCG ability to provide assistance to fishing vessels in distress in or around arrays

- Transit Lanes

    - Systemic approach to design and safety
    - Allision risk correlation with number and position of turbine, and appropriate transit lane scenarios

- Traffic

    - Impacts from project maintenance traffic
    - Effects of changes in vessel traffic to surrounding fishing areas

5.2.4.1.6 Supply Chain

- Costs and Benefits

    - Cost and economic impact of energy production overall and to the consumer, including government subsidies
    - Cost of long-term maintenance
    - Cost-benefit of OSW vis-a-vis other energy sources, including climate and environmental impacts
    - Net energy production considering energy costs of supply chain
    - Net climate benefits and carbon footprint of OSW given environmental costs of production, operation, and decommissioning
    - Economic and environmental impacts of downstream project challenges, such as insolvency, unforeseen maintenance, pollution, or excessive removal cost

- Technology

    - Effect of seismic activity on turbines and infrastructure harbors
    - Lifespan and maintenance plans
    - Impact of local contamination resulting from routine maintenance or mechanical failure
    - Feasibility and associated risks of floating and fixed turbine technology in specific, occasionally extreme, weather and ocean conditions of areas under consideration
    - Potential responses to equipment failure
    - Operational effects of changes in wind

  - Maximum depth of floating OSW deployment, specifically feasibility of siting deeper than 1300 m
  - Differing impacts of floating substations compared to fixed substations
  - Specific examples raised on this topic include tsunamis, Crescent City Harbor, and specific conditions of the California coast from Cape Mendocino northward

5.2.4.1.7 Transmission

- Environmental impacts of cables along their routes

  - Fish and protected resource movement (localized and migration patterns) over transmission and inter-array cables
  - Impacts of cable burial techniques, including jet plowing, on benthic and demersal species
  - Impacts to the marine environment of turbine failure or cable breach
  - Ecological and socioeconomic impacts associated with transmission
  - Effects of cable placement in sensitive habitats
  - Impacts to nearshore benthic habitat
  - *Specific examples raised on this topic include shellfish and fish species, conch, Vineyard bay scallops and clams, sole, flounder, halibut, whelk, estuaries, and squid spawning habitat

- Operational interactions between fishing activities and cables

  - Ability to anchor amongst turbines, including considerations for floating cables and mooring lines
  - Mobile bottom tending gear
  - Probability of cables becoming unburied
  - Monitoring options for cable burial based on local and regional conditions, including currents and sediment types.
  - Minimum safe cable burial depth, including analyses of exposed cables off Block Island and Europe

- Cable technology

  - Differing impacts of AC and DC transmission cables
  - Impacts of transmission cables running long distances to land
  - Specific examples raised on this topic include shellfish and fish species, conch, Vineyard bay scallops and clams, sole, flounder, halibut, whelk, estuaries, squid spawning habitat, and very large potential West Coast cable routes

6. TABLES AND FIGURES

Table 1. Summary of knowledge gaps for benthic habitat modification and recommended future studies

Criterion	Description
Primary	Theme: Fisheries and Food Webs
Knowledge Gaps	We have some knowledge about effects on fish conditions at spatial scales local to the turbines; less on fish population dynamics
Recommended Future Studies	Develop integrated measurements of functionality of both hard and soft substrata communities in relation to carbon flow, nutrient cycling, provision of biomass, and secondary productivity. We have some knowledge on effects on carbon flows but lack a complete picture needed to be able to assess the position of all commercial and recreational fish in the affected food web Effects of introduced habitat on food web interactions (increased predation/better refuge)
Scale	Species: Individual and population Spatial: Far-field Temporal: Short- through long-term
Primary	Theme: Fisheries Interactions

Criterion	Description
Knowledge Gaps	We have poor knowledge on the effects of substrate change on fisheries operations
Recommended Future Studies	Examine spatial and temporal changes in gear use, amount of fishing effort, and species and size composition of catch
Scale	Species: Population Spatial: Near- and far-field Temporal: Short- through long-term
Secondary	Theme: Environmental Disturbance
Knowledge Gaps	We have limited knowledge about how stochastic events, such as Nor'easters and hurricanes, factor into variability in distribution and abundance of fish species
Recommended Future Studies	Estimate changes before and after past stochastic events using existing fishery independent and dependent data
Scale	Species: Individual and population Spatial: Near- and far-field Temporal: Short-term
Secondary	Theme: Dispersal Pathways and Non-Native Species

Criterion	Description
Knowledge Gaps	It is unclear whether the results of modeling of larval dispersal and occupation of OSWs by non-indigenous organisms can be generalized and affect wider habitats. Even less clear is the effect on highly mobile organisms in pelagic and demersal habitats.
Recommended Future Studies	Modeling additional build-out scenarios based on regional data (ECOMON) and site-specific data collected from projects as they are constructed. Data should include distribution and abundance of plankton (including larvae), colonizing species, and associated mobile species.
Scale	Species: Individual and population Spatial: Near- and far-field Temporal: Long-term
Tertiary	Theme: Monitoring Methods
Knowledge Gaps	Standardized sampling strategies and techniques
Recommended Future Studies	Evaluation of applicability of existing standardized monitoring strategies and sampling techniques
Scale	Species: Population Spatial: Near- and far-field Temporal: Short- through long-term

Table 2. Summary of benthic habitat modification topics that would benefit from additional or expanded research.

Criterion	Description
Primary	Theme: Scale of Interactions and Fisheries
Knowledge Gaps	How differential spatial and temporal effects translate to the population dynamics of those species affected by OSWs is key to our understanding of how offshore wind infrastructure and associated OSW artificial reefs impact marine ecosystems, but this is yet to be fully understood.
Recommended Future Studies	Coordinate site-specific studies of OSW impacts with ongoing stock assessment processes to estimate the marginal effects of wind development on changes in abundance relative to other forcing factors.
Scale	Species: Population Spatial: Near- and far-field Temporal: Short- through long-term
Primary	Theme: Wind Farm Design, Scale of Interactions, and Fisheries
Knowledge Gaps	Effects of turbine spacing and orientation.

Criterion	Description
Recommended Future Studies	Food web dynamics and habitat connectivity are very important to connect local benthic effects to fish commercial and recreational species and ecosystem effects. Within the U.S. OSW context, the emerging consensus is that the patch size of benthic effects will be relatively uniform across OSWs (ca. 1 nautical mile [NM] distance from patch to patch with a patch size of about 20,000 m^2 [0.06 NM^2]). Consider how these distances influence the catchability of these species in recreational or commercial fishing gears. Consider how turbine spacing relative to oceanographic features contributes to connectivity through alterations in distribution of nutrients, phytoplankton, and larvae. Consider how spatial scales of fish movement align with occurrence and spacing of windfarms and the implications of this alignment, or lack thereof.
Scale	Species: Individual and population Spatial: Near- and far-field Temporal: Short- through long-term
Primary	Theme: Fisheries, Dispersal Pathways, Non-Native species, Sensitive Species, and Climate Change
Knowledge Gaps	Habitat suitability questions

Criterion	Description
Recommended Future Studies	Collate results of site-specific monitoring of individual turbine foundations and within wind farm effects in comparison to changes in adjacent natural hard-bottom habitat as feasible. Comparative studies designed to address some or all of the following questions: Which species currently use artificial structures associated with wind farms and why? What environmental variables govern species distribution? Are species very highly, highly, or moderately dependent on particular habitat types? What are the implications of this dependence regarding species fitness? As habitats change due to climax species assemblages or other external factors (e.g., climate change), how do they become suitable for prey and structure-forming species, as well as associated fish species? What are the mechanisms underlying these changes? How does sediment modification affect the availability of substrate for larval settlement? Will reduced habitat suitability effects on migratory species passing through a wind farm seasonally cause impacts that can be detected at the population level? Does this suggest that the wind farm creates a less suitable water column habitat for some species?
Scale	Species: Individual and population Spatial: Near- and far-field Temporal: Short- through long-term
Primary	Theme: Food Web

Criterion	Description
Knowledge Gaps	Does the biofilter effect influence food availability for planktivorous larval fishes?
Recommended Future Studies	See Dannheim et. al 2020
Scale	Species: Individual Spatial: Near-field Temporal: Short-term
Secondary	Theme: Sedimentation
Knowledge Gaps	What are the effects of sediment modification and artificial reef effect on natural reefs that are inherently more complex habitat than sandy bottoms? We know a lot about effects in mobile sandy sediments, less about natural geogenic reefs.
Recommended Future Studies	Conduct BACI or BAG studies to estimate reef effects in complex habitats, building on existing work in sandy bottoms.
Scale	Species: Individual and population Spatial: Near- and far-field Temporal: Short- through long-term
Secondary	Theme: Dispersal Pathways, Non-Native Species, and Sensitive Species
Knowledge Gaps	How will adding OSW structures to the marine environment facilitate the movement of sessile species within a region?

Criterion	Description
Recommended Future Studies	Collate results of site-specific monitoring of individual turbine foundations and within wind farm effects in comparison to changes in adjacent natural hard-bottom habitat as feasible. Comparative studies designed to address some or all of the following questions: Will there be a latitudinal variation in attached species (intertidal and subtidal) that form artificial reefs on OSWs from South Carolina to Maine? Which invasive species are of concern? What are the mechanisms by which these species are transported from one location to another? Are there ways to minimize spread? Will OSW structures provide habitat and connectivity for rare species (e.g., hard corals, soft corals)? With time, will secondary biogenic reefs created by previously rare epifaunal species attract associated and previously rare fish species, as suggested in DeGraer et al. 2020, referring to Fowler et al. 2020?
Scale	Species: Individual and population Spatial: Near- and far-field Temporal: Short- through long-term
Tertiary	Theme: Wind Farm Design
Knowledge Gaps	Differential effects of type of structure on degree of artificial reef effect
Recommended Future Studies	We know a lot about reef effects on gravity-based and monopile foundations, less about jacket foundations, and essentially nothing about floating wind turbines. Studies of the relative utilization of diverse types of nature-based design structures that might be used for enhancement of habitat value of scour protection would be very useful.

Criterion	Description
Scale	Species: Individual and population Spatial: Near- and far-field Temporal: Short- through long-term
Tertiary	Theme: Scale of Interactions
Knowledge Gaps	We know a lot about short-term effects at spatial scales local to the turbines, less about regional-scale and long-term effects
Recommended Future Studies	Effects of sediment modification and artificial reef effect on primary, secondary, and tertiary production more than 250 m from wind turbine generators (WTGs). Effects of sediment modification and artificial reef effect on biogeochemistry of sediments more than 250 m from WTGs. Regional-scale effects of “patchiness” on productivity. Succession-driven changes in effect type and size. For species that are attracted to turbines and other structures for feeding, shelter, and spawning, the gradient of usage in time and space is poorly known. That being said, additional local-scale studies of habitat use—identifying range of habitat parameters that are suitable—would benefit management at the scale of a wind farm.

Criterion	Description
Scale	Species: Individual and population Spatial: Far-field; stratifying by depth as needed Temporal: Short- through long-term
Tertiary	Theme: Wind Farm Design
Knowledge Gaps	We know little about the effects of decommissioning because the first European wind farms are only just beginning to reach the end of their service life.
Recommended Future Studies	It is possible that removal of structures and associated species will look something like the reverse of the colonization trajectory that occurs after construction, but this is unknown.
Scale	Species: Individual and population Spatial: Near-field Temporal: Long-term

Table 3. Summary of knowledge gaps in the interacations of offshore wind on oceanographic processes.

Theme	Knowledge Gap
Wind Stress	• The role of wind extraction in the wake of a turbine on surface wind stress is poorly considered and largely unstudied. This process could be important and may interact or counteract mixing, if there is any, due to pilings. • Presumably the reduction in surface wind stress in the vicinity of OSWs will reduce upper ocean turbulence and mixing; however, there are few studies of this topic and none considering the specific conditions of the Mid-Atlantic Bight.
Wind Wakes	• The interaction between wind wakes and impacts to oceanic processes is not fully understood and is difficult to separate from natural variability. The formation of a microclimate is also less understood (changes in temperature and moisture downwind), in particular for Mid-Atlantic ocean and atmospheric conditions. • Develop an improved understanding of the net effects of wind field modification and in situ structure friction. Consider regional wind-wake/hydrodynamic effects from multiple OSWs.
Flow, Turbulence, and Mixing	How far these impacts are discernable (i.e., how far these impacts reach before flows return to ambient, how/if regional scale stratification will be impacted, and how to distinguish between facility impacts and natural variability/climate change). There is a particular lack of information for Mid-Atlantic ocean and atmospheric conditions.

Theme	Knowledge Gap
Stratification	• More experimental and observational data are needed on stratification impacts. For the studies that have been done, few provide detailed descriptions of the oceanographic conditions at the study sites (e.g., degree of stratification) that are needed to interpret results from elsewhere in the context of the Mid-Atlantic ocean region. • How potential changes in ocean currents, alteration of predominant Mid-Atlantic features, such as stratification and the Cold Pool, and shifts in habitat from sandy bottom to hard substrates will affect the important fisheries resources in the region.
Scour	Global scour over an entire facility. How scour protection impacts hydrodynamic changes caused by piles (i.e., increasing water column turbulence and the downstream extent of flow recovery).
Fisheries	Impacts on larval fish and invertebrate dispersal from wind farm infrastructure modifications of currents and turbulence in the Mid-Atlantic.

Table 4. Recent advances in measuring electromagnetic fields from subsea power cables. Cables reported may be considered a proxy for similar capacity to export cables of future offshore wind development (OSW) scenarios. The Block Island Wind Farm (BIWF) sea2shore cable is also reported. Table modified by Hutchison et al. (2021), based on Gill and Desender (2020). A = current in amps. AC = alternating current. AUV = autonomous underwater vehicle. DC = direct current. Hz = hertz. kV = kilovolt. m = meter. MW = mega watts. mV = millivolt. mV/m = millivolt per meter. nT = nanotesla. SEMLA = Swedish Electromagnetic Low-Noise Apparatus. μT = microtesla. μV/m = microVolts per meter.

Cable			**EMF Measurements**				
Cable and Location	Specifications	Type	Method	Magnetic field	Electric field	Spatial Extent	Ref
Belgian OSW farms	Inter-array: not powered	AC	**Platform:** vessel towed/suspended	Max: 4 nT inter-array	Max: 0.3 mV/m	n/a	1

Cable			**EMF Measurements**				
Cable and Location	Specifications	Type	Method	Magnetic field	Electric field	Spatial Extent	Ref
(Preliminary trial of SEMLA device) **Use: OSW inter-array (C-Power) and export cable (Northwind)** **Position: both buried**	Export: 70 A		Swedish Electromagnetic Low-noise Apparatus ‘SEMLA’ (sledge). **Measured:** electric and magnetic fields, 3D. **Position:** on the seabed (magnetic sensor, 0.15m above seabed, electric sensors 0.52-1.04m above seabed).	cable (OSW not operational; device suspended) Max: 17 nT export (at 15 m distance)	inter-array (not operational) Max: 1.5 m/V export (at 15 m distance)	10’s m	
Cable near the Naval Surface Warfare Centre, South Florida Ocean Measurement Facility,	2-2.4 A 0.98-1.59 amps, 60 Hz	DC	**Platform:** AUV towed device **Measured:** magnetic fields, 3D. **Position:** 2.2 m above seabed.	**Powered:** Max 150 µT positive deviation, -50 µT negative deviation from ambient. **Not powered:** Mean 30 nT	n/a **Powered:**	~10’s m (estimated) ~150 m	2

Cable			**EMF Measurements**				
Cable and Location	Specifications	Type	Method	Magnetic field	Electric field	Spatial Extent	Ref
South Florida, USA* **Use: naval test site Position: not stated**		AC	**Measured:** electric fields, 3D. **Position:** 4 m above seabed.	above ambient n/a	60µV/m Mean 32 µV/m. **Not powered:** 10 µV/m	(estimated)	
Trans Bay Cable (85 km), San Francisco Bay, **California, USA**** **Use: domestic Position: buried**	Max rating: 200 kV, 400 MW (variable power during survey)	DC	**Platform:** vessel towed drop-down device. **Measured:** magnetic field. **Position:** Surface tow (c.a. 14 m above seabed) and deep tow (c.a. 8 m above seabed).	**Surface tow**: mean 117.0 nT (sd = 22.1) **Deep tow**: mean 300.5 nT (sd = 130.5)	n/a	~80 m (40 m either side of cable)	3
Basslink (290 km), Bass Strait, Tasmania, Australia **Use: state transfer**	592 A, 237 MW (1500 A, 600 MW)	DC	**Platform:** vessel towed drop down device. **Measured:** magnetic field, 2D. **Position:** 5, 10, 15, 20 m above seabed.	**Range:** 57.2 – 61.5 µT (background 61.6 µT)	n/a **At 5m**: 5.8 µV/m***	up to 20 m from seabed and 10-15 m either side of cable horizontally	4

Cable				EMF Measurements			
Cable and Location	Specifications	Type	Method	Magnetic field	Electric field	Spatial Extent	Ref
Position: buried				**At 5 m height:** 57.9 µT (background, 58.3 µT)			
Cross Sound Cable (40 km), Connecticut, USA **Use: domestic Position: buried**	0-345 A (300 kV, 330 MW)	DC	**Platform:** vessel towed Swedish Electromagnetic Low-noise Apparatus 'SEMLA' (sledge). **Measured:** electric and magnetic fields, 3D. **Position:** on the seabed (magnetic sensor, 0.15m above seabed, electric sensors 0.52-1.04m above seabed).	**DC:** 0.4-18.7 µT (expected) **AC:** max 0.15 µT (unexpected) (background, 51.3 µT)	n/a **AC:** max 0.7 mV/m	Magnetic fields: 5-10m. Electric field: up to 100 m (either side)	5,6
Neptune Cable (105 km), New Jersey, USA **Use:**	500 kV, 660 MW	DC	**Platform:** vessel towed Swedish Electromagnetic Low-noise Apparatus 'SEMLA'	**DC:** 1.3-20.7 µT (expected)	n/a **AC:** max 0.4 mV/m	Magnetic fields: 5-10m. Electric field: up to	5,6

Cable			EMF Measurements				
Cable and Location	Specifications	Type	Method	Magnetic field	Electric field	Spatial Extent	Ref
Position: buried			(sledge). **Measured:** electric and magnetic fields, 3D. **Position:** on the seabed (magnetic sensor, 0.15m above seabed, electric sensors 0.52-1.04m above seabed).	**AC:** max 0.04µT (unexpected)		100 m (either side)	
BIWF Sea2shore (32 km), Rhode Island, USA **Use: OSW export Position: buried**	502 amps, 30 MW	DC	**Platform:** vessel towed Swedish Electromagnetic Low-noise Apparatus 'SEMLA' (sledge). **Measured:** electric and magnetic fields, 3D. **Position:** on the seabed (magnetic sensor, 0.15m above seabed, electric sensors 0.52-1.04m above seabed).	**AC:** 0.005 - 3.0 µT	**AC:** 0.02 - 0.25 mV/m	Up to 100 m either side of cable	6

*Magnetic and electric field measuring devices were towed independently while the cable was powered and unpowered with AC or DC currents.
**Mean anomalies accounting for total range for positive and negative deviations, in absence of bridges.
***Motionally induced electric field arising from water movement through the measured magnetic field, calculated at 0.1m/s water flow.
References:

1. Thomsen et al. 2015;
2. Dhanak et al. 2015;
3. Kavet et al. 2016 and supp. Material;
4. Sherwood et al. 2016,
5. Hutchison et al. 2020b;
6. Hutchison et al. 2018.

Table 5. Summary of major knowledge gaps and future research needed to understand impacts of offshore wind development on the physical habitat.

