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THEMED ISSUE: OFFSHORE WIND INTERACTIONS WITH FISH AND FISHERIES

Science Priorities for Offshore Wind and Fisheries Research in the Northeast U.S. Continental Shelf Ecosystem: Perspectives from Scientists at the National Marine Fisheries Service

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Abstract
Offshore wind development (OWD) is set to expand rapidly in the United States as a component of the nation's effort to combat climate change. Offshore wind development in the United States is slated to begin in the Greater Atlantic region, where it is expected to interact with ocean ecology, human dimensions, fisheries data collections, and fisheries management. Understanding these interactions is key to ensuring the coexistence of offshore wind energy with sustainable fisheries and a healthy marine ecosystem. These anticipated interactions compelled the authors, all fisheries scientists or managers at National Oceanic and Atmospheric Administration (NOAA) Fisheries who are actively engaged in offshore wind science to identify scientific research priorities for OWD in the Northeast U.S.

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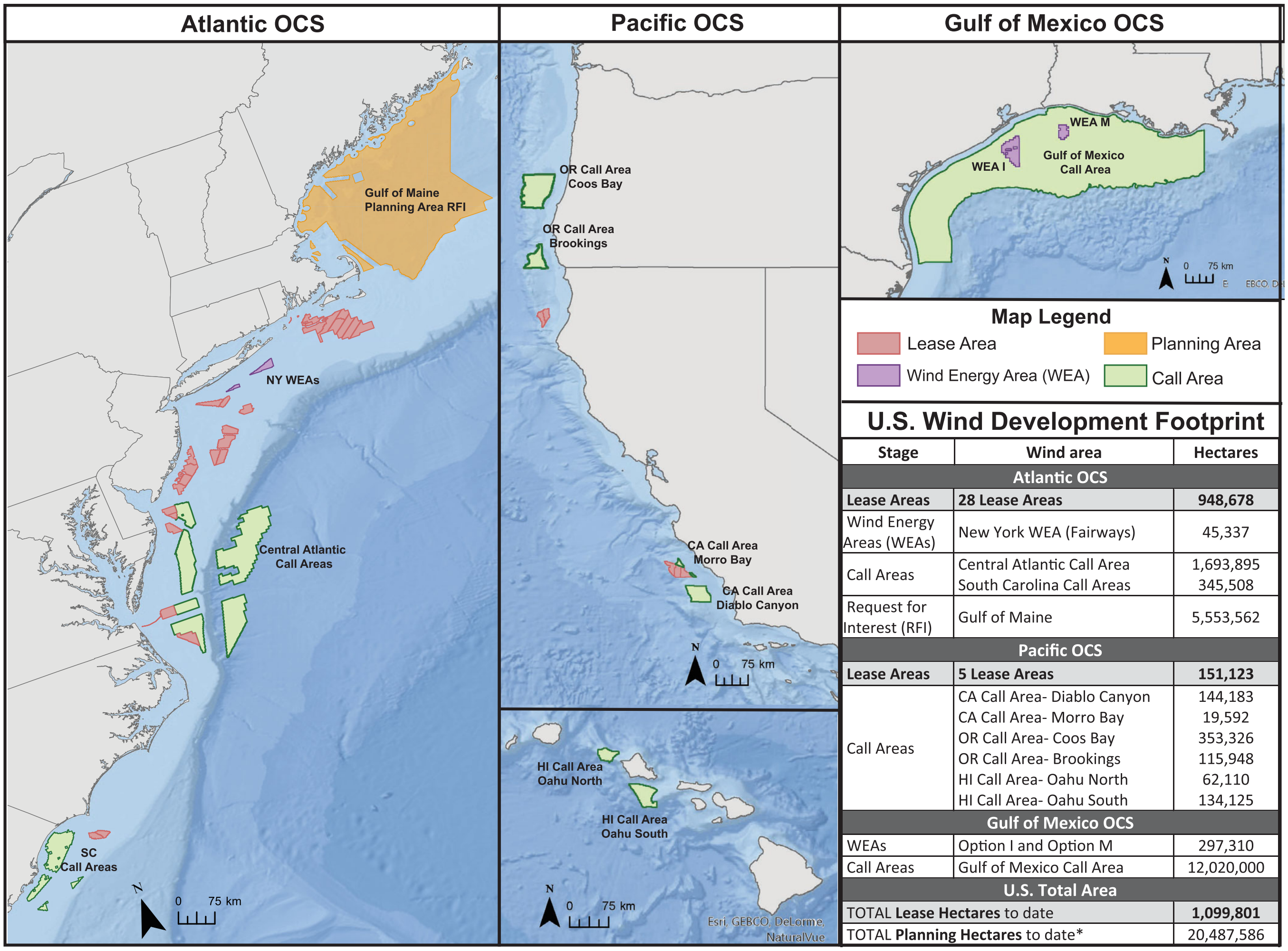
Continental Shelf ecosystem, specifically in support of NOAA Fisheries' role as the nation's leading steward of marine life. We extracted and analyzed OWD research needs from existing scientific documents and used this information as the basis to develop a list of priorities that align with five major OWD science themes that are of high interest to NOAA Fisheries. These NOAA Fisheries themes include supporting the regulatory process; mitigating the impacts to NOAA Fisheries' surveys; advancing science to understand interactions with NOAA Fisheries trust resources, the marine ecosystem, and fishing industries/communities; advancing the science of mitigation for NOAA Fisheries trust resources and fishing industries/communities; and advancing data management methods. The areas identified as research priorities will support the coexistence of offshore wind and sustainable fisheries and inform the development of NOAA Fisheries' science plan for offshore wind in the Northeast U.S. Continental Shelf ecosystem as well as cross-sectoral science planning efforts at the regional, national, and international levels.

Offshore wind development (OWD) has advanced globally at a record-setting pace for more than a decade. At the end of 2021, there were 57 GW of installed offshore wind energy generating capacity worldwide, representing an increase greater than 60% relative to the previous year (GWEC 2021, 2022). In the United States, offshore wind is an integral component of the federal government's strategy to reduce the nation's reliance on fossil fuels, curtail carbon emissions, and mitigate the impacts of climate change. To date, the United States has granted federal approval for just under 1 GW of commercial-scale energy and plans to support the goal of 30 GW of new offshore wind energy by 2030, with a pathway to 110 GW by 2050. In the U.S. Northeast, designated lease areas cover more than 930,777 ha (2.3 million acres), with over 25 projects proposed for development by 2030. The Bureau of Ocean Energy Management (BOEM) plans to hold up to seven new offshore wind lease sales by 2025 in other regions of the United States (Figure 1). Although OWD may play a central role in the nation's plan to combat climate change, wind developments will interact with the ocean and its inhabitants. Understanding these interactions is key to avoiding, minimizing, and mitigating adverse impacts and ensuring the coexistence of offshore wind energy with sustainable fisheries and a healthy marine ecosystem.

Offshore wind development will modify the ocean environment and affect fisheries (Gill et al. 2020; Mooney et al. 2020; Christiansen et al. 2022). It will also necessitate making alterations to the methodologies used to survey and monitor protected species and natural resources (Gill et al. 2020; Methratta et al. 2020), thus affecting the information yielded by those surveys and potentially the management and policy decisions that rely upon that information (Hare et al. 2022). Although the U.S. Coast Guard has not legally restricted fishing activities within OWDs (Kearns and West 2018), maneuverability of fishing vessels within wind areas may vary depending on many factors, including vessel size, the fishing gear or method used, or environmental conditions (BOEM 2021a). This will lead to displacement (Murawski et al. 2005; Bergström et al. 2014; De Backer et al. 2019) for both commercial and recreational fisheries if they are excluded from accessing fishing grounds during the construction phase and de facto (practical) exclusions during operational phases for some mobile-gear commercial fisheries (Mackinson et al. 2006; Gray et al. 2016; ten Brink and Dalton 2018; NYSERDA 2022). Potential increases in recreational fisheries attracted to OWD structures may also occur (ten Brink and Dalton 2018; Smythe et al. 2021). Floating offshore wind (as proposed for the Gulf of Maine, West Coast, and central Atlantic) will further exclude fisheries due to the presence of cables within the water column. In Scotland, survey research is ongoing to trial safe fixed-gear fishing within floating wind farms (Equinor 2022). The effects of interactions with OWD at sea will ripple through fishing communities and land-based supply chains (Haggett et al. 2020; Haraldsson et al. 2020). Offshore wind development will also have social and cultural (nonmaterial) impacts on fishing communities, including effects on well-being and quality of life (Mackinson et al. 2006; Hooper et al. 2015; Haraldsson et al. 2020) as well as seafood supply and labor impacts (Qu et al. 2021).

The National Oceanic and Atmospheric Administration (NOAA) is the trusted federal government authority on science, conservation, and management of a broad range of fish, wildlife, and cultural "trust" resources; fisheries; and fishing communities. The National Oceanic and Atmospheric Administration serves as a cooperating agency to BOEM, which is the lead federal agency for offshore energy exploration and development. In pursuit of NOAA Fisheries' mission to preserve marine life while practicing ecosystem-based management (EBM), the agency conducts economic and sociocultural research to support management by evaluating the benefits and costs of different activities, identifying and prioritizing needs, and encouraging policies that maximize societal benefits for communities that depend on these resources (e.g., fishermen, Indigenous communities, and coastal community members). The Northeast U.S. Continental Shelf (hereafter, referred to as "the Northeast Shelf") ecosystem, defined as the portion of the continental shelf extending from Cape Hatteras, North Carolina, to Nova Scotia (an



U.S. Wind Development Footprint

Stage	Wind area	Hectares
Atlantic OCS		
Lease Areas	**28 Lease Areas**	**948,678**
Wind Energy Areas (WEAs)	New York WEA (Fairways)	45,337
Call Areas	Central Atlantic Call Area	1,693,895
	South Carolina Call Areas	345,508
Request for Interest (RFI)	Gulf of Maine	5,553,562
Pacific OCS		
Lease Areas	**5 Lease Areas**	**151,123**
Call Areas	CA Call Area- Diablo Canyon	144,183
	CA Call Area- Morro Bay	19,592
	OR Call Area- Coos Bay	353,326
	OR Call Area- Brookings	115,948
	HI Call Area- Oahu North	62,110
	HI Call Area- Oahu South	134,125
Gulf of Mexico OCS		
WEAs	Option I and Option M	297,310
Call Areas	Gulf of Mexico Call Area	12,020,000
U.S. Total Area		
TOTAL **Lease Hectares** to date		**1,099,801**
TOTAL **Planning Hectares** to date*		20,487,586

FIGURE 1. Federal commercial offshore wind leasing footprint in the U.S. Outer Continental Shelf (OCS) regions. Note: Offshore wind development (OWD) areas are continuously changing. All values represent the total footprint as of November 2022. Vineyard Wind 1 and South Fork Wind are the first two commercial-scale wind development areas approved in federal waters and account for 31,970 ha (79,000 acres). There are two projects under operation: the Block Island Wind Farm in Rhode Island state waters and the Coastal Virginia Offshore Wind research lease. Asterisk indicates that the total footprint reported for planning areas is anticipated to be winnowed down through the Bureau of Ocean Energy Management's lease area identification process.

area of 260,000 km^2), is the nation's vanguard for OWD. Therefore, it was the first NOAA Fisheries region to identify the agency's role in the U.S. OWD process (Table 1) and to assemble teams of scientists to begin addressing regulatory analyses, mitigating the impacts of OWD on scientific surveys, and developing areas of research to understand the potential interactions between OWD and NOAA Fisheries trust resources. Given the connectivity of habitats in the marine environment, the coexistence of OWD with a healthy marine ecosystem and sustainable fisheries would greatly benefit from a clear and comprehensive research plan. Such a plan will help to avoid permanent adverse impacts, assist in understanding the costs and benefits of OWD, and support continued sustainable seafood harvesting.

Much of our understanding of OWD impacts comes from Europe, where offshore wind has existed for four decades. Several European countries have identified and implemented integrated research approaches within their territorial seas to address priorities at both the single wind farm scale and the territory scale. For example, within Belgium's 238-km^2 portion of the North Sea, all offshore wind projects are required by law to implement a two-tiered research and monitoring system (Degraer et al. 2019). Tier 1 requires project monitoring of key impacts on the marine ecosystem, whereas tier 2 implements more focused

TABLE 1. Central themes addressed by National Oceanic and Atmospheric Administration (NOAA) Fisheries in the U.S. offshore wind development process.

Theme	Description
1. Support regulatory processes	This includes science to support the planning, development, regulatory review, and impact analysis of regional wind projects on the ocean environment (e.g., physical and chemical processes), marine trust resources (e.g., fish and invertebrate species, essential fish habitat, and protected species), fishing operations, and fishing communities. These are activities conducted by the Northeast Fisheries Science Center (NEFSC), Greater Atlantic Regional Fisheries Office (GARFO), and the NOAA Fisheries Office of Protected Resources to address regulatory responsibilities under the National Environmental Policy Act, Magnuson–Stevens Fishery Conservation and Management Act, Endangered Species Act, and Marine Mammal Protection Act.
2. Mitigate impacts to NOAA Fisheries scientific surveys	This refers to NEFSC-led activities to mitigate impacts of offshore wind projects on scientific surveys (see Table 4).
3. Advance science to understand interactions with NOAA Fisheries trust resources, the marine ecosystem, and fishing industries/communities	This includes research conducted by the NEFSC and collaborators to understand offshore wind effects in order to inform fisheries management actions and wind project permitting decisions.
4. Advance the science of mitigation for NOAA Fisheries trust resources and fishing industries/communities where impacts cannot be avoided	This includes research conducted by the NEFSC and GARFO that will provide recommendations and a greater degree of certainty to the development process by promoting ocean co-use and the conservation of marine ecosystems simultaneously.
5. Advance data management methods	This includes methods and approaches for standardizing and harmonizing data collection, data storage, and data dissemination.

monitoring and research based on an integration of ecosystem understanding gained from tier 1. This integrated and consistent approach applied over time has allowed officials the ability to advance understanding from the short-term and local-effect scale to benefit scientific understanding of the longer-term and regional scale (Degraer et al. 2019). Despite these strides, the absence of preconstruction baseline data, coupled with the lack of a cross-boundary research plan prior to the large-scale build-out that now exists, has limited scientists' ability to understand how OWD has affected those ecosystems (Wilding et al. 2017). This underscores the need to develop a regionally integrated research plan in the United States before OWD commences (Gill et al. 2020). The international importance of this work is further underscored by the work of the multiple International Council for the Exploration of the Sea (ICES) working groups that are focused on offshore wind science (e.g., ICES 2021a, 2021b, 2021c).

An important step toward developing a regional research plan is to establish key offshore wind–fisheries science priorities for the Northeast Shelf ecosystem. A number of recently convened workshops, presentations, and guided panel discussions has brought together technical subject matter experts, fishing industry experts, wind industry members, and other stakeholders. These efforts have yielded several published documents that characterize priority marine research needs in the form of recommendations, goals, data gaps, and questions for future endeavors. Some of the documents cover a comprehensive array of research needs, including those associated with biological and physical habitat, ecological interactions, human dimensions, fisheries data collections, cumulative impacts, and data collection methods (MADMF 2018; NOAA 2023). Others were focused on specific topics, such as the benthic impacts of OWD (Degraer et al. 2021) or the effects of sound and vibration on fish and invertebrates (e.g., Popper et al. 2021). Still others offered perspectives of a specific stakeholder group, such as the fishing industry (RODA 2022), or were focused on a specific subset of wind energy areas (Petruny-Parker et al. 2015; MADMF 2018). These documents offer a wealth of scientific information and stakeholder perspectives that can inform the development of a regionally integrated science plan.

The purpose of this paper is to identify research priorities for the NOAA Fisheries Greater Atlantic Region from our perspectives as fisheries scientists or managers at NOAA Fisheries who are actively engaged in OWD science. This was done by first conducting a comprehensive review of existing documents that provided research needs and then using this information, combined with our collective knowledge and expertise, to formulate a list of priority research areas for the NOAA Fisheries Greater Atlantic Region. We have intentionally avoided ranking research priorities to encourage individual researchers and interested parties with the expertise and capacity to contribute to addressing any of the identified research needs based on available resources. In this paper, we present the method by which we collected existing information, the type of information that was extracted from each document, and the thought process used to identify research priorities. We then present the research priorities together with metadata characterizing how, where, and by whom these research priorities should be addressed. Finally, we highlight how this information will inform a regionally integrated science plan for offshore wind and fisheries for the Northeast Shelf ecosystem as well as other regions of the United States and how it will contribute to regional marine resource management needs and actions.

METHODS

We compiled documents from the United States that provided priority marine research needs, including syntheses of existing offshore wind–fisheries science, reports, and science plans. These documents were from regional, cross-sectoral working groups; federal and state agency websites; and nongovernmental organization (NGO) websites. Although the majority of the documents resided in the gray literature, we also conducted a traditional academic literature search using the key words "offshore wind"; "renewable energy"; "syntheses," "impacts," or "recommendations"; and "fish" or "fisheries" in the United States using Web of Science and Google Scholar to ensure a comprehensive search.