Theme	Knowledge Gap	Recommended Future Studies	Scale
Sound and Vibration	Measurements of pressure and particle motion field from driving large monopiles, with and without attenuation systems	• Measure particle motion in at different parts of the water column • measure substrate vibrations to determine the distance at which energy re-radiates into the water column • Measure pressure field in different parts of the water column	• Spatial: conduct measurements at a range of distances, i.e., 10s of meters to 1000s of meters • Temporal: during construction, repeat with and without attenuation systems in place
Sound and Vibration	Measurements of pressure and particle motion from OSW operations	• Measure particle motion in water • Measure pressure in water	• Spatial: conduct measurements at a range of distances, i.e., 10s of meters to 1000s of meters • Temporal: during operations, during different wind conditions
Sound and Vibration	Measurements of sounds from cable-laying, installation of scour protection systems, and cutting	• Measure pressure in water	• Spatial: at least one location near equipment • Temporal: while different types of equipment are being used
Sound and Vibration	Little is known about the substrate-borne particle motion from in-water pile driving and its potential effects on benthic fauna	• Measure substrate-borne particle motion from pile driving on benthic faunal receptors	• Spatial: conduct measurements at a range of distances, i.e., 10s of meters to 1000s of meters

Theme	Knowledge Gap	Recommended Future Studies	Scale
			• Temporal: during construction, operations, and decommissioning
EMF	Models presently lack contextual realism for assessing effects on receptive species (i.e., reliant on models of single static scenarios (e.g., maximum power rating and single burial depth) yet scenarios are variable for cables temporally and even along cable routes.)	• Validate models with in situ measurements (magnetic and electric fields) to ensure all EMF components are accounted for • Advance models to consider variable and realistic scenarios that species may encounter • Include movement ecology for species of interest	• Spatial: the scale of the cable/network and movement ecology of species of interest • Temporal: based on power level fluctuations from OSW and species interaction
EMF	Better understanding of the components of the EMF emissions (magnetic field, induced electric field, motionally induced electric fields) are required, as well as their interaction with the local geomagnetic field and spatial-extents.	• Take in situ measurements (magnetic and electric fields) to ensure all EMF components are accounted for and provide • Update models based on measurements where needed • Consider different geomagnetic scenarios	• Spatial: the scale of the cable/network and movement ecology of species of interest • Temporal: based on power level fluctuations from OSW and species interaction
EMF	A better understanding of the temporal variations in power levels and the resulting spatio-temporal variations in the emitted EMF are required.	• Source data on power level fluctuations which can be used in modeling and in situ measurement design • Validate models with in situ measurements and knowledge of power level fluctuations • Take measurements with high resolution over long time-frames to capture temporal variability	• Spatial: the scale of the cable/network and movement ecology of species of interest • Temporal: based on power level fluctuations from OSW and species interaction

Theme	Knowledge Gap	Recommended Future Studies	Scale
EMF	The knowledge base would be better informed by the specifics of the cables in use by OSW now and expected cable characteristics (e.g., cores, shielding) to be in use in the near future, based on trends.	• Knowledge exchange with cable industry specific to OSW and non-OSW, in collaboration with biologists	• Spatial: the scale of the cable/network and movement ecology of species of interest • Temporal: based on power level fluctuations from OSW and species interaction
EMF	EMFs from dynamic cabling associated with floating OSW have been collected and the measurement EMFs associated with inter-array and export cables is lacking.	• Model and measure EMFs from dynamic cabling • Consider the movement of dynamic cables in the design of the study	• Spatial: the scale of the cable/network and movement ecology of species of interest • Temporal: based on power level fluctuations from OSW and species interaction
EMF	The interaction of cable EMFs with the geomagnetic field and transferability of modelled and measured EMFs at one location to another is not well defined.	• Model and measure EMFs from variable cable scenarios in different locations and start to build a knowledge base • Develop consistency in reporting • Develop standardized method for measuring, modeling and reporting	• Spatial: multiple geographical areas • Temporal: based on power level fluctuations from OSW and non-OSW industries (and species interactions)
EMF	The need for mitigation should be based on evidence needs for species and the suitability of the mitigation under consideration. Cable burial (for cable protection) increases distance from source and may reduce exposure to maximum EMF	• Sensitivity of species to EMF is required to define specific mitigation needs; requires targeted species specific studies. • Exploration of mitigation options based on above	• Spatial: scale of species-cable EMF encounter • Temporal: based on power level fluctuations from OSW and non-OSW industries and species interactions

Theme	Knowledge Gap	Recommended Future Studies	Scale
	intensities but may also bring EMF into a more perceivable range.		
Thermal	There is a lack of information of thermal regimes specific to OSW cables and local environments taking account of the sediment types and/or water velocities.	• Model realistic scenarios of OSW cable thermal regimes accounting for natural variability in habitats • Collect data on thermal changes to habitat from operational OSW cables *in situ* and/or in laboratory setting	• Spatial: close to the cable if exposed, in and on the seabed if buried, extend spatial extent based on findings • Temporal: based on power level fluctuations from OSW cables
Secondary Gear Entanglement	There is a paucity of information regarding empirical or modeling studies examining impacts of secondary gear as bycatch and entanglement risk of marine species.	• Modeling studies on risk of secondary gear entanglements by various offshore wind moorings and foundations on managed fishery species. • Modeling studies on regional and local drift patterns in conjunction with commercial fishing patterns and abundance of derelict fishing gear to determine risk level of secondary gear entanglement associated with specific wind farms. • Post-construction monitoring studies to determine frequency of secondary gear entanglements and impacts on marine species, including managed fishery species.	• Spatial: at local 10 m and regional 1000 m scales • Temporal: during construction, operations, and decommissioning

Table 6. Small pelagic fish species in the Northeast U.S. shelf ecosystem

Common Name	Scientific	Habit
Atlantic herring	*Clupea harengus*	marine
Blueback herring	*Alosa aestivalis*	anadromous
Round herring	*Etrumeus sadina*	marine
Alewife	*Alosa pseudoharengus*	anadromous
Atlantic mackerel	*Scomber scombrus*	marine
Chub mackerel	*Scomber japonicus*	marine
Gizzard shad	*Dorosoma cepedianum*	anadromous
American shad	*Alosa sapidissima*	anadromous
Hickory shad	*Alosa mediocris*	anadromous
Round scad	*Decapterus punctatus*	marine
Rough scad	*Trachurus lathami*	marine
Bigeye scad	*Selar crumenophthalmus*	marine
Atlantic menhaden	*Brevoortia tyrannus*	marine
Atlantic saury	*Scomberesox saurus*	marine
Atlantic silverside	*Menidia Menidia*	marine
Bay anchovy	*Anchoa mitchilli*	marine
Butterfish	*Peprilus triacanthus*	marine

Table 7. Common and scientific names for the medium and large finfishes referenced in this volume. We refer to these fishes collectively as highly migratory species.

Common name	Scientific name	Common name	Scientific name
Medium pelagic finfish		*Sharks*	
Bluefish	*Pomatomus saltatrix*	Basking shark	*Cetorhinus maximus*
Striped bass	*Morone saxatilis*	Thresher shark	*Alopias vulpinus*
Atlantic bonito	*Sarda sarda*	White shark	*Carcharodon carcharias*
Little tunny (False albacore)	*Euthynnus alletteratus*	Shortfin mako	*Isurus oxyrinchus*
Cobia	*Rachycentron canadum*	Porbeagle	*Lamna nasus*
Spanish mackerel	*Scomberomorus maculatus*	Blue shark	*Prionace glauca*
King mackerel	*Scomberomorus cavalla*	Tiger shark	*Galeocerdo cuvier*
Sea run (brown) trout	*Salmo trutta*	Sand tiger	*Carcharias taurus*
Atlantic salmon	*Salmo salar*	Sandbar shark	*Carcharhinus plumbeus*
		Dusky shark	*Carcharhinus obscurus*
		Blacktip shark	*Carcharhinus limbatus*
Large pelagic finfish		Spinner shark	*Carcharhinus brevipinna*
Albacore	*Thunnus alalunga*	Scalloped hammerhead	*Sphyrna lewini*
Bluefin tuna	*Thunnus thynnus*	Smooth hammerhead	*Sphyrna zygaena*
Bigeye tuna	*Thunnus obesus*	Smooth dogfish	*Mustelus canis*
Yellowfin tuna	*Thunnus albacares*	Spiny dogfish	*Squalus acanthias*

Skipjack tuna	*Katsuwonus pelamis*	Atlantic angel shark	*Squatina dumeril*
Mahi Mahi (dolphinfish)	*Coryphaena hippurus*	*Rays*	
Wahoo	*Acanthocybium solandri*	Atlantic stingray	*Dasyatis sabina*
Swordfish	*Xiphias gladius*	Roughtail stingray	*Dasyatis centroura*
White marlin	*Kajikia albida*	Cownose ray	*Rhinoptera bonasus*
Roundscale spearfish	*Tetrapturus georgii*	Bullnose ray	*Myliobatis freminvillii*
Blue marlin	*Makaira nigricans*	Atlantic torpedo ray	*Torpedo nobiliana*
Ocean sunfish	*Mola mola*		

Table 8. Shellfish species of commercial importance in the Northeast U.S. The species list is based on NOAA statistics for annual commercial landings in 2019 for the following states: Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Delaware, Maryland, and Washington (https://www.fisheries.noaa.gov/foss).
**** = aggregations of more than one species (they are not inclusive but represent landings where species-specific data are unavailable).**

		Common Name	Species/Genus
Crustaceans	Shrimp	Brine shrimp	*Artemia salina*
		Northern shrimp	*Pandalus borealis*
		Ocean shrimp	*Pandalus jordani*
		Spot shrimp	*Pandalus platyceros*
		Shrimps**	Caridea
		Mantis shrimps **	Stomatopoda
		Penaeid shrimps **	Penaeidae
	Crabs	Atlantic rock crab	*Cancer irroratus*
		Blue crab	*Callinectes sapidus*
		Dungeness crab	*Cancer magister*
		Green crab	*Carcinus maenas*
		Horseshoe crab	*Limulus polyphemus*
		Jonah crab	*Cancer borealis*
		Lady crab	*Ovalipes ocellatus*
		Northern stone crab	*Lithodes maja*
		Red deepsea crab	*Chaceon quinquedens*
		Red rock crab	*Cancer productus*
		Brachyura ** crabs	Brachyura
		Spider ** crabs	Majidae
	Lobster	American lobster	*Homarus americanus*
Bivalves	Clams	ARK or Blood clam	*Anadara ovalis*
		Manila clam	*Corbicula manilensis*
		Pacific littleneck clam	*Protothaca staminea*
		Pacific razor clam	*Siliqua patula*
		Pacific gaper clam	Tresus
		Northern quahog clam	*Mercenaria mercenaria*
		Ocean quahog clam	*Arctica islandica*
		Atlantic razor clam	*Ensis directus*
		Soft clam	*Mya arenaria*

		Common Name	Species/Genus
		Arctic surf clam	*Mactromeris polynyma*
		Atlantic surf clam	*Spisula solidissima*
		Clams **	Bivalvia
		Pitar clams **	Pitar
	Mussels	California mussel	*Mytilus californianus*
		Sea Mussel (Blue/edible)	*Mytilus edulis*
	Scallops	Bay scallop	*Argopecten irradians*
		Sea scallop	*Placopecten magellanicus*
		Scallop **	*Pectinidae*
	Oysters	Eastern oyster	*Crassostrea virginica*
		Edible oyster	*Ostrea edulis*
		Pacific oyster	*Crassostrea gigas*
Cephalopods	Squid	Longfin squid (loligo)	*Loligo pealeii*
		Shortfin squid (illex)	*Illex illecebrosus*
		Loliginidae squids **	Loliginidae
		Squids **	Teuthida
	Octopus	Octopuses **	Octopodidae
Echinoderm	Urchins	Green sea urchin	*Strongylocentrotus droebachiensis*
		Sea Urchins **	*Strongylocentrotus* spp.

Note: Due to space limitations, examination of potential interactions for each individual shellfish species (Table 5) was not possible. Rather, we take the approach of synthesizing existing research on the species when available as well as their analogs from other ecosystems and use this information to draw inferences across commercially important shellfish groups in the U.S. ecosystem.

Table 9. Summary of ecosystem models examining offshore wind development (OSW) effects. ERSEM = European Regional Seas Ecosystem Model. GIS = Geographical Information Systems. km = kilometer. MRED = marine renewable energy device. NE = northeast.

Citation	Water Body	Hypotheses/Questions	Modeling Methods	OSW Phases considered	General Findings
Alexander et al. 2016	NE Atlantic; west coast of Scotland and Firth of Lorn	Question: What is the utility of Ecospace to address the question of whether MREDs can benefit, and thus mitigate a potential loss of access for the fishing industry by providing: (a) habitat through the "reef-effect" and (b) protection through the "exclusion zone effect".	Ecopath with Ecosim and Ecospace; 41 functional groups Model includes five fishing fleets which encompasses all the fishing that occurs in the area	Baseline and Operation	Biomass changes mostly occurred within the OSW rather than outside; Decreases predicted for catch value for the Nephrops trawlers in the AR scenarios and for the Nephrops and other trawls in the EZ scenarios.
Burkhard et al. 2011	German North Sea	Hypotheses: 1) artificial reef is more productive, more efficient at cycling energy/nutrients than baseline, more biodiverse; 2) essential ecosystem processes are disturbed by OSW leading to irreversible system degradation	Biophysical-chemical Model: ERSEM (European Regional Seas Ecosystem Model); Food web model: Ecopath with Ecosim; Hydrodynamic model: MIKE21; and the Geographical Information Systems (GIS) data	Baseline, Construction, Operation	Exergy capture, nutrient cycling and nutrient loss returned within the 1st year post-construction to a state similar to that of the year before; this supports the hypothesis of a resilient system dynamic. Storage capacity and entropy production indicators showed minor alterations of the system. Slight increase of ascendancy suggests an increased organization of the system; There was a loss in species numbers, diversity

Citation	Water Body	Hypotheses/Questions	Modeling Methods	OSW Phases considered	General Findings
					and evenness during construction and operation of the OSW.
Dannheim et al. 2018	North Sea	Question: How does ecosystem functioning compare in each of these scenarios: a "typical soft bottom", an "offshore wind development", and an "oil and gas platform"?	Ecopath with Ecosim; 12 functional groups	Baseline and Operation	Increased carbon retention capacity (stored as organic matter by each trophic level) at OSWs when compared to oil and gas platforms; The blue mussel *Mytilus edulis*, is a key organism responsible for the high carbon retention capacity at OSWs when compared to oil and gas platforms or natural sediments.
Halouni et al. 2020	Bay of Seine, English Channel	Question: What are the ecosystem level consequences of the spillover effect given a fishery closure at an OSW?	Ecopath with Ecosim and Ecospace; Spatial resolution: ≈1.6 km side; Two sub-areas around the OSW: a first sub-area adjacent to the OSW 3.2 km wide and a second sub-area adjacent to first one also 3.2 km wide.	Baseline and Operation	Spillover effect could mitigate the negative impact of access loss on fishing activities if OSW is closed. The Ecospace model predicted an increase of catches up to 7% near the OSW and a slight increase in the proportion of high trophic level species. Spillover effects were limited in space and the expected increase of

Citation	Water Body	Hypotheses/Questions	Modeling Methods	OSW Phases considered	General Findings
					biomass and catches were highly localized in areas around the OSW.
Pezy et al. 2020a	Eastern English Channel	Question: What are the baseline biological dynamics prior to construction at the DLT OSW?	Ecopath with Ecosim; 28 trophic groups	Baseline	Trophic web is most likely detritus based and that the ecosystem biomass is dominated by “Non-Consumed benthic invertebrates”, which could act as a trophic dead end or cul-de-sac for fish due to the size of these filter feeders against size of sampling fish in this OSW area.
Pezy et al. 2020b	Bay of Seine	Question: What are the potential consequences of OSW development on the structure and functioning of the local ecosystem, for each of 3 existing sedimentary types?	Ecopath with Ecosim; 28 trophic groups; 9 scenarios; 3 sedimentary types X 3 seasons (winter, summer, whole year)	Operation	Trophic structures were strongly linked to the sedimentary types. There was a maturity gradient moving between the three types of sediment identified.
Raoux et al. 2017	Bay of Seine, English Channel	Question: How do benthos and fish aggregation caused by the introduction of additional hard substrates from the piles and the scour protections lead to the development of an artificial reef system, and also what are the	Ecopath with Ecosim; 37 trophic groups	Operation	(1) Total ecosystem activity, the overall system omnivory (proportion of generalist feeders), and the recycling increased after the construction of the OSW; (2) Higher trophic levels such

Citation	Water Body	Hypotheses/Questions	Modeling Methods	OSW Phases considered	General Findings
		consequences of this for food-web functioning?			as piscivorous fish species, marine mammals, and seabirds responded positively to the aggregation of biomass on piles and turbine scour protections; and (3) Change in keystone groups after the construction towards more structuring and dominant compartments; Possible reef effect would increase total system biomass by 55%; Bivalves build-up would lead to a food web dominated by detritivory; Benthos and keystone fish biomass increases attracted apex predators.
Raoux et al. 2018	Bay of Seine	Questions: How will ecosystem structure and function if top predators avoid/are attracted to OSWs? And if trawling is increased or decreased inside?	Ecopath with Ecosim; (same as Raoux et al., 2017; 9 trophic groups	Operation	OSW construction could lead to an increase in benthos species and fish benthos feeders whatever the perturbation scenario, while the predicted response of top predators was ambiguous across all

Citation	Water Body	Hypotheses/Questions	Modeling Methods	OSW Phases considered	General Findings
					perturbation scenarios.
Raoux et al. 2019	Bay of Seine, English Channel	Question: What are the ecosystem consequences of the reef effect, reserve effect, and their combined effects?	Ecopath with Ecosim; same as Raoux et al., 2017; 37 trophic groups	Operation	Ecosystem structure and functioning changed after the OSW construction; Ecosystem maturity increased, but no alterations in overall resilience capacity.
Wang et al. 2019	Jiangsu coastal ecosystem	Question: How did trophic flow and ecosystem system structure change after the construction of an OSW?	Ecopath with Ecosim; 14 functional groups	Baseline and operation	After OSW construction, detritus, phytoplankton, zooplankton, anchovies, and some benthic fish were positively impacted. The increased primary production and detritus resulted in the increased food supply for zooplankton, which made it possible for planktivorous species (particularly anchovies) to be fed. Consequently, the biomass and production of some benthic fish increased, which indicates a potential reef effect.

Table 10. Interactions of port infrastructure with commercial and recreational fisheries and offshore wind development; table recreated from Table 3.5.3-1 from South Fork Wind Farm and South Fork Export Cable Project Final Environmental Impact Statement.
CT = Connecticut, MA = Massachusetts, MD = Maryland, NJ = New Jersey, NY = New York, RI = Rhode Island, VA = Virginia.