For each relevant document, we extracted the specific marine science research needs related to OWD. This large list was reduced in the following ways: research needs that were redundant with each other were entered into our list only once; those that were outdated or already sufficiently addressed were not included in our list; and those that addressed similar research priorities using different methodologies were entered only once into our list but information on their methodologies was retained in the "available methods or approaches" column in one of our tables. Using this reduced list, individual research questions were formulated and placed into categories according to the research priority that they addressed (e.g., energy emissions–electromagnetic field [EMF] impacts, cultural–traditional values, economics–impacts and costs, etc.). In some instances, priority research questions were refined or expanded from marine science needs culled from existing documents to more closely align with NOAA Fisheries' mission (e.g., survey mitigation). The final result was a list of research priorities and specific questions to be addressed within each priority. Criteria that were used to identify research priorities included importance to NOAA Fisheries' mission, urgency with which the research is needed, and the ability of the research to contribute to emerging knowledge and reduce uncertainties associated with ecological impacts, human dimension interactions, or fisheries management processes. We grouped the resulting research priorities into the five themes that define NOAA Fisheries' role related to OWD (Table 1).

For each research priority, we characterized the following metadata to determine the relevance of a given recommendation to NOAA Fisheries priorities:

1. Research priority: a priority area of scientific need that is aligned with the NOAA science themes.
2. Research questions: clearly defined questions within each research priority to be researched.
3. Temporal scale and resolution, need for baseline data: when the research project should occur relative to the phases of OWD and the frequency at which it should occur; duration of the research project; and whether baseline data are needed.
4. Question stated as a null hypothesis: statement of the research question in the form of a null hypothesis.
5. Available methods or approaches: what, if any, current research methods or approaches are available at this time.
6. Location: identify whether the research question(s) should be addressed at specific OWDs or whether the question is relevant to all OWDs.
7. Entity that should lead: the entity that is best suited to lead this work (e.g., NOAA Fisheries, other federal or state agencies, research community, developers, etc.).
8. How NOAA Fisheries would be involved with this research: this may be through conducting, funding, or reviewing research; or providing scientific expertise or data.
9. Importance to NOAA Fisheries: specific issues within its broader processes/activities that NOAA Fisheries needs to address with this information.
10. Management implications: indicates how the information derived from this research would inform decision making on fisheries resources, essential fish habitat, protected species, fishery operations, and other NOAA trust resources.

RESULTS AND DISCUSSION

Our search for documents that provided OWD marine science research needs uncovered 17 relevant documents (Table 2). Federal agency reports were the most common type of document ($n = 7$), followed by state government

TABLE 2. List of documents that provided priority marine science research needs for offshore wind development (OWD; NGO = nongovernmental organization).

Source	Sector	General content area
MAFMC (2021)	Council	Impacts to fisheries-independent data collection; impacts to council-managed stocks; fisheries and socioeconomic indicators
NOAA (2023)	Federal	Benthic and oceanographic habitat impacts; ecological impacts; fisheries-dependent and fisheries-independent data collection; human dimensions; fisheries; fisheries management
NREL (2022a)	Federal	Cumulative effects
NREL (2022c)	Federal	Fish resources and habitat; reef effects
NREL (2022b)	Federal	Fish resources and habitat
Copping and Hemery (2020)	Federal	Noise; electromagnetic fields (EMFs); benthic and pelagic habitat impacts; oceanographic systems impacts; socioeconomics; collision; entanglement
Petruny-Parker et al. (2015)	Federal	Protected species; fish resource impacts; habitat impacts; impact-producing factors (IPFs); critical locations
BOEM (2021b)	Federal	Floating offshore wind effects on fisheries, ecology, and transit routes
NASEM (2022)	NGO	Effects on marine vessel radar
Kraus et al. (2019)	NGO	Protected species; IPF effects on specific organismal and population processes
RODA (2022)	NGO	Human dimensions; ecological; fisheries; stock; protected species; fisheries data collection; benthic and pelagic habitat; oceanographic; impact factors
Kershaw et al. (2022)	NGO	Habitat; fish, turtles, birds, and mammals
MADMF (2019)	State	Fish, fisheries, and human dimensions
MADMF (2018)	State	Fisheries; fish resources and habitat; fisheries management; human dimensions
NJDEP (2021)	State	Impacts on benthic and pelagic habitat; benthos, birds, bats, fishes, mobile invertebrates, sea turtles, and marine mammals; fisheries; fisheries-independent data collection
NYSERDA (2021)	State	Acoustic impacts on turtles, marine mammals, fish, and invertebrates; oceanographic stratification; birds; benthic impacts; bats
Maxwell et al. (2022)	Academic and NGOs	Floating offshore wind effects on ecological receptors; marine mammals; birds; benthos; habitat; IPFs

reports (n = 4) and reports led by NGOs (n = 4), a fisheries management council (n = 1), and a mixed team of academic researchers and NGOs (n = 1). Compilation of scientific research needs resulted in a list of 533 individual research needs. Thirty-three research priorities were identified and placed into one of the five NOAA Fisheries offshore wind science themes: 15 to support regulatory processes; 2 to mitigate impacts to NOAA Fisheries scientific surveys; 12 to advance science to understand interactions with trust resources, the marine ecosystem, and fishing industries/communities; 2 to advance the science of mitigation for NOAA Fisheries trust resources and fishing industries/communities; and 2 to advance data management methods (Table 3). Additional information for each theme is presented in Tables S1–S5 (available in the Supplement separately online).

Theme 1: Support Regulatory Processes

In order to achieve NOAA Fisheries' vision of resilient and healthy ecosystems, communities, and economies, science is needed to support the regulatory processes of OWD. One of the key gaps in information to support the regulatory process involves the impacts of OWD on the human dimensions, which need to be studied over time given the long-term and fluid nature of interactions between OWD and people. Offshore wind will impact fishing operations, including changes in fishing behavior and shifts in fishing grounds, target species, and effort displacement. Studies on the economic effects for individual fishermen, fishing entities, Indigenous Peoples, industries, support businesses, and the wider coastal communities are needed. Economic impact measures are often used to support the OWD regulatory process, but additional research about specific parametric inputs to these models, such as changes in cost (trip and fixed costs), value of permits and fishing businesses, new gear innovation, and lost fishing time, is needed. In addition, these models are explicitly static in nature and do not allow for substitution (such as between areas or fisheries or among recreational activities). Innovative data collections, including further

TABLE 3. Research priorities identified and their alignment with the National Oceanic and Atmospheric Administration (NOAA) Fisheries theme areas from Table 1. See Tables S1–S5 for complete metadata.

Research priority	Specific questions with research priority	Temporal scale, resolution, need for baseline data	Available methods or approaches	Location where it should occur
Theme 1: support regulatory processes				
Fishing operations, access, and safety	Will there be de facto exclusions on fishing? What are the de facto exclusions (e.g., insurance restrictions, turbine spacing, cable protection, radio interference, search and rescue restrictions)? What are the spatial operational needs and the fishing footprints of different gear types? What factors affect decisions to fish in wind farms and the frequency with which fishermen operate in wind farms (e.g., whether vessels avoid them completely; changes in effort within wind farms; the number of days wind farms are avoided due to sea states, crowded areas, traffic, and changes to wind patterns)?	30+ year duration; before, during, after construction; annually for the life of the project, including decommissioning; baseline needed	Fishing behavior studies/models; primary data collection/ survey protocols; expanded/improved fine-scale data collections through collaborations with industry; technical assessments that identify fishing vessels with gear in the water as a navigation status; collision/allision risk assessments with commercial fishing vessels; radar interference studies; vessel traffic/transit lane studies; fisheries-dependent data analyses of changes in fishing effort and location	All developments; regional assessments for all fisheries types; desktop data analyses and field interviews
Displacement and space use conflicts	Where is fishing effort distributed spatially and temporally? How will fishing pressure change inside or outside of wind farm areas? How will direct or indirect prohibitions on fishing affect other fishing areas? Where will displaced fishermen go to fish, and how will increased pressure elsewhere affect non-wind-farm-displaced fishermen?	30+ year duration; before, during, after construction; annually for the life of the project, including decommissioning; baseline needed	Baseline information (with limitations) can answer where fishing occurs and patterns over time; fishing behavior studies/ models; expanded/improved fine-scale data collections through collaborations with industry; models of fishing effort/CPUE; spatial analyses of fishing inside and outside of wind areas; models to assess changes in fishing pressure, level of fisheries impacted, and pressure elsewhere; primary data collection/survey protocols; fisheries-dependent data analyses of changes in fishing effort and location	All developments; regional assessments for all fisheries types; desktop data analyses and field interviews

TABLE 3. Continued.

Research priority	Specific questions with research priority	Temporal scale, resolution, need for baseline data	Available methods or approaches	Location where it should occur
Economics–impacts and costs	What additional costs (trip and fixed costs) will fisheries have (e.g., fuel/transit time, dockage, insurance, supply chain, new gear innovation, lost fishing time, devalue in permits with historic catch in wind farms)? How will revenue (i.e., owners, owner-operators, crew) be impacted by offshore wind?	30+ year duration; before, during, after; every 3 years for the life of the project; baseline needed	Adapt/expand NOAA Fisheries cost survey; primary data collection for lost fishing time and new gear innovation costs; economic models of supply chain cost changes, fuel costs; analysis of changes in landings revenue data; economic impact assessments	All developments; regional assessments for all fisheries types; desktop data analyses and field interviews
Fisheries resilience and adaptation	What is fishermen's perceived ability to adapt and respond to changes from offshore wind? What are existing vulnerabilities that could impact the ability of individual fishermen, businesses, and communities to adapt and remain fishing (e.g., business risk/uncertainty, consolidation, aging vessels and fishermen, limited access to capital/loans)? What are adaptation strategies that can assist fishing communities? What opportunities do fishermen have (e.g., new species, new gear), and what are the barriers to economic opportunities?	30+ year duration; before, during, after; every 3 years for the life of the project; baseline needed	Subjective resilience and adaptation scales/primary data collection on perceived adaptation; social impact assessments; community vulnerability assessments; expanding fishing community profiles	Regional assessments for all fisheries types; desktop data analyses and field interviews
Economics–shoreside business	How will shoreside fishing business revenue, sales, employment (processors, bait and tackle, markets, vertically integrated businesses) be affected by offshore wind development (OWD)?	30+ year duration; before, during, after; every 5 years for the life of the project; baseline needed	IMPLAN (Impact Analysis for Planning) input/output modeling; fisheries expenditures analyses; economic impact assessments	All developments; regional analyses; desktop analyses

TABLE 3. Continued.

Research priority	Specific questions with research priority	Temporal scale, resolution, need for baseline data	Available methods or approaches	Location where it should occur
Infrastructure–port and space use conflicts	How will offshore wind interact with fisheries infrastructure in ports? Can fisheries benefit from wind industry-funded updates to aging infrastructure? Will wind exacerbate existing gentrification pressure? How will wind affect existing port conflicts between recreational and commercial fishing (i.e., an increase in recreational fishing around turbines increases recreational industry/tourism/infrastructure)?	30+ year duration; before, during, after; every 5 years for the life of the project, including decommissioning; baseline needed	Primary data collection on port infrastructure needs; social indicator data analysis; ethnographic field work; analysis of dependence in ports; modeling of where landings may shift as a result; home port versus landing port analyses	All developments; regional analyses; desktop analyses; field work
Cultural–traditional values	How will wind affect cultural identity within fishing communities (place based and communities of interest)? How will fishing heritage and heritage tourism be impacted? How will fishing affect traditional uses of ocean space and sharing of knowledge?	30+ year duration; before, during, after; every 5 years for the life of the project, including decommissioning; baseline needed	Studies on fishing cultural tourism (i.e., change in the number/frequency of seafood festivals, blessing of the fleet, working waterfront festivals); primary data collection; NOAA Fisheries Northeast Fisheries Science Center (NEFSC) crew survey analyses; ethnographic fieldwork; continuation of NOAA Fisheries NEFSC Social Science Branch fishing community profile ground-truthing data collection	Regional analyses; desktop analyses; fieldwork
Individual well-being	How will OWD affect the well-being of fishermen, including job satisfaction, safety, mental health, and ability to sustain an economically viable career? How will OWD affect the social capital in fisheries?	30+ year duration; before, during, after; every 5 years for the life of the project, including decommissioning; baseline needed	Primary data collection–subjective well-being studies; social capital measures; some data will be collected through the NOAA Fisheries crew surveys every 3–5 years	All developments; regional analyses; desktop analyses; fieldwork

TABLE 3. Continued.

Research priority	Specific questions with research priority	Temporal scale, resolution, need for baseline data	Available methods or approaches	Location where it should occur
Equity and environmental justice concerns	What are the environmental justice concerns in fishing communities (place based and communities of practice)? Are underserved communities displaced due to OWD? Are disadvantaged communities provided with the resources and empowered to participate in the process? How do underserved communities receive information? What resources are/can be made available to these communities? What are the best practices of procedural and distributive justice?	30+ year duration; before, during, after construction; every 5 years for the life of the project, including decommissioning; baseline needed	U.S. Census data; primary data collection targeting underserved members of the fishing industry; analysis of equity; evaluation of efforts to include environmental justice communities in regulatory processes	Regional assessments for all fisheries types; desktop data analyses and field interviews
Seafood supply, industry, and employment	How will offshore wind affect the seafood industry, seafood supply, and regional welfare? How will OWD affect the fisheries job market (e.g., deter fishermen from entering fishing, compete with the wind industry)? How will OWD impact crew labor, quality of workers, and transfer of knowledge? How will OWD affect the U.S. seafood supply and the nation's access to seafood?	30+ year duration; before, during, after construction; every 5 years for the life of the project, including decommissioning; baseline needed	U.S. Census data/employment data; IMPLAN modeling; primary data collection/survey protocols; analysis of NOAA Fisheries seafood supply chain data; monitoring of changes in the NOAA NEFSC crew survey; analysis of overlapping skills/jobs with OWD and fishing industry	Regional assessments for all fisheries types; desktop data analyses and field interviews
Ecosystem effects–cumulative effects	What are the cumulative effects of wind farm development aggregated across space and time?	30+ year duration; before, during, after construction; 2 years post-construction for initial analysis; updated every 2 years for the life of the project as more data become available; baseline needed	Desktop assessment that incorporates data from all developments (e.g., integrated ecosystem assessments [IEAs], assessments, fishery surveys/monitoring plans, literature review, socioeconomic analysis, etc.)	Desktop assessment that incorporates data from all developments

TABLE 3. Continued.

Research priority	Specific questions with research priority	Temporal scale, resolution, need for baseline data	Available methods or approaches	Location where it should occur
Catch composition	How does catch composition change in wind energy areas after construction compared to before (commercial and recreational fisheries target and nontarget catch)?	30+ year duration; before, during, after construction; annually for the life of the project, including decommissioning; baseline needed	Evaluation of fisheries-dependent data on changes in catch by species and gear type in areas around OWD; models of fishing effort/CPUE; expanded/improved fine-scale data collections	All developments; regional assessments
Ecosystem-based management (EBM)	Evaluate and deploy EBM approaches and tools to improve decision making	Early and prior to construction; baseline needed	Evaluating and deploying EBM approaches and tools to improve decision making	All developments; desktop analysis informed by field-collected data
Fisheries management–thresholds for impacts	What are the acceptable thresholds for changes in benthic and pelagic environments? What management actions should be taken when the threshold for adverse impact is crossed?	Prior to construction; baseline needed	EBM, IEA approaches	Subset of wind farms; initially the first projects to be built
Fisheries management–data and advice	What social, economic, and ecological data do fishery managers need to assess fishery impacts on multiple scales as a result of wind energy development? Will fisheries management organizations (New England Fishery Management Council, Mid-Atlantic Fishery Management Council, Atlantic States Marine Fisheries Commission, states) implement actions to address changes in removals or catch allocation? Will they implement actions to balance use conflicts? Will they consider how changes in fisheries-independent surveys that cannot access wind farms for sampling will affect stock assessments and the impact of additional uncertainty in management advice?	Early and prior to construction; initiate as early as possible; baseline needed	Statistical analysis of various fishery-dependent data sets; work currently underway comparing vessel trip report (VTR) and fishing footprint data to the longfin inshore squid *Doryteuthis pealeii* study fleet for spatial resolution and data accuracy	Desktop; regionally

TABLE 3. Continued.

Research priority	Specific questions with research priority	Temporal scale, resolution, need for baseline data	Available methods or approaches	Location where it should occur
Theme 2: mitigate impacts to NOAA Fisheries scientific surveys				
Fisheries management–survey access and advice	How do changes in survey approaches (design and methods) affect the provisioning of scientific advice?	Early and prior to construction; baseline needed	Simulation experiments (e.g., Observing System Simulation Experiment method); Marine Strategy Evaluation to examine impacts, new approaches on management advice	Desktop modeling; workshops
Survey impacts mitigation	Can alternate methods and advanced technologies augment or replace existing survey activity while maintaining time series, precision, and accuracy? Includes exploring whether or not given methods can be operationalized.	Early and prior to construction; baseline needed	Design and implement Northeast Federal Survey Mitigation Program for Fisheries, Ecosystem, and Protected Species surveys; validation and calibration studies; quantifying life history collections; assessment of workflows to incorporate new data streams	Desktop modeling; field experiments
Theme 3: advance science to understand interactions with NOAA Fisheries trust resources, the marine ecosystem, and fishing industries/communities				
Energy emissions–displacement by noise	Are trust resource species displaced by noise derived from OWD (preconstruction survey, construction, operation)? What are the spatial and temporal scales of effect?	5–10-year duration on a seasonal basis; longer depending on outcome of studies; before, during, and after; baseline needed	Noise monitoring during preconstruction and construction activities; long-term passive acoustic monitoring (PAM)	All developments
Energy emissions–impacts of noise	What are the effects of preconstruction survey noise, construction noise, and operational noise (i.e., sound pressure, particle motion, and substrate vibration) on shellfish physiology, shellfish settlement, fish physiology, fish movement, and fish behavior?	5–10-year duration; longer depending on outcome of studies; seasonally every year for first 5 years, then seasonally every 2 years thereafter; before, after; baseline needed	Laboratory/mesocosm studies examining response to impact-producing factors; noise monitoring during preconstruction and construction activities; long-term PAM; optical and video studies	In the lab and field for the set of noise conditions similar to a subset of developments

TABLE 3. Continued.