Port/Facility Name/ Place Name	City/Town	County, State	Fabrication, Assembly, Deployment	Crew Transfer, Logistics, Storage	SFEC Site	Commercial Fishing	For-Hire Recreational Fishing
Port of New London	New London	New London, CT	X	X		X	
Stonington	Stonington	New London, CT				X	X
Fairhaven	Fairhaven	Bristol, MA				X	X
New Bedford Marine Commerce Terminal	New Bedford	Bristol, MA	X	X		X	X
Westport	Westport	Bristol, MA				X	X
Sparrow's Point	Edgemere	Baltimore, MD	X				
Paulsboro Marine Terminal	Paulsboro	Gloucester, NJ	X				
East Hampton	East Hampton	Suffolk, NY			X		
Port of Montauk	Montauk	Suffolk, NY		X	X	X	X
Shinnecock Fishing Dock	Hampton Bays	Suffolk, NY		X		X	X
Greenport Harbor	Greenport	Suffolk, NY		X			X
Port of Providence	Providence	Providence, RI	X				
Port of Galilee/Point Judith	Narragansett	Washington, RI		X		X	X
Old and New Harbor	New Shoreham	Washington, RI		X		X	X
Port of Davisville and Quonset Point	North Kingstown	Washington, RI	X	X			X
Newport	Newport	Newport, RI				X	X
Tiverton	Tiverton	Newport, RI				X	X
Little Compton	Little Compton	Newport, RI				X	X
Port of Norfolk/Norfolk International Terminal	Norfolk	Norfolk City, VA	X				

Table 11. Summary of Mitigation Strategies (taken from Table 8-3) in Industrial Economics (2012).

Mitigation *	Summary of Mitigation Strategy
Conflict Avoidance	Avoiding negative impacts to habitats and resources, maintaining the ability to access/utilize fishing grounds, and preventing impacts to safety.
Communication/Stakeholder Engagement	Stakeholder engagement efforts must embrace differences in the needs of the communities. Communication during the construction, operation, and decommissioning phases of a renewable energy development project will be important in terms of warning fishermen of activities that could affect their operations. Participation in any planning or decision-making process should be broad-based, with an emphasis on traditional users whose sometimes unique schedules should be accommodated.
Coastal and Marine Spatial Planning	Coastal and marine spatial planning identifies areas most suitable for various types or classes of activities in order to reduce conflicts among uses, reduce environmental impacts, facilitate compatible uses, and preserve critical ecosystem services to meet economic, environmental, security, and social objectives.
Impact Minimization through Design/Construction	The design and construction of offshore renewable energy projects can be accomplished in ways that will minimize disruption to other ocean users. For example, scheduling construction for times when fisheries are inactive.
Environmental Assessments	Environmental assessments can potentially yield a tremendous amount of fisheries-related information such as a project's capacity to function as an artificial reef, and the associated impacts; the effects of excluding or limiting fishing access within the vicinity of a project; changes in the water column due to noise and vibrations; and colonization by non-native species
Mitigation Funds and Subsidies for Displaced/Impacted Users	Renewable energy projects may displace fisheries operations, requiring them to go around developments or steam to fishing grounds further away—both of which can cause fuel consumption to rise. Low interest loans or grants could be made available to the fleets for the specific purchase of additional or upgraded safety gear (e.g., life rafts, flares, lifejackets, and radar) or for vessel safety training programs. Financial assistance could be provided to design and test new gear
On and Off-Site Stock Enhancement	Stock enhancement activities can include those intended to mitigate (1) impacts at the site of the renewable energy project and (2) impacts in other locations accessible to fishermen (e.g., crowding due to displacement of fishermen).
Research	Results from research opportunities could enhance fishing in sectors that absorb any displaced fishing effort that might result from the construction of offshore renewable energy facilities.
Facilities Improvements	In situations where ports are modified to support offshore renewable energy development, opportunities may exist to make port modifications (for example, with mitigation funds, but also with external funding) that also support other ocean users (e.g., new dockage, dredging projects, repair facilities, gear/fuel storage).
Fishing Effort Increases	If fishermen are displaced or significantly inconvenienced by the development of an offshore renewable energy project (e.g., being required to increase their travel time to fishing grounds in order to avoid a project area), they may benefit from increasing a quota or extending the season to provide a way to financially justify the extra effort needed to fish.

Mitigation *	Summary of Mitigation Strategy
Fishing Area Re-Opening	Displaced areas could be off-set by opening previously closed fishing areas.
Fishing Ground Access Restrictions for Public	A specific group of fishermen is given the right to fish in an area, while prohibiting others (including the public) from fishing at that location.
Access Allowed Within Facility Area	If an offshore energy facility is sited in an area of high commercial and recreational use, it may be feasible to permit access to vessels of a suitable size, draft, and use
Vessel Routing Measures	A number of vessel routing measures could be required to improve the safety of navigation in areas where, among other things, freedom of vessel movement is inhibited by restrictive searoom and obstructions to navigation.
Safety Fairways	Offshore waters in high traffic areas can be designated as safety fairways to prohibit the placement of surface structures.
Buffer Zones around Existing Uses	Buffer zones could be placed around existing uses such as shipping lanes, traffic separation schemes, fishing grounds, and pipes and cables.
Guard Ships	Consider the use of guard ships in areas of high traffic density. Displaced fishermen may be able to help fill this guard role.
Chart Updates to Reflect Changes Related to Safe Navigation	As changes are made to navigation, it is imperative that charts be updated to ensure safe passage in the vicinity of the offshore renewable energy projects.
Notices to Mariners	Radio Navigational Warnings and Notices to Airmen must be promulgated in advance of and during any OSW construction.
Mariner Education	Education for mariners travelling in the vicinity of offshore renewable energy projects should help ocean users identify and avoid hazards. Education efforts should cover the different hazards associated with each phase of a project, and may include guidance on how to operate safely given the hazards.
Power Cables Trenching	Power cables between wind turbines, between wind turbines and the transformer station, and between the transformer station and the shore should be sufficiently trenched to avoid exposure from scouring / sand migration or trawling activities.
Radar, Radio Navigation, and Radio Communication Interference Research	Wind energy projects have uncertain impacts on radar, radio navigation and radio communications. Efforts to evaluate those impacts on a site-by-site basis should be taken
Post-Construction Obstruction Removal	Once a project is complete, the operator / contractor should remove all obstructions and return the sea floor to its pre-construction depth and topography.

*See original table in Industrial Economics (2012) for more information on these recommended mitigation strategies for particular conflicts (navigation, gear, natural resource, physical space), project phases (planning, siting/permitting, construction, operation, decommissioning), and primary implementation authorities (e.g., BOEM, NOAA) for each mitigation strategy.

Table 12. Summary of compensatory mitigation plans in Europe and U.S.
BOEM = Bureau of Ocean Energy Management. FLOWW = Fishing Liaison with Offshore Wind and Wet Renewables Group. MA = Massachusetts. NOAA = National Oceanic and Atmospheric Administration. NYSERDA = New York State Energy Research and Development Authority. OSW = offshore wind development. RI = Rhode Island. SAMP = Special Area Management Plan. VMS = vessel monitoring system. VW = Vineyard Wind. WHOI = Woods Hole Oceanographic Institute.

Country	Comp. Y/N	Legal Framework	Type and Description of Compensation	Data/Analysis Used	Other monetary mitigation measures
UK	Yes	None, negotiations between Developer and local community	Community Funds: Compensation is considered last resort when significant impact has not been avoided through planning; FLOWW guidance indicates compensation should be paid on accurate and justifiable claims. .[1]	Affected fishermen must provide evidence (e.g., catch records)	West of Morecamble Fisheries- funds by OSW that will benefit fishing community Employment of local fishermen in OSW work
Denmark	Yes	*Danish Fisheries Act*	Direct Compensation: The Developer has to negotiate compensation with every affected fisherman, and the licence to produce electricity from the offshore wind development (power plant) can be granted to the Developer only if an agreement has been made with all affected fishermen. Negotiations of compensation are carried out by the Danish Fishermen's Association (verified by an independent consultant).[2] Can compensate for suspension of fishing activities at survey, construction, operation phases and longer distances traveled to fishing grounds.	The amount depends on the analysed impact for fisheries which is part of the EIA and based on the existing data from Danish Fishery Agency (e.g., log book data, VMS data)	Insurance Community Funds
Netherlands	No	None			
Germany	No	None			
Belgium	No	None			
U.S. **Rhode Island** **South Fork**	Yes	Negotiations through States Coastal Zone	$12 million dollars over 30 years; or $5 million up front 100% loss compensated in	Two Economic Exposure Analyses by (1)economist for RI Fisheries	

Country	Comp. Y/N	Legal Framework	Type and Description of Compensation	Data/Analysis Used	Other monetary mitigation measures
		Management Act	construction and decommissioning phase and 5% loss during operational phase (info based on NOAA/States/BOEM mitigation meetings)	Advisory Board and consultants to Developer (WHOI and Industrial Economics)	
U.S. Rhode Island Vineyard Wind	Yes	Negotiations through States Coastal Zone Management Act	Direct Compensation Fund: available through funds held in escrow for Rhode Island vessels or fisheries interests impact claims ($4.3 million over 29 years) Eligibility: RI fishermen, fishing companies, and companies that support fishing interests that have direct impacts or losses	Economic Exposure Analysis by economist hired by Developer using Fishing Vessel Trip Reports, Dealer Reports, and Vessel Monitoring System data (King and Associates 2019)	RI Fishermen's Future Viability Trust. VW will disperse funds in accordance with the purpose of the Trust and the goals of RI Ocean SAMP: $2.5 million per year for 5 years
U.S. MassachusettsVineyard Wind	Yes	Negotiations through States Coastal Zone Management Act	MA Compensatory Mitigation Fund: $19.2 million, Fishing interests broadly defined as: owners and operators of vessels, vessel crews, shoreside processors, vessel supplier, and support services, and other entities that can demonstrate losses directly related to the Vineyard Wind Project	Economic Exposure Analysis by economist hired by Developer using Fishing Vessel Trip Reports, Dealer Reports, and Vessel Monitoring System data (King and Associates 2019); can compensate for any claims by MA fishing businesses for impacts resulting in economic losses during construction, operation, decommissioning)	Funded research through the Fisheries Innovation Fund Navigation Enhancement and Training Funding
U.S. New York Liberty Wind, Sunrise Wind	No	Negotiations through States Coastal	No compensatory mitigation programs as of September 2021. See Section 8 within		

Country	Comp. Y/N	Legal Framework	Type and Description of Compensation	Data/Analysis Used	Other monetary mitigation measures
		Zone Management Act	Appendix D of NYSERDA RFP guidelines: Compensation Programs are Optional as per NYSERDA RFP Mitigation Plan Requirements.		

[1] https://op.europa.eu/en/publication-detail/-/publication/056c9ec0-d143-11ea-adf7-01aa75ed71a1/language-en

[2] https://ens.dk/sites/ens.dk/files/Globalcooperation/offshore_wind_and_fisheries_in_dk.pdf

Table 13. Summary of the strengths and limitations of fishery dependent data sets as they pertain to offshore wind research in the Northeast U.S.
FDD = Fishery Dependent Data. VMS = Vessel Monitoring System.

	Strengths	Limitations
Vessel Trip Reports	Nearly universal coverage for federally-managed fisheries	Only one location/trip, with limited sub-trip accuracy and minimal tow-by-tow reporting
	Easy to link with dealer reports to estimate revenue	Limited coverage for the lobster and Jonah crab fisheries.
	Longest time series of FDD	Self-reported
Dealer Reports	Only revenue source	No operational information (gear, area, effort)
	Accurate landings	
Vessel Monitoring System	More precise area based on automated global positioning system data (satellite or cellular)	Most, but not all fisheries
	Declaration of trip intent	Some fisheries not fully included in VMS data
		Activity (fishing vs. transit) can be misinterpreted
		Assigning valuation relies on assumptions of catch rate
Observer/At-Sea Monitors	Precise area (tow-by-tow)	Low and variable coverage
	More comprehensive data	Observer effect may bias data
	Source of biological and socioeconomic data	
Study/Research Fleet Data	Precise area and catch data (tow-by-tow and global positioning system data)	Low and variable coverage
Electronic Monitoring	Same as observer, but not a source of socioeconomic data	Same as observer
	More accurate catch data in full-retention fishery operations	
Dockside Monitoring		No operational information of area fished or effort metrics

	Strengths	Limitations
		Limited catch data to just retained and landed catch
Traditional Ecological Knowledge (industry expertise and knowledge)	Available for all fisheries	Labor intensive to access via interviews
		Difficult to quantify
Automatic Identification System	More precise location area based on automated source	Not on vessels less than 65 feet
	Publicly available	Can be turned off further than 12 nm from shore

Table 14. Percent landings, by Fishery Management Plan (FMP), that were landed by vessels using Vessel Monitoring Systems (VMS). Data sources are NMFS VMS, Dealer and Vessel Trip Report (VTR), linked through the Data Matching and Imputation system (DMIS).

FMP	2014	2015	2016	2017	2018	2019	Average
American Lobster	2.9%	3.1%	3.5%	3.8%	3.4%	3.5%	3.4%
Atlantic Herring	95.9%	97.1%	96.8%	99.1%	97.7%	99.2%	97.6%
Bluefish	15.6%	17.2%	20.6%	17.9%	22.1%	31.9%	20.9%
Golden and Blueline Tilefish	23.1%	20.7%	36.5%	35.3%	28.6%	26.5%	28.5%
Highly Migratory Species	7.2%	4.1%	2.9%	2.7%	6.8%	6.8%	5.1%
Jonah Crab	10.3%	7.4%	6.5%	8.2%	10.3%	7.4%	8.4%
Mackerel, Squid, and Butterfish	96.4%	94.3%	93.8%	95%	96.8%	96.9%	95.5%
Monkfish	97.8%	97.2%	96.4%	98.7%	98.6%	98.9%	97.9%
Northeast Multispecies	96.7%	97.4%	93.4%	96.2%	98%	97.6%	96.6%
Sea Scallop	98.2%	99%	99.1%	99%	99.3%	99.6%	99%
Skates	72.6%	82.1%	80%	80.4%	87.2%	86.5%	81.5%
Small-Mesh Multispecies	95.7%	96%	95.4%	96.5%	92.5%	91.1%	94.5%
Spiny Dogfish	41%	37.6%	36.7%	35.4%	32%	28.7%	35.2%
Summer Flounder, Scup, Black Sea Bass	78.7%	80.3%	79.6%	78.9%	77.8%	79.1%	79.1%
Surfclam, Ocean Quahog*							

*The Surfclam, Ocean Quahog FMP uses clam specific logbooks which are not matched in DMIS. This FMP has required VMS since Jan 1, 2008. Based on this, and the specific gear needed to fish for these species (clam dredge), the percentage represented by VMS should be nearly 100%.

Table 15. Annual Commercial Fishing Revenue Exposed in the maximum work area (MWA) and Offshore South Fork Export Cable (SFEC) during Project Construction by Fishery Management Plan (FMP) Fishery. Taken from Table 3.5.1-17 in the South Fork Wind Farm Draft Environmental Impact Statement (BOEM 2021a).

Fishery Management Plan (FMP) Fishery	Peak Revenue ($1,000s)	Average Annual Revenue ($1,000s)	Percentage of Total Revenue from the Mid-Atlantic and New England Regions
American Lobster	$129,003	$68.3	0.07%
Atlantic Herring	$102,500	$41.0	0.15%
Bluefish	$26,614	$10.3	0.78%
Golden and Blueline Tilefish	$36,467	$10.9	0.20%
Highly Migratory Species	$14,350	$2.4	0.11%
Jonah Crab	$15,128	$8.3	0.09%
Mackerel, Squid, and Butterfish	$290,559	$110.2	0.22%
Monkfish	$244,776	$164.6	0.77%
Northeast Multispecies (large-mesh)	$233,511	$141.3	0.19%
Sea Scallop	$932,978	$416.3	0.08%
Skates	$154,404	$97.3	1.27%
Northeast Multispecies (small-mesh)	$54,502	$32.0	0.28%
Spiny Dogfish	$12,334	$5.4	0.18%
Summer Flounder, Scup, Black Sea Bass	$273,818	$211.1	0.53%
Non-disclosed and non-FMP fisheries*	$341.4	$168.4	NA
All FMP and non-FMP fisheries	$2,106.2	$1,487.8	0.16%

Source: Developed using NMFS (2020b).

Notes: Revenue is adjusted for inflation to 2019 dollars. ND = not disclosed; NA indicates that the number cannot be calculated with the available data.

*Includes revenue from the Surfclam/Ocean Quahog, Red Crab, and River Herring FMP fisheries and species that are not included in the fisheries listed in the table, but which are harvested by federally permitted vessels.

Table 16. Ongoing FDD and Offshore Wind Research by Organization as of 2021/2022.
ICES = International Council for the Exploration of the Sea. NREL = National Renewable Energy Laboratory. RI DEM = Rhode Island Department of Environmental Management. RODA = Responsible Offshore Development Alliance. SCeMFiS = Science Center for Marine Fisheries. URI = University of Rhode Island. UMaine = University of Maine. VIMS = Virginia Institute of Marine Science. WHOI = Woods Hole Oceanographic Institute.

Project Name	Organization	PI(s)	Expected Completion Date
Development of spatial data and site choice models to support economic impact analysis of offshore energy and aquaculture siting in the Northeast region.	NOAA Fisheries	DePiper, Christel	2021
Collaborative development of strategies and tools to address commercial fishing access in U.S. offshore wind developments	NREL, RODA	Green	2022
Using fine-scale fishery dependent data to evaluate potential impacts of offshore wind energy development on fishery operations	NOAA Fisheries	Allen-Jacobson, Jones, Mercer, Christel	2022
ICES-WGOWDF- ROA A. Review paper on lessons learned on effects of wind on distribution of fishing operations	ICES	Gill, Gimpel, Hooper, Lipsky, Hawkins	2022
Development of a fishery owned knowledge trust and demonstration of its use in the assessment of potential offshore wind energy development impacts on Atlantic herring and clam fisheries	RODA	Hawkins, Jacobs	2022
Fishing status of vessels using the AIS: a big data and machine learning approach	URI, RIDEM	Sproul, Livermore	2023
Bioeconomic impacts of offshore wind energy development on the commercial sea scallop fishery	Rutgers	Monroe, Powell	2021
Evaluation of economic impact from wind energy development on the surfclam fishery	VIMS	Scheld	2021
Wind energy development team supporting fisheries	US, /SCEMFIS	Powell	2022
Vessel trip reports catch-area reporting errors: potential impacts on the monitoring and management of the Northeast United States groundfish resource	NOAA Fisheries	Palmer	2017
ICES WG Spatial Fisheries Data: Developing a Common Framework for Spatial Valuation of Fisheries	ICES	Martinez	2022
Socioeconomic implications of offshore wind on fishing communities	NOAA Fisheries	Silva	2022
Impact Assessment of Offshore Wind on Fishing and Safety using Spatial Data	NOAA Fisheries	Galuardi	2021
Fisheries and Offshore Wind Interactions: Synthesis of the Science	RODA	Hogan	2021
Incorporating Communities into Equitable Ocean Planning for the Blue Economy	Rutgers	St. Martin, Griffin	2023
Integrated Ecosystem Assessment: Fisheries and Offshore Wind	NOAA Fisheries	Tyrell, Large, Hogan	2023

Project Name	Organization	PI(s)	Expected Completion Date
Economic Impact of south Fork Wind Farm	WHOI	Jin, Kite-Powell	2022
Evaluating changes in commercial and recreational fishing in the North Atlantic, Mid-Atlantic, Great Lakes, Pacific, and numerous inland fisheries throughout the United States	Verita Economics	Kinnell, Bingham	2022
Can proprietary commercial lobstering data be used to inform offshore wind development?	UMaine, Maine Lobstermen's Association, RODA	Kate Beard	2024

Table 17. Percentage of lobster landings captured in federal VTRs (data pull from Greater Atlantic Regional Fisheries Office (GARFO) in 2020).
CT = Connecticut. DE = Delaware. MA = Massachusetts. MD = Maryland. ME = Maine. NC = North Carolina. NH = New Hampshire. NJ = New Jersey. NY = New York. RI = Rhode Island. VA = Virginia.