Research priority	Specific questions with research priority	Temporal scale, resolution, need for baseline data	Available methods or approaches	Location where it should occur
Energy emissions–electromagnetic field (EMF) impacts	How do fisheries species respond to EMF-emitting cables? Responses include behavior, movement, navigation, physiology, foraging, egg development, hatching success, and larval fitness. Are EMF-sensitive species aggregating or avoiding energized cables?	5–10-year duration; longer depending on outcome of studies; seasonally every year for the first 5 years, then seasonally every 2 years thereafter; before, after; baseline needed	Acoustic tagging and telemetry; fish sampling; direct measurements of EMF gradient in situ; concurrent laboratory studies to examine species- and life-stage-specific responses	Subset of developments; focus on developments where EMF-sensitive species are expected to be abundant and/or transit during migration
Habitat–benthic habitat impacts	What benthic habitats are present in the project area prior to construction, and how do they change during and after construction? For example, bottom types, sediment grain size, sediment organic content, biogenic, etc. Do they recover, and how long does this take?	5–10-year duration; longer depending on outcome of studies; seasonally every year for the first 5 years, then seasonally every 2 years thereafter; before, after; baseline needed	Benthic habitat characterization and mapping (NOAA GARFO 2021a, 2021b); standard benthic monitoring methods (e.g., acoustic, optical, ground-truthing with grab samples); sediment profile and plan view imaging; transect sampling with before–after-gradient (BAG) design	All developments
Habitat–ecological function of benthic habitat	How does the ecological function of habitats change after construction? Ecological function equals habitat for spawning, settlement, food availability, growth, fecundity, etc.	30+ year duration; seasonally for the first 5 years, then seasonally every 2 years thereafter; before, during, after; baseline needed	Habitat characterization, mapping, and monitoring as above (NOAA GARFO 2021a, 2021b) plus monitoring of ecological function (e.g., fish maturity, size at age, etc.) using trawls, fish pots, acoustic tagging and telemetry; PAM; autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and optical technologies; feeding studies using gut content analysis and stable isotope analysis	Subset of developments

TABLE 3. Continued.

Research priority	Specific questions with research priority	Temporal scale, resolution, need for baseline data	Available methods or approaches	Location where it should occur
Habitat–artificial reef–benthic and epibenthic invertebrates	How do the density and species composition of benthic and epibenthic organisms on the turbines and scour/cable protections compare to densities and species composition on natural hard-bottom habitat in the project area? How does this change over time? Indicate which species, if any, are nonnative.	30+ year duration; seasonally for the first 5 years, then seasonally every 2 years thereafter; before, during, after; baseline needed	Standard benthic characterization, mapping, and monitoring (NOAA GARFO 2021a, 2021b); e.g., acoustic, optical, ground-truthing with grab samples; transect sampling with BAG design	Developments where natural hard-bottom habitats occur prior to construction
Habitat–artificial reef–finfish	What are the density, species composition, diet, and condition of finfish associated with the artificial reefs on turbines and scour/cable protections? How do these attributes compare with the density, species composition, diet, size, condition, growth, and fecundity of fish that were present prior to construction? Indicate which species, if any, are nonnative.	30+ year duration; seasonally for first 5 years, then seasonally every 2 years thereafter; before, during, after; baseline needed	Fish monitoring methods, such as trawl, optical, acoustic tagging and telemetry; PAM; AUVs; ROVs; environmental DNA; stomach sampling and stable isotopes; methods should be consistent across wind projects for species × habitat × research question.	All developments; different subsets of species at each development
Habitat–impacts to pelagic habitat	How do the characteristics of the pelagic environment (i.e., upwelling, stratification, nutrients, vertical temperature profile, chlorophyll *a*, phytoplankton, zooplankton) change after construction compared to before? What is the spatial scale of effects?	30+ year duration; seasonally for the first 5 years, then seasonally every 2 years thereafter; before, during, after; baseline needed	Temperature, salinity, current speeds collected with oceanographic instrumentation, acoustic doppler current profilers (ADCPs), mounted on buoys, offshore wind structures; plankton surveys; sensor arrays deployed with BAG design; data collected to inform coupled biological–hydrodynamic models	All developments

TABLE 3. Continued.

Research priority	Specific questions with research priority	Temporal scale, resolution, need for baseline data	Available methods or approaches	Location where it should occur
Distribution–larval transport	How are the transport, settlement, and distribution of fish and shellfish larvae affected by turbine operation?	5–10-year duration; longer depending on outcome of studies; seasonally every year for first 5 years, then seasonally every 2 years thereafter; before, after; baseline needed	Temperature, salinity, current speeds collected with oceanographic instrumentation, ADCPs, mounted on buoys, offshore wind structures; plankton surveys; sensor arrays deployed with BAG design; data collected to inform coupled biological–hydrodynamic models	Wind developments that overlap spatially with shellfish fishing areas
Distribution–species distribution	How do the abundance and distribution of fishery species and protected species change after construction compared to before? How do they change within the wind farm, near the wind farm, and in the region?	30+ year duration; seasonally for the first 5 years, then seasonally every 2 years thereafter; before, during, after; baseline needed	Targeted surveys; acoustic tagging and telemetry; PAM; for large pelagics, potentially continue/expand long-term monitoring programs already in place in the area, such as conventional tagging programs (e.g., Cooperative Shark Tagging Program and Cooperative Tagging Center) and surveys and reports of catch data (e.g., Large Pelagics Survey, Marine Recreational Information Program, and VTRs)	All developments; focus on specific species at each development (e.g., scallops, where developments overlap spatially with scallop fishing grounds)
Contaminants	Do shellfish or finfish living on or near offshore wind structures have elevated contaminant loads compared to those prior to construction? Do contaminant levels exceed seafood safety levels?	30+ year duration; seasonally for the first 5 years, then seasonally every 2 years thereafter; before, during, after; baseline needed	Field-based sampling employing existing seafood safety monitoring protocols (e.g., FDA 2019)	All developments; focus on species known or suspected to feed directly in or around offshore wind structures
Ecosystem effects	What are the ecosystem-level effects of OWD? Example effects include stock-level effects, food web dynamics, functional feeding groups, ecosystem status indicator changes. How do these effects compare with other ecosystem changes, such as climate change?	30+ year duration; seasonally for the first 5 years, then seasonally every 2 years thereafter; before, during, after; baseline needed	Offshore wind-specific indicator development; IEAs; ecosystem models; ground-truth with field data	All developments

TABLE 3. Continued.

Research priority	Specific questions with research priority	Temporal scale, resolution, need for baseline data	Available methods or approaches	Location where it should occur
Theme 4: advance the science of mitigation for NOAA Fisheries trust resources and fishing industries/communities where impacts cannot be avoided				
Fisheries compensation–framework and monitoring methods	Which impacts should be included in compensatory mitigation programs (e.g., vessels, crew, shoreside)? What data are available and what methods should be used when evaluating revenue impacts, costs, and losses for compensatory mitigation programs? How should cumulative impacts be considered in compensatory mitigation programs? How should impacts be monitored and compensation estimates re-evaluated to ensure that estimates are accurate and effective?	30+ year duration; framework development should occur prior to construction; monitoring should occur during, after construction; every 3 years for the life of the project	Develop a comprehensive framework that addresses proper considerations for fisheries compensatory mitigation using best available scientific methods; develop monitoring guidance/methodologies for the life of the project to ensure that compensatory mitigation estimates are accurate and effective	All developments
Fisheries mitigation	What mitigation strategies are necessary to avoid, minimize, or reduce impacts to trust resources and the fishing industry? Are impacts to fisheries mitigated through a fair and equitable process? Are mitigation strategies effective to mitigate interactions and sustain our trust resources and fishing communities/seafood industry? Are stakeholders meaningfully involved and heard in decision making? What social license-to-operate challenges exist between OWD and fisheries?	30+ year duration; before, during, after construction; every 3 years for the life of the project for mitigation assessments	Develop decision support tools; analysis and assessment of mitigation measures; review of decision support tools and effective/meaningful engagement processes; analysis of fisheries engagement, burden/demand to decision-making processes	Regional assessments; all developments; desktop analyses
Theme 5: advance data management methods				
Data management–data standardization	Develop standardized data collection/sharing mechanisms, including quality assurance/quality control; define what should be measured by developers	30+ year duration; before, during, after; baseline needed	Gear standardization and calibration methods; paired vessel sampling	Desktop analysis; all developments

TABLE 3. Continued.