Row Labels	CT	DE	MA	MD	ME	NC	NH	NJ	NY	RI	VA
2010	83%	100%	61%	100%	9%		84%	90%	86%	66%	100%
2011	56%	100%	61%	100%	7%	100%	84%	89%	96%	68%	100%
2012	61%	100%	60%	100%	7%	100%	84%	94%	98%	69%	100%
2013	33%	98%	56%	93%	7%	100%	85%	93%	91%	64%	100%
2014	43%	100%	56%	100%	7%	100%	86%	98%	89%	66%	100%
2015	36%	100%	58%	95%	7%	100%	88%	97%	87%	65%	100%
2016	53%	100%	58%	100%	7%	61%	88%	98%	94%	72%	100%
2017	31%	100%	64%	100%	7%	100%	90%	99%	99%	74%	100%
2018	38%	100%	62%	100%	6%	100%	89%	99%	98%	72%	100%
2019	34%	100%	62%	100%	5%	100%	89%	98%	98%	72%	100%
2020	100%		65%	100%	5%		74%	62%	92%	72%	100%

Table 18. Federal Surveys Impacted by Offshore Wind Development in the Northeastern United States. TBD = To be determined.

Survey	Year Started	Survey Design	Major Applications	Interaction with Wind Energy Areas
Autumn Bottom Trawl Survey	1963	Stratified Random Design – North Carolina to Nova Scotia (bottom trawl)	abundance; length, age, sex, weight, diet, maturity samples, distribution, components of Ecosystem Monitoring survey	Overlaps with wind energy leases, Wind energy Planning areas, and Gulf of Maine; Range (%) Survey Strata overlaps: 0.1-75.7%; New design and methods within wind energy will be required
Spring Bottom Trawl Survey	1968	Stratified Random Design – North Carolina to Nova Scotia (bottom trawl)	abundance; length, age, sex, weight, diet, maturity samples, distribution, components of Ecosystem Monitoring survey	Overlaps with wind energy leases, Wind energy Planning areas, and Gulf of Maine; Survey strata overlaps: 0.1-75.7%. New design and methods within/outside wind energy will be required
Scallop Survey	1979	Stratified Random Design (dredge); line transect (HabCam)	biomass, abundance, distribution, size and sex of sea scallops and other benthic fauna	Overlaps with wind energy leases, Wind energy Planning areas, and Gulf of Maine; Survey strata overlaps: 0.1-75.7%. New design and methods within/outside wind energy will be required
Atlantic Surfclam and Ocean Quahog Surveys	1980	Stratified Random Design (hydraulic dredge)	biomass, abundance, distribution, size and sex of Atlantic surfclam and ocean quahog	Overlaps with wind energy leases, Wind energy Planning areas; Ocean Quohog Survey strata overlaps: 8.2-35.4%. Surf Clam Survey strata overlaps: 0.1-28.1%.New design

Survey	Year Started	Survey Design	Major Applications	Interaction with Wind Energy Areas
				and methods within/outside wind energy will be required
Northern Shrimp Survey	1983	Stratified Random Design (commercial shrimp trawl)	biomass, abundance, length	Overlaps with areas now being considered and planned for wind development in the Gulf of Maine which are in early phases of pre-leasing process. Survey Strata impacted: Unknown
Gulf of Maine Cooperative Bottom Longline Survey	2014	Stratified Random Design (bottom longline)	abundance, biomass, length, age, sex, weight, maturity samples, distribution, focused on hard-bottom habitat data	Overlaps with areas now being considered and planned for wind development in the Gulf of Maine which are in early phases of pre-leasing process. Survey Strata impacted: Anna to Insert
Ecosystem Monitoring Survey	1977	Stratified Random Design (linked to Trawl Survey Design); fixed stations embedded in design (plankton and oceanographic sampling)	Phyto/nkton, zooplankton, ichthyoplankton, carbonate chemistry, nutrients, marine mammals, sea birds	Overlaps with wind energy leases, Wind energy Planning areas, and Gulf of Maine; Survey strata overlaps: TBD. New design and methods within/outside wind energy will be required
North Atlantic Right Whale Aerial Surveys	1998	Aerial line transects	Right Whale population estimates; dynamic area management	Overlaps with wind energy leases, Wind energy Planning areas, and Gulf of Maine; Survey strata overlaps:

Survey	Year Started	Survey Design	Major Applications	Interaction with Wind Energy Areas
				TBD. New design and methods within/outside wind energy will be required
Marine mammal and sea turtle ship-based and aerial surveys	1991	Line transects for ship and aerial surveys. Plus opportunistic biological and physical oceanographic sampling from shipboard surveys	Abundance and spatial distribution of marine mammals, sea turtles, and sea birds	Overlaps with wind energy leases, Wind energy Planning areas, and Gulf of Maine; Survey strata overlaps: TBD. New design and methods within/outside wind energy will be required
Large Coastal Shark Bottom Longline Survey	1996	Fixed station design in US continental shelf waters from Florida to Delaware with stations generally located 30 nm apart except where the shelf narrows off Cape Hatteras, NC	Abundance, distribution, migrations (tagging), and biological sampling of Atlantic coastal shark species for assessment, EFH designations, and life history studies	Overlaps with wind energy leases in the Mid-Atlantic, Wind energy Planning areas,
Cooperative Atlantic States Shark Pupping and Nursery (COASTSPAN) Longline and Gillnet Surveys	1998	Stratified Random (longline) and fixed station (longline and gillnet) surveys in estuarine and nearshore waters from Florida to Delaware	Abundance, distribution, migrations (tagging), and biological sampling of Atlantic coastal shark species for assessment, EFH designations, and life history studies	Overlaps with wind energy submarine cable corridors

Table 19. National Standards for fishery conservation and management listed in section 301 of the Magnuson-Stevens Fishery Conservation and Management Act.

National Standards
1. Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry.

National Standards
2. Conservation and management measures shall be based upon the best scientific information available.
3. To the extent practicable, an individual stock of fish shall be managed as a unit throughout its range, and interrelated stocks of fish shall be managed as a unit or in close coordination.
4. Conservation and management measures shall not discriminate between residents of different States. If it becomes necessary to allocate or assign fishing privileges among various United States fishermen, such allocation shall be (A) fair and equitable to all such fishermen; (B) reasonably calculated to promote conservation; and (C) carried out in such manner that no particular individual, corporation, or other entity acquires an excessive share of such privileges.
5. Conservation and management measures shall, where practicable, consider efficiency in the utilization of fishery resources; except that no such measure shall have economic allocation as its sole purpose.
6. Conservation and management measures shall take into account and allow for variations among, and contingencies in, fisheries, fishery resources, and catches.
7. Conservation and management measures shall, where practicable, minimize costs and avoid unnecessary duplication.
8. Conservation and management measures shall, consistent with the conservation requirements of this Act (including the prevention of overfishing and rebuilding of overfished stocks), take into account the importance of fishery resources to fishing communities by utilizing economic and social data that meet the requirements of paragraph (2), in order to (A) provide for the sustained participation of such communities, and (B) to the extent practicable, minimize adverse economic impacts on such communities.
9. Conservation and management measures shall, to the extent practicable, (A) minimize bycatch and (B) to the extent bycatch cannot be avoided, minimize the mortality of such bycatch.
10. Conservation and management measures shall, to the extent practicable, promote the safety of human life at sea.

Table 20. Example risk table from the MAFMC ecosystem risk assessment recreated from Gaichas et al. (2018).
l = low risk (green). lm = low-moderate risk (yellow). mh = moderate to high risk (orange) h = high risk (red).

Species	Assess	Fstatus	Bstatus	FW1Pred	FW1Prey	FW2Prey	Climate	DistShift	EstHabitat
Ocean Quahog	l	l	l	l	l	l	h	mh	l
Surfclam	l	l	l	l	l	l	mh	mh	l
Summer flounder	l	h	lm	l	l	l	lm	mh	h
Scup	l	l	l	l	l	l	lm	mh	h
Black sea bass	l	l	l	l	l	l	mh	mh	h
Atl. Mackerel	l	h	h	l	l	l	lm	mh	l
Butterfish	l	l	l	l	l	l	l	h	l
Longfin squid	lm	lm	lm	l	l	lm	l	mh	l
Shortfin squid	lm	lm	lm	l	l	lm	l	h	l

Golden tilefish	l	l	lm	l	l	l	mh	l	l
Blueline tilefish	h	h	mh	l	l	l	mh	l	l
Bluefish	l	l	lm	l	l	l	l	mh	h
Spiny dogfish	lm	l	lm	l	l	l	l	h	l
Monkfish	h	lm	lm	l	l	l	l	mh	l
Unmanaged forage	na	na	na	l	lm	lm	na	na	na
Deepsea corals	na	na	na	l	l	l	na	na	na

Table 21. Active remote technologies in rough order of scale (i.e., high to low resolution and short to long range). "Active" means energy is transmitted into the water and the received energy is converted to information. Operational readiness refers to a subjective assessment of the ability of the technology to provide useful information in days to weeks. These technologies can be deployed on mobile or fixed platforms.

Technology	Measurement scale: resolution	Measurement scale: range	Operational Readiness	References
Holographic camera[1]	sub-millimeter	centimeters	Medium: hardware and acquisition software are well developed, but processing software is custom-built.	Benfield et al. 2007 Lombard et al. 2019
Optical plankton counters[2]	millimeter	centimeters	Medium-high: hardware and acquisition software are well developed. Mix of custom-built and commercial processing and image analysis software.	Benfield et al. 2007 Lombard et al. 2019
Acoustic lens (e.g., DIDSON, ARIS)[3]	centimeter	10s of meters	Medium-high: hardware and acquisition software are well developed. Mix of custom-built and commercial processing and image analysis software.	Danxiang et al 2017 van Hal et al. 2017
Laser scanners[4]	centimeter	10s of meters	Medium: hardware and acquisition software are well developed, but processing software is custom-built.	Yoklavich et al. 2003 Churnside et al. 2012.
Narrowband single-beam echosounders[5]	centimeter	100s-1000s of meters depending on frequency	High: hardware, acquisition, and processing/analysis software well developed.	
Wideband single-beam echosounders[6]	centimeter	100s-1000s of meters depending on frequency	Medium-high: hardware and acquisition software are well developed, but processing software is mostly custom-built with some commercial software.	Demer et al. 2017
Lidar[7]	meter	10s-100s meters depending on swath	Medium: hardware and acquisition software are well developed, but processing software is custom-built.	Churnside et al. 2011a Churnside et al. 2011b https://oceanservice.noaa.gov/facts/lidar.html,

Technology	Measurement scale: resolution	Measurement scale: range	Operational Readiness	References
				https://psl.noaa.gov/technology/instruments/floe
Sidescan and synthetic aperture sonar (SAS)[8]	centimeter	10s of meters	High: hardware, acquisition, and processing/analysis software well developed.	Grothues et al. 2016
Multibeam echosounders[9]	centimeter	100s-1000s of meters depending on frequency	Medium-high: hardware and acquisition software are well developed. Bathymetry software is well developed, but water-column processing software is mostly custom-built with some commercial software.	Trenkel et al. 2008 Colbo et al. 2014 Dunlop et al. 2018
Fisheries sonars[10]	meters	100s-1000s meters depending on frequency	Medium-high: hardware and acquisition software are well developed. Bathymetry software is well developed, but water-column processing software is mostly custom-built with some commercial software.	Peña et al. 2021
Acoustic Telemetry[11]	meter	10s-100s meters depending on acoustic propagation	High: hardware, acquisition, and processing/analysis software well developed.	Crossin et al. 2017 Goulette et al. 2021
Acoustic Doppler Current Profiler (ADCP)[12]	meters	100s meters depending on frequency	High for monitoring current speed; Medium for monitoring and process for backscatter.	https://oceanservice.noaa.gov/education/tutorial_currents/06measure5.html https://oceanexplorer.noaa.gov/technology/acoust-doppler/acoust-doppler.html
Long-range sonar (e.g., OAWRS, bioalpha)[13]	10s of meters	1000s of meters	Low-medium: Hardware systems are not commercially available, and acquisition and analysis software are custom built.	Diachok et al. 2001 Makris et al. 2009 Jones et al. 2017 Makris et al. 2019
Environmental DNA (eDNA)[14]	? (meter)	?	Low-medium: Promising technology but many questions remain about all aspects of the data.	Govindarajan et al. 2021 Stoeckle et al. 2021

[1] Holographic cameras provide microscopic quality images of millimeter to centimeter sized objects.

[2] Optical plankton counters provide photographic quality images of millimeter to centimeter sized objects.

[3] Acoustic lens technology provides digital images of centimeter to meter sized objects to map and classify objects in the water column and benthic habitat.

[4] Laser scanners provide digital images of centimeter to meter sized objects to map and classify objects in the water column and benthic habitat.

[5] Narrowband echosounders are used to map the seabed and animals throughout the water column. These maps have many applications ranging from navigational charting and mapping benthic habitat to abundance estimates used in fisheries assessments.

[6] Wideband echosounders are equivalent to narrowband echosounders with greater spectral content that can be informative for classification of animals in the water column and seabed type.
[7] Lidar uses laser technology to provide similar information as echosounders, but is limited to ranges of 10s of meters.
[8] Sidescan and SAS are acoustic instruments that provide digital images of the seabed to map and classify the benthic habitat.
[9] Multibeam echosounders substantially expand the spatial coverage of conventional echosounders and are used for many applications from navigational charting and mapping benthic habitat to mapping schools and shoals of fish and plankton aggregations.
[10] Fisheries sonars are used to locate and map shoals and schools of fish.
[11] Acoustic telemetry is used to map movements of animals that have acoustic tags attached.
[12] ADCP is used to measure and monitor water current direction and velocity throughout the water column.
[13] Long-range sonars are used to quickly map the areal distribution of shoals and schools of fish over very large areas.
[14] Analysis of eDNA is used as a non-intrusive method to identify genetic material from animals in the water column.

Table 22. Passive remote technologies in rough order of scale (i.e., high to low resolution and short to long range). Operational readiness refers to a subjective assessment of the ability of the technology to provide useful information in days to weeks.

Technology	Measurement scale: resolution	Measurement scale: range	Operational Readiness	References
Still and video cameras[1]	sub-millimeter	10s meters depending on light and turbidity.	High: hardware, acquisition, and processing/analysis software well developed. Image analysis is in development.	Churnside et al. 2012 Richards et al. 2019
Passive acoustic monitoring (PAM)	meters	100s to 1000s meters depending on acoustic propagation	Medium-high: hardware and acquisition software are well developed. Processing and analysis software is mostly custom-built with some commercial software.	Luczkovich et al 2008 Mann, D. A. 2012. Zmeckis et al. 2019, Van Parijs et al. 2021

[1] Photographic quality images are used for identification of objects in the water column and on the seabed and can be used to detect the presence of animals.

Table 23. Capture Gear. While not remote "technology", capture gear is necessary to interpret active and passive technologies and provide biological data, such as age, maturity, sex, diet, and DNA. Operational readiness refers to a subjective assessment of the ability of the technology to provide useful information in days to weeks. "?" indicates unknown or unverified range and resolution.

Gear	Measurement scale: resolution	Measurement scale: range	Operational Readiness	References
Nets and trawls[1]	100s meters	1000s meters	High: Data processing is done in real time and data are available quickly.	
Traps[2]	? (meter)	? (10s meters)	High: Data processing is done in real time and data are available quickly	
Spearfishing[3]	meter	10s meters	High: Data processing is done in real time and data are available quickly.	
Angling[4]	? (meter)	?	High: Data processing is done in real time and data are available quickly.	

[1] Nets and trawls are mobile gear towed in the water column or on the seabed deployed and recovered from vessels.
[2] Traps are fixed gear located on the seabed and are deployed and recovered from vessels.
[3] Spearfishing is done by divers typically in and around reef areas.

[4] Angling is primarily done in a fixed location, but bait can be trolled along a cruise track.

Table 24. Platform technology. The active and passive sensors and instrumentation must be mounted to something to allow sampling. The sensors require power and data communication and/or recording capabilities. The platforms most often provide these requirements. Operational readiness refers to a subjective assessment of the ability of the technology to successfully operate under a variety of conditions.

Platform	Duration	Power and data communication	Operational Readiness	References
Diver[1]	hours	NA	High: divers are well trained to collect data.	Amend et al. 2007
Occupied surface vessels[2]	months	unlimited	High: research and commercial vessels have been used for decades to collect data	https://www.fisheries.noaa.gov/new-england-mid-atlantic/science-data/cooperative-research-northeast
Occupied aerial vehicles[3]	hours	unlimited	High: aerial vehicles (i.e., airplanes) have been used for decades to collect data	https://www.fisheries.noaa.gov/new-england-mid-atlantic/population-assessments/atlantic-marine-assessment-program-protected
Unoccupied aerial vehicles (aka drones)[4]	minutes	limited to battery	medium-high: drones are widely used, but quantitative use of data requires development	Jech et al. 2020
Satellites[5]	years	power is limiting, but data communication is not	High: satellites have been used for decades to collect data.	https://www.noaa.gov/satellites
Remotely operated vehicles (ROV)[6]	days	unlimited if the vehicle is directly connected to a vessel. limited if semi-autonomous.	Medium-high: many ROVs are well developed, but some semi-autonomous systems are still in development.	https://www.whoi.edu/what-we-do/explore/underwater-vehicles/ https://www.mbari.org/at-sea/vehicles/remotely-operated-vehicles/
Autonomous platforms[7]	months	limited to type of power available (e.g., solar, battery) and data communication is limited to satellite communication.	Medium-high: mix of developmental to well developed systems.	Colefax et al. 2018 https://www.mbari.org/at-sea/vehicles/autonomous-underwater-vehicles/, https://www.whoi.edu/what-we-do/explore/underwater-vehicles/auvs/ https://www.fisheries.noaa.gov/new-england-mid-atlantic/science-data/passive-acoustic-technologies

Platform	Duration	Power and data communication	Operational Readiness	References
Bottom mounted/stationary platforms[8]	months to years	limited by power availability and data storage e.g. acoustic recording packages	High: A wide range of well developed systems are available	https://oceanobservatories.org https://www.fisheries.noaa.gov/new-england-mid-atlantic/science-data/passive-acoustic-technologies
Real time data transmission platforms[9]	months to years	limited by power availability and iridium satellite or VHF transmission speed and data packaging	Medium-high: mix of developmental to well developed systems.	https://oceanobservatories.org https://www.fisheries.noaa.gov/new-england-mid-atlantic/science-data/passive-acoustic-technologies

[1] Divers sample in and around reef areas, which are especially difficult for other sampling gear to collect samples.

[2] Surface vessels are the most common platform for all types of oceanographic sampling. Daily costs range from thousands to tens of thousands USD.

[3] Aircraft are used for visual observations, atmospheric measurements, and Lidar, and can survey large areas in a short time, but are limited to operation by qualified personnel, weather conditions, and daylight for visual observations.

[4] Drones are used to collect optical data and atmospheric measurements and can access areas unreachable by other platforms, but require qualified personnel and batteries to operate.

[5] Satellites are used to monitor sea-surface properties, such as temperature and ocean color, over very large areas and extended periods of time.

[6] ROVs are used to collect samples and images of primarily the sea floor (but can collect data in the water column) not accessible by other gear, but require a support vessel and qualified personnel to operate.

[7] Autonomous surface and subsurface vehicles collect optical, acoustical, and environmental data and can extend spatiotemporal sampling and can be cost-effective supplements to occupied platforms.

[8] Bottom-mounted platforms collect optical, acoustical, and environmental data at the same location over extended periods providing time-based information, such as behavioral observations.

[9] Platforms can collect and record data that need to be downloaded when the platform is available to satellite link or recovered, or if the platform is permanently connected to a land-based computer, can provide real-time data and information.

Table 25. Examples of field studies that have either been completed or are ongoing in the U.S. wind energy areas (WEAs) including the sampling gear used, target species/species groups, and questions addressed.
BIWF = Block Island Wind Farm; WEA = Wind Energy Area

Wind Energy Area	Sampling Gear	Target Species or Groups	Question Addressed	Reference
BIWF	Bottom Trawl	Demersal fish community	How does the abundance and distribution of demersal fish change before vs. after construction?	Carey et al. 2020; Wilber et al. in press; Wilber et al. 2018
BIWF	Ventless trap	Lobster and crab	How does the abundance and distribution of lobster and crab change before vs. after construction?	Carey et al. 2020; Wilber et al. 2020

Wind Energy Area	Sampling Gear	Target Species or Groups	Question Addressed	Reference
BIWF	Drop down camera/video; Smith-Mcintyre grab sampler with mounted GoPro camera	Benthos around structure	How does the abundance and distribution of benthic invertebrates change before vs. after construction?	Hutchison et al. 2020c; HDR 2018
BIWF	Multibeam echosounder; Towed video sled; Plan view still imagery	Benthic habitat	What are the anchoring-related impacts of construction on moraine habitats?	Guarinello and Carey 2020
DE WEA	Acoustic telemetry	Atlantic sturgeon, winter skate and other fish species	What is the spatial and seasonal distribution of Atlantic sturgeon and winter skate?	Haulsee et al. 2020
MD WEA	Acoustic Telemetry	Striped bass and Atlantic sturgeon	What is the seasonal incidence and movement behavior of striped bass and Atlantic sturgeon in the near-shelf region?	Rothermel et al. 2020; Secor et al. 2020
MD WEA	Towed camera sled; Image analysis; Beam trawl	Benthic and demersal community	What is the baseline status of bottom habitats and epibenthic communities?	Cruz-Marrero et al. 2019
NY WEA	Acoustic telemetry	Atlantic sturgeon	What is the baseline distribution of Atlantic sturgeon?	Ingram et al. 2019; Frisk et al. 2019
RI-MA WEA	Ventless traps and Mark/recapture	American lobster and Jonah crab	What is the baseline abundance and distribution of lobster and crab?	Collie and King 2016; Collie et al. 2019
RI-MA WEA	Scallop dredge; Towed video camera sled	Scallop; Winter flounder, Windowpane flounder, Yellowtail flounder, and Monkfish	What is the baseline distribution of scallop, winter flounder, windowpane flounder, yellowtail flounder, monkfish, and bottom types?	Siemann and Smolowitz 2017
RI-MA WEA (VW)	1) Ventless trap and mark/recapture; 2) Fish pots; 3) Neuston nets	1) American lobster; 2) Black sea bass; 3) Lobster larvae	What is the baseline abundance and distribution of lobster, lobster larvae, and black sea bass?	Stokesbury et al. 2020

Wind Energy Area	Sampling Gear	Target Species or Groups	Question Addressed	Reference
RI-MA WEA (VW)	Bottom Trawl	Finfish abundance, length, weight	What is the baseline abundance and size distribution of bottom fish?	He and Rillahan 2021
RI-MA WEA (VW)	Drop Camera	Benthic community	What is the baseline status of benthic invertebrates and their habitats?	Bethoney et al. 2021a,b,c
RI-MA WEA	Acoustic telemetry; Stationary array and autonomous glider with hydrophone	Atlantic cod and commercial fisheries resources	What is the baseline distribution of spawning Atlantic cod and other fish species on Cox's Ledge?	NMFS Link; BOEM Link2
RI-MA WEA	Acoustic telemetry	Highly migratory species	What is the baseline distribution of HMS species?	MassCEC
RI-MA WEA	Neuston nets	Larval lobster and neuston	What is the baseline distribution of lobster larvae and neuston?	MassCEC
Wilmington-East Call Area	Split beam echosounder; Diver observation and photo survey	1) Finfish with swim bladders; 2) Benthic invertebrates and habitat	1) What is the baseline distribution of fish with a swim bladder?; 2) What is the baseline benthic community composition (abundance, density, and height for some spp.), finfish abundance and size, and bottom habitat?	BOEM 2016
RI-MA WEA	Passive acoustic monitoring and acoustic telemetry	Atlantic Cod	Determining the spatial and temporal extent of spawning behavior of Atlantic Cod	https://www.boem.gov/sites/default/files/documents/environment/environmental-studies/Movement-Patterns-of-Fish-in-Southern-New-England_0.pdf

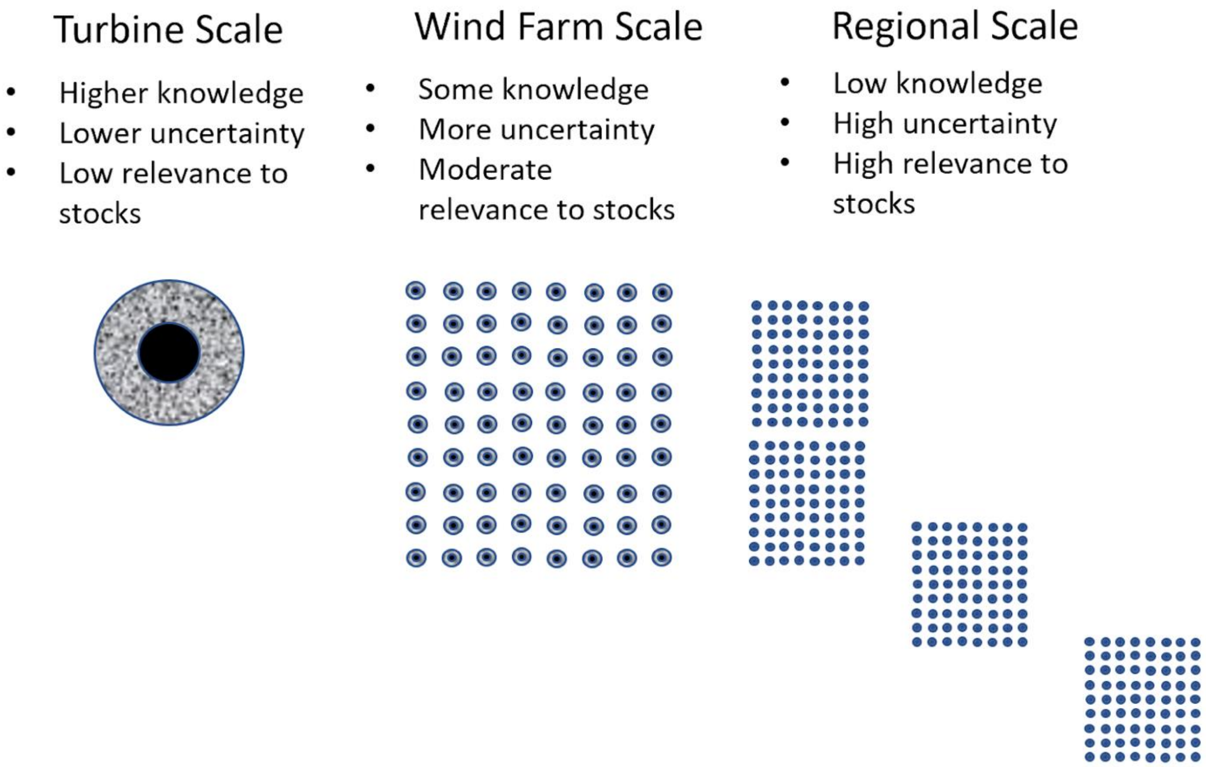


Figure 1. Hypothesis of connectivity of sediment modification from direct effects (turbine scale) with high knowledge, low direct effects on commercial stocks and low uncertainty to indirect effects at wind farm scale and regional scale with decreasing knowledge, increasing indirect effects on stocks and high uncertainty.

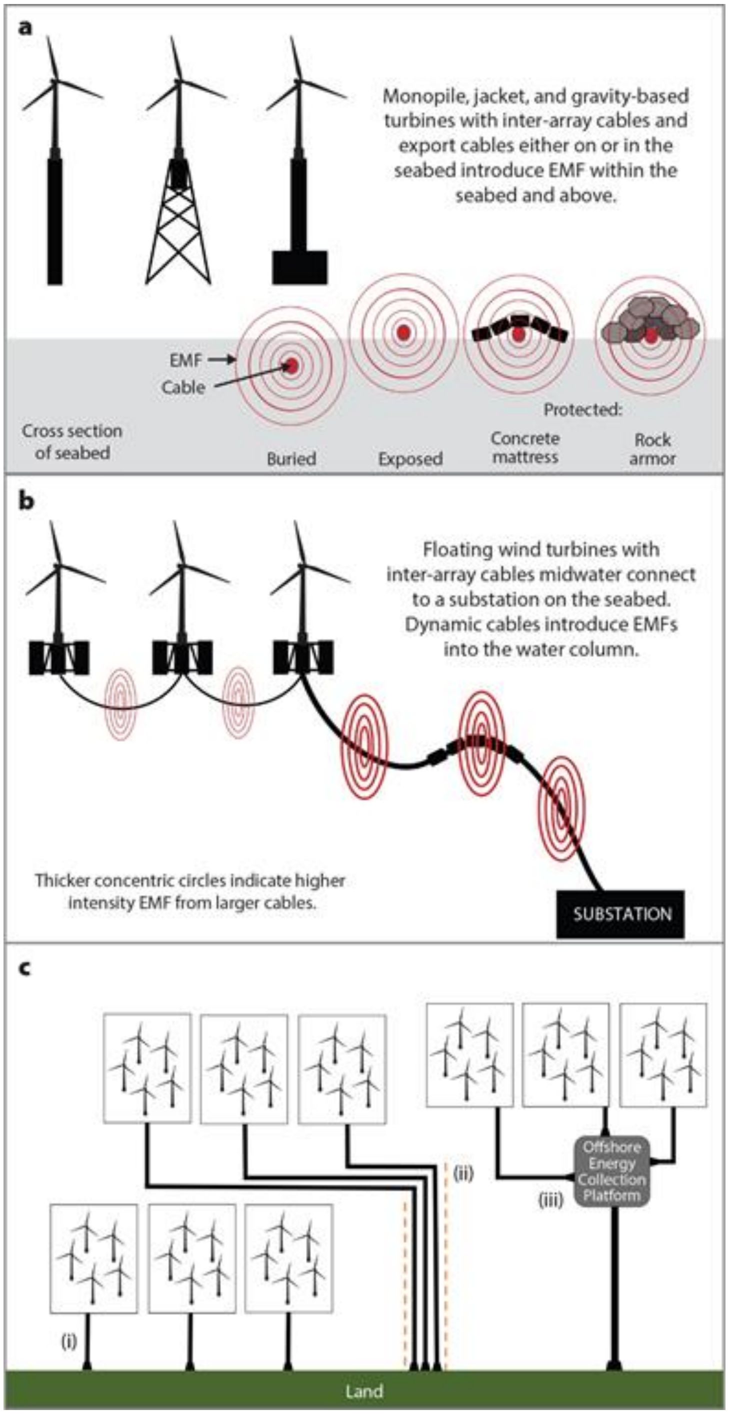


Figure 2. Cables may take different positions within the marine environment. (a) Cables are typically buried for their protection, and where burial is not possible (e.g. geology does not allow burial or connecting points to turbines), they may be laid on the surface of the seabed and protected with concrete mattressing or rock armor. (b) Floating wind introduces dynamic (free-hanging) cables into the water column; however, floating wind farms will still have bottom fixed export cables associated with the development, as in (a). (c) Where wind farms are large, multiple export cables may be required and cable corridors may accommodate multiple export cables from one or multiple OSW arrays. Figure from Hutchison et al., 2020a.

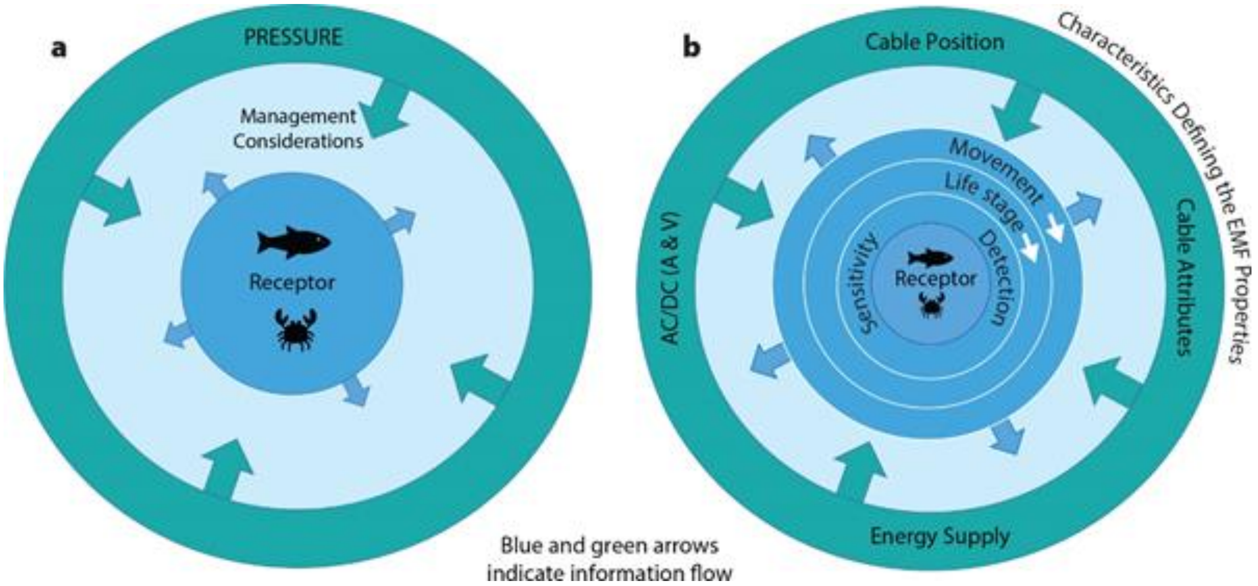


Figure 3. The vantage point of the receptor species must be considered together with an improved understanding of electromagnetic fields. (a) Management must be informed by characteristics defining the pressure (here, EMF) and receptor response. (b) Sensory capabilities and detection thresholds are at the core of receptor species attributes and must be considered through the integration of life history ecology. Simultaneously, EMF characteristics must be known so that exposure levels can be determined and management can consider the likely encounter rate and potential consequences of exposure. A = Current (amps). V = Voltage (volts). Figure from (Hutchison et al., 2020a).

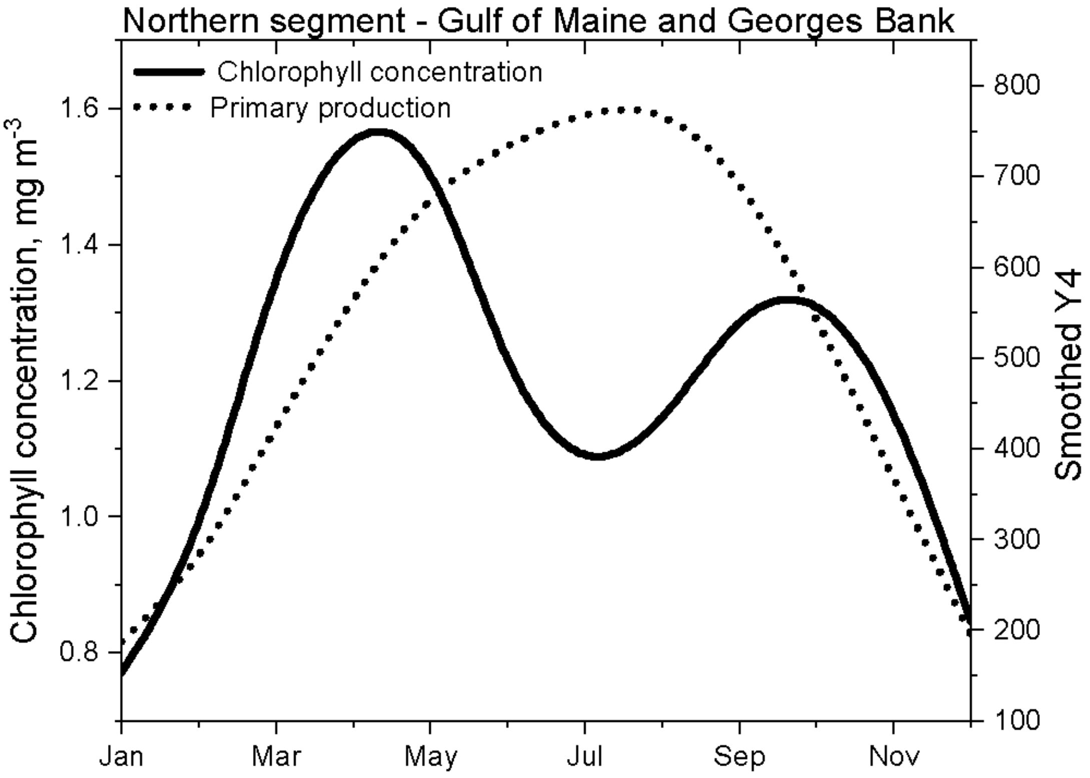


Figure 4. The mean annual cycle of chlorophyll concentration and primary production in the northern segment of the NES ecosystem.

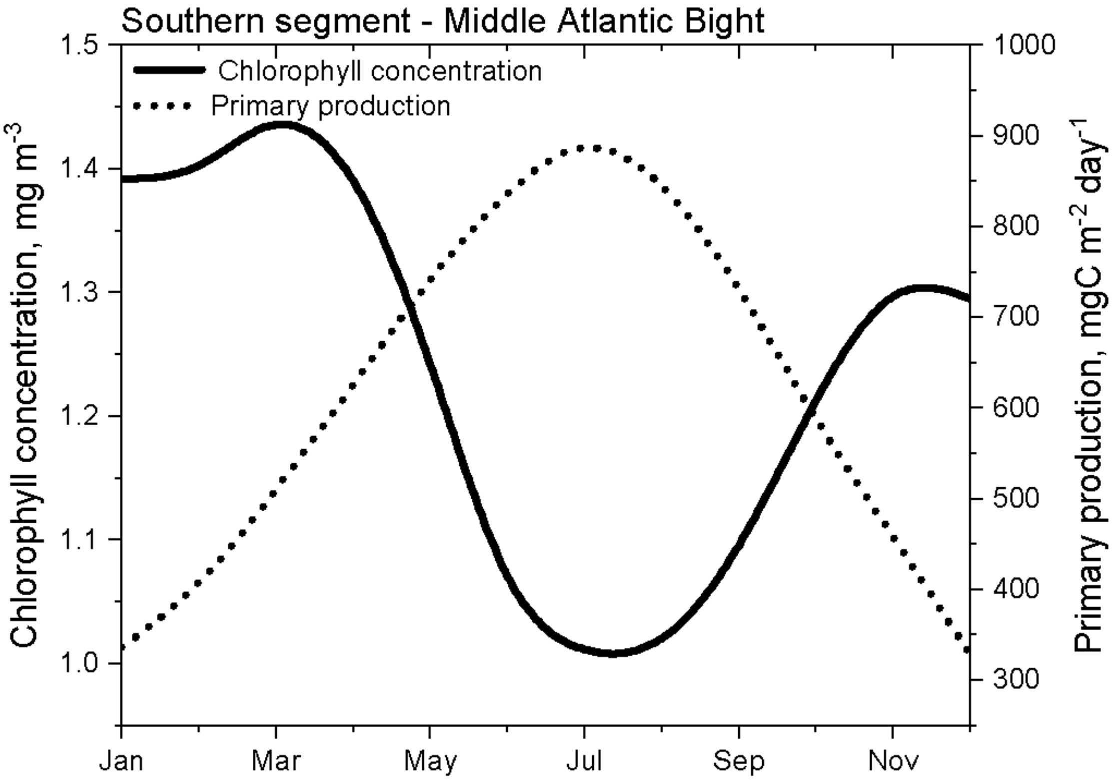
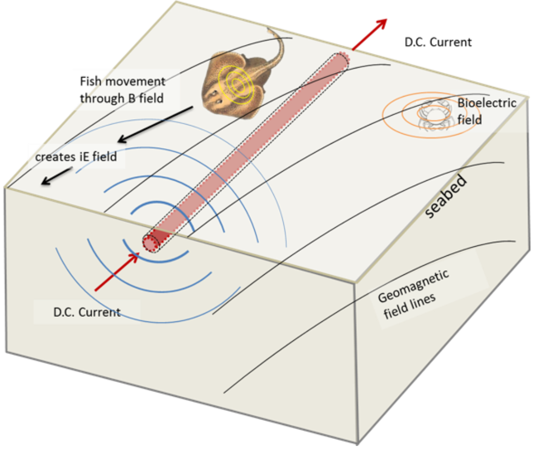


Figure 5. The mean annual cycle of chlorophyll concentration and primary production in the southern segment of the NES ecosystem.