Research priority	Specific questions with research priority	Temporal scale, resolution, need for baseline data	Available methods or approaches	Location where it should occur
Data management–data systems	Develop and communicate new regional data systems	30+ year duration; before, during, after	Develop new or utilize existing data portals, such as Northeast Regional Association of Coastal Ocean Observing Systems, National Centers for Environmental Information, InPort, etc.	Desktop analysis

collaborations with the fishing industry, collecting fine-scale data, and primary data collections through survey protocols before, during, and after construction, would allow socioeconomic impact models to serve as effective tools for evaluating the effects of OWD on fishing communities. Although fisheries resilience and adaptation research has been conducted in the region for climate change, regulatory changes, and disasters (Pollnac et al. 2015; Seara et al. 2016; Young et al. 2019; Smith et al. 2020), further research is needed specific to offshore wind and fisheries interactions, including fishermen's perceived resilience as well as methods of adapting and ability to adapt to changes from OWD.

Social and cultural or nonmaterial effects, such as way of life, multi-generational connectivity to an industry, employment changes, social capital, social license to operate, mental health, and environmental justice concerns with OWD and fisheries, are also identified as research priorities. Social and cultural data and information are often very limited, and they vary in coverage and attributes and thus are not used to support regulatory OWD processes. A common and consistent framework with recommended metrics for evaluating OWD impacts (e.g., primary data collections, fishing behavior models, and social and economic impact assessments) is needed to evaluate socioeconomic effects. Broader, market-based effects were also identified as needing additional research, including effects on the insurance that vessels carry, effects on the supply of seafood, labor market impacts, and impacts on fishing-related infrastructure provision. These effects are likely location specific, necessitating in-depth community profiles to inform the types of market-related effects that may occur. Again, however, data are often limited, and consistent evaluation frameworks are needed.

Identifying and evaluating spatial conflicts and cumulative effects of OWD constitute another current gap in the information needed to support the regulatory process. Holistic approaches that consider OWD impacts on processes at scales relevant to populations and ecosystems, such as integrated ecosystem assessment (IEA), cumulative impact analysis (CIA), and EBM approaches, are needed to support regulatory decisions. The IEA approach is a multi-step process that allows for the evaluation of cross-sector trade-offs (Samhouri et al. 2014; Spooner et al. 2021). Integrated ecosystem assessments can be used to evaluate future OWD lease areas that have the least overlap with NOAA Fisheries trust resources and existing ocean uses. Cumulative impacts—that is, the spatial and temporal accumulation of impact-producing factors (IPFs) on physical, biological, economic, or cultural resources (BOEM 2020)—have been difficult to assess due to high uncertainty and limited understanding of cause–effect pathways (Gulka et al. 2022). The NOAA Fisheries trust resources and fishing operations may be affected by OWD throughout their spatial range and during each phase of project development, including by geotechnical site surveys prior to construction, operations, and decommissioning activities (Willsteed et al. 2017; Gusatu et al. 2021; NREL 2022a). Ecosystem-based management provides a framework for balancing the ecological and human dimensions of OWD through consideration of how ecosystem components, including humans, interact with management sectors across the entire ecosystem (Levin and Lubchenco 2008). The IEAs are an operational approach to EBM and can be used to integrate OWD impacts into broader marine resource management decisions and to ensure that all impacts, including cumulative impacts, are considered and thoroughly evaluated under the umbrella of EBM. As OWD will be concurrent with the research that is being developed to study its effects, iterative approaches that use the outcomes of current and future studies to update and inform IEA, CIA, and EBM models should be used, consistent with the conclusions made by European researchers (Degraer et al. 2019). Integrated ecosystem assessment methodologies are currently being applied to identify aquaculture opportunity areas (Riley et al. 2021) and conceptual OWD in the Gulf of Maine (S. Lucey, NOAA Fisheries, personal communication) and could be expanded to other regions of the United States.

Theme 2: Mitigate Impacts to NOAA Fisheries Scientific Surveys

The overlap between NOAA Fisheries surveys and OWD in the Northeast Shelf ecosystem is substantial. Offshore wind development has the potential to impact fisheries-independent surveys in four ways: preclusion of NOAA Fisheries sampling platforms from OWD areas due to operational and safety limitations; impacts on the statistical design of surveys (including random-stratified, fixed-station, transect, opportunistic, and other designs), which is the basis for scientific assessments, advice, and analyses; alteration of benthic and pelagic habitats and airspace in and around OWD, requiring new designs and methods to sample new habitats; and reduced sampling productivity through navigation impacts of wind energy infrastructure on aerial and vessel surveys (Hare et al. 2022).

There are currently 14 NOAA Fisheries surveys (Table 4) that will be impacted by current OWD in the Northeast Shelf ecosystem. As the footprint of OWD grows, additional surveys may be impacted and the impacts to existing surveys will likely increase (NOAA 2023), but the extent of the impacts and how to address those impacts are currently undefined. For example, the severity of the preclusion impact will depend on turbine foundation type (e.g., fixed or floating), turbine spacing, and cable spacing and burial, which will vary across OWDs. Preclusion impacts also vary according to the vessel and gear used for individual surveys. Mobile-gear surveys on large vessels and aerial surveys that cannot fly above OWD are expected to be the most impacted by preclusion if stations fall within OWD areas. The National Oceanic and Atmospheric Administration and BOEM released a Federal Survey Mitigation Strategy in 2022 (Hare et al. 2022) to outline the U.S. Government's approach to mitigating the impacts of OWD on NOAA Fisheries scientific surveys and the risks posed to living marine resource management. The strategy outlines actions that must be taken to develop and implement regional survey mitigation programs. The strategy outlines five goals that federal agencies should pursue: (1) mitigate any unavoidable impacts of OWD on NOAA Fisheries surveys; (2) evaluate and, to the extent practicable, integrate OWD monitoring studies with NOAA Fisheries surveys; (3) collaboratively plan and implement NOAA Fisheries survey mitigation with partners, stakeholders, and other ocean users; (4) adaptively implement the Federal Survey Mitigation Program and the Federal Survey Mitigation Strategy, recognizing the long-term nature of the surveys and the dynamic nature of OWD, survey technology and approaches, marine ecosystems, and human uses of marine ecosystems; and (5) share experiences and lessons learned with other regions and countries where OWD is being planned or is underway (Hare et al. 2022).

An adaptive, resourced, and comprehensive Northeast region survey mitigation program is needed to ensure that fisheries and protected species management needs can continue to be met, with fisheries, habitat, and ecosystem data that are accurate, timely, and precise (e.g., Hare et al. 2022). Specifically, continuity of new sampling methods with existing time series is critical to maintain the precision and accuracy of data collections. Advancing research methods and scientific practices for evaluating existing scientific survey designs and the identification, evaluation, and integration of new survey approaches are primary steps (Gill et al. 2020; Methratta et al. 2020). The effects of changing survey approaches on the provisioning of scientific advice can be examined using observation system simulation models (Regular et al. 2020). Research into new methods that can augment existing surveys is also needed. Testing, validating, and operationalizing remote sensing techniques like passive and active acoustics, environmental DNA, optical sensing technologies, uncrewed sampling platforms, expanded use of tagging, isotopic studies, and the use of artificial intelligence in automating species detection and identification were identified as priorities (e.g., MAFMC 2021; NEFMC 2021). All such research will need to ensure appropriate integration or calibration to existing time series. Ensuring that data streams from new or expanded data collections are effectively designed to

TABLE 4. List of National Oceanic and Atmospheric Administration (NOAA) Fisheries trust resource surveys that will be impacted by offshore wind development (OWD) and the impact mechanism that results in one or more of the four potential survey impacts (preclusion, statistical design, habitat, and sampling efficiencies).