(a) DC EMF



(b) AC EMF

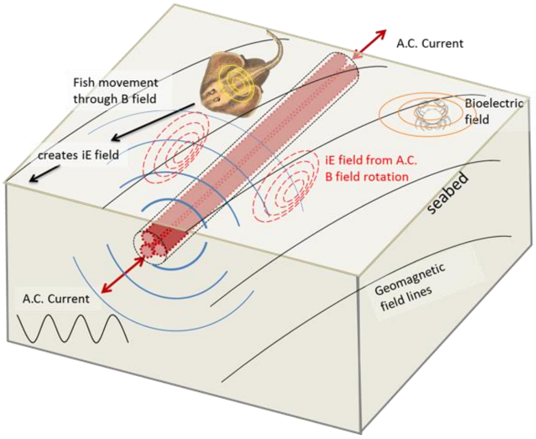
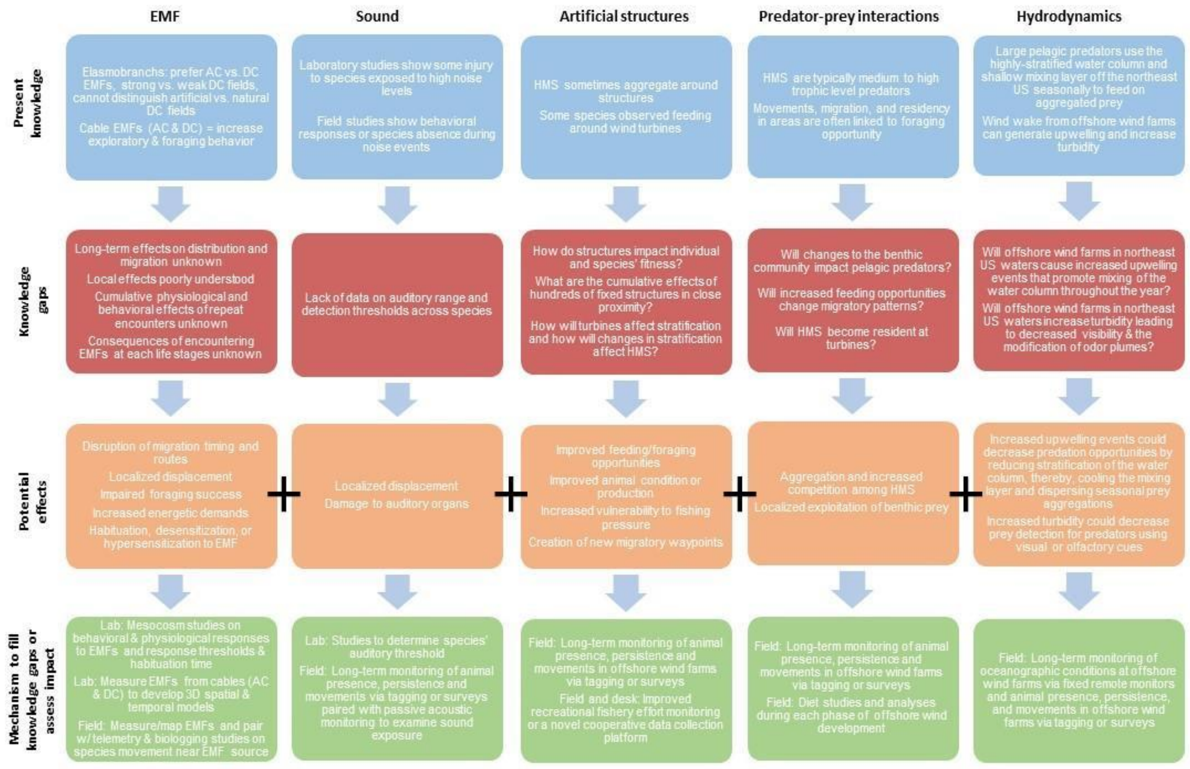


Figure 6. Depiction of natural and anthropogenic electric (E-field) and magnetic (B-field) fields encountered by an electroreceptive fish moving across the seabed. The separate E-field and B-field components of the electromagnetic fields (EMF) emitted by a buried subsea cable (red) are shown as well as the ambient geomagnetic field (GMF, black lines) and bioelectric fields from living organisms (orange lines). (a) The scenario with EMF associated with a DC subsea cable; (b) the EMF associated with a standard three core AC subsea cable with the current following a typical sine wave back and forth through each core. For both cables the direct E-field is shielded by cable material (black outer cable); however, B-fields are not able to be shielded, hence get emitted into the environment. Figure from Newton et al. (2019). DC EMF = Direct Current Electromagnetic Field. AC EMF = Alternating Current Electromagnetic Field.



	EMF	Sound	Artificial structures	Predator-prey interactions	Hydrodynamics
Present knowledge	Elasmobranchs: prefer AC vs. DC EMFs, strong vs. weak DC fields, cannot distinguish artificial vs. natural DC fields Cable EMFs (AC & DC) = increase exploratory & foraging behavior	Laboratory studies show some injury to species exposed to high noise levels Field studies show behavioral responses or species absence during noise events	HMS sometimes aggregate around structures Some species observed feeding around wind turbines	HMS are typically medium to high trophic level predators Movements, migration, and residency in areas are often linked to foraging opportunity	Large pelagic predators use the highly-stratified water column and shallow mixing layer off the northeast US seasonally to feed on aggregated prey Wind wake from offshore wind farms can generate upwelling and increase turbidity
Knowledge gaps	Long-term effects on distribution and migration unknown Local effects poorly understood Cumulative physiological and behavioral effects of repeat encounters unknown Consequences of encountering EMFs at each life stages unknown	Lack of data on auditory range and detection thresholds across species	How do structures impact individual and species' fitness? What are the cumulative effects of hundreds of fixed structures in close proximity? How will turbines affect stratification and how will changes in stratification affect HMS?	Will changes to the benthic community impact pelagic predators? Will increased feeding opportunities change migratory patterns? Will HMS become resident at turbines?	Will offshore wind farms in northeast US waters cause increased upwelling events that promote mixing of the water column throughout the year? Will offshore wind farms in northeast US waters increase turbidity leading to decreased visibility & the modification of odor plumes?
Potential effects	Disruption of migration timing and routes Localized displacement Impaired foraging success Increased energetic demands Habituation, desensitization, or hypersensitization to EMF	+ Localized displacement Damage to auditory organs	+ Improved feeding/foraging opportunities Improved animal condition or production Increased vulnerability to fishing pressure Creation of new migratory waypoints	+ Aggregation and increased competition among HMS Localized exploitation of benthic prey	+ Increased upwelling events could decrease predation opportunities by reducing stratification of the water column, thereby, cooling the mixing layer and dispersing seasonal prey aggregations Increased turbidity could decrease prey detection for predators using visual or olfactory cues
Mechanism to fill knowledge gaps or assess impact	Lab: Mesocosm studies on behavioral & physiological responses to EMFs and response thresholds & habituation time Lab: Measure EMFs from cables (AC & DC) to develop 3D spatial & temporal models Field: Measure/map EMFs and pair w/ telemetry & biologging studies on species movement near EMF source	Lab: Studies to determine species' auditory threshold Field: Long-term monitoring of animal presence, persistence and movements via tagging or surveys paired with passive acoustic monitoring to examine sound exposure	Field: Long-term monitoring of animal presence, persistence and movements in offshore wind farms via tagging or surveys Field and desk: Improved recreational fishery effort monitoring or a novel cooperative data collection platform	Field: Long-term monitoring of animal presence, persistence and movements in offshore wind farms via tagging or surveys Field: Diet studies and analyses during each phase of offshore wind development	Field: Long-term monitoring of oceanographic conditions at offshore wind farms via fixed remote monitors and animal presence, persistence, and movements in offshore wind farms via tagging or surveys

Figure 7. Summary of present knowledge, knowledge gaps, and potential effects of anticipated impacts related to offshore wind development with proposed mechanisms to fill knowledge gaps and monitor potential effects for each category of impacts. The "+" symbols denote the potential cumulative effects between impacts. EMF = Electromagnetic Field.

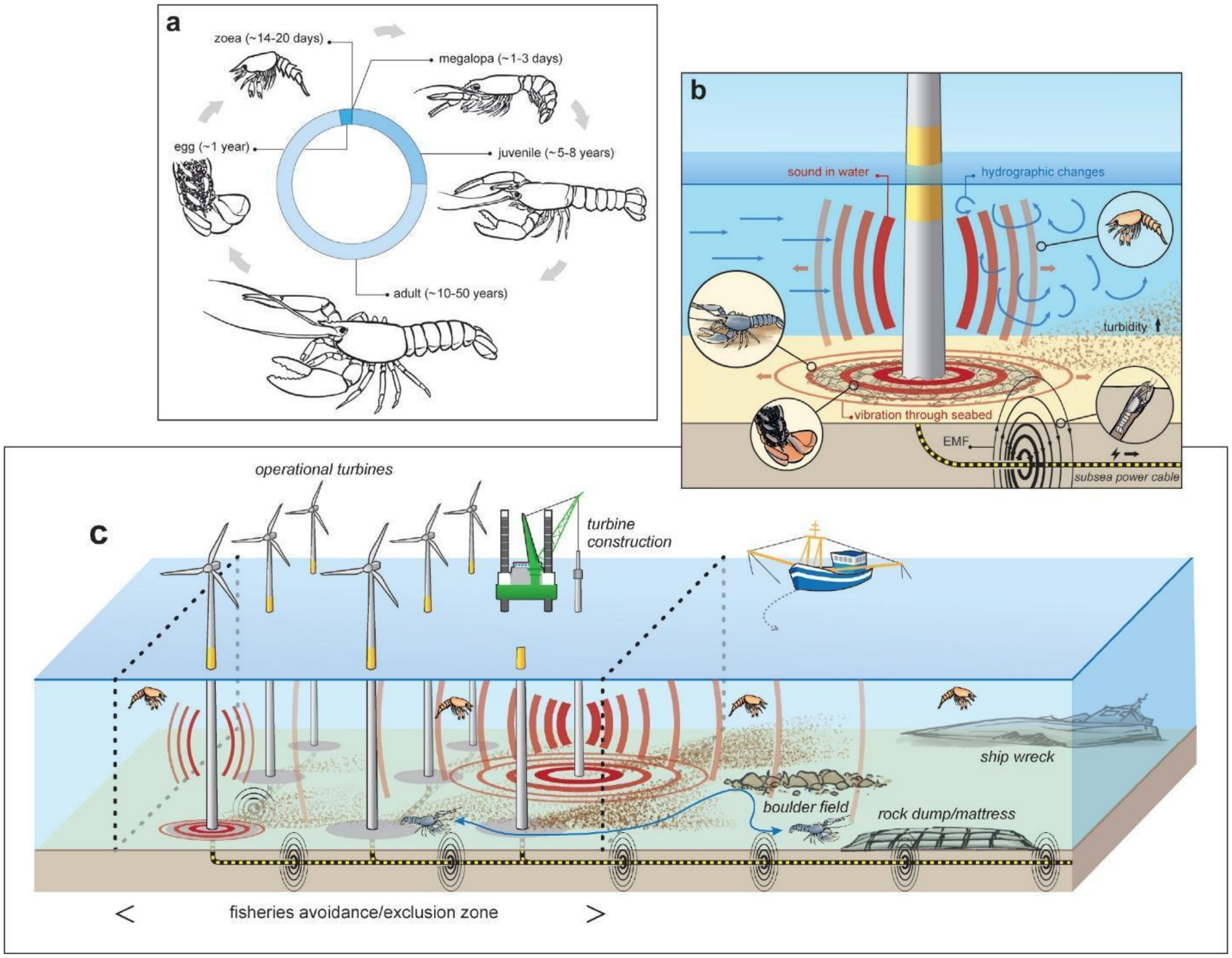


Figure 8. Overview of the main effects on the different life stages of the lobster genus *Homarus* during the different offshore wind farm (OWF) development phases (not to scale). (a) Life cycle of *Homarus* spp. with five distinct life stages: embryonic egg, larval zoea, early benthic juvenile (megalopa), juvenile, and adult, with an indication of the duration of each life stage; the larval zoea has several molt stages. (b) and (c) Composite pictures of OWF effects during construction and operation on the different life stages of the lobster genus *Homarus* at a (b) turbine scale and at a (c) wider scale. Sound and vibration are transmitted during both construction and operation (Mooney et al. 2020), though at a much lower intensity during operation. Construction sounds, which propagate over longer distances (particularly at low frequencies) compared to operational sounds, can have effects outside the OWF boundaries with decreasing intensity (c). Electromagnetic fields (EMFs) are only emitted when electrical current is transported through power cables. EMFs are emitted into the seabed and seawater from the infield cables (those extending between turbines in the array) and at higher intensities from the export cable (to the coast). Cables here are shown buried 1–2 m. The EMF extends several meters, and intensity decreases with distance above the seabed (Hutchison et al. 2020). Where the cables cannot be buried, they are protected by rocks or mattresses. Other factors that can affect the different life stages of the lobster are the artificial reef effect, fisheries avoidance (indicated by the broken arrow in front of the fishing vessel) and fisheries exclusion; changes in hydrography (including boundary layer mixing); and turbidity. Exclusion of fisheries can either be operational exclusion or regulatory exclusion, and can include the cable route to the coast. Image generated by Hendrick Geerardyn) and (adapted) legend sourced from Gill et al. (2020).

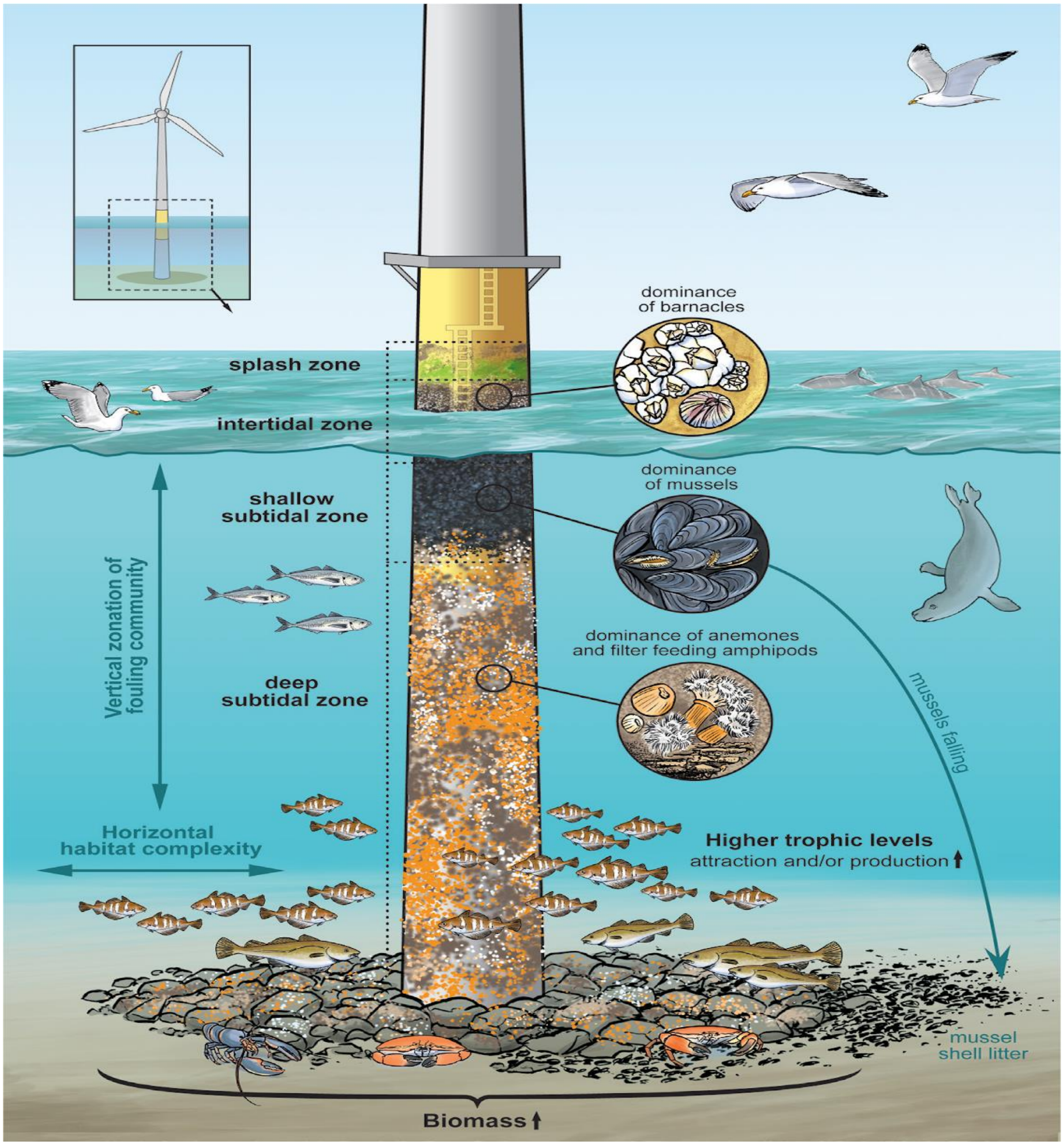


Figure 9. Artificial reef effect and vertical zonation around an OWF foundation. Illustration by Hendrik Gheerardyn. Borrowed with permission from Degraer et al. 2020a. doi.org/10.5670/oceanog.2020.405. Creative Commons license: https://creativecommons.org/licenses/by/4.0/legalcode

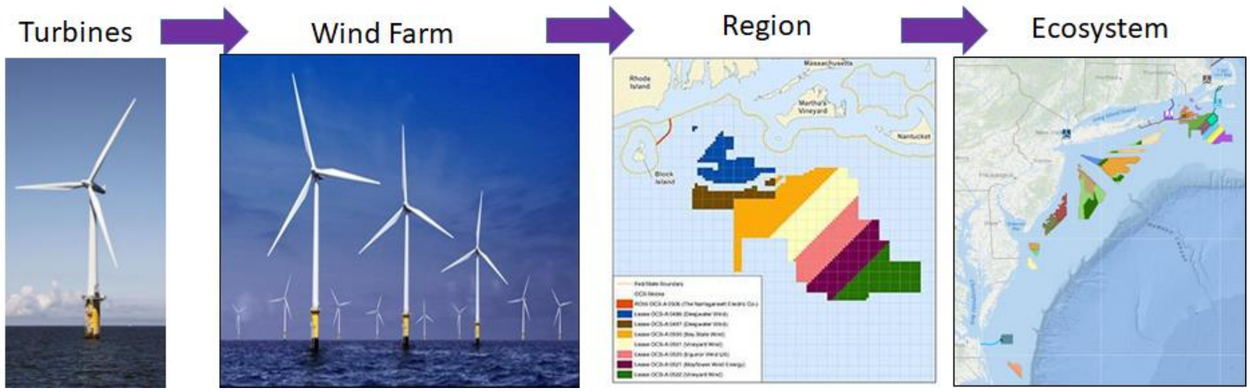


Figure 10. Generalized spatial scales in the context of impacts of offshore wind development and the formation of a regional framework for research and monitoring.