Survey	Year started	Survey design	Primary data acquired[b]	Impact mechanism[c]
1. Autumn Bottom Trawl Survey	1963	Random stratified design with towed bottom trawl and, at select stations, towed bongo net and vertical sampling with CTDs[a]; North Carolina to Nova Scotia	Biomass, abundance, distribution, length, age, sex, weight, diet, and maturity of groundfish; plankton; and oceanography	Large vessel and mobile gear may not be able to tow gear or transit safely in wind farms
2. Spring Bottom Trawl Survey	1968	Random stratified design with towed bottom trawl and, at select stations, towed bongo net and vertical sampling with CTDs; North Carolina to Nova Scotia	Biomass, abundance, distribution, length, age, sex, weight, diet, and maturity of groundfish; plankton; and oceanography	Large vessel and mobile gear may not be able to tow gear or transit safely in wind farms
3. Sea Scallop Dredge Survey/ Integrated Benthic Habitat Survey	1979	Random stratified design with towed scallop dredge and line transect with towed camera (HabCam); at select stations, vertical sampling with CTDs; Virginia to Georges Bank	Biomass, abundance, distribution, size, and sex of Atlantic sea scallops *Placopecten magellanicus* and other benthic fauna	Large vessel and mobile gear may not be able to tow gear or transit safely in wind farms
4. Atlantic Surfclam and Ocean Quahog Surveys	1980	Random stratified design with towed hydraulic dredge; Virginia to Georges Bank	Biomass, abundance, distribution, size, and sex of Atlantic surfclam *Spisula solidissima* and ocean quahog *Arctica islandica*	Large vessel and mobile gear may not be able to tow gear or transit safely in wind farms; high risk of cable interactions due to dredge gear
5. Northern Shrimp Survey	1983	Random stratified design with towed modified commercial shrimp trawl; Gulf of Maine	Biomass, abundance, and length of northern shrimp *Pandalus borealis*; biomass, abundance, distribution, length, age, sex, weight, and maturity of groundfish	Occurs in area where floating wind development is expected; smaller vessel and mobile gear may not be able to tow gear safely in wind farms
6. Gulf of Maine Cooperative Bottom Longline Survey	2014	Random stratified design with fixed bottom longline (tub trawl); Gulf of Maine	Biomass, abundance, distribution, length, age, sex, weight, and maturity of groundfish; habitat data	Occurs in area where floating wind development is expected; commercial vessels with longlines may not be able to deploy and retrieve gear safely in wind farms
7. Ecosystem Monitoring Survey	1977	Selection of stations on Autumn and Spring Bottom Trawl surveys and additional fixed stations; plankton and oceanographic sampling with towed bongo nets and vertical casts of CTDs and plankton imaging instruments; North Carolina to Nova Scotia	Phytoplankton, zooplankton, ichthyoplankton, carbonate chemistry, nutrients, marine mammals, and seabirds	Large vessel may not be able to tow gear or transit safely in wind farms
8. North Atlantic right whale aerial surveys	1998	Aerial line transects with cameras and observers	Abundance and spatial distribution of North Atlantic right whales *Eubalaena glacialis*; dynamic area management	Flights currently occur at altitudes that are too low for safe transit and sampling through wind farms

TABLE 4. Continued.

Survey	Year started	Survey design	Primary data acquired[b]	Impact mechanism[c]
9. Marine mammal, sea turtle, and seabird ship-based surveys	1991	Stratified random start line transects with observers; biological and physical oceanography sampling at stations via vertical casts	Abundance and spatial distribution of marine mammals, sea turtles, and seabirds	Large vessel may not be able to transit and sample safely in wind farms
10. Marine mammal and sea turtle aerial surveys	1993	Stratified random start line transects with cameras and observers	Abundance and spatial distribution of marine mammals and sea turtles	Flights currently occur at altitudes that are too low for safe transit through wind farms
11. Seal abundance aerial surveys	1990	Targeted on haul-out sites and pupping colonies with cameras and observers; tagging individuals to account for availability from Virginia to Maine (nearshore)	Abundance, distribution, migration (tagging) of harbor seals *Phoca vitulina* and gray seals *Halichoerus grypus*	Flights currently occur at altitudes that are too low for safe transit through wind farms; habitat disturbance associated with OWD
12. Coastal Shark Bottom Longline Survey	1986	Fixed stations with Florida-style commercial bottom longlines from Florida to Delaware	Abundance, distribution, length, age, sex, weight, diet, maturity, and migration of sharks	Commercial vessels with longlines may not be able to deploy and retrieve gear safely in wind farms
13. Cooperative Atlantic States Shark Pupping and Nursery Survey (COASTSPAN)	1998	Random stratified and fixed station with longline and gill net from Florida to Delaware (estuarine and nearshore)	Abundance, distribution, length, age, sex, weight, diet, maturity, and migration of sharks	Habitat disturbance associated with offshore export cable landfalls
14. Cooperative Shark Tagging Program	1962	Volunteer tagging by shark fishermen from North America and Atlantic Europe	Distribution, migrations of sharks	Increased fishing opportunity in OWD may lead to increase tagging capacity

[a]Conductivity, temperature, and depth instruments.
[b]All surveys contribute data to ecosystem status reports, stock assessments, essential fish habitat designations, and life history studies for fish and protected species.
[c]Offshore wind development on the continental shelf will introduce large amounts of new hard bottom and vertical structure. In addition, various impact-producing factors (e.g., oceanographic wind and ocean wakes, sound, electromagnetic fields, and others) can alter habitats. These habitat changes could affect how certain species and life stages are spatially distributed, which could have population-level consequences. Each survey conducted at the Northeast Fisheries Science Center will need to consider whether current survey designs adequately sample the population ranges of their target species or whether habitat changes due to OWD will introduce the need to change survey location, frequency, duration, and spatial resolution.

support scientific operations and data users and contribute to management advice (i.e., operationalizing the technologies) remains a key challenge, in part because of underinvestment and the complexity of integrating and maintaining large new data sets (e.g., Goodwin et al. 2020). Due to the importance of life history information, the need for biological sample collections must also be considered.

Theme 3: Advance Science to Understand Interactions with NOAA Fisheries Trust Resources, the Marine Ecosystem, and Fishing Industries/Communities

Understanding the interactions between OWD and NOAA Fisheries trust resources, the marine ecosystem, and fishing industries/communities will require long-term, cross-sectoral collaborations among state, federal, academic, and NGO scientists as well as the fishing community, Indigenous communities, and wind developers. These questions are large in spatial and temporal scope, and our ability to address them successfully will depend heavily upon the combined knowledge base, expertise, and resources of the research community. Because OWD will occur in a dynamically changing ecosystem (Pershing et al. 2021; Friedland et al. 2022), it is critical to collect a minimum of 3 years of robust baseline data for all field-based studies in order to accurately characterize both the spatial and temporal variability of the system prior to construction (Petruny-Parker et al. 2015; ROSA 2021). This will enable researchers to account for the range of natural variation in statistical models, to accurately estimate IPF effect sizes, and to disentangle the effect of IPFs from background variability.

Direct effects of energy emissions (i.e., noise and EMFs) on NOAA Fisheries trust resources were identified as research priorities by our study. Alterations to the soundscape will occur during preconstruction surveys, construction, operation, and decommissioning (Mooney et al. 2020). These changes can cause sublethal physiological effects and mortality as well as changes in movement, behavior, communication, habitat utilization, migration patterns, and vital population rates, such as growth, reproduction, and mortality (Roberts and Elliott 2017; de Jong et al. 2020; Jones et al. 2021; van der Knaap et al. 2022). Electromagnetic fields emitted by the network of sub-bottom interarray and export cables alter the surrounding EMF and have the potential to affect behavior, movement, and migratory patterns throughout the entire operational phase of wind projects (Gill et al. 2012, 2020; Hutchison et al. 2020). Understanding the impacts of energy emissions will require complementary field and laboratory studies that focus on species and life stages that are expected to be impacted (Table 3).

Habitat changes, including the development of artificial reefs (Degraer et al. 2020), the modification of sediment grain size and organic content near structures (Coates et al. 2014), and changes in vertical water column properties (e.g., current flow, velocity, and direction), along with altered stratification of temperature and salinity (Christiansen et al. 2022; Dorrell et al. 2022), were all identified as research priorities. These changes can have multiple biologically relevant knock-on effects, including those effects on vital rates (Reubens et al. 2013; NOAA 2022), facilitation of nonnative range expansion (Coolen et al. 2020), and food provision (Mavraki et al. 2021).

Contamination of the water column and benthic sediments, uptake by benthic organisms, and biomagnification through the food web were also identified as a research priority. The anti-corrosives used to maintain the integrity of structures in salt water contain compounds such as bisphenol A and metals such as aluminum, zinc, and indium, which can leach out into the water and interact with the water column, sediments, and biota (Kirchgeorg et al. 2018; ICF 2020).

Theme 4: Advance the Science of Mitigation for NOAA Fisheries Trust Resources and Fishing Industries/Communities

Science to support environmental mitigation for NOAA Fisheries trust resources and mitigation for fishing industries and associated communities, including compensatory mitigation, is critical for providing certainty to the development process and for promoting ocean co-use and the conservation of marine ecosystems. The NOAA Fisheries' proposed definition of mitigation of impacts to NOAA Fisheries trust resources and fishing industries/communities is derived from the Council on Environmental Quality's National Environmental Policy Act (2022) regulations to avoid, minimize, and compensate (from the draft NOAA Mitigation Policy for Trust Resources; https://www.fisheries.noaa.gov/resource/document/noaas-draft-mitigation-policy-trust-resources). The Bureau of Ocean Energy Management also recommends practices for mitigating impacts to commercial and recreational fisheries and associated communities per the Council on Environmental Quality's regulations (Ecology and Environment 2014). Examples of science to support mitigation include regional spatial planning to inform siting of wind, trade-off analyses, and understanding the effectiveness of seasonal construction limits, bubble curtains, and other construction and operation methods that are designed to avoid or minimize impacts to marine life. Obtaining measurements that are necessary to quantify impacts to fishing industries/communities is also a priority. While NOAA Fisheries collects information on socioeconomic factors, such as operational costs and employment, data are not always as comprehensive, spatially explicit, or inclusive of all sources of short-term and long-term economic losses that might be incurred by regional fisheries affected by OWD. Regional comprehensive methodologies for evaluating impacts to fisheries for compensation evaluations will need to be developed and adaptive approaches will need to be taken as we continue to learn more about the impacts of OWD over time. Advancing science for mitigation will require collaborations among state, federal, and NGO scientists; fishing communities; and wind developers.