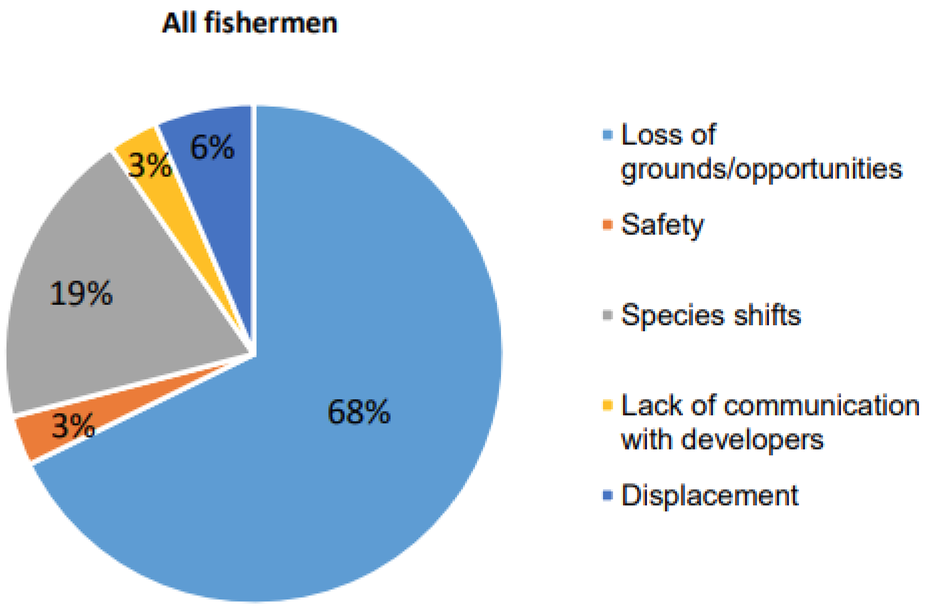


Figure 11. Survey results: What is the main negative impact of the Offshore Wind Development on the fishing industry? (Gray et al. 2016).

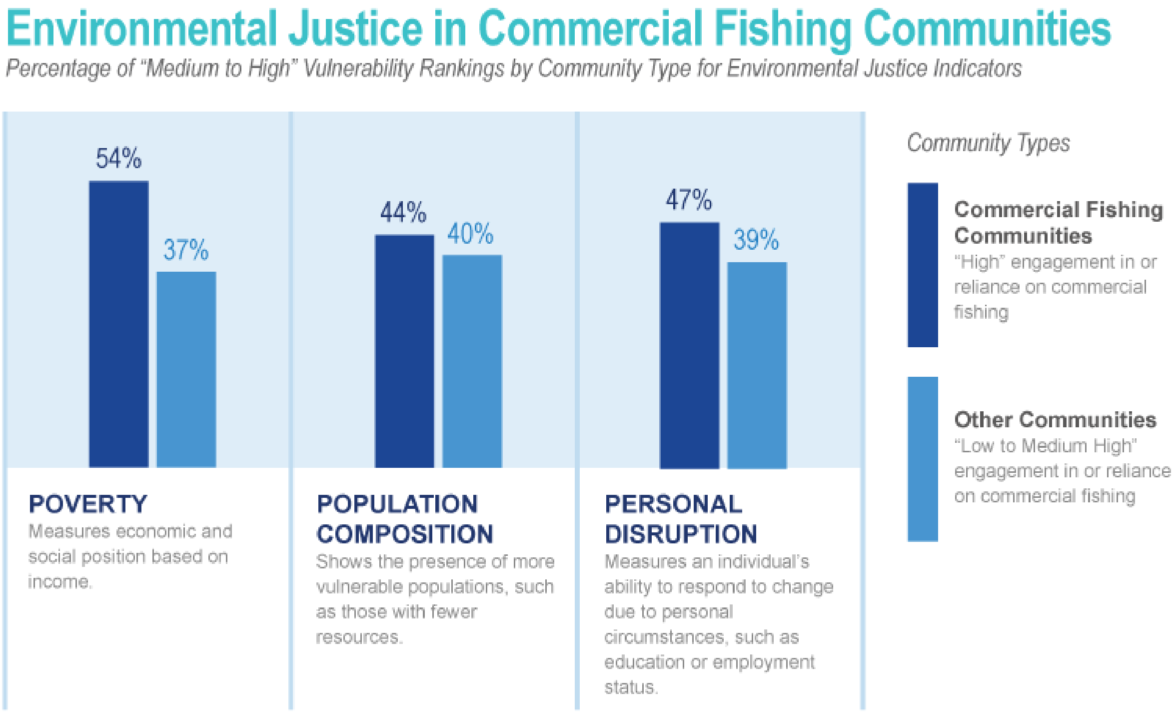


Figure 12. Environmental Justice Concerns in Commercial Fishing Communities

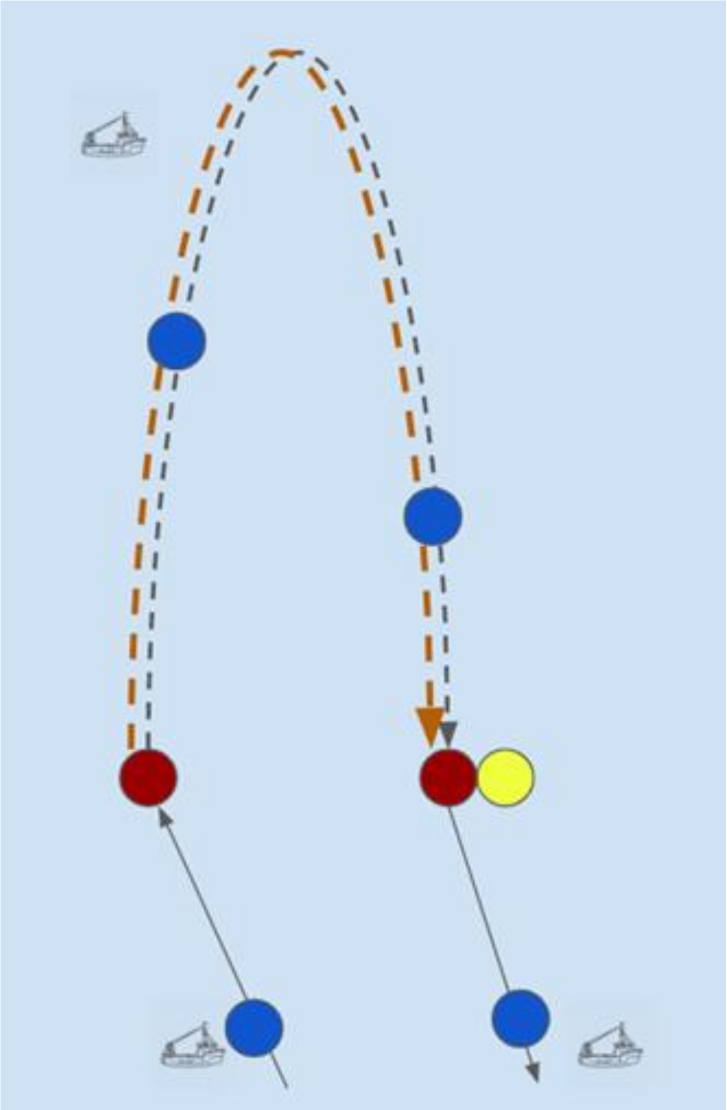
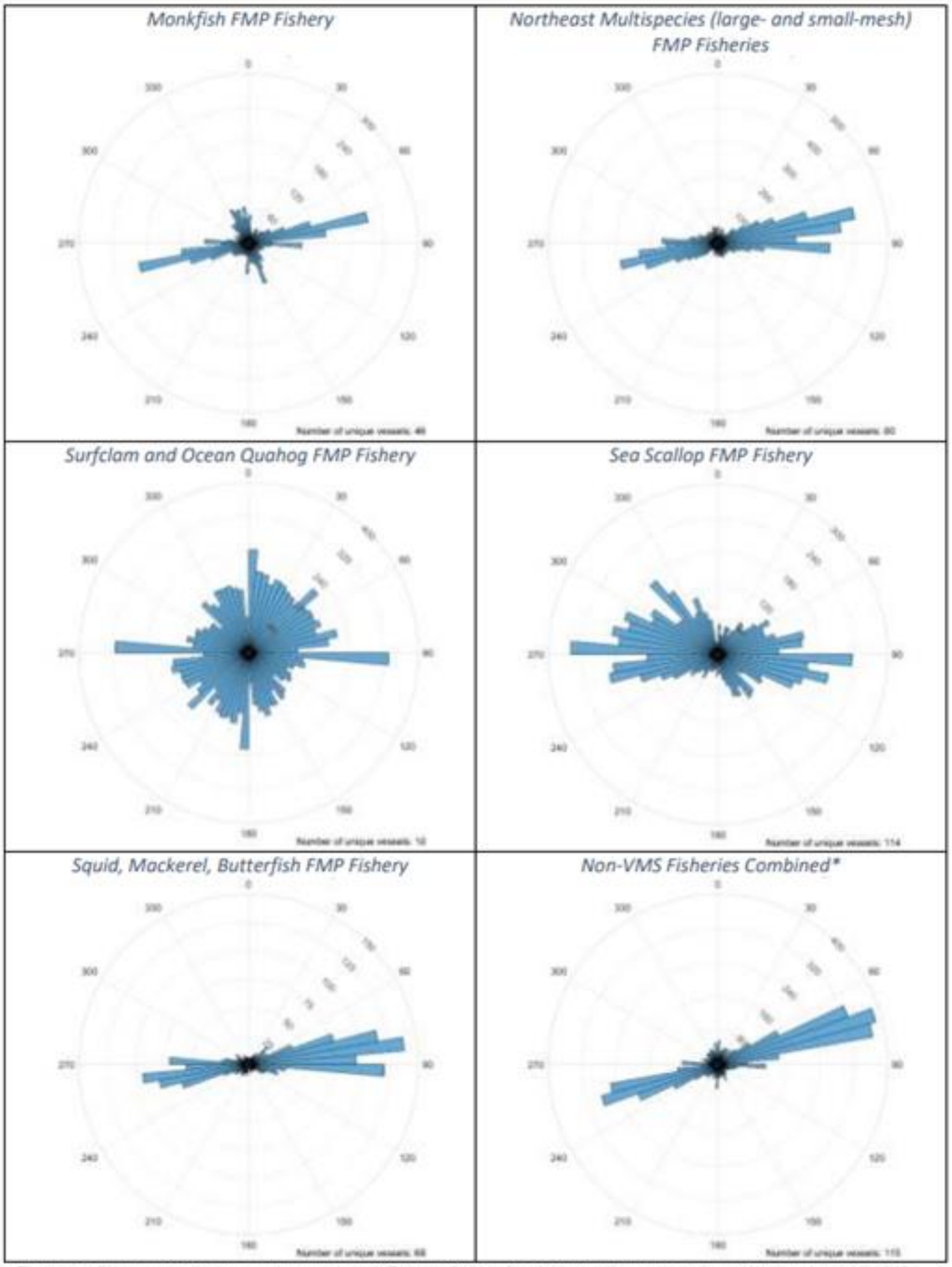


Figure 13. Schematic depicting the spatial resolutions of Vessel Trip Report (VTR; Yellow), Observer (Red), Vessel Monitoring System (VMS; Blue), and Study Fleet (red dotted line) data. Note the curvature in the tow track (black dotted line) and how that is captured differently within each data set. Source: Andrew Jones, Northeast Fisheries Science Center.



** These are fishing vessels that are transmitting VMS data after having declared themselves as participating in a non-VMS fishery—(e.g. Lobster, Jonah Crab, River Herring, etc.).*

Figure 14. Vessel Monitoring System (VMS) bearings of vessels actively fishing within the Rhode Island – Massachusetts Wind Energy Areas (RI-MA WEAs) by Fishery Management Plan (FMP) fishery, January 2014–August 2019 taken from South Fork Wind Farm Final Environmental Impact Statement (FEIS) see Figure 3.5.1-2 (BOEM 2021a).

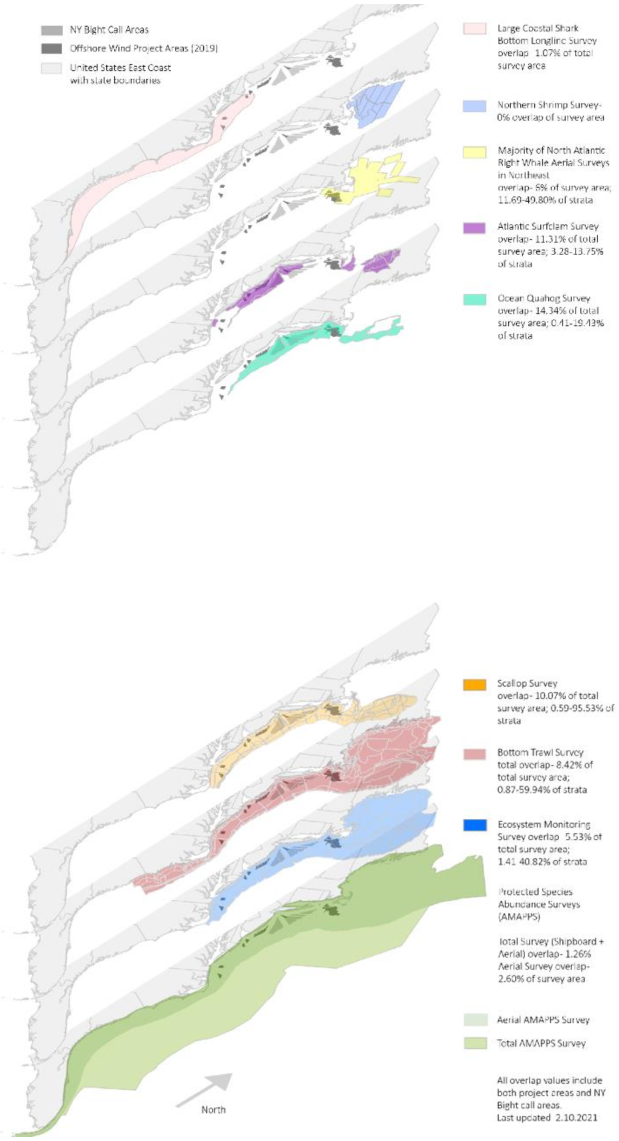


Figure 15. Spatial overlap between fishery independent surveys and planned offshore wind energy development in the northeast region (as of April 2021). Source: Angela Silva, NEFSC. [Higher Resolution Figures to be furnished]

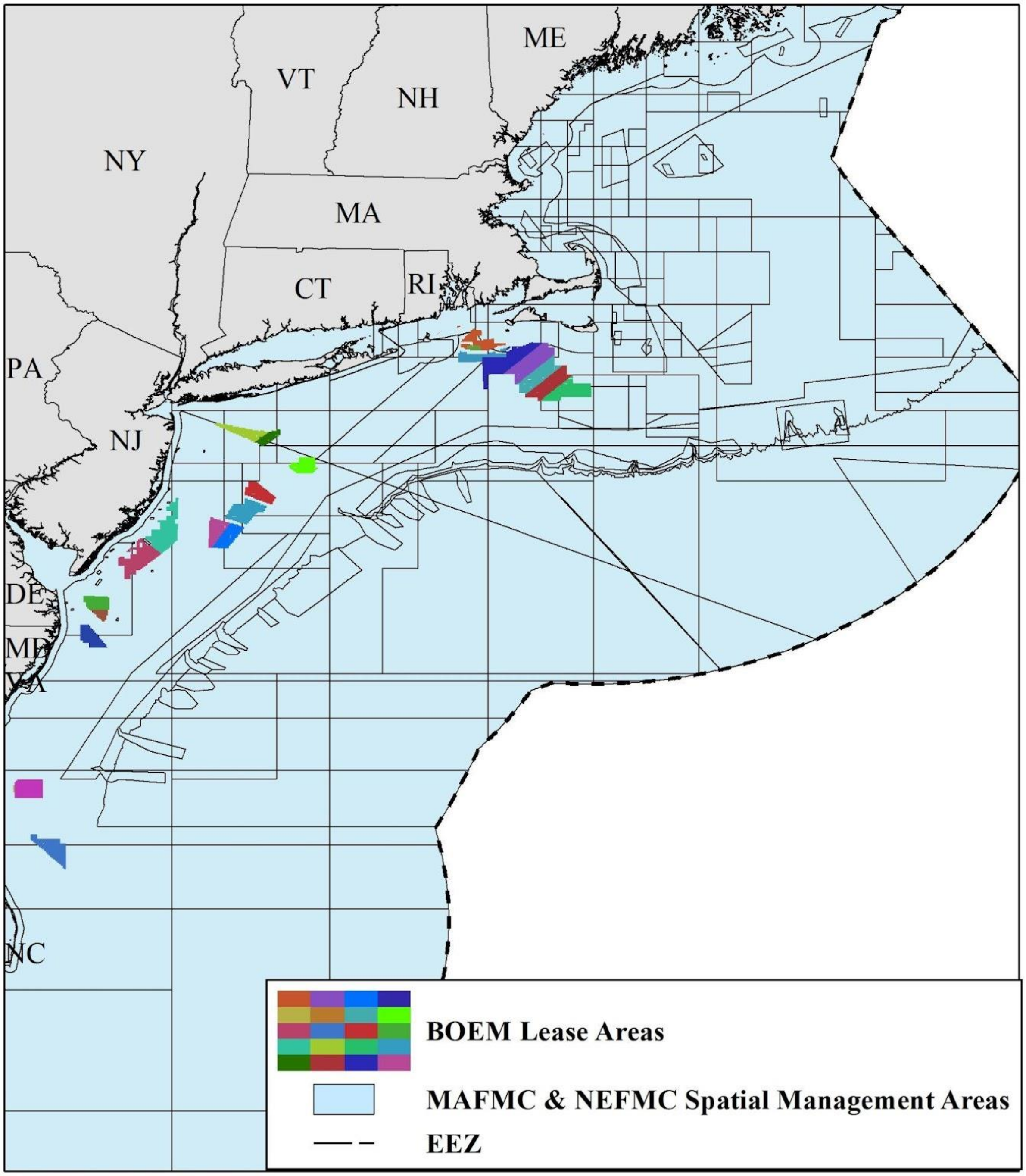


Figure 16. Spatial management measures adopted by the Mid-Atlantic Fishery Management Council and New England Fishery Management Council (showing areas implemented as of April 2022; may not be a complete representation of all spatial management measures) and BOEM offshore wind energy lease areas (as of April 2022). BOEM = Bureau of Ocean Energy Management. MAFMC = Mid-Atlantic Fishery Management Council. NEFMC = New England Fihsery Management Council.

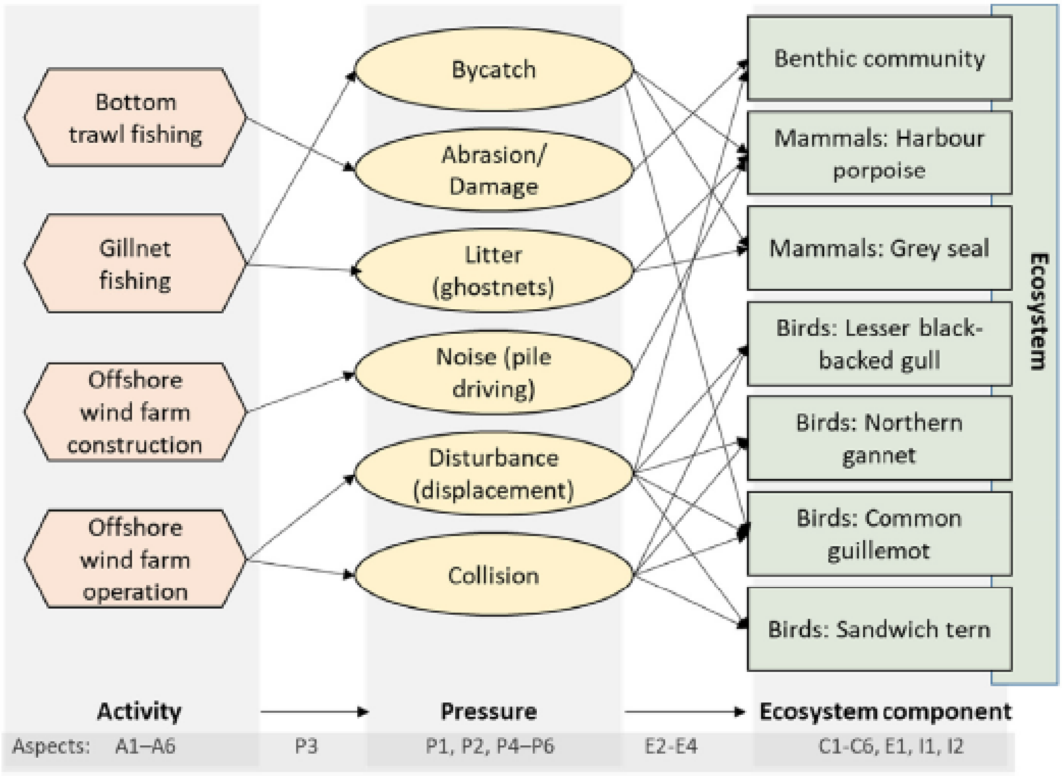


Figure 17. Conceptual framework listing the current linkages based on elements and relationships. The conceptual diagram considers exposure, effect and impact. These elements can help to then identify relevant scales and data sets (Taken from Piet et al. 2021).

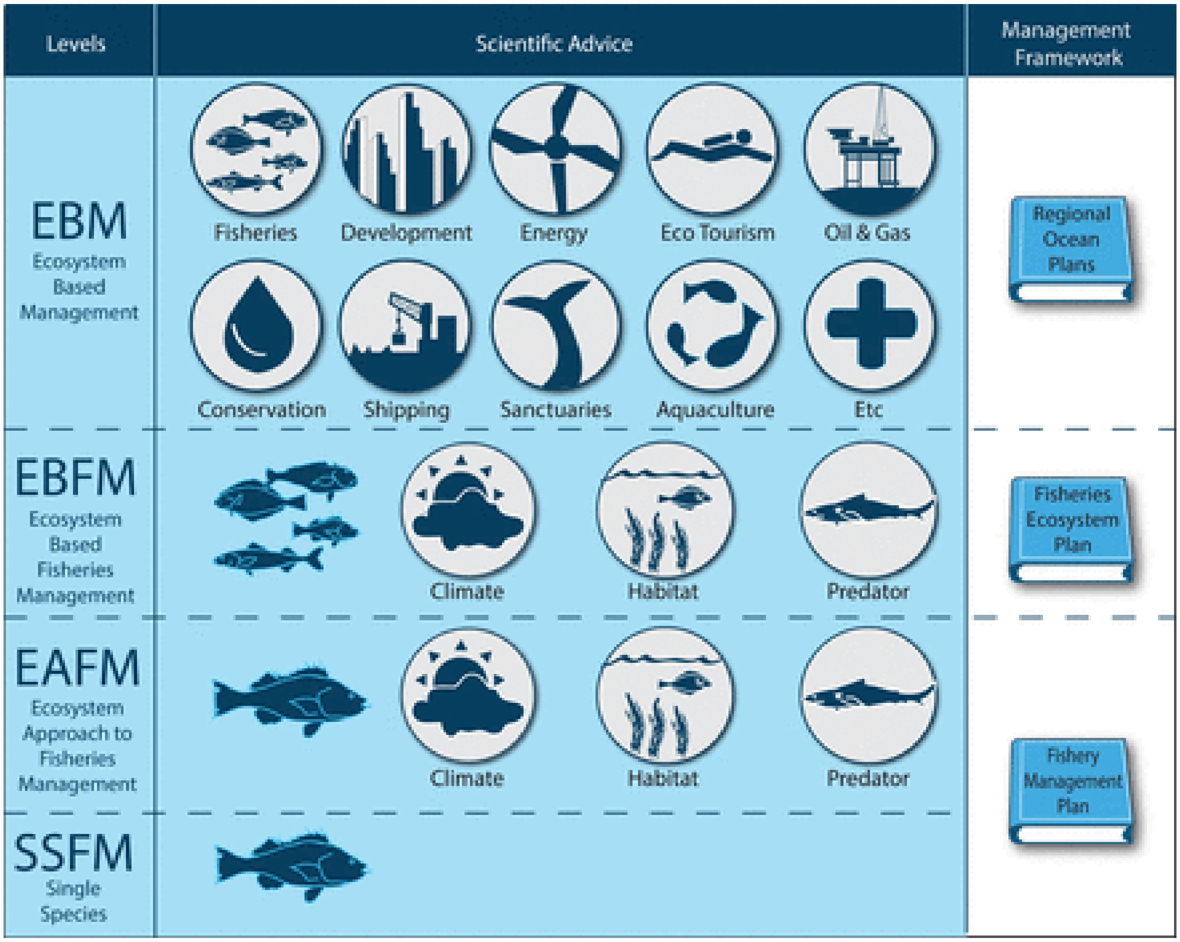


Figure 18. Hierarchy of ecosystem management. Traditional fisheries management is focused on single species/stocks (SSFM). The next level up, an ecosystem approach to fisheries management (EAFM), incorporates relevant ecosystem factors to improve single species management decisions. Full integration within the fisheries sector is referred to as ecosystem-based fisheries management (EBFM). While integration across multiple sectors is done through ecosystem-based management (EBM). Recreated from Dolan et al. 2016.

Figure 19. The Integrated Ecosystem Assessment (IEA) process. Figure is recreated from Samhouri et al. (2014). The IEA process is an iterative loop where one or all parts of the loop may be implemented.

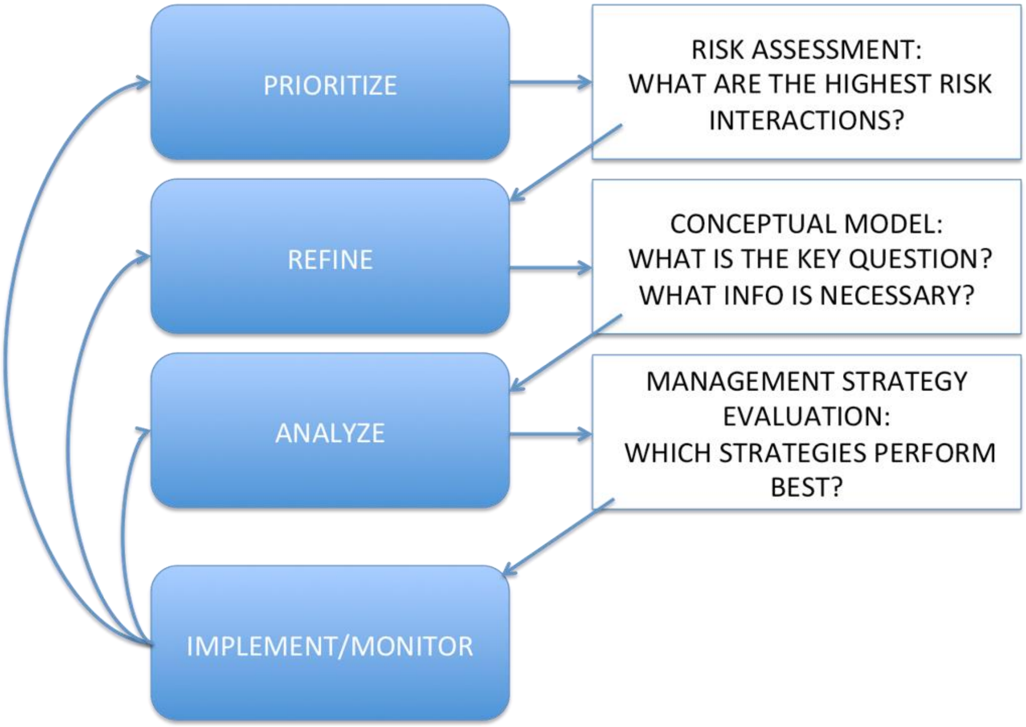


Figure 20. The modified Integrated Ecosystem assessment (IEA) loop used by the Mid-Atlantic Fishery Management Council's Ecosystem Approach to Fisheries Management (EAFM) process for incorporating ecosystem considerations into management. Figure is recreated from Gaichas et al. (2016).

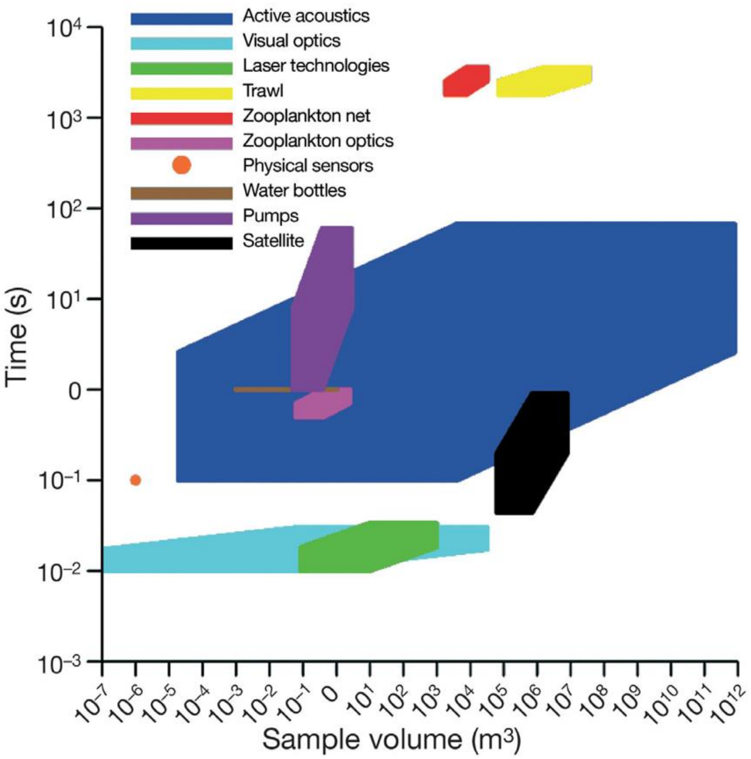


Figure 21. Spatiotemporal scale of a single observation by various sampling devices and sensors. Resolution of the measurement is indicated by the lower-left side of the polygon and its range by the upper-right side. For example, visual optical systems range from in-situ cameras to sensors on satellites (indicated by the light-blue polygon in the lower left portion of the graph). An in-situ camera can snap an image in 1/100s of a second (time scale) with sub-centimeter to meters spatial resolution and range. Sampling volume is the cube of the resolution or range, so a 1 centimeter voxel is $(10^{-2})^3$ or 10^{-6} m^3. Because of the physics of sound in the aquatic environment, acoustic systems have the greatest overall range and resolution of any sampling sensor (indicated by the blue polygon in the middle of the graph). Acoustic lens technology can collect an image in 1/10s of a second with sub-meter range and resolution (lower left corner of the blue polygon) and long-range sonars (e.g., OAWRS) can sample 10s of kilometers over 10s of seconds (upper right corner of the blue polygon). More detail is provided in Trenkel et al. (2011). (Figure from Trenkel et al. (2011))

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8. APPENDIX – FINFISH SPECIES LISTS

Table A1. List of species considered to be demersal.

Common Name	Scientific
Atlantic sturgeon	*Acipenser oxyrinchus oxyrinchus*
Shortnose sturgeon	*Acipenser brevirostrum*
Atlantic cod	*Gadus morhua*
Haddock	*Melanogrammus aeglefinus*
Polluck (saithe)	*Pollachius spp.*
Scup (porgy)	*Stenotomus chrysops*
Silver hake	*Merluccius bilinearis*
Wolffish	*Anarhichas lupus*
Ocean pout	*Zoarces americanus*
Monkfish (goosefish)	*Lophiidae spp.*
Atlantic halibut	*Hippoglossus hippoglossus*
Windowpane flounder	*Scophthalmus aquosus*
Winter flounder	*Pseudopleuronectes americanus*
Yellowtail flounder	*Pleuronectes ferruginea*
Witch flounder (grey sole)	*Glyptocephalus cynoglossus*
Summer flounder (fluke)	*Paralichthys dentatus*
Fourspot flounder	*Hippoglossina oblonga*
American plaice (dab)	*Hippoglossoides platessoides*
Gulf Stream flounder	*Citharichthys arctifrons*
Smallmouth flounder	*Etropus microstomus*
Anglerfish	*Lophiiformes spp.*
Northern stargazer	*Astroscopus guttatus*
Toadfish	*Batrachoididae spp.*
Striped sea robin	*Prionotus evolans*
Northern sea robin	*Prionotus carolinus*
sea raven	*Hemitripteridae spp.*
Longhorn sculpin	*Myoxocephalus octodecimspinosus*
Shorthorn sculpin	*Myoxocephalus scorpius*
Red hake	*Urophycis chuss*
White hake	*Urophycis tenuis*
Spotted hake	*Urophycis regia*
Whiting	*Merlangius merlangus*
Black Whiting	*Sillaginodes punctata*
King Whiting (kingfish)	*Menticirrhus saxatilis*
Atlantic Tomcod	*Microgadus Tomcod*
Red porgy	*Pagrus Pagrus*
Black sea bass	*Centropristis striata*
Cunner	*Tautogolabrus adspersus*

Common Name	Scientific
Tautog	*Tautoga onitis*
Black drum	*Pogonias cromis*
Golden tilefish	*Lopholatilus chamaeleonticeps*
Blueline tilefish	*Caulolatilus microps*
Sand tilefish	*Malacanthus plumieri*
Planehead filefish	*Stephanolepis hispidus*
John Dory	*Zeus faber*
Conger eel	*Congridae spp.*
American eel	*Anguilla rostrata*
Fawn cusk eel	*Lepophidium profundorum*
Sand eel (Sand lance)	*Hyperoplus/Gymnammodytes/Ammodytes spp.*
Weakfish (squeteague)	*Cynoscion regalis*
Spot (Spot croaker)	*Leiostomus xanthurus*
Atlantic croaker	*Micropogonias undulatus*
Triggerfish	*Balistidae spp.*
Northern puffer	*Sphoeroides maculatus*
Leatherjacket	*Oligoplites saurus*
Acadian redfish	*Sebastes fasciatus*
Golden redfish	*Sebastes norvegicus*
Red snapper	*Lutjanus campechanus*
Spadefishes	*Ephippidae spp.*
Inshore lizardfish	*Synodus foetens*
Snakefish	*Trachinocephalus myops*
Pinfish	*Lagodon rhomboides*
Blue runner	*Caranx crysos*
Fourbeard rockling	*Enchelyopus cimbrius*
Wrymouth	*Cryptacanthodes maculatus*
Northern sennet	*Sphyraena borealis*
Dwarf goatfish	*Upeneus parvus*
Cornetfish (flutemouth)	*Fistularia spp.*
Atlantic moonfish	*Selene setapinnis*
Short bigeye	*Pristigenys alta*
Spotted driftfish	*Ariomma regulus*
Silver rag driftfish	*Ariomma bondi*
Wreckfish	*Polyprionidae spp.*
Lumpfish (lumpsuckers)	*Cyclopteridae spp.*
Three spined stickleback	*Gasterosteus aculeatus*
American Silver perch	*Bairdiella chrysoura*
Sheepshead minnow	*Cyprinodon variegatus*
Seahorses (pipefish, sea dragons)	*Syngnathidae spp.*
Little skate	*Leucoraja erinacea*

Common Name	Scientific
Barndoor skate	*Dipturus laevis*
Clearnose skate	*Raja eglanteria*
Winter skate	*Leucoraja ocellata*
Thorny skate	*Amblyraja radiate*
Roughtail stingray	*Dasyatis centroura*
Round stingray	*Urolophus halleri*
Bullnose ray	*Myliobatis freminvillii*
Atlantic torpedo ray	*Torpedo nobiliana*

Table A2. List of species considered to be small pelagic forage fish.

Common Name	Scientific
Atlantic herring	*Clupea harengus*
Blueback herring	*Alosa aestivalis*
Round herring	*Etrumeus sadina*
Alewife	*Alosa pseudoharengus*
Atlantic mackerel	*Scomber scombrus*
Chub mackerel	*Scomber japonicus*
Gizzard shad	*Dorosoma cepedianum*
American shad	*Alosa sapidissima*
Hickory shad	*Alosa mediocris*
Round scad	*Decapterus punctatus*
Rough scad	*Trachurus lathami*
Bigeye scad	*Selar crumenophthalmus*
Atlantic menhaden	*Brevoortia tyrannus*
Atlantic saury	*Scomberesox saurus*
Atlantic silverside	*Menidia Menidia*
Bay anchovy	*Anchoa mitchilli*
Butterfish	*Peprilus triacanthus*

Table A3. List of species considered to be pelagic predators – mid-sized pelagics.

Common Name	Scientific
Bluefish	*Pomatomus saltatrix*
Striped bass	*Morone saxatilis*
Atlantic Bonito	*Sarda sarda*
Little tunny	*Euthynnus alletteratus*
Cobia	*Rachycentron canadum*
Spanish mackerel	*Scomberomorus maculatus*

Common Name	Scientific
King mackerel	*Scomberomorus cavalla*
Sea run (brown) trout	*Salmo trutta*
Atlantic salmon	*Salmo salar*
Smooth dogfish	*Mustelus canis*
Spiny dogfish	*Squalus acanthias*
Atlantic angel shark	*Squatina dumeril*

Table A4. List of species considered to be pelagic predators – highly migratory species.

Common Name	Scientific
Albacore	*Thunnus alalunga*
Bluefin tuna	*Thunnus thynnus*
Bigeye tuna	*Thunnus obesus*
Yellowfin tuna	*Thunnus albacares*
Skipjack tuna	*Katsuwonus pelamis*
Mahi Mahi (dolphin)	*Coryphaena hippurus*
Wahoo	*Acanthocybium solandri*
Swordfish	*Xiphias gladius*
White marlin	*Tetrapturus albidus*
Roundscale spearfish	*Tetrapturus georgii*
Blue marlin	*Makaira nigricans*
Basking shark	*Cetorhinus maximus*
Thresher shark	*Alopius vulpinus*
Great White shark	*Carcharodon carcharias*
Shortfin mako shark	*Isurus oxyrinchus*
Porbeagle	*Lamna nasus*
Blue shark	*Prionace glauca*
Tiger shark	*Galeocerdo cuvier*
Sand tiger	*Carcharias taurus*
Sandbar shark	*Carcharhinus plumbeus*
Dusky shark	*Carcharhinus obscurus*
Spinner shark	*Carcharhinus brevipinna*
Scalloped hammerhead shark	*Sphyrna lewini*
Smooth hammerhead shark	*Sphyrna zygaena*

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