Theme 5: Advance Data Management Methods

Data management is an essential element of planning a successful collaborative program at the scale of OWD. Although not an explicit role associated with the protection of NOAA Fisheries trust resources, data management emerged as an important theme because of its implicit role nested within the needs and outcomes of ongoing and new research and monitoring projects. Five of the research recommendation documents specifically addressed the need for standardization of data collection efforts (Petruny-Parker et al. 2015; MADMF 2018, 2019; NYSERDA 2021; RODA 2022), and four explicitly called for publicly available data (Petruny-Parker et al. 2015; MADMF 2018, 2019; NYSERDA 2021). The reasons for standardization included (1) to clearly define what is required of developers (Petruny-Parker et al. 2015; MADMF 2019) so as to improve efficiency of permitting (MADMF 2018); (2) to ensure that the data collections are done appropriately to address the survey objective (Petruny-Parker et al. 2015); and (3) to enable the integration of studies over regional scales (MADMF 2019; RODA 2020:19). There is also significant concern that existing long-standing data collection efforts will be unable to operate in OWD areas. Therefore, OWD area-specific surveys may prove crucial to filling data gaps in time series necessary to inform management needs (Hare et al. 2022). Clarion calls for publicly available data are driven by the interest in ensuring maximum value of relatively rare and expensive oceanographic and fisheries studies (NYSERDA 2021) as well as providing transparency to the development and management processes (MADMF 2018). The prominent recommendation for publicly accessible data is a reflection of the increased expectation for rapid, easy, and efficient access to data through centralized network portals (e.g., Northeast Regional Association of Coastal Ocean Observing Systems, National Centers for Environmental Information, InPort, Environmental Research Division Data Access Program, Ocean Data Portals, Ocean Reports Tool, and GitHub). Stakeholders also recognize that data management cannot be taken for granted, as they have experienced difficulty in accessing data from existing public data collections, including NOAA Fisheries sources. Concerns that the existing data infrastructure is insufficient and needs modernization and that private interests will keep valuable information proprietary have precedent and are legitimate. A need that arises from this focus on data management is to explicitly prioritize planning and investment in the data management needs of novel data collection programs and changes to long-standing survey programs within NOAA Fisheries.

Conclusions and Path Forward

The United States is at the precipice of commercial-scale OWD in its offshore marine environment. As scientists and fisheries managers at NOAA Fisheries, we identified an initial set of research priorities relative to OWD in order to support the agency's role as the nation's leading steward of marine life. The research priorities are broad in scope, and although we have organized them into categories, these priorities are inherently intertwined. All of these research priorities will support the coexistence of offshore wind and sustainable fisheries by advancing our understanding of offshore wind interactions; enhancing our ability to avoid, minimize, and mitigate impacts; informing accurate and precise population assessments; and reducing regulatory and fisheries management uncertainties. The research priorities presented here should be considered as a starting point based on the best available science. The body of knowledge regarding OWD and its interaction with the NOAA Fisheries themes identified in Table 1 is rapidly growing. The focus of OWD science is expected to evolve and continue to be refined as studies progress and as our understanding grows. We wish to highlight that the research priorities presented here are not representative of NOAA Fisheries policies; rather, this study represents the views and opinions of the authors, who are actively engaged in offshore wind science at NOAA Fisheries.

Strong leadership, combined with cross-sectoral collaboration, is essential for each priority science need. Collaborations currently underway include that between NOAA and BOEM; these agencies recently released an implementation strategy that describes their collaborative approach to mitigating the effects of OWD on NOAA Fisheries scientific surveys (Hare et al. 2022). The National Oceanic Atmospheric Administrion, BOEM, and the Responsible Offshore Development Alliance (a coalition of fishing industry members) embarked on a 10-year memorandum of understanding (MOU) in 2019. This MOU is intended to foster collaborative work between regional commercial fishing communities and federal regulators on areas of mutual interest. The Synthesis of the Science Workshop and report (NOAA 2023), an effort to compile and integrate existing scientific knowledge about offshore wind and fisheries interactions, constituted one of the initial products of the MOU and also served as one of the resources for the formulation of the science priorities described here. Some states have initiated preconstruction research plans in coordination with research institutions within their jurisdiction (e.g., NJDEP 2021; MA CEC 2022; NYSERDA 2022). The Northeast Sea Grant Consortium recently partnered with NOAA Fisheries and the

U.S. Department of Energy to provide research grants to study the coexistence of OWD with Northeast region fishing and coastal communities (DOE 2022). Offshore wind developers have also engaged the research community by supporting the Responsible Offshore Science Alliance and the Regional Wildlife Science Collaborative as well as providing some research funds (e.g., UMCES 2022). Collaborations are also underway among vessel operators to improve real-time data collection, create new uses of owner-collected data, and develop survey methods that may be compatible within OWD areas. The impact of offshore wind on fish, habitat, and fisheries is a multi-jurisdictional, multi-stakeholder, and multi-dimensional issue, and addressing these issues meaningfully will depend upon productive and successful collaborations.

New research endeavors will also foster opportunities for innovation in the areas of monitoring technology, experimental design, cooperative research, integration of fishermen's local and traditional ecological knowledge and Indigenous traditional ecological knowledge, and data management. Opportunities exist for applying new and developing technologies, including passive acoustic monitoring (PAM), environmental DNA, both aerial and underwater autonomous vehicles, remotely operated vehicles, digital aerial photography, automated sensors, stereo camera technology, artificial intelligence, and machine learning (e.g., Thomsen et al. 2012; Kresimir et al. 2016; van Parijs et al. 2022). Opportunities also exist to apply novel experimental designs, such as the before–after-gradient design (Methratta 2020, 2021); to combine new study designs with new technologies (e.g., PAM; van Parijs et al. 2022); and to configure existing platforms or develop new platforms for hosting large data sets to ensure data accessibility and transparency.

The work presented here is expected to have numerous applications. It underscores the urgent need for scientific advancement to understand and mitigate the impacts of OWD in the Northeast Shelf ecosystem. The identification of research priorities from the scientific and regulatory perspective can support the development of a formalized NOAA Fisheries science plan for the Northeast Shelf ecosystem, which would inform decisions about how to allocate funding and other resources for research. This would ensure that the limited available resources are focused on research of greatest scientific need, that resources are used efficiently, and that redundancies in resource use in the region are minimized. We anticipate that a NOAA Fisheries science plan could connect with a regionally integrated framework for research and monitoring led by regional entities and stakeholders, including the Responsible Offshore Science Alliance and the Regional Wildlife Science Collaborative. Stakeholders each have unique concerns; the exercise of identifying research priorities is one that each stakeholder group would benefit from undertaking in order to inform discussions about building a regionally integrated framework (MADMF 2018). We also expect that the work presented here can inform NOAA Fisheries' discussions with external partners, the wider research community, fishing industry members, Indigenous communities, and developers about how to target funding use for research. This information may also enhance international collaborations. For example, several ICES working groups that include many U.S. members are currently working on research products to aid in understanding OWD impacts (e.g., Dannheim et al. 2020). Although there is no near-term OWD planned in Canadian waters, projects totaling 3.6 GW off the coasts of Nova Scotia, Prince Edward Island, and New Brunswick have been proposed (CER 2022), which could potentially affect boundary-spanning species and ecosystems.

The Northeast Shelf ecosystem was the focus of our analysis because this is where OWD is slated to occur first in the United States. Other regions have specific suites of species, environmental, societal, and fisheries concerns, as well as other ocean co-uses, including aquaculture, oil, and gas. Although many of the research priorities identified here will be relevant for other regions of the United States, additional refinement, expansion, or adaptation of these priorities may be needed in order to address specific regional concerns in other parts of the country. For example, on the West Coast and elsewhere in the United States where OWD is planned for waters beyond the 50-m depth contour, floating wind platforms will likely be installed. The methodologies used to install and operate floating OWDs differ from those used for fixed foundations; thus, additional research priorities may be needed to address their impacts.

If current plans for offshore wind are realized, there will be thousands of wind turbines in the waters of the Northeast Shelf ecosystem by the year 2050. There is an imminent need to develop foundational research to build our knowledge base. Collaborative cross-sectoral research focused on high-priority needs and underpinned by the best available science can begin to fill knowledge gaps and ensure the coexistence of sustainable fisheries and offshore wind.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